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**Propagation of Hydrogen Air Vapor Flame in
presence of Water Droplets**

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Introduction

The need to guarantee high safety standards in the production of nuclear energy represents a continuing challenge for the scientific research. The Fukushima Accident in 2011 has definitively re-sparked the interest of the hydrogen explosion risk mitigation. During this event, the complete destruction of the Reactor 2, has led to a significant release of radioactive dusts in the atmosphere with severe consequences on the environment which are still object of study.

By considering the importance of the nuclear energy production on the French territory, the government has decided to initiate and support scientific projects which aim to amplify the knowledge of all the phenomena related to the Hydrogen Risk. For this purpose, this scientific work is included in the framework of the MITHYGENE Project (ANR-PIA-RSNR) which was carried out by IRSN, the CEA, the ICARE Institute and various industrial and academic partners (EDF, Air Liquide, Areva, Jülich Research Institute of Germany).

The in-depth knowledge of the propagation of a hydrogen flame, in a confined environment, is crucial to understand the conditions for which, there is a transition from deflagration to detonation flames regimes which can compromise the structural integrity of the containment building. One of the aspects that requires a greater understanding, regards the impact that the activation of the cooling water sprays can have on the possible spread of flame.

The water spray injection can have two antagonistic effects on the flame propagation: an inhibition effect, related to the inerting potential of the water and a promoting effect, related to the induced turbulence.

The study of such phenomena goes through for the development of models that can represent the dynamics of propagation of flames in large volumes, which need therefore to be validated experimentally.

The aim of this thesis work is to better understand which role could have, the water spray injection, on the hydrogen air vapor flame propagation and to provide an experimental data base. The experimental campaign carried out takes into consideration different levels of hydrogen concentration and highlights the impact of the aspersion for an ascending, descending flame. For each of the conditions, is evaluated the sensitivity of different characteristic parameters of the spray, on the flame position over time, the propagation speed and the evolution of the pressure.

This scientific work is divided in 6 chapters.

The first chapter is dedicated to the context and to the State of Art about the context of severe accident in a nuclear power plant, the water spray generation and the combustion fundamentals. The second chapter is dedicated to the description of the experimental facility, the associated diagnostic with the fully description of the experimental procedure.

The third chapter shows the preliminary calculation conducted in order to evaluate the impact of the presence of the water vapor on the combustion temperature and pressure. Furthermore, 1-d simulations are conducted in order to evaluate the impact of the water vapor on the thickness of the flame and its laminar flame speed.

The fourth chapter is dedicated to the characterization of the spray, produced by 2 different monofluid nozzles. It is described the experimental setup and the 2 methods used in order to characterize the size of the droplets and the density of the spray.

The fifth chapter reports the experimental results about the interaction of the water spray and the upward flame propagation, with and without obstacles.

The sixth chapter, instead reports the result about the downward propagation flames, with and without water spray, in presence or not of obstacles.

In the last part, the conclusions and the perspectives are reported.

Chapter 1: Explosion Hydrogen in Nuclear Power Plants

This first chapter introduces the context of severe accident in nuclear power plants and summarizes the state of art of the interaction of a flame with water spray.

The first part is dedicated to the context of severe accident from the nuclear safety point of view. The mechanism which lead to hydrogen production and are presented the safety mitigation strategies, including activation of water spray system.

The second part is dedicated to the spray generation, technology, spray parameters and diagnostics relevant to our study.

The third part is focused on the combustion theory, including hydrogen air vapour mixture.

The last part will present the knowledge concerning the interaction between hydrogen flames and water sprays.

The structure of this chapter is schematically described in the following figure.

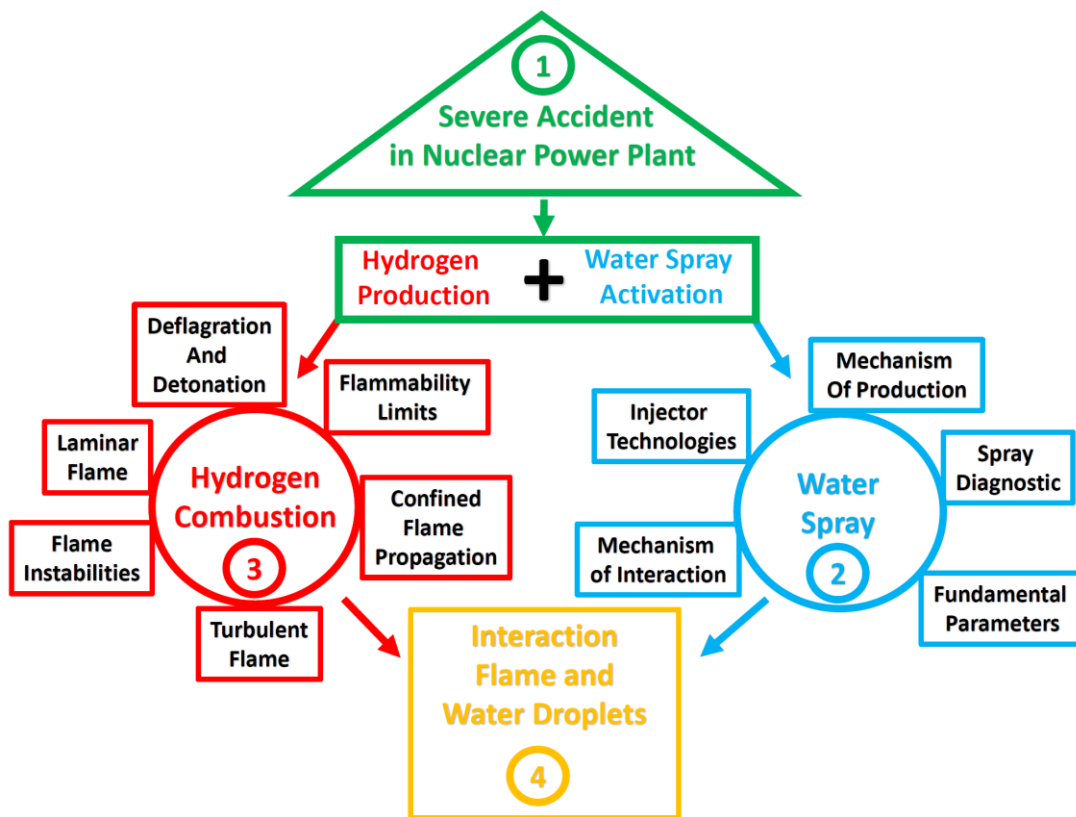


Figure 1: First Chapter Structure.

1 Nuclear Safety: Severe Accident Scenario

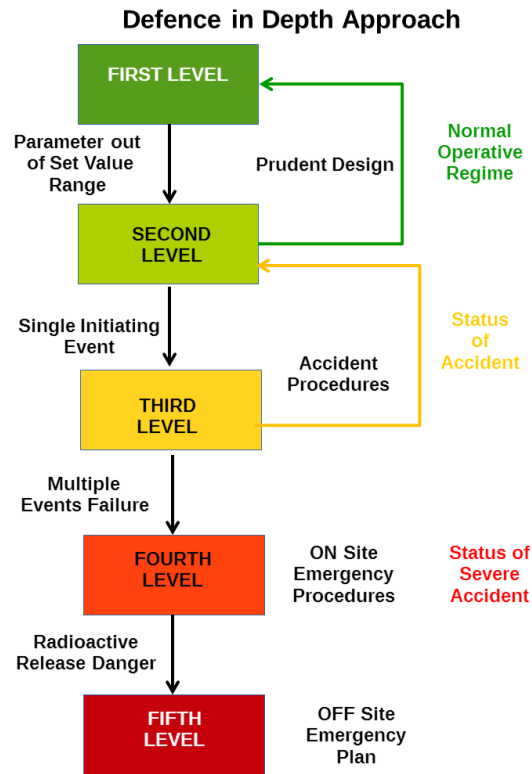
An open nuclear safety issue is the Management of the Hydrogen Risk in a reactor in Severe Accident context. In terms of Nuclear Safety, Hydrogen Risk is related to the possible endanger of the containment integrity or of the safety systems following combustion of the hydrogen released during the core degradation [1].

Historically, the Hydrogen Risk in the context of Severe Accident, was already identified as an issue in the first half of the last century. It arrived on the scene with the Three Mile Island accident in the 1979, where a partial nuclear meltdown, ended with a hydrogen deflagration which involved the Reactor unit 2. The Nuclear Authorities, since this event, have taken into account for all the existing and the future nuclear reactor, strategies in order to contain and to avoid this risk.

The normal domain of operations for the nuclear power plants facility has general rules and operating procedures designed for the prevention of anomalies and failures in components, equipment and systems. If an anomaly occurs, one of the essential physical parameters goes beyond their set values range and systems are designed to correct the anomaly and to let return the facility to its normal operating mode.

By considering the “Defence in Depth” approach [2], the status of accident occurs when a single fail initiating event, compromises the possibility to bring the reactor back to a safe conditions. Resources, basic safety functions and emergency operating procedures are implemented in order to ensure the integrity of the core structure and limit releases into the environment.

The Severe Accident scenario occurs when multiple human or equipment failures, could significantly damage the reactor fuel with more or less extensive melting of the reactor core [3]. In a Pressurized Water Reactor (PWR) during the development of a core melt, the reactor core remains dry for a considerable length of time. The temperature of the fuel rods rises and may locally reach levels that cause significant and irreversible core degradation. The mechanisms of this degradation are both chemical and mechanical and they may result: hydrogen production, fission product (FP) release, and molten corium formation.



1.1 Hydrogen Generation Mechanism

Hydrogen production, in case of Severe Accident, can be considered as the sum of two contributions:

1. In-Vessel Production (short term phase)
2. Ex-Vessel Production (long term phase)[4].

During the in vessel hydrogen production, the main H_2 contribution comes from the Zirconium oxidation in contact with hot steam. The oxidation reaction is: $Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$ (ΔH_{reac} between -600 and -700 kJ/mole) with a H_2 production estimated to be 0.0442 kg of H_2 per kg of oxidised zirconium. By considering an intact geometry, the rate of H_2 production In-is around 0.2 kg/s for a typical 1000 MW(e) PWR [5].

Because of the highest temperatures, the UO_2 can liquefy with a relative loss of geometry of the core as show in Figure 3. In this case the hydrogen production comes from the interaction U-Zr-O

but this production can be lower than the previous one. The 100% of the Zr-oxidation of the core inventory defines the theoretical upper limits for the hydrogen production. However, it is not possible to reach this limit because the fuel assemblies do not allow the complete clad oxidation.

During the Ex-vessel phase, there are several sources of H_2 production. In this scenario, the uranium may come into contact with steam, through the release of corium from the reactor pressure vessel into a flooded cavity [2] as shown in Figure 4 . The mechanisms which contribute to a further H_2 production are:

3. Reaction of Core debris with water (when corium is released in the flooded cavity)
4. Corium- Concrete Interaction (when corium is released in a dry cavity)
5. Metal components
6. Corrosion Reaction of the Zinc related to paint and galvanized steel used
7. Radiolysis of the water (significant on the long term period)

Initially, hydrogen is released in the containment atmosphere which is composed of air and steam. Hydrogen, due to its low density, has a great role in altering condensation on the walls and steam diffusion. Convection may thus be altered, and the entire contained gaseous volume or only part of it, is set in motion as a result.

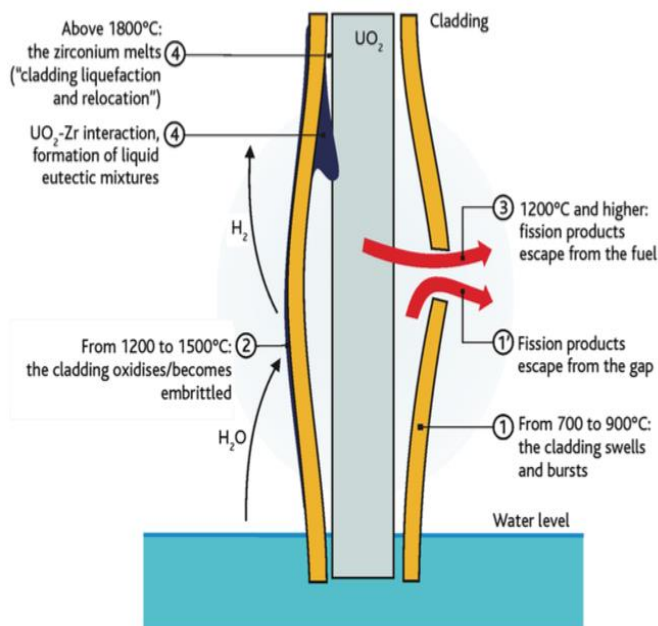


Figure 3: Degradation mechanism of Fuel Cladding [2].

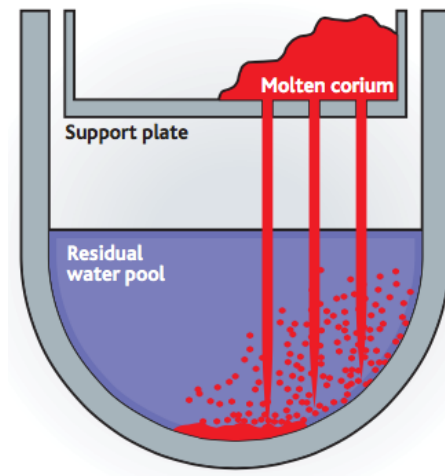


Figure 4: Schematic Diagram of molten corium [2].

1.2 Hydrogen Risk

Depending on the mixing, if a considerable hydrogen stratification exists, local concentrations of hydrogen may become substantial, exceeding the lower flammability limit [6]. It is possible trigger a combustion event even with a weak energy source of a few mJ, such as an electrical power sources or hot spots.

The ternary diagram [7], showed in Figure 5, is used to define whether mixture composition is flammable and if some or all the amount of hydrogen will burn. The region in which is possible ignite a mixture is limited by the Flammability Limits and it is defined in the graph by the red curve.

In terms of composition, by considering the theoretical upper limit of Hydrogen amount (18%_{vol}) and the needed energy source (100 kJ) , a direct detonation event is less probable than a deflagration one (“weak explosion”). Despite this, it is possible to have a detonation event by starting from a deflagration one, through a transition. In fact, in presence of hydrodynamic instabilities and turbulence, under certain conditions, an initially laminar deflagration (1 m/s) may accelerate. The acceleration leads to fast combustion regimes as: fast deflagration (hundreds m/s), the deflagration-detonation transition (DDT more than 1000 m/s) and detonation which compromise the structural integrity of the containment building.

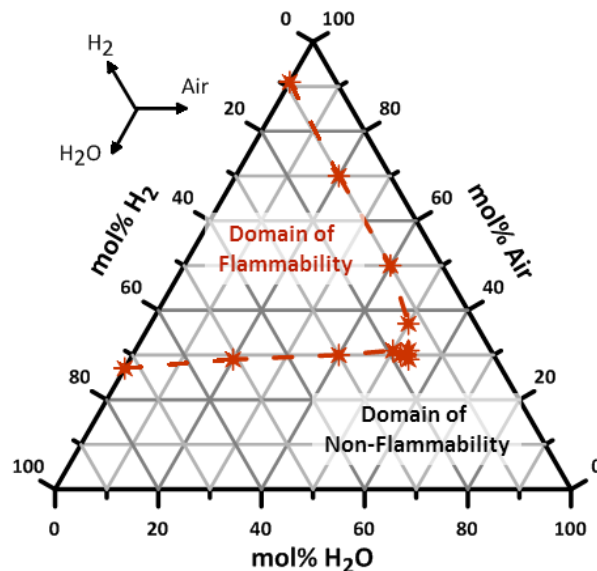


Figure 5: Ternary Diagram hydrogen-air-steam mixtures: Flammability limits [7].

According to the scenario, the concentration of Hydrogen changes during the development of the accident and the mixture can enter in a flammable region. Figure 6 represents an example of accident chain events in a PWR which is triggered by an initiating event, a leak on the primary circuit. There are identified six phases:

1. Normal Operation (dark green)
2. Leak on the primary Circuit (light green)
3. Release of Steam in the containment building (yellow)
4. Hydrogen production (dark yellow)
5. Hydrogen accumulation (orange)
6. Explosion (red)

For each phase is reported the ternary diagram is plotted with the burnable mixture domain (red highlighted) and the corresponding condition of the containment atmosphere (black line with red star). It is possible to notice that after the leak in the primary circuits (phase 2), water vapor concentration increases during steam release phase (phase 3).

After this phase, starts the core degradation with hydrogen release (phase 4).

The hydrogen concentration increases during the accumulation processor (phase 5) and the containment atmosphere becomes burnable and it leads to a hydrogen explosion (phase 6).

The severity of the explosion is strongly dependent on the initial conditions of the mixture, such as initial fuel concentration, temperature, pressure, source of ignition and level of confinement.

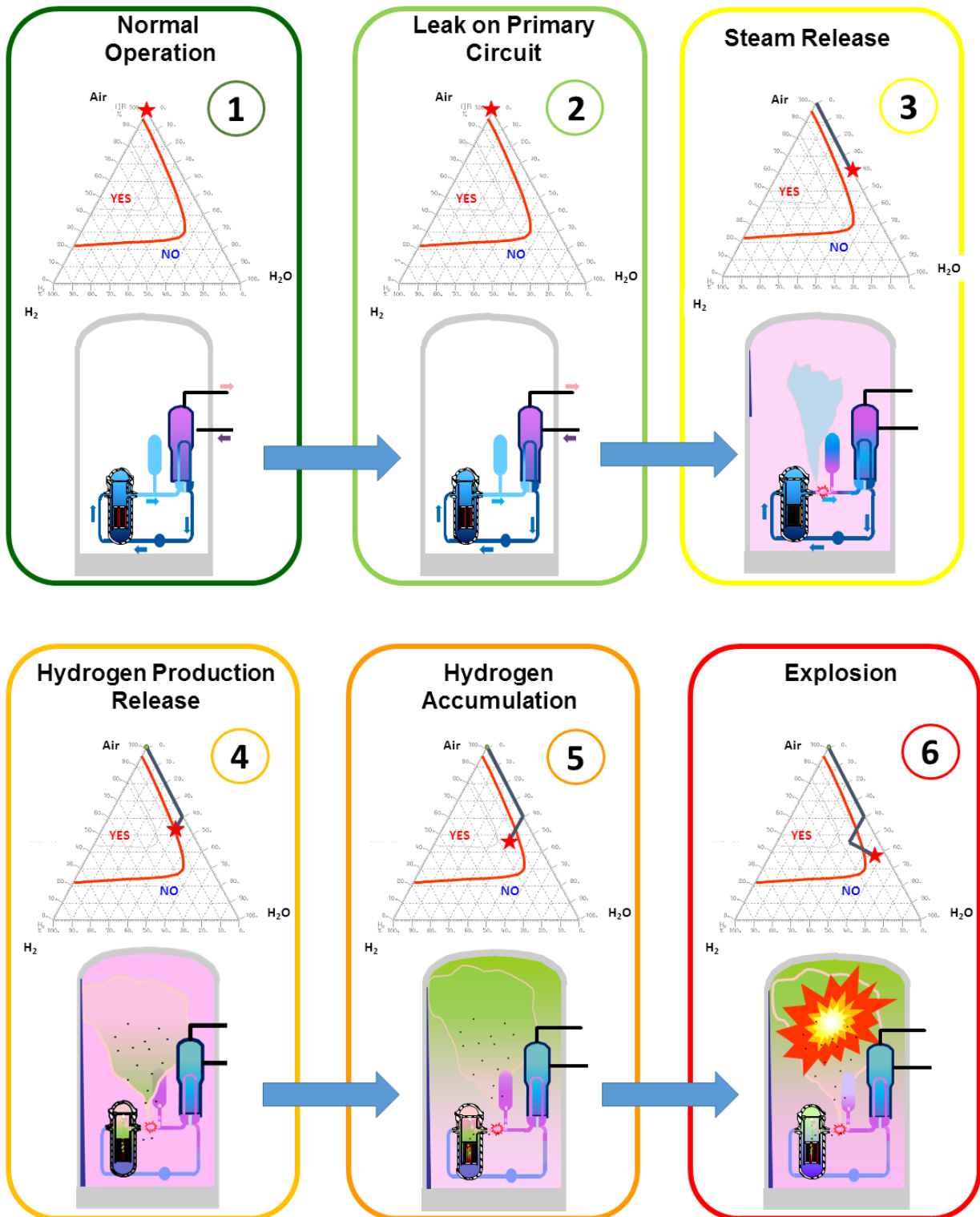


Figure 6: Example of Hydrogen Concentration as a function of the Accident Development.

1.3 Mitigation Strategies

In order to limit the severity of an H₂ explosion in a NPP, the French safety guidelines [8] are to limit the H₂ concentration to:

- Mean value below 8 % vol in order to avoid a complete combustion
- Local value below 10 % vol in order to avoid flame acceleration

Several strategies can be implemented during the design phase as diluting through an enlargement of the containment building volume. Other countermeasures are implemented during the normal and/or the accident state as [4] :

1. Pre- or Post-inertization
2. Hydrogen removal by Deliberate Ignition
3. Releasing Hydrogen by venting
4. Recombination of Hydrogen

The Pre-Inertization can be achieved, during the normal operation, by using N₂ and it is the most common measure in the BWR reactors. This kind of operation is not feasible if the free volume of the containment building, is too large or is accessible to the staff. In this case, only the post-accident inertization is feasible, by injecting inert gas, according to the containment atmosphere.

The deliberate ignition is made by using igniters (glow-plug, Spark, Catalytic) in order to initiate a slow deflagration when a flammable mixture, close to the lower flammability limits, arise. The releasing of hydrogen by venting, is done when the containment pressure exceeds the design limits, and usually it is done during the early stage of the accident.

The catalytic oxidation of H₂ using passive auto-catalytic Recombiners (PAR) will consume H₂ and maintain its concentration below the flammability domain. Most of them are constructed using catalytic materials (platinum or palladium) and housed in a metallic structure. The reaction rate is diffusion limited and its total recombination rate is nominally 0.3 g/s for a medium-sized re-combiner in an atmosphere containing 4% hydrogen [1]. The research is ongoing to optimize the efficiency and to reduce the probability of ignition due to the hot surface of the catalyst.

1.4 Activation of the Containment Spray System

The activation of the Containment Spray System (CSS) is one of the emergency operations employed during a severe accident development. It has the goal to contain the fission products and to avoid the containment building pressurization by reducing the temperature. The Severe Accident Management guidelines (SAMG) [9] give specific recommendations regarding the use of water spray. The water should be not injected at the beginning of the core degradation if the flow rate is not sufficient to compensate residual power. The nozzles are located on the top of the containment building in order to spread the spray to the whole volume. The nozzles employed in the French nuclear power plants are provided by the LECHER company and the most common is the SPRACO 1713A. This injector has an internal spiral shape which accelerates the liquid before to exit from a injection diameter of 9.5 mm. No mechanical system is present inside to prevent binding and blocking the nozzle. The cone of output is of 60° and the theoretical speed of the flux is about 13-17 m/s. The presence of several nozzles makes difficult the estimation of the main properties of the resulting produced spray.

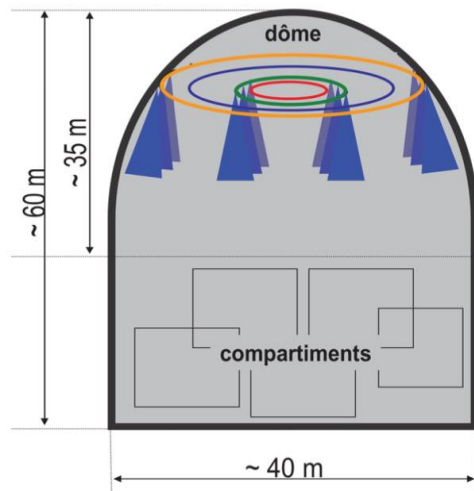


Figure 7: Spray Position in the Containment buildings.



Figure 8: Lecher SPRACO 1713A Nozzle.

To this purpose, Foissac [10] has conducted experimental investigations and simulation in order to characterize the LECHER's nozzles: Spatial Distribution of droplets, Mean Diameter d_{10} and d_{32} , Mean velocity axial, radial and normal/radial, Size Distribution of droplets, Relationship size/velocity. In Table 1 are reported the main results of the stability tests conducted after 30 s and 30 min of activation of the hydraulic pump, at 3.5 bar. The geometric diameter varies from 280

μm to $340\ \mu\text{m}$ and the Mean Sauter Diameter from $430\ \mu\text{m}$ to $520\ \mu\text{m}$. Between 5 and 25 cm of distance from the exit the mean velocities of the droplets is around 10-20 m/s. From the experimental and simulated results, in presence of one or more nozzles, the droplet fragmentation phenomenon is more probable than the coalescence one. This suggest that the size of the droplets could decrease during the falling.

	Average	Minimum	Maximum	Dispersion	Value (30 min test)
D10	$316\ \mu\text{m}$	$313\ \mu\text{m}$	$318\ \mu\text{m}$	$1.4\ \mu\text{m}$	$313\ \mu\text{m}$
D32	$521\ \mu\text{m}$	$511\ \mu\text{m}$	$534\ \mu\text{m}$	$7\ \mu\text{m}$	$518\ \mu\text{m}$
Axial Velocity	15.8 m/s	15.6 m/s	15.9 m/s	0.1 m/s	15.7 m/s
Radial Velocity	7.7 m/s	7.6 m/s	7.8 m/s	0.1 m/s	7.8 m/s

Table 1: Stability Test Spraco Nozzles [10].

The flowrate ($\sim 1\ \text{l/s}$ for each nozzle), the size of the droplets and the water flowrate employed by the CSS make prohibitive an experimental investigation with the same type nozzle, as showed in Figure 9.



Figure 9: General Aspect of the Lecher nozzle employed in NPPin case of 3.5 bar and ambient temperature [10].

2 Sprays Generation Fundamentals

In this part are introduced generalities about the sprays, in terms of:

1. Atomization Process,
2. Spray Characteristic Parameters and corresponding diagnostics,
3. Droplets generation technologies,
4. Mechanism of interaction with a surrounding gas phase.

2.1 Spray Production

Liquid droplets are employed in a very wide range of applications which are related not only to combustion fields, as the injection of fuel in turbine, internal combustion engines, rockets but also for industrial processes, medicine, agriculture and cooling, washing and humidifying processes.

A spray can be defined as a dispersion of droplets with sufficient momentum to penetrate the surrounding medium. The process which permits the generation of a spray is called Atomization and it can be defined as the fragmentation of a liquid structure by the conversion of energy, typically mechanical into surface energy. The atomization processes are usually described in the literature by considering simple example as breaking of droplets, jets and planar lamina, because from these simplest geometries, it is possible to understand most of the real and more complicated cases. The atomization process can be divided in two steps:

1. Primary atomization, close to the nozzle,
2. Secondary atomization, which is the break-up of drops further downstream.

2.1.1 Primary Atomization

The Primary Atomization consists of the production of large droplets, directly at the output of the injection nozzle orifices. The breaking of the liquid structure occurs usually because of the vibrations (wave oscillations) at the interface gas-liquid. In some conditions, these oscillations can be amplified, leading to the disaggregation or the stripping of the liquid portion from itself.

The kinetic energy of the liquid jet itself or of the gas flow, which interacts with it, is used to increase the amplitude of the wave oscillations and to reach different kind of fragmentations. As the energy of the system liquid-gas increases, it is possible distinguish 5 type of Regimes depending on the dominant forces causing the break-up:

1. Droplet Formation Regime,
2. Rayleigh Regime,
3. First Wind induced Regime,
4. Second Wind induced Regime,
5. Atomization Regime.

The droplet formation regime is observed when liquid is issued steadily into an immiscible fluid at low flow rates. The formation of droplet occurs at the nozzle exit similar to that of a gas bubble.

The Rayleigh regime occurs when the jet velocity increases. When a critical flow is reached, there is the formation of jets and droplets. This regime is dominated by growth of long wavelength, small disturbance amplitude due to the interaction between the liquid jet and the surrounding gas.

The first wind induced (transition) regime is dominated by similar axisymmetric long wavelengths, which induce a sinuous type of breakup. The disturbance amplitudes grow as the velocity is increased.

At higher velocities the second wind or turbulent induced regime is obtained. This regime is thought to result from the unstable growth of short wavelength waves. The breakup mechanisms are mainly due to mixing of coarse breakup mechanism and stripping from the jet body.

At even higher velocities, the Atomization Regime is observed, leading to almost instant breakup upon entry into the surrounding gas. It is useful to report a qualitative diagram of the different regimes, as function of the length of the jet breakup L_b and of the velocity of the jet u_0 as showed in Figure 10.

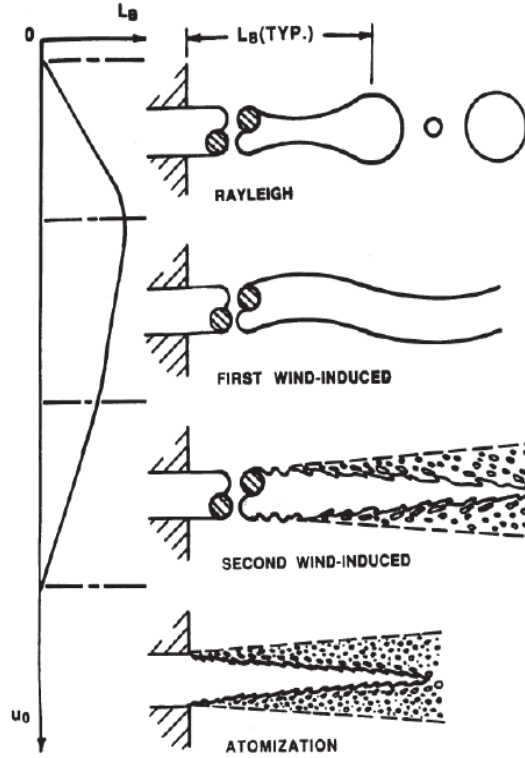


Figure 10: Breakup Regime as function of the L_b and u_0 .

2.1.2 Secondary Atomization

The Secondary Atomization [11] is related to a furthermore fragmentation, by starting from a system of large droplets already created. It useful to describe the various mechanisms of droplet breaking, by using, as variable, the Number of Weber, which represents the ratio between the aerodynamic forces, which cause the rupture, and the restorative surface tension force, which acts as stabilizing force.

The number of Weber (Equation 1) indicates the possibility to fragment a liquid. It depends on the density of the gas ρ_g [kg/m³], the relative velocity between gas/liquid v [m/s], the diameter of the orifice D [m] and the surface tension σ [Kg/s²]. The increasing of the Number of Weber, at the same liquid conditions, means the increase of the aerodynamic stress on the droplets. High value of We indicate higher tendency to breakup.

$$We_g = \frac{\rho_g v^2 D}{\sigma}$$

Equation 1: Number of Weber.

Another important adimensional number, useful to identify the effect of the forces on a droplet, is the Number of Ohnesorge (Equation 2) which depends on: the drop viscosity of the liquid μ_d [Ns/m²], the density of the drop ρ_0 [kg/m³], the initial drop spherical diameter d_0 [m] and the surface Tension σ [N/m]. The Ohnesorge number is the ratio between viscous force and surface tension force which both act to reduce the likelihood of a fragmentation. Usually when $Oh > 0.1$ the droplet viscous force is not significant.

$$Oh = \frac{\mu_d}{\sqrt{\rho_0 d_0 \sigma}}$$

Equation 2: Number of Ohnesorge.

It is possible to classify the break up modes by using the Number of Weber and the Number of Ohnesorge:

1. Vibrational [$0 < We < 11$ and $Oh < 0.1$],
2. Bag [$We_c=11 \pm 2$ and $Oh > 0.1$],
3. Multimode [$80 < We < 350$ and $Oh < 0.1$],
4. Sheet thinning [$35 < We < 80$ and $Oh < 0.1$],
5. Catastrophic [$We < 350$ and $Oh < 0.1$],

The Vibrational Breakup mode occurs when an unequal static pressure distribution is acting on a spherical drop and it cause an initial deformation of the shape. If the oscillations are important, the drop breaks into few large fragments. This kind of secondary atomization is not so easy to obtain because this mode is slower than the others.

The Bag breakup mode instead, is considered the most common mechanism of the secondary atomization. During this breakup, the drop is deformed until it takes the shape of a toroidal ring, before to create fragment with a mean of the 4% of the original diameter. As the number of Weber increases, it is possible observe the Sheet-Thinning Breakup where at the periphery of the drop, there is the formation of a sheet which will break up into a multitude of fragments and the process continues until all the drop is fragmented.

The Multimode Breakup is an intermediate mode which combines a bag mode with a Sheet thinning.

At high value of Weber there is the Catastrophic Breakup which is possible only at high initial relative velocities. The wave penetrates into the droplet causing breakup into a very large number of fragments. The practical application of this breakup mode are limited.

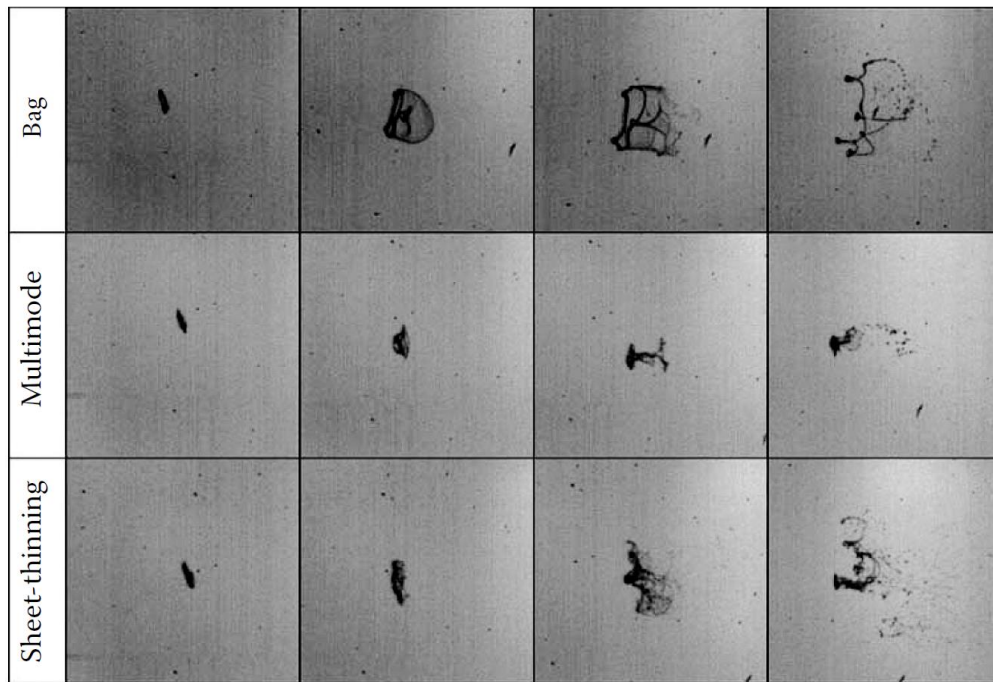


Figure 11: Secondary Atomization Break Up modes Picture Example [12].

2.2 Spray Characteristic Parameters

This section is dedicated to the characteristics of a spray.

2.2.1 Description of the Droplets Size: Characteristic Diameter

One of the basic spray characteristic is the average diameter of the droplets. Figure 12 gives an overview of the spray classification based on the droplets size. Water spray employed in nuclear safety application, are used to contain the radioactive aerosols and decrease the containment temperature. They fall in the droplets range for fire-fighting between 1000-100 μm .

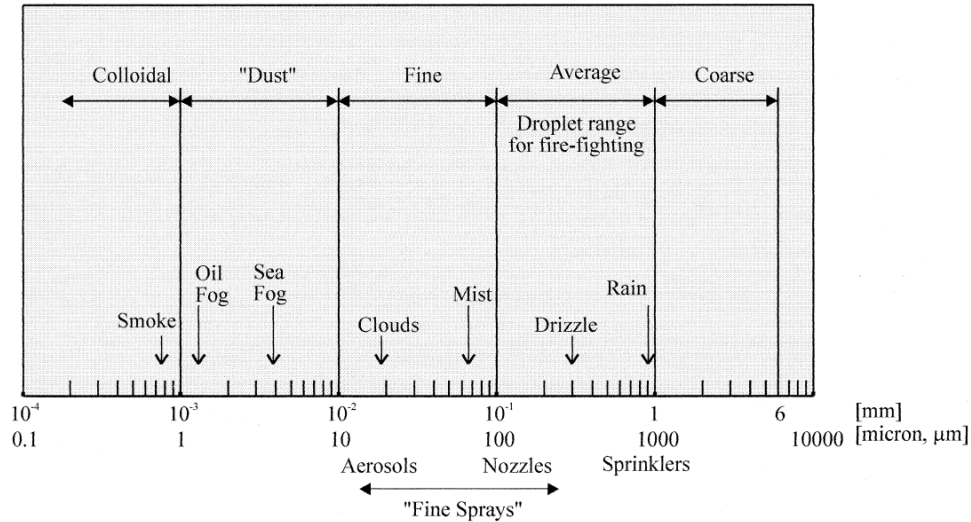


Figure 12: Spectrum of droplets Diameter [12], [13].

Because of the heterogeneous nature of the atomization process, real nozzles do not produce uniform spray in terms of droplet size at any given operating condition. For this reason, the spray is considered as a spectrum of droplet sizes distributed about defined mean value. A typical way to describe a spray distribution is to use histograms

Figure 13) and/or Frequency plot of the Number Distribution or Volume Size Distribution.

The Number Distribution describe the number of droplets/or particles falling in a certain range ($D + \Delta D/2$, $D - \Delta D/2$) of size.

The Volume Size distribution is another way to describe the range of droplet size and it allows to highlight what is the droplet size which provides the main contribution on the total mass or volume of the spray.

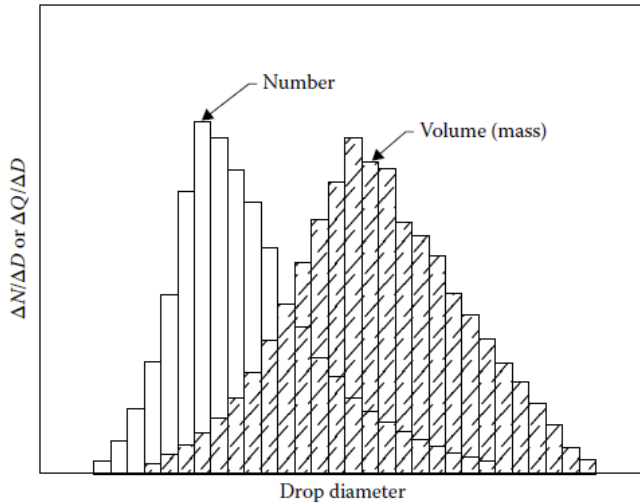


Figure 13: Droplet Size Histogram on number and volume [12].

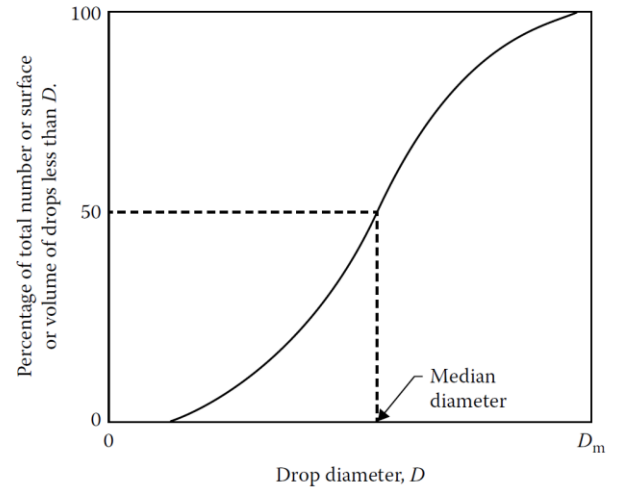


Figure 14: Cumulative Size Distribution Curve[12].

Another useful representation is the cumulative distribution which is the integral of the frequency curve distribution. Based on the number, surface area or volume, it provides information about the percentage of total number of droplets with size below a given size. Based on the cumulative function, it is possible to introduce a representative diameter of a distribution as:

- $D_{0.1}$ = the 10% of the total liquid volume has a diameter lower than this value
- $D_{0.5}$ = the 50% of the total liquid volume has a diameter lower than this value (Mass Median Diameter –MMD)
- $D_{0.9}$ = the 90% of the total liquid volume has a diameter lower than this value
- D_{peak} = value of Diameter corresponding to peak of drop size frequency distribution curve

In order to describe the droplets size involved in mass transfer and flow processes, it is useful to define the mean diameter:

1. Length Mean Diameter (D_{10}),
2. Surface Mean Diameter (D_{20}),
3. Volume Mean Diameter (D_{30}),
4. Sauter Mean Diameter (D_{32}).

The Length Mean Diameter D_{10} is the linear average value of all the drops in the spray.

D_{20} and D_{30} are defined as the diameter of a drop whose surface (or volume in case of D_{30}), multiplied by the numbers of drops, equals the total surface (or volume) of the sample.

The Mean Sauter Diameter (SMD) is important to represent a droplet involved in reactive process, as a droplets fuel or an evaporating droplets, because it takes into account the ratio Volume/Surface area. A simple relationship (Lefebvre [12]) allows to express all these mean diameter according to the effect to study:

$$D_{ab} = \left[\frac{\sum N_i D_i^a}{\sum N_i D_i^b} \right]^{\frac{1}{a-b}}$$

Equation 3: Mean Diameter Relationship.

Where: a and b depends on the application (for example Volume/Surface for evaporation (32), Surface/length for the absorption (D_{21}); I is the size range considered; N is the number of drop in the range I; D_i is the middle diameter of size range.

2.2.2 Spray Density

According to the special application, when nozzles are employed, it is necessary to define how much dense is the produced cloud. From the practical point of view, an important parameter which is used to characterize a spray is the number of particles for unit of volume called Number Density. In terms of design criteria, this parameter plays an important role in order to define a critical concentration necessary to the specific application (as extinguish a fire, paint a surface, cooling down an object).

It is common to use a spray density based on the liquid flowrate: Spray Flux Density [14] which refers to the amount of water spray in a unit volume (Lpm/m^3) or applied to a unit area (Lpm/m^2). A spray nozzle produces a non-homogeneous spatial distribution in the spray cone. According to the spray pattern produced by the injector, the spray could be highly concentrated in the centre of the cone (full cone) or less concentrated in case of hollow cone.

2.2.3 Spray Momentum

The momentum of a spray [14] is related to the spray mass, velocity and direction. It is influenced by many factors such as the droplet size, spray velocity, discharge pressure, cone angle, surrounding gas conditions. It will gradually decrease as the droplets size and velocity are reduced respectively by the evaporation and by the gravitational and drag forces.

With regard to an interaction with a flame, the spray momentum defines not only the capability to penetrate and react with a flame but also the entrainment rate of the surrounding air, water vapour and fuel into the flame plume.

The momentum can be express as the following relationship developed for the interaction between water mist and fire:

$$M_W = (m_{WL} + m_{WV} + m_{WA}) \times V_W$$

Equation 4: Spray Momentum [14].

Where m_{wl} , m_{wv} and m_{wa} are the mass of liquid water, water vapour and air entrained by the mist and V_w is the velocity vector associated to the water spray.

By considering the influence of the surrounding gas temperature, if the droplets are too small they will evaporate before to reach with a flame.

Furthermore, if the flame produces a significant opposite momentum (exhaust gas in case of fire or propagation wave in case of premixed flames), the water spray can be carried away from the interaction zone of interest or it can evaporate before reacting the flame.

In order to ensure an interaction droplet/flame, it is necessary that the spray has a momentum at least equal in magnitude and opposite direction to the one produced or induced by the flame.

2.3 Spray Diagnostic

The features of a spray can be defined by using several techniques as the mechanical counting, electrical pulse detections, high speed visualization techniques. The most used techniques, are related to the interaction of the droplets with a light source as: Phase Doppler Anemometry, Laser Particle Diffraction, Laser Particle Diffusion. Several commercial solutions exist for the particle

characterization because they guarantee measurement repeatability and they are not intrusive. The laser particle diffraction is used in this work in order to characterize the size of the produced droplets and laser particle extinction, to characterize qualitatively the density of the spray.

2.3.1 Phase/Doppler Particle Analyser

The Phase Doppler Anemometry uses a combination of phase and Doppler frequency signal in order to obtain a measure of a particle size and velocity [13]. A periodic signal, produced by 2 intersecting laser beam is scattered by the cross of the particle in a probe volume. The scattered light interferes at three detectors placed at carefully designed locations to generate sinusoidal Doppler burst signals with a frequency proportional to droplet velocity and with phase (for spherical particle) related by Mie scattering theory to droplet diameter [14].

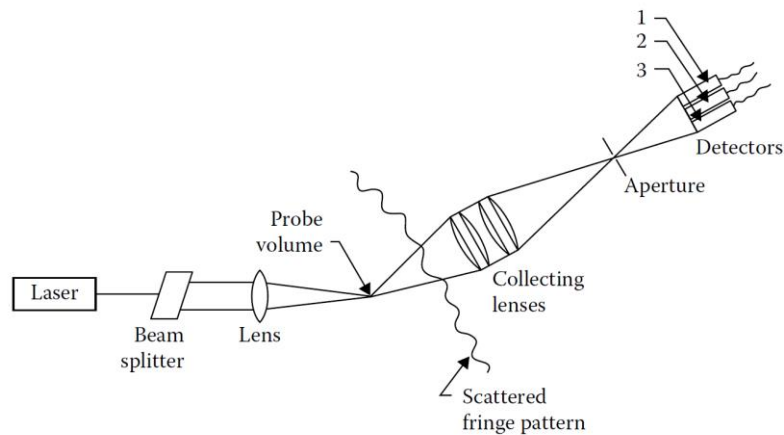


Figure 15: Schematic of the Phase/Doppler Particle Analyzer.

2.3.2 Laser Particle Diffraction

Laser particle diffraction technique are based on the theory of Fraunhofer and Mie. The theory of Fraunhofer describe the scattering of the light due to a particle when the optical properties of the particle are unknown. The Mie theory describes the interaction light/particle (schematically showed in Figure 16) making the assumption that the particles are spherical, the cloud is homogenous and the refractive index is known. Smaller the particles are, bigger is the diffraction pattern created by the Light as showed in Figure 17.

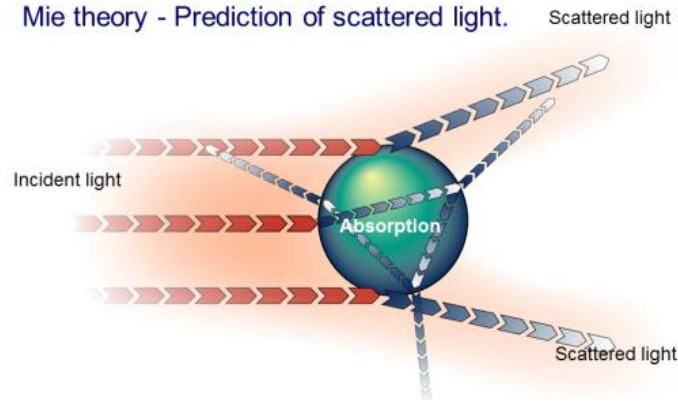


Figure 16: : Scattered Light Mie Theory .

The laser diffraction particle analyser instruments provide a method to quickly and accurately assess the drop size distributions at a local, or global, location within the spray plume. A laser unit is used to provide a collimated light source and, as droplets pass through the laser beam, a receiving unit detects the diffraction pattern. The diode array is a series of semi-circular detectors. Small droplets will project a larger diffraction pattern due to their large surface curvature, while large droplets will have a smaller diffraction pattern (as showed in Figure 17).

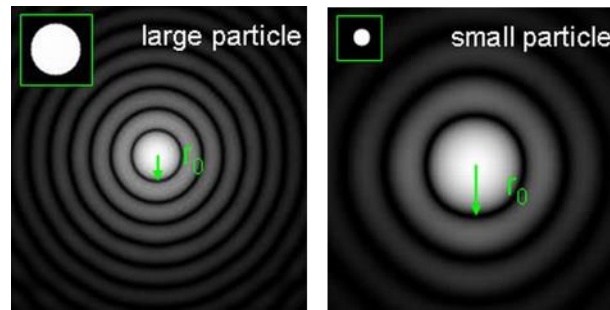


Figure 17: Diffraction Pattern for large and small Particle.

Based on the diffraction pattern, a data analysis system can calculate the size of the particle by using the following formula:

$$d_i = \frac{I_i L_i}{\sum_1^n I_n L_n}$$

Equation 5: Diameter of Particle from detected light.

Where I is the intensity detected from the i-class, L is the characteristic length (length, Surface Area, Volume Diameter), n is the number of class. Limitation on the use of this kind of instrument

are related to the measurement of dense cloud of particles and about the possibility to have a multiple scattering which can affect the measurement. Most of current laser diffraction instrument incorporate, correction in order to perform a measurement up to extinction (or obscuration) of the original light up to 95%.

2.3.3 Laser Extinction Technique

The Laser Extinction Technique can be used to characterize the density of a spray, by measuring the number of density, according to the Beer-Lambert Law which is based on the following hypothesis: Homogeneous Medium, Spherical Particles, Multiple Scattering Neglected, Particle Size $\ll$ Wave Length.

By using an emitting Unit and a Detector unit, it is possible to measure the intensity of the laser light transmitted (I) by the passing of a spray cloud as a voltage signals. The ratio between the 2 signals I/I_0 (where I_0 laser beam light intensity detected without particles), defined as Transmittance [15], results to be proportional also to the number of droplets for unit of volume (N) as showed in the following equation.

$$\frac{I}{I_0} = \frac{V_{100\%} - V_t}{V_{100\%} - V_{0\%}} = e^{-l N C_{ext}}$$

Equation 6: Transmittance.

- Where: $V_{100\%}$ corresponds to the Voltage signal detected by the Detector when the laser beam is completely obscured;
- $V_{0\%}$ corresponds to the Voltage signal without a spray passing through the laser Beam;
- V_t corresponds to the voltage signal when the spray passes through the laser beam;
- N is the number of density [m^{-3}]
- C_{ext} is the extinction cross section (or scattering and or adsorption) [m^2]
- l is the distance to the medium [m]

The logarithm of the Transmittance is called Optical Density or Absorbance and is proportional to the Number of particles and the extinction cross section which depends on the sizes of the particles and the efficiency of adsorption.

2.4 Water Spray Injector Technologies

This paragraph makes a focus on the technology useful for our scientific purpose.

The most common atomizer realizes a fragmentation of a liquid stream by using an induce pressure gap between the liquid and gas phase. The generation spray systems need of a stockage or pressurizing system, pipe lines and nozzles. The kind of nozzles are several, they work at different operative pressure and they can produce spray with different features.

A classification of the nozzles can be done by considering the inlet mass flow so it is possible define: one-fluid or two-fluid nozzles [16].

The one-fluid have one entry, for the liquid phase and the interaction between the liquid and gas stream, happens only to the exit of the orifice (external mixing).

In the two-fluid nozzles, the liquid and gas phase fluid enter together and the atomization process takes place inside the nozzle (internal or external mixing).

For some application, as diesel engine, atomizers use different principle as the electrostatic or the ultrasonic atomization.

2.4.1 One-fluid Atomizers

The simplest one-fluid atomizer is the Hydraulic nozzle which induce high pressure into the liquid, by forcing it through a specifically shaped chamber and orifice. The delta of pressure is responsible of the atomization process.

This atomizer is the most common and the size of the produced droplets decreases with the pressure. The shape of the spray can be a cone (hollow or full) or a flat fan (either even or parabolic) according to the desired application.

Some of them, impingement jet nozzles, have an internal deflector and the liquid stream is atomized by impacting on this discharge surface. The size of the produced droplets and the shape of the spray cone, in this case, depends also on the shape of the deflector.

2.4.2 Ultra fine water mist nozzle

The ultra-fine water mist or pressure fog nozzles have been employed as innovative systems for fire safety application. They are mono-fluid nozzles with small orifice ($<200\text{ }\mu\text{m}$).

The produced aerosols through a pressurized chamber and the size of the droplets is $\text{SMD} < 20\text{ }\mu\text{m}$. Because of the smaller size of the droplets, compared to the traditional sprinkler systems, the produced droplets have higher ratio Volume/Surface which enhances the extinguishment effect, as the cooling of the flame temperature, the displacement of oxygen, the dilution of the fuel vapor. The performances, in terms of time needed to extinguish a fire and quantity of water injected, makes the UFWM attractive for special fire safety applications from Aerospace, military, server rooms. The produced clouds, due to the low inertia of the droplets, is employed for fire safety application related to obstructed fire [14]. The capability to spread easily the liquid phase in larger volume lead to the necessity to define designing criteria. The main challenges related to this technology are to define optimal position and optimal water loading.



Figure 18: Norsim Ultra Fine water Mist Nozzle.



Figure 19: Mist Spreading.

2.4.3 Two Fluid Atomizers

They have a mixture chamber with 2 entries, one for the liquid and one for the gas, in which takes place a first atomization. They are able to produce fine droplets at low liquid rate. They work with low pressure (3-12 MPa). The mixing can be done, both internally and externally. When the nozzle has an internal mixing, a high pressure/velocity gas supply is introduced to the liquid, inside

the nozzle. The internal mixing is done by using swirl or impaction. In case of external mixing the gas and liquid stream are accelerated inside the nozzle, by using chambers or orifices, but they remain separated until the exit orifice

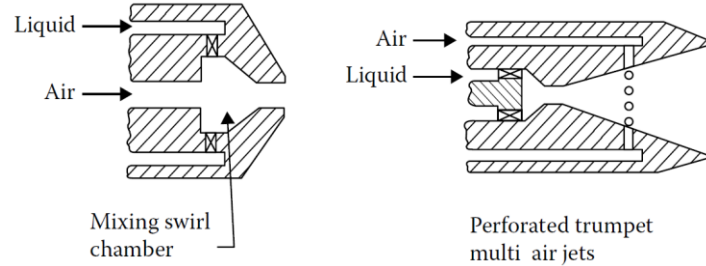


Figure 20: Internal Mixing Example [13].

The performances of this nozzles are defined by the ratio between compressed air and liquid mass: the ALR (Equation 7)

$$ALR = \frac{m_{air}}{m_{liq}}$$

Equation 7: Air Liquid Ratio.

Krawczyk et al. [17] showed a correlation between the amount of compressed air and the performance of the injector. They point out that a higher ALR leads to a reduction of the droplets diameters and their range of variation. From their experimental investigation, by increasing the ALR up to 1.5, it is possible to reduce the SMD by 5 times.

2.4.4 Ultrasonic Atomizer

The ultrasonic atomization is particularly suited to produce low flow rate spray (less than 0.2 l/min) with low velocities and narrow size distributions. They induce an atomization from a liquid film on a vibrating surface which oscillates with a certain frequency. Usually, one or more piezoelectric crystals vibrate a surface which increases the velocity in the liquid. The mean drop size seems to be related to the ripple wavelength, which is controlled by the vibration frequency [13]. They are not employed for fire safety purposes essentially due to their low flowrate and the complexity of their design.

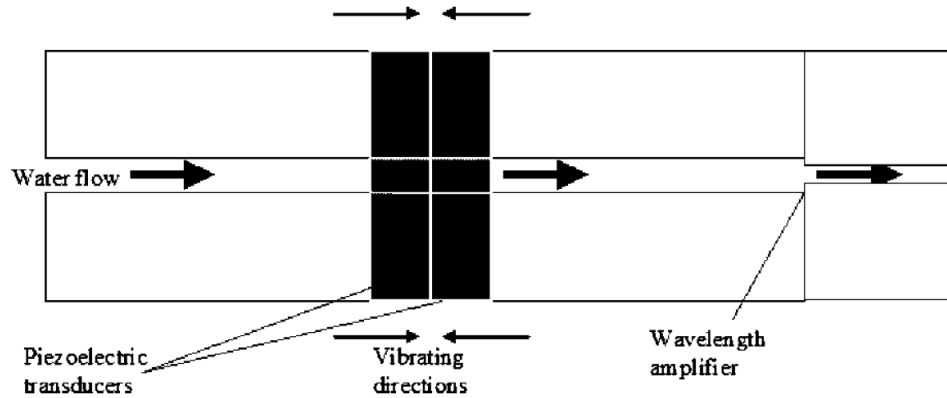


Figure 21: Schematic representation of an Ultrasonic Nozzle [16].

2.5 Mechanism of Interaction

The Spray injection interact with a flame in different ways. The main mechanism of interaction comes from the evaporation of the droplet which affect the initial concentration of the mixture and the development of the combustion phenomena. The mechanism of interaction can be divided between promoting effect and inhibitor effect.

Inhibiting Effect are:

Evaporation of the droplets leads to the:

- dilution of the mixture,
- cooling down the flame temperature,
- decreasing the maximum pressure,
- Thermal radiation blockage (secondary effect important for interaction fire-water spray),
- Oxygen displacement.

The displacement of O_2 plays an important role in extinguishing a flame in case of a diffusion flame only. This configuration is far from the scenario of a severe accident.

The promoting effects are:

- Mixing effect (spray momentum)
- Supplementary turbulence (changing of specific volume between liquid-water vapour)

The interaction of a droplet with a flame involves all these mechanisms in different measures. The relative importance between them in the resulting effect on the flame propagation is not easy to discern.

2.5.1 Evaporation of a Droplet

The mechanism of evaporation of a droplet in a gaseous medium is governed by mass and heat transfer mechanism. While the droplet is approaching the flame, part of the droplets evaporates. The water vapour, around the droplet has a concentration gradient which promotes the diffusion of the vapour in the gaseous medium. If the temperature of the droplet is lower than the gaseous medium, the size of the droplets can also increase by increasing their mass and temperature due to the condensation.

The vaporization of a droplets is ruled by the so called “d square law”:

$$d^2 = d_0^2 - K \cdot t$$

Equation 8: Vaporization of a droplet – d² law.

In which the diameter of the droplet d , is a function of the time (t), the initial diameter (d_0), and a vaporization rate constant ($K[m^2/s]$). According to Sapko et al [18], for water droplets of $18\mu m$, the evaporation rate K is $0.15 \text{ mm}^2/s$.

The previous relationship was described by Spalding [19] and Godsave [20] which have experimentally investigated the combustion of a droplet. The model which describes the evaporation of a droplet and the evolution of its diameter is based on different hypotheses:

1. The droplets do not move and convection is neglected
2. Steady condition in the gaseous medium (the drop changes in quasi-steady way)
3. Constant and uniform pressure on the droplet surface
4. Constant Transport Properties ($Le=1$)
5. Liquid-vapour Equilibrium
6. Temperature of the droplet constant and uniform
7. Mass diffusion and heat flux are neglected

The main limitation to this mode, is that it concerns a single droplet dynamic. In case of a cloud of droplets or of a spray, the rate of evaporation depends strongly on the position of the droplet in

the cloud. The evolution of the radius of the droplets can follow the d-square law, but the K coefficient can be even 2 times smaller compared to the single droplet [21].

Furthermore, the turbulence can affect the evaporation rate and the shape of the droplets. The hypothesis of quasi steady condition, for a spray system is also weak because it assumes a constant pressure and a uniform temperature around the droplets.

3 Combustion Fundamentals: Premixed Flames

According to the combustion theory, a flame is defined as very thin zone, in which several chemical reactions take place with diffusion of gaseous species, production of heat and light.

Combustion system consist of 2 reactants, fuel and oxidizer and they are brought together and mixed at molecular level before the reaction can take place [22]. The behavior of the system is quite different depending on the mixing of the oxidizer and fuel. It is possible to classify 2 different type of flames: diffusive or non-premixed flame and premixed flames. In a non-premixed flame, the reactants are initially separated and they are brought mainly by diffusion processes and convective motion into a common zone, where they mix and subsequently react. In a premixed system the reactants are already well mixed before the initiation of the reaction. In case of diffusive system, the flame represents the border between fuel and oxidizer. In case of premixed system, the flame divides burned gases from the unburned ones.

In our work, our focus is only on premixed flames. In fact, in the explosive mixture, produced in the containment building, in case of severe accident, H_2 is already mixed with air when an ignition source initiates the combustion.

In order to draw a clear picture of the state of art about the flame propagation, the following paragraphs, are dedicated to deepen the following aspects with regard of hydrogen-air mixtures:

1. The Flammability Limits, with regard to the hydrogen-air-vapor mixture
2. The impact of the water spray injection on the flammability domain
3. Propagation Regime: Deflagration and Detonation
4. Laminar Flame Fundamentals
5. The flame Instabilities, which can define the transition from a regime to an other
6. The behaviour of flame propagation in a tube

3.1 Flammability Limits

A mixture of fuel and oxidizer is flammable when the ratio, between them, reaches certain value for a given pressure and temperature. The leanest and the richest fuel concentration, which can self-support the flame, after the removal of the ignition source, are called lower and upper Flammability

limits [23]. The main reason of the flammability limits existence is the competition between the generated heat by the chemical reactions and the external heat losses.

Because of the importance of the volumetric heat losses, it is possible to define the quenching diameter d_t which is the smallest diameter of a tube, below which, a flame cannot propagate. The difference of densities, between the burned and unburned gas, according to the direction of propagation have an influence on the flammability limit.

In the literature is possible to find flammability limits for upward, downward and horizontal propagation. They are experimentally defined by using a spherical bomb or a tube and they are expressed in volume % and they refer to air or oxygen based mixture. The lean limit usually does not differ for air and oxygen instead the richest one, change significantly due to the presence of the nitrogen as shown in the table 2.

	Lean		Rich	
	Air	Oxygen	Air	Oxygen
H ₂	4	4	75	94
CO	12	16	74	94
NH ₃	15	15	28	79
CH ₄	5	5	15	61
C ₃ H ₈	2	2	10	55

Table 2: Comparison of Oxygen and Air Flammability Limits for upward propagation [23].

Different parameters have an influence on the flammability limits: pressure, temperature, presence of dilution, turbulence.

The impact of the initial pressure depends on the specific mixture and generally, for simple hydrocarbon fuel, the upper limits are more sensitive to this variation, than the lower ones. For initial pressure higher than the atmospheric one, the upper limit, can increase or decrease. By decreasing the initial pressure, the limits converge and the range of flammability narrow itself until a value called Propagation Limit. It is possible reduce the pressure until a certain value below which the flame will not propagate.

For the hydrogen-air mixtures, Kuznetson et al. [24] have studied the impact of the decreasing of initial pressure on the lower and upper flammability limits. This study shows that the LFL essentially is not affected by the reducing of the initial pressure up to 50 mbar. Otherwise the Upper limit is more sensitive to the variation of the pressure than the LFL by reaching a value of 50%_{vol}

for an initial pressure of 50 mbar. The initial temperature has an impact on the flammability limits less marked compared to the initial pressure. In particular, when the temperature increases, the range of flammability is extended by reducing the lower limit and increasing the upper one.

Cheikhravat et al. [25] studied the effect of an increasing of pressure, from 100 kPa to 250 kPa, at constant temperature of 298 K in a spherical bomb of 56 l. They show a decreasing of the upper flammability limit from 74%_{mol} to 70%_{mol}. Cheikhravat et al.[25] confirm also the trend for which, by increasing the temperature from 298 K to 423 K at 250 kPa, the Upper flammability limit increases as showed in Figure 22 . They have also reported that the increasing of the flammability range, occurs also at 100 kPa except for the case the temperature varies from 298 K to 358 K , in which the upper flammability limit slightly decreases.

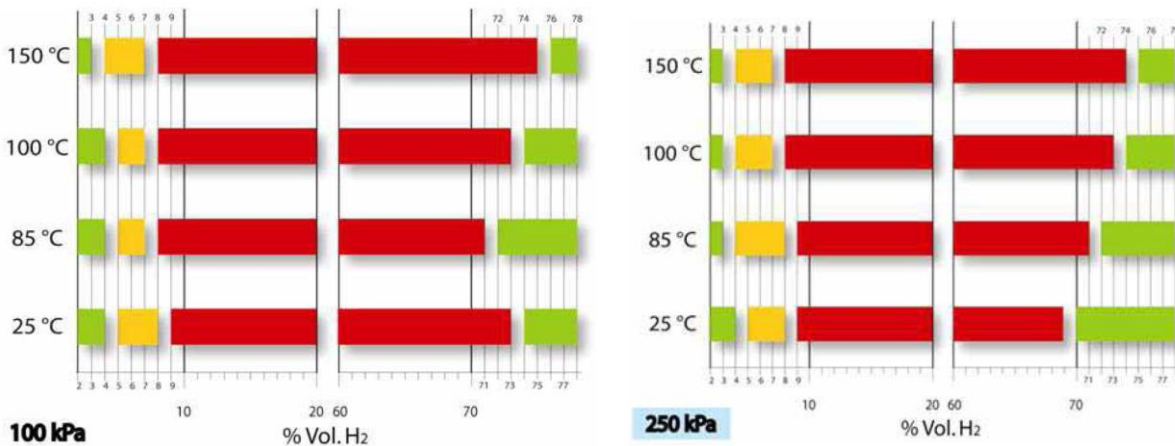


Figure 22: Flammability Limit H2-Air as function of the initial temperature and pressure [25].

The difference between the flammability limits in presence of N₂, shows that the presence of a diluent plays a great role.

Kumar [26] studied experimentally, by using a tube (1.8 m high with a section of 5 cm), the impact of CO₂ and steam, on H₂/air and H₂/O₂ mixtures. He conducted experiments both upward and downward propagation, at different initial temperature (295K, 373K, 473K) and pressure (20 kPa to 51 kPa). He shows that the presence of water vapor or CO₂ narrows the flammability domain. In particular, if steam reaches the value of 63%_{vol}, no ignition is possible as showed in Figure 23.

The decrease of the flammability domain in presence of steam, for H₂-air mixtures, was observed by Cheickhravat et al. [25] at 100 kPa (373K). By increasing the steam concentration, from 0-50%vol, the LFL increases from 4 to 7 %_{vol} and the UFL decreases from 74 to 52 %_{vol}.

Another parameter which affects the flammability limits is the turbulence. Abdel-Gayed et al. [27] observed, by considering the probability of ignition on 20 tests, that the turbulence has an impact on the probability to ignite an hydrogen-air and methane-air mixture. By using an ignition source of 10 J, they showed that the regime of ignitability can be affected by increasing the turbulence.

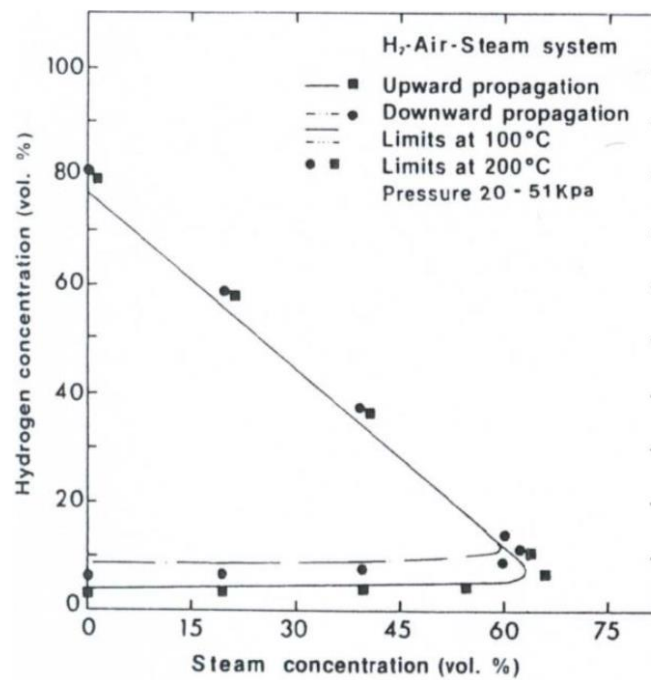
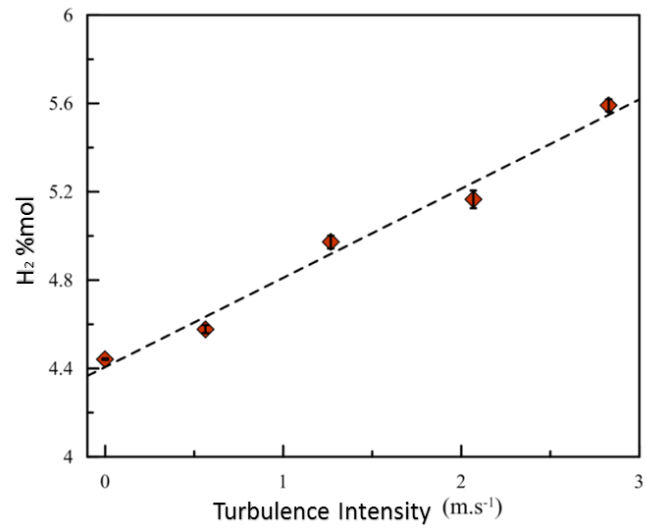


Figure 23: Flammability Limits of H₂-Air-water vapor mixture[26].

Goulier et al. [28] have experimentally studied the impact of the initial turbulence on the LFL by using a 56 l stain steel spherical bomb for the hydrogen air mixtures. They point out that the LFL at 293 K increases from 4.5%H₂ to 5.6% H₂ by increasing the turbulence intensity.



Lower Flammability Limit for H₂-air mixtures as a function of the initial velocity fluctuation in the volume at 293 K and 101 KPa [28].

3.2 Propagation Regime: Deflagration and Detonation

According to the initial conditions of a burnable mixture such as composition, pressure, temperature, ignition energy source, turbulence, a flame can propagate following two different ways: a deflagration or a detonation.

A deflagration can be observed in an opened long tube following a weak ignition source. The velocity at which the flame propagates, is supported by the heat conduction, and by the radical diffusion, from the burned gases to the unburned ones. The flame divides unburned from burned gases and it has a finite thickness. The resulting combustion wave has a velocity lower than the speed of sound and it induces ahead, in the unburned gases, a weak increase of the pressure. The flame speed profile, in a tube, is not flat because of the viscosity forces. It is closed to zero, close to the wall and maximum in the centre of the tube.

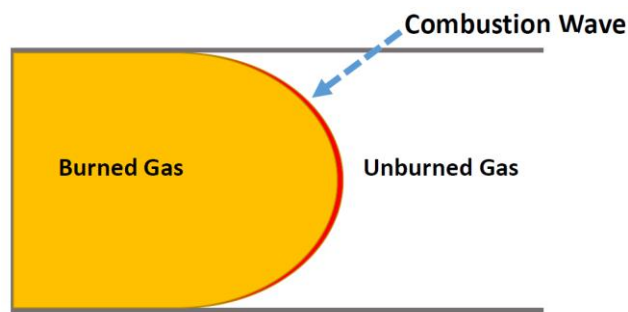


Figure 24: Schematic Representation of a Deflagration.

A detonation can be observed, in a closed tube, when the flame propagation reaches a supersonic speed. It can be obtained directly, if sufficient energy is rapidly deposited in a small volume during the ignition, or by a transition from a deflagration. The propagation velocity is not anymore controlled by the heat and mass diffusion but essentially by the increase of pressure ahead the unburned gases via a precursor shock. A detonation wave can be described as a shock wave followed by a reaction zone. The supersonic wave increases significantly the temperature and pressure in the unburned gases which undergo an auto ignition [22] [23] [29].

According to the Chapman-Jouguet theory a detonation wave, is described as a mono-dimensional discontinuity which divides burned from unburned gas. This simplification allows to evaluate the velocity of propagation, by knowing the initial state (pressure and temperature) of the burnable mixture. By considering the wave reference (as showed in Figure 25) and a mono-

dimensional case, the equations system, which describes the wave phenomenon, is the following table.:

$$\rho_1 u_1 = \rho_2 u_2$$

Equation 9: Continuity

$$P_1 + \rho_1 u_1^2 = P_2 + \rho_2 u_2^2$$

Equation 10: Momentum

$$c_p T_1 + \frac{1}{2} u_1^2 + q = c_p T_2 + \frac{1}{2} u_2^2$$

Equation 11: Energy

$$P_1 = \rho_1 R T_1$$

Equation 12: State unburned gas

$$P_2 = \rho_2 R T_2$$

Equation 13: State burned gas

With u is the velocity of the gas, ρ the density, P the pressure, T the temperature, c_p specific heat at constant pressure, R the ideal gas constant and q is the heat released by the reaction.

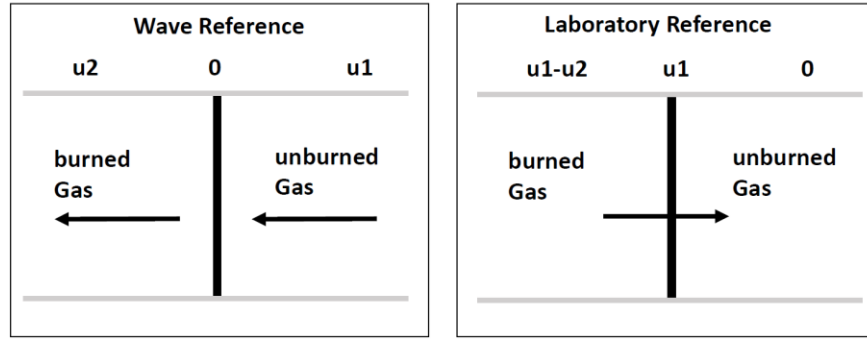


Figure 25: Reference System 1-D representation.

The conservation equations and the state equations, for burned and unburned gases, can be analytically manipulated in order to obtain the Hugoniot Relationship (

Equation 14) and the Rayleigh line (

Equation 15):

$$\frac{\gamma}{\gamma - 1} \left(\frac{P_2}{\rho_2} - \frac{P_1}{\rho_1} \right) - \frac{1}{2} (P_2 - P_1) \left(\frac{1}{\rho_1} - \frac{1}{\rho_2} \right) = q$$

Equation 14: Hugoniot Relationship.

$$\gamma M_1^2 = \frac{\left(\frac{P_2}{P_1} - 1 \right)}{\left[1 - \frac{(1/\rho_2)}{(1/\rho_1)} \right]}$$

Equation 15: Rayleigh Line.

Where M_1 is the Mach number and γ is the ratio between specific heat at constant pressure on the one at constant volume. The Hugoniot Relationship describes an hyperbole which represents,

all the families of possible solutions in terms of P_2 and ρ_2 , for given initial conditions (q , P_1 and ρ_1).

The diagram Figure 26 shows that, the solutions which define a detonation ($M > 1$) or a deflagration ($M < 1$). The Rayleigh line describes 2 tangents to the Hugoniot Curve, in the point J and K. Among the all solutions, only the point J, K and the region E-K have physical meaning and they are stable too (the red line in Figure 26).

The points above the J (red dash line in Figure 26), are physically possible but they define an unstable detonation. Heat losses, turbulence and friction can promote rarefaction phenomena which affect the detonation propagation.

Only the point J corresponds to a "self-sustained" detonation and the velocity of the detonation wave is the velocity of sound in the burned gases, plus their mass velocity. In this case, the rarefaction will not overtake it which results in a stable detonation (constant speed).

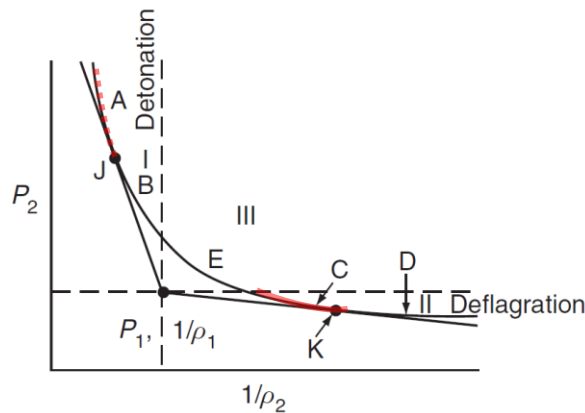


Figure 26: Hugoniot Relationship and Rayleigh Line Plot [23].

3.3 Laminar Flame Speed Fundamentals

In case of laminar deflagration, it is possible to define an important parameter of the flame, called Laminar Flame speed (LFS). This speed is more precisely defined as the velocity at which unburned gases move through the combustion wave in the direction normal to the wave surface. It represents a very important reference point in order to understand the fundamentals of each combustion phenomena.

In order to calculate the LFS, there are 2 different approaches which are based on different assumptions, concerning the main controlling mechanism for the propagation.

Thermal theories consider the heat transfer, as the main responsible of the flame propagation.

Diffusion theories consider the heat propagation as well as the diffusion of molecules and active species as the radicals. In the following paragraph, the following theories will be addressed:

1. Thermal Theory of Mallard and le Chatelier based on the heat propagation
2. Diffusion Theory of Zeldovich and Frank-Kamenetskii which includes both diffusion of molecules and of heat.

3.4.1 Theory of Mallard and Le Chatelier

The thermal theory was, historically, the first one and it was developed by Mallard and Le Chatelier in 1885. They postulated that the heat transfer through the fresh gases, is the controlling mechanism of the flame propagation. Based on the Energy equation, they consider that the flame is composed of 2 zones: a preheat zone and a reaction zone as showed in Figure 27 .

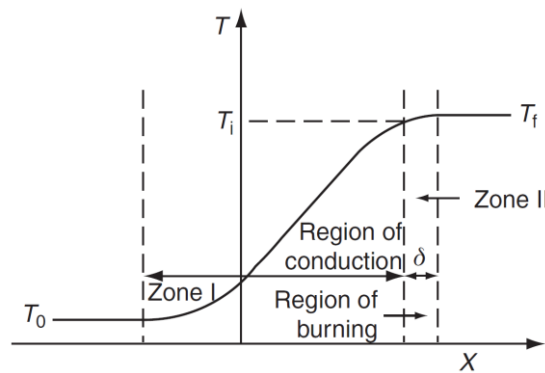


Figure 27: Description of the Temperature - Mallard-le Chatelier [23].

The conducted heat from the reaction zone, is equal to the one necessary to increase the temperature of the unburned gas (T_0) until the Ignition Temperature (T_i), which defines the boundary between the 2 zones.

The Ignition temperature is a fictitious parameter necessary to correlate the flame speed to physical-chemical properties of the mixture. After the reaction zone (Region of Burning in the figure), the temperature increases until a stabilization at T_f .

By considering a linear evolution of the temperature and a mono dimensional case, it is possible to obtain, by using the energy balance and mass continuity (between the 2 zones), the following relationship:

$$S_L = \frac{\lambda_f(T_f - T_i)}{\rho_0 c_p(T_i - T_0)} \cdot \frac{1}{\delta}$$

Equation 16: Laminar Flame Speed Mallard-Le Chatelier.

Where λ [$\text{W m}^{-1} \text{K}^{-1}$] is the thermal conductivity, c_p [$\text{J kg}^{-1} \text{K}^{-1}$] specific heat at constant pressure, ρ_0 [kg m^{-3}] is the density of the unburned gases and δ [m] is the reaction zone thickness. The Reaction thickness can be correlated to the propagation speed (S_L) and to the reaction speed ($\dot{\omega}$). By replacing this term in Equation 16, is possible obtain a relationship, which correlates explicitly the reaction rate ($\dot{\omega}$) [mol s^{-1}] and the thermal diffusivity (α) [$\text{m}^2 \text{s}^{-1}$] to the flame speed:

$$S_L = \sqrt{\frac{\lambda_f(T_f - T_i)}{\rho_0 c_p(T_i - T_0)} \cdot \frac{1}{\rho_0} \frac{d\zeta}{dt}} \sim \left(\alpha \frac{\dot{\omega}}{\rho_0} \right)^{1/2}$$

Equation 17: Laminar Flame Speed.

Although, based on this theory we cannot derive an absolute value of the flame speed, it is very valuable to foresee its variation with T° and P° .

3.4.2 Theory of Ze'ldovich, Franck-Kamenetskii and Semenov

The Zeldovich-Hamenetskii and Semenov theory is an extension of the simplified approach developed by Mallard–Chatelier. They take into account the diffusion of the species as well as heat. They were focused on the energy transported by the diffusion of the species but not on the diffusion of active species as the radicals. The main assumptions they postulated:

- that the ignition temperature is very close to the flame temperature,
- the specific heat at constant pressure and the thermal conductivity are constant and they do not depend on the temperature.

The assumption, related to c_p and λ , and to a simplified kinetic theory of the gases, allow to define:

$$\frac{\lambda}{c_p} = D\rho \Rightarrow \alpha = D = \nu$$

where α is the thermal diffusivity, D [$\text{m}^2 \text{s}^{-1}$] is the mass diffusivity and ν [$\text{m}^2 \text{s}^{-1}$] is the kinematic viscosity. The ratios among them provide important dimensionless numbers for the flame phenomena:

$$\mathbf{Pr} = \frac{\nu}{\alpha} \quad \text{kinematic viscosity / thermal diffusivity}$$

Equation 18: Prandtl Number.

$$\mathbf{Sh} = \frac{\nu}{\alpha} \quad \text{kinematic viscosity / mass diffusivity}$$

Equation 19: Schmidt Number.

$$\mathbf{Le} = \frac{\alpha}{D} \quad \text{thermal diffusivity / mass diffusivity}$$

Equation 20: Lewis Number.

The assumption of an elementary kinetic theory provides a first approximation as: $\text{Le} = \text{Pr} = \text{Sc} = 1$. The solution of the mass, energy and momentum, in a mono-dimensional and steady case, provides another relationship for the laminar flame speed. This equation correlates the laminar flame speed to the thermal diffusivity, global rate of reaction, temperature and pressure.

$$S_L = \sqrt{\frac{2}{\psi_b} \left(\frac{\lambda}{\rho_0 c_p} \right) (\dot{\omega}) \left(\frac{RT_b^2}{E_a(T_b - T_u)} \right)}$$

Equation 21: Laminar Flame Speed - Ze'ldovich Frank-Kamenetskii Theory.

Where ψ_b [mol m^{-3}] is the concentration of the burned gases, $\dot{\omega}$ [mol s^{-1}] is the global reaction rate ($\dot{\omega} = A e^{-E_a/RT}$, Arrhenius Expression) and E_a [J mol^{-1}] is the global Activation Energy. The accuracy of the expression, in order to evaluate the speed, can be improved by increasing the order of the reaction (first or second order). It is possible to introduce another important dimensionless number: the Zeldovich Number. By considering the non-linear behavior of the rate of reaction, they normalize the Energy of Activation.

The number of Zeldovich gives information related to the reactivity of a mixture which is important to understand the capacity of a flame to accelerate as it will be shown later.

$$Ze = \frac{E_a}{RT_b^2} (T_b - T_u)$$

Equation 22: Zelovich Number.

3.4.3 Laminar Flame Thickness

The Flame thickness is an important parameter which provide information about the flame structure. In this study, the flame thickness plays a great role, by considering the interaction with the spray. The water droplets interact directly with the flame propagation, according to the capability to fully evaporate through the flame front. There are many ways to calculate the thickness of a premixed flames. Here are introduced 2 of them which have been used for our preliminary calculation. The first one, based on the thermal parameters, can be evaluated, as soon the flame speed is known as:

$$\delta = \frac{\lambda}{\rho_0 c_p} \cdot \frac{1}{S_L}$$

Equation 23: Premixed Flame Thickness based on scaling laws.

Where λ , ρ , c_p are evaluated in the fresh gases. This flame thickness is also called “Diffusive Thickness” may be too approximate and usually is too small by a factor of order 5 [30].

The second way takes into account the temperature profile as showed in Figure 28. The evaluation is based on the detailed kinetic scheme. In our case, the detailed kinetic mechanism for the hydrogen flame developed by Mevel in [31], has been used to perform this calculations.

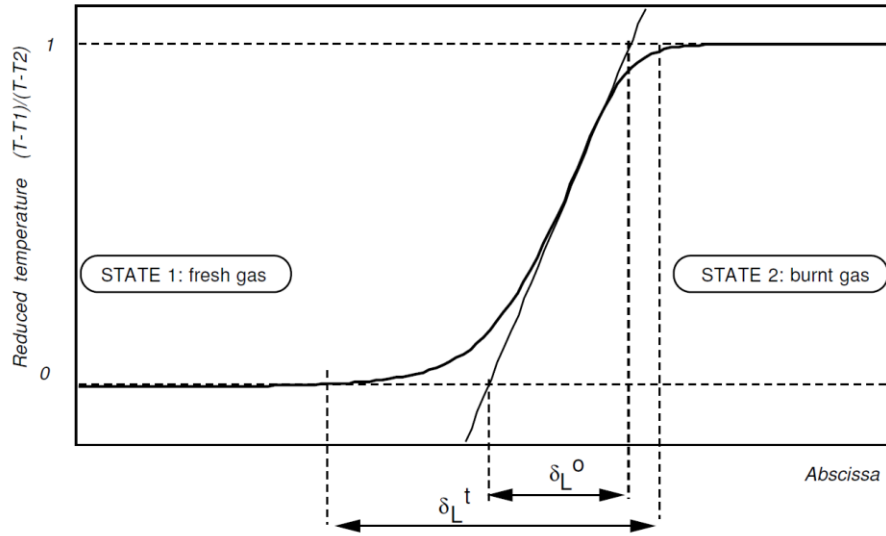


Figure 28: Flame thickness based on Temperature Profile[30].

This thickness is also called “Thermal Thickness” and can be evaluated as:

$$\delta_L^0 = \left(\frac{T_2 - T_1}{\max \left| \frac{\partial T}{\partial x} \right|} \right)$$

Equation 24: Thermal Thickness.

The other thickness, showed in Figure 28, is the “total thickness” δ_L^T which takes into account a reduced temperature, changes from 0.01 to 0.99. In real flame case, the reaction in the unburned side, create long “temperature tail” leading a large value of the total thickness so the thermal thickness result to be more appropriate to be considered [30]. By knowing the flame thickness is possible express the combustion time τ_c as the ratio between the flame thickness and flame speed.

$$\tau_c = \frac{\delta}{s_L}$$

Equation 25: Combustion Time.

It represents the time that fresh gases need to transit trough the flame. Concerning the interaction with water droplets, this will be the time window in which the droplets can interact, by evaporating, with the flame.

3.5: Flame Instabilities: Mechanism of DDT transition

The transition from a deflagration to a detonation is the acceleration of the flame. The initial conditions of the mixture and the geometry (wall, presence of obstacle) can accelerate the flame until supersonic speed, which leads to a transition. The instabilities of the flame promote the acceleration. They introduce distortion in the flame front which lead to a turbulent flame. Some of this instabilities, belong to the flame nature itself and others come from external factors as the confinement volume and the presence of obstructions. It is possible to distinguish [29]:

1. Darreus-Landeaun Instabilities,
2. Thermo-diffusive Instabilities,
3. Acoustic Instabilities (promoted by confinement and obstacles).

The Darreus-Landeaun instabilities are provoked by the gas dynamic effect related to the expansion of the combustion products. In a flame slightly curved, the streamline in the burnt gases converge behind the convex part and it diverge behind the concave part. This is showed for two different times, $t_2 > t_1$, in

Figure 29 . These instabilities make a planar laminar flame unstable. In absence of other factors, they have a contribution on the acceleration of a premixed spherical flame, proportional to the radius.

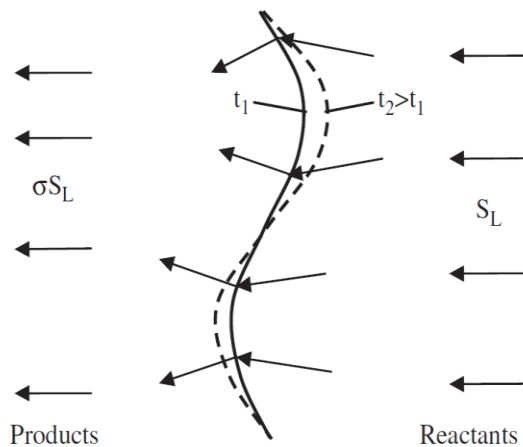


Figure 29: Schematic representation Darreus-Landeaun Instabilities [29].

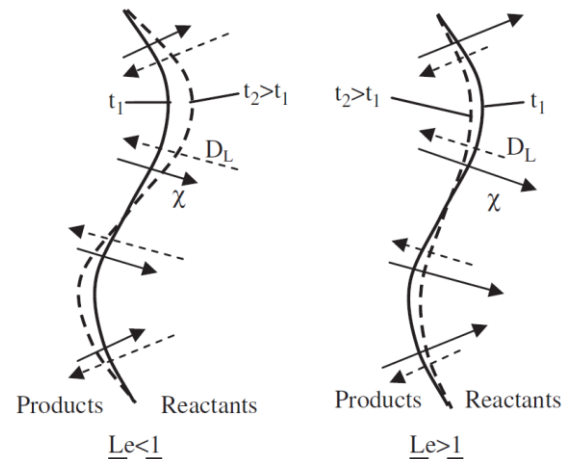


Figure 30: Schematic representation thermal-Diffusive Instabilities [29].

In a flame slightly wrinkled, in addition to the previous ones, there are the diffusive instabilities. They are related to a un-balanced ratio between thermal and species diffusion. In fact, their behavior can be explained by considering the Lewis Number [Equation 20].

In the Figure 30, they are represented, for 2 different times ($t_2 > t_1$) and for 2 value of Lewis ($Le < 1$ and $Le > 1$). In the first case for $Le < 1$, the local temperature increases in the convex part of the flame because the diffusive flux of the limiting component (D_L) increase and the flux of heat (χ) decrease. On the contrary, in the concave part of the flame, the local temperature decreases, because the mass flux decrease and the flux of heat increases. The result of this dynamic is a local increase of the burning velocity and a tendency to wrinkle the flame.

In the second case for $Le > 1$, the diffusive flux of the limiting component and the flux of heat, smooth the flame wrinkles and they lead to a stable flame.

The propagation of a flame in an enclosure, is characterized by the generation of acoustic waves. These waves can interact with the flame front after being reflected by walls and obstacles and they can perturb the flame through a variety of instability mechanism.

The acoustic wave are the main responsible of the acceleration of a slow flame and they play a great role especially during the propagation without obstacles.

Tamanini et al. in [32] showed that the turbulence induced by the obstacles, decrease the impact of the acoustic wave on the flame acceleration and pressure build-up.

Teodorzyc and Lee, they experimentally in [33] show that is possible reduce the increasing of final velocity (of a 10 factor), by using walls made by adsorbing material.

3.6 Turbulent Flames Fundamentals

To better addresses the fundamental of flame acceleration, it is necessary introduce some concepts related to turbulence and turbulent flames. The turbulence of a flow is defined by the number of Reynolds which is a dimensionless number useful to evaluate wherever the motion of a flow is in laminar or turbulent condition:

$$Re = \frac{\rho \bar{u} d}{\mu}$$

Equation 26: Number of Reynolds.

Where ρ is the density, μ is the viscosity, d is the characteristic linear dimension, and $\bar{u}$ is the average speed of the fluid. In case of turbulent regime, the chaotic changes in the flow speed, it is possible to define the velocity in a point (u), as the sum of an average value ($\bar{u}$) plus a fluctuation (u') called Root Mean Square which is evaluated statistically.

Based on the Reynold Number, it is possible to define for a flow in a:

- Laminar Regime $Re < 2000$,
- Transition Regime $2000 < Re < 3000$,
- Turbulent Regime $Re > 3000$.

The kinetic energy of the turbulence is a function of this fluctuation and it affects the size of the vortex and eddies created in a flow. The eddies are the main mechanism of the fluid to dissipate the kinetic energy and the dissipation occurs through the formation of eddies ever more small until to convert the energy by viscous dissipation (the Kolmogorov Scale). The size of the eddies ranges from the integral length scale (L_T) to the Kolmogorov scale (L_K). The energy is dissipated with different velocities, according to the scale of the turbulence, so it is possible to associate to the scale previously introduced, 2 with different time constants: τ_T and τ_K .

As described previously, the laminar flames are intrinsically unstable and are influenced by the condition of the unburned gas flow ahead. If the unburned gases flow field is non-uniform, because of the presence of some turbulence, the flame will be distorted and this mechanism will produce further modification of the upstream flow. The impact on the flame front can be different according to the level of the turbulence. Low level of turbulence can increase the surface of the flame front, by stretching, without modifying the structure. Instead an intense turbulence can modify completely the structure of the flame.

When the flame is not laminar, it is not anymore possible to consider the speed as a physicochemical and chemical kinetic property of the mixture. When the flame is turbulent, the speed S_T is a mass consumption rate per unit area divided by the unburned gas density [23], according to the level of turbulence.

Borghi in [34] has proposed a diagram (Figure 31) which allows the classification of turbulent flames based on the characteristic of the turbulence and of combustion. In order to describe the diagram, it is necessary to introduce some dimensionless number: the Damköhler number, the Turbulent Reynolds number and the Karlovitz number.

The Damköhler number is the ratio between the integral time scale of the turbulence and the time of combustion. It correlates the turbulence and the parameters characteristic of the laminar flame as the laminar flame speed (S_L) and the laminar flame thickness (δ):

$$Da = \frac{\tau_T}{\tau_c} = \left(\frac{u'}{S_L} \right)^{-1} \times \left(\frac{L_T}{\delta} \right) = \left(\frac{L_T}{u'} \right) \times \left(\frac{\delta}{S_L} \right)$$

Equation 27: Number of Damköhler.

The number of Karlovitz which correlates the time characteristic of the small scale τ_K and the chemical time scale to the Kolmogorov time τ_c :

$$Ka = \frac{1}{Da(\eta_k)} = \frac{\tau_c}{\tau_K} = \left(\frac{S_L}{\delta} \right) \times \left(\frac{\eta_K}{u'} \right)$$

Equation 28: Number of Karlovitz.

The number of Reynolds Turbulent which takes into account the u' and it allows to discriminate laminar from turbulent flames:

$$Re_T = \frac{u' L_T}{\nu} = \left(\frac{u'}{S_L} \right) \left(\frac{L_T}{\delta} \right) = Da^2 Ka^2$$

Equation 29: Number of Reynolds Turbulent.

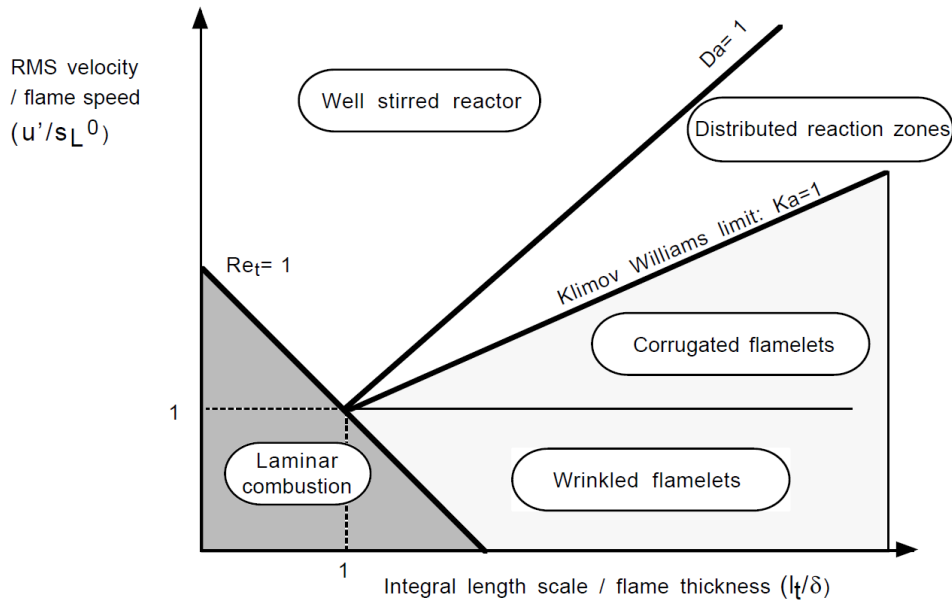


Figure 31: Turbulent Combustion Diagram [30].

In the Diagram of Borghi are plotted 4 curves corresponding to $Da=1$, $Ka=1$, $Re_T = 1$ and $u'/S_L=1$. The curve defines 4 main Regime of flame:

1. Laminar combustion,
2. Well stirred reaction,
3. Wrinkled and Corrugated Flamelets,
4. Distributed Reaction Zone.

The domain of the laminar flames is limited for $Re_T < 1$.

In the well stirred reactor, $Ka > 1$, $Da > 1$, $Re_T > 1$, the time characteristic of the turbulence (τ_T) is smaller than the one of the reaction (τ_C). In this case it is not possible define a combustion front flame.

The structure of the flame in case of “Wrinkled Flamelets regime” ($Ka < 1$, $Da > 1$, $Re_T > 1$, $\tau_C < \tau_T$) is showed in Figure 32 a .The flame front is thin and it is wrinkled by the turbulence. The structure of the flame is close to the one of the laminar case and it is possible identify a preheat zone and a reaction zone.

The structure of the flame in case of “Corrugated Flame Regime” or “Thin regime with pocket” is showed in Figure 32 b. In this case, the turbulent motion velocity becomes important and there is the formation of pockets of fresh and burned gases.

The structure of the flame in case of “Distributed reaction” or “Thickened flame regime”, ($Ka > 1$, $Da > 1$, $Re_T > 1$, the $\tau_K < \tau_C < \tau_T$) is showed in Figure 32 c . The turbulence affects the inner flame structure. The turbulent integral time scale is still larger than the chemical time scale but the Kolmogorov scales are smaller than the flame thickness. If the stress induced by Kolmogorov scales, reaches a critical value, it is possible to quench the flame. The combustion process can be suppressed, if the flame front is submitted to external losses or strong aerodynamic stretch which reduce the reaction rate to a negligible value.

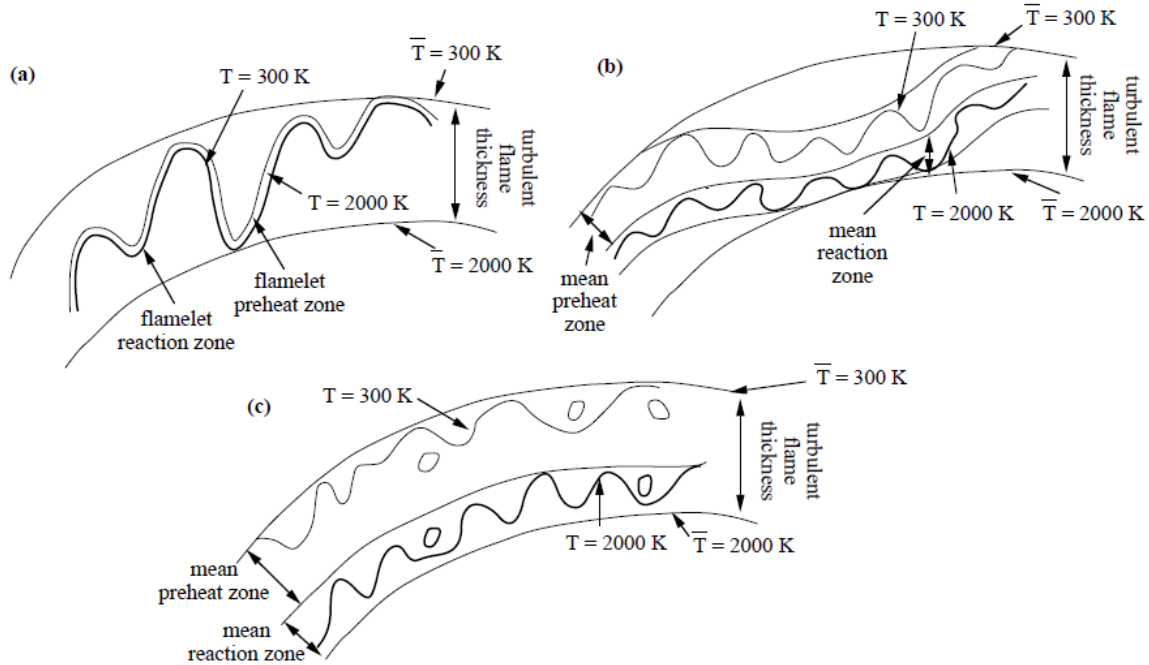


Figure 32: Combustion Regimes Flame structure (Borghi Destriau) [30].

3.6.1 Flame Propagation in a smooth tube

Historically, the study of the propagation of a flame in a vertical tube is done in upward propagation condition. The tube used to study this phenomenon can be with rectangular or cylindrical, so it is common to express the evolution of the flame parameters as a function the geometrical ratio L/D (length/internal diameter).

Phylaktou in [35] studied the combustion of different fuel-air mixture in upward propagation, as methane, propane, propylene in a vertical tube (both ends closed) 1.64 m high, with an internal diameter of 76 mm. He discriminates, 4 phases related to the developing of the flame as showed in Figure 33.

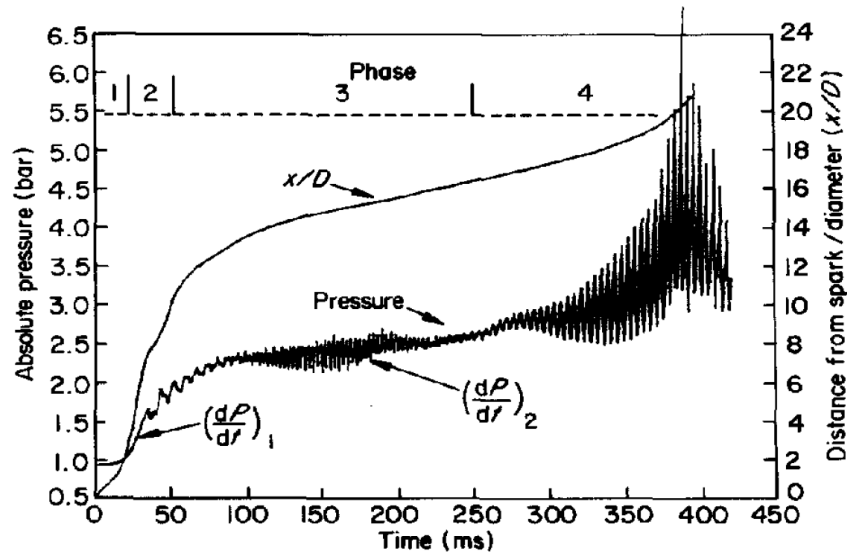


Figure 33: Pressure-Time and distance-time curves 10% methane/air explosion[35].

In the first phase, the flame propagates in all the direction with a hemisphere shape. This kind of propagation takes place until the flame radius is about half of the tube diameter. The phase is very short and it occurs with no significant increasing of pressure. The propagation is very similar to the one observable, in a spherical bomb apparatus during a constant pressure explosion. The second phase is characterized by an increasing of speed and pressure rise and the maximum in terms of velocity is observable when the flame distance from ignition is almost 4 times the internal diameter.

In the third phase, the pressure rise and speed are significantly slower and constant. For slower flame, the flame shape appears as a classical “tulip”. The Fourth phase, is characterized by pressure oscillations, amplified in the last part of the explosion.

By considering the ignition on the bottom part, Phylaktou studied the impact of different pipe configurations:

- opened bottom and closed top,
- closed bottom and opened top,
- opened bottom and opened top,
- closed bottom and closed top.

The differences among the cases, are related to the possibility to freely expand or compress, respectively burned gases and fresh gases. The first configuration, lead to a uniform flame propagation. The resulting speed are lower because the expansion of the burned gas is limited and it cannot increase the flame speed. In the second configuration, when the end, at to the ignition point, is closed, and the bottom part is opened, the speeds are more important than the previous case. The combustion exhibits important oscillations. In the third configuration, the flame propagation is similar to the first configuration but after a certain distance from ignition, the flame speed are similar to the second configuration. When the tube is closed at the 2 ends, the expansion of the burned gases and the movement of the fresh gases are limited.

The description of the premixed flame propagation in a tube (0.15 m internal diameter and 2.95 high), was done also by Lamoureux [36], for stoichiometric mixture of methane/air and ethane/air. The ignition spark system was composed by 2 electrodes at one end of the tube. By using a high speed camera, it was possible to observe the four phases (Figure 34) described by Phylaktou.

1. First phase: Spherical evolution of the flame until the tube wall (flame speed 0.45 m/s)
2. Second Phase: Laminar flame propagation with a hemisphere shape (flame speed 60 m/s)
3. Third Phase: the speed slow down and the flame front exhibit an internal cone made by burned gases. The flame speed is higher close to the wall than at the axe;
4. Fourth Phase: The flame front is wrinkled and the flame speed is constant;

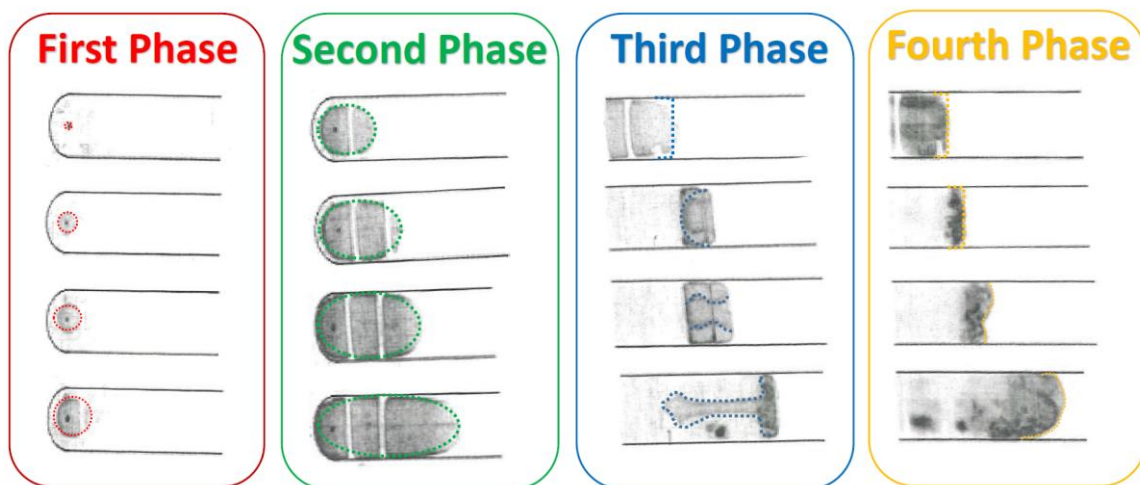


Figure 34: Flame propagation smooth tube: stoichiometric mixture ethane/Air at 16 kPa [36].

3.6.2 Flame Propagation in obstructed tubes

The flame propagation in a tube equipped with internal obstacles is useful to study the acceleration of a flame. In real cases, a flame rarely can propagate freely in a confined volume. Obstacles, obstructions and confinement affect the propagation of a flame. The presence of these “imperfections” can increase the speed of a flame and can promote, according to the configuration and initial conditions, the transition from one regime of propagation to another. The obstruction in a volume can have different shape and size and to describe the pattern of obstacle, it is useful to define the blockage ratio of as: $BR=1-(d/D)^2$, where d is the inner diameter of the obstacle and D is the diameter of the tube. The main responsible of the acceleration is the Feedback Mechanism in which the expansion of the burned gases, compress the fresh gases against the obstacle, increasing their velocity. The flow field of the fresh gases, is distorted and there is the creation of eddies which contribute to increase the turbulence. As the acceleration increases, the unburned gas flow become more turbulent. The mass transport and momentum of the fresh gases into the flame is enhanced by turbulence and the burning velocity augments.

Repeated obstacles in the tube can amplify the effect as showed by Moen et Al [37], which observed an increasing of the flame speed of 24 times higher than the case in absence of obstacles. He addressed the increasing of velocity (from 3 m/s up to 100 m/s) to the coupling between the feedback effect and the interaction flame/upstream flow. The large scale flow field distortion depends critically on the size of obstacles and the distance between them.

Johansen and Ciccarelli in [38] have studied the effect of different blockage ratio ($BR=0.33, 0.5, 0.67$), on the early phase of the flame acceleration, by using a 2.44 m long channel with a 7.6 cm x 7.6 cm cross section. The visualization of the unburned gas flow field provides information about the evolution of the flame shape, the combustion mode. They observed, by using helium injection, the formation of vortex responsible of the increasing of velocity as showed in Figure 35a where is clearly showed:

- the onset of the turbulence from a separation bubble lends,
- the development of the turbulence at multi scale level,
- the growth of recirculation zone between adjacent obstacles,

Figure 35b shows the simultaneous propagation of the flame and the unburned gas flow field in the case of $BR=0.33$. In this case, the acceleration provided by the obstacles is lower compared to $BR=0.50$ and 0.67 . It is possible observe that as the flame tips remain smooth and as the flame

advances to the last obstacle, the shear layer becomes more turbulent and the flame burns in the

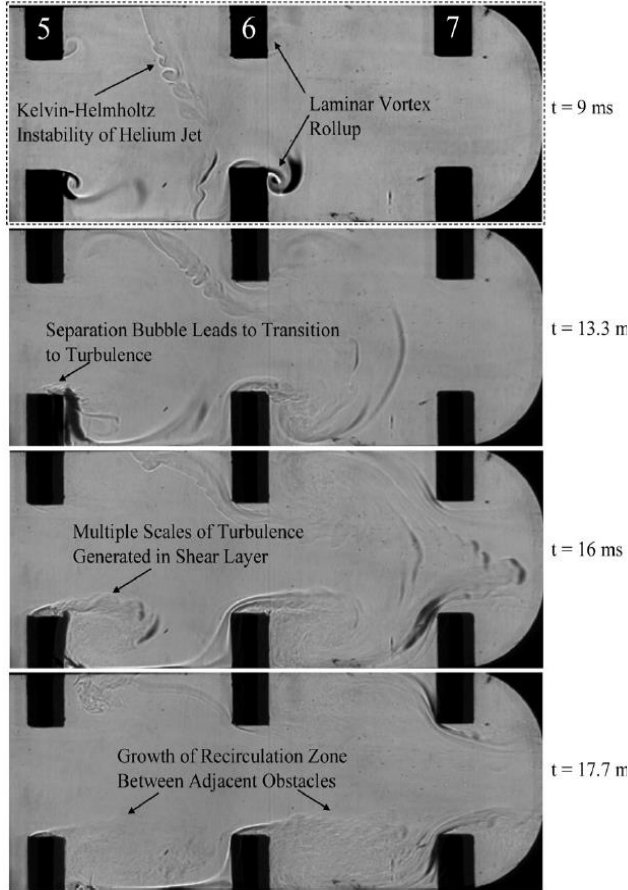


Figure 35a : Development unburned gas flow field .

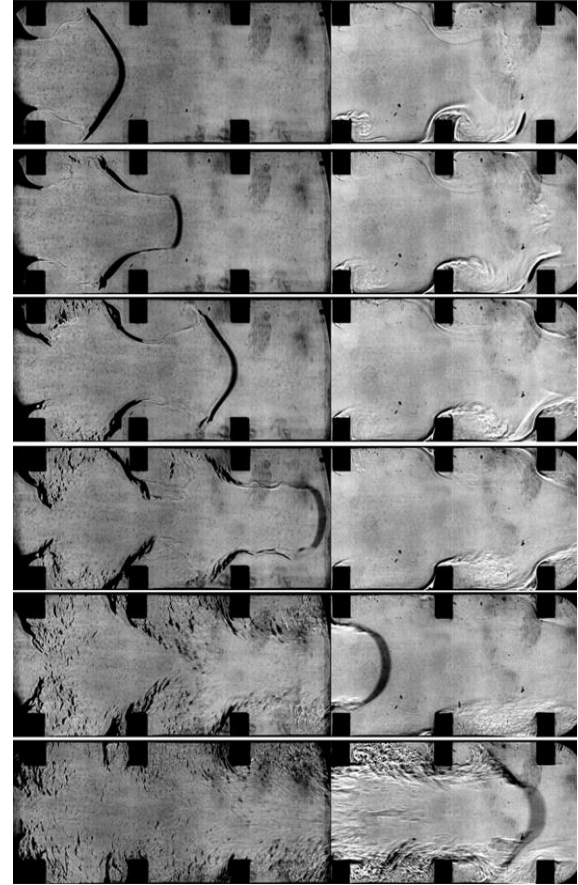


Figure 36b: Simultaneous evolution flame and unburned gas flow field.

recirculation zone earlier.

3.7 Acceleration Criteria

The possibility to accelerate of a flame is related to both to the properties of the mixture and to the geometry of the channel. Then it is possible to estimate, for a given mixture and geometry, the potential for effective flame acceleration (FA), by using basic flame parameters.

Dorofeev et al. have identified a set of parameters that can influence the flame-flow-flame feedback in obstructed area [39] as : Laminar Flame Thickness (δ), laminar burning velocity (S_L), Specific Heat Ratio in reactants (γ_r), Lewis Number (Le), Zeldovich Number (Ze), the densities in

reactants and products (ρ_r , ρ_p), the speed of sound in reactants and products (c_{sr} , c_{sp}) and the internal length scale of turbulence (L_T).

They measured (Figure 37) for different hydrogen concentrations, the flame propagation velocity as a function of the ratio X/D at $BR=0.6$. It is possible to identify:

1. Slow Flame Regime (flame speed is lower than 200 m/s)
2. Fast Flame Regime (flame speed is around 600 m/s)
3. Quasi detonation regimes (flames speed around 1300 m/s)

The velocity increase as the hydrogen concentration increase and the flame accelerate until a certain value of X/D , before to reach a stable condition.

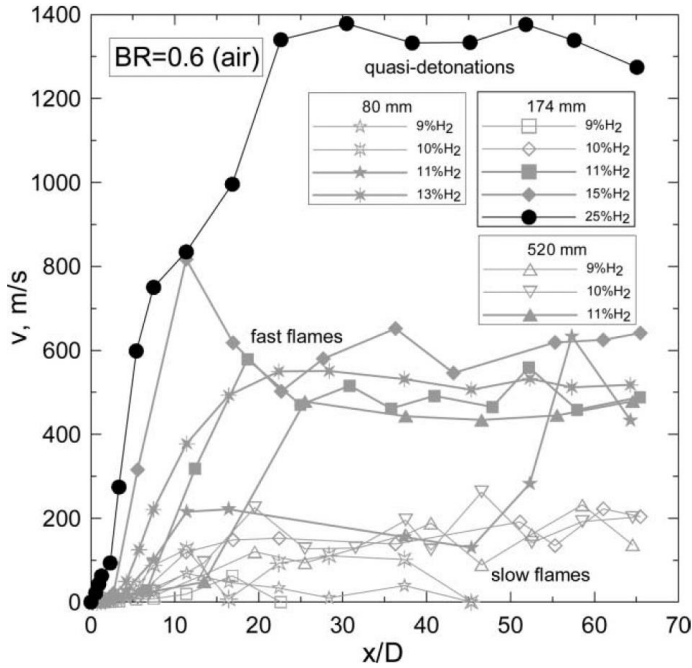


Figure 37: Propagation Speed of flames and detonation along the tube versus X/D [39].

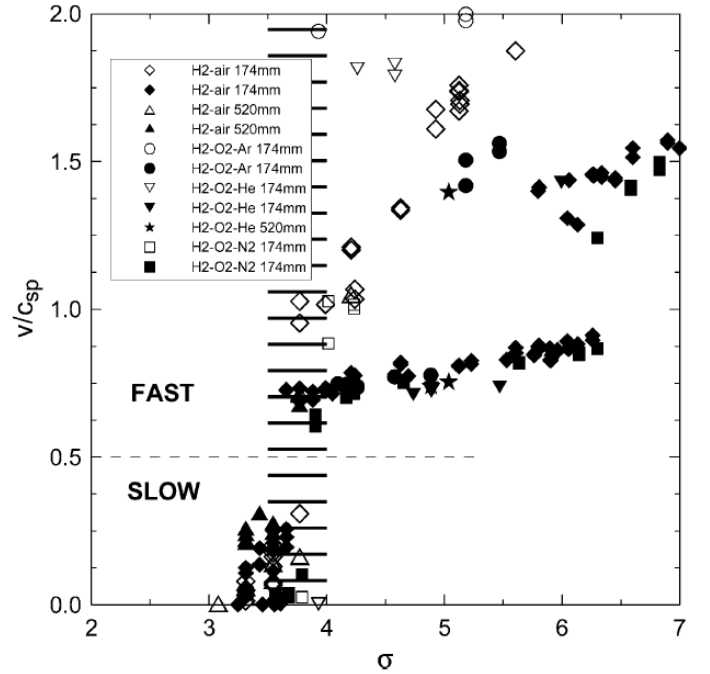


Figure 38: Ratio flame speed to sound speed plotted against the expansion ratio.

The classification of the flames usually is done by comparing the maximum flame propagation velocity (V_{MAX}) and the velocity of the sound in the burned gases C_{sp} (Figure 38):

1. $V_{MAX}/C_{sp} > 0.5 \Rightarrow$ Fast Flames
2. $V_{MAX}/C_{sp} < 0.5 \Rightarrow$ Slow Flames

Malet [40] have defined an acceleration criteria for the hydrogen-air flame mixture for lean mixture of hydrogen (10.5, 11, 11.50, 13% $_{vol}$ H_2). His experimental investigation was conducted in

ENACCEF 1 with different obstacles (shape and BR). He concluded that, at 10.5 and 11% H₂, the propagation is not in the fast regime, apart in the case of 11.5 %H₂ with BR>0.40. In case of 13% H₂ the flames are fast with BR>0.30. The most accelerating configuration, is with BR=0.63 (9 annular ring obstacles).

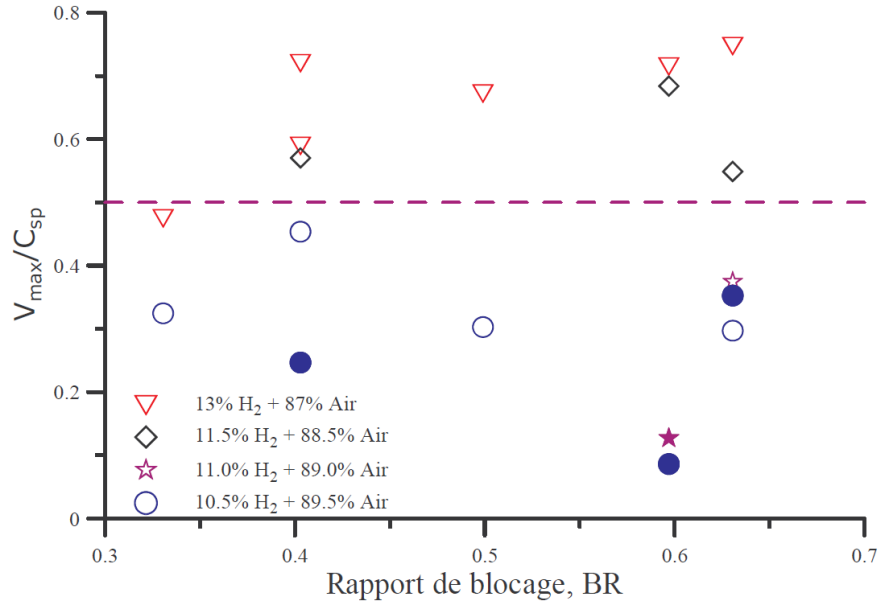


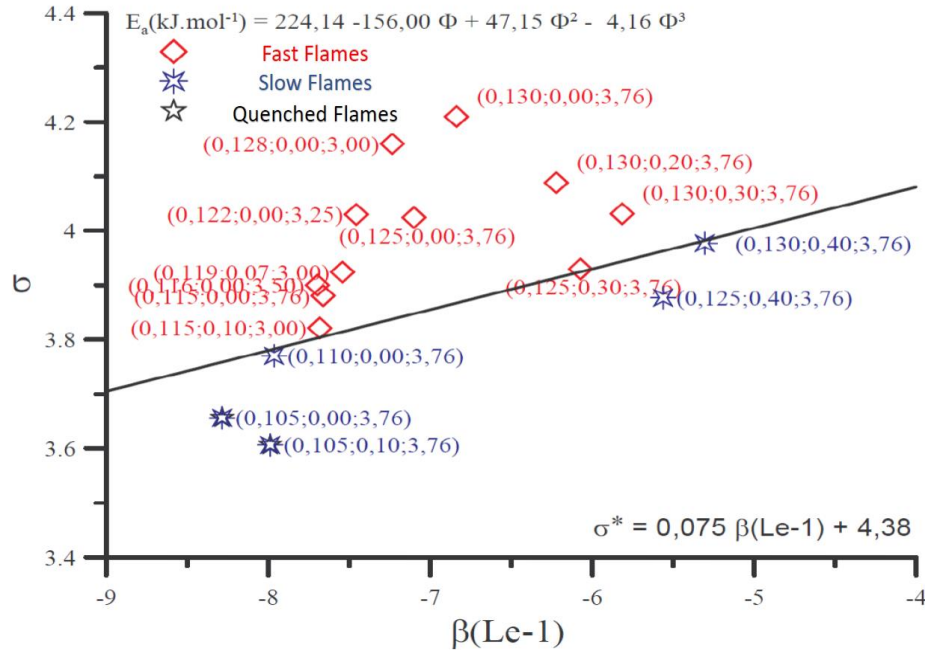
Figure 39: Maximum Flame Propagation Speed / the speed of sound in the reactants as function of BR [40].

Malet defined a simple relationship to describe the critical value of the expansion ratio σ^* , as a function of the Zeldovich number and the Lewis Number:

$$\sigma^* = 0.075 \beta (Le-1) + 4.38$$

Figure 40: Critical Expansion Ratio - Malet, 2005 [40].

This expression allows to divide, a priori, slow flames from fast flames, by knowing the expansion ratio and the Zeldovich number. It was derived for mixture at room temperature and atmospheric pressure by taking into account a large number of experiments including dilution with He, CO₂, N₂ and He-CO₂.



Concerning, the explosion hazard, the safety standard criteria used to design process industry equipment, are based on the comparison between the maximum pressure and the equipment failure pressure. For this purpose, in the case of confined gas and vapour explosion, the severity of an explosion can be well defined by the Deflagration Index, which takes into account the time of the combustion and the maximum peak of pressure reached during the explosion phenomena. The deflagration index K_G (or K_{ST} in case of dust explosion) is expressed as:

$$K_G = \left(\frac{dP}{dt} \right)_{max} \cdot V^{\frac{1}{3}}$$

Equation 30: Deflagration Index.

Where the $(dP/dt)_{max}$ is the maximum value of the pressure rise on the time. The classification of the severity of an explosion based on the deflagration index (for each particles class) is provided by Gustin [42].

Intensity of the explosion	K_{ST} (bar.m.s-1)
Not explosive	0
Moderate Explosion	$0 < K_{ST} < 200$
Strong Explosion	$200 < K_{ST} < 300$
Very Strong Explosion	$K_{ST} > 300$

Table 3 Dust Classification based on the Deflagration Index [42].

The evaluation of $(dP/dt)_{max}$ can be done by using 2 different approach. The first starts from the knowledge of the Laminar Burning Velocity:

$$\left(\frac{dP}{dt} \right)_{max} = f(P^0, P_{ad}, \gamma) \cdot \frac{S_L}{R_b} = \frac{K_G}{V^{\frac{1}{3}}}$$

Equation 31: Correlation Cubic Root Square Law.

Where, P^0 and P_{ad} are the initial pressure and the adiabatic pressure and γ is the specific heat ratio of the mixture. This approach is based on the assumption that that dP/dt is maximum when the radius of the burned gases is equal to the vessel radius and that the S_L is constant. This latter assumption provides a significant limitation to the application of this approach and it makes it not suitable for our experimental campaign.

The second approach, provides an evaluation of the K_G directly by using pressure combustion evolution. This is the method that will be used in this work.

4 Interaction water droplets with the flame

This part presents the state of art about the interaction between a premixed hydrogen flame with water droplets. It describes how the presence of the water droplets affect a flame in terms of flammability domain, propagation regimes and evolution of pressure.

4.1 Impact of water droplets on the Flammability Domain

Several studies in the literature focused on the possibility to inert a burnable mixture by introducing water droplets. The presence of water droplets, in a mixture can modify the flammable region by acting on the initial temperature, pressure and composition. Different experimental studies tried to highlight the impact of the spray properties, as density and size of the droplet, by using different kind of injection system.

Cheikharavat et al. [7] have studied the impact of the water spray injection ($SMD=5\mu m$), on the lower flammability limit in a stainless spherical vessel (56 l of volume). They have injected different amount of liquid water, in a H_2 /air mixture (at $T_{ini} = 298$ K and $P_{ini} = 100$ kPa) by using mono-fluid and bi-fluid nozzle injectors.

The water mist modifies slightly the LFL, as long as, by increasing the injected water, the mean distance between 2 droplets, is less than 10 times the SMD. This result is showed in Figure 42, in which the green zone is the one with no ignition, the yellow zone is the domain of ascending flame (partial combustion) and the red zone is the one of full combustion. They have highlighted that to quench efficiently the flame, the droplet must evaporate totally during the residence time in the flame front and the Optimal Diameter rapidly decreases as the equivalence ratio is close to unity. Concerning the impact of the spray injection at high temperature (358-383K), they observed that, a non flammable H_2 /air/steam mixture, could be made explosive by cold water aspersion ($T_{H_2O} = 283$ K and SMD between 38-75 μm).

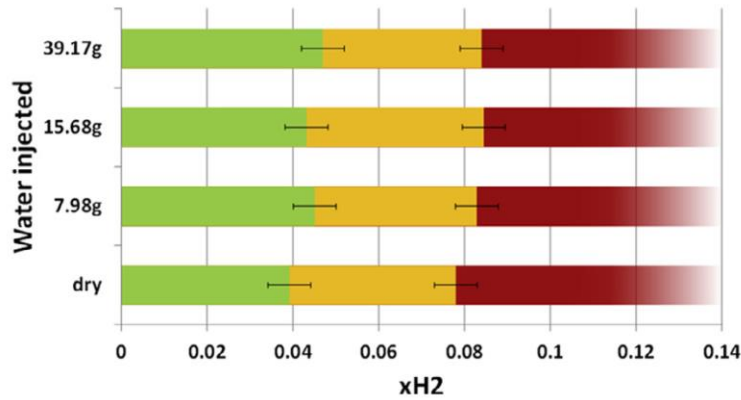


Figure 42: Lower flammability limits H₂/Air/water mist [7].

Jones et al. [43] have studied the inerting capability of water droplets, numerically and experimentally. Experiments have been performed with a wire igniter extremely powerful (≈ 30 J) either by using 5 disc ultrasonic fog units and cold fog nozzles and they have demonstrated that it is possible to inertize, a hydrogen-air mixture, in the range 7-8 H₂%vol. Their theoretical analysis and simulations suggest that the Inerting Potential is crucially dependent upon the distribution of very fine water mist droplets (less than 10 μm in diameter) and as a result, they were able to inert significantly hydrogen concentration, of the order of 15 H₂ %vol.

Battersby et al. [44] observed a significant reduction of hydrogen-air-nitrogen flammable region by using a combination of Water Mist injected by using ultrasonic units (SMD=5-6 μm) and of oxygen depletion. Their experimental apparatus, consisted of a cylindrical steel chamber, equipped with high exploding wire igniter (≈ 9 J) and with a sheet of aluminium foil as vent. From their results, a significant mitigation effect could be obtained even for concentrations of 20 H₂ %vol. and the density of the mist, above about 200 mg/l, plays an important role on the inertization capability of the droplets.

Holborn et al. [45] have investigated a combination of high density water fog ($D_{V90} = 10$ μm) and nitrogen dilution. Experiments were performed in a vented cylindrical explosion rig chamber equipped with a high igniter (≈ 9 J) and with 5-disc ultrasonic fog. Their result concludes that the water fog can affect significantly the Upper Flammability Limit and the total extension of the flammable region.

4.2 Quiescent water droplets Effect on the flame propagation

If an ignition occurs, in a flammable mixture, the presence of the liquid water can affect the flame propagation through different ways:

- The water evaporation inhibits the heat transfer mechanism during the flame, propagation (sensible and latent heat of the liquid and vapor phase);
- The water vapor affects kinetically the combustion reaction;
- The droplets can increase the turbulence in the unburned gases;
- The droplets can disturb physically the flame front;

Several investigations based on modelling, calculation and computational fluid dynamic, have identified that:

1. smallest droplets (less than 10 μm) are more efficient in terms of explosion mitigation, compared to the largest one because they lead to a significant decreasing of the burning velocity in case of freely propagating methane air flame [46] and hydrogen air laminar flames [47].
2. The mitigation effect is increased by increasing the water loading ratio and the density of the spray increases [48].
3. the mitigation effect is related mainly to thermal cooling effect [49] and to a lesser extent to a kinetic inhibition effect due to the presence of water vapor.

The most part of the experimental investigations has employed ultrasonic devices, in order to obtain a spray close to the monodisperse conditions and to reduce the induced turbulence. They agree with a significant reduction of the burning velocities in case of lean hydrogen air mixtures and about the possibility to affect the parameters related to the severity of an explosion as: the overpressure, the rise of pressure and the acceleration of the flame.

Holborn et al. [50] investigated on the burning velocity in presence of very fine water fog (SMD=5-6 μm) and nitrogen dilution, from experimental pressure-time data obtained using the LSBU cylindrical explosion rig. For H₂ content between 14%_{vol} and 20%_{vol}, the burning velocity was found to be significantly lower in presence of water fog than without. The results suggest a difficulty to totally suppress lean mixture even at high fog densities.

They have studied numerically and experimentally [51] the potential explosion overpressure reduction that might be achieved using water fog. For Hydrogen concentration of 15%_{vol} and 10%_{vol} there is a significant lower rates of pressure rise and pressure peaks. They suggested [48] that the rate of pressure rise and peak of overpressure decrease with the decreasing of the fogger

operating units. Their results showed, in Figure 43, that the mist density plays an important role both for the diminution of the burning velocity and for the pressure evolution.

Butz et al. [52] studied the impact of fine water mist on a hydrogen-air deflagration. By using two different spray droplet size distributions ($<100\text{ }\mu\text{m}$) in a deflagration test chamber, with $\text{H}_2=6\%\text{vol}$. The cooling effect reduces the measured peak pressure and measured temperature, in the test chamber during the deflagration event. They suggest that smaller droplets should be able to quench the deflagration even at lower mist concentration.

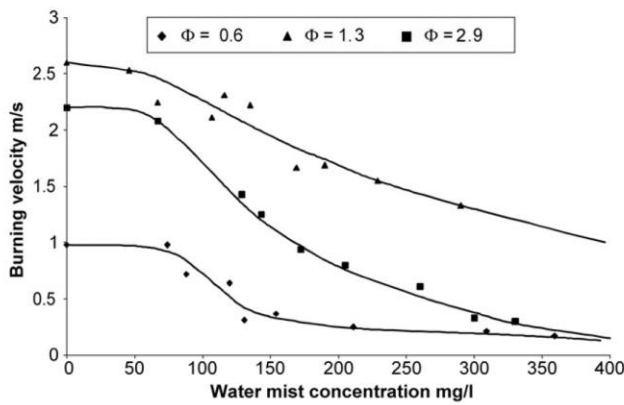


Figure 43: Burning Velocity on Mist concentration [53].

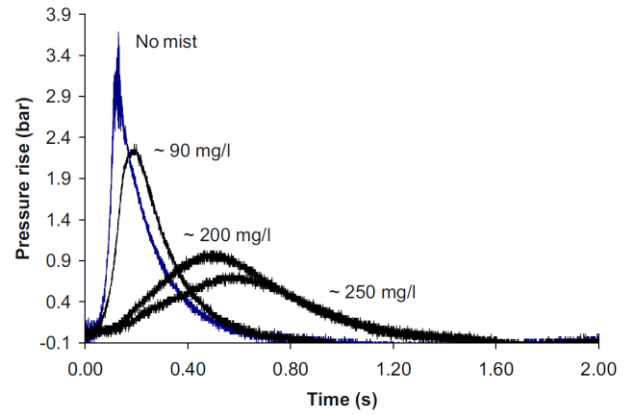


Figure 44: Pressure Evolution on time by varying the mist density ($\phi=0.39$) [44].

Concerning the acceleration of the flame, Boeck et al. [54] have studied, the behavior of hydrogen-air slow flames, accelerating flames, transition to detonation and detonations in presence of quiescent water mist ($\text{SMD} = 13\text{ }\mu\text{m}$). The experiments were conducted in a classical explosion channel (length of 4.2 m) with a rectangular cross section (0.06 m height and 0.3 m width) and flat plate obstacles. By injecting 0.09 kg/m^3 of water, for slow flames ($12.6\text{ -}14\%\text{vol H}_2$), they observed an overpressure reduction up 23-36%, compared to the dry case. In this range, they do not notice a significant flame acceleration. Concerning the transition from slow to fast flames, the water mist can hinder this phenomena, which occur for wet mixture at $19\%\text{H}_2$, instead of $15.9\text{ -}16.8\%\text{H}_2$ in dry mixture. By increasing the water loading $0.11\text{ -}0.12\text{ kg/m}^3$, they observed a reduction of 75% of overpressure compared to the dry. They conclude that water mist retards clearly the DDT mechanism.

4.3 Water Spray Generated Turbulence

After the activation of a spray, part of its momentum is transferred to the ambient gas and eventually turbulence will rise in the gas phase. The gas phase turbulence intensity could enhance or deteriorate the efficiency of the combustion. There may be two source of turbulence: small scale generated in the wake of droplets through the gas and large scale due to bulk flow interaction with obstacles and vessel walls.

Gieras [55] has studied experimentally and numerically, the flame acceleration due to water droplets action (2.5-1 mm). He used a vertical tube of 1.2 m long and $0.05 \times 0.05 \text{ m}^2$. He links the flame acceleration to the turbulence generated by the droplets, in terms of bulk flow of water. The droplets are responsible of the high disturbance and corrugation of the flame front shape.

Thomas [56] has analysed different scientific works about the combustion with a spray-generated turbulence. By considering the analysis of the flame acceleration, flame front velocity and burning velocity of different research activities, he concludes that the activation of water spray causes an increasing of turbulence in which the large-scale effect are dominant.

Van Wingerden et al. have conducted experiments [57] [58] using different kind of water spray nozzles in a 1:5 scale model of an offshore module (1.5 m^3), for premixed mixture propane-air and methane-air. Their experiments were performed by using different commercial spray (Average droplets size from 800 to $200 \mu\text{m}$) and fog nozzles (Average droplets size $40\text{-}50 \mu\text{m}$). They have highlighted an important effect of the distance between water spray nozzles and ignition source location. They observed an increasing of the pressure (compared to the test in absence of water spray), when the nozzles are located close to ignition and there is no significant increasing when water spray is activate both close and far away from the ignition source. They have investigated the turbulence generation by water spray system for propagation of a premixed mixture propane-air and methane-air flames. They concluded that, in absence of a clear relationship about interaction droplets parameters and flame propagation, the bulk flow of water into the vessel is the main source of Turbulence generation. They have observed that the turbulence length scale and the increasing of flame speed are too important in terms of magnitude, to be addressed by the small scale (generated in the wake of droplets).

Zhang et al. [59] have studied the enhancement effect of methane/air explosion caused by water spraying (ultra fine water mist $\text{SMD}=28\text{-}43\mu\text{m}$) in a vertical channel 910 mm high and $150 \times 150 \text{ mm}$ cross section. Their results show that the maximum explosion overpressure, pressure rising rate

and the flame acceleration, increase significantly after spraying. They suppose that the aerodynamic effect produced by the moving water droplets leads to the turbulization of the flammable mixture and the flame is accelerated (as showed in Figure 45).

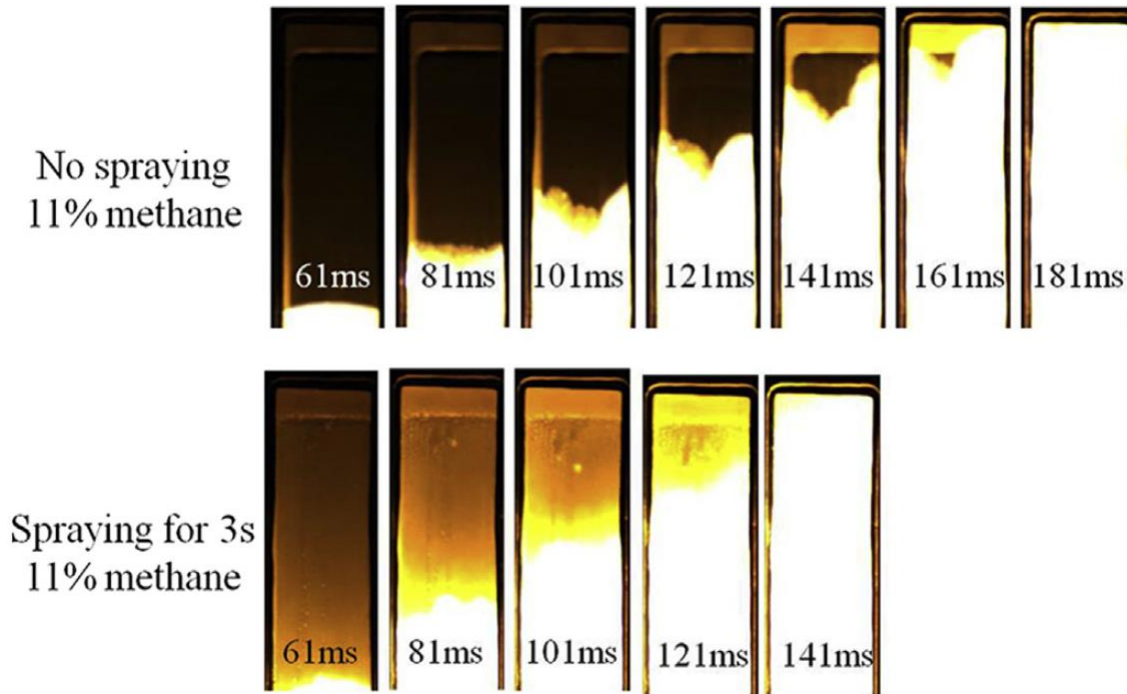


Figure 45: Comparison of propagation pictures in the upper part of the vessel with and without water mist. (Zhang et al. [59]).

The maximum increase range of $\Delta P_{\max}$ (plus 51%) and $dP/dt_{\max}$ (plus 108%), for 9.5%_{vol} of methane with droplets size of a SMD of 43.3 μm . In the case of droplets size of a SMD of 28.2 μm SMD, the increasing of $\Delta P_{\max}$ and $dP/dt_{\max}$ are of 14% and of 64%. The spray time slightly increases the explosion enhancement effect.

4.4 Spray Generation: Droplet Fragmentation and attenuation of shock wave

The droplet breakup takes part in the process of atomization and is one of the most important mechanism of spray generation. Several research activities are focused on the dependence of mitigation/extinction effects and regimes of droplets breakup. The goal of these investigations is to understand the role of the breakup phenomena induced by a shock wave.

Adiga et al. [60] has studied the effect of the droplet breakup process forming ultra fine water mist on the blast mitigation process. By considering, the energy required to fragment the initial droplets into child-droplets, he concluded that it is not significant in terms of weakening the shock. In fact, the rate of the breakup energy to break 0.5 parent droplet into a spray of 20 μm is 18 J/kg. This rate, in terms of attenuation, is not comparable to the energy extracted by vaporization from the same quantity of water ($2.5 \cdot 10^6$ J/kg).

Jourdan [61] experiments in a vertical shock tube in order to understand the possible attenuation of a shock wave (with Mach Number of 1.1, 1.5, 1.8) using a water mist ranging in size from 120 to 500 μm . They highlighted that no breakup is occurred until $We_{\min} = 12$ and for value of $12 \leq \theta \leq 50$ is observed a bag-type fragmentation. They have successfully measured an attenuation of a normal shock wave (attenuation of 65% with droplets of 500 μm) and they highlighted its dependence with parameter as volume of water, size, loading rate, shock wave strength and specific surface area, everything included in the ratio $We/\sqrt{Re}$.

4.5 Previous Research Activities on Hydrogen-air-steam flame propagation in presence of water droplets

In [7], Cheikhvat et al., have studied the interaction between water droplets and hydrogen-air-vapour flame by using a stain steel Spherical Bomb (56 l). They conclude that the spray injection, obtained with a bi-fluid and mono-fluid nozzle, can considerably disturb the flame propagation and improve the efficiency of the turbulence.

The disturbing of the flame is not visible as the velocity of the droplet V_{drop} approached the value of S_L even in lean mixture. According to the hydrogen concentration and droplets size, different behaviours have been identified depending on the ratio $s = S_L / V_{\text{drop}}$. For large droplets

(SMD= 200 –250 μm) and high values of $s \ll 1$, have been observed any significant effects also in terms of maximum combustion pressure. For small values of s ($s \sim 1$), water droplets evaporation occurs and flame wrinkling is observed, especially for low H_2 concentration. For equivalence ratio between 0.25 and 3.57, they did not observe the quenching of the flame but the presence of water droplets, slightly mitigates the maximum Pressure P_{max} and the normalized maximum rate of pressure K_G associated with the decrease of the burning speed. With small droplets diameter (SMD=10 μm), the violence of explosion was slightly mitigated except for lean mixtures ($\text{H}_2 < 10_{\text{mol}\%}$) in the domain where the combustion was not complete. In this case, the turbulence generated by the spray was sufficient to increase the combustion rate.

The same authors have conducted another experimental investigation by using a vertical Acceleration Tube (ENACCEF), with a internal volume of 686 L [62]. The experimental study focused on the effect of the water injection with 2 different spray nozzles: one with SMD=158 (85 ml of injected water at 1.7 l/min) and the second with a SMD 270 μm (430 ml of water injected at 8.6 l/min) on an upward propagation hydrogen-air-vapour accelerated Flame (initial fuel concentration from 10 to 13% $_{\text{volH}_2}$). The results show that the spray injection has an impact in terms of P_{max} and $(dP/dt)_{\text{max}}$ reduction.

The author highlight that the impact increases as the flame speed increases due to the initial hydrogen concentration. The impact between flame and large droplets results in a flame speed reduction only if the flame speed is high enough to induce a furthermore droplets fragmentation.

Unfortunately, as also the author acknowledged, the results do not provide an exhaustive picture of the effect on the flame propagation in terms of the water spray parameters as the size of the droplets, number of densities and velocity of the spray.

4.6 Conclusion State of the Art

The analysis of the scientific literature about the propagation of hydrogen-air-vapour flame in presence of droplets confirms the explorative nature of the subject. The few experimental works showed that there are some limitations to the development of an exhaustive experimental campaign.

The first limitation is due to the difference between the laboratory scale ($< \text{m}^3$) and the real scale (80000 m^3). The most part of the experimental work has been done in small scale or medium scale by using spherical bomb or explosion chambers. These studies have highlighted the fundamental phenomena involved but they do not take into account for example a context in which the flame propagates in a large volume and interacts with walls and obstacles. By considering the initial concentration of H_2 in the containment building (up to 18%vol), is necessary to identify a set of initial lean fuel concentrations which can be representative of the real severe accident conditions.

The second limitation is the absence of experimental investigation on the direction of the flame propagation. In a real case, the position of the ignition source is unknown and several ignition locations are possible. So the flame could propagate in upward or /and in downward direction and according to the position of the spray nozzle, the impact on the flame can be different in terms of mitigation or enhancement effect of the severity of the explosion.

The third limitation is related to the choice of the water spray for the experimental investigation. The droplet size and the flowrate involved in a NPP accident oblige to consider different nozzles than the real one. This approach followed by the scientific community, has identified qualitatively the impact of only one or few water spray parameters.

Great interest has sparked the possibility to mitigate an explosion by reducing the droplet size and by increasing the density number. Unfortunately, most of the experimental works on the use of mist and clouds, has been conducted by using ultrasonic devices which produce very small droplets but they cannot take into account the effect of the induced turbulence. The results give a contribution in terms of fundamentals comprehension of the involved phenomena but they are slightly representative of the real case.

Other studies on the effect of the smallest droplets, have used bi-fluid nozzles which introduce at same time a mass flow of air and water. The disadvantage of this kind of nozzle is that during the injection, the experimental volume is not homogenous because the spray cone is occupied by liquid droplets and air. This outlines some experimental issue related to the homogeneity of the mixture, if the goal is to study the flame propagation during the injection phase.

By standing these considerations, here are listed the decisions made during our experimental campaign:

1) The criteria based on the possibility to accelerate the flame, suggest to investigate flammable mixtures in the range of 10 to 13%vol because: the flame exhibits different sensitivities to acceleration induced by obstacles and there are previous numerical and experimental data especially for dry mixtures.

2) A study which take into account the impact of the spray injection position on upward and downward flame propagation, is necessary.

3) In order to maximize the effect of the interaction flame and droplet, it is necessary to investigate on the smallest droplets ($SMD = 10 \mu m$) but produced by a monofluid nozzle which can induce a turbulence due only to the droplets momentum as in the real scenario.

Contexte et état de l'art

Le premier chapitre présente le contexte de l'accident grave dans les centrales nucléaires et résume l'état de l'art de l'interaction d'une flamme avec l'eau pulvérisée.

L'analyse de la littérature scientifique sur la propagation de la flamme hydrogène-air-vapeur en présence de gouttelettes confirme le caractère exploratoire du sujet. Les quelques travaux expérimentaux ont montré qu'il y a des limites au développement d'une campagne expérimentale exhaustive. C'était mis en évidence l'importance des paramètres caractéristiques de la pulvérisation : taille des gouttelettes, densité et dynamique de pulvérisation et leur impact sur les différents aspects de la combustion. Une partie de la littérature scientifique a montré la possibilité d'atténuer la gravité de l'explosion en utilisant une pulvérisation à faible inertie avec une densité de pulvérisation plus élevée [Holborn, 2012] et des gouttelettes de petite taille [Yang 2002], [Modak 2006]. D'autres travaux scientifiques mettent plutôt l'accent sur l'effet d'explosion de la bombe en raison de la turbulence générée par la bombe [Gieras 2008], [Thomas 2000], [Zhang, 2014]. La plupart des travaux scientifiques sont réalisés dans de petites chambres d'explosion à faible inertie de pulvérisation et ne tiennent pas compte de l'impact de la direction de propagation de la flamme par rapport à la direction d'injection de pulvérisation.

L'analyse de l'état de l'art montre des limitations. La première limitation est due à la différence entre l'échelle de laboratoire ($< 1\text{m}^3$) et l'échelle réelle (80000m^3). La plus grande partie du travail expérimental a été réalisée à petite ou moyenne échelle à l'aide de bombes sphériques ou de chambres d'explosion. Ces études ont mis en évidence les phénomènes fondamentaux mais elles ne prennent pas en compte par exemple un contexte dans lequel la flamme se propage en grand volume et interagit avec les murs et les obstacles. En considérant la concentration initiale de H_2 dans le bâtiment de confinement (jusqu'à 18 % vol), il est nécessaire d'identifier un ensemble de concentrations initiales de combustible pauvre qui peut être représentatif des conditions réelles d'accident grave. La deuxième limite est l'absence d'étude expérimentale sur la direction de propagation de la flamme. Dans un cas réel, la position de la source d'inflammation est inconnue et plusieurs points d'inflammation sont possibles. Ainsi, la flamme pourrait se propager vers le haut et/ou vers le bas et selon la position de la buse de pulvérisation, l'impact sur la flamme peut être différent en termes d'atténuation ou de renforcement de l'effet de la gravité de l'explosion.

La troisième limitation est liée au choix de l'eau pulvérisée pour l'étude expérimentale. La taille des gouttelettes et le débit impliqué dans un accident de centrale nucléaire obligent à considérer des buses différentes de la buse réelle. Cette approche suivie par la communauté scientifique a permis d'identifier qualitativement l'impact d'un seul ou de quelques paramètres de pulvérisation d'eau. Un grand intérêt a suscité la possibilité d'atténuer une explosion en réduisant la taille des gouttelettes et en augmentant leur densité. Malheureusement, la plupart des travaux expérimentaux sur l'utilisation du brouillard et des nuages, ont été menés à l'aide d'appareils à ultrasons qui produisent de très petites gouttelettes mais qui ne peuvent prendre en compte l'effet de la turbulence induite. Les résultats apportent une contribution en termes de compréhension fondamentale des phénomènes impliqués, mais ils sont légèrement représentatifs du cas réel. D'autres études sur l'effet des plus petites gouttelettes, ont utilisé des buses bi-fluides qui introduisent en même temps un débit massique d'air et d'eau. L'inconvénient de ce type de buse est que pendant l'injection, le volume expérimental n'est pas homogène car le cône de pulvérisation est occupé par les gouttelettes de liquide et l'air. Ceci met en évidence un problème expérimental lié à l'homogénéité du mélange, si l'objectif est d'étudier la propagation de la flamme pendant la phase d'injection. En tenant compte de ces considérations, voici la liste des décisions prises au cours de notre campagne expérimentale :

1) Les critères basés sur la possibilité d'accélérer la flamme, suggèrent d'étudier les mélanges inflammables dans la gamme de 10 à 13% vol parce que : la flamme présente différentes sensibilités à l'accélération induite par les obstacles et il existe des données numériques et expérimentales antérieures, notamment pour les mélanges secs.

2) Une étude tenant compte de l'impact de la position d'injection de la pulvérisation sur la propagation de la flamme vers le haut et vers le bas est nécessaire.

3) Afin de maximiser l'effet de l'interaction flamme-gouttelettes, il est nécessaire d'étudier les plus petites gouttelettes ($\text{SMD} = 10\text{ }\mu\text{m}$) mais produites par une buse monofluide qui peut induire une turbulence due uniquement à la dynamique des gouttelettes comme dans le scénario réel.

Chapter 2: Experimental Apparatus

In this chapter are described into details, the facilities and equipment which have been used during the course of this study:

1. ENACCEF 1 a vertical acceleration tube;
2. The water injection Systems (Pump and water spray nozzles);
3. The micro-gas chromatographer (MicroGC) used for the gas sampling;
4. Diagnostics for flame propagation velocity and pressure Evolution measurement;

The last part concerns the experimental procedure which has been followed during the tests.

1 ENACCEF 1 Facility Overview

The interaction between flame and water spray is experimentally studied in a stainless steel vertical flame acceleration tube, called ENACCEF 1, located at the ICARE laboratory (CNRS, Orleans, France). The facility (Figure 46) is a scale down of a pressurized water reactor (PWR) and it has already been used to conduct experimental investigations related to the nuclear safety and explosions . In particular, it has been used in order to study: hydrogen explosion in presence of H_2 gradient and water spray [62]. ENACCEF 1 is made of stainless steel and it is 7 m high with an internal volume of 721 l.

It is composed of 2 parts:

1. the Acceleration Tube is 3.2 m long (volume 62.1 l) and it can be equipped with repeated obstacles, of various geometry (representing the steam generator casemate)
2. the Dome is 1.7 m long (volume of 658 l) representing the PWR dome.



Figure 46: Dome and Acceleration Tube.

1.1 ENACCEF1: Acceleration Tube Geometry

The acceleration tube is constituted of 6 cylindrical parts of 168.3mm external diameter and 7.11 mm thickness (154 mm internal diameter):

- 1) Bottom Cap (Figure 47),
- 2) Acceleration Part 1, 2, 3 (Figure 48),
- 3) Acceleration Part 4 (Figure 48),
- 4) Acceleration Part 5 (Figure 49).

At both ends of each cylindrical part, a flange is welded in order to assemble the different parts.

The Bottom Cap is constituted of a cylindrical tube, 200 mm long. At its bottom part it is welded to a tori-spherical cap (168.3 mm external diameter, 7.11 mm thick). At its upper end, it is welded to a flat flange, 50 mm width. The total length is 299.8 mm for a total volume of 6 l. It is equipped with:

- 2 ports, diametrically opposed which are used in order to mount 2 tungsten electrodes for the ignition (Upward Flame propagation),
- 1 port used to mount a Pressure sensor in case of downward propagation,
- 1 port for the introduction of the gases.

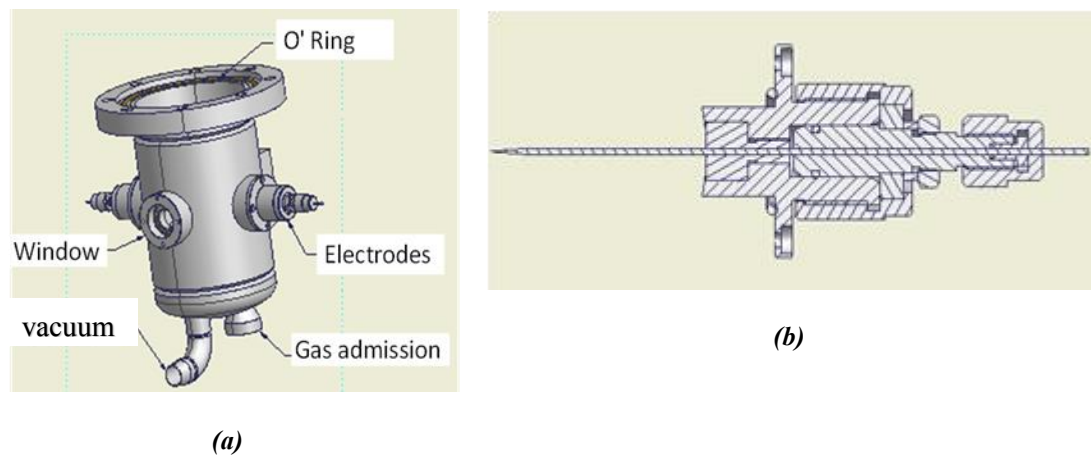


Figure 47: Bottom Cap(a) and Electrodes for the bottom cap (b).

The Acceleration Part 1, 2, 3 are identical. Each one is constituted of a 508 mm de long tube
And it is equipped with:

- 2 ports, 30 mm diameter, equipped with quartz windows (10 mm optical diameter, 3mm thick) to allow the use of Photomultipliers tubes,
- 1 port, 30 mm diameter, host a piezo-electric pressure transducer,
- 3 ports, type DN ¼", are located at the same heights as the quartz windows; they are meant to be used for gas sampling.

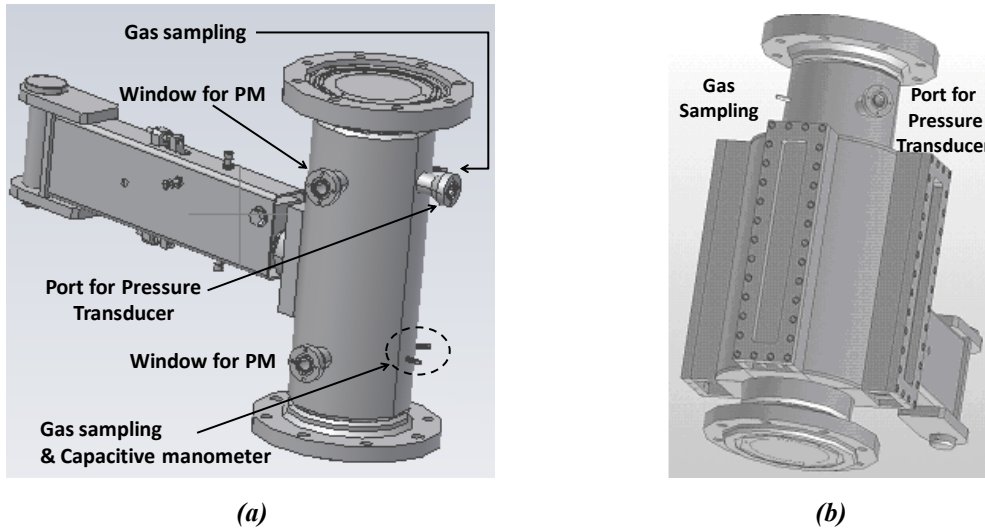


Figure 48: Acceleration Part 1, 2, 3 (a) and Acceleration Part 4 (b)

The Acceleration Part 4 is constituted of a 608 mm long tube and it is equipped with:

- 3 rectangular quartz windows (40 x 300 mm optical path) allow the recording of the flame front during its propagation along the tube (shadowgraph or a tomography),
- 2 ports on which, quartz windows (10 mm optical diameter, 3 mm thick) allow using Photomultipliers Tubes to record the light emission from the flame,
- 1 port, type DN ¼", used for the gas sampling.

The Acceleration Part 5, 909 mm long, is equipped with:

- 3 ports, 30 mm diameter, on which quartz windows (10 mm optical diameter, 3 mm thick) allow using Photomultipliers Tubes,
- 3 ports, can host piezo-electric pressure transducers (Chimie-Métal) and Kistler pressure sensors,
- 1 port, type DN ¼", its axis is located at 635 mm from the external face of the bottom flange. It is meant to be used for gas sampling.

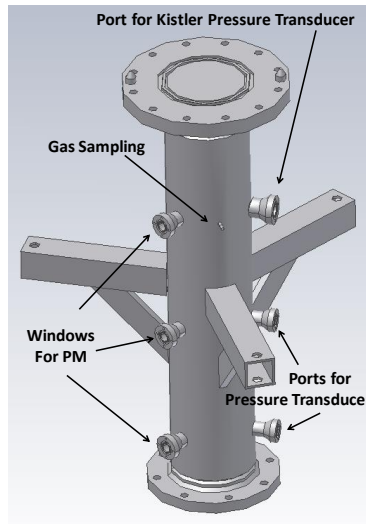


Figure 49: Acceleration Part 5.

1.2 ENACCEF 1: Dome Geometry

The larger part of ENACCEF 1, called the dome, is a cylindrical tube of 0.75 m external diameter (6.2 mm thick) for a length of 1.43 m. The total length of the dome is 1681.95 mm and the total volume is 658 l. The cylindrical part of the dome is equipped with:

- 3 series of 3 ports, 168.3 mm in diameter, 7.0 mm thickness, 80.0 mm long. 2 of them are opposed to each other, the third one being perpendicular to the others. These ports can be used in order to mount quartz windows (180 mm diameter and 42 mm thickness) to enable 2D-imaging diagnostics.
- 5 ports, on which quartz windows (10 mm optical diameter, 3 mm thick) are fixed. The axis of the first one is located 199.5 mm from the external side of the bottom flange. The 5 ports are equally spaced by 250 mm.
- 2 port, linked to 2 primary vacuum pumps.
- 2 ports, DN8 NPT, the first one, located at 310 mm from the external side of the flat flange is meant for the gas introduction; the second one is located at 120 mm from the first one and is connected to a capacitive manometer manufactured by MKS.
- 1 port NPT is meant to be used for the gas sampling.
- The upper part of the dome (tori-spherical part) is equipped with: 7 port of 30 mm diameter. One host a piezo-electric pressure transducer in upward propagation or the

ignition spark system in downward propagation. The central one host the port for the spray injector.

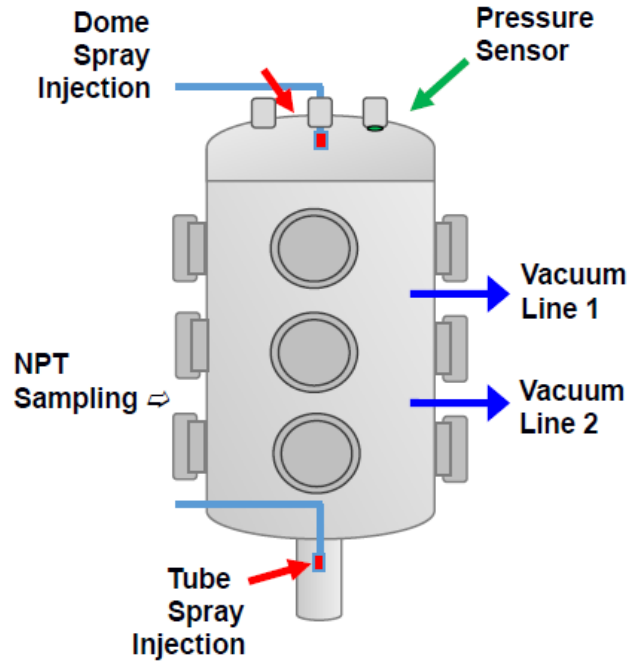


Figure 50: Scheme Dome.

Figure 50 also shows the location of the spray nozzle in the dome (at 4.9 m) and in the tube (at 2.40 m).

1.3 Internal Obstacles

The acceleration parts from N°1 to N°5 can be equipped with several obstacles. Two different shapes can be used: annular obstacles of different blockage ratios (from 0.33 up to 0.63) and hexagonal mesh grids (with holes of 10 mm diameter spaced by 15 mm) for which the blockage ratio was equal to 0.6. In this study annular obstacles were used as showed in Figure 51. The series is constituted by 9 obstacles with a blockage ratio BR, of 0.63

$$BR = 1 - \left(\frac{d}{D} \right)^2$$

Equation 32: Blockage Ratio.

where D ($D=0.154$ m) is the acceleration inner tube diameter and d represents the inner diameter of the annular obstacle (0.093 m). The thickness of the obstacles is about 2 mm. They are equally placed by 0.154 m corresponding to the tube diameter.

They are placed in the bottom part of the acceleration tube, at 0.160 m from the ignition point between the bottom cup and acceleration part 1 and they are meant to accelerate the flame in the Acceleration Tube Part 1, 2, 3, 4.

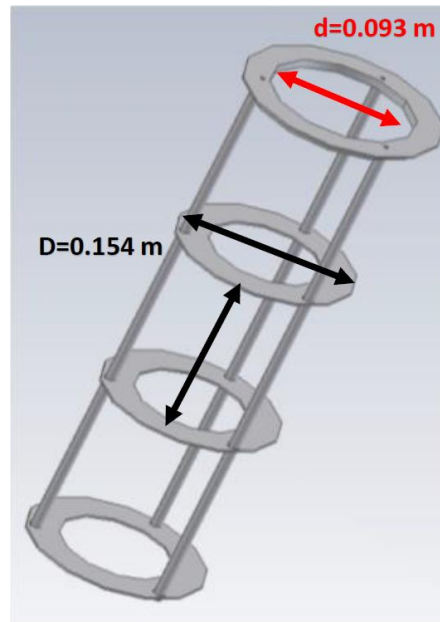


Figure 51: Annular Obstacles.

1.4 Water Injection Systems

The water injection System is composed by a water tank of 10 l filled with distilled water, a dual piston pump (Pre Pump - SSI), a system of pipe (4 mm i.d.) and the spray nozzles Norsim.

The Prep high performance liquid chromatography (HPLC) pump is ideal for chromatography application and it is designed to be a metering pump for general laboratory or industrial application. The flowrate of the Prep pump fitted with two standard 50 mL pump heads can be set in 0.1 mL/min increments from 0.1 to 100.0 ml/min. The maximum operative pressure is 4000 psi (~275 bar) and the system controls only the flowrate.

The Spray nozzles are produced by Norsim. They are employed for Fire Safety application. They belong to the category of the Pressure Fog Nozzles or Ultra Fine Water Mist Nozzle. They produce a spray with a Sauter Mean Diameter in the order of ten micrometres with operative pressure from (100-200 bar). In Particular, the one used for our experimental campaign are the Norsim Water Mist 0.1 Nozzle (orifice of 100 μm) and Norsim Water Mist 0.2 Nozzle (orifice of 200 μm) which are called for simplicity in our experimental study respectively: WM1 and WM2.



Figure 52: Pump used for water spray injection(Pre Pump SSI).

2 Diagnostics

2.1 Gas Mixtures Analysis

A Gas sampling method is used in order to measure the concentration of hydrogen at different heights. The analysis is necessary to verify that the mixture is homogenous inside the ENACCEF 1 and that there is no H_2 gradient.

The value of the concentrations of hydrogen provide also an information about the success of the filling operations and eventually about the presence of a leak in the whole system. Before the preparation of the sampling, each balloon is emptied together with the whole facility by using 2 pumps. The minimum pressure is around 10 Pa.

After the filling of the facility, 4 glass balloons are filled with the mixture directly from ENACCEF 1 at different heights. Three balloons are located in the acceleration tube and one is in the dome. The analysis of the gas composition is then verified using a MicroGC (Figure 53) with a relative uncertainty lower than 3% in mass.

The microGC, SRA Instrument, is equipped with a Thermal Conductivity Detector (TDC) uses the gas chromatography in order to detect the different species in the mixture analysed.



Figure 53: MicroGC for gas concentration analysis.

The gases are sampled using glass bulb once the mixture introduced in ENACCEF. For each sample, 5 analyses are performed: 4 blanks and 1 final. The 4 blanks analysis are done to flush the MicroGC channels and to avoid the influence of the previous analysis. The averaged value, on 4

samples, of H_2 concentration is included in a range of ± 0.20 of the desired value. Each analysis take 90 s which is a sufficient time to detect in our case H_2 (43 s), O_2 (50 s), N_2 (54 s).

2.1.1 Gas Chromatography Method

The chromatography allows to identify singly the chemical species in a mixture by providing a measure of the molar concentration. Each species is separated from the rest of the mixture composition, by interacting with a mobile phase, called carrier gas (Argon in our case), and a steady phase, called chromatographic column. Each specie has a characteristic elution time which corresponds to the needed time to exit from the column.

Once the species are separated, they provide a different response to a thermal stress which is quantified by a Thermal Conductivity Detector (TCD) which does a comparison between the specie and the carrier gas. As result, it provides, for each detected species, a volt signal as a function of the time called Chromatographic Diagram showed in Figure 54.

The integral of the peak on the time is proportional to the concentration of the specie in the analyzed gaseous mixture. An example of Chromatogram is provided in Figure 54. The apparatus need to be calibrated regularly with a mixture in which the single species are precisely known in terms of molar concentration.

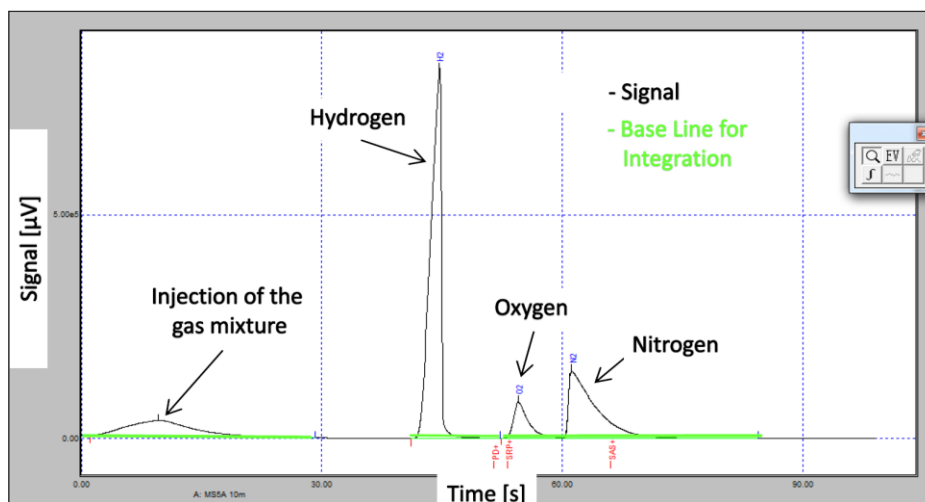


Figure 54: Example of Chromatography Diagram for an 15% H_2 -Air mixture.

2.1.2 Calibration Curve

The calibration of the apparatus is done monthly and it is checked daily by using reference gas sample of 9-11-13-15 H₂%_{vol} and air (alpha2–AirLiquide Mixture). The aim of this operation is to obtain a precise measurement of the hydrogen concentration. The reference sample are prepared by using partial pressure method in a premix chamber equipped with a magnetic stirrer. After the gas filling, the composition inside the balloons is mixed for 30 min by using a magnetic stirrer. For each sample 5 analyses are performed: 4 blanks and the 1 final. An example of calibration result is showed in the following figure. The graphs show the real concentration as a function of the detected area by the analysis. The fitting of the points provides the calibration curve, for each species.

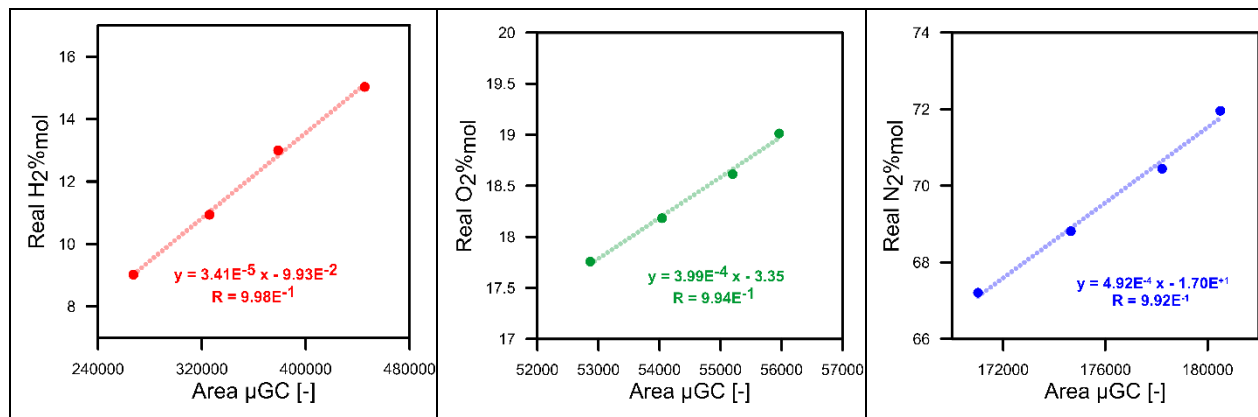


Figure 55: Calibration Curves for H₂, O₂, N₂.

2.1.3 Example of Measurement

In the following paragraph, an example of initial composition of a specific test is given. For the Run 89, the target mixture was 13% H₂ + 87% Air (air flow: 19552 cm³ min⁻¹ and H₂ flow: 3110 cm³ min⁻¹). Table 4 summarizes the following data:

- the location of the sampling using the glass balloon in the ENACCEF facility,
- the residence time,
- the chromatogram pic area,
- the corresponding gas concentration.

The measured Areas are converted to molar fraction, using the corresponding calibration curve which is checked daily. It is possible to notice that the sum of the molar fraction is slightly lower

than 100% (98.34%). This essentially due to uncertainty of the microGC (3%) which affect significantly the measurement of the Nitrogen concentration ($67.84\%N_2 \pm 2.03$).

Location	Ballon	Peak Time [s]	Surface	%H ₂ ± error 3%	Average H ₂
tube 0.27m	1	43.022	386608.29	13.01 ± 0.39	13.00
tube 0.77m	2	43.037	386990.6	13.02 ± 0.39	
tube 1.77 m	3	43.053	386146.25	12.99 ± 0.39	
dome 3.34	4	43.065	386482.57	13.00 ± 0.39	

Location	Ballon	Peak Time [s]	Surface	%O ₂ ± error 3%	Average O ₂
tube 0.27m	1	50.507	49065.82	17.53 ± 0.49	17.50
tube 0.77m	2	50.52	48932.21	17.47 ± 0.49	
tube 1.77 m	3	50.535	48954.26	17.48 ± 0.49	
dome 3.34	4	50.548	49014.06	17.51 ± 0.49	

Location	Ballon	Peak Time [s]	Surface	%N ₂ ± error 3%	Average N ₂
tube 0.27m	1	54.139	170548.15	67.85 ± 2.03	67.84
tube 0.77m	2	54.151	170584.76	67.86 ± 2.03	
tube 1.77 m	3	54.165	170510.84	67.83 ± 2.03	
dome 3.34	4	54.177	170481.68	67.82 ± 2.03	

Table 4: Example of gas composition measurement results.

2.1.3 Temperature Measurements

The temperature of the facility is measured by using a no-contact IR-thermometer with an accuracy of $\pm 2\%$. The measurements are performed at 10 cm from the surface facility at 4 different heights corresponding to the balloons sampling location: 3 in the acceleration tube (0.27 m, 0.77 m, 1.77 m) and one in the dome (at 3.34 m).

2.2 Spark Ignition System

The spark ignition system is linked to a high voltage source (primary voltage of about 10 kV) which produces a spark at the centre of the bottom-cap. The intensity and voltage of the discharge are adjustable and can be measured through a current and voltage probe. The energy delivered is estimated to be around 10 to 20 mJ. As showed in Figure 57, the spark ignition system is connected to TTL generator which triggers, at same time t_0 , the acquisition of the different signals. The detection of the flame position is recorded by an acquisition card and the pressure evolution is recorded by an oscilloscope.

In case of upward flame propagation, the spark is produced by two thin tungsten electrodes (2 mm diameter) placed at 138 mm from the bottom of the facility (Figure 56). In case of downward propagation, the spark is produced by using an engine spark plug placed at the top of the dome.

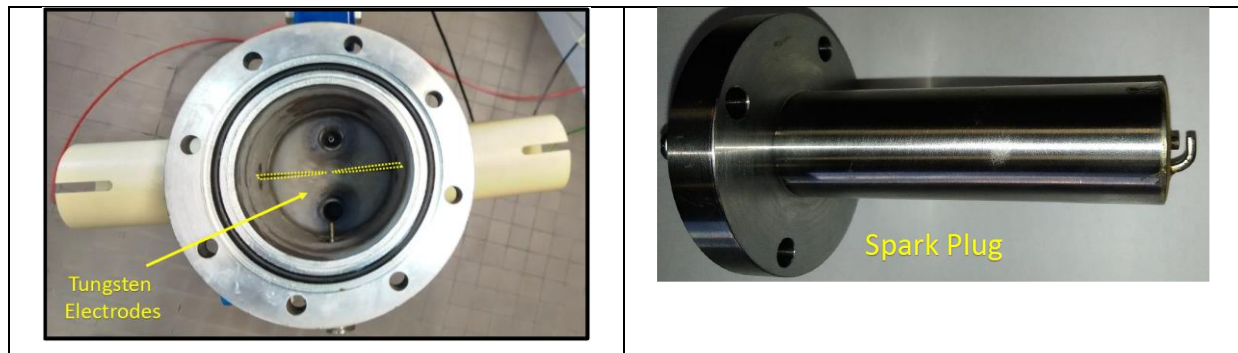


Figure 56: Spark System: Electrodes-downward propagation and Spark Plug-upward propagation.

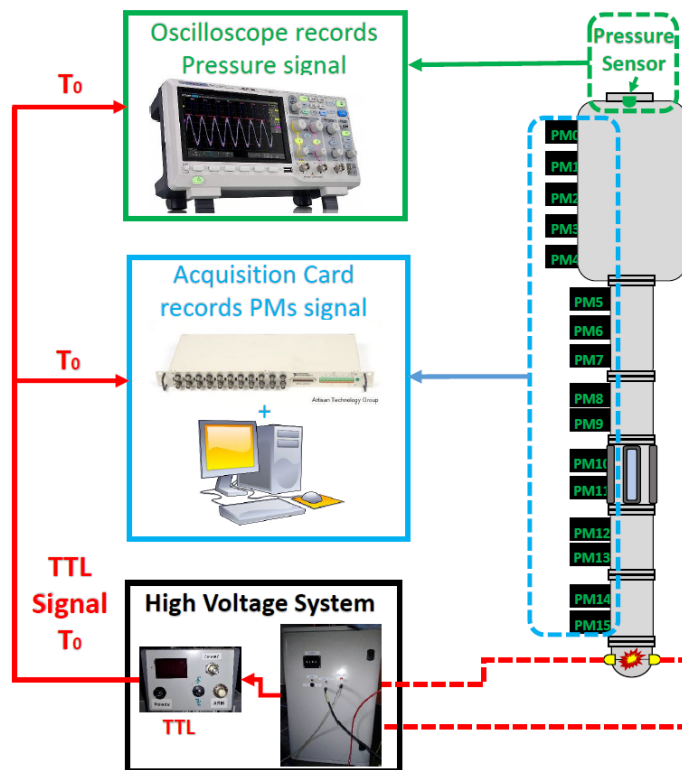


Figure 57: System for the acquisition of the flame speed position and pressure evolution triggered by TTL Generator.

2.3 Flame Propagation Speed Measurement

The Flame propagation speed measurements are done by using Photomultiplier tubes. The signal is recorded by an Acquisition Card, synchronised using the TTL system generated by the synchronizer of the spark ignition. The following part is dedicated to the detailed description of these systems. The system includes 16 PMs (Hamamatsu IP28) which are fed by two different High Voltage Transformer (HV1 at 940 V and HV2 at 890 V). The Photo-Multiplier is a transducer able to convert the flame light signal, emitted by the OH radicals, into a variation of Voltage. They are located all along the acceleration tube (PM15-PM5) and of the Dome (PM4-PM0), as showed in Table 5.

Sensors	Distance from ignition point (m)	Sensors	Distance from ignition point (m)
PM0	4.3415	PM8	2.037
PM1	4.0915	PM9	1.772
PM2	3.8415	PM10	1.527
PM3	3.5915	PM11	1.277
PM4	3.3415	PM12	1.027
PM5	2.877	PM13	0.777
PM6	2.627	PM14	0.527
PM7	2.377	PM15	0.277

Table 5: Photo Multipliers Location from the Ignition Point in the Bottom Cap.

Each PM is placed in a tube with an optical system designed to obtain a 4 mm layer thickness observation window. It is composed by a: UV-filter (Schott UG11) in order to detect mainly the OH* emission, Focal Lens (5 mm) horizontal slot (1 mm x 10 mm). The housing system of a photomultiplier tube is showed in Figure 58.

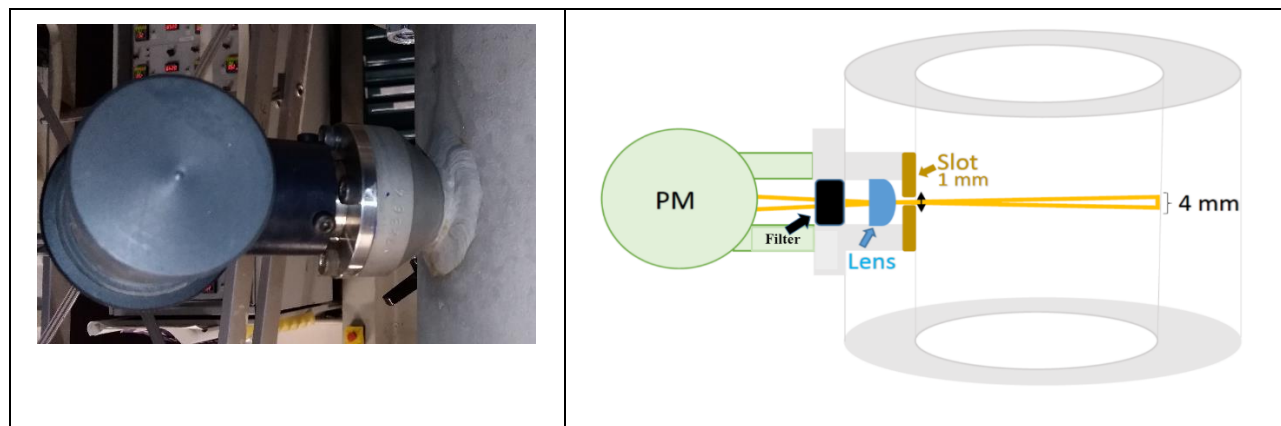
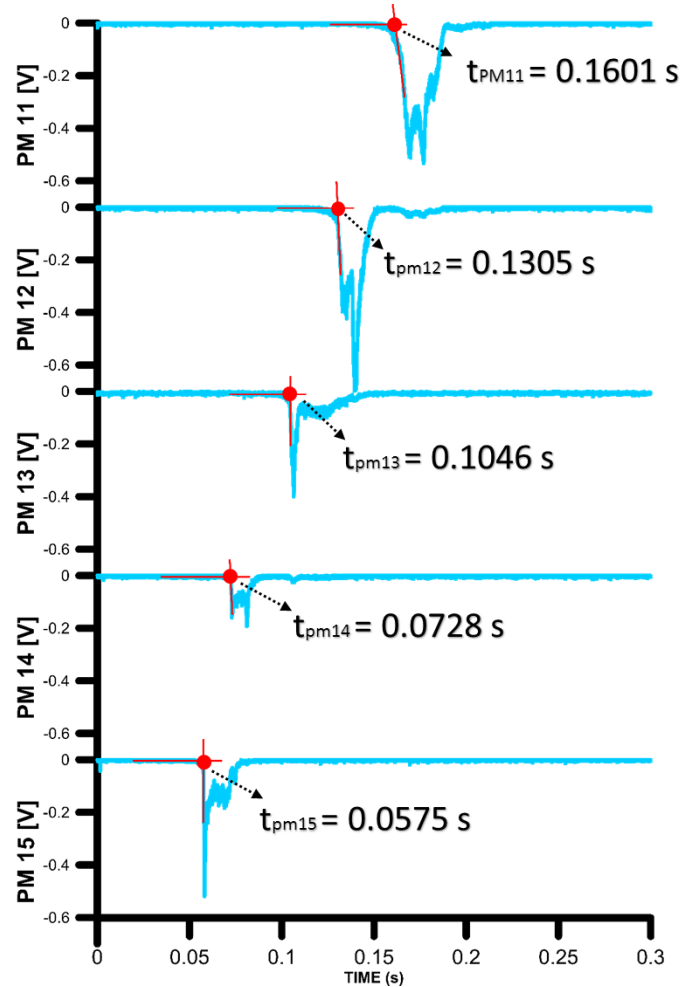


Figure 58: Mounting Scheme of a Photo Multipliers Tube.

When the flame passes in front of each photomultiplier, the emitted light, induces a voltage variation in the PM signal. By considering the tangent to this voltage drop, it is possible to measure the time at which the flame passes in front of the observation window. The Figure 59 shows an example of PMs signals processing (from PM15 to PM11) related to an upward flame propagation at 13%_{vol}H₂. For each peak, it is possible to detect the crossing flame time and, by knowing the distance between the PMs, it is possible to evaluate the propagation velocity with the following equation:

$$V_{PM} = \frac{X_{PM+1} - X_{PM-1}}{T_{PM+1} - T_{PM-1}}$$

Equation 33: Flame Velocity from detected time.



*Figure 59: Example of crossing flame time Detecting
(exp. 114 –Dry condition 13%_{vol}H₂-1bar –ambient temperature- upward propagation).*

The PM's system, connected to a 16 channels bank box (BNC-2090), are recorded by an Acquisition Card (National Instrument PCI-MIO-16E-1). In our case the rate of acquisition is of 48125 point/s each Photomultiplier.

2.3.1 The uncertainty on the Flame Speed

The uncertainty on the flame speed depends on the uncertainty on the position and on the detected time of the flame.

The uncertainty on the position of the flame is directly related to the optical system which introduce an uncertainty $\delta = \pm 2$ mm (Figure 58). In order to evaluate this error, is necessary to consider the minimum distance between 2 PM, which is of $d_{\min} = 245$ mm (in the the acceleration tube part). By considering the ratio $\delta/d_{\min}$, the maximum error on the position is equal to 1.63 %.

The uncertainty on the detected time, depends on the shape of the voltage signal which introduces an ambiguity related to the slope to choose (as showed in Figure 61). According to the distance from the ignition point, the shape of the flame provides different voltage profiles and the evaluation of the error, has been done by considering the worst case (Figure 60) and the best case (Figure 61).

The worst case, in terms of detection of the time, is the signal provided from the first PM which the flame encounters (showed in Figure 60). The maximum error related to the position can be of 6.37% on the detected time.

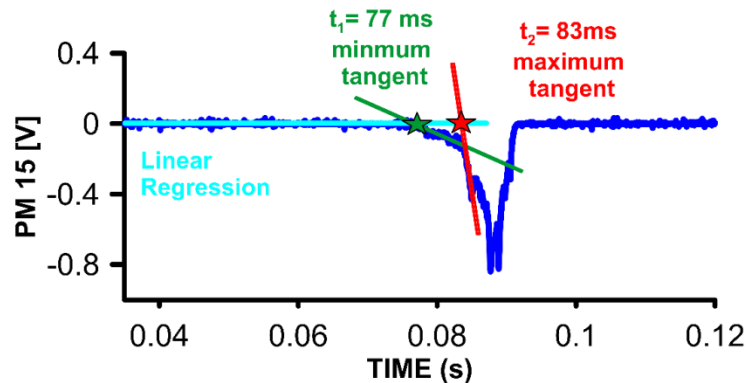


Figure 60: Example of error Analysis- B015 13%vol H_2 +87%vol Air –upward BR=0.63-fast flames-PM15.

For all the other PMs signals, the profile of the voltage signal is like the one showed in Figure 61 and it leads to a $\Delta t = 0.015$ ms which correspond to an error of 1.68% on the detected time.

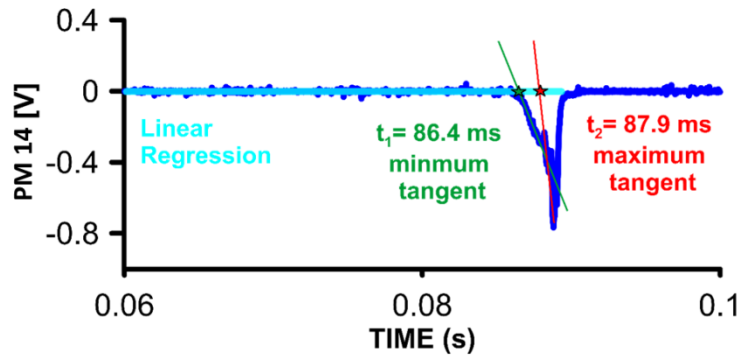


Figure 61: Example of error Analysis- B015 13%vol H_2 +87%vol Air –upward $BR=0.63$ -fast flames –PM14.

By taking into account the worst case (PM1), the maximum error on the flame speed is 7.27%.

For the other values of flame speed, evaluated by considering a signal profile similar at the one in Figure 61, the error on the flame speed is 3.8%

2.4 The pressure Sensor characteristic

According to the propagation direction, a pressure sensor Kistler 601A is mounted on the top part of the dome, or in the bottom part of the acceleration tube (Figure 65). The sensor is housed in a metal adaptor and its sensitive surface is protected by an aluminium foil and thermal grease. The protection film is necessary because when the flame touches the sensor sensitive surface, it induces a thermal shock which affects the quality of the measurement [63], [64].

The sensor is connected to a charge amplifier which allows to select the measurement parameters and to record via oscilloscope the pressure dynamic as a voltage drop signal. The signal is corrected by a factor which takes into account the initial pressure in order to have the absolute pressure variation during the combustion propagation phenomena. In the Table 6, are summarized the main characteristics of the used sensor used in this study.

Range	0 - 25 bar
Sensitivity	16 pC/bar
Frequency	150 kHz
Output	positive

Table 6: Pressure Sensor Technical Characteristic, Kistler 601A.

2.4.1 Uncertainty on the pressure evolution measurement

The uncertainty on the pressure measurement is related to 2 contributions: an error on the voltage value (Y axis) and an error on the time instant (X axis).

The error on the voltage value (Y axis) provides an error on the value of pressure. It can be calculated by considering: the number of bit/div, the number of volt per division, number of bar per volt. The following table summarizes the error on the pressure calculated based on the setting of our experimental campaign:

bar/Volt	bit	Y division	Volt/div	Error %
1	256	8	1	3.1%
2	256	8	0.5	1.6%

Table 7: Error on the Pressure value.

The error on the time (X axis) is related to the acquisition rate of the oscilloscope and the recorded number of points. In our case, the acquisition rate changes as a function of the flame speed and it

is 50000 points/s in case of fast flames and 20000 pt/s in case of slow flames. These acquisition rate provide an error of: $\pm 2 \cdot 10^{-6}$ s and $\pm 5 \cdot 10^{-6}$ s.

2.4 Spray Diagnostic: Experimental Setup

In this paragraph the diagnostic and the experimental set up used in order to characterize the water spray are described. The laser diffraction particle analyser instruments provide quickly and accurately an assessment of the droplets size distributions at a local, or global, location within the spray plume. A laser unit provides a collimated light source and the receiving unit detects the diffraction pattern created when the droplets pass through the laser beam.

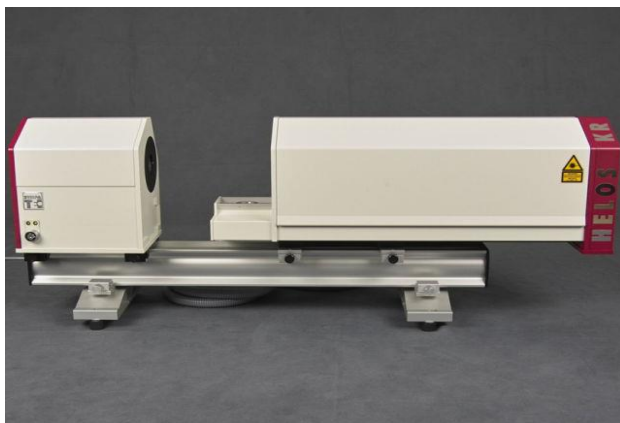


Figure 62: Helos System Sympatech.

Our goal is to understand if the size of the droplets can be significantly increased or decreased due to coalescence or fragmentation phenomena during the injection phase. Due to the difficulty to measure at different height directly in the acceleration tube of the ENACCEF, the experimental campaign was conducted by using a tube 2.40 m long with an internal of 158 mm.

The experimental set up allows to place the nozzles in the centre of the tube at different heights from the measuring point (laser beam) as showed in Figure 63. In this way it is possible to measure the size of the water droplet from 0.26 m to 1.86 m from the nozzle exit.

The distance between the laser unit and the detector unit depends on the focal lens used and in our case is equal to 200 mm (focal lens R4 for particle between $0.5\mu\text{m}$ to $350\mu\text{m}$).

The experimental procedure consists of the following steps:

- Trigger the laser measurement at $t=0$ s;
- Activate the spray injection at $t=10$ s;
- Stop the spray injection at $t=130$ s;
- End the measurement at $t=200$ s;

The result about the spray characterization are presented and explained in the Chapter: Water Spray Characterization.

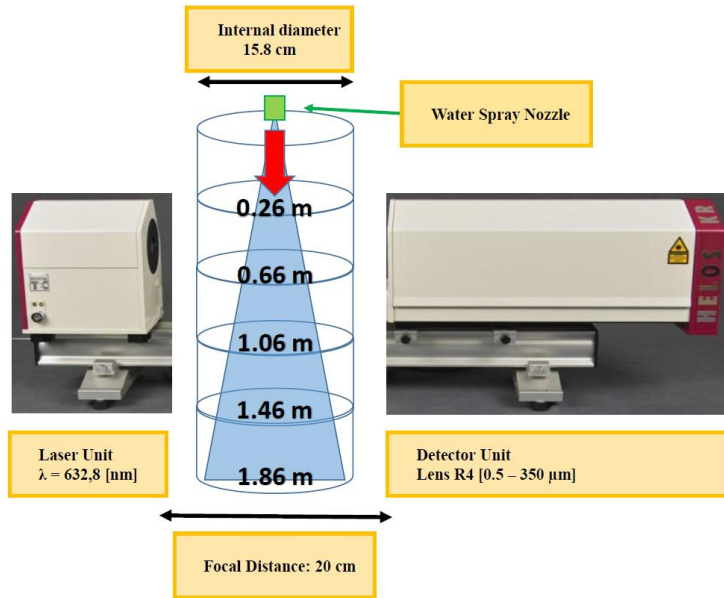


Figure 63: Experimental set up for water spray characterization.

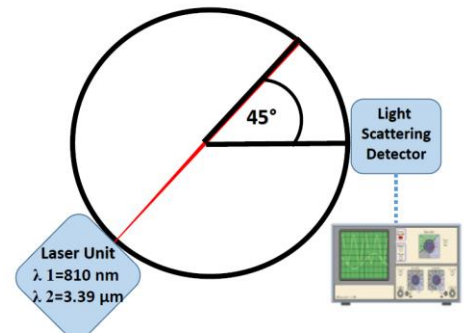


Figure 64: Laser Extinction Setup.

With the same setup, 2 different laser units with 2 different wave lengths (810 nm and 3.39μm) have been employed in order to conduct laser extinction measurement at different heights. The scattered light detectors are placed with an angle of 45° to the laser beams as showed in Figure 64. The laser extinction measurements have been conducted from 0.26 m and from 1.86 m from the injection point.

The results about these measurements are described in the Chapter: Water Spray Characterization.

3 Experimental Procedure for the flame propagation

First, the facility and all the connecting lines for the gas introduction are vacuumed down to around 10 Pa. The gas mixture is introduced via mass-flow controllers. The air flowrate is fixed at 19552 cm³/min and the hydrogen flowrate is adjusted in order to obtain the desired composition (10.50-11-13%_{vol}H₂). The Air is taken from the compressed air system of the ICARE laboratory. The hydrogen, alpha2 quality is from Air Liquide®.

The filling operation takes almost 40 minutes and it is stopped when the pressure inside the facility is slightly higher than the atmospheric pressure in order to account for sampling and hence to reach an initial pressure of 1 atm when ignition is triggered.

For the gas sampling, 4 sampling balloon (3 in the acceleration tube and 1 in the dome) previously vacuumed which are filled and then analysed using the μ GC (paragraph 2.1.3 Example of Measurement).

The spark ignition system is activated manually and in case of spray injection, it occurs after 1 minute of spray injection. The spark ignition system triggers at the same time, the recording of the pressure evolution signal and the photomultipliers tube (flame detector).

4 Configuration for Upward and Downward Flame Propagation

In this study, the ignition location can be located either at the bottom of the facility (upward flame propagation) or at the top of the facility (downward flame propagation).

The sequence is from the bottom to the top: bottom cap, acceleration tube part 1, part 2, part 4 (Quartz windows), part 3, part 5 and dome. According to the ignition point, the direction of flame propagation, will be from the bottom to the top or vice versa. For this reason, it is important to place the pressure sensor in order to follow the pressure evolution during the combustion phenomena. The pressure sensors are very sensitive to the temperature variation and the thermal shock due to the flame, which can affect the quality and the reliability of the measurements. In order to minimize this effect, the pressure sensor is protected by a layer of grease and aluminium foil and is placed at the top of the Dome in case of an upward propagation or at the bottom part of the Acceleration tube in case of downward propagation as in Figure 65.

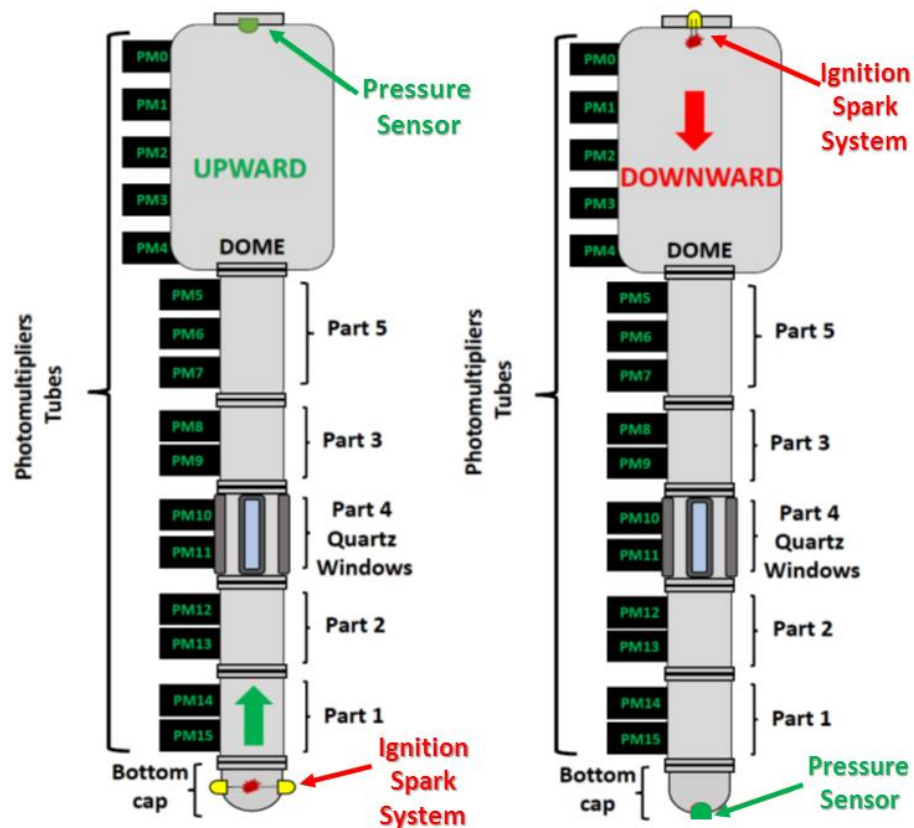


Figure 65: Upward and Downward Setup Scheme ENACCEF.

Le dispositif expérimental et les diagnostics associés

Dans ce chapitre, nous décrivons les installations et l'équipement qui ont été utilisés au cours de cette étude :

1. ENACCEF 1 un tube d'accélération verticale (Dome plus Acceleration tube) ;

2. Diagnostic de la vitesse de propagation de la flamme et de la pression Mesure de l'évolution. Cette installation verticale d'un volume interne de 720 l est composée d'un tube d'accélération et d'un dôme conçu pour reproduire la dynamique de l'explosion se produisant dans un bâtiment de confinement nucléaire. L'appareil était équipé pour étudier l'impact de l'injection de pulvérisation sur la flamme dans la direction de propagation ascendante et descendante, avec différents endroits de pulvérisation et différents débits d'eau.

L'équipement d'essai est équipé pour acquérir le signal relatif à l'évolution de la pression (capteurs de pression) et à la position de la flamme dans le temps (photomultiplicateurs).

Chapter 3: Preliminary Calculations

Preliminary equilibrium calculations and 1D flames simulations are conducted by using COSILAB software which is comprehensive simulation tool for the numerical simulation of a variety of industrially and scientifically relevant reactive flow.

The goal was to obtain basic information about the impact of the water vapour on:

1. Adiabatic Temperature,
2. Isochoric Adiabatic Complete Combustion Pressure,
3. the hydrogen dry-air laminar flame thickness,
4. the hydrogen humid-air laminar flame thickness,
5. hydrogen dry-air laminar flame Speed,
6. hydrogen humid air laminar flame speed.

The Chapter is divided in 2 Parts:

- 1) Chemical Equilibrium Calculation
- 2) One Dimensional Flame Simulation;

1 Thermodynamic Equilibrium Calculation

1.1 Water vapor content

The first Step is to understand what are the conditions in which the flame will propagate in our experimental set-up. A water spray at ambient temperature, is injected from the top of our vertical facility, which is filled previously, with a mixture of Hydrogen-Air mixture at 1 bar and ambient temperature. As the injection starts, part of the liquid water evaporates and the quantity of water which will pass from liquid to gas phase, corresponds to Saturation Pressure. It is possible to evaluate vapour pressure by using the Antoine relationship (Equation 34).

$$\text{Log}(P_{sat}) = A - \frac{B}{T + C}$$

*Equation 34: Antoine Relationship
for saturate vapor pressure .*

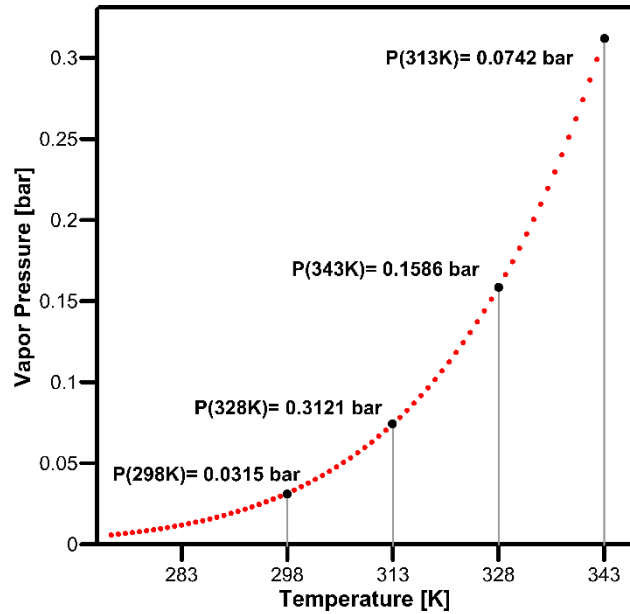


Figure 66: Vapor Pressure as function of the initial temperature .

The Coefficients have to be chosen according to the range of temperature and they are provided by semi-empirical relationships. In our case, by considering our range of temperature, the Stull coefficient were used: A=4.6543; B=1435.264; C=-64.848 which are valid from 273K to 343K. The graph in Figure 66 shows the evolution of the vapour pressure as a function of the initial temperature and it reports the vapour pressure corresponding to the initial temperature used for our equilibrium calculation: 298K, 313K, 328K and 343K.

1.2 Impact of the water vapor on the flame temperature

Since water spray will be used prior to the ignition of the combustible mixture, it is necessary to account for the vaporized water in the estimation of the equilibrium properties such as the adiabatic complete combustion either considering a constant pressure (p_b density of the burned gases) or at constant volume (maximum pressure at T_{AICC})

The molar concentrations of the species are evaluated by considering

$$(1 - \alpha) \cdot \{H_2 + Air\} + \alpha$$

where α is the initial molar concentration of the water vapor which depends on the initial temperature. Table 8 show an example of initial mixture composition for different water vapor content at constant E.R.

Dry Mixture: 10% H ₂ + 18.9% O ₂ + 71.1% N ₂				
T [K]	H ₂ O vap	H ₂	O ₂	N ₂
298	3.2%	9.7%	18.3%	68.8%
313	7.4%	9.3%	17.5%	65.8%
328	15.9%	8.4%	15.9%	59.8%
343	32.1%	6.8%	12.8%	48.3%

Table 8: Mixture composition at different initial temperature. 1 bar and constant equivalence ratio ($\phi = 0.26$).

Figure 67 shows the flame temperature in case of dry air mixtures, as a function of the equivalence ratio ($0.099 < \phi < 2$) at 1 bar. By increasing the initial temperature, the flame temperature slightly increases and this increasing is more marked especially for rich mixtures.

The graph in Figure 68 ,instead shows the flame temperature in case of humid air mixtures, as a function of the equivalence ratio ($0.099 < \phi < 2$) at 1 bar. One can see that compared to the dry case, for the same ϕ , the flame temperature is lower. By increasing the initial temperature, it decreases significantly due to the higher initial water vapor content.

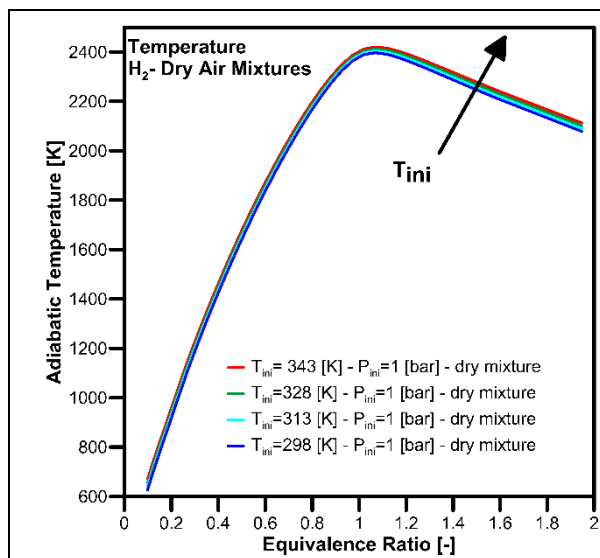


Figure 67: Dry Hydrogen Air Mixture - Impact of the Initial Temperature on the Adiabatic Flame Temperature.

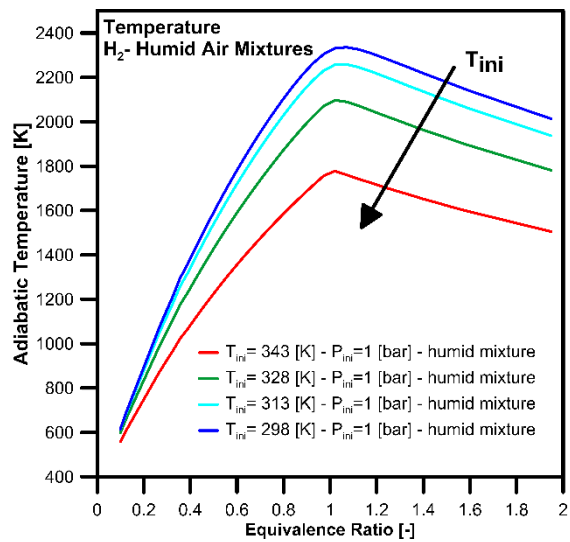


Figure 68: Humid Hydrogen Air Mixture - Impact of the Initial Temperature on the Adiabatic Flame Temperature.

1.3 Impact of the water vapour on the combustion pressure

The combustion pressure, evaluated with transformation at constant volume and internal energy, is called adiabatic isochoric complete combustion Pressure (P_{AICC}).

The graph in Figure 69 shows the impact of the initial temperature on P_{AICC} as a function of the equivalence ratio ($0.099 < \phi < 2$) for dry hydrogen air mixtures. It is possible to notice that as the temperature increases, the combustion pressure decreases and this trend is more marked on the rich side.

Figure 70 shows instead the impact of the initial temperature on P_{AICC} as a function of the equivalence ratio ($0.099 < \phi < 2$) for humid hydrogen air mixtures. The increase of the initial temperature has a strongest impact on the decreasing of the equilibrium pressure, compared to the dry case.

In presence of water vapor, at ambient temperature, the P_{AICC} is slightly lower than the one evaluated in the dry case and this decrease is more pronounced as the initial temperature increases due to the higher quantity of water vapor in the initial mixture.

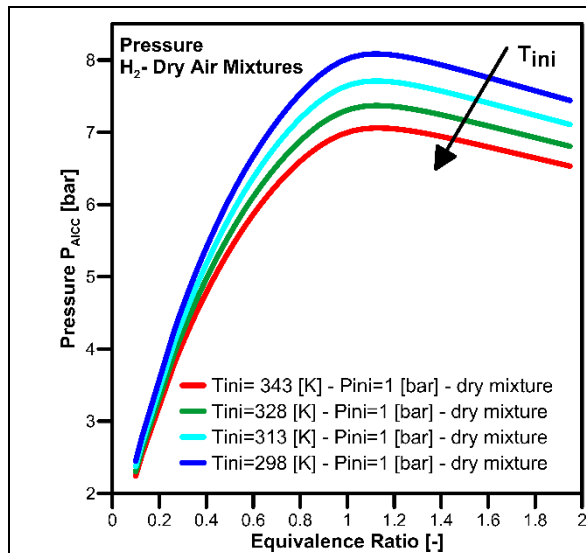


Figure 69: Dry Hydrogen Air Mixture - Impact of the Initial Temperature on the P_{AICC} at 1 bar.

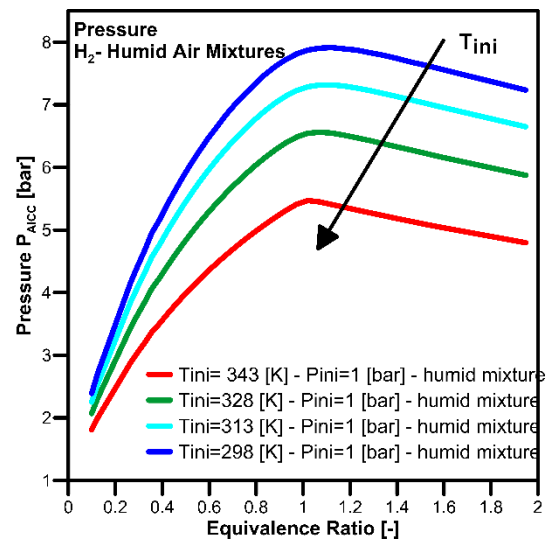


Figure 70: Humid Hydrogen Air Mixture - Impact of the Initial Temperature on the P_{AICC} at 1 bar.

2 Laminar Flame Speed Calculations

The analyses of flame acceleration rely on the knowledge of different fundamental combustion properties such as the laminar flames speed and the laminar flame thickness.

2.1 One-Dimensional laminar flame speed simulations details

The governing equation system takes into account equations of continuity, energy, ideal gas and species-mass (for i -number of species). The mathematical system, with $i+3$ equations for $i+3$ unknowns (temperature, density, velocity and species) is closed and it can be solved by providing a first attempted flame speed profile. The solution of the equation systems describes the one dimensional Un-streamed freely propagating premixed flame in terms of: spatial profile of the mass density [kg/m^3], mass flux [kg/s m^2], enthalpy [J/kg], mole fraction, temperature [K], velocity [m/s], volumetric rate Heat Release [J/s^3] and one-dimensional spatial domain [m].

Concerning the calculations, the software uses as input data:

1. List of Reaction involved in the Hydrogen Combustion (Mevel Mechanism -2009),
2. Thermal Parameters (Nasa Polynomials),
3. Transport Properties,
4. Control Parameters.

The Control Parameters define: the flame type (freely propagating), the models of transport (Thermal Diffusion governed), the pressure dynamic (constant at 1 bar), grid (1500 points with adaptive gridding), time stepping, numerical method (steady and unsteady Newton). In our case, Steady Newton Method usually is adequate to obtain a solution by starting from the initial guess. For some simulations at low hydrogen concentrations, the initial guess is too far from the solution and the Unsteady Newton method has been used initially to approach the final solution before switching to steady one.

2.3 Flame Speed Simulation Results

The flame speed simulations are conducted for lean mixtures from 10%_{vol}H₂ to 30%_{vol}H₂ ($0.26 < \phi < 1.02$), by considering 2 initial Temperature 298 K and 313 K.

Figure 71 shows the impact of the initial temperature on the laminar flame speed evaluated for dry air mixtures (solid lines) and in case of humid air mixtures (dash-dot lines). In case of dry hydrogen air mixture, when ϕ increases, the LFS increases:

1. from 0.005 m/s to 2.0 m/s at 298 K,
2. from 0.008 m/s to 2.3 m/s at 313 K.

For dry mixtures, the increase of the initial temperature leads to an increase in the laminar flame speed. In case of humid mixtures, the presence of the water vapor slows down the flame. By increasing the initial temperature, the decrease of the flame speed is more marked due to the higher water vapor concentration in the initial mixture. In fact, as ϕ increases, in presence of water vapor, the LFS ranges:

1. from 0.003 m/s to 1.9 m/s at 298K,
2. from 0.002 m/s to 1.8 m/s at 313K.

Figure 72 shows the laminar flame speed variation compared to the dry case at 298 K. The differences between the LFS in dry case at 298 K and LFS for the others, are more important for initial hydrogen concentration between 10-16%_{vol} and they are reduced by increasing the equivalence ratio. In case of dry mixture, at 313 K the flame speed is at least 10% higher than the one at 298 K. In case of humid hydrogen air mixtures, at 298 K the presence of the water vapor reduces the LFS by at least of 10%. When the initial temperature is increased to 313 K, the LFS reduction is more remarked and it is in the order of 20%.

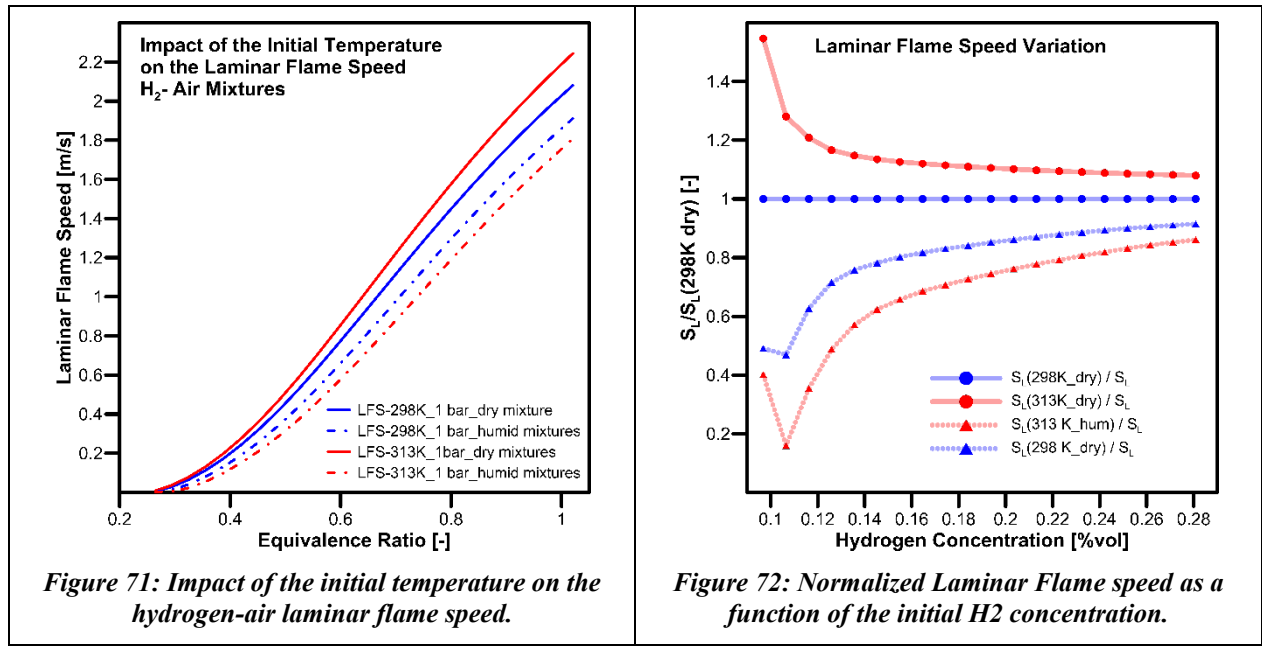


Table 9 reports a summary of the main flame properties interesting for this study: adiabatic temperature, P_{AICC} , laminar flame speed (LFS), ratio between unburned/burned gases (σ) and the effective Lewis Number.

The effective Lewis number is function of the activation energy (E_a in Table 10) and it is evaluated by extrapolation [65]. Lower Lewis Number indicates a higher tendency of the flame to be unstable in the early phase of its development.

E.R	%H2	%O2	%N2	T _{equil} [K]	P _{aicc} [bar]	speed _{sim} [cm/s]	sigma [-]	Lewis _{effective}
0.279	0.105	0.19	0.71	1135	4.40	1.42	3.60	0.362
0.294	0.110	0.19	0.70	1173	4.54	2.86	3.72	0.375
0.356	0.130	0.18	0.69	1323	5.06	11.32	4.15	0.401

Table 9: Hydrogen air Flame properties evaluated at 1 bar and 298K.

Ea _{extracted} [J/mol]	β [-]
198986.67	15.52
196400.00	14.97
186533.33	13.10

Table 10: Calculation Lewis Number: Extracted Activation Energy and Zel'dovich Number

3 Laminar Flame Thickness

The flame thickness is an important parameter because it is related to the possibility to have a fully evaporation of water droplets into the flame front. The laminar flame thickness can be calculated according to two methods:

1. by using the maximum temperature gradient from the spatial temperature profile of the flame temperature.
2. by considering the laminar flame speed and the thermal parameters as the thermal conductivity, the density and the specific heat at constant pressure of the unburned gas.

By considering a 1-d description of the flame front, the thickness based on the temperature gradient, describes a total flame thickness which takes into account the region of burning and the region of conduction. The flame thickness evaluated by using the thermal parameters, is more representative of the flame zone where the reaction take place (reaction zone thickness). The following Figure 73 summarizes the input data and the relationship used for the flame thickness evaluation.

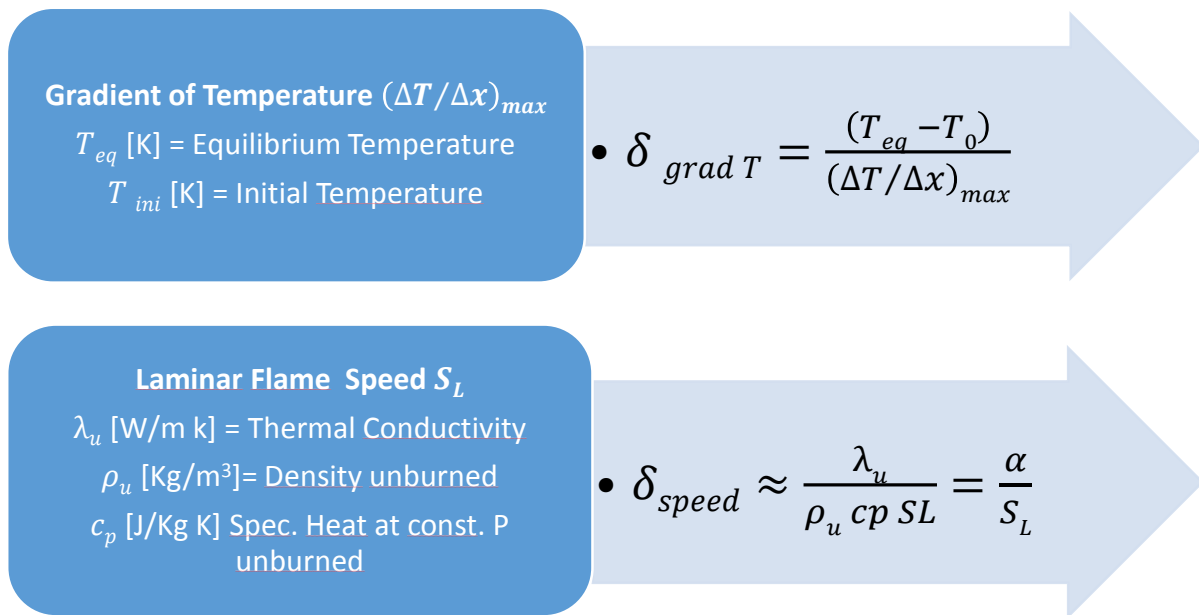


Figure 73: Laminar Flame thickness Calculations.

The result of the calculation are showed in Figure 74 and in Figure 75. They highlight the impact of the initial temperature and of the water vapor content on the thickness of the flame.

The flame thickness, calculated by using the laminar flame speed and the thermal parameters (Figure 74), is included in a range of variation from 10^{-5} m to 10^{-3} m (at 10%_{vol}H₂). The increase of the flame thickness, due to the presence of the water vapor, is more marked for the leanest mixtures because, as showed in Figure 72, the water vapor has in that region a strongest impact on the laminar flame speed.

The flame thickness, calculated by using the gradient of temperature (Figure 75) is higher by one order of magnitude compared to the one calculated by using the LFS. It is included in a range of variation from 10^{-4} m to 10^{-3} m (at 10%_{vol}H₂).

In both calculation, in absence of water vapor, as the temperature increases, the thickness of the flame slightly decreases. In presence of water vapor instead, the increases of the temperature correspond to an increase of the flame thickness which is more important as the initial water content increases.

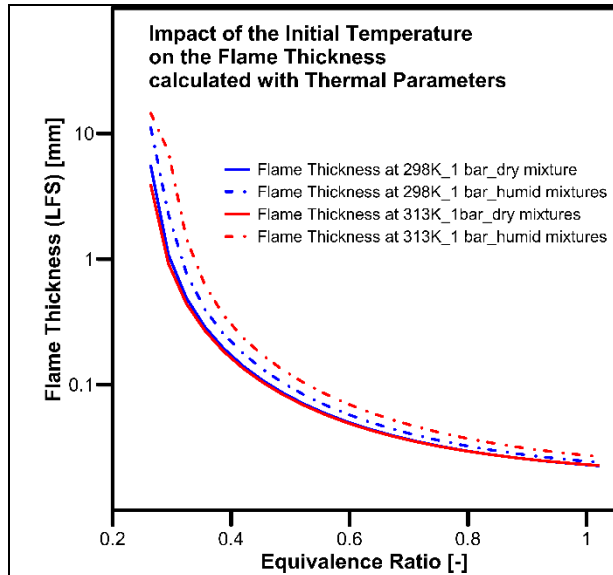


Figure 74: Impact of the initial temperature on hydrogen-air laminar flame thickness evaluated from the thermal parameters and LFS.

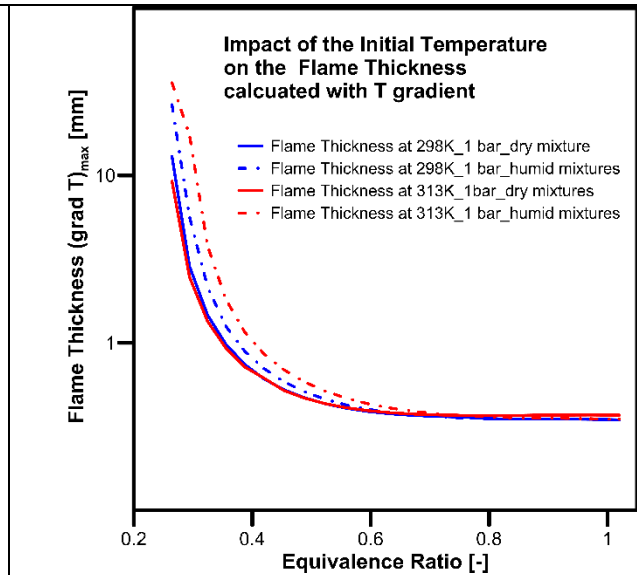


Figure 75: Impact of the initial temperature on hydrogen-air laminar flame thickness evaluated from the temperature gradient.

4 Preliminary Calculation Results Discussion

The aim of this chapter is to estimate to what extent the water vapor that will inevitably form when the spray is activated and will modify the fundamental parameters of combustion

From the equilibrium calculation, it is possible to highlight how the temperature variation has a different impact on the adiabatic temperature and on the combustion pressure, whether the water vapor is taken into account or not in the initial mixture.

The increase of the temperature, in humid mixtures induces a decrease of the T_{ad} and P_{AICC} due to the higher water vapor content. These observations are confirmed by the 1-D simulations which highlights also that the impact of the water vapor on the laminar flame speed is stronger for very lean mixture. It is important to note that the result on the laminar speeds for very lean mixtures are not representative of the reality in terms of velocity and thickness of the flame. Experimentally, it is not possible to obtain a premixed flame which can be rigorously defined as laminar for initial hydrogen content lower than 16%_{vol}H₂.

Nevertheless, the results show that the increase of temperature has a mitigation effect on the flame propagation, because the initial mixture can host higher water vapor content.

The results about the flame thickness, reflect the ones on the laminar flame speed and they show that the water droplets (10^{-5} m) involved in our experimental investigation, are:

1. smaller than flame thickness calculated with the thermal parameter ($\sim$ reaction flame zone)
2. smaller at least of 1 order of magnitude that the flame thickness calculated with the gradient of temperature ($\sim$ total flame thickness)

Calcul préliminaire

Les calculs préliminaires d'équilibre et les simulations de flammes 1D sont réalisés à l'aide du logiciel COSILAB qui est un outil de simulation complet pour la simulation numérique d'une variété de flux réactifs. L'objectif était d'obtenir des informations de base sur l'impact de la vapeur d'eau :

1. Température adiabatique,
2. Pression de combustion complète adiabatique isocorique,
3. l'épaisseur de la flamme laminaire d'hydrogène plus air sec/humide,
4. vitesse de la flamme laminaire de l'hydrogène avec l'air sec/humide.

Le but est d'estimer dans quelle mesure la vapeur d'eau qui se formera inévitablement lorsque le spray sera activé et modifiera les paramètres fondamentaux de la combustion. À partir du calcul d'équilibre, il est possible de mettre en évidence comment la variation de température a un impact différent sur la température adiabatique et sur la pression de combustion, que la vapeur d'eau soit prise en compte ou non dans le mélange initial. L'augmentation de la température, dans les mélanges humides, induit une diminution du T_{ad} et du P_{AICC} en raison de la teneur plus élevée en vapeur d'eau. Ces observations sont confirmées par les simulations 1-D qui mettent également en évidence que l'impact de la vapeur d'eau sur la vitesse de la flamme laminaire est plus fort pour un mélange très pauvre. Il est important de noter que le résultat sur les vitesses laminaires pour les mélanges très maigres n'est pas représentatif de la réalité en termes de vitesse et d'épaisseur de la flamme. Expérimentalement, il n'est pas possible d'obtenir une flamme prémélangée qui peut être rigoureusement définie comme laminaire pour une teneur initiale en hydrogène inférieure à 16%volH₂. Néanmoins, les résultats montrent que l'augmentation de la température a un effet d'atténuation sur la propagation de la flamme, car le mélange initial peut contenir plus de vapeur d'eau. Les résultats sur l'épaisseur de la flamme, reflètent ceux sur la vitesse de la flamme laminaire et ils montrent que les gouttelettes d'eau (10-5 m) impliquées dans notre étude expérimentale, le sont :

1. inférieure à l'épaisseur de la flamme calculée avec le paramètre thermique (~ zone de flamme de réaction)
2. inférieure d'au moins 1 ordre de grandeur que l'épaisseur de la flamme calculée avec le gradient de température (~ épaisseur totale de la flamme).

Chapter 4: Water Spray Characterization

In this chapter, the results about the spray characterization of 2 different nozzles are discussed.

The aim of this experimental campaign is to evaluate if the characteristic parameters of the spray can be significantly modified by the geometry of our experimental apparatus.

In particular, the goal is:

- To understand if the internal walls of the acceleration tube (i.d.=0.154 m) can promote the condensation of a large quantity of water on the walls
- To have a qualitative idea of the spray densities and its evolution in the acceleration tube in terms of droplet size during the spray propagation in the acceleration tube

The chapter is divided in 3 parts:

1. Optimization of the experimental conditions
2. Characterization of the droplets size
3. Laser extinction measurement for the spray density.

1 Characterization of the Droplets Size: Experimental Conditions

In this section the experiments conducted in order to characterize the size of the droplets are described. The pump system (Figure 52) used to inject the water is able to sustain a maximal pressure of 4000 PSI (275 bar). The control of the pressure is possible only by setting the water flowrate which can be fixed at 100 ml/min, which is the maximum achievable.

When the nozzle WM1 is used (orifice of 100 μm), the maximum flowrate that can be fed by the pump is limited to 60 ml/min. Larger flowrates could not be obtained as at the needed pressure was beyond the capabilities of the pump.

For the WM2 nozzle (orifice of 200 μm), a steady spray could be achieved only for flowrates higher than 70 ml/min.

By standing this limitation, the choice was to investigate the size of the droplets by using a flowrate of 50 ml/min for the WM1 and 100 ml/min for the WM2.

	Orifice [μm]	Operating Flow Rate	Pressure	Temperature H2O
WM1	100	0 - 60 [ml/min]	150 bar	Ambient
WM2	200	70 - 100 [ml/min]	150 bar	Ambient

Table 11: Operative Conditions Water Spray Nozzles.

1.1 Optimization of the experimental conditions for the spray characterization

Figure 76 shows the volume diameter evolution as a function of the time, during the spray injection. The size of the droplets is measured for 110 s and the evolution versus time in terms of $d_{V(0.90)}$, $d_{V(0.50)}$, $d_{V(0.10)}$ are reported. The water spray is activated after 10 s from the beginning of the measurement and it is stopped after 120 s from the beginning of the measurement. It is possible to notice that after few seconds (< 5 s) from the spray activation, the volume diameter of the droplets is stable during all the injection time. The size of the droplets, does not change during the spray injection of 110s. When the spray is stopped, it remains stable for few seconds (< 5 s) and after that the laser particle sizers does not detect particles (after 125 s).

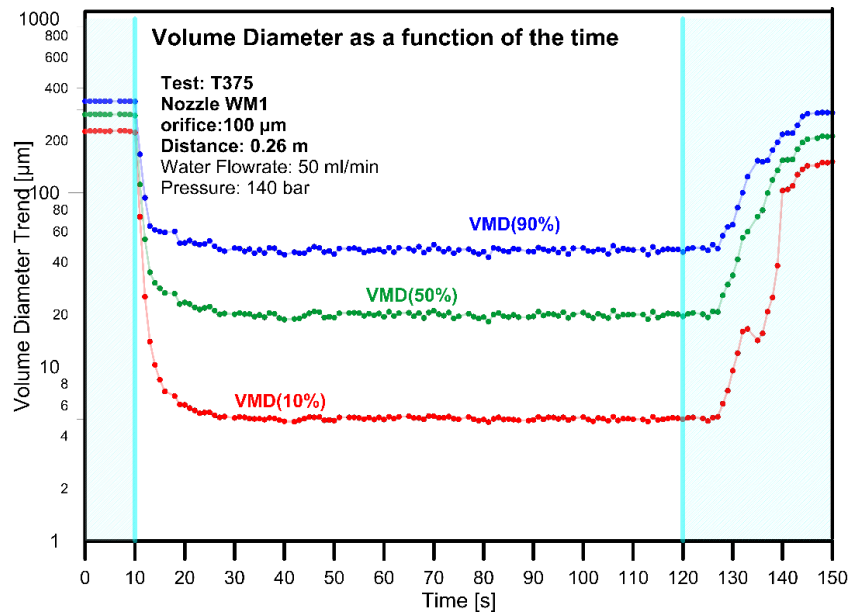


Figure 76: Example of Temporal of the Volume Diameter during the measurement with Particle Laser Sizer.

During the time of injection, the size of the droplets, at increasing distance from the spray nozzle: 0.26 m, 0.66 m, 1.06 m, 1.46 m and 1.86 m, has been measured. For each test, the averaged value of $D_{V(0.50)}$ is evaluated. Each test is repeated 10 times.

The results are reported in Figure 77 where are showed the averaged volume diameter as a function of the distance from the nozzles for the WM1 (red line) and WM2 (blue line). In both cases, the volume mean diameter does not show a significant evolution along the tube and it is in the range of 13-18 μm for WM2 and 15-18 μm for WM1.

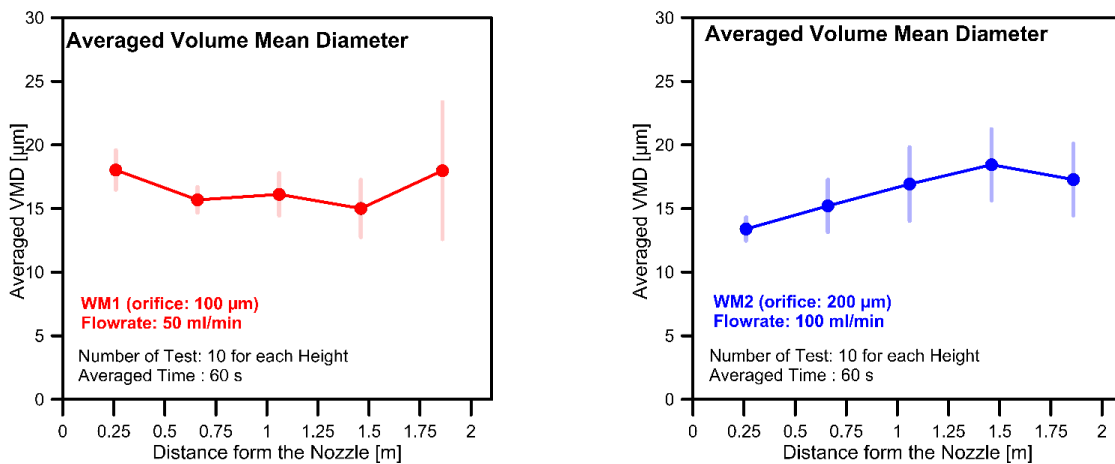


Figure 77: Averaged Volume Diameter Evolution As a Function of the distance from the nozzle.

From the graph, we can see that the result shows a certain variability which is higher as the distance from the nozzle increases, an optimization of the number of test, as a function of the VMD and the corresponding error bar has been conducted. It was repeated for 80 times, the measurement with the WM1 at 1.86 m which is the case with the higher variability compared to the other measurements.

Figure 78 shows the averaged $d_{V(0.50)}$ as a function of the number of repeated tests (red circles). The green triangles represent the corresponding Sauter Mean Diameter. It is possible to notice that by increasing the number of tests up to 80, the averaged diameter changes from 18 μm to 23 μm which is 30% of the initial value and the error bar is reduced from 5 μm to 3 μm which is almost the 40 % of his initial value. By considering the Sauter Mean Diameter is possible to notice that it exhibits a lower variation compared to the Volume one and it vary from 12 μm to 14 μm , by reaching a convergent value for 30 measurements.

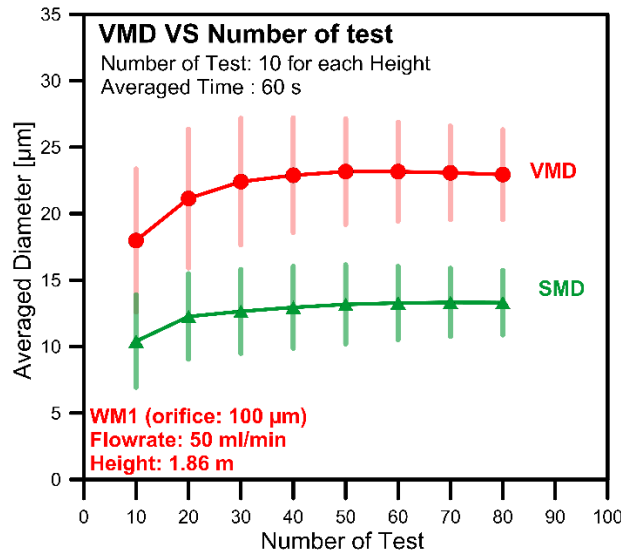


Figure 78: Averaged Volume Mean Diameter as a function of the Number of tests.

The final experimental campaign has been conducted by considering:

1. the minimum and the maximum distance from the nozzles (0.26 m and 1.86 m),
2. By repeating each test for at least 30 times.

1.2 Droplet Size as a function of the distance from the nozzle

Table 12 show the averaged SMD on 30 repeated tests, at 0.26 m and 1.86 m from the nozzle location. Both nozzles, for the water flowrate considered, produce a very similar spray in terms of SMD which is in the range of 10-15 μm . The error bar is higher as the distance from the nozzle location increases and it is in the order of 3% at 0.26 m and of 15% at 1.86 m (WM1 case).

The WM1 nozzle with a flowrate of 50 ml/min has an averaged SMD of $12 \pm 0.2 \mu\text{m}$ at 0.26 m from the injection point and $13 \pm 2.4 \mu\text{m}$ at 1.86 m from the injection point.

The WM2 nozzle with a flowrate of 100 ml/min has an averaged SMD of $10 \mu\text{m} \pm 0.3$ at 0.26 m and $13 \mu\text{m} \pm 2.4 \mu\text{m}$ at 1.86 m from the injection point.

	WM1	WM2
Orifice Diameter	100 [μm]	200 [μm]
Flowrate	50 [ml/min]	100 [ml/min]
SMD at 0.26 m	12 ± 0 [μm]	10 ± 0 [μm]
SMD at 1.86 m	13 ± 2 [μm]	15 ± 1 [μm]

Table 12: Sauter Mean Diameter average on at least 30 measurement at 0.26 m and 1.86 m from the nozzle.

1.3 Laser Extinction Measurements

In order to have a qualitative idea of the density of the sprays, an experimental campaign using the laser extinction method (Figure 64) has been conducted. The following table reports the experimental conditions of the measurements.

Nozzle	Laser Wave Length		Distance	N. of Tests
WM1	810 nm	3.39 μm	0.26 m and 1.86 m	3
WM2	810 nm	3.39 μm	0.26 m and 1.86 m	3

Table 13: Experimental conditions Laser Extinction Measurements.

The light detected has a profile like the one showed in Figure 79. The green line represents the averaged signal during the spray injection which begin at 10 s and it is stopped after 110 s. When the injection is triggered, the initial signal decreases from $V(0\%)$ to $V(t)$ and it is stable during all the injection time. When the spray is stopped, the signal starts to increases until to reach the initial value. The value $V(100\%)$ is obtained by covering completely the laser beam with a non-transparent surface and it represents the reference signal corresponding to a total adsorption of the laser beam. By using the following relationship, it is possible to evaluate the transmittance and its logarithm: the absorbance or optical concentration.

$$\frac{I}{I_0} = \frac{V_{100\%} - V_t}{V_{100\%} - V_{0\%}} = e^{-l N c_{ext}} = T$$

$$-\log(T) = \text{Absorbance}$$

Equation 35: Evaluation of the Absorbance from the Transmittance.

The graph in Figure 79 shows the results about the absorbance measured at 0.26 m and 1.86 m from the nozzle. The WM1 is represented with the star symbol and the WM2 is represented with the circle symbol. It is possible to notice that the spray density is higher close to the nozzle and as the distance from the nozzle increases, it decreases. The WM2, the one with the highest flowrate (100 ml/min) produce a denser spray compared to the WM1 (50 ml/min).

At 0.26 m from the nozzle, the absorbance of the WM2, for both the laser wavelengths, is the double of the one with the WM1. At 1.86 m, the optical density of the WM2 is higher than the WM1 but the difference between the 2 cases are less marked compared to the one at 0.26 m.

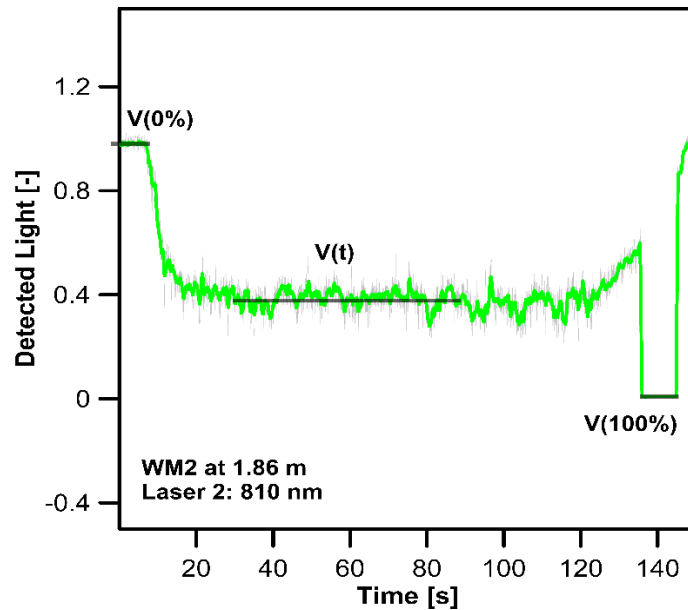


Figure 79: Laser extinction Measurement Signal Profile

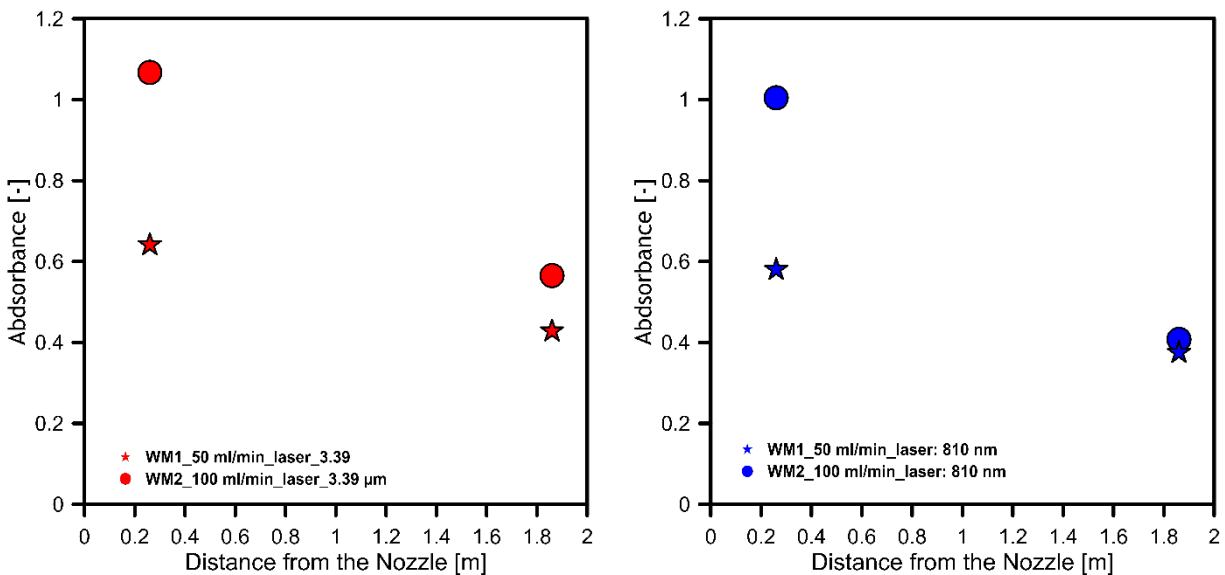


Figure 80: Optical Density at different distance from the nozzle for WM1 and WM2

This results shows that, although both sprays produce similar mean sauter diameter, the number of droplets/cm³ is higher when the flowrate is increased from 50 to 100 ml/min.

1.4 Volume Fraction of water during the injection in ENACCEF

By considering 60 s of water spray injection in our facility ENACCEF 1, it is possible to write the balance of mass as following:

$$m_{total} = m_{wall_total} + m_{susp_total}$$

Equation 36: Total Mass balance of the injected spray

Where m_{total} is the total mass injected in 60 s (0.1 kg for WM2 and 0.05 kg for WM1), m_{wall_total} is the water deposited on the inner walls of the facility and m_{susp_total} is the water spray.

By taking into account the geometry of the ENACCEF (Dome plus acceleration tube Figure 46), the suspended mass can be evaluated as:

$$m_{susp_total} = m_{susp_DOME} + m_{susp_TUBE}$$

Equation 37: Suspended Mass Balance

Where m_{susp_DOME} is the mass of water collected at the bottom of the dome and m_{susp_TUBE} is the mass collected in the acceleration tube.

This two terms were measured by using, at different heights of our facility, a collecting water plate which does not collect the water which is deposited on the walls but only the water spray which flows in the facility.

The following table show the averaged mass of water spray (on 5 repeated tests), at different heights:

Distance from the nozzle [m]	WM1_dome injection m_{susp_total} [g]	WM2_dome injection m_{susp_total} [g]
4.77	0.23 ± 0.07	1.00 ± 0.26
3.77	0.25 ± 0.08	1.08 ± 0.25
2.77	0.27 ± 0.07	1.59 ± 0.44
1.7	0.50 ± 0.06	1.82 ± 0.28
1.6 (dome)	11.61 ± 2.18	35.25 ± 2.53

Table 14: Measured Suspended Water with the dome injection

Distance from the nozzle [m]	WM2_tube injection m_{susp_TUBE} [g]
3.12	1.30 ± 0.54
2.12	1.58 ± 0.11
1.12	9.71 ± 0.52

Table 15: Measured Suspended Water with the Tube injection (WM2)

It is possible calculate the averaged suspended water spray mass which is in the dome during 1 min of injection: 11g (WM1 with 50 ml/min) and 33.43 g (WM2 with 100 ml/min). By considering this results, with the highest flowrate, the volume fraction of spray in the dome is $4.87 \cdot 10^{-5}$.

1.5 Conclusions about the Spray Characterization

The result about the spray characterization shows that the two nozzles produce a very similar spray in terms of SMD. The averaged SMD is measured at different heights in a tube with equivalent diameter to the acceleration tube of ENACCEF1 (i.d. =154 mm). The produced sprays have SMD in the range of 10-15 μm and there is no evidence of fragmentation or coalescence phenomena which could change, in terms of order of magnitude, the size of the droplets.

The laser extinction measurements provide a rough idea of the density evolution along the pipe. The density of the spray is higher close to the nozzle at 0.26 m and at 1.86 m from the nozzle, it decreases by at least of 30% from the initial value. The spray produced from the WM2 is denser than the one produced by WM1. This result can be easily justified by considering that the 2 nozzle produce 2 spray with the same droplets size but by using different flowrate.

Considering these results, the experimental study on the interaction between droplet and the flame will be conducted using 2 sprays characterized by:

- same droplets size which should lead to comparable behaviour in terms of interaction with the flame
- different flowrates which correspond to 2 different spray density, allowing 2 different water loading

The results are summarized in Table 16.

	WM2	WM1
Mass Flow	100 ml/min	50 ml/min
SMD at 0.26m	10 $\mu\text{m} \pm 1\mu\text{m}$	12 $\mu\text{m} \pm 1\mu\text{m}$
SMD at 1.86m	15 $\mu\text{m} \pm 2\mu\text{m}$	14 $\mu\text{m} \pm 1\mu\text{m}$
Absorbance at 0.26m	1.00 (λ_1) – 1.07 (λ_2)	0.58 (λ_1) - 0.66 (λ_2)
Absorbance at 1.86m	0.41 (λ_1) – 0.57 (λ_2)	0.37 (λ_1) – 0.43 (λ_2)

Table 16: Summery Results about the spray characterization of the 2 nozzles. ($\lambda_1 = 810 \text{ nm}$, $\lambda_2 = 3.39 \mu\text{m}$).

Caractérisation des buses

Dans ce chapitre, les résultats de la caractérisation de 2 buses différentes sont discutés.

Le but de cette campagne expérimentale est d'évaluer si les paramètres caractéristiques du jet peuvent être modifiés de manière significative par la géométrie de notre appareil expérimental.

En particulier, l'objectif est :

- Comprendre si les parois internes du tube d'accélération (i.d.=0,154 m) peuvent favoriser la condensation d'une grande quantité d'eau sur les parois.
- Avoir une idée qualitative des densités de pulvérisation et de leur évolution dans le tube d'accélération en termes de taille des gouttelettes lors de la propagation de la pulvérisation dans le tube d'accélération.

Le résultat de la caractérisation de la pulvérisation montre que les deux buses produisent une pulvérisation très similaire en termes de SMD. Le SMD moyenné est mesuré à différentes hauteurs dans un tube de diamètre équivalent au tube d'accélération de l'ENACCEF1 (i.d. = 154 mm). Les sprays produits ont des SMD de l'ordre de 10-15 μm et il n'existe aucun signe de fragmentation ou de phénomènes de coalescence qui pourraient modifier, en termes d'ordre de grandeur, la taille des gouttelettes. Les mesures d'extinction laser donnent une idée approximative de l'évolution de la densité le long de la conduite. La densité de la pulvérisation est plus élevée près de la buse à 0,26 m et à 1,86 m de la buse, elle diminue d'au moins 30% par rapport à la valeur initiale. La pulvérisation produite par le WM2 est plus dense que celle produite par le WM1. Ce résultat peut être facilement justifié en considérant que les 2 buses produisent 2 gouttelettes de même taille mais avec des débits différents. Tenu compte de ces résultats, l'étude expérimentale sur l'interaction entre la gouttelette et la flamme sera menée à l'aide de 2 pulvérisations caractérisées par :

- même taille de gouttelettes, ce qui devrait conduire à un comportement comparable en termes d'interaction avec la flamme
- des débits différents qui correspondent à 2 densités de pulvérisation différentes, permettant 2 charges d'eau différentes.

Chapter 5: Upward Flame Propagation Results

This chapter is dedicated to the upward flame propagation for hydrogen mixture containing 10.50, 11, 13 %_{vol} H₂.

The propagation of the flame will be studied in a smooth tube conditions and in presence of repeated annular obstacles (BR=0.63). For each condition, the results in terms of flame position, flame propagation speed and the evolution of the pressure during the combustion, is presented.

The first part concerns the result about the test conducted in smooth tube in dry and in presence of water spray conditions. In this case, the impact of the spray flowrate and the impact of the volume of injection on the flame propagation and subsequent pressure build-up are studied.

The Second part concerns the results about the test conducted in presence of obstacles (BR=0.63) for dry mixtures and with water spray. In this case, investigation of the impact of the spray flow rate on fast flames will be presented.

The experimental conditions and the repeatability for each case are showed in ANNEX 1.

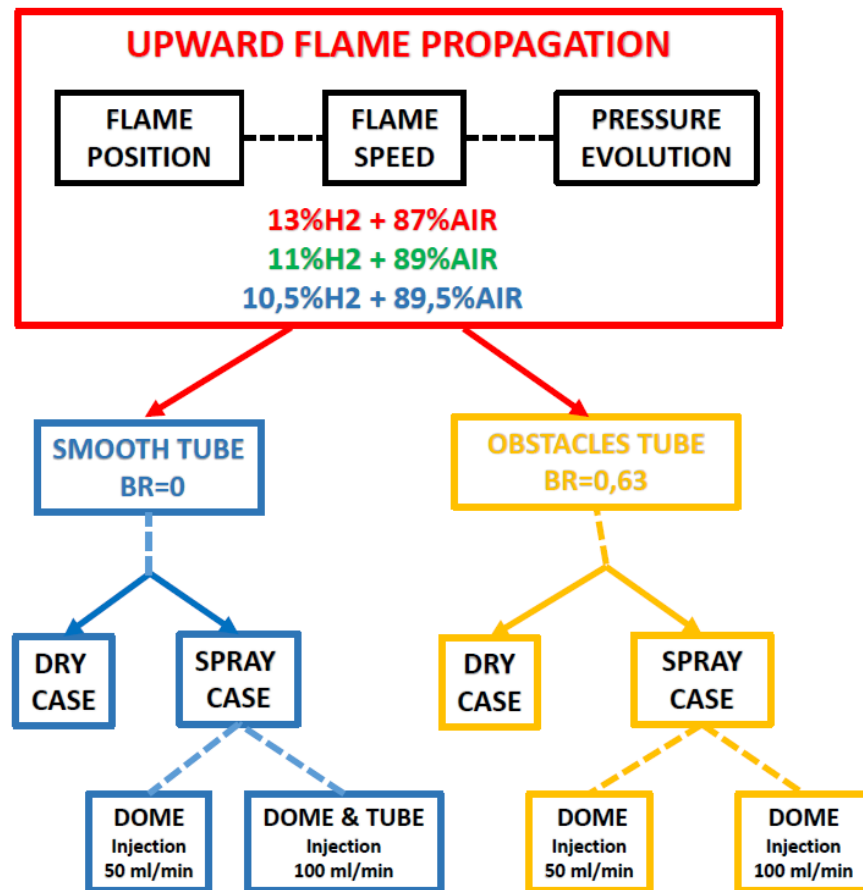


Figure 81: Chapter 5 Overview.

1 Dry Mixture in smooth tube for upward propagation

This paragraph shows the condition investigated for dry mixture in upward propagation in smooth tube condition.

The flame trajectory and the flame speed are evaluated by using 11 PMs signals, in the acceleration tube and 3 PMs signals in the dome. The trend showed are average on at least 6 experiment for each conditions of initial hydrogen concentration.

The pressure profiles are registered for each run, the average behaviour is then reported.

1.1 Upward Flame Position for dry mixtures

The position of the flame versus the time, in the acceleration tube and in the dome, is showed in Figure 82. On the right hand side of the graph is represented ENACCEF 1 and the corresponding position of the photomultipliers. The y-axis is the position of the photomultipliers and the x-axis is the time.

For all the conditions, the mixture is ignited at $t=0$ s. From the early stage of the flame propagation, it is possible to distinguish the impact of the initial hydrogen concentration. From the ignition to the first PM at 0.26 cm, the flame has already expanded spherically until the walls and it starts to propagate trough the acceleration tube.

As the hydrogen concentration increases, the flame takes less time to propagate along the tube. In case of 13%_{vol} of Hydrogen, the flame takes almost 0.25 s to propagate in the acceleration tube. When the hydrogen concentration decreases to 11%_{vol} H₂ the flame takes 0.58 s so more than the double of the time compared to the 13%_{vol} H₂ case. By reducing the hydrogen concentration to 10.5 %_{vol}H₂, the flame takes in average almost 1 second to travel in the acceleration tube.

The results on the flame position, shows also that the error bar increase slightly as the flame propagates in the tube. This trend is more marked when the concentration of fuel decreases.

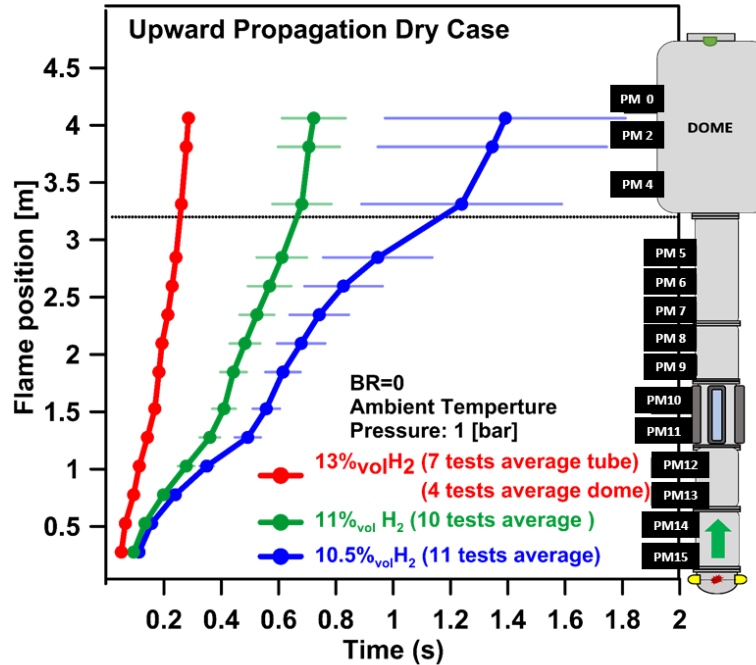


Figure 82: Flame Position Dry Case Upward Propagation - Smooth Tube. $t=0$ s :Spark Ignition; red: dry case at 13% H_2 + 87%Air; green: dry case at 11% H_2 + 89%Air; blue: dry case at 10.50% H_2 + 88.5%Air

When the flame enters in the dome, there is a significant change in the volume in which it propagates. The detected times, as long as the flame propagate from PM4 to PM1 are consecutive and this suggest that the flame does not propagate as a jet flame but it burns progressively from the bottom to the top. The delay in the flame position trajectory, is more noticeable as the initial hydrogen concentration decreases.

1.2 Upward Flame Propagation Speed for dry mixtures

The profiles of the flame propagation speed as a function of time, are plotted in Figure 83. The x axis is the distance from the ignition point of the mixtures which corresponds to the electrode position. On the top of the graph is represented the experimental apparatus with the corresponding photomultipliers position.

When the flame reaches section 4, equipped with 3 large optical accesses it accelerates and decelerates as it exits section 4 to enter in section 3. This phenomenon is due to the modification of the internal tube structure. The flame speed clearly depends on the initial H_2 concentration and

it decreases as the fuel concentration decreases. This dependency is clearly showed in the first part of acceleration tube, where the propagation speed has a smaller variation compared to the last part of the tube.

In the first part of the tube, the flame speed slightly decreases until 1.25 m from the ignition. When the flame enters in the section with the windows (PM11 and PM10 positions), the speed start to increases until to reach the maximum value at 1.77 m from the ignition point (at PM9 position). The averaged maximum values of speed, reached in the, are: 22 m/s for 13 %H₂, 9 m/s for 11 %H₂, and 6 m/s for 10.50 % H₂. Due to the presence of rectangular windows, the section, has an internal volume slightly bigger of the other perfectly cylindrical section. This variation could be responsible of some additional turbulence which promotes slightly an acceleration observable also in case of 10.50 % H₂.

The flame speed, before to enter in the dome, exhibits a slight acceleration, compare to the last value in the acceleration tube. This acceleration is more marked in the case of 13%_{vol}H₂ and 11%_{vol}H₂ and the maximum peak of flame speed is slightly higher than the one in the tube. In case of 10.50%_{vol} the maximum of speed reached in the dome is slightly lower than the one reached in the tube. For these conditions, the observed flame speed was always well below the speed of sound in the fresh gases. The combustion regime is then qualified as slow deflagration.

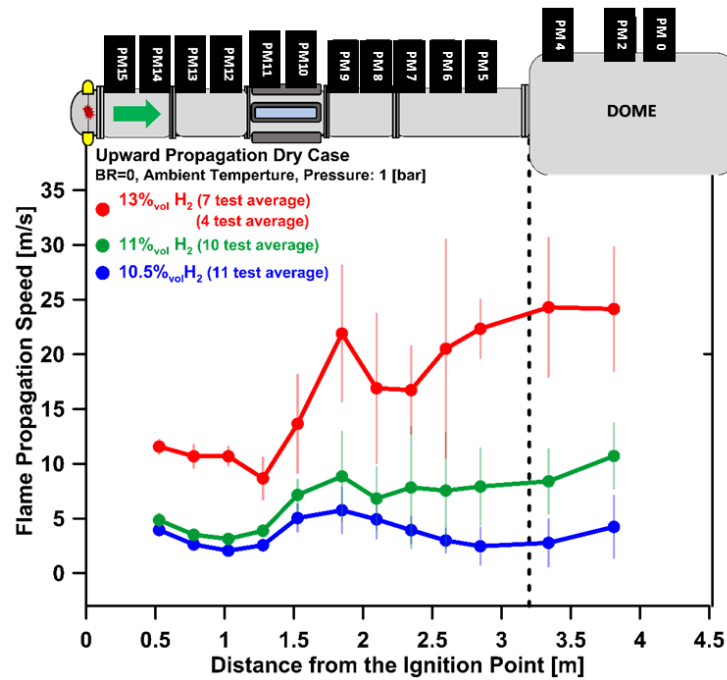


Figure 83: : Flame Speed Dry Case - upward propagation - Smooth tube. $t=0$ s :Spark Ignition; red: dry case at 13%H₂ + 87%Air; green: dry case at 11%H₂ + 89%Air; blue: dry case at 10.50%H₂ + 88.5%Air

1.3 Comparison Experimental flame speed with analytical models

In this paragraph is presented a comparison between the experimental results in upward propagation with 2 different analytical models proposed by Veser [66] and Valien [67]. Both models aim at estimating the flame acceleration in channels in presence of obstacles in non-compressible flame condition.

The Veser model [66] aims at describing the flame acceleration distance by taking into account the internal diameter of the channel, the blockage ratio, the laminar burning rate and the expansion ratio between burned and unburned gases. It is based on simulated and experimental tests performed for Hydrogen mixtures in a tube of 12-m long with internal tube diameter of 0.35 m with a blockage ratio in the range 0.3-0.75. The mathematical expression of the flame propagation speed is written as:

$$V_F = \frac{4(\sigma - 1) \cdot S_L}{d} \cdot \left[1 + \frac{1}{2(\sigma - 1)} \right] \cdot \left[\frac{1 + 1.5 BR}{1 - BR} \right] \cdot x$$

Equation 38: Veser et al. Model for flame acceleration in channels with obstacles [66].

The Valiev model[67] aims at providing a description of the flame acceleration in channels with obstacles by using a background theory which includes the role of the flame pockets, in fresh fuel mixture. The analytical expression takes into account: the internal diameter of the channels, the blockage ratio, the laminar burning rate and expansion ratio between burned and unburned gases.

$$V_F = \frac{4(\sigma - 1) \cdot S_L^0}{d} \cdot \left[1 + \frac{1}{2(\sigma - 1)} \right] \cdot \left[\frac{1}{\sqrt{1 - BR}} \right] \cdot x + \sigma \cdot S_L^0$$

Equation 39: Valiev et al. Model for flame acceleration in channels with obstacles [67].

Both models need as input the laminar flame speed but for the concerned initial hydrogen concentration, the laminar propagation of the flame is not possible to obtain experimentally due to the instability of the flame. The calculated laminar flame speed, showed in the Chapter 3, are not physically meaningful and they cannot be used as a reference. Standing these consideration, it is necessary to use as input velocity in the model, the experimental flame propagation for expansion radius close to the one of the ENACCEF1 (75 mm).

The input velocities take into account the expansion ratio. In case of 13% H_2 , the experimental velocity is available for $R=70$ mm. For the other cases, and it was evaluated by starting from the experimental velocity at 10% H_2 at $R=40$ mm. The input velocities are:

- 0.26 m/s for 13% H_2
- 0.38 m/s for 11% H_2
- 0.07 m/s for 10.5% H_2

Figure 84 shows the comparison between the experimental data and the analytical models. The model of Vesper overestimates the flame propagation velocity and the gap between the analytical and experimental value increases significantly as the distance from the ignition increases. The model of Valiev gives results closer to the experimental ones compared to the model of Vesper. It is able to describe the experimental speed value, especially to the beginning of the propagation but for the rest of the propagation, it overestimates the flame speed.

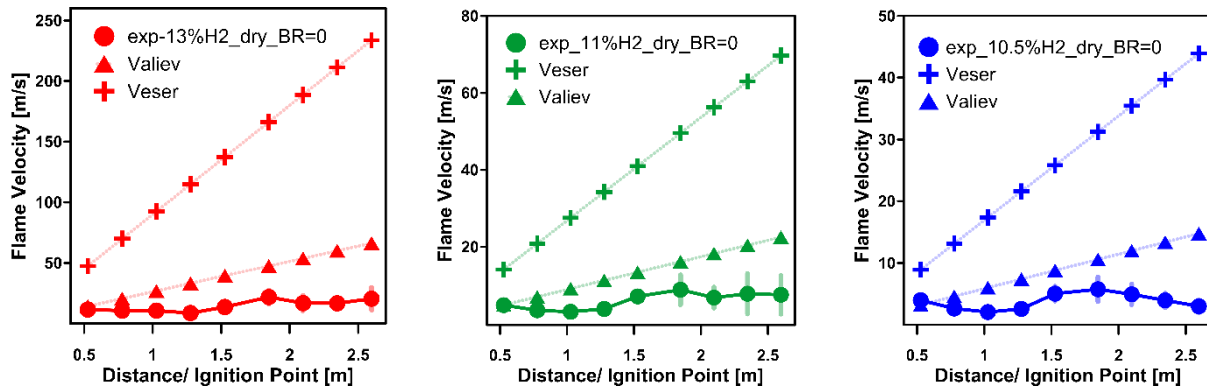


Figure 84: Comparison between the experimental data and the analytical model for flame acceleration in the channels for $BR=0$.

1.4 Preliminary consideration on the Pressure Evolution

Figure 85 shows an example of the pressure signal evolution over the time (Exp 113-13% H_2) for upward propagation in a smooth tube conditions. The left y-axis corresponds to the pressure and the right y-axis is the TTL signal. The TTL triggers the recording of the pressure signal at $t=0$. In the graph are plotted in green the time detected by the PMs in the acceleration tube, where the flame burns almost the 10% of the burnable mixture. During this period, it is not possible to appreciate a significant increase in the pressure which remains constant at 1 bar. When the flame enters in the dome (at time PM4 in the grey line), the pressure will burn the 90% of the unburned mixture and the pressure increase up to a maximum value. As showed in the previous paragraph, the flame velocity has a certain variability. The instant of time corresponding to the peak of pressure will be affected by the history of the flame in the acceleration tube (ANNEX 1). In order to better compare the time needed to reach the peak of pressure, at different conditions, without their dependency to the flame history in the tube, the time zero will be shifted Time PM5 ($t_0 - t_{PM5}$).

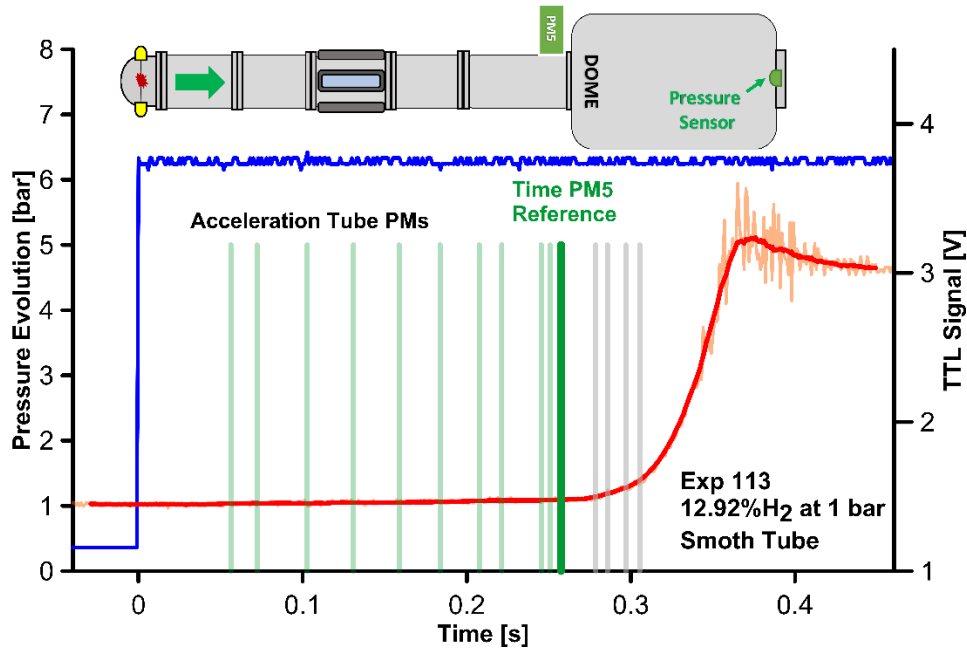


Figure 85: Example of Pressure Signal - Upward propagation - smooth Tube. orange line: raw pressure signal, solid red line: filtered pressure signal.

The pressure signals, according to the severity of the explosion, exhibit a noise especially in the region where there is the maximum Peak. In order to evaluate the peak of pressure, the time to reach the peak and the slope of the curve, each signal is processed with a matlab routine. The

routine processes the signal with a Savitzky–Golay Filter and evaluates the aforementioned parameters.

1.5 Pressure Evolution in a smooth tube for dry mixtures (Upward Propagation)

The following graph shows the pressure evolution in the dome as a function of time. The three curves are representative of the behaviour of the pressure for dry mixture in upward propagation. The maximum peak decreases as the fuel concentration decreases. Also the time to reach the peak and the slope of the curve decreases as the initial H_2 concentration decreases as reported in Table 19.

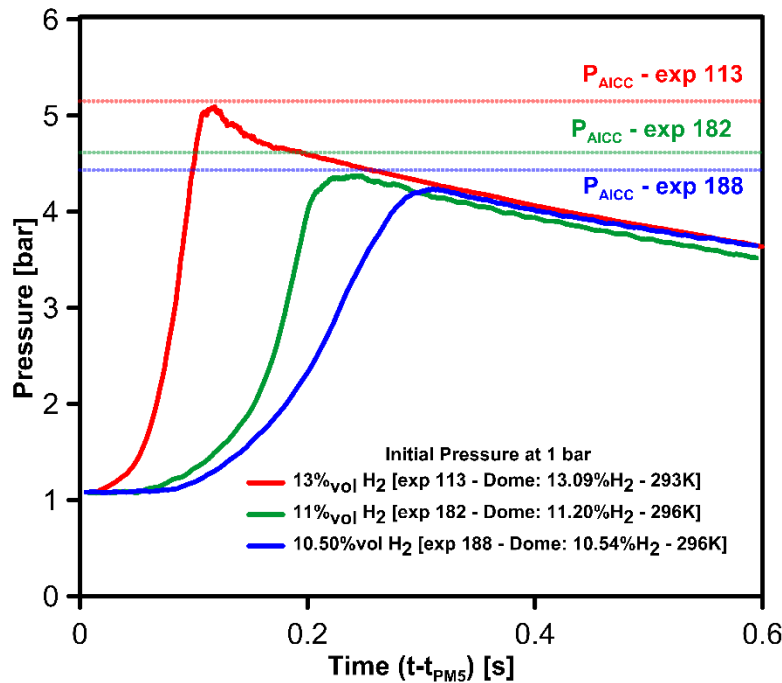


Figure 86: Pressure Evolution – Dry Mixtures in Upward Propagation without obstacles. $t=0$ s :Time PM5; red: dry case at 13% H_2 + 87%Air; green: dry case at 11% H_2 + 89%Air; blue: dry case at 10.50% H_2 + 88.5%Air.

For each condition, the number of tests, the averaged value of hydrogen concentration(in the acceleration tube and in the dome), the initial temperature and pressure, are reported in Table 17. The concentration and temperature in the dome are used to calculate with Cosilab the Isochoric Adiabatic Complete Combustion pressure in order to compare with the measured pressure.

	N° of tests	Measured (μ GC) H ₂ tube	Measured (μ GC) H ₂ dome	T _{tube} [K]	T _{dome} [K]	P [bar]
13% DRY	4	13.07 $\pm$ 0.13	13.10 $\pm$ 0.10	292.7 $\pm$ 0.0	293.0 $\pm$ 0.0	1
11% DRY	6	11.04 $\pm$ 0.11	11.07 $\pm$ 0.09	295.3 $\pm$ 1.2	296.7 $\pm$ 1.5	1
10.5% DRY	6	10.45 $\pm$ 0.06	10.47 $\pm$ 0.07	295.2 $\pm$ 0.8	297.6 $\pm$ 0.7	1

Table 17: Smooth Tube Dry conditions Experiment.

Table 18 reports the averaged values for the Adiabatic Isochoric Complete Combustion pressure and the averaged measured maximum peak of pressure with relative error bars. The peak of pressure is more than 90% of the one corresponding to an adiabatic isochoric complete combustion which means that the pressure sensor is able to track the pressure evolution quite well and it confirms a complete combustion in adiabatic conditions.

	P _{AICC} [bar]	P _{max} [bar]	ratio P _{max} / P _{AICC}
13%H₂	5.16 $\pm$ 0.03	4.99 $\pm$ 0.07	97%
11%H₂	4.57 $\pm$ 0.03	4.31 $\pm$ 0.08	94%
10.5%H₂	4.40 $\pm$ 0.02	4.10 $\pm$ 0.08	93%

Table 18: Comparison P_{max} and P_{AICC} -dry mixture - upward smooth tube

As one can see, the ratio P_{max}/P_{AICC}, decreases with the content in the mixture. Indeed, as H₂ is decreased, the flame speed is lower leading to more heat losses. As heat losses are more prominent, P_{max} will be lower.

Table 19 reports the averaged time to reach the peak (t=0 at time PM5) and the maximum dP/dt for the dry mixture in upward propagation in smooth tube condition. As the H₂ concentration decreases, the time to reach the peak increases from 0.11s at 13%_{vol}H₂ to 0.40s at 10.50%_{vol}H₂. As a results, the maximum dP/dt decreases as H₂ concentration decreases from 87 $\pm$ 7 [bar/s] to 17 $\pm$ 3 [bar/s] at 10.5%H₂.

	t@P _{max} [s]	(dP/dt) _{max} [bar/s]
13%H₂	0.11 $\pm$ 0.01	86.56 $\pm$ 6.67
11%H₂	0.22 $\pm$ 0.03	26.51 $\pm$ 3.17
10.5%H₂	0.40 $\pm$ 0.13	16.82 $\pm$ 3.20

Table 19: Time to Peak and dP/dT_{max} dry mixture -upward smooth tube

Figure 87 shows the K_G index which is related to the severity of an explosion. In our case, all the deflagrations are included in the domain of the weak explosion with a K_G index lower than 100 [bar m/s]. The severity depends on the initial concentration and it increases as the initial fuel concentration increases.

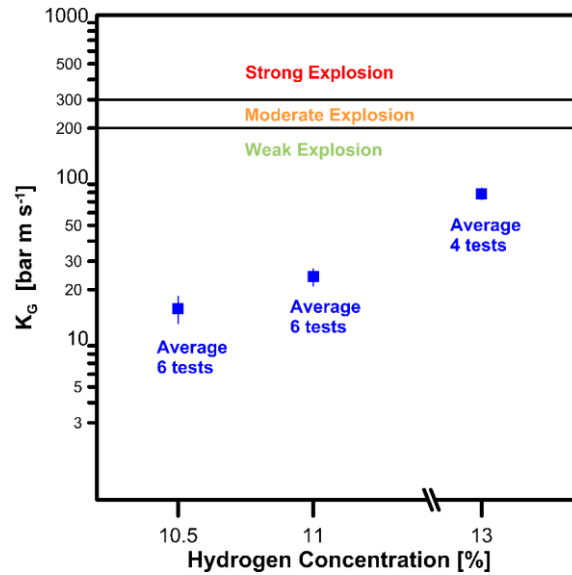


Figure 87: Inherent Safe criteria: Deflagration Index based on the pressure evolution- Upward Propagation dry mixtures

2 Spray activation in smooth tube: upward propagation

In this part the impact of the spray injection on the flame propagation is showed. The following injecting conditions are investigated:

- The impact of the injection of 100 ml of liquid water in the dome (WM2 nozzle);
- The impact of the injection of 100 ml of liquid water in the acceleration tube (WM2 nozzle);
- The impact of the injection of 50 ml of liquid in the dome (WM1 nozzle);

The ignition spark is created while the water injection is running in order to reproduce, for all the experiments, the same turbulence conditions and to reproduce an explosion dynamic similar to the real case. Indeed, by considering that the spray is running during the combustion, an additional m_{H_2O} is injected according to the flowrate:

- 100 ml/min $\Leftrightarrow$ 1.66 ml/s
- 50 ml/min $\Leftrightarrow$ 0.83 ml/s

According to the time of combustion, it is possible to neglect it or not.

2.1 The impact of the location of the spray on the Flame Position

In this part, the results about the flame position for H₂-air-water spray flames are showed. The first step is to understand the impact of the injected volume on the flame propagation. By changing the position of the injection, it is possible to check the influence of the spraying injection volume.

Figure 88 shows the impact of the injection only in the Dome and only in the Tube on the flame position at 13%H₂. In presence of water droplets, the flame takes more time, compared to the dry case to propagate along the acceleration tube. This trend is more noticeable in the last part of the acceleration tube and in the dome. In the first part of the acceleration tube, both injections, do not produce a significant appreciable delay. After the fourth PM (at 1.27 m from the ignition points), the effect of the water start to be appreciable. The flame position trajectory in the dome, shows that even when the injection is limited to in the tube at 13%H₂, the flame position in the dome is affected and it is delayed (grey line).

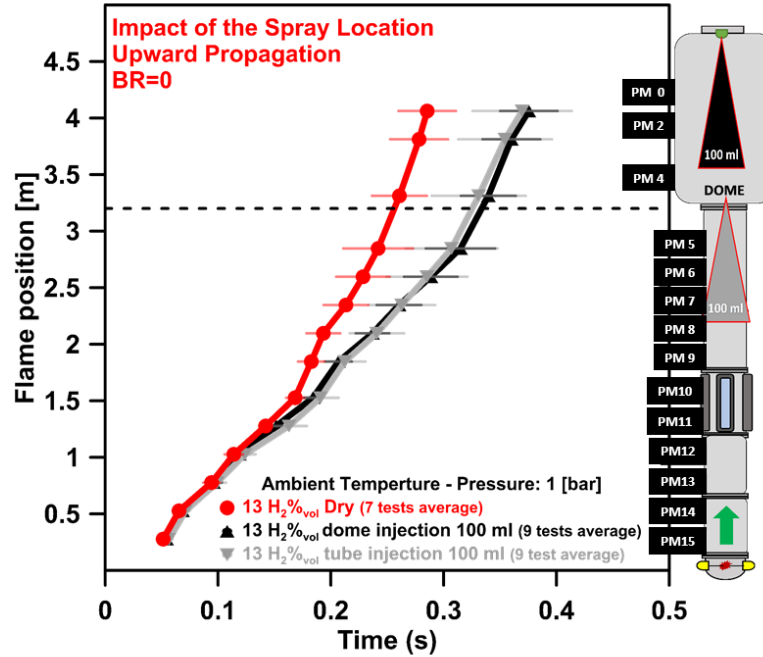


Figure 88: Flame Position at 13%_{vol}H₂ Dome VS Tube Injection – smooth tube – Upward. . $t=0$ s : Spark Ignition; red: dry case at 13%H₂ + 87%Air; grey :spray injection 100 ml only in the tube; black: spray injection 100ml only in the dome.

In Figure 89, the trajectory of the flame at 11%_{vol} H₂ is showed. Like in the previous case, the presence of water droplets increases the time needed to propagate along the acceleration tube. The injection in the dome has a strongest impact on the flame position, compared to the injection in the tube. The spray injection in the tube, induces a delay in the acceleration tube around 10% of the flame arrival time compared to the dry case. Instead the injection in the dome, induces a delay of 50% compared to the dry case.

The flame trajectory in the dome at 11%H₂, shows more clearly that when the spray injection is activated in the tube, the flame position in the dome is slightly delayed but is close to the dry case (achieved time is 10% delayed).

The spray injection in the dome affects more the flame position in the dome, especially at the entrance of the dome, between PM5 and PM4 signal. The time needed to reach the last PM1 is the double compared to the dry case.

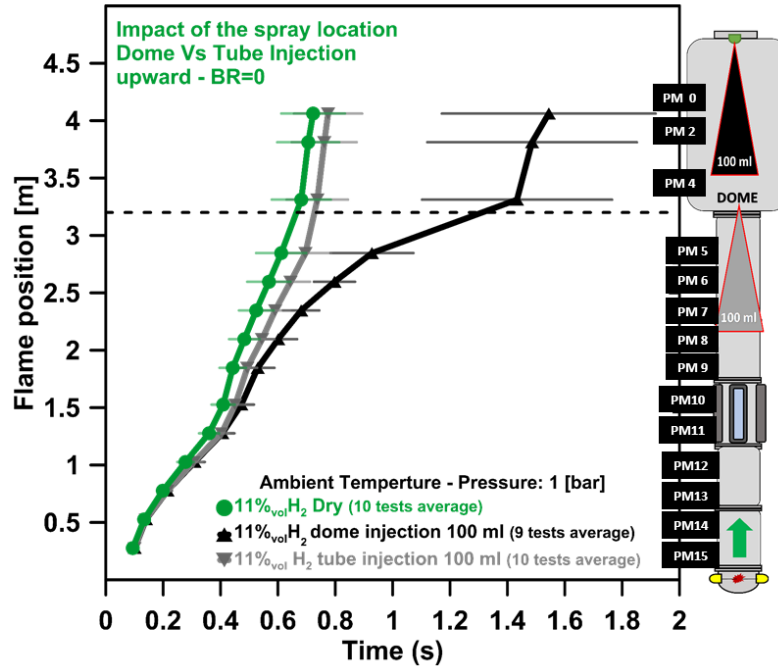


Figure 89: Flame Position at 11%volH₂ –Dome VS Tube Injection – smooth tube – Upward. $t=0$ s : Spark Ignition; green: dry case at 11%H₂ + 89%Air; grey :spray injection 100 ml only in the tube; black: spray injection 100ml only in the dome.

Figure 90 shows the impact of the injection from the tube and dome, in case of 10.50%volH₂. It is possible to appreciate a delay in terms of the time needed to propagate along the acceleration tube. Differently to the case of 13% and 11%, in this case the spray injection from the tube, shows a strongest impact in the acceleration tube with a delay of 70% while the dome injection dome has a delay of the 35% compared to dry case. The slope of the grey curve (at 2.62 m) starts to increase when it passes through the spray region.

When the flame enters in the dome, the delay showed in the acceleration tube, is recovered and the flame trajectory does not exhibit a significant difference from the case in which the water spray is injected in the dome.

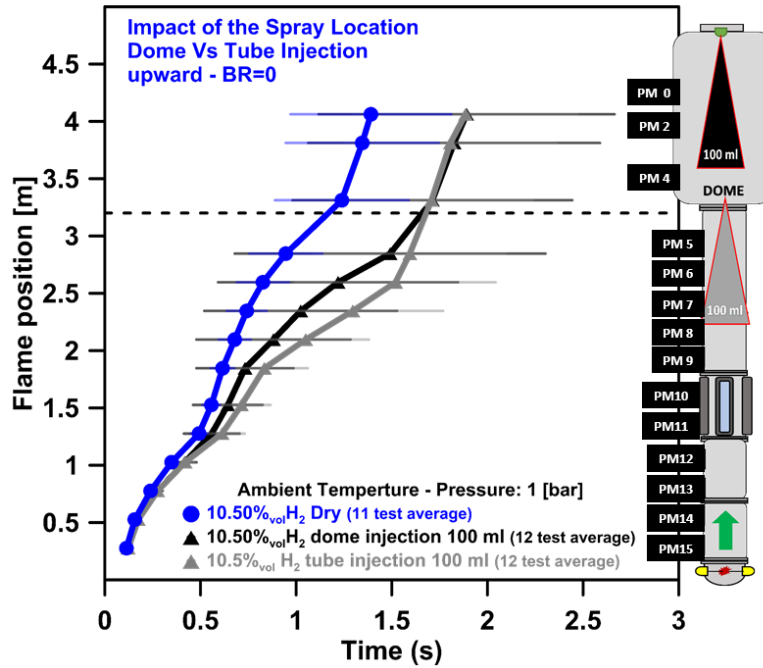


Figure 90: Flame Position at 10.5% H_2 – Dome VS Tube Injection – smooth tube – Upward. $t=0$ s : Spark Ignition; green: dry case at 10.50% H_2 + 88.50%Air; grey :spray injection 100 ml only in the tube; black: spray injection 100ml only in the dome.

2.2 The impact of the spray location on the Flame Propagation Speed

The impact of the spray location on the flame speed propagation is studied.

Figure 91 shows the flame propagation speed as a function of the distance from the ignition point in case of 13% $_{vol}H_2$. The grey dash-line is the averaged flame propagation speed in case of tube injection (10% of the entire volume). The black dot line is the averaged propagation speed in case of the water injection in the dome (90% of the entire volume). The spray injection in both cases, induces a decreasing of the velocity compared to the dry case. This trend is more noticeable after 1.27 m from the ignition point, where the dry flame starts to accelerate and the behaviour is observable even for the propagation in the dome. By comparing the flames speeds in the acceleration tube, the injection in the dome (black dot line), has the strongest impact on the decrease of the propagation speed.

By considering the propagation in the dome, the presence of the water spray reduces the flame speed both when it is injected in the tube and when it is injected in the dome. The spray injection in the tube and in the dome, do not lead to an observable difference in terms of flame speed propagation until 4 m from the ignition point.

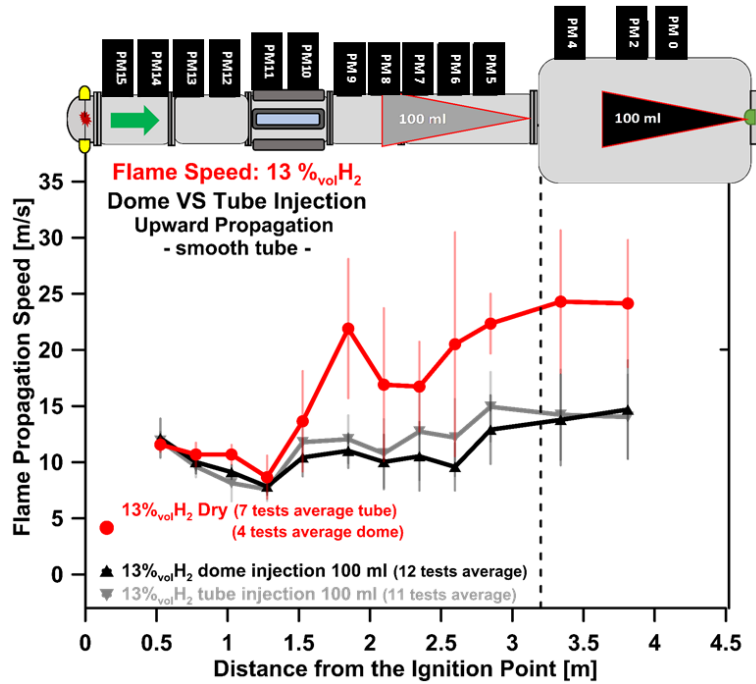


Figure 91: Flame Speed at 13%_{vol}H₂ – Dome VS Tube Injection - smooth tube- Upward. $t=0$ s : Spark Ignitio
red: dry case at 13%_{vol}H₂ + 87%_{vol}Air; grey :spray injection 100 ml only in the tube; black: spray injection 100ml
only in the dome.

Figure 92 shows the case of 11%_{vol} H₂. The green line is the flame propagation speed in the dry case.

The grey dash line represents the flame speed in the case of water injection in the tube (10% of the entire volume), the dot black line represents the flame speed in case of water injection in the dome (90% of the entire volume).

When the water spray is injected, the flame speed exhibits a slight deceleration, compared to the dry case. In the acceleration tube, this deceleration is more marked, in case of injection in the dome (black line). In this case the maximum of the averaged velocity (10 m/s at 1.77m for the dry case) is decreased by 47% and shifted at 1.52 m from the injection.

In case of spray injection in the tube (grey line), the averaged maximum of flame speed is decreases by 40% compared to the dry case and shifted at 1.52 m from the ignition point.

Furthermore, the flame speed is accelerated, as it moves toward the spray injection location in the last part of the acceleration tube where the spray nozzle is located. The speed in the dome recovers the flame speed values of the dry case.

When the injection is done in the dome (black line), the flame speed in the dome does not exhibit that remarkable acceleration and it remains in the order of 5 m/s during the propagation.

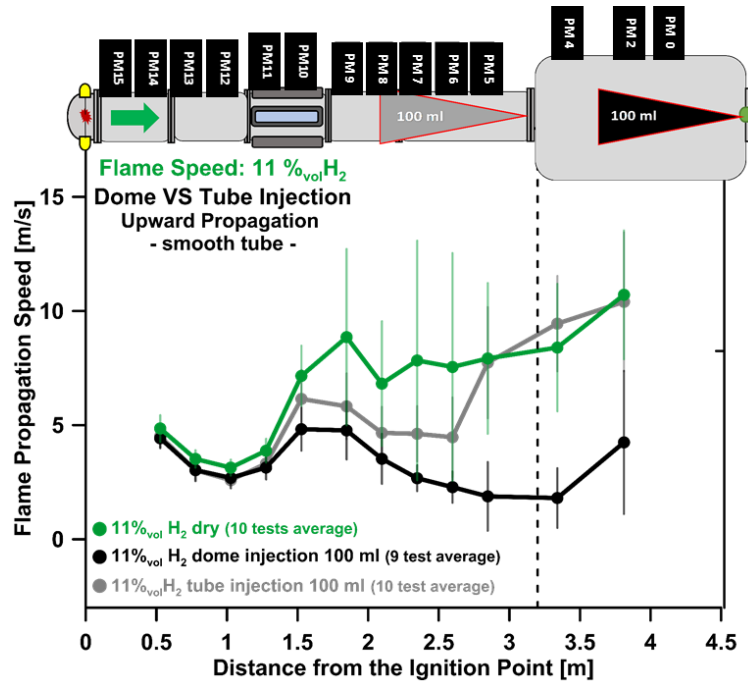


Figure 92: Flame Speed at 11%H₂ - Dome VS Tube Injection - smooth tube- Upward . $t=0$ s : Spark Ignition; green: dry case at 11%H₂ + 89%Air; grey :spray injection 100 ml only in the tube; black: spray injection 100ml only in the dome.

Figure 93 shows the case of 10.50%_{vol} H₂. The blue line represents the flame speed in dry case for 10.50%_{vol} H₂. The grey dash line represents the flame speed in the case of water injection in the tube (10% of the entire volume) and the dot black line represents the flame speed with water injection in the dome (90% of the entire volume). Unlike from the other 2 case, at 10.50%_{vol} H₂, the injection from the tube (grey line) has the strongest impact on the flame velocity. Up to 2.5 m from the ignition point, the flame speed decreases, even more than the case of dome injection. When the flame reaches the last part of the acceleration tube, the flame speed is strongly increased and it reaches values higher (twice) than the one reached in the dry case. When the flame enters in the dome, the flame speed starts to decrease and it reaches value close to the dry case.

The spray injection from the dome (black line), induces a slight decrease of the flame speed both in the tube and in the dome, compared to the dry case.

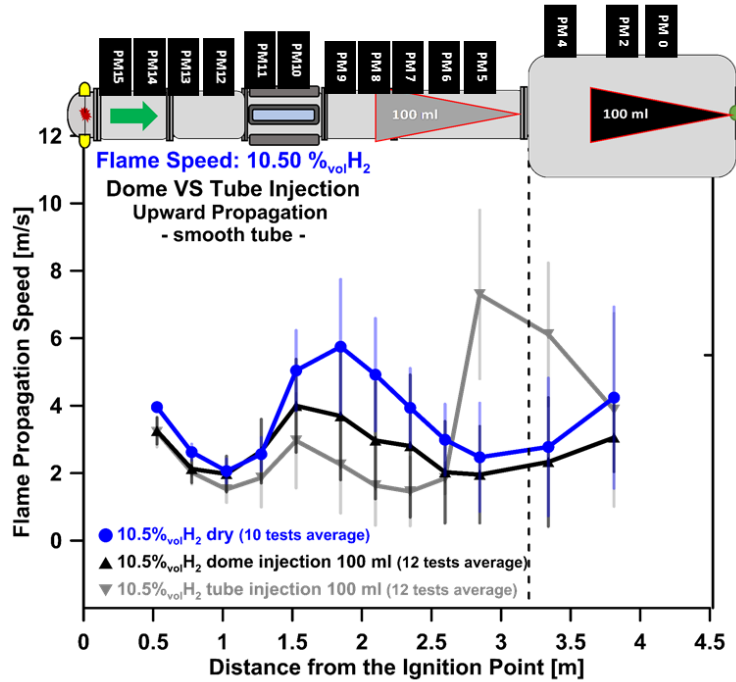


Figure 93: Flame Speed at 10.50% H₂ - Dome VS Tube Injection - smooth tube- Upward. $t=0$: Spark Ignition; green: dry case at 10.50% H₂ + 88.50% Air; grey: spray injection 100 ml only in the tube; black: spray injection 100 ml only in the dome.

2.3 The impact of the spray location on the Pressure Evolution

In this paragraph the impact of the spray location on the pressure evolution is showed. In each graph, the pressure signal is a representative example of the pressure evolution on at least 4 tests. For each pressure signal, the corresponding calculated P_{AICC} is reported.

Figure 94 shows the pressure evolution at 13% vol H₂ as a function of the time. The red curve is the evolution of the pressure in dry condition already showed previously and it is almost the 97% of the corresponding P_{AICC} evaluated at the same condition of H₂ concentration and temperature.

The black curve represents the case in which 100 ml of water spray is injected in the dome. The measured pressure maximum is lower than the 11% of the dry case on an average of 6 tests. The decrease of the maximum peak can be the result of dilution effect due to the presence of saturated water vapor in the mixture and to the effect of the spray evaporation.

In order to discriminate the effect of the interaction of water droplets from the dilution effect of the saturated vapor, the value of the P_{AICC} in humid air is reported. It is evaluated at the same initial

condition in terms of initial temperature and pressure. The results show that the P_{AICC} in dry case is 5.16 bar and in the humid cases is 5.10 bar. The differences, between the P_{AICC} in dry case and humid, are around 1% because the air at ambient temperature can include only a small content of water vapor. The decrease of P_{max} cannot be explained only by the humidity but it is mainly related to the effect of the spray evaporation during the combustion. The Time to reach the peak is strongly delayed due to the evaporation of the droplets which induce a sink heat. Part of the droplets evaporate and hence two antagonist results: (i) heat sink from the burned gases leading to a lower P_{max} , and (ii) the evaporation should lead to a higher pressure. The cooling effect is probably the dominating mechanism. The slope of the curve and maximum dP/dt decrease compared to the dry case.

The grey curve represents the pressure evolution, when 100 ml of liquid water is sprayed only in the tube. In this case, no water is injected directly in the dome but the P_{max} is slightly lower anyway, than the dry case (around 7%). The decrease of P_{max} is still not only due to the presence of water vapor in the initial mixture. The absence of a spray injection in the dome makes the pressure evolution close to the dry case but the time to reach the peak and the slope of the curve are slightly affected in terms of mitigation.

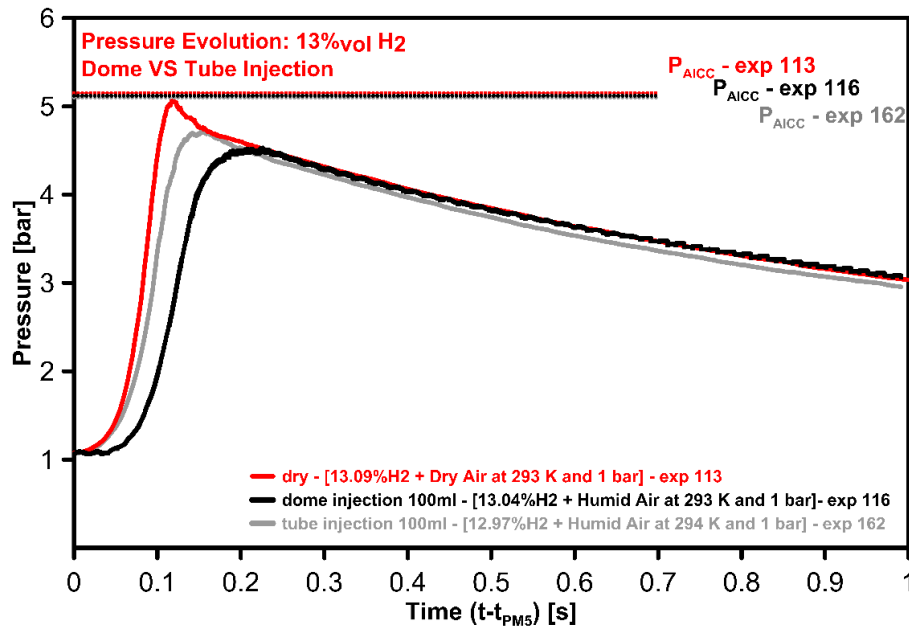


Figure 94: Pressure Evolution 13%H₂- Dome vs Tube Injection. Time PM5: Spark Ignition; red: dry case at 13%H₂ + 87%Air; grey :spray injection 100 ml only in the tube; black: spray injection 100ml only in the dome

Figure 95 shows the case of an initial concentration of 11%_{vol}H₂. The injection from the dome (black line) has the strongest impact on the pressure evolution, in terms of decreasing of the

maximum pressure peak, delay of the combustion time and the slope of the curve. The measured $P_{\max}$ is decreased of 13% compared to the one measured in the dry case (average on 6 measurements). Even in this case, the decrease cannot be inferred to the presence of an initial water content in the air. The grey curve, represent the injection in the tube and as previously, affects less the pressure evolution in the dome but still the severity explosion parameters are slightly mitigated compared to the dry case. Even in this case, it is possible to notice a change in the slope, around 0.3 s but in this case is not as marked as in the case in for which the injection is in the dome.

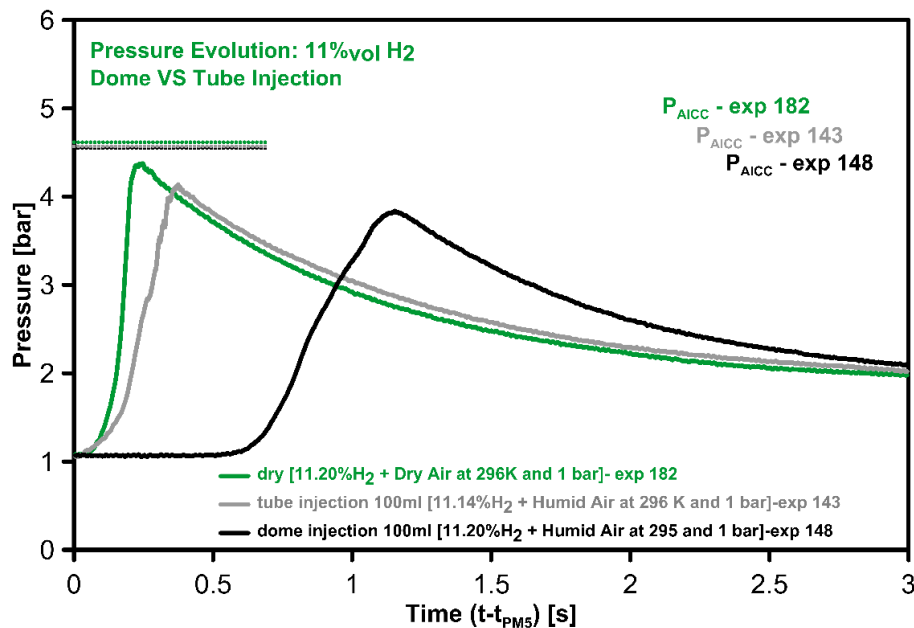


Figure 95: Pressure Evolution 11%H₂ - Dome vs Tube Injection. Time PM5: Spark Ignition; green: dry case at 11%H₂ + 88%Air; grey :spray injection 100 ml only in the tube; black: spray injection 100ml only in the dome

The last graph represents the case of an initial concentration of 10.50%_{vol} H₂. The black line represents the injection of 100ml of water in the dome. In this case the decrease of the measured peak of pressure, compared to the dry case is around 10% lower (averaged on 6 tests). The time to reach the peak is delayed and the slope of the curve is decreased by 45% compared to the dry case. Even in this case, a change in the slope of the curve which occurs at 0.3 s. The injection in the tube (the grey line), decreases the explosion parameters compared to the dry case but its influence is less strong than the case in which the injection is directly in the dome. The maximum of pressure is decreased by 5% compared to the dry case. In this case the slope shows a change between 0.3 s and 0.4 s but the effect is less marked compared to the case of dome injection.

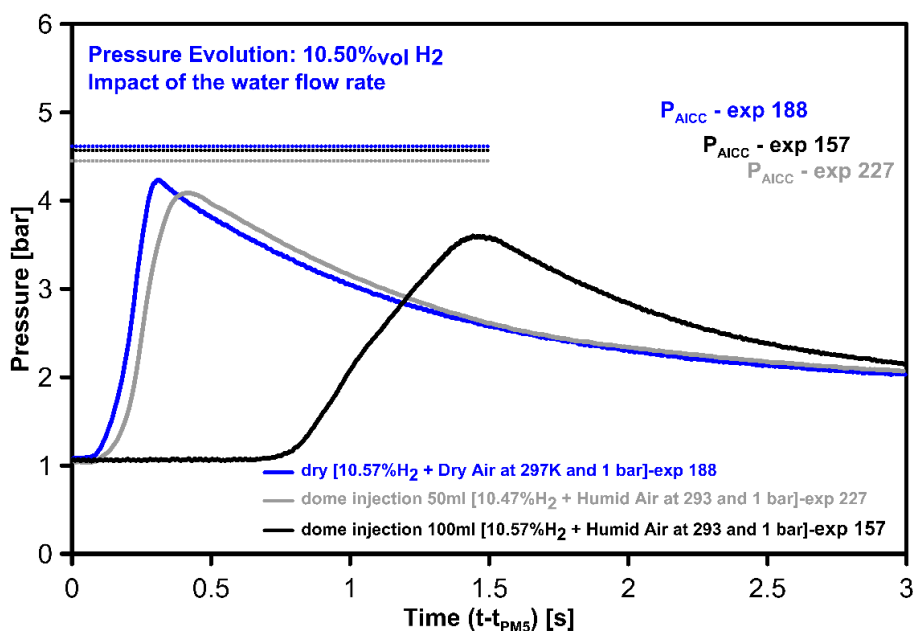


Figure 96: Pressure Evolution 10.50% H_2 - dome Vs Tube Injection. Time PM5: Spark Ignition; blue: dry case at 11% H_2 + 88%Air; grey :spray injection 100 ml only in the tube; black: spray injection 100ml only in the dome

For each conditions, it is reported in Table 20 the number of tests, the hydrogen concentration the initial temperature and pressure. Each test is repeated at least 4 times

	N. of repeated tests	Measured (μ GC) H_2 tube	Measured (μ GC) H_2 dome	T tube [K]	T dome [K]	P [bar]
13%H_2 + 100ml dome	6	12.97 ± 0.09	13.06 ± 0.07	293.5 ± 1.0	294.2 ± 1.6	1
11%H_2 + 100 ml dome	5	10.95 ± 0.09	10.99 ± 0.05	293.5 ± 0.6	294.4 ± 0.8	1
10.5%H_2+100ml dome	7	10.57 ± 0.09	10.64 ± 0.06	292.1 ± 1.0	292.5 ± 0.9	1
	N. of repeated tests	Measured (μ GC) H_2 tube	Measured (μ GC) H_2 dome	T tube [K]	T dome [K]	P [bar]
13%H_2 + 100ml tube	4	12.94 ± 0.09	13.04 ± 0.08	291.9 ± 0.8	293.8 ± 0.8	1
11%H_2 + 100 ml tube	3	11.14 ± 0.05	11.16 ± 0.04	292.9 ± 0.3	294.3 ± 1.6	1
10.5%H_2 + 100 ml tube	6	10.50 ± 0.07	10.62 ± 0.07	291.7 ± 1.0	292.5 ± 0.5	1

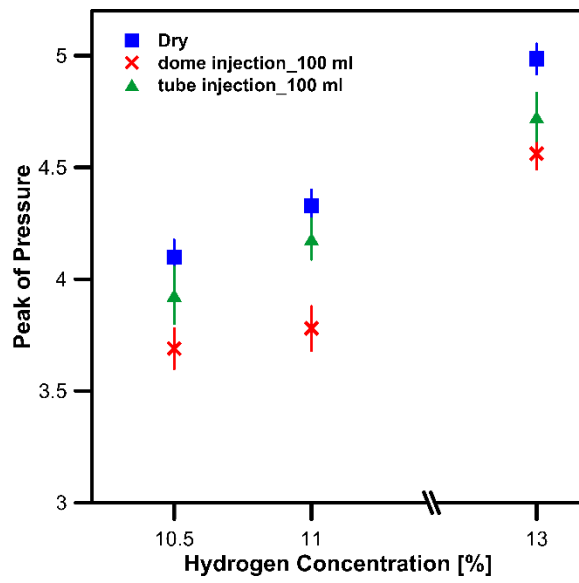
Table 20: Smooth Tube experimental conditiosns – tube and dome spray injection of 100 ml of water

Figure 97 shows a summary of the impact of the spray location on the explosion parameters as the pressure peak (a), the time to reach the pressure peak (b) and the slope of the pressure signal (c)

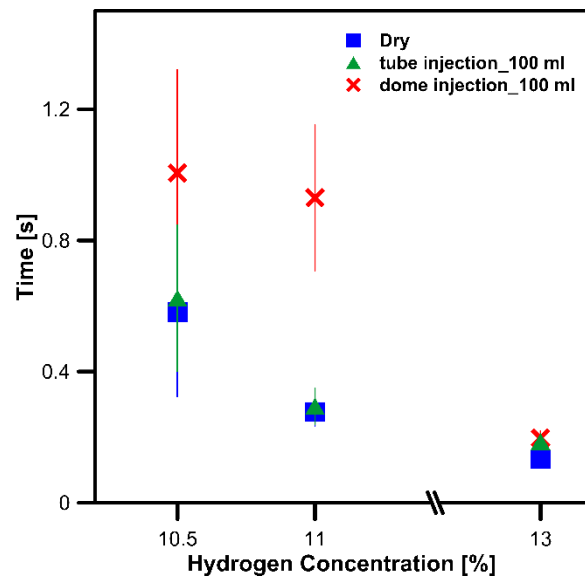
curve. The blue line represents the dry case, the green line the injection in the tube and the red line the injection in the dome. The injection of the water spray slightly mitigates all these parameters and its influence is more marked when the water spraying interests the 90% of the facility volume as expected.

The K_G index, evaluated for all the condition, shows different regime of severity of the explosion. In our case both dry and two-phase mixtures, lead to a $K_G < 200$ bar m /s which corresponds to a weak explosion. The spray injection slightly reduces the severity and there is no transition from a domain of severity to another. In terms of mitigation effect, the injection from the dome has the strongest impact.

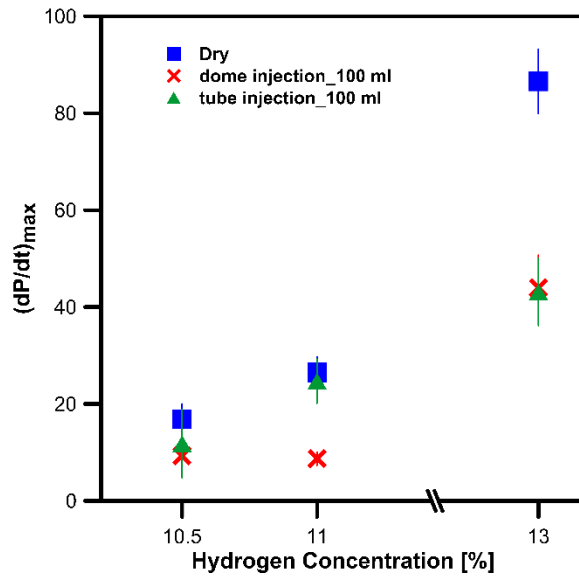
Figure 97 (d) represents the K_G index evaluated from the dP/dt_{max} . The injection of 100 ml of water (green symbol), has less impact on the severity of the explosion. The spray injection decrease slightly the severity of the explosion and there is no transition from a severity domain to another. In terms of mitigation, the spray injection in the 90% of the volume exhibits a strongest impact especially for the case of 11% and 10.50 %H₂.



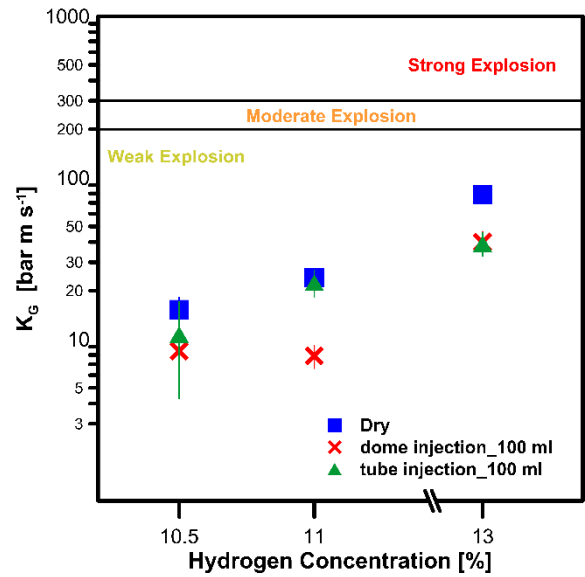
(a)



(b)



(c)



(d)

Figure 97: Explosion Parameter summary – Impact of the spray location in upward propagation BR=0. Blue: Dry Case; Red: spray injection 100ml only in the dome; Green: spray injection 100ml only in the tube

2.4 The impact of the flowrate on the Flame Position

In this paragraph is studied the impact on the flame position of the water injection flow rate. The investigation is based on the comparison between the impact of two water flowrates, injected from the dome:

- 50 ml/min of water injection in the dome with WM1 nozzle
- 100 ml/min of water injection in the dome with WM2 nozzle (already showed in Figure 88, Figure 89, Figure 90)

For completeness, in each graphs, the corresponding dry case is also showed.

Figure 98 reports the flame position as a function of the time, in the case of an initial concentration of 13%_{vol} H₂. The grey line is the flame position versus the time in the case of an injection with a flow rate of 50 ml/min. The trajectory of the flame position is similar to the dry case and the flame does not exhibit a significant delay in terms of flame arrival time, especially up to PM9. If we compare these results with the one obtained with an injection of 100 ml/min (black curve), one can see that a higher flowrate induces a higher delay on the flame arrival time.

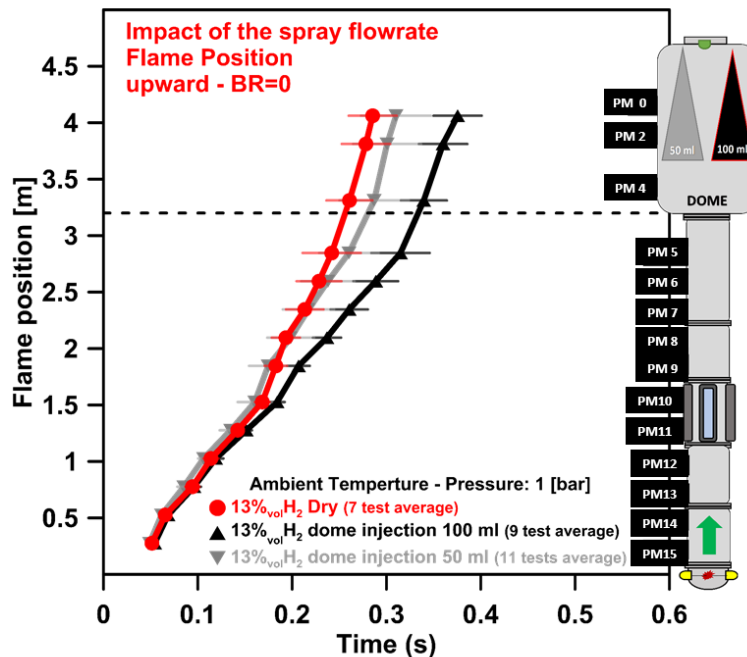


Figure 98: Flame Position at 13%H₂ impact of flow rate– smooth tube – Upward. $t=0$ s : Spark Ignition; red: dry case at 13%H₂ + 87%Air; grey :spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome

Figure 99 shows the case of 11%_{vol}H₂ and the behaviour of the flame position trajectory fits very well, the one of the dry case. The injection of 50 ml/min of water does not affect the flame position. As the spray flowrate is increased up to 100 ml/min (the black line), the flame takes more time to travel in the acceleration tube. The delay in terms of arrival time starts to be more marked in last part of the acceleration tube.

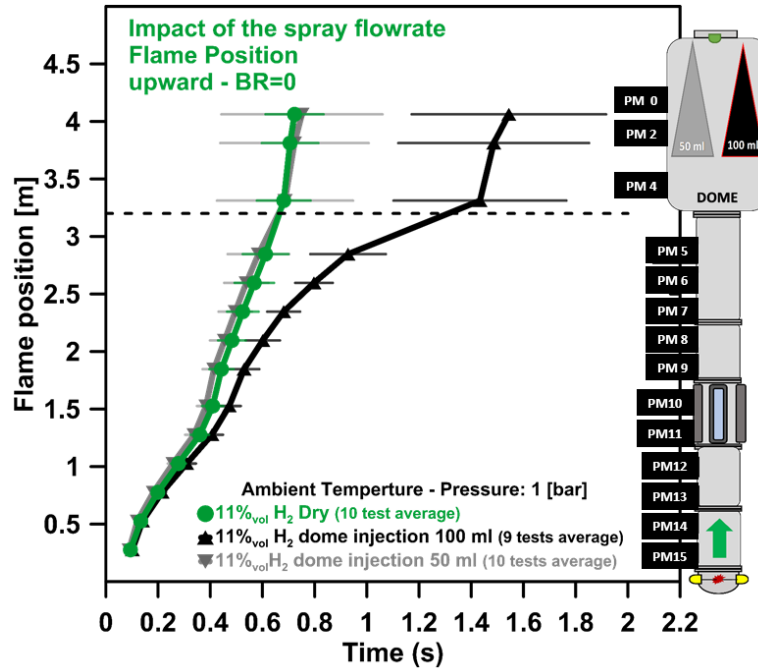


Figure 99: : Flame Position at 11%H₂ impact of flow rate– smooth tube – Upward. $t=0$ s : Spark Ignition; red: dry case at 11%H₂ + 89%Air; grey :spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome

Figure 100 shows the impact of the injection flowrate in case of 10.50%_{vol} H₂. The grey line is the flame position trajectory, with an injection flow rate of 50 ml/min. In the first part of the acceleration tube, the flame position follows the dry case. After 1 meter, the flame takes, in average, slightly less time to propagate, compared to the dry case.

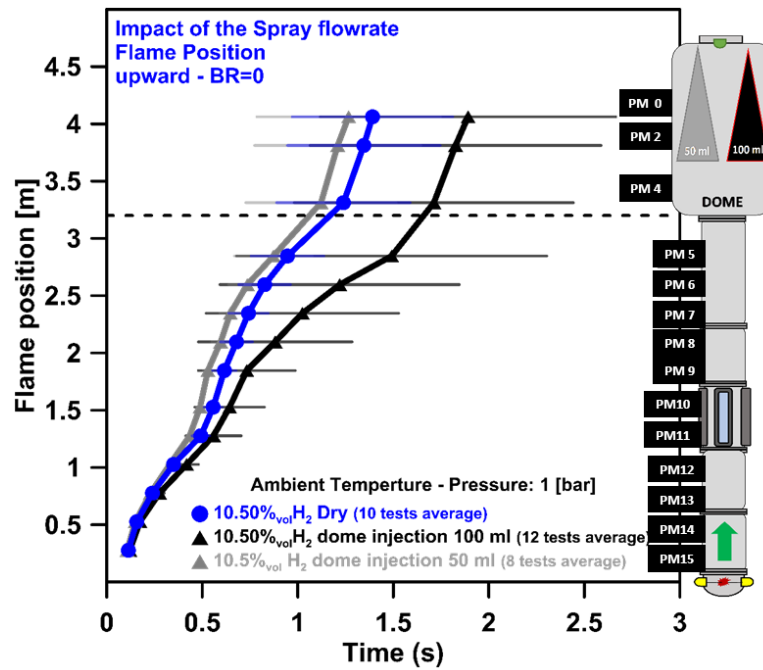


Figure 100: Flame Position at 10.50%H₂ impact of flowrate– smooth tube – Upward. $t=0$ Spark Ignition; red: dry case at 10.5%H₂ + 89.5%Air; grey :spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome .

2.5 The impact of the flowrate on the Flame Propagation Speed

The impact on the flame speed, of the water injection flow rate, in case of 13%_{vol} H₂ is showed in Figure 101. The grey line is the flame propagation speed with a water injection of 50 ml/min. In this case, the flame propagation exhibits a decrease, compared to the dry case and this trend is more marked on the last part of the tube. By increasing the water injection flow (black line), up to 100 ml/min, affects more the flame, in terms of speed reduction.

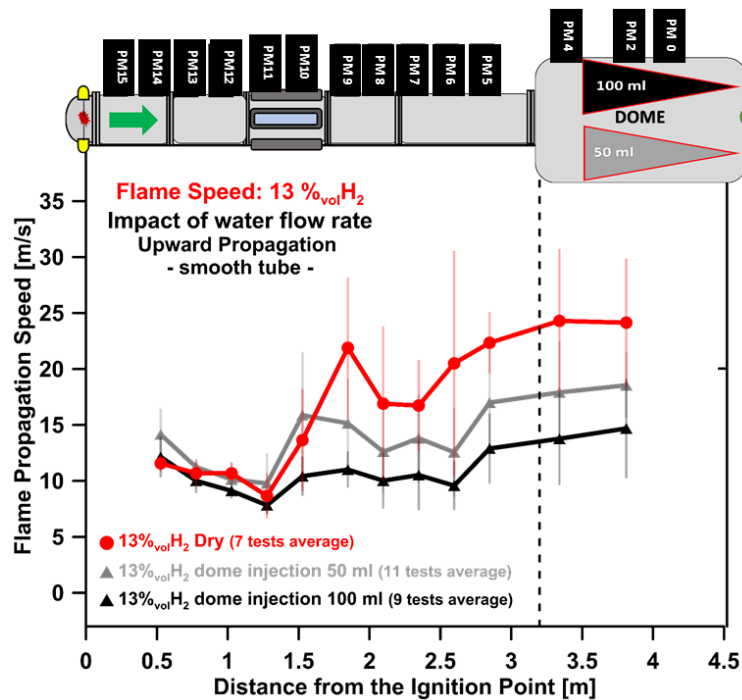


Figure 101: Flame Speed at 13%H₂ – Impact of injection flowrate - smooth tube- Upward. $t=0$ s : Spark Ignition; red: dry case at 13%H₂ + 87%Air; grey :spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome

Figure 102 shows the impact of the water spray flowrate on the flame speed in case of 11%_{vol} H₂. In this case, the injection of 50 ml/min of water (grey line) does not affect at all the flame speed propagation. By increasing the flowrate up to 100 ml/min (black line), the flame speed is slightly decreased. In case the flame speed does not exhibit a significant acceleration along the propagation in the acceleration tube.

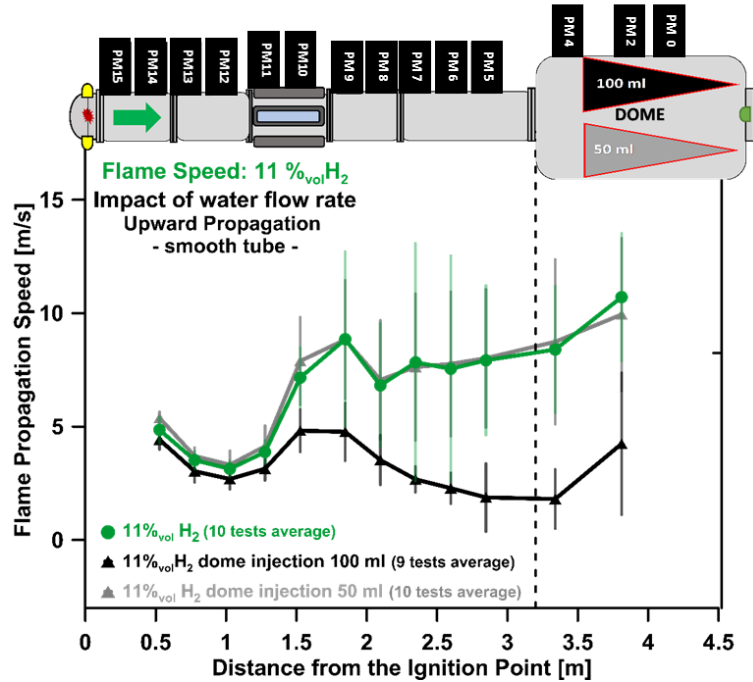


Figure 102: Flame Speed at 11%H₂ – Impact of injection flowrate - smooth tube- Upward. $t=0$ s: Spark Ignition; green: dry case at 11%H₂ + 89%Air; grey :spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome

Figure 103 shows the impact of the water flowrate in case of 10.50%vol H₂. The grey line represents the case in which the flowrate is 50 ml/min and the flame propagation speed is slightly increased compared to the dry case. This trend is more marked after 1.77m from the ignition point, when the flame enters in the access window block, where the internal volume, slightly increases. The maximum speed is increased by 23% (average of 6 test), compared to the dry case. By increasing the flowrate up to 100 ml/min (black line), the flame propagation is more affected.

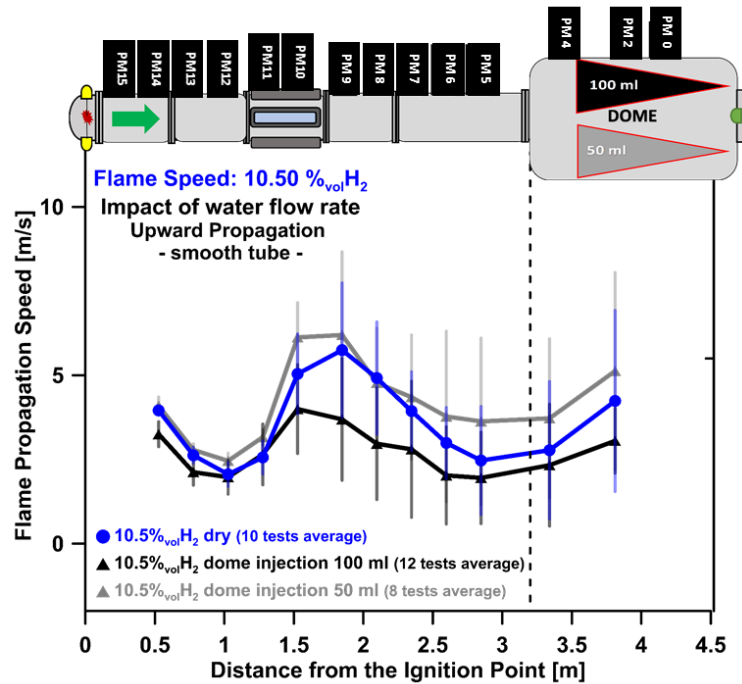


Figure 103: Flame Speed at 10.5% H_2 – Impact of injection flowrate - smooth tube- Upward. $t=0$ s: Spark Ignition; blue: dry case at 10.5% H_2 + 89.5% Air ; grey :spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome .

2.6 The impact of the flow rate on the Pressure Evolution

Table 21 reports the number of tests, the hydrogen concentration and the initial temperature and pressure for all the test performed by injecting 50 ml of water in the dome. The result have been compared with the dry cases and with the spray injection of 100 ml of water already showed in Table 20.

	N° of repeated tests	Measured (μGC) H_2 tube	Measure d (μGC) H_2 dome	T tube [K]	T dome [K]	P [bar]
13% $_{vol}H_2$ + 50 ml dome	7	12.95 ± 0.1	13.01 ± 0.1	295.2 ± 0.8	296.4 ± 1.3	1
11% $_{vol}H_2$ + 50 ml dome	10	10.95 ± 0.1	10.97 ± 0.9	295.9 ± 1.1	297.8 ± 1.9	1
10.5% $_{vol}H_2$ + 50 ml dome	8	10.48 ± 0.1	10.53 ± 0.8	293.7 ± 1.5	294.4 ± 1.4	1

Table 21: Smooth Tube experimental conditions – dome injection of 50 ml of water

The graphs in Figure 104, Figure 105, Figure 106, show the impact of the spray flowrate at 13, 11, and 10.50%_{vol} H₂, on the combustion pressure. The grey line is the pressure evolution with 50 ml/min of flow rate and the black line is the pressure evolution with 100 ml/min.

In case of 13%_{vol} H₂, the maximum pressure peak (P_{max}) is affected by 50 ml/min spray and it decreases by 4% compared to the dry case. Instead the injection of 100 ml of water spray (the black line), induces a decrease of 10% compared to the dry case. By comparing the measured P_{max} , with the corresponding ideal P_{AICC} , it is possible notice that the gap between the dry and spray cases cannot be explained only with the presence of humid air. The time to reach the peak and the pressure slope increase when water is injected spray with a higher flow rate. The presence of water droplets delays slightly the flame propagation and consequently the evolution of the pressure.

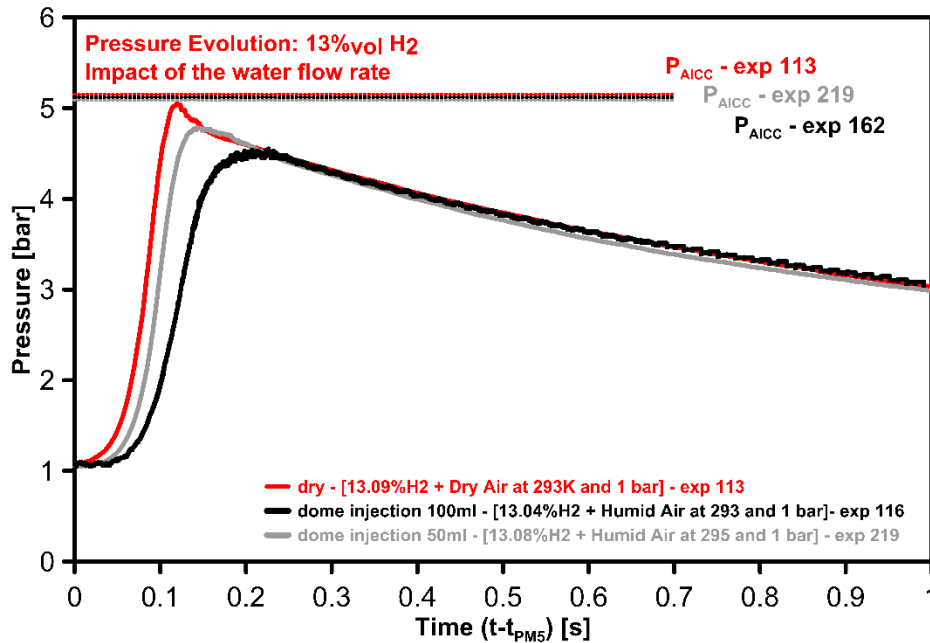


Figure 104: Pressure Evolution at 13% H_2 - Impact of the water flowrate. . $t=0$ s: Time PM_5 ; red: dry case at 13% H_2 + 87% Air ; grey :spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome

In case of 11%_{vol}H₂ (Figure 105) a decrease of the severity explosion parameters is noticed. The injection of the 100 ml/ min is more effective than the injection of 50 ml/ min on the decrease of the P_{max} , time to reach the peak and the slope of the curve. Compared to the dry case, P_{max} is decreased by 4% in case of 50 ml/min and of 12% when 100 ml/min are injected.

In case of 10.50%_{vol}H₂ (Figure 106), the injection of 50 ml of water (grey line), reduces the P_{max} by 4% compared to the dry case. By doubling the water flow injection (black line), the P_{max}

decreases on average by 9% compared to the dry case. The time to reach the peak and the delay are more affected as the water flow rate increases.

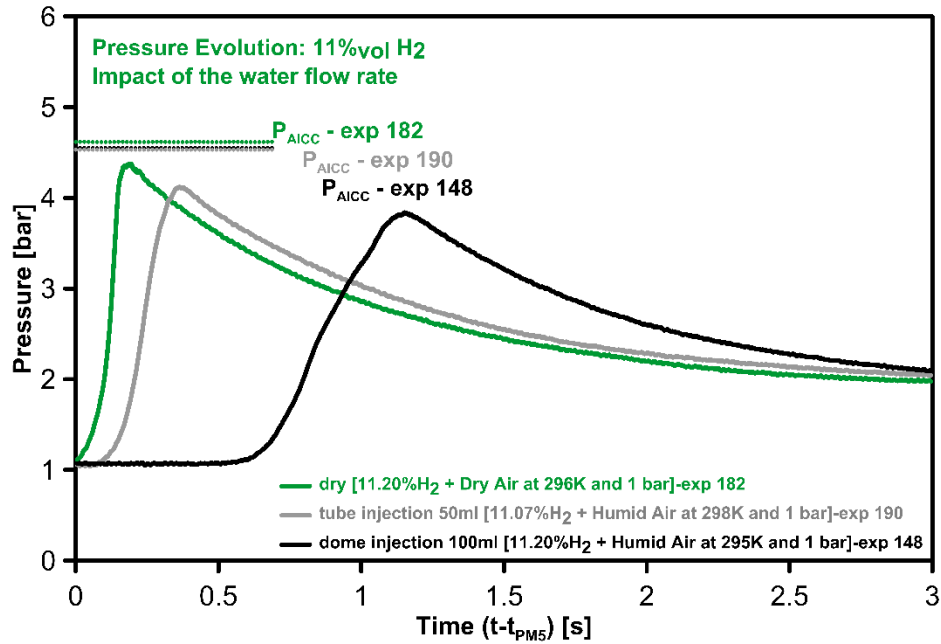


Figure 105: Pressure Evolution at 11% H₂- Impact of the water flowrate. $t=0$ s: Time PM5; green: dry case at 11% H₂ + 89% Air; grey: spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome

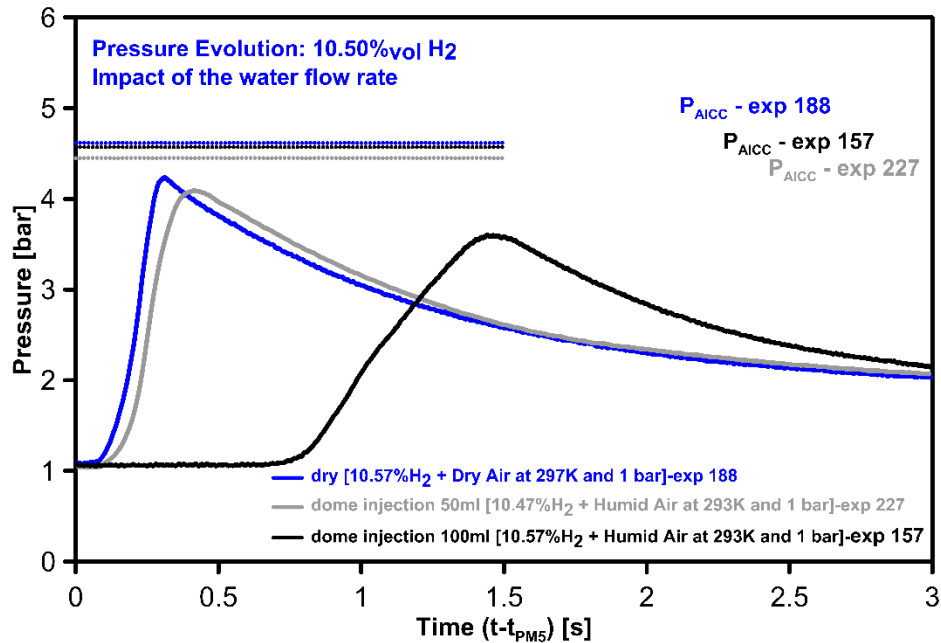


Figure 106: Pressure Evolution at 10.50% H₂- Impact of the water flowrate. $t=0$ s: Time PM5; green: dry case at 10.50% H₂ + 89.5% Air; grey: spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome

Figure 107 reports a summary of the impact of the water flow injection on explosion parameters. The mitigation of the explosion, in term of pressure evolution, is observable when water spray in injected. By increasing the water flow rate, it is possible to decrease the $P_{\max}$ (Figure 107, a). The differences between the dry cases and water spraying cases, are in all the cases, slight, apart from the case of 11%_{vol}H₂.

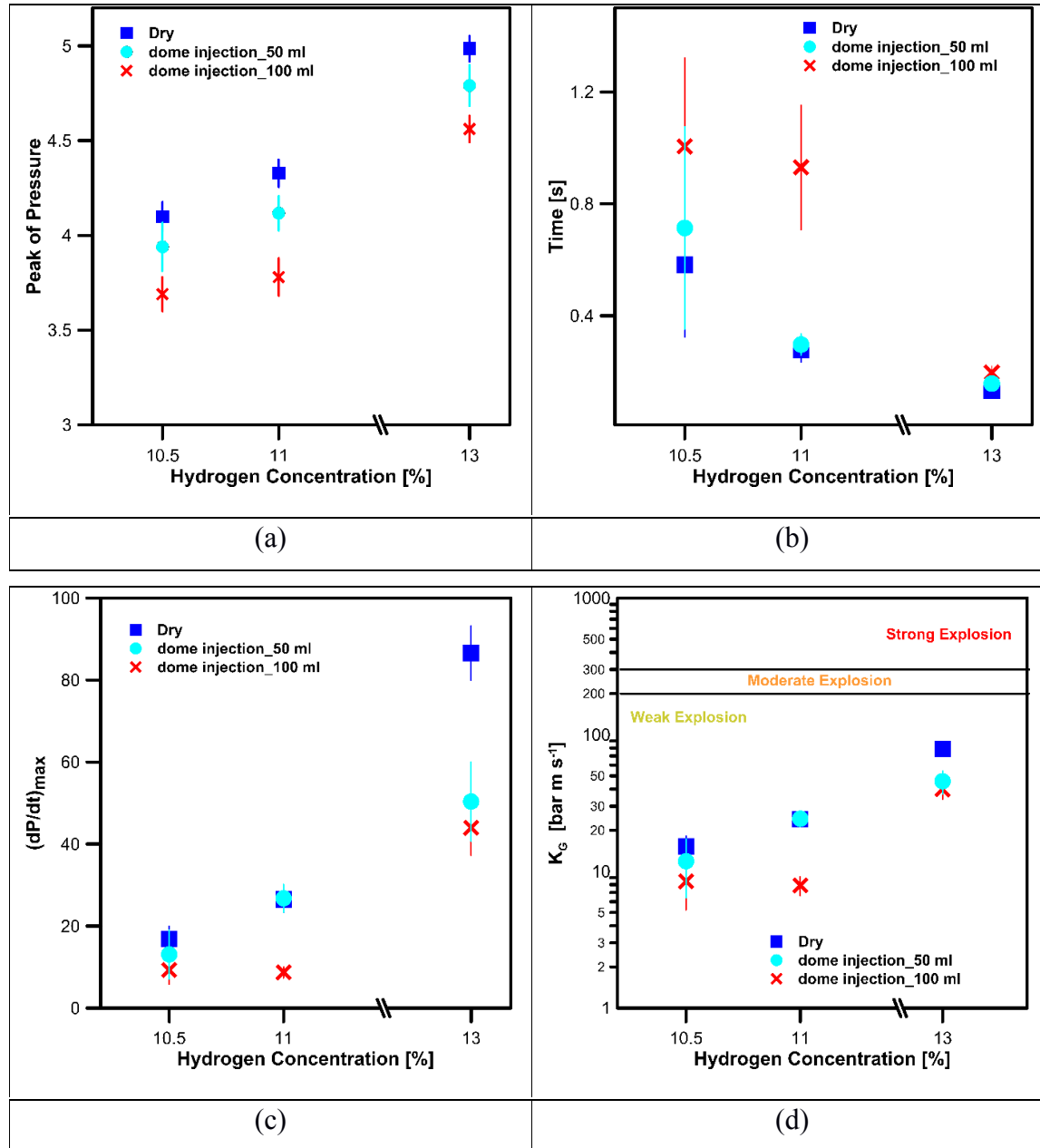


Figure 107: Explosion Parameter summary – water flowrate impact in upward propagation BR=0. Blue: Dry Case; Red: spray injection 100ml only in the dome; light blue: spray injection 100ml only in the dome

3 Conclusions on the Upward Flame Propagation in smooth tube conditions

The flame speed increases as the H_2 content in the mixture is raised from 10.50% to 13% in air. The maximum velocity in the tube or in the dome, it reaches 5 m/s when the mixtures contain 10.50% $_{vol}H_2$, 10 m/s for 11% $_{vol}H_2$ in air and 22 m/s for 13% $_{vol}H_2$ in air.

The maximum pressure observed in the facility is also directly linked to the H_2 content. It reaches 93% of the P_{AICC} for 10.50% $_{vol}H_2$ case (4.10 bar), 94% of the P_{AICC} for the 11% $_{vol}H_2$ case (4.31 bar) and 97% of the P_{AICC} for 13% $_{vol}H_2$ case (4.10 bar). This is a good indication that the combustion was complete. The explosion index, K_G , was found to be below 200 [bar m/s] which classifies the studied mixtures to be “weak explosion” and as expected, K_G increases as the H_2 content in the mixture increases from 10.50% $_{vol}H_2$ to 13% $_{vol}H_2$.

When water spray are activated, the results show that there is a mitigation of the combustion. The effect depends both on the total quantity of injected water and on its location. The location of the spray injection was studied in the case of 100 ml of injected water. The flame speed as well as the maximum pressure are impacted by the water spray. Both parameters decrease, with a stronger decrease, when the spray is injected in the dome. This decrease is observed for all 3 hydrogen content investigated in this study. As a result, the explosion index decreases with the activation of the spray. For all conditions investigated in this study, K_G was found to be less than 50 bar m/s.

The effect of the amount of water was investigated in the case of volume injection. The results show that when water is injected in the dome, the trajectory of the flame is modified only after 1.5 m from the ignition point. This effect is pronounced for the largest flowrate (100 ml/min). As a result, both the flame speed and the maximum combustion pressure are reduced when water spray is activated. The impact depends both on the hydrogen content and on the lowest K_G as well for all 3 hydrogen content in the air investigated in this study.

The activation of the water spray, in all the cases, induces an initial velocity in the fresh gases and a certain turbulence is created in the medium, despite this effect, the presence of the water spray reduces the maximum velocity as well as the maximum combustion pressure. In this configuration where the flame propagates in opposite direction of the water spray (still activated as the combustion progresses), the latter is successful in mitigating combustion, although it is not a strong effect, it is still appreciable.

4 Dry mixtures in obstructed tube upward propagation

In this part, the effect of the water spray injection on the accelerated flames is studied. The acceleration tube is equipped with a series of annular obstacles (BR=0.63) as showed in Figure 51. This configuration was already tested during the course of the experimental work of Malet [40], to be the most accelerating configuration.

The following table reports the condition investigated with the averaged value of hydrogen concentration and temperature.

H₂%_{vol}	N° of repeated tests	Measured (μGC) H₂ tube	Measured (μGC) H₂ dome	T tube [K]	T dome [K]	P [bar]
13	4	12.95±0.08	12.95±0.07	302.6 ± 0.9	305.3 ± 0.3	1
11	4	10.91±0.05	10.92±0.04	302.1 ± 0.7	303.6 ± 0.8	1
10.5	4	10.45±0.04	10.49±0.05	302.2 ± 0.9	303.9 ± 0.7	1

Table 22: Tube with Obstacles - Dry Condition List of Experiments

The nine annular obstacles are placed in the first part of the acceleration tube, between 0.160 m and 1.438 m, from the ignition point as showed in Figure 108. They are equally placed by 0.154 m corresponding to the tube diameter.

In the previous experimental campaign conducted with the same apparatus by Malet [40] and By Cheickhravat [62], on the flame acceleration phenomena, the obstacles where placed at the beginning of the second block between 0.813 m and 2.091 m from the ignition point.

The data of flame position and speed are available only in the acceleration tube (first 11 PMs).

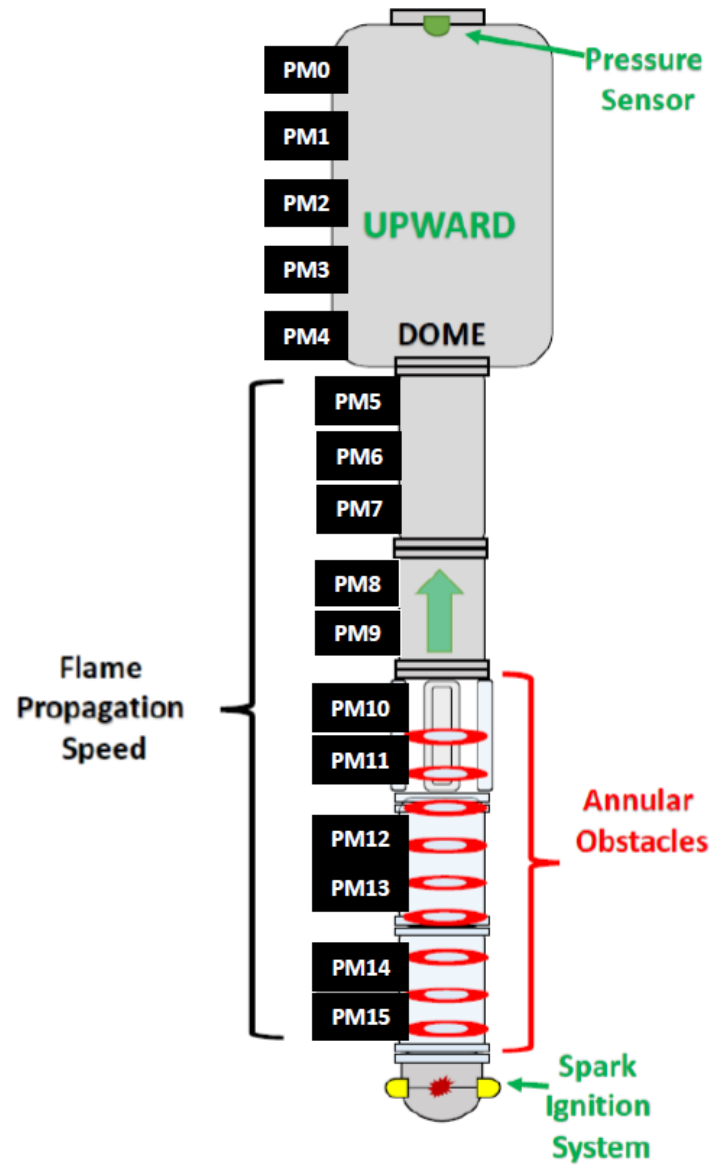


Figure 108: Scheme of ENACCEF equipped with Obstacles placed. 9 obstacles equally placed by 0.154 m. First obstacle at 0.160 m from the ignition point. Last Obstacle at 1.438 m from the ignition point

4.1 Upward Flame Position for dry mixtures in presence of obstacles

In this paragraph, the impact of the initial hydrogen concentration on the trajectory of the flame position in case of accelerated flames is showed.

Figure 109 shows the flame position trajectory as a function of the time. On the graph are represented the obstacles placed at 0.135 m from the ignition point up to 1.45 m. The flames are faster and even to reach the first PM, the flame take less time compared to the dry case in absence of obstacles.

The time to pass through the acceleration tube, decreases as the hydrogen concentration decreases. In case of 13%_{vol}H₂ (the red curve), the flame takes almost 0.049 s to travel from the bottom to the top of the acceleration tube. In case of 11%_{vol} H₂, the flame takes 0.092 s and in case of 10.50 %_{vol} H₂, the flame takes 0.106 s. The error bar, evaluated on at least 4 experiments, does not exhibit a significant variation neither during the flame trajectory nor due to the hydrogen concentration variation.

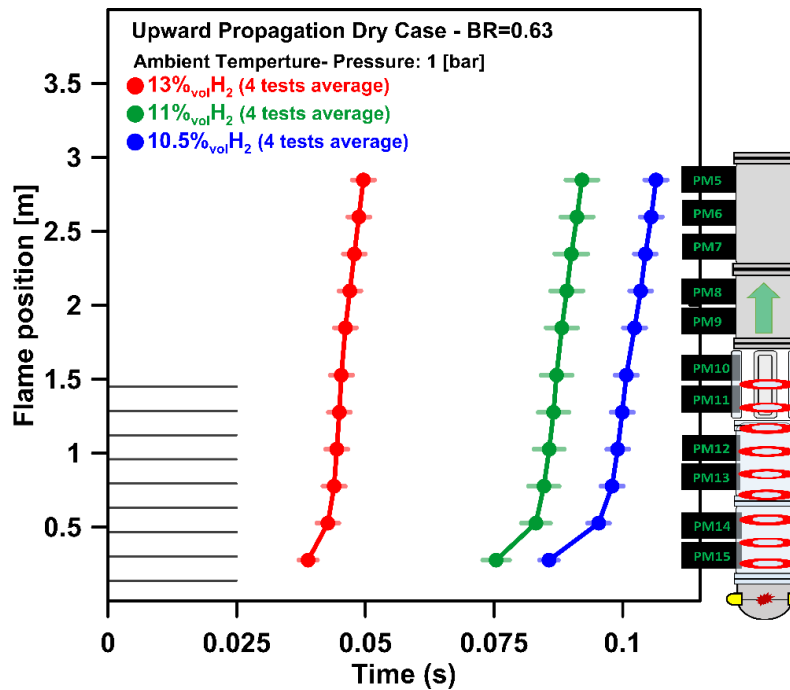


Figure 109: Flame Position Dry Case - Upward Propagation – BR=0.63. $t=0$ s :Spark Ignition; red: dry case at 13%H₂ + 87%Air; green: dry case at 11%H₂ + 89%Air; blue: dry case at 10.50%H₂ + 88.5%Air.

4.2 Upward Flame Propagation Speed for dry mixtures in presence of obstacles

Figure 110 shows the impact of the initial hydrogen concentration on the flame propagation speed in case of accelerated flames. The positions of the obstacles are reported with the black dot lines

The 3 curves describe the flame speed propagation as a function of the distance from the ignition point. In case of 13%_{vol} H₂, the flame is strongly accelerated, from the beginning. The first value of velocity, corresponds to a flame which has travels through 3 obstacles, so the initial value result to be around 100 m/s (instead of 10 m/s in case of smooth tube Figure 83). The maximum of the flame speed is around 560 m/s and then the flame speed starts to decrease when it is still in the region of obstacles. After the obstacles region, the flame speed decreases until reaching an almost constant velocity before to enter in the Dome.

In case of 11%_{vol} H₂, the flame speed has an initial value of 50 m/s (instead of 5 m/s in the case of smooth tube). The obstacles have a lower impact on the increase of the velocity compared to the previous case. The maximum flame speed is about 350 m/s in the last part of the acceleration tube. After the obstacles region, the flame starts to decreases in terms of velocity. This trend is less marked compared to the case with higher initial concentration.

In case of 10.50%_{vol} H₂, the initial value of flame speed is about 40 m/s. The maximum flame speed occurs inside the acceleration section before the last obstacle at 1.28 m form the ignition point. After the accelerating section, the velocity decreases and this trend is less marked compared to the other cases. At 2.10 m, the flame speed does not exhibit a significant acceleration and it remain almost constant.

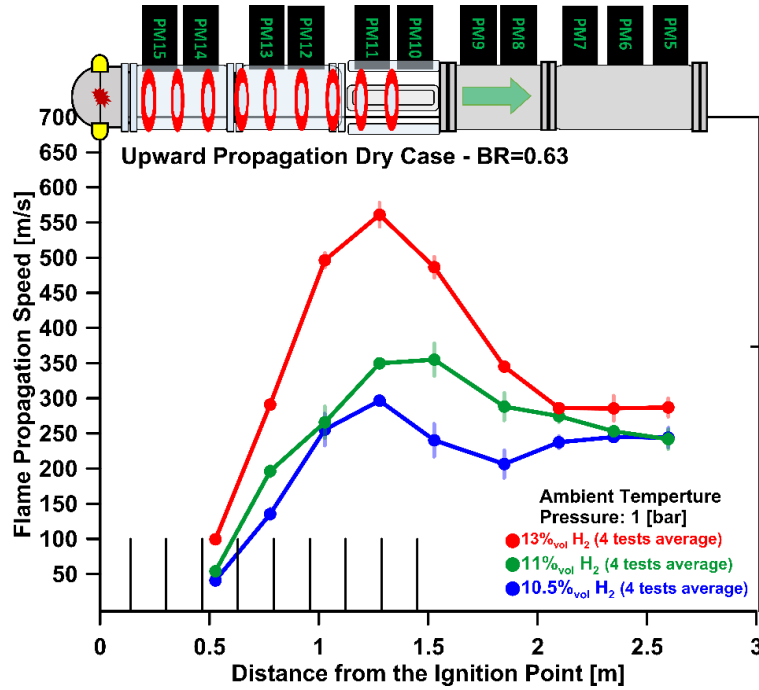


Figure 110: Flame Propagation Speed Dry Case - Upward Propagation –BR=0.63. $t=0$ s :Spark Ignition; red: dry case at 13% H_2 + 87% Air ; green: dry case at 11% H_2 + 89% Air ; blue: dry case at 10.5% H_2 + 88.5% Air .

In order to better understand the effect of the induced acceleration by the annular obstacles, the speed of sound in the burned gas is calculated for each test. The initial conditions for each equilibrium calculation are relative to the initial hydrogen composition and temperature in the acceleration tube (average on 3 samples). The criteria take into account the half of the speed of sound in the burned gases as a limit value to define if a flame accelerates strongly and the combustion regime is considered as fast. Figure 111 shows the flame speed propagation normalized for the speed of sound as a function of the normalized distance on the internal diameter. The speed of sound is evaluated for each experimental test by considering:

$$a_{sound} = \sqrt{\frac{\gamma_{burned} T_{burned} R}{M}} = \sqrt{\frac{\frac{c_p}{c_v - R} T_{burned} R}{w}}$$

Equation 40: Speed of Sound relationship

Where: T_{burned} the temperature of the burned gases (adiabatic temperature) [K], c_p and c_v are the specific heat at constant pressure and volume (burned gases) [$J mol^{-1} K^{-1}$], R is the universal gas constant [$J mol^{-1} kg^{-1} K^{-1}$] and M is the molar mass of the burned gases [$kg mol^{-1}$].

It is possible to observe that the flame is accelerated in case of 13%_{vol}H₂ and 11%_{vol}H₂ because the flame speed has at least one point higher than the half of the speed of sound. In case of 10.50%_{vol}H₂, the highest accelerating configuration, 9 annular obstacles are not enough to increase the flame speed up to half of the corresponding speed of sound. This result compares with the previous experimental results obtained with ENACCF1 [40], [62], [63].

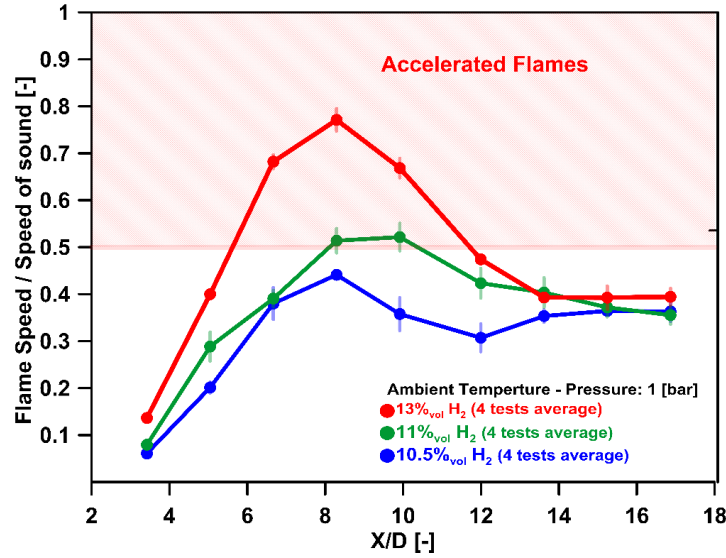


Figure 111: Acceleration Criteria Dry Mixture in upward propagation $BR=0.63$. $t=0$ s :Spark Ignition; red: dry case at 13%H₂ + 87%Air; green: dry case at 11%H₂ + 89%Air; blue: dry case at 10.5%H₂ + 88.5%Air.

4.2.1 Comparison with flame acceleration models

In this paragraph the comparison between the experimental flame speed and the one evaluated analytically is showed, by using the model of Valiev and the one of Vesper, already used for the comparison in the upward propagation in absence of obstacles. Equation 38 and Equation 39 are corrected by changing the value of BR corresponding to 0.63.

The input velocities take into account the expansion ratio and they are the same used in the previous comparison (Paragraph 1.3, Chapter 5):

- 0.26 m/s for 13%H₂ (experimental value R=70 mm)
- 0.38 m/s for 11%H₂ (from experimental value R=40 mm at 10%H₂)
- 0.07 m/s for 10.5%H₂ (from experimental value R=40 mm at 10%H₂)

Figure 112 shows the comparison between the experimental flame propagation velocity and the one obtained by using the 2 models, previously described, in the acceleration region (obstacles zone). The Valiev model underestimates of 2 order of magnitude the flame speed in the acceleration region. The Vesper model, at 10.50%_{vol}H₂ and 11%_{vol}H₂, is closer to the initial flame speed value (at 0.52 m) but as the flame propagates, it underestimates significantly the flame acceleration.

At 13%H₂, the Vesper model overestimates the initial speed velocity but as the flame propagates, it describes more accurately the flame speed evolution especially for the last part of the obstacles region. The gap between experimental and analytical value is essentially due to the fact that:

1. the 2 models aim to describe flame propagation which lead to a DTT phenomenon but they are not made to describe the flame propagation controlled by heat transfer mechanism (slow deflagration with H₂-air lean mixtures) and turbulence.
2. the input data velocity, they do not represent rigorously the definition of laminar flame speed which can be obtained for higher H₂ concentration (H₂ > 16%_{vol}).

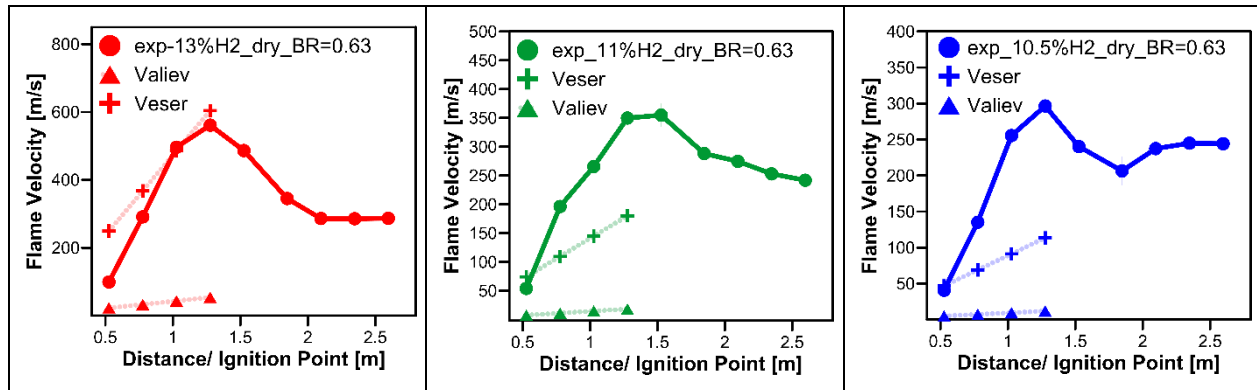


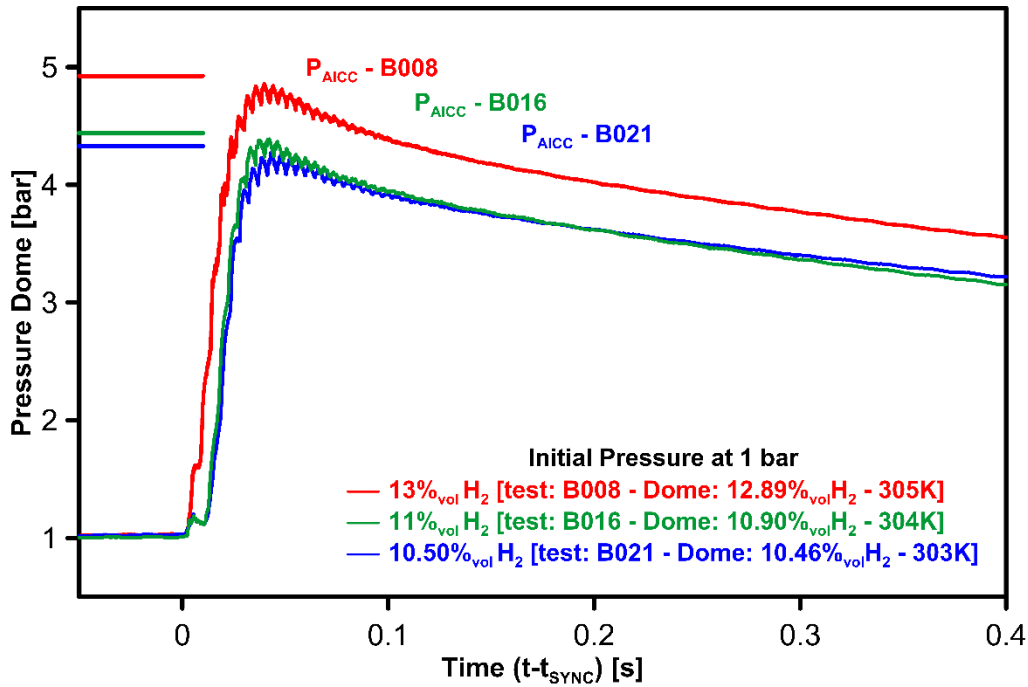
Figure 112: Comparison between the experimental data and the analytical model for flame acceleration in the channels equipped with obstacles

4.3 Upward propagation Pressure Evolution in obstructed tube for dry mixtures

Here is presented the pressure evolution in case of accelerate flames. The curves are synchronised to the entry in the dome which correspond to the small peak of pressure placed at time equals zero. This variation of pressure was already observed by previous experimental investigation by using the ENACCEF and it corresponds to a shock wave induced by the flame propagation in the tube. It is attenuated when entering is entering in the dome. The signal have

been filtered with Savitzky-Golay filter in order to reduce the noise which is higher than the case of slow flame due to the violence of the deflagration.

Figure 113 shows the pressure evolution in the dome for the dry mixture in case of accelerated flames and the relative Adiabatic Isochoric Complete combustion Pressure. The red curve corresponds to the case of 13%_{vol} H₂, the green curve to 11%_{vol} H₂ and the blue curve to 10.50%_{vol} H₂. In case of accelerated flames, as the hydrogen concentration decreases, the maximum peak of pressure decreases but the slope of curve is not significantly affected by initial fuel concentration as in the case of slow flame (Figure 86). The differences between the P_{AICC} and the measured Pressure are around the 2-4% and they are smaller than the case of slow flame, in which there were between 3-7%.



*Figure 113: Pressure Evolution -Accelerated flames-Dry Mixtures in Upward Propagation with obstacles.
 $t=0$ s : Time flame entry in the dome; red: dry case at 13% H_2 + 87% Air ; green: dry case at 11% H_2 + 89% Air ;
blue: dry case at 10.50% H_2 + 88.5% Air .*

Table 23 reports the averaged measured P_{MAX}, the averaged P_{AICC} (calculated for each experimental conditions) and the ratio between them. As the fuel concentration decreases, the maximum pressure decreases, so the time to reach the maximum ($t=0$ at time PM5) is slightly longer at 11% and 10.50, compared to the 13% (Table 24).

	P_{AICC}	P_{max}	ratio P_{max}/P_{AICC}
13%_{vol} H₂	4.94 ± 0.02	4.77± 0.06	96%
11%_{vol} H₂	4.45 ± 0.01	4.35± 0.08	98%
10.5%_{vol} H₂	4.33 ± 0.01	4.25± 0.05	98%

Table 23: : Comparison P_{max} and P_{AICC} -dry mixture - upward BR=0.63

	T to P_{max} [s]	$(dP/dt)_{max}$ [bar/s]
13%_{vol} H₂	0.040±0.004	277.69± 29.27
11%_{vol} H₂	0.023 ±0.007	256.92± 22.40
10.5%_{vol} H₂	0.039±0.004	160.77± 9.20

Table 24 Time to Peak ($t=0$: flame entry in the dome) and dP/dT_{max} dry mixture -upward smooth tube-BR=0.63.

Figure 114 report the K_G index evaluated in upward propagation condition, with and without obstacles, in order to evaluate the impact of the flame acceleration on the explosion severity.

In case of 13%_{vol}H₂ and 11%_{vol}H₂, the deflagration index is shifted form the zone of the weak explosion ($K_G < 200$ bar m/s) to the one of the moderate explosion ($200 < K_G < 300$ bar m/s). In case of the 10.50%_{vol}H₂, the K_G is also increased but still it remains in the range of the weak explosion.

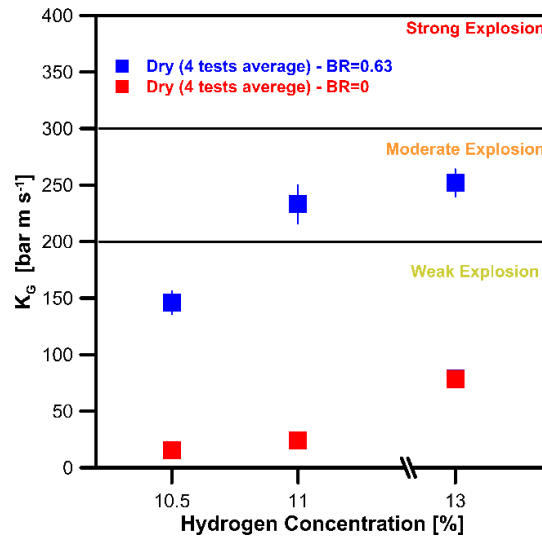


Figure 114: Inherent Safe criteria: Deflagration Index based on the pressure evolution- Comparison Dry case Upward Propagation BR=0.63 and BR=0.

5 Spray Activation in obstructed tube: upward flame propagation

In this section the results about the interaction between water spray and accelerated hydrogen-air-vapor flames are presented. Two water flow rates (50 ml/min and 100 ml/min) are used . The injection is performed done for both flowrates conditions.

Table 25 summerizes the experimental conditions investigated in this part: the number of repeated tests, the H₂ content measured bt μ GC and the initial temperature.

H ₂ % _{vol}	N. of repeated tests	Measured (μ GC) H ₂ tube	Measured (μ GC) H ₂ dome	T tube [K]	T dome [K]
13%H ₂ + 100 ml	3	12.94 $\pm$ 0.03	12.97 $\pm$ 0.04	304.5 $\pm$ 0.6	307.1 $\pm$ 0.5
11%H ₂ + 100 ml	4	10.98 $\pm$ 0.16	11.05 $\pm$ 0.04	302.7 $\pm$ 1.3	305.0 $\pm$ 1.3
10.5%H ₂ + 100 ml	3	10.50 $\pm$ 0.09	10.54 $\pm$ 0.04	302.4 $\pm$ 0.4	304.4 $\pm$ 0.6
	N. of repeated tests	Measured (μ GC) H ₂ tube	Measured (μ GC) H ₂ dome	T tube [K]	T dome [K]
13%H ₂ + 50 ml	3	12.92 $\pm$ 0.06	12.98 $\pm$ 0.02	300.8 $\pm$ 0.6	303.3 $\pm$ 1.2
11%H ₂ + 50 ml	3	10.90 $\pm$ 0.03	10.95 $\pm$ 0.06	301.3 $\pm$ 1.3	302.6 $\pm$ 0.7
10.5%H ₂ + 50 ml	3	10.52 $\pm$ 0.10	10.53 $\pm$ 0.11	300.7 $\pm$ 0.3	301.9 $\pm$ 0.7

Table 25: Tube with Obstacles – Experimental Conditions : injection of 100 ml and 50 ml of liquid water in the dome

5.1 Impact of the water flowrate on the Flame Position: Accelerated Flames

This paragraph reports the impact of the water flow injection on the flame position for accelerated flame.

Figure 115 shows the impact of the water flow rate on the flame position at 13%_{vol}H₂. The red curve is the flame position in absence of spray. The black curve is the flame position trajectory in case of an injection of 100 ml with a water flowrate of 100 ml/min. The grey curve is the case of injection of 50 ml with a water flow rate of 50 ml/min.

When the spark is activated a flame kernel is created by interaction of the plasma with the mixture. A certain delay is observed between the moment when the energy is deposited and the moment when a flame is created. This delay depends on several parameters such as the mixture composition, the surface of the electrodes and the gap between them. This delay can become important.

After the obstacle region, in which the flame is accelerated, for all the cases the flame position exhibits a slight decreasing of the slope. The time needed to the flame to propagate along the acceleration tube is 0.051s in case of 100 ml of water and it is 0.057s in case of an injection of 50 ml. Anyway the slope of the flame position for both the injection cases, does not exhibit a significant variation compared to the dry case.

The same trend is observable for the flame trajectory in case of an initial concentration of hydrogen at 11%_{vol} H₂ (Figure 116). The green curve is the dry case at 11%_{vol} H₂, the black line is corresponding to the case of an injection of 100 ml of water. The grey curve corresponds to the injection of 50 lm of water. In presence of water spray, the flame does not exhibit a significant variation form the dry case.

With an injection of 100 ml/min, the flame takes 0.091 s to propagate from PM15 to PM5 and with an injection of 50 ml/min, the flame takes 0.096 s to propagate in the acceleration tube.

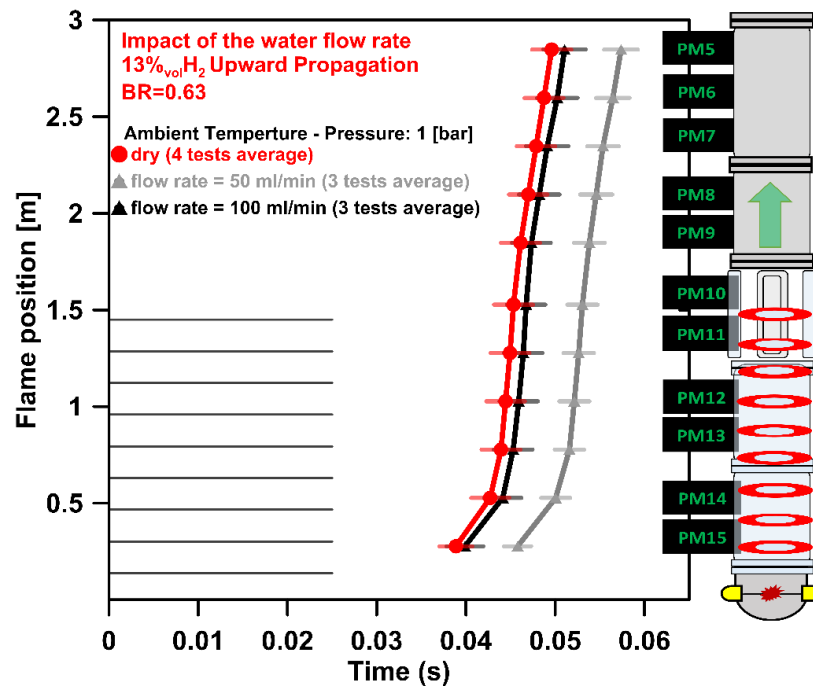
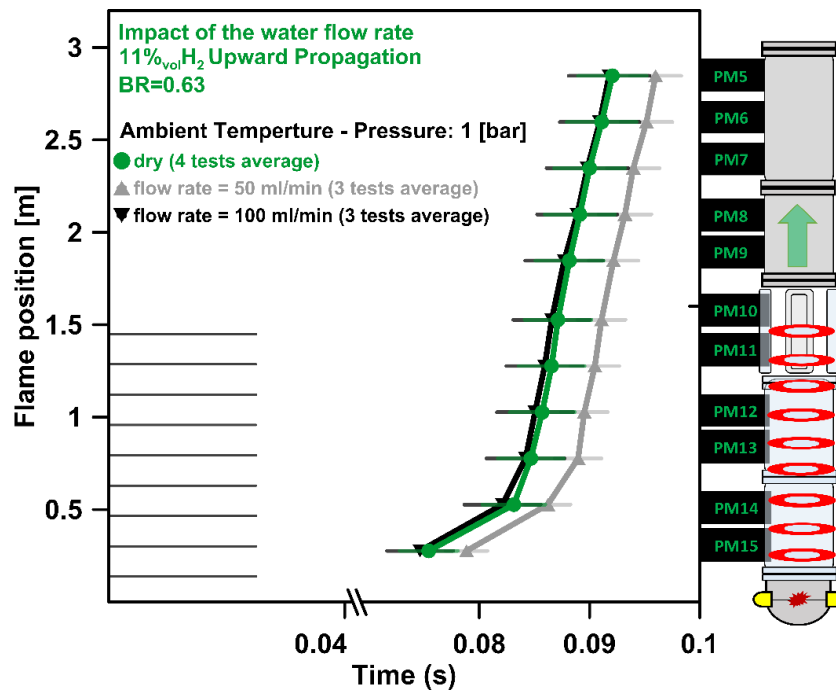


Figure 115: Impact of the water flow rate on 13%_{vol} H₂ Flame Position Upward Propagation – BR=0.63. $t=0$ s : Spark Ignition; red: dry case at 13%_{vol} H₂ + 87%_{vol} Air; grey : spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome.



*Figure 116: : Impact of the water flow rate on 11%vol H₂ Flame Position - Upward Propagation – BR=0.63. .
 t=0 s : Spark Ignition; green: dry case at 11%H₂ + 89%Air; grey :spray injection 50 ml only in the dome; black:
 spray injection 100ml only in the dome.*

Figure 117 shows the flame position as a function of the time; In case of an initial concentration of hydrogen at 10.50%vol H₂.

The black curve is for the case with injection from the dome of 100 ml of liquid water. The grey line represents the case 50 ml of liquid water are injected in the dome. The flame trajectory, in presence of spray does not exhibit a significant variation in terms of slope, compared to the dry case.

When the flame passes the obstacles region, the presence of the spray, leads a delay in the flame trajectory. In case of an injection of 100 ml /min, the flame takes, 0.011 s to reach the top of the tube, instead of 0.012 s with an injection of 50 ml/min the flame takes, 0.012s.

In general, the delay in the flame trajectory due to the presence of the spray on the accelerated flames is not so significant, compared to the case of slow flames, in which the presence of the spray delays the trajectory of the flame at least by 30% for 100 ml of water injected and by 20% for 50 ml, compared to the dry case.

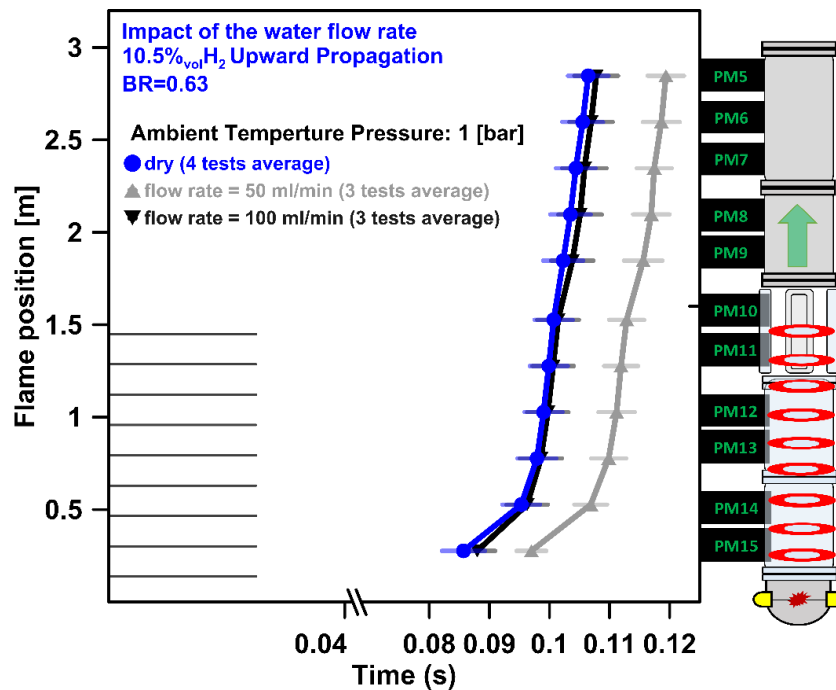


Figure 117: : Impact of the water flow rate on 10.50%_{vol} H₂ Flame Position - Upward Propagation – BR=0.63. $t=0$ s : Spark Ignition; blue: dry case at 11%_{H₂} + 89%_{Air}; grey :spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome.

5.2 Impact of the water flowrate on Flame Propagation: Accelerated flames

This section is dedicated to the impact of the water flowrate on hydrogen-air flame in case of accelerated flames. Figure 118 shows in red the flame propagation speed in dry mixture as a function of the distance from the ignition point. The grey curve represents the case propagation speed with an injection of 50 ml of water with a flowrate of 50ml/min. The black line is the propagation flame speed with an injection of 100 ml of liquid water with a flowrate of 100 ml/min.

In case of 50 ml of injected water (grey line), the speed is slightly lower than the dry case for almost all the propagation in the tube. The maximum flame speed is equal to the one reached at for the dry case and it occurs at the same position (1.27 m from the ignition point).

In case of 100 ml of injected water (black line), the flame speed is initially close to the dry case. At the end of the obstacles section, the flame exhibits a significant acceleration which lead to a peak of 628 m/s, almost 11% higher than the dry case (560 m/s). The flame deceleration in the last part of the tube lead to a flame speed closer to the one of the dry case.

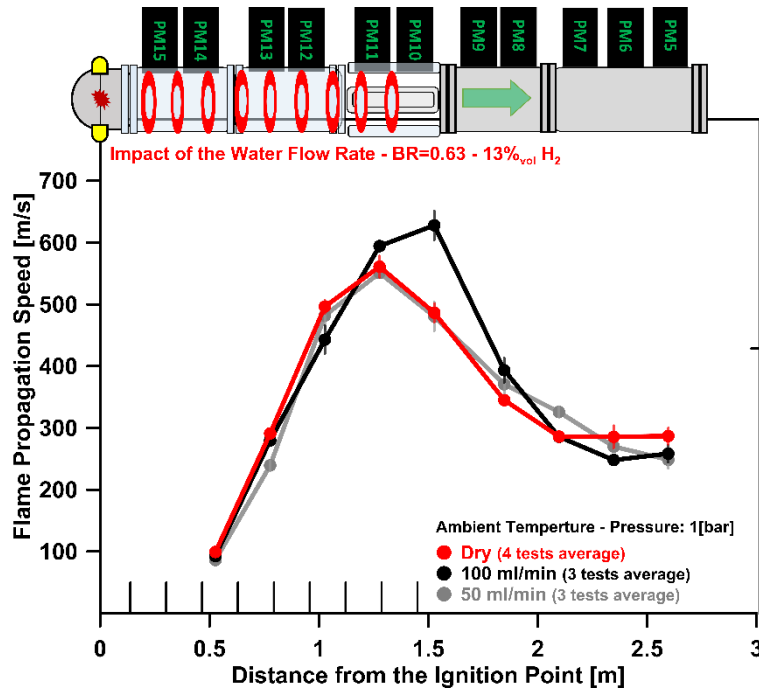


Figure 118: Impact of the water flow rate at 13%_{vol} H₂ on the Flame Propagation Speed Dry Case - Upward Propagation –BR=0.63. $t=0$ s : Spark Ignition; red: dry case at 13% H₂ + 87% Air; grey : spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome.

Figure 119 shows the impact of the flowrate on the flame propagation at 11%_{vol} H₂. The green line represents the flame speed in case of dry mixture, the black curve, represent the flame speed with an injection of 100 ml/min and the grey curve represent the case in which water is injected at 50 ml/min. In case of an injection of 100 ml/min (black curve), the speed does not differ significantly from the dry case, especially in the region of obstacles. The maximum flame speed is slightly lower than of the dry case around the (7% less) but the flame is not accelerated by the impact of the spray, also after 1.52 m when the flame can freely propagate without obstacles. At the end of the acceleration tube, the flame speed reaches value close to the dry case.

In case of an injection of 50 ml of water with 50 ml/m of flowrate, the flame propagation evolution is closer to the dry case. The flame speed exhibits a slight acceleration around 1 m from the ignition point but for the rest of the propagation does not differ from the dry case. The averaged maximum of speed is 5% less than the dry case.

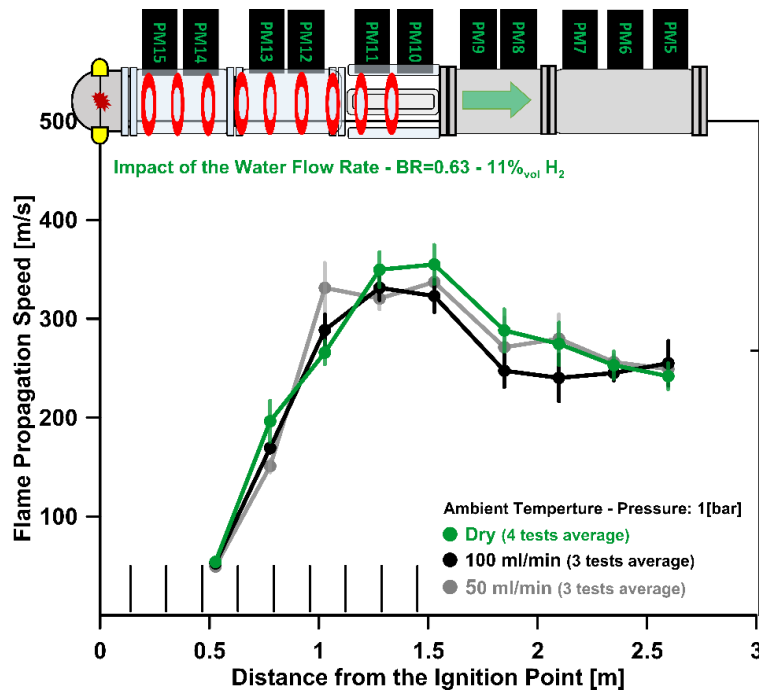


Figure 119: Impact of the water flow rate at 11%_{vol} H₂ on the Flame Propagation Speed - Upward Propagation – BR=0.63. $t=0$ s : Spark Ignition; green: dry case at 11%_{vol} H₂ + 89%_{vol} Air; grey : spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome.

Figure 120 shows the impact of the flowrate on the flame propagation at 10.50%_{vol} H₂. The blue line is the flame speed propagation in dry case, the black one is the case of the injection of 100 ml of water and the grey line is the injection of 50 ml of water.

The spray injection of 50 ml/min, the grey line, has the strongest impact on the flame speed. In the first phase of acceleration, the flame speed does not differ from the dry case. The maximum speed does not differ from the one reached in dry case. Before the last obstacle, at 1.27m from the ignition point, the flame starts to decelerate until reaching a value of 140 m/s which is 35% less than the dry case at the same position. At 2 m the flame accelerates again and the averaged speed is higher than the dry case until the end of the tube.

In case of 100 ml of injection, the flame speed exhibits the same behaviour observed with injection of 50 ml but the deceleration after the maximum flame speed and the acceleration around 2 m is less marked. The maximum flame speed does not differ from the dry case, but the deceleration after is in the order of 27% lower than the dry case. After 2 m from the ignition point, the flame starts to accelerate and the averaged value are higher than the dry case. The impact on the flame speed is less marked as in the case of an injection of 50 ml/min. The general trend, in presence of obstacles is that the presence of obstacles limits the water spray impact, which is not significant in the

obstacles region. When the flame passes the obstacles region, the behaviour of the flame depends on the initial hydrogen concentration. At 13%_{vol} H₂, the flame is accelerated as the water flow increases. At 11%, the flame does not exhibit a variation. At 10.50% the flame is decelerated in the first part and then accelerated.

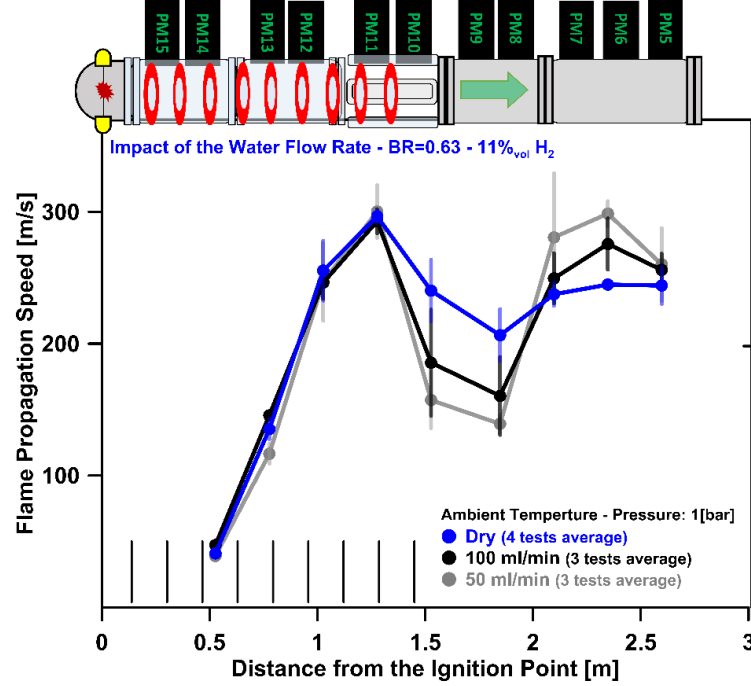


Figure 120: Impact of the water flow rate at 10.50%volH₂ on the Flame Propagation Speed - Upward Propagation BR=0.63. $t=0$ s : Spark Ignition; blue: dry case at 10.5%H₂ + 89.5%Air; grey :spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome.

The speed of sound in the fresh mixture, has been calculated by using the following relationship which take into account the compressibility of the gas phase [68]:

$$\frac{1}{c^2} = [\rho_L(1 - \alpha) + \rho_G\alpha] \left[\frac{\alpha}{\gamma P} + \frac{(1 - \alpha)}{\rho_L c_L} \right]$$

Table 26: Relationship for Speed of Sound in Diphasic Mixture.

Where: ρ_L and ρ_G [kg/m³] are the densities of the liquid and gaseous phase, α [-] is the volume fraction of air; γ [-] is the ratio between specific heat at constant pressure and volume, P [Pa] is the pressure and c_L [m/s] is the speed of sound in the liquid water (1500 m/s).

Table 27 summarizes the speed of sound as a function of the hydrogen concentration in mixture at ambient temperature for different liquid volume fraction at ambient temperature.

As one can see, the presence of droplets can affect strongly the speed of sound according to the ratio between liquid and gaseous phase.

In our case the injected water cannot modify strongly the speed of sound because by supposing that any water is deposited on the internal walls of the facility ($0.000146 \text{ m}_{\text{H}_2\text{O}}/\text{m}_{\text{air}}$), only the flames at 13% and 11% H_2 propagates supersonically. The last columns shows the impact of the water spray on the speed of sound by considering the suspended mass of water ($\text{m}_{\text{susp_DOME}}$) in case of WM2 injection (Chapter 2, Paragraph 1.4).

	Without droplets	Liquid Volume Fraction = 0.01	Liquid Volume Fraction = 0.0001 (no losses)	Liquid Volume Fraction = $4.87 \cdot 10^{-5}$ (measured)
13%	371.2 m/s	113.2 m/s	347.1 m/s	362.6
11%	367.4 m/s	113.1 m/s	343.9 m/s	359.0
10.50%	366.5 m/s	113.0 m/s	343.1 m/s	358.1

Table 27: Speed of Sound Calculation for two-phase mixture

Figure 121 shows the flame speed propagation normalized for the speed of sound in the burned gases as a function of the normalized distance on the internal diameter. The speed of sound is calculated by using the thermal properties of the burned gases calculated by considering the initial conditions for each experiment. It is possible to observe that both sprays do not affect the possibility to accelerate the flame. In case of 13%_{vol}, and the one of 11%_{vol} the flames are supersonic and they are considered accelerated. In case of 10.50%_{vol}, the flame speed is lower than the half of the speed of sound in the burned gases and it is also lower than the speed of sound in the unburned gases, so it is sub-sonic and it is not accelerated.

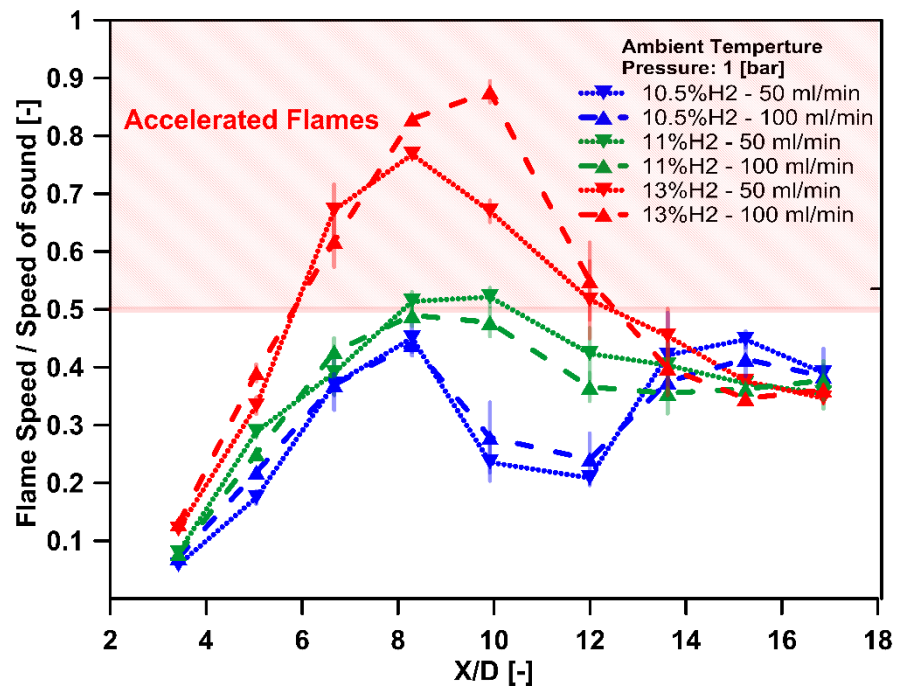


Figure 121: Acceleration Criteria Wet Mixtures in upward propagation $BR=0.63$

5.3 Impact of the water flowrate on the Pressure Evolution of Accelerated Flames

In this paragraph the impact of the water spray flowrate on the pressure evolution is showed.

Figure 122 shows the impact of the spray flowrate on the pressure evolution at 13%_{vol}H₂. The black curve represents an example of the pressure evolution with a spray injection of 100ml/min. The grey line represents an example of the spray injection of 50 ml/min.

The presence of the spray decreases slightly $P_{\max}$ compared to the dry case and the decrease is higher as the water flowrate increases. The differences between the measured $P_{\max}$ and the calculated P_{AICC} are in the order of 2% (below the experimental uncertainty) which is a good indication of a complete combustion.

This result suggests that the impact of the spray, in terms of $P_{\max}$ reduction is less important compared to the case of slow flames (peak reduction of the 10% compared to the dry case).

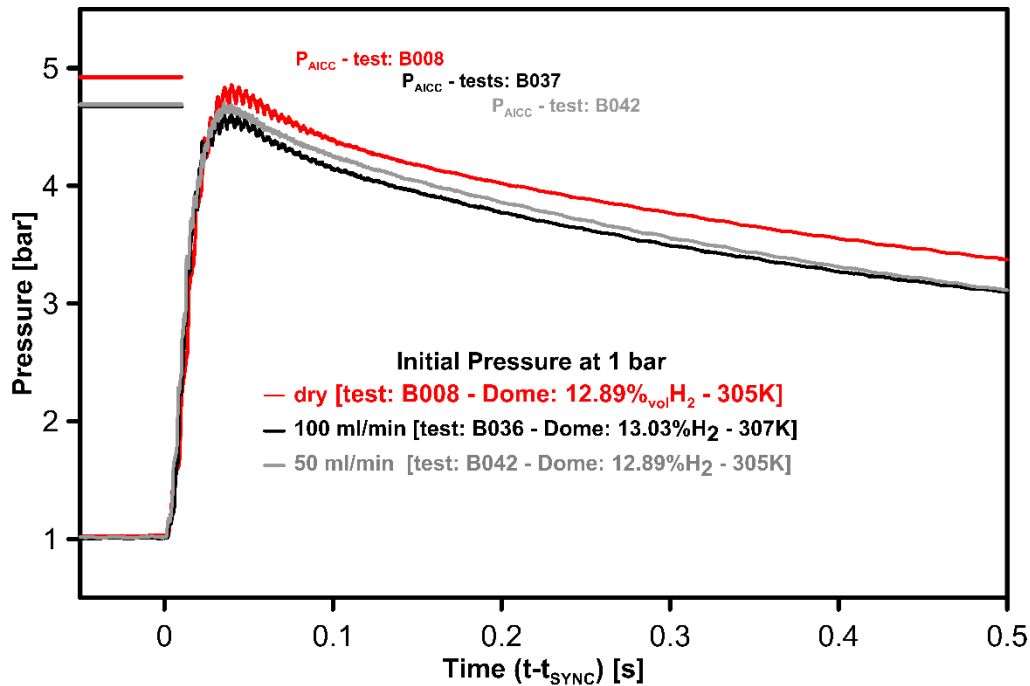


Figure 122 Pressure Evolution at 13%_{vol}H₂- Impact of the water flowrate-Upward - BR=0.63 t=0 s : entry of the flame in the dome; red: dry case at 13%_{H₂} + 87%_{Air}; grey :spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome

Figure 123 shows the impact of the water spray flowrate at 11%_{vol}H₂. The injection of 100 ml/min of water spray has the strongest impact in terms of $P_{\max}$ reduction and in terms of time to reach the peak. The differences between the measured $P_{\max}$ and the calculated P_{AICC} (with humid air mixtures) are in the order of 3% (below the experimental uncertainty).

The injection of the spray reduces slightly the maximum peak of pressure, compared to the dry case and the decrease is more important as the spray flow rate increases. In case of 100 ml/min (black curve), the rise of the overpressure is also delayed significantly compared to the case of injection of 50 ml/min (grey curve).

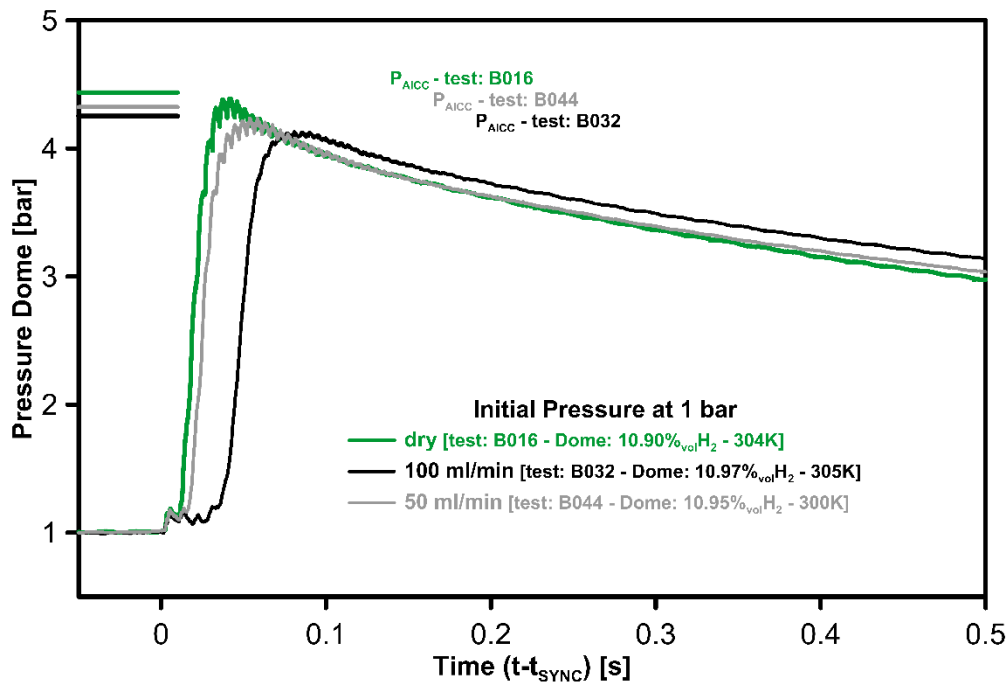


Figure 123 Pressure Evolution at 11%_{vol}H₂- Impact of the water flowrate-Upward - BR=0.63. $t=0$ s : entry of the flame in the dome; green: dry case at 11%_{vol}H₂ + 89%_{vol}Air; grey :spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome

Figure 124 shows the impact of the spray flowrate on the pressure evolution in case 10.50%_{vol}H₂. The difference between the $P_{\max}$ and the calculated P_{AICC} are in the order of 3%. Even in this case, the spray injection of 100 ml/min has the highest impact in terms of $P_{\max}$ reduction compared to the case of 50 ml/min of flowrate.

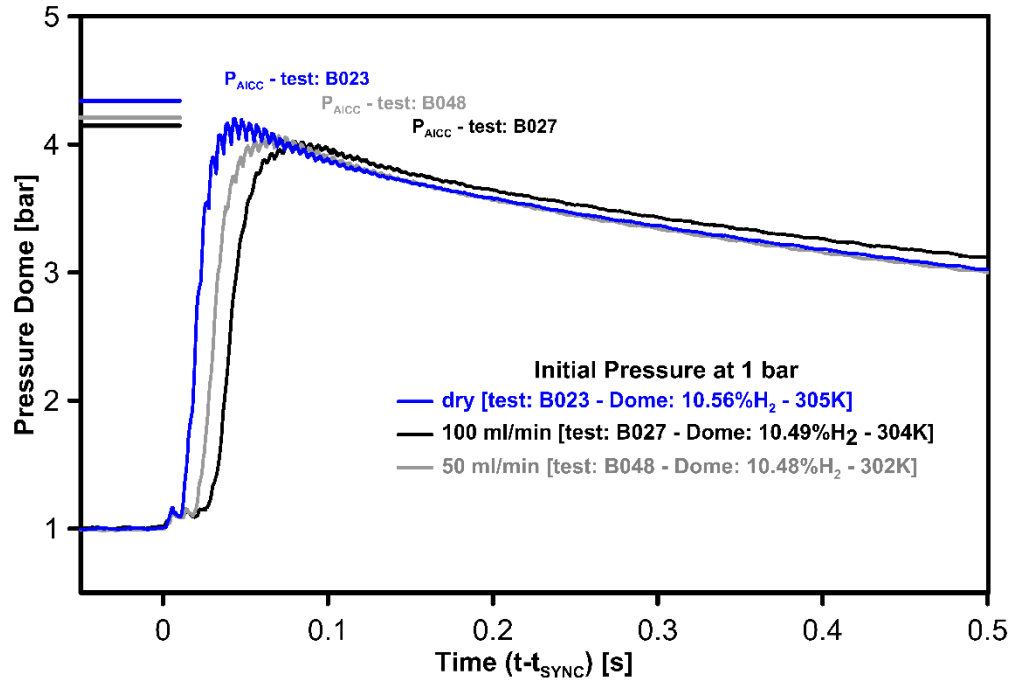


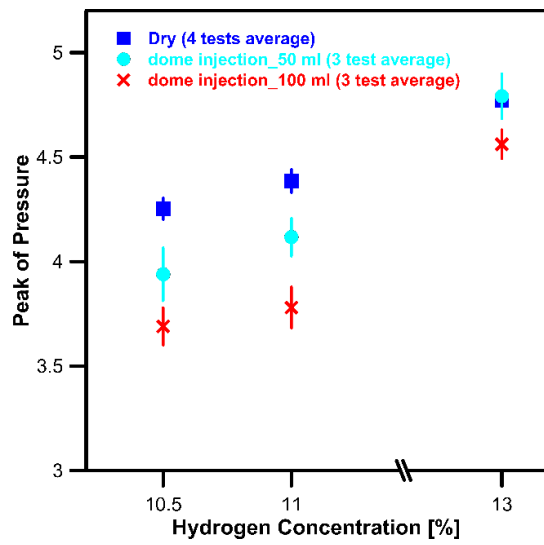
Figure 124: Pressure Evolution at 11%_{vol}H₂- Impact of the water flowrate-Upward - BR=0.63. $t=0$ s : entry of the flame in the dome; blue: dry case at 10.5%_{H₂} + 89.5%_{Air}; grey :spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome

Figure 125, reports a summary of the explosions parameters as P_{max} (a), the time to reach the peak (b), dP/dt_{max} (c) and the K_G deflagration index (d).

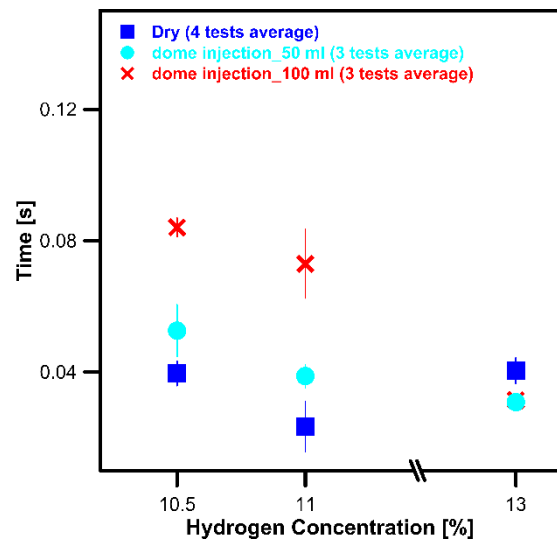
A mitigation effect of the severity of the deflagration (Figure 125 (d)) is observable at 11%_{vol}H₂ in which the K_G , with the injection of 100 ml/min (red symbol) is decreased from 230 to 130 [bar m/s]. In this case the severity of the explosion is downgraded from moderate to weak. For the same initial hydrogen concentration; the spray injection of 50 ml/min (blue light symbol) mitigates the deflagration but not enough to consider the explosion as a weak deflagration.

In case of 10.50%_{vol}H₂, the K_G is still decreased but this effect is not so marked as at 11%_{vol}H₂.

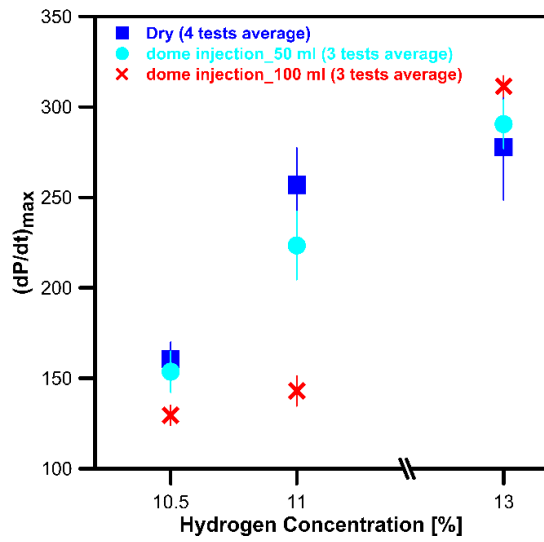
Despite the other cases, in case of 13%_{vol}H₂, the K_G index slightly increases with the spray injection from 252 [bar m/s] in the dry case, to 282 [bar m/s] with an injection of 100 ml/min of water spray.



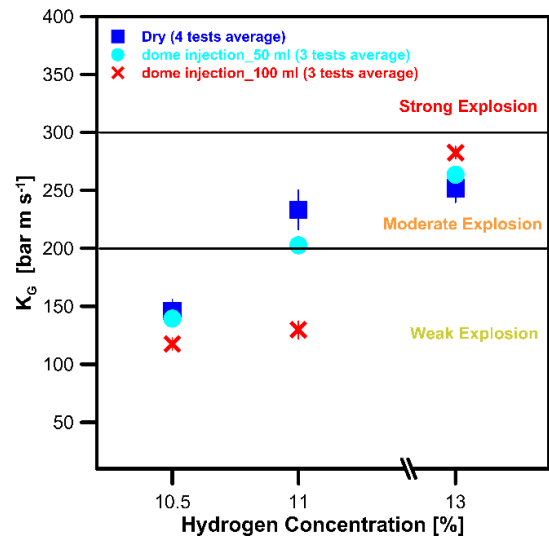
(a)



(b)



(c)



(d)

Figure 125: Explosion Parameter Summary-BR=0.63 –Impact of the water spray flowrate - Blue: Dry Case: Red: spray injection 100ml only in the dome; light blue: spray injection 100ml only in the dome

6 Conclusions on the Upward Flame Propagation in presence of obstacles

The presence of obstacles affects the flame propagation by inducing change in the flame surface which increase the flame velocity and which lead to the creation of turbulence.

In absence of water spray injection, for initial mixtures of 13%_{vol}H₂ and 11%_{vol}H₂ in dry air, the flame speed exceeds the acceleration criteria, based on the speed of sound in the burned gases. This result confirms that with an initial hydrogen content higher than 11%_{vol}, the flame has a tendency to accelerate in presence of obstacles.

By considering the K_G index, the severity of the explosion results to be significantly increased by the presence of the obstacles and when the flames are accelerated, the explosion severity transit from the domain of the weak explosions ($K_G < 200$ [bar m/s]) to the one of the moderate ones ($200 < K_G < 300$ [bar m/s]).

The results about the interaction with the water spray have to be interpreted by considering the initial hydrogen concentration and the resulting flame behaviour in terms of acceleration.

The impact on the flame propagation is stronger as the water spray flowrate increases but it results in a mitigation effect only for the slow flames which do not have the tendency to accelerate.

In fact at 13%_{vol}H₂ in presence of spray injection, it is not possible observe any significant mitigation explosion effect. Furthermore, when the flowrate increases to 100 ml/min, there is an enhancing effect of the flame propagation which increase slightly the severity of the explosion.

In case of 10.50%_{vol}H₂ mixtures, the flame without water spray does not accelerate and the spray injection disturbs the flame propagation speed by inducing a significant mitigation effect. This effect increases as the water flowrate increases.

The case of 11%_{vol}H₂ represents a limit case between the flame which accelerate and the ones which do not. Anyway, in this case, the spray injection and the resulting droplets evaporation promotes the mitigation explosion effect which increases as the injected quantity of water increases.

Propagation de la flamme vers le haut

La propagation de la flamme (pour les mélanges d'hydrogène contenant 10,50, 11, 13 % vol H₂) sera étudiée dans un tube lisse et en présence d'obstacles annulaires répétés (BR=0.63). Pour chaque condition, les résultats en termes de position de flamme, de vitesse de propagation de la flamme et d'évolution de la pression pendant la combustion, sont présentés. La première partie concerne le résultat de l'essai réalisé en tube lisse en conditions sèches et en présence d'eau pulvérisée. Dans ce cas, l'impact du débit de pulvérisation et l'impact du volume d'injection sur la propagation de la flamme et la montée en pression subséquente sont étudiés. La deuxième partie concerne les résultats de l'essai effectué en présence d'obstacles (BR=0,63) pour les mélanges secs et avec pulvérisation d'eau. Dans ce cas, une étude de l'impact du débit de pulvérisation sur les flammes rapides sera présentée. La vitesse de la flamme augmente lorsque la teneur en H₂ du mélange passe de 10,50% à 13% dans l'air. La vitesse maximale dans le tube ou dans le dôme, elle atteint 5 m/s lorsque les mélanges contiennent 10,50%volH₂, 10 m/s pour 11%volH₂ dans l'air et 22 m/s pour 13%volH₂ dans l'air. La pression maximale observée dans l'installation est également directement liée à la teneur en H₂. Il atteint 93% du P_{AICC} pour le cas 10,50%volH₂ (4,10 bar), 94% du P_{AICC} pour le cas 11%volH₂ (4,31 bar) et 97% du P_{AICC} pour le cas 13%volH₂ (4,10 bar), ce qui est une bonne indication que la combustion était complète. L'indice d'explosion, K_G, s'est révélé inférieur à 200[bar m/s], ce qui classe les mélanges étudiés dans la catégorie "faible explosion" et, comme prévu, K_G augmente à mesure que la teneur en H₂ du mélange passe de 10,50%volH₂ à 13%volH₂. Lorsque la pulvérisation d'eau est activée, les résultats montrent qu'il y a une atténuation de la combustion. L'effet dépend à la fois de la quantité totale d'eau injectée et de son emplacement. L'emplacement de l'injection par pulvérisation a été étudié dans le cas de 100 ml d'eau injectée. La vitesse de la flamme () ainsi que la pression maximale sont influencées par le jet d'eau. Les deux paramètres diminuent, avec une diminution plus forte, lorsque le jet est injecté dans le dôme. Cette diminution s'applique aux trois teneurs en hydrogène étudiées dans le cadre de cette étude. Par conséquent, l'indice d'explosion diminue avec l'activation du jet. Pour toutes les conditions étudiées dans cette étude, la K_G s'est avérée inférieure à 50 bar m/s.

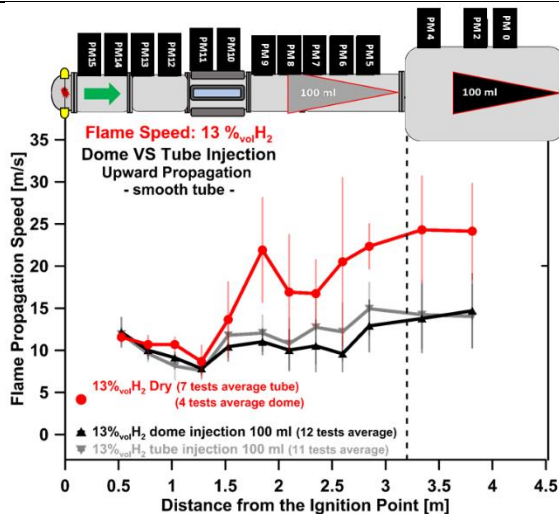


Figure 2 : Vitesse de flamme à 13%volH₂ - Dôme VS Tube Injection - tube lisse - vers le haut. t=0 s : Allumage par étincelle ; rouge : boîtier sec à 13%H₂ + 87%Air ; gris : injection spray 100 ml uniquement dans le tube ; noir : injection spray 100ml uniquement dans le dôme.

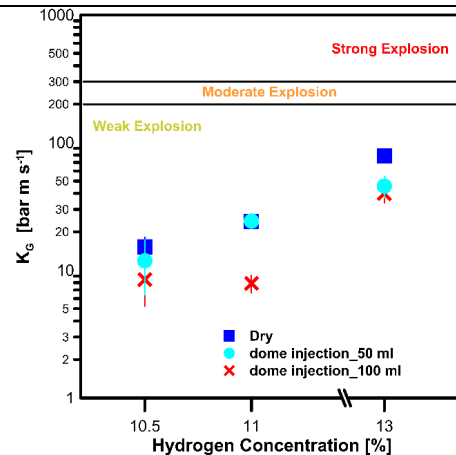


Figure 3 : Paramètre d'explosion - impact du débit d'eau dans la propagation ascendante BR=0. Bleu : Cas sec ; Rouge : Injection par pulvérisation 100ml seulement dans le dôme ; bleu clair : injection par pulvérisation 100ml seulement dans le dôme

L'effet de la quantité d'eau a été étudié dans le cas de l'injection de volume. Les résultats montrent que lorsque de l'eau est injectée dans le dôme, la trajectoire de la flamme n'est modifiée qu'après 1,5 m du point d'inflammation. Cet effet est prononcé pour le débit le plus important (100 ml/min). Par conséquent, la vitesse de la flamme et la pression de combustion maximale sont réduites lorsque le jet d'eau est activé. L'impact dépend à la fois de la teneur en hydrogène et de la teneur en KG la plus faible ainsi que de la teneur en hydrogène de l'air

étudié dans cette étude. L'activation de la pulvérisation d'eau, dans tous les cas, induit une vitesse initiale dans les gaz frais et une certaine turbulence est créée dans le milieu, malgré cet effet, la présence de la pulvérisation d'eau réduit la vitesse maximale ainsi que la pression de combustion maximale. Dans cette configuration où la flamme se propage en sens inverse du jet d'eau (toujours activé au fur et à mesure que la combustion progresse), ce dernier parvient à atténuer la combustion, bien qu'il ne soit pas un effet important, il est quand même appréciable. La présence d'obstacles affecte la propagation de la flamme en induisant des changements dans la surface de la flamme qui augmentent la vitesse de la flamme et qui conduisent à la création de turbulences. En l'absence d'injection d'eau pulvérisée, pour les mélanges initiaux de 13%volH₂ et 11%volH₂ dans l'air sec, la vitesse de la flamme dépasse les critères d'accélération, basés sur la vitesse du son dans les gaz brûlés. Ce résultat confirme qu'avec une teneur initiale en hydrogène supérieure à 11%vol, la flamme a tendance à s'accélérer en présence d'obstacles. En considérant l'indice K_G, la sévérité de l'explosion est significativement augmentée par la présence des obstacles et lorsque les flammes sont accélérées, la sévérité de l'explosion passe du domaine des explosions faibles (K_G<200[bar m /s]) à celui des modérées (200 <K_G<300[bar/m /s]). Les résultats de l'interaction avec l'eau pulvérisée doivent être interprétés en tenant compte de la concentration initiale d'hydrogène et du comportement de la flamme qui en résulte en termes d'accélération.

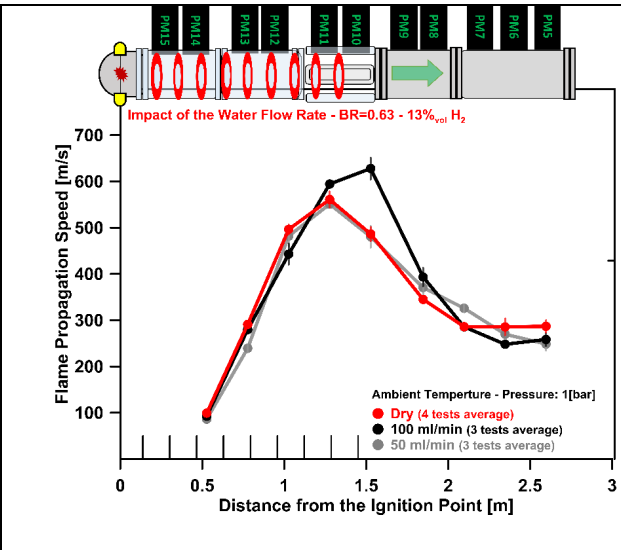


Figure 4 : Vitesse de flamme à 13%volH₂ - Dôme VS Tube Injection - tube lisse - vers le haut. t=0 s : Allumage par étincelle ; rouge : boîtier sec à 13%H₂ + 87%Air ; gris : injection spray 100 ml uniquement dans le tube ; noir : injection spray 100ml uniquement dans le dôme.

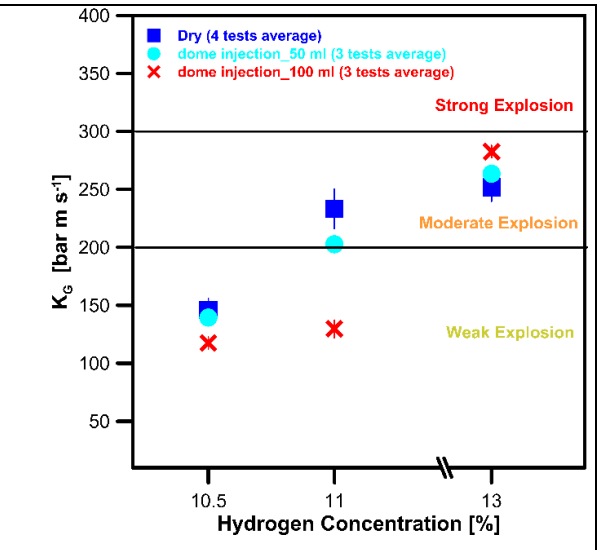


Figure 5 : Paramètre d'explosion - impact du débit d'eau dans la propagation ascendante BR=0.63. Bleu : Cas sec : Rouge : Injection par pulvérisation 100ml seulement dans le dôme ; bleu clair : injection par pulvérisation 100ml seulement dans le dôme

L'impact sur la propagation de la flamme est plus fort à mesure que le débit d'eau augmente, mais il n'a d'effet d'atténuation que pour les flammes lentes qui n'ont pas tendance à accélérer.

En fait, à 13%volH₂ en présence d'une injection par pulvérisation (Figure 4), il n'est pas possible d'observer d'effet d'atténuation significatif d'explosion. De plus, lorsque le débit augmente à 100 ml/min, il y a un effet de propagation de la flamme qui augmente légèrement la gravité de l'explosion (Figure 5). Dans le cas de mélanges à 10,50%volH₂, la flamme sans pulvérisation d'eau n'accélère pas et l'injection de pulvérisation perturbe la vitesse de propagation de la flamme en induisant un effet d'atténuation significatif. Cet effet augmente à mesure que le débit d'eau augmente. Le cas de 11%volH₂ représente un cas limite entre la flamme qui accélère et celles qui ne l'accélèrent pas. Quoi qu'il en soit, dans ce cas, l'injection par pulvérisation et l'évaporation des gouttelettes qui en résulte favorisent l'effet d'atténuation de l'explosion qui augmente à mesure que la quantité d'eau injectée augmente.

Chapter 6: Downward Flame Propagation Results

This chapter is dedicated to the downward condition flame propagation for hydrogen mixture of 10.50, 11, 13 %_{vol} H₂.

The propagation of the flame has been studied in a smooth tube conditions (BR=0) and in presence of annular obstacles (BR=0.63).

For each condition, the impact of the water flowrate on the position of the flame, the flame propagation speed and the evolution of the pressure, is presented

The experimental conditions and the repeatability of each presented result, it is showed in ANNEX2.

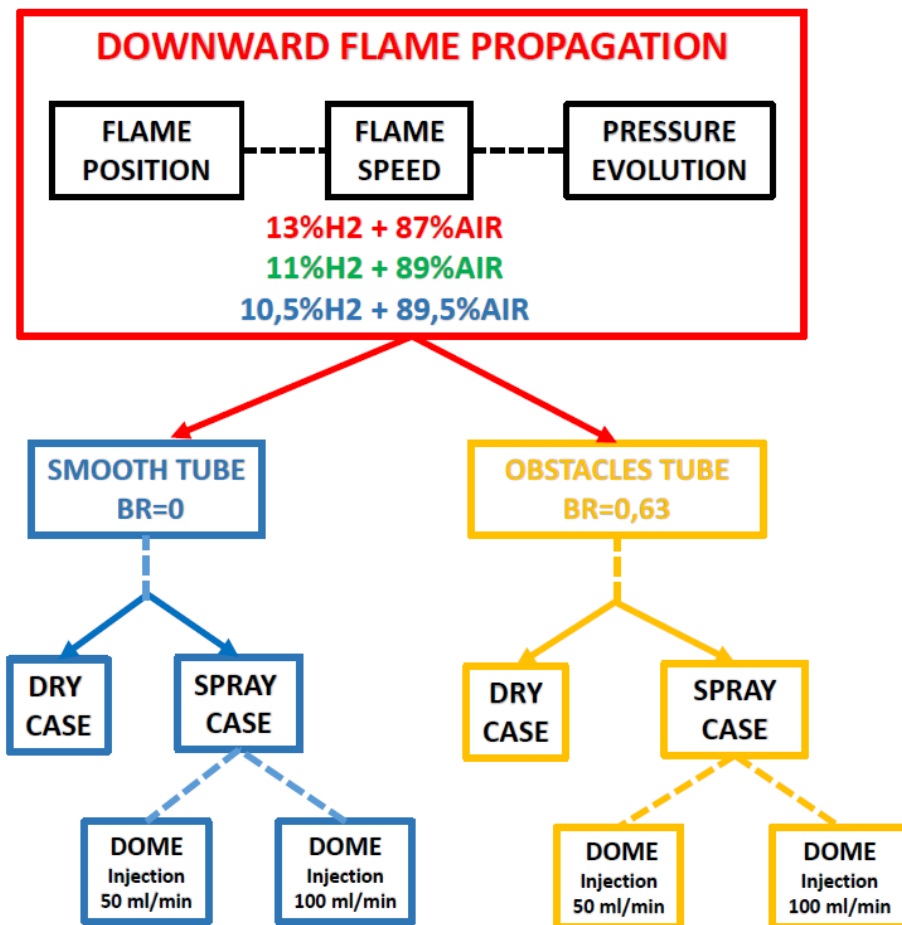


Figure 126: Chapter 6 Scheme

1 Dry Mixtures in smooth tube downward propagation

This paragraph shows the results concerning the propagation in downward condition without any spray injection.

The flame trajectory and the flame speed are evaluated by using 11 PMs signals, in the acceleration tube and 5 PMs signals in the dome. The trends are averaged on at least 4 tests for each conditions of initial hydrogen concentration.

Table 28, shows, for each initial hydrogen concentration: the number of repeated test, the averaged value, the related standard deviation of the $H_2\%_{vol}$ and the corresponding initial temperature.

$H_2\%_{vol}$	N. of repeated tests	Measured (μGC) H_2 tube	Measured (μGC) H_2 dome	T tube [K]	T dome [K]	P [bar]
13	9	12.95 $\pm$ 0.08	12.96 $\pm$ 0.07	293 $\pm$ 1.4	294 $\pm$ 2	1
11	5	10.87 $\pm$ 0.05	10.90 $\pm$ 0.06	295 $\pm$ 0.9	296 $\pm$ 2	1
10.5	4	10.45 $\pm$ 0.04	10.44 $\pm$ 0.05	296 $\pm$ 0.8	296 $\pm$ 2.1	1

Table 28: List of Experiments Downward Propagation Dry Mixtures – BR=0

The pressure sensor is placed in the bottom cap in order to read the pressure evolution until the end of the propagation (as showed in Figure 127).

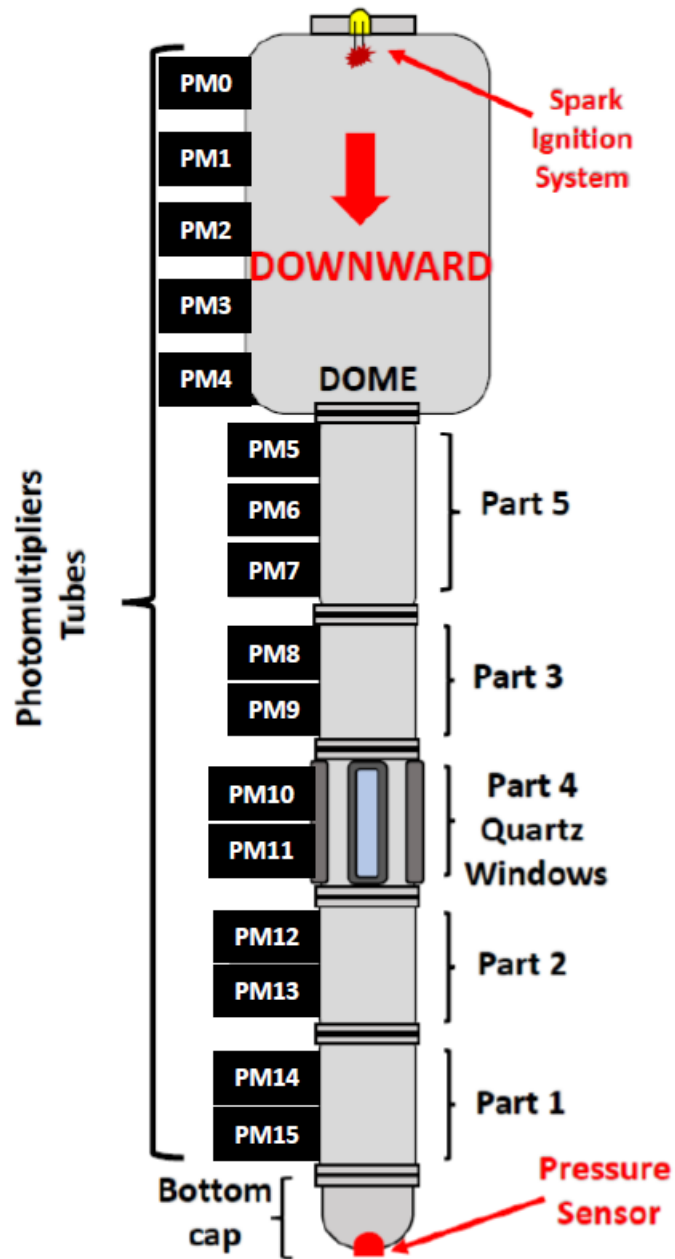


Figure 127: ENACCEF 1 equipped for the Downward Flame Propagation

1.1 Flame Position for dry mixtures in downward propagation

Figure 128 presents the flame trajectory versus time, for a downward propagation. On the right side of the graph is represented the ENACCEF 1 and the corresponding position of the photomultipliers. The y-axis is the position of the photomultipliers and the x-axis is the time.

For all the conditions, the mixture is ignited at $t=0$ s. From the early stages of the flame, it is possible to distinguish the impact of the initial hydrogen concentration.

In case of 13%_{vol}H₂, the red curve, the flame takes 0.34s to propagate from the ignition to the last PM of the dome (PM4). After the exit from the dome, the slope of the curve exhibits a slight increase due to the change of internal diameter between the dome (i.d.=750 mm) and the tube (i.d.=154 mm). At 2.55 m from the ignition point, the flame position shows a significant delay in terms of arrival time. The flame takes 1.84 s to reach the last photomultipliers at 4.62 m from the ignition points.

In case of 11%_{vol}H₂ in air (the green curve), the flame takes almost 0.27 s to reach the first PM. When the flame enters in the acceleration tube, the slope of the curve increase slightly until the PM7 at 2.30 m. After that point, there is a significant decrease of the slope which remain almost constant until the window section at 3.37 m (PM10 and PM11). The change of the internal volume, due to the presence of the access windows section (acceleration part block 4) increases slightly the slope of the flame position trajectory. On average, the flame takes almost 4.15s to reach the last PM at 4.62 from the ignition point.

The blue curve represents the flame position trajectory in case of 10.50%_{vol} H₂ in air. The first PM, detects the flame at 0.34 s and up to 2.30 m the flame position shows the same behaviour of the 11%_{vol}H₂ case but slightly delayed. It is possible to observe a slight increase of the slope, when the flame crosses the window section but especially in the last part of the tube, the flame position trajectory is more delayed (compared to the case of 11%_{vol}H₂). The flame takes 5.66 s to reach the last PM.

In case of downward propagation, for the same initial fuel concentration, the time needed to travel from the top to the bottom of the facility, is considerably longer compared to the case of the upward propagation without obstacles (Figure 82).

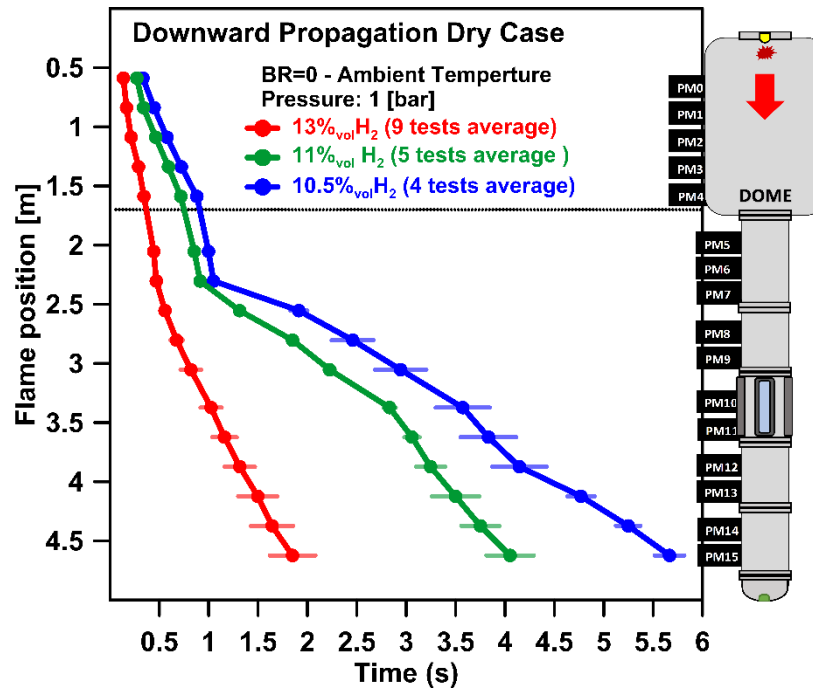


Figure 128: Flame Position Dry Mixtures - Downward Propagation – BR=0. . $t=0$ s :Spark Ignition; red: dry case at 13% H_2 + 87%Air; green: dry case at 11% H_2 + 89%Air; blue: dry case at 10.50% H_2 + 88.5%Air

1.2 Flame Propagation Speed for dry mixtures in downward propagation

Figure 83 shows the downward propagation speed in smooth tube conditions, for dry mixtures, as a function of the time.

In case of 13%_{vol}H₂ in air (the red curve), the speed in the dome decrease from an initial value of 6.92 m/s to 4 m/s. The entry in the acceleration tube causes an increases of the flame speed up to 5.79 m/s. For the rest of the flame propagation, the speed decreases until to reach a minimum of 1.40 m/s at 4.34 m from the ignition point.

In case of 11%_{vol}H₂, the flame speed decreases in the dome from 2.76 m/s to 1.94 m/s. The entry in the acceleration tube leads to an increase of the flame speed up to 4.06 m/s at 2.05 m but after this point, the speed decreases until the access windows section which increases slightly the speed. At the end of the acceleration tube, the flame speed is less than 1 m/s.

In case of 10.50%_{vol}H₂ (blue curve), the flame speed shows the same trend as the previous case but is slightly lower (apart at 2.05 m form the ignition point). In the dome, the initial flame speed is 2.06 m/s and it decreases until the entry in the acceleration tube which increases, the flame speed

up to 4.26 m/s at 2.05 m. After this point, the speed decreases until the end of the acceleration tube and it reaches a final value of 0.58 m/s.

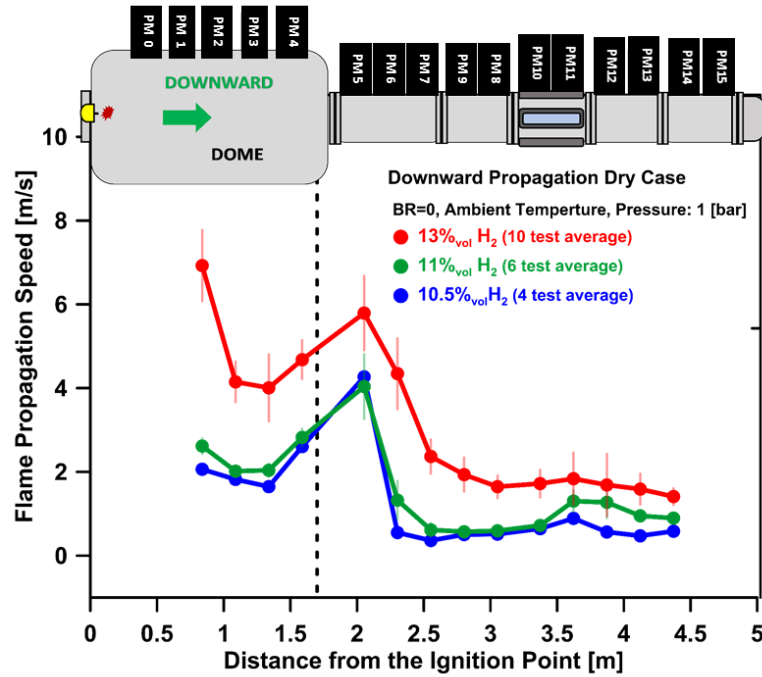


Figure 129: : Flame Speed Dry Case - Downward propagation - Smooth tube. . $t=0$ s :Spark Ignition; red: dry case at 13% H_2 + 87% Air ; green: dry case at 11% H_2 + 89% Air ; blue: dry case at 10.50% H_2 + 88.5% Air

By comparing the observed speed range in upward and downward propagation (Figure 130), it is possible to notice that the flame speed in downward propagation are not only considerably lower than the upward case but they have a smaller range of variation between maximum and minimum flame speed.

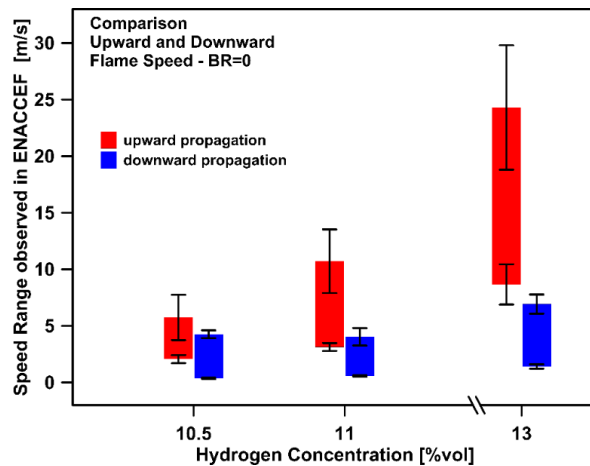


Figure 130: Comparison Speed Range for upward and downward propagation in Enaccef 1, BR=0.

1.3 Downward dry mixture Pressure Evolution in a smooth tube

Figure 131 shows the pressure evolution in case of dry mixtures in downward propagation without obstacles. The red curve represents the pressure evolution with an initial hydrogen content of 13%_{vol}H₂, the green curve at 11%_{vol}H₂ and the blue curve at 10.50%_{vol}H₂.

The dot lines are the P_{AICC} , calculated by using initial conditions of temperature, pressure and concentration for each tests. It is possible to notice that the measured P_{max} is considerably lower than P_{AICC} . Table 29 reports these values and the ration between them. The Table 30 reports the averaged time to reach the peak ($t=0$ spark ignition) and the dP/dt_{max} .

By comparing the results about the pressure evolution between upward (Table 18) and downward propagation; it is possible to notice that in downward propagation, the pressure evolution exhibits lower peaks of pressure and a significant delay compared to the upward propagation.

	P_{AICC} [bar]	P_{max} [bar]	ratio P_{max}/P_{AICC}
13%_{vol} H₂	5.12 ± 0.02	4.15 ± 0.07	81%
11%_{vol} H₂	4.55 ± 0.03	3.70 ± 0.05	81%
10.5%_{vol} H₂	4.41 ± 0.02	3.67 ± 0.02	83%

Table 29: Comparison between P_{max} and P_{AICC} -dry mixtures - Downward Propagation $BR=0$

	Time to P_{max} [s]	$(dP/dt)_{max}$ [bar/s]
13%_{vol}H₂	0.63 ± 0.03	8.26 ± 0.62
11%_{vol}H₂	0.92 ± 0.04	4.25 ± 0.16
10.5%_{vol}H₂	1.07 ± 0.03	3.66 ± 0.11

Table 30: Time to Peak and dP/dt_{max} dry mixtures downward smooth tube- $BR=0$.

At 13%_{vol}H₂ the pressure reaches a P_{max} of 4.15 bar which corresponds to the 80% of the P_{AICC} . Before to reach the peak, the slope of the curve exhibits a slight increasing which corresponds to the moment at which the flame enters in the acceleration tube (0.3 s). During the propagation in the acceleration tube, the pressure decreases almost linearly until 1.8 s where there is a slight increases of the pressure due to the arrival of the flame in the bottom cap (Figure 47).

At 11%_{vol}H₂ the pressure signal reaches a max at 0.86s of 3.80 bar and the corresponding P_{AICC} is 4.51 bar. Before to reaches the maximum the pressure evolution, there is an increasing of the

slope at 0.7s which corresponds to the time at which the flame enters in the acceleration tube. The flame takes almost 3 s from the ignition time to propagate until the end of the acceleration tube.

At 10.50%_{vol}H₂ the pressure reaches the maximum at 1.10 s of 3.64 bar and the corresponding P_{AICC} is 4.43 bar. Even in this case, the entry of the flame in the dome, leads to an increase of the pressure slope at 0.8 s. The flame reaches the end of the acceleration tube in almost 3.5 s and the pressure decreases almost linearly until the end of the tube.

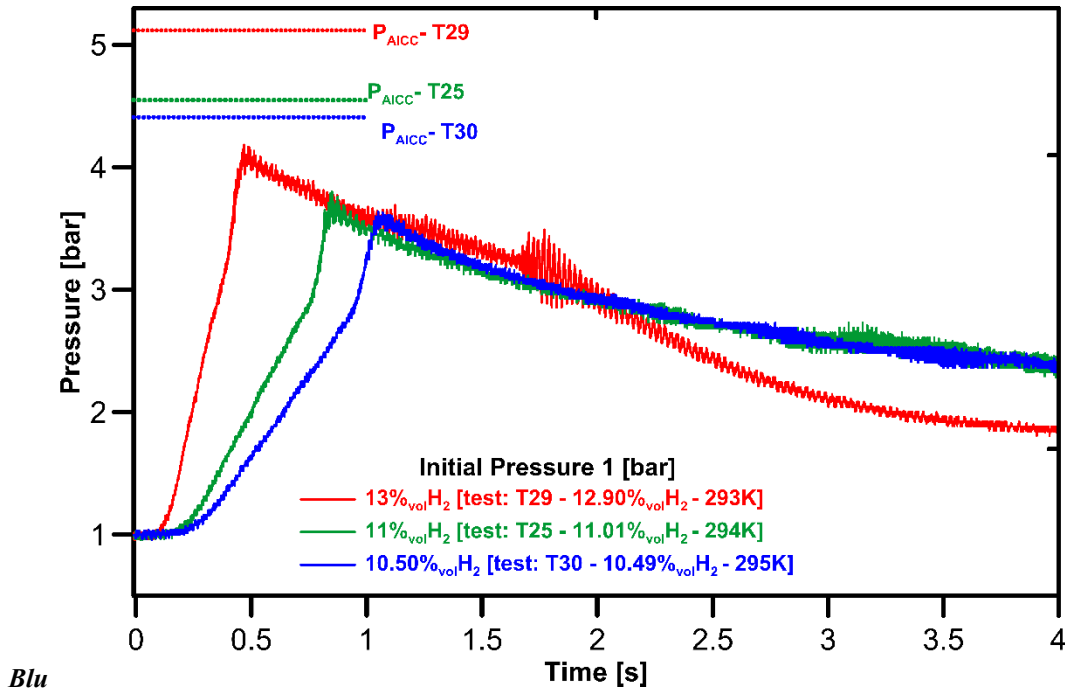


Figure 131: Pressure Evolution for dry mixtures in Downward Propagation without Obstacles

The Figure 132 compares the pressure evolution with the position of the flames during the propagation (PM4-PM15 and PM0) at 13%vol in upward and downward propagation. The violet zone corresponds to the time at which the flame is in the acceleration tube (10% of the entire volume) and the blue light zone is the time in which the flame propagates in the dome (90% of the entire volume). In upward propagation (the graph on the top), the pressure evolution remains almost constant in the acceleration tube and it starts to increase up the P_{max} in almost 0.3s from the ignition time. At this time the flame has reached the top of the dome and all the mixture is burned.

In downward propagation, when the flame propagates in the dome (from PM0 to PM4), the overpressure does not reach the expected P_{max}. The pressure continues to increase until to reach a maximum which is almost 10% less than the one reachable for the same fuel concentration in

upward propagation. The flame reaches the last PM15 after 1.6 s from the ignition time and the end of the combustion phenomena occur at 1.8 s.

The $P_{\max}$ is lower because the burned gases start to condensate before the end of the combustion when the flame is still propagating in the acceleration tube. The temperature decrease in the burned gases leads to a pressure decrease which affect the flame propagation.

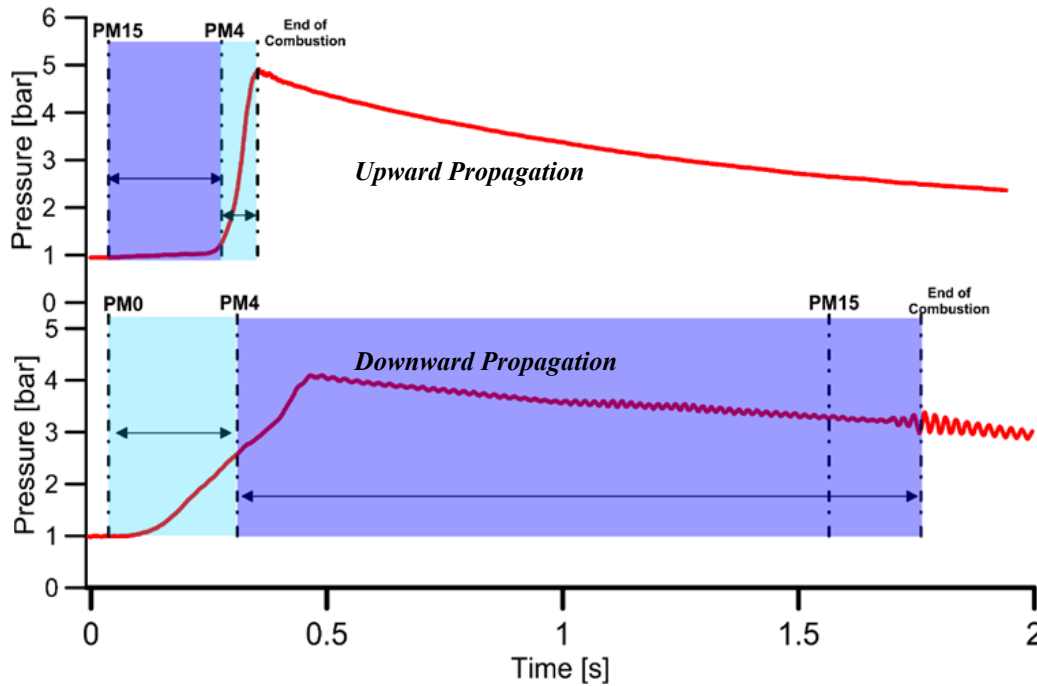


Figure 132: Comparison Propagation Time between upward and Downward Propagation BR=0

The Figure 133 reports the comparison of the K_G index between the upward and downward propagation. The red arrows represent the case of upward propagation and the red ones the downward propagation. It is possible to notice that the downward propagation explosion is less severe than the one observed in upward propagation. In downward propagation, the K_G is decreased by 1 order of magnitude.

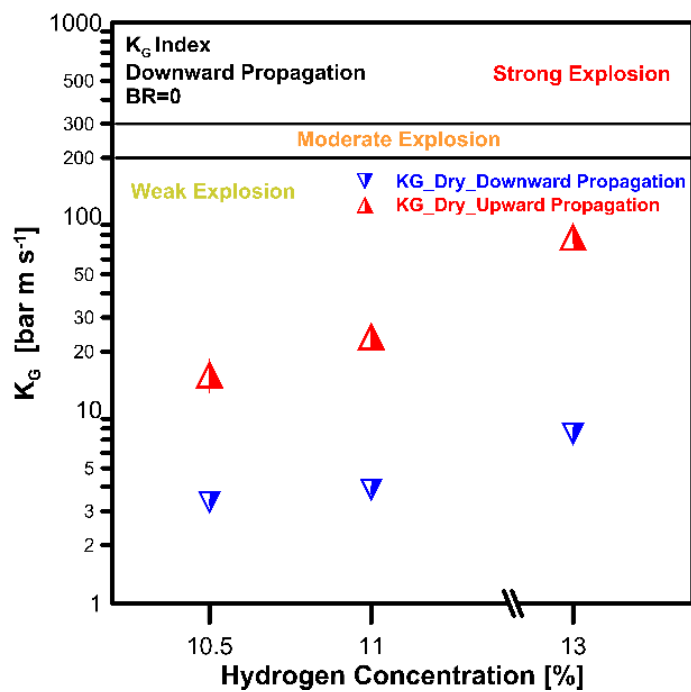


Figure 133: Comparison K_G index for Upward and Downward propagation for Dry mixture – $BR=0$

2 Spray Activation in smooth tube: downward flame propagation

This paragraph shows the results about the downward propagation in presence of water spray injection with a blockage ratio equal to 0.

Table 31 reports for each initial hydrogen concentration, the number of repeated test, the averaged value of $H_2\%_{vol}$, the related standard deviation and the corresponding initial temperature.

$H_2\%_{vol}$	N. of repeated tests	Measured (μGC) H_2 tube	H_2 dome	T tube [K]	T dome [K]
13% H_2 + 100 ml	4	12.89 ± 0.03	12.89 ± 0.05	299 ± 0.4	301 ± 1.1
11% H_2 + 100 ml	4	10.99 ± 0.08	11.05 ± 0.04	297 ± 0.9	298 ± 1.7
10.5% H_2 + 100 ml	3	10.53 ± 0.06	10.40 ± 0.15	297 ± 0.6	299 ± 0.8
	N of repeated tests	Measured (μGC) H_2 tube	H_2 dome	T tube [K]	T dome [K]
13% H_2 + 50 ml	3	13.06 ± 0.11	13.08 ± 0.11	299 ± 1.1	300 ± 1.1
11% H_2 + 50 ml	3	11.03 ± 0.11	11.03 ± 0.12	299 ± 1	299 ± 1.2
10.5% H_2 + 50 ml	3	10.45 ± 0.10	10.47 ± 0.08	300 ± 0.4	300 ± 1.4

Table 31: Experimental Conditions in downward Propagation BR=0: injection of 100 ml and 50 ml of liquid water in the dome.

2.1 Impact of the water flowrate on the Flame Position

Figure 134 shows the impact of the spray injection on the flame position in downward propagation without obstacles at 13% $_{vol}H_2$. The red curve is the averaged flame position trajectory at 13% $_{vol}H_2$ in dry air. The grey curve is the averaged flame position trajectory with an injection flowrate of 50 ml/min and the black curve is the one with an injection of 100 ml/min.

In case of a spray injection with a flowrate of 100 ml/min, it is possible to observe that the flame takes almost 0.67 s to reach the first PM at 0.58 m from the ignition point. The time is almost 50 % smaller than the dry case. The flame takes 0.14 s to propagate in the dome and 0.45 s to reach the end of the tube. In the first part of the acceleration tube is possible to observe a slight increase of the curve slope due to the passage from the dome to the tube. In the last part of the flame propagation, at 4.12 m from the ignition point, the position trajectory exhibits a decrease of the curve slope.

In case of 50 ml/min (grey curve), the flame position is slightly delayed compared to the previous case (the black curve) but the trends are similar. The arrival time on the first PM at 0.58 m from the ignition point is 0.077s and the flame takes almost 0.17 s to exit from the dome part. Due to the internal volume change, between the dome and tube, even in this case, there is an increase of the curve slope. The flame takes 0.61s to reach the last photomultiplier placed at 4.62 m from the ignition point.

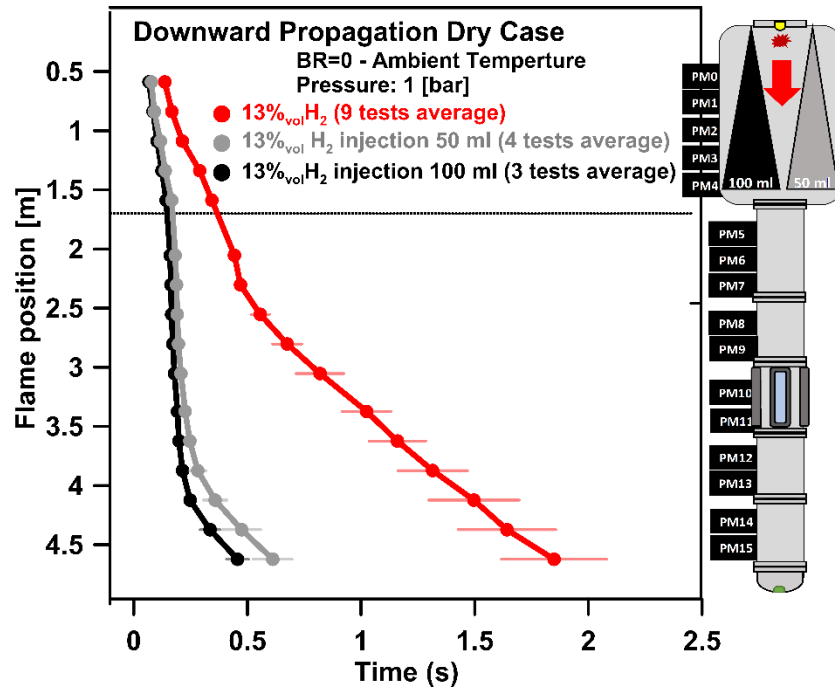


Figure 134: Impact of the water flow rate on 13%_{vol} H₂ on the Flame Position – Downward Propagation – BR=0. t=0 s : Spark Ignition; red: dry case at 13%_{vol} H₂ + 87%_{vol} Air; grey : spray injection 100 ml only in the dome; black: spray injection 100ml only in the dome.

Figure 135 shows the impact of the flowrate in case of 11%_{vol} H₂ on the flame position in downward propagation without obstacles. The green curve is the dry case at 11%, the black curve is the flame position trajectory with a spray injection of 100 ml/min and the grey curve is the one with a spray injection of 50 ml/min. Both the spray injection lead to an acceleration of the flame in the facility.

When the water spray is injected with a flowrate of 100 ml/min, the flame reaches the first PM (at 0.58 m from the ignition point) in 0.11s instead of 0.27 s of the dry case. The curve slope increases at the exit of the dome up to PM11 (at 3.62 from the ignition point). The arrival flame time of the last four PMs exhibit a changing in the slope which introduces a delay in the flame position trajectory. The flame takes 1.44 s to reach the last PM15.

The case of 50 ml/min of spray flowrate, does not differ significantly from the previous case in terms of behaviour. The flame reaches the first PM in 0.12 s and it propagates in the dome in almost 0.26 s. The flame trajectory, in the first part of the acceleration tube, is slightly accelerated compared to the flame position trajectory in the dome. In the last part of the acceleration tube, there is a delay and the flame takes 1.63 s to reach the last PM at 4.62 m from the ignition point.

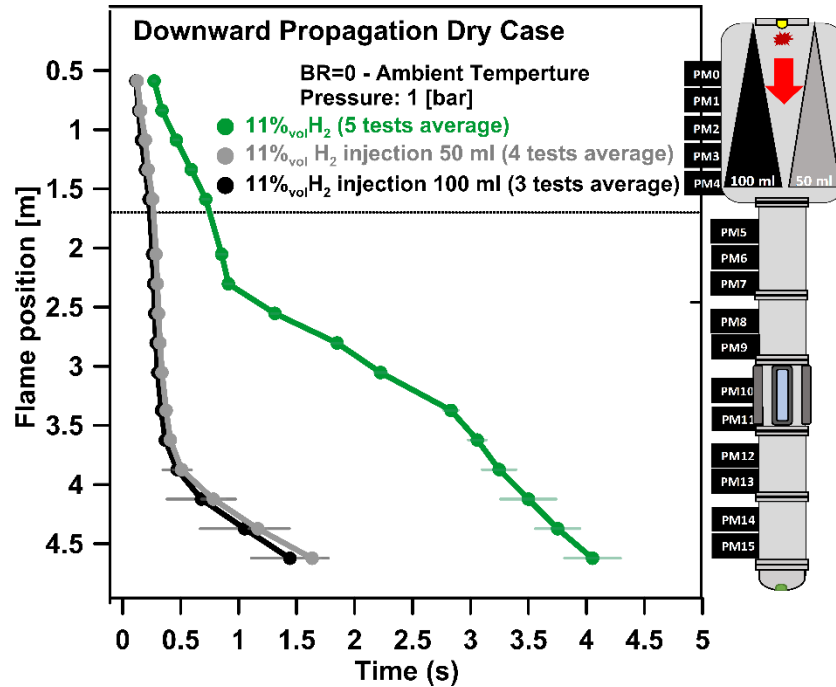


Figure 135: Impact of the water flow rate on 11%_{vol} H₂ on the Flame Position – Downward Propagation – BR=0.
t=0 s : Spark Ignition; green: dry case at 11%_{vol} H₂ + 89%_{vol} Air; grey :spray injection 100 ml only in the dome; black: spray injection 100ml only in the dome.

Figure 136 shows the impact of the water flowrate on the flame position at 10.50%_{vol} H₂ in downward propagation without obstacles. The black curve is the averaged flame position trajectory in case of an injection of 100 ml/min. The flame reaches the first PM in 0.13 s instead of 0.33 s of the dry case. The curve slope increases slightly at the entry of the acceleration tube and the arrival flame time exhibits a significant delay in the last part of the tube. At 3.62 m from the ignition point, (PM12), the slope of the curve changes and the flame arrives on the last PM after 1.62 s from the ignition time which is almost 3 times faster than the dry case.

The injection with a flowrate of 50 ml/min does not differ, in terms of trend from the injection of 100 ml/min but the flame trajectory is slightly more delayed. The flame reaches the first PM in

0.14 s and it takes 2.17 s to reaches the last PM which is almost half of the needed time in the dry case.

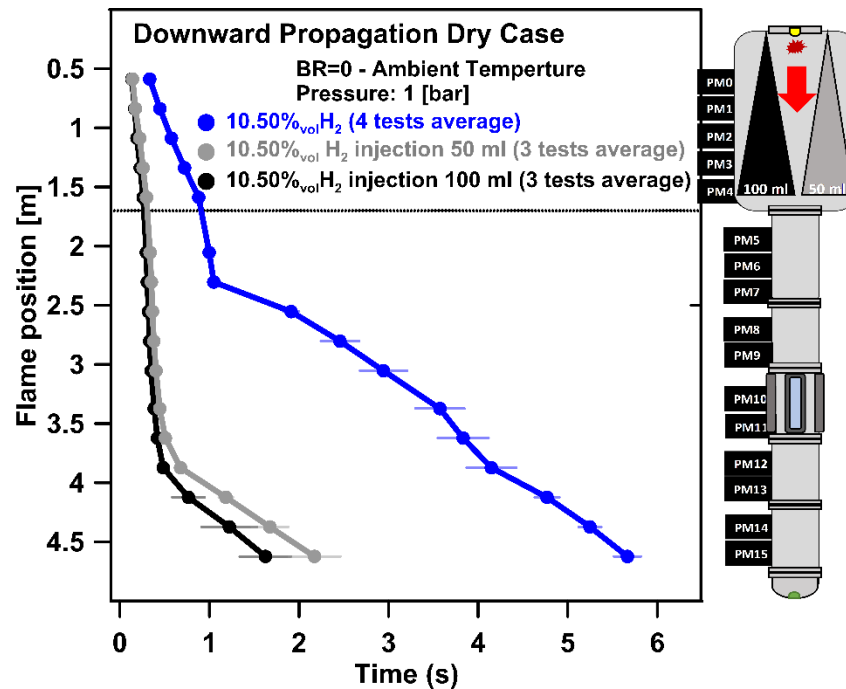


Figure 136: Impact of the water flow rate on 10.50%_{vol} H₂ on the Flame Position Wet Mixtures – Downward Propagation – BR=0. t=0 s : Spark Ignition; blue: dry case at 10.5% H₂ + 89.5% Air; grey : spray injection 100 ml only in the dome; black: spray injection 100ml only in the dome.

2.2 Impact of the water flowrate on the downward Flame Propagation Speed

This paragraph shows the results about the impact of the water flowrate on the flame speed in downward propagation without obstacles. In each graph, the black line and the grey line, represent the flams speed in case of an injection of 100 ml/min and 50 ml/min.

Figure 137 shows the impact on the flame speed in case of 13%_{vol} H₂. It is possible to notice that in both the cases the spray injection increases strongly the flame speed, especially at the entry of the acceleration tube, in which the speed can be also 1 order of magnitude higher than the dry case.

The injection with a flowrate of 100 ml/min leads to an initial velocity of 14 m/s which is the double of the case without spray injection. The flame speed decreases slightly in the dome and it starts to accelerate at PM4 (1.58 form the ignition point). The presence of the spray and the internal volume change (from the dome to the tube), increases the flame speed which reaches an averaged value of 83 m/s at 2.30 m. After this point, the speed decreases until the PM11 in correspondence

of the access observation window block where there is a slight increases of the flame speed. In the last part of the acceleration tube, the flame speed decreases until to reach a final value of 2 m/s, comparable with the one reached in the dry case (1.40 m/s).

The injection of 50 ml/min of spray (grey line) increases the flame speed, compared to the dry case but the impact on the flame acceleration is slightly less marked than the 100 ml/min injection. Initially the flame speed is almost 12 m/s and it decreases until the last PM of the dome. When the flame enters in the acceleration tube, it starts to accelerate up to 61 m/s at 2.55 m. The last part of the acceleration tube is characterized by a decrease of the flame speed which reaches a final value of 2 m/s.

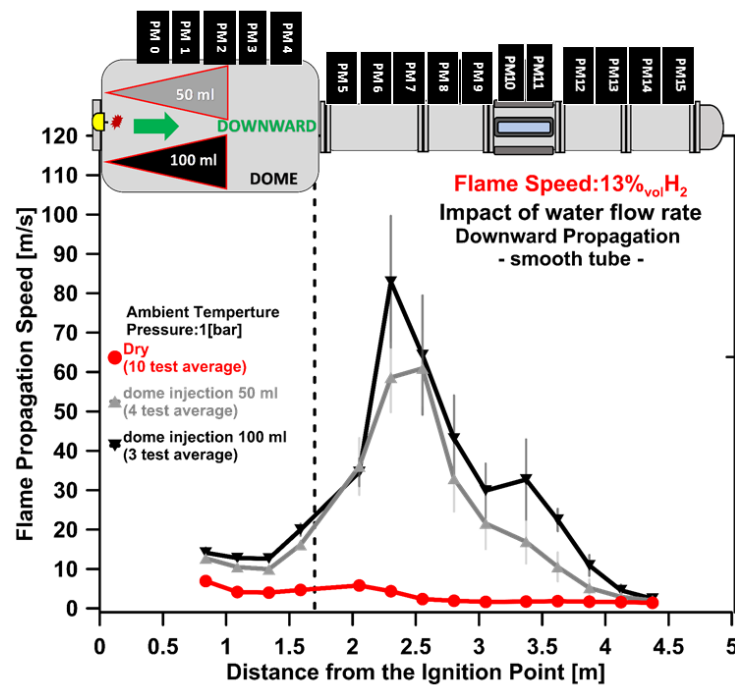


Figure 137: Impact of the water flow rate on 13%_{vol} H₂ on the Flame Speed in Downward Propagation – BR=0. t=0 s : Spark Ignition; red: dry case at 13%_{vol}H₂ + 87%_{vol}Air; grey :spray injection 100 ml only in the dome; black: spray injection 100ml only in the dome.

Figure 138 shows the impact of the water flowrate in case of an initial hydrogen concentration of 11%_{vol}H₂. The injection of 100 ml/min of water leads to an increase of the initial flame speed which is of 11 m/s instead of 2.6 m/s (in absence of spray injection). The flame speed decreases slightly until the PM3 (at 1.33 m from the ignition point) and then it starts to accelerate up to 27 m/s at 2.30 m. At the end of the acceleration tube, the speed reaches an averaged value of 2.45 m/s which is at least 2 times higher than the dry case (0.89 m/s).

The injection of the spray with a smaller flowrate (grey line), increases also the flame speed but in general the velocities are lower than the one with an injection of 100 ml/s. The initial flame speed is 7 m/s instead of 2.6 m/s of the dry case. The flame speed decreases slightly in the first part of the dome and it accelerates at the entry of the acceleration tube. The maximum speed is maximum 24 m/s at 2.3 m from the ignition point. Then the speed decelerates and it reaches a minimum value at the end of the acceleration tube of 0.6 m/s which is comparable with the case of without spray injection.

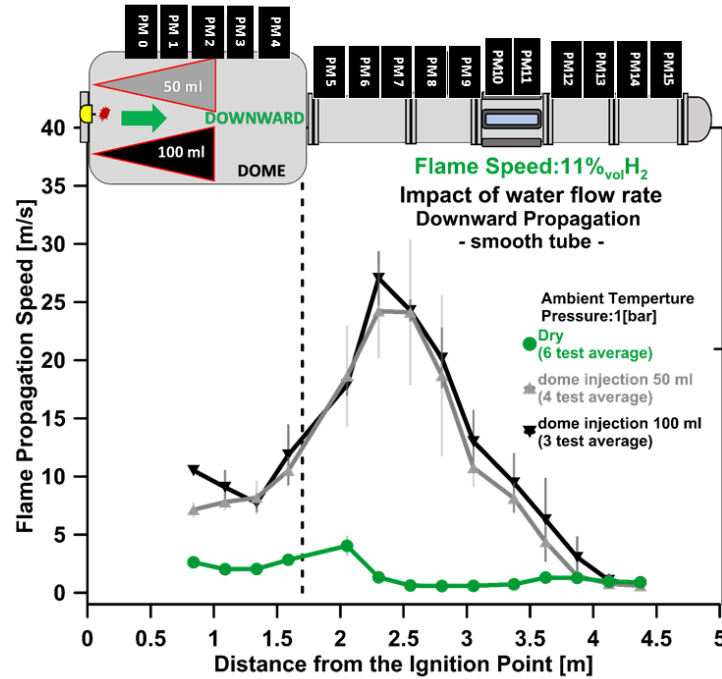


Figure 138: : Impact of the water flow rate on 11%vol H₂ on the Flame Speed in Downward Propagation – BR=0. t=0 s : Spark Ignition; green: dry case at 11%_{vol}H₂ + 89%_{vol}Air; grey :spray injection 100 ml only in the dome; black: spray injection 100ml only in the dome.

Figure 139 shows the impact of the water flow rate on the flame propagation speed in case of an initial hydrogen content of 10.50 %_{vol}. The spray injection increases the flame speed especially in the first part of the acceleration tube.

In case of 100 ml/min of injected spray flowrate, the initial flame propagation speed is 10 m/s which is 5 times higher than the dry case. The flame decelerates slightly in the dome and then accelerate at the entry of the acceleration tube until to reach a maximum of 18 m/s at 2.30 m (4 times higher than the dry case). The flame speed decreases until the end of the acceleration tube with a final speed value of 0.52 m/s.

The flame speed, in case of 50 ml/min (grey line) is slightly lower than the one observed with 100 ml/min of spray flowrate (black curve). The initial flame speed is 8 m/s which is 4 times higher than the dry case. The maximum flame speed is of 20 m/s at 2.3 m from the ignition point. After this point the flame speed decreases up 0.60 m/s comparable with the dry case.

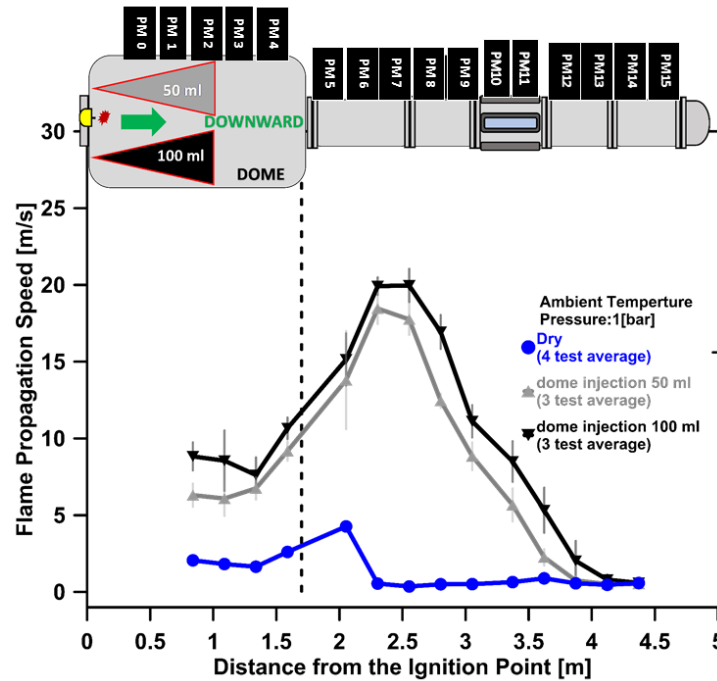


Figure 139: Impact of the water flow rate on 10.50%vol H_2 on the Flame Speed in Downward Propagation – $BR=0$. . $t=0$ s : Spark Ignition; blue: dry case at 10.5% H_2 + 89.5%Air; grey :spray injection 100 ml only in the dome; black: spray injection 100ml only in the dome.

2.3 Impact of the water flowrate on Pressure Evolution downward propagation

This paragraph reports the impact of the water flowrate on the pressure evolution in downward propagation without obstacles.

Figure 140 shows the impact of the spray flowrate on the pressure evolution. The 3 curve are representative of the dry case at 13%_{vol}H₂ in dry conditions (red curve), with 100 ml/min of water spray injection (black curve) and with 50 ml/min of spray injection (grey curve). The dot lines are the corresponding adiabatic isochoric complete combustion pressures, calculated by using the initial condition for each tests in terms of concentration and temperature.

The spray injection with a flowrate of 100 ml/min, increases the $P_{\max}$ from 4.15 bar (of the dry case) to 4.85 bar (+16%) which is 97% of the corresponding P_{AICC} . The time to reach the peak is reduced and it is in averaged 0.28 s (instead of 0.63 s without spray). The curve exhibits a slight increase of the pressure around 0.6 s when the flame reaches the end of the acceleration tube where the pressure sensor is located. The time to reach the $P_{\max}$ is shorter than the needed time to propagate. In this case is not possible neglect the condensation of the burned gases. Anyway in this case, the condensation of the burned gases, does not affect the pressure evolution because when it occurs, the flame has already burned the mixture in the dome (90 % of the entire volume). The slope of the curve, the $dP/dt_{\max}$ increase also significantly from 8 bar/m s (dry case) to 28 bar/m s so there is an increase of the explosion severity.

The injection of 50 ml of water increases the $P_{\max}$, the $dp/dt_{\max}$ and it reduces the time to reach the peak. The enhancing effect on the flame propagation is less marked compared to the case of 100 ml of injection. The averaged $P_{\max}$ is 4.74 bar which is the 97% of the corresponding P_{AICC} . The time to reach the peak is in average slightly delayed compared to the case with 100 ml of injected water but it is still considerably smaller than the dry case. The rise of the pressure, result to be increased and it is almost 28 bar /s.

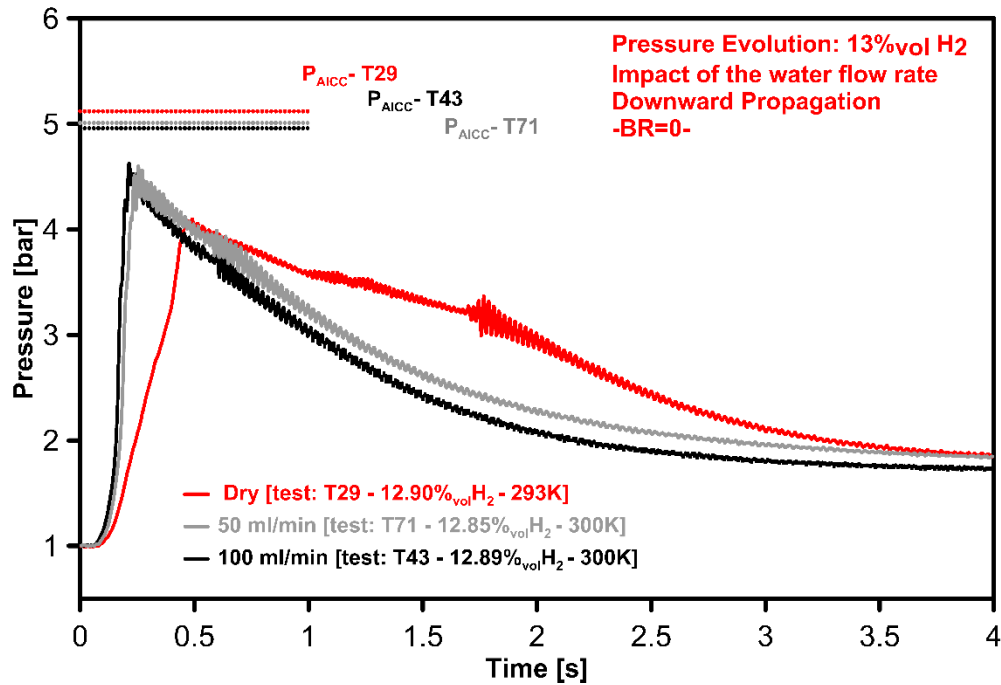


Figure 140: Pressure Evolution at 13%volH2- Impact of the water flowrate-Downward - BR=0

Figure 141 shows the impact of the water flowrate on the pressure evolution at 11%volH₂ in downward propagation without obstacles.

The black curve represents the pressure evolution in case of 100 ml/min of water spray injection. The time to reach the peak is reduced by the 50% compared to the dry case (0.43 s).

$P_{\max}$ is 4.13 bar and it is on average 9% less than the corresponding P_{AICC} . The slope of the curve is significantly increased from 4 (dry case) to 17 bar/ s.

By injecting the water spray with a flowrate of 50 ml/min, the impact on the pressure evolution is very close to the previous case (100 ml/min) but the enhancing effect on the explosion is slightly less marked. $P_{\max}$ is on averaged 4.13 bar, the time to reach the peak is 0.47 s (almost 50% shorter than the dry case) and the $Dp/dt_{\max}$ is 15 bar/m s (3 times the one in dry case).

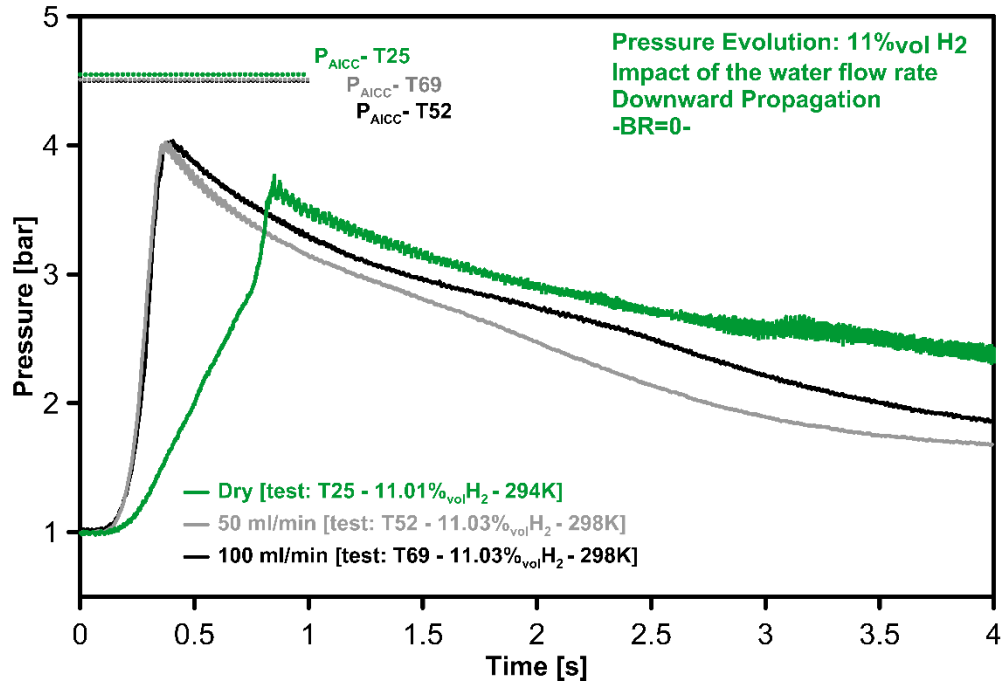


Figure 141: : Pressure Evolution at 11%volH₂- Impact of the water flowrate-Downward - BR=0

Figure 142 shows the impact of the water flowrate on the pressure evolution in downward propagation at 10.50%volH₂. The injection of 100 ml of water spray (the black curve), increases the severity of the explosion compared to the dry case. The $P_{\max}$ increases, compared to the dry case, from 3.65 bar to 4 bar which is 91% of the corresponding P_{AICC} . The pressure reaches the maximum peak in 0.50 s (instead of 1.07 s of the dry case) and the $dP/dt_{\max}$ results to be increased to 15 bar/s which is 3 times higher than of the dry case.

The injection with a flowrate of 50 ml/min increases the severity of the explosion by increasing the $P_{\max}$, the $dP/dt_{\max}$ and by reducing the needed time to reach the peak. The impact on the pressure evolution is anyway slightly less marked compared to the case of 100 ml of water spray injection. The averaged $P_{\max}$ is 3.98 bar which is 8% less than the corresponding P_{AICC} . The time to peak is 50% shorter than the dry case. The $dP/dt_{\max}$ increases form 3.68 bar/s to 14.13 bar/m s.

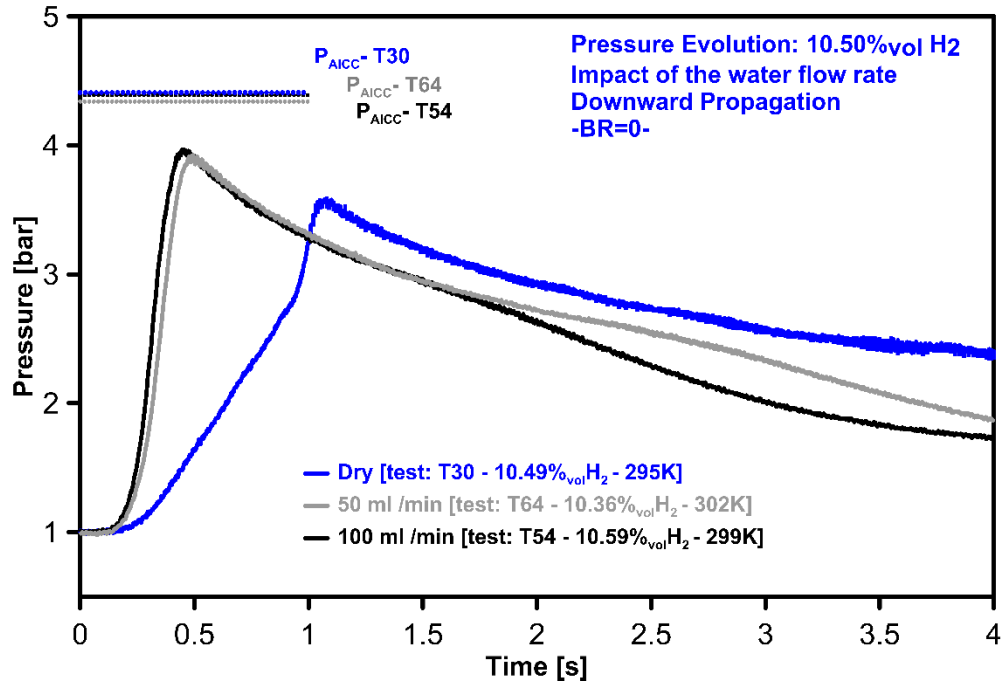


Figure 142: Pressure Evolution at 10.50%vol H₂- Impact of the water flowrate-Downward - BR=0

Figure 143 summarizes the impact of the water flow injection on the explosion parameters. The results, in term of $P_{\max}$, time to reach $P_{\max}$ and the $dp/dt_{\max}$, show that the spray injection enhances the severity of the explosion in downward propagation.

The results for both flowrates are very close but the impact is slightly stronger as the flowrate injection increases. The spray injection leads to:

- an increase of the $P_{\max}$
- a reduction of the combustion time
- an increase of the $dp/dt_{\max}$;

The K_G index versus the initial hydrogen concentration, show that the severity of the explosion is increased of 1 order of magnitude but it remains in the domain of the weak explosions.

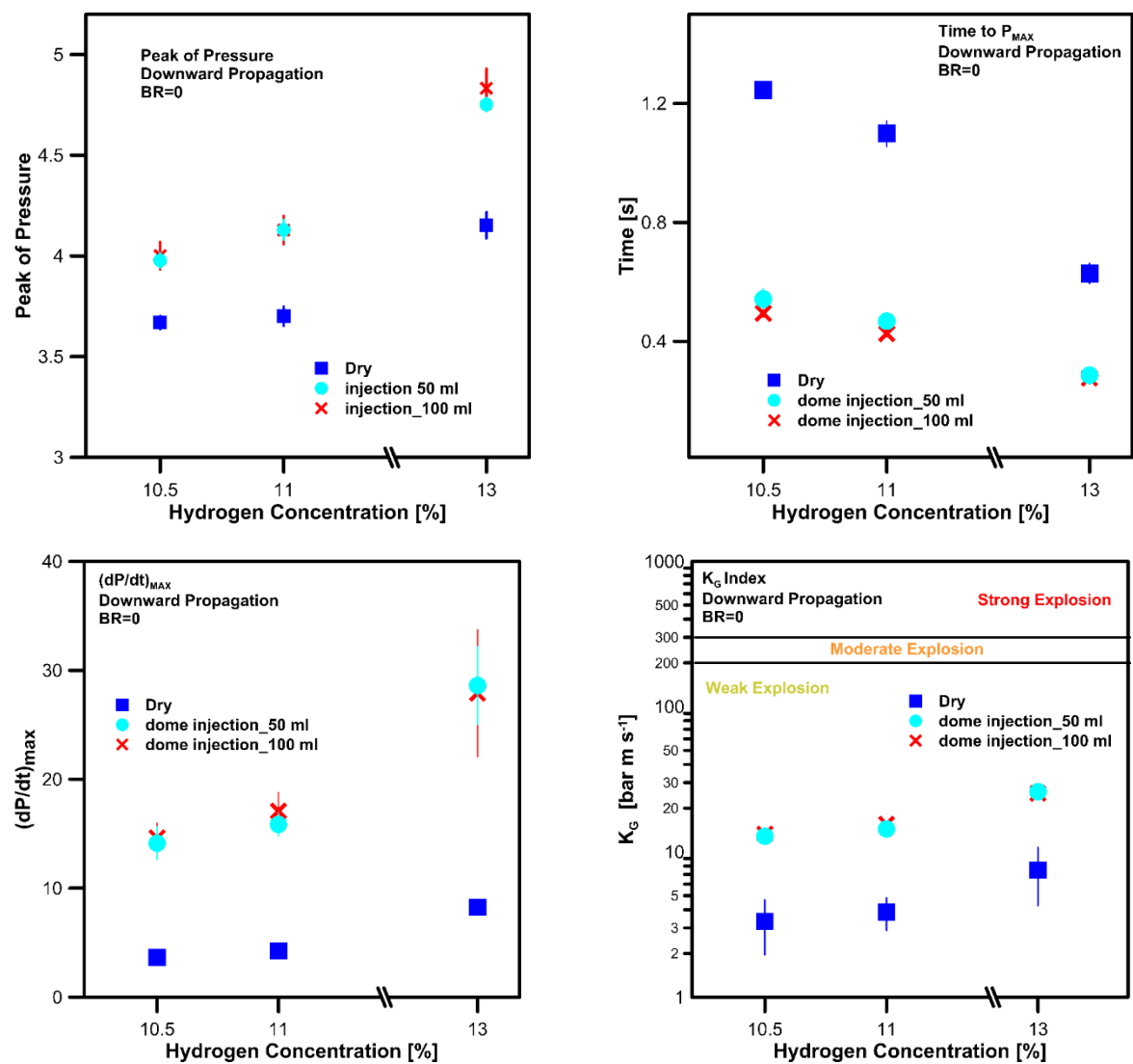


Figure 143: Explosion Parameter summary-Downward Propagation-BR=0

3 Conclusions on the Downward Propagation in smooth tube conditions

The results on downward flame propagation show a profound difference from the upward flame propagation.

By considering the case without spray water injection, it can be observed that the deflagration phenomenon is strongly influenced by the buoyancy effects which act as flame propagation inhibitors. The geometric configuration of the experimental apparatus and the low velocities of the flame, lead to a slower combustion time that is in competition with the condensation time of the burned gases. The flame propagation results are influenced by the condensation of the burned gases which inhibits the pressure increase during the combustion phenomenon. The resulting $P_{\max}$ is significantly lower than the one achievable in adiabatic conditions. The severity of the explosion is significantly lower than the one corresponding to the dry case in upward propagation.

The activation of the spray introduces turbulence in the fresh gases both because of the moment transferred (bulk effect) and because of the evaporation of the drops (into the flame front and/or upstream of it). The flame speed in the acceleration tube increases sharply compared to the dry case as well as the severity of the explosion. The results of the flame velocities show a greater promoting effect as the water spray flow rate increases. However, due to the presence of the condensation effect, the explosion parameters do not clearly confirm a dependence on the amount of water injected.

The downward propagation, in smooth tube conditions, highlights the importance of the propagation direction on the study of this phenomenon and it shows an example of a clear worsening of the severity of the explosion induced by the activation of the spray.

4 Dry Conditions in obstructed tube for downward propagation

This paragraph shows the results about the downward flame propagation in presence of obstacles without the water spray injection (dry air mixtures). The flame position and the flame speed are evaluated by using 11 PMs signals, in the acceleration tube and 5 PMs signals in the dome. The pressure sensor is placed in the bottom cap in order to follow the pressure evolution until the end of the propagation (as showed in Figure 144).

The trends are averaged on at least 4 tests for each conditions of initial hydrogen concentration. The obstacles are placed in the bottom part of the acceleration tube in the same configuration and position used for the upward propagation.

Table 32 shows for each initial hydrogen concentration: the number of repeated tests, the averaged values, the related standard deviation of the $H_2\%_{vol}$ and the corresponding initial temperature.

$H_2\%_{vol}$	N° of repeated tests	Measured (μGC) H_2 tube	Measured (μGC) H_2 dome	T tube [K]	T dome [K]	P [bar]
13	4	12.92 ± 0.05	12.96 ± 0.06	299 ± 0.54	300 ± 0.84	1
11	3	10.85 ± 0.04	10.85 ± 0.05	300 ± 0.70	302 ± 1.77	1
10.5	3	10.40 ± 0.10	10.40 ± 0.10	299 ± 1	301 ± 0.70	1

Table 32: List of Experiments Downward Propagation Dry Mixtures – BR=0.63

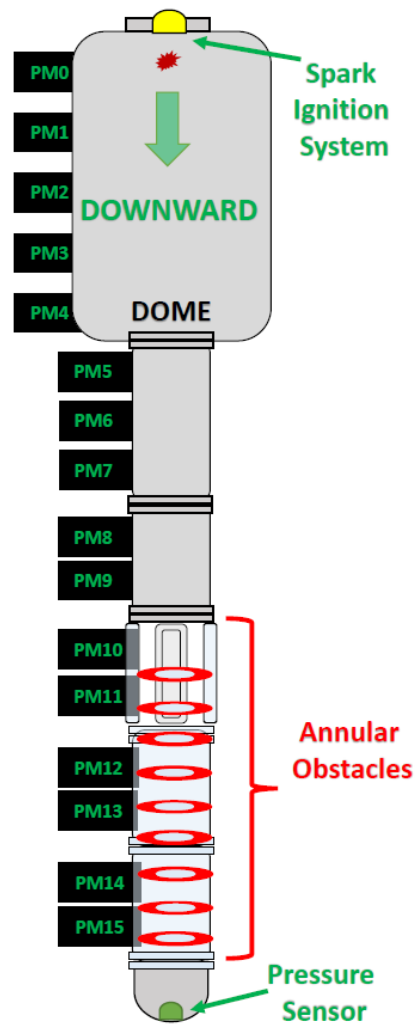


Figure 144: ENACCEF 1 equipped for Downward Flame Propagation $BR=0.63$. 9 obstacles equally placed by 0.154 m. First obstacle at 0.160 m from the ignition point. Last Obstacle at 1.438 m from the ignition point

4.1 Downward Flame Position in presence of obstacles for dry mixture

This paragraph reports the results about the flame trajectory in downward propagation in presence of obstacles (BR=0.63) for dry mixtures.

Figure 145 shows the impact of the initial hydrogen concentration on the flame position trajectory. The obstacles are placed at 3.45 m from the ignition point by using the same configuration used for the upward propagation.

In case of 13%_{vol}H₂, the averaged flame position is represented with the red curve. The flame reaches the first PM at 0.14 s and it takes almost 0.20 s to propagate in the dome. At the entry of the acceleration tube, the curve slope increases slightly but the presence of the obstacles does not affect the flame position trajectory. The flame takes 1.42 s to reach the last PM.

The green curve is the averaged flame position trajectory in case of 11%_{vol}H₂. The first PM, at 0.58 m from the spark ignition system, detects the flame after 0.27 s from the ignition time. The flame takes 0.72 s to propagate up to the last PM of the dome (PM4 at 1.58 m). and after this point, the curve slope is slightly increased by the internal volume change from the dome to the tube. The last PM is reached by the flame 3.4 s after the ignition and the presence of the obstacles does not increase significantly the slope of the trajectory curve.

The case of 10.50%_{vol}H₂ is represented by the blue curve. The flame is detected by the first PM at 0.35 s and it takes 0.92 s to propagate in the dome. The curve slope increases slightly at 2 m from the ignition position. After 2.3 m, the flame position trajectory exhibits an almost linear shape and the flame takes 4.33 s to propagate up to the last PM15 at 4.62 m from the ignition point.

The result shows that the presence of the obstacles does not induce a change in the flame position trajectory, in terms of curve slope and needed time to propagate. The results are comparable with the ones without obstacles (Figure 129).

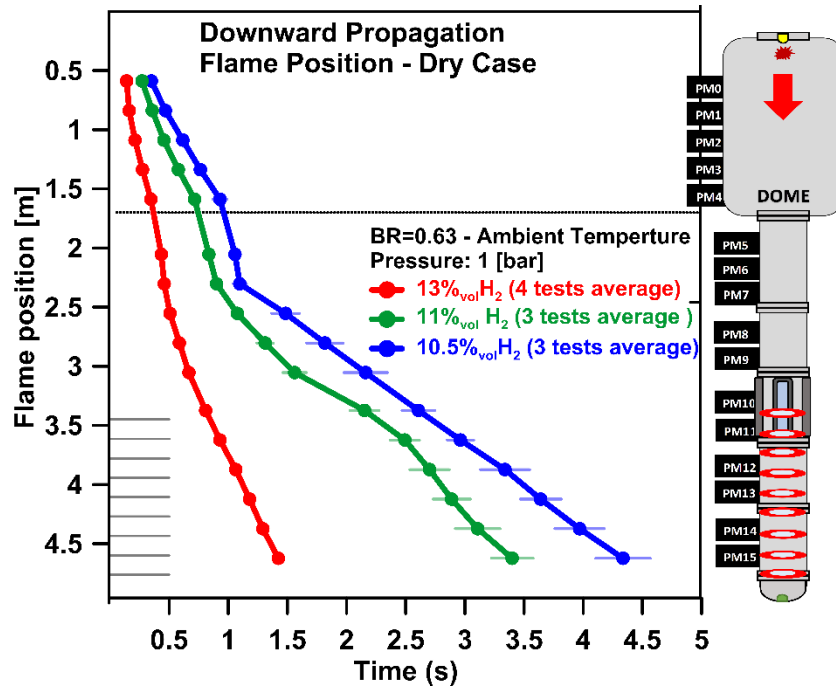


Figure 145: Flame Position Dry Mixtures - Downward Propagation – BR=0.63. $t=0$ s :Spark Ignition; red: dry case at 13% H_2 + 87%Air; green: dry case at 11% H_2 + 89%Air; blue: dry case at 10.50% H_2 + 88.5%Air.

4.2 Downward Flame Propagation Speed in presence of obstacles for dry mixture

This paragraph is dedicated to the downward propagation flame speed for the dry mixtures with a blockage ration of 0.63.

Figure 146 shows the impact of the initial hydrogen content on the flame speed over the distance from the ignition. On the X-axis is reported the distance from the ignition point and the position of the annular ring obstacles.

The red curve is the averaged flame speed in case of 13%_{vol}H₂ in dry air. The initial speed is around 7 m/s and it decreases during the propagation in the dome up to 3.7 m/s at 1.08 m from the ignition point. At the exit of the dome, the speed starts to increase and it reaches values in average close to the initial one (6.7 m/s) at 2.3 m from the ignition point. The velocity of the flame decreases to the end of the tube and it does not show a significant interaction with the obstacles. The final speed value is around 2 m/s.

The green curve is the averaged flame speed in case of initial concentration of 11%_{vol}H₂. The initial flame speed is of 2.6 m/s and it decelerates in the dome up to 1.9 m/s at 1.08 m from the spark ignition point. The flame speed accelerates when entering the acceleration tube and it reaches a maximum of 4 m/s value (at 2.05 m). After 2.05 m, the flame decelerates until the end of the acceleration tube where it reaches a final value of almost 1 m/s.

The blue curve represents the averaged speed in case of 10.50%_{vol}H₂ in presence of obstacles. The initial speed, at 0.58 m from the ignition point, is 1.9 m/s at it decreases slightly during the propagation in the dome up to PM3 at 1.33m. The velocity increases and it reaches the maximum of 4.3 m/s at PM6 at 2.05 m from the ignition point. Between 2.05 m and 2.55 m, the propagation speed decreases and it remains almost constant until the end of the acceleration tube where the last speed value is around 0.7 m/s.

The presence of the obstacles does not introduce a significant increase of the flame speed in fact the results about the flame speed propagation with and without obstacles do not exhibit a significant difference.

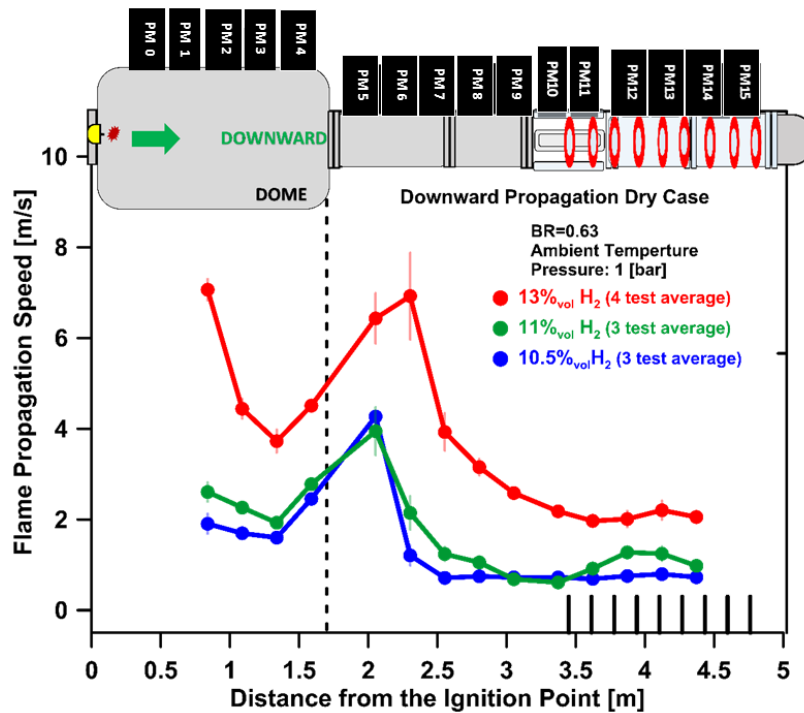


Figure 146: Flame Speed Dry Case - Downward propagation - tube with obstacles. $t=0$ s :Spark Ignition; red: dry case at 13%_{vol}H₂ + 87%_{vol}Air; green: dry case at 11%_{vol}H₂ + 89%_{vol}Air; blue: dry case at 10.50%_{vol}H₂ + 88.5%_{vol}Air.

4.3 Downward dry mixture Pressure Evolution in presence of obstacles

Figure 147 shows the impact of the initial hydrogen concentration on the pressure evolution in presence of a blockage ration equal to 0.63. The dot line curves represent the P_{AICC} calculated using the initial condition of each experiments in terms of composition and temperature.

At 13%_{vol}H₂ (the red curve) the P_{max} is 4.12 bar in 0.5 s which is the 80% of the corresponding P_{AICC} .

By considering the needed time to propagate, in this case test T96, the flame reaches the last photomultiplier of the acceleration tube in 1.40 s and P_{max} occurs at 0.50 s. So P_{max} does not occurs when all the available mixture is burned but it occurs after the exit from the dome. When the flame enters in the acceleration tube, the condensation of the burned gases plays a mitigation role in terms pressure evolution. When the flame reaches the pressure sensor at the end of the acceleration tube, the pressure evolution exhibits a small peak at 1.50s from the ignition time. The pressure signal is comparable with the case without obstacles.

By decreasing the hydrogen concentration to 11%_{vol} (green curve), P_{max} is on average equal to 4.47 bar on average and it corresponds to the 82% of the related P_{AICC} . The difference between P_{max} and the P_{AICC} is also due to the condensation of the burned gases. Before reaching the peak, at 0.87 s the pressure profile (test T86) exhibits a slight increase in the dP/dt due to the passage from the dome to the acceleration tube. The pressure evolution is not different from the case without obstacles in terms of maximum peak, time to reach the peak and slope of the curve.

In case of 10.50%_{vol} H₂, the blue curve represents the pressure evolution in presence of obstacles. P_{max} is 3.63 bar on average which corresponds to 83% of the P_{AICC} (4.37 bar). The pressure exhibits an increase before reaching the peak at almost 1 s form the ignition time. This increase corresponds, for the example showed (test T82), to the time at which the flame enter in the acceleration tube. Even in this case, the flame propagation is decelerated by the burned gas condensation.

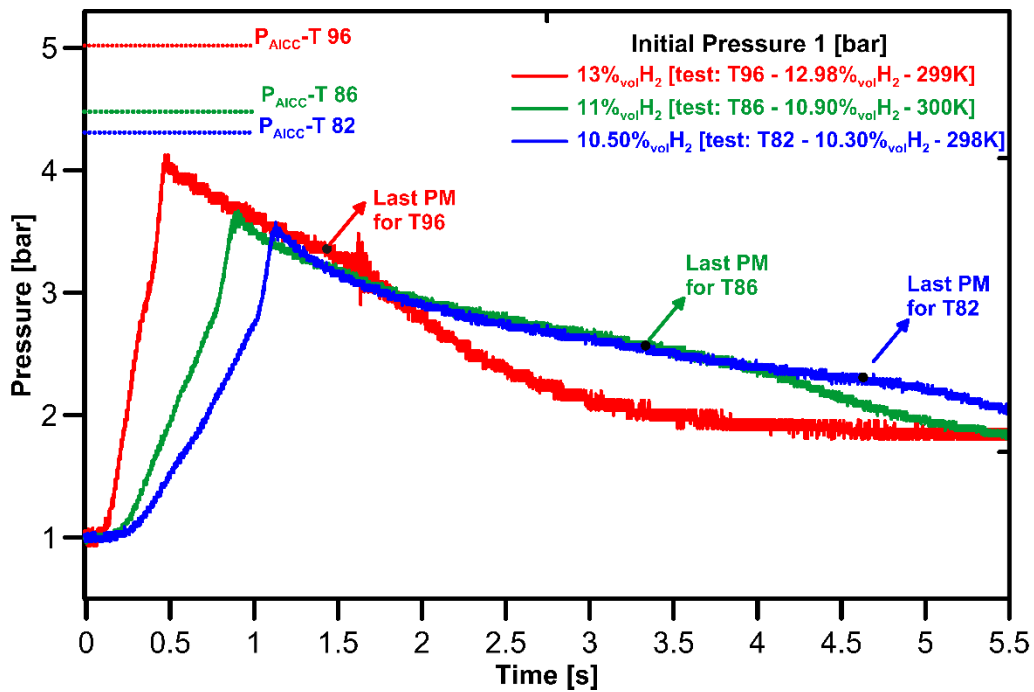


Figure 147: Pressure Evolution for dry mixtures in Downward Propagation with Obstacles. $t=0$ s :Spark Ignition; red: dry case at 13% H_2 + 87%Air; green: dry case at 11% H_2 + 89%Air; blue: dry case at 10.50% H_2 + 88.5%Air.

Table 33 and Table 34 summarize the results about the explosion parameter for the dry mixture in presence of obstacles which does not exhibit a considerable difference compared to the one in absence of obstacles showed in Table 29 and Table 30.

	P_{AICC} [bar]	P_{max} [bar]	Ratio P_{max}/P_{AICC}
13% $_{vol} H_2$	5.02 ± 0.01	4.08 ± 0.04	81%
11% $_{vol} H_2$	4.47 ± 0.01	3.67 ± 0.01	82%
10.5% $_{vol} H_2$	4.35 ± 0.04	3.63 ± 0.05	84%

Table 33: Comparison Maximum Peak and P_{AICC} -dry mixtures - Downward Propagation $BR=0.63$

	Time to P_{max} [s]	$(dP/dt)_{max}$ [bar/s]
13% $_{vol} H_2$	0.55 ± 0.02	9.50 ± 0.43
11% $_{vol} H_2$	0.96 ± 0.01	5.94 ± 0.72
10.5% $_{vol} H_2$	1.20 ± 0.05	4.68 ± 0.17

Table 34: Time to Peak from $t=0$ time of ignition and Max dP/dT dry mixtures downward smooth tube- $BR=0.63$

In order to compare the impact of the presence of the obstacles in downward propagation on the severity of the explosion, Figure 148 shows the comparison based on the K_G index. The presence

of the obstacle, in this configuration, does not affect the severity of the explosion which remains in the zone of the weak explosion.

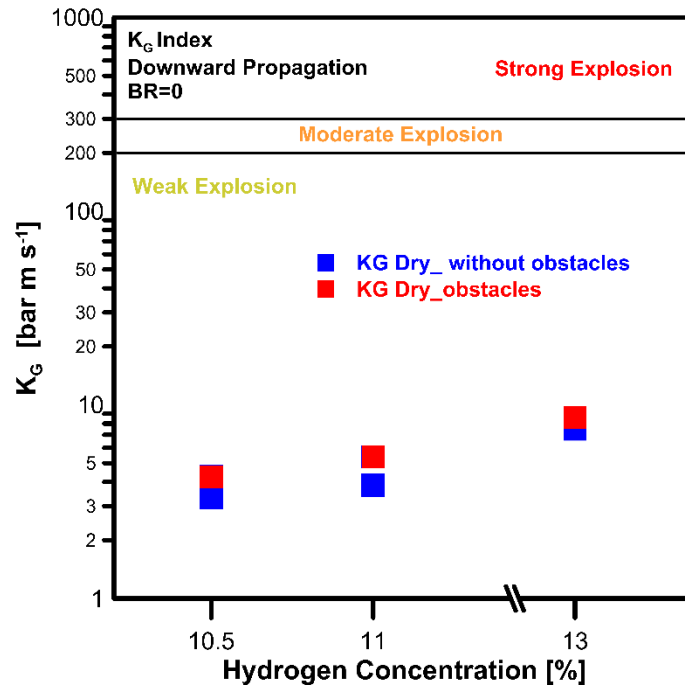


Figure 148: Impact of the Blockage ratio on the K_G in downward propagation in case of dry mixtures

5 Spray Activation in obstructed tube: downward flame propagation

This section is dedicated to the results concerning the downward flame propagation in presence of obstacles with water spray injection.

Table 35 reports for each initial hydrogen concentration, the number of repeated test, the averaged value of $H_2\%_{vol}$ (for the acceleration tube and dome), the related standard deviation and the corresponding initial temperature.

	N. of repeated tests	Measured (μ GC) H2 tube	Measured (μ GC) H2 dome	T tube [K]	T dome [K]
13%H2 + 100 ml	3	12.87 $\pm$ 0.04	12.97 $\pm$ 0.04	304 $\pm$ 0.7	304 $\pm$ 1.0
11%H2 + 100 ml	4	10.94 $\pm$ 0.1	11.02 $\pm$ 0.10	304 $\pm$ 1.1	306 $\pm$ 1.5
10.5%H2 + 100 ml	3	10.46 $\pm$ 0.07	10.53 $\pm$ 0.04	302 $\pm$ 1.8	304 $\pm$ 1.3
	N. of repeated tests	Measured (μ GC) H2 tube	Measured (μ GC) H2 dome	T tube [K]	T dome [K]
13%H2 + 50 ml	3	12.91 $\pm$ 0.03	12.98 $\pm$ 0.02	304 $\pm$ 0.7	304 $\pm$ 0.2
11%H2 + 50 ml	3	10.91 $\pm$ 0.04	10.95 $\pm$ 0.05	304 $\pm$ 1.1	305 $\pm$ 0.8
10.5%H2 + 50 ml	3	10.51 $\pm$ 0.02	10.52 $\pm$ 0.11	302 $\pm$ 1.8	303 $\pm$ 0.9

Table 35: Wet Mixtures- Experiments in downward Propagation BR=0.63

5.1 Impact of the water flowrate on the Flame Position in presence of obstacles

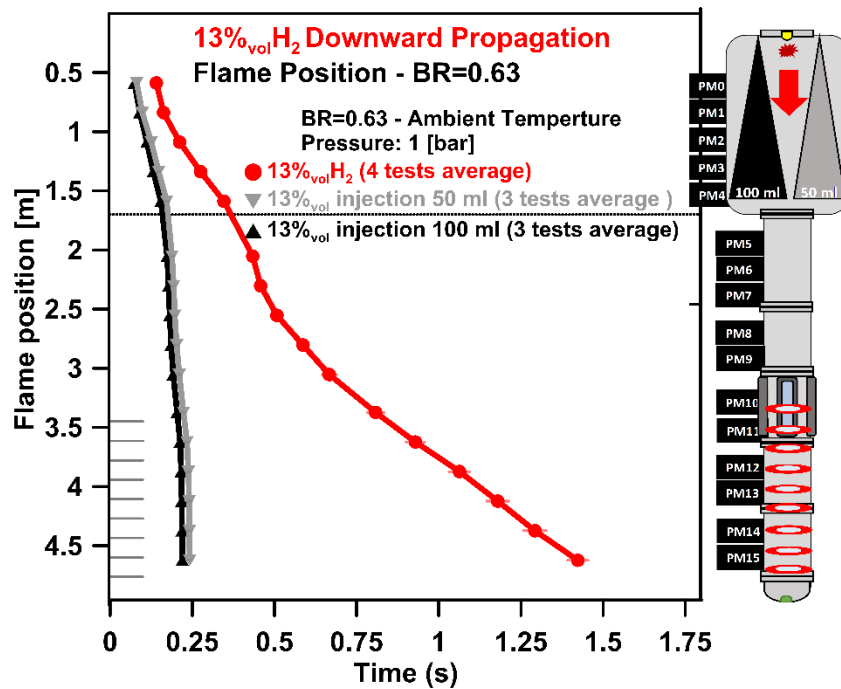
This paragraph presents the results concerning the impact of the water spray injection on the flame trajectory in downward propagation conditions with a blockage ratio equal to 0.63.

Figure 149 shows the comparison between the flame position at 13% $_{vol}H_2$ without water spray injection (red curve) and with water spray injection of 100 ml/min (black curve) and 50 ml/min (grey curve). One can see that in both the cases, the spray injection affects the flame trajectory by reducing the needed time to propagate from the top to the bottom.

In case of a water flowrate of 100 ml/min, the flame takes 0.7 s to reach the first PM at 0.58 m from the ignition point instead of 0.14 s of the dry case. During all the propagation in the dome, the flame takes 0.15 s to reach the PM4 and from 0.58 m to 1.58 m, the slope of the trajectory curve slightly decreases. The entry in the acceleration tube induces an increase of the curve slope and the flame takes 0.20 s (instead of 0.8 s of the dry case) to reach the obstacle region. The

presence of the obstacle increases the curve slope and the flame reaches the last PM 15 at 4.62 m from the ignition point in almost 0.22 s.

The impact of the spray injection with a flowrate of 50 ml/min on the flame position corresponds to the grey curve. The behaviour is similar to the case of 100 ml/min but the flame trajectory is slightly slower and it takes 0.8 s to reach the first PM at 0.58 m. The flame propagation in the dome takes 0.17 s which is almost half of the time of the dry case. The curve slope of increases due to the entry in the acceleration tube and then it decreases slightly until obstacles region at 3.3 m from the ignition point. The presence of the obstacle increases the slope of the curve and the flame takes 0.24 s to reaches the las PM.



**Figure 149: Impact of the water flow rate on 13%_{vol} H₂ Flame Position -Downward Propagation – BR=0.63. .
 t=0 s : Spark Ignition; red: dry case at 13%H₂ + 87%Air; grey :spray injection 50 ml only in the dome; black:
 spray injection 100ml only in the dome.**

Figure 150 shows the impact of the spray injection on the flame position in case of 11%_{vol}H₂. Even in this case, the water spray injection reduces the needed time to propagate from the top to the bottom compared to the dry case.

The black curve is the case in which is injected water spray with a flowrate of 100 ml/min. The flame takes 0.12 s to reach the first PM at 0.58 m from the ignition point (instead of 0.27 s of the case without spray). The curve slope slightly decreases in the dome and the flame takes 0.23 s to propagate until the end of it at 1.58 m from the top. The variation between the internal diameter of

the dome and the one of the acceleration tube, induces an increase of the flame position trajectory up to PM7 (at 2.30 m). The presence of the obstacles affects the flame propagation by increasing the slope of the curve in the last part of the acceleration tube. The flame takes 0.35 s to reach the last PM instead of 3.40 s in the case without water spray injection.

The grey curve is the case in which water spray is injected with a flowrate of 50 ml/min. The first PM detects the flame after 0.13 s from the ignition time and the flame takes 0.24 s to propagate in the dome. The slope of the curve exhibits a slight increase at the entry of the acceleration tube and the flame reaches obstacles region in 0.36 s from the ignition time. The presence of the obstacles increases the curve slope and the flame takes 0.38 s to reaches the last PM at 2.4 m from the top of the facility.

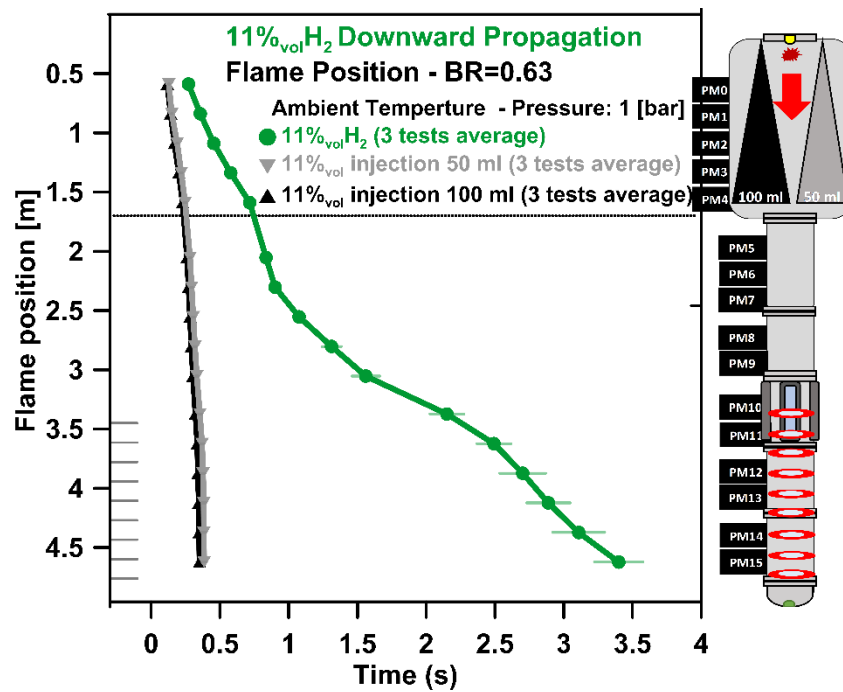


Figure 150: Impact of the water flow rate on 11%_{vol} H₂ Flame Position - Downward Propagation – BR=0.63. .
t=0 s : Spark Ignition; green: dry case at 11%H₂ + 89%Air; grey :spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome.

Figure 151 illustrates the impact of the water spray flowrate on the flame position trajectory in case of 10.50%_{vol}H₂. The spray injection (black and grey curve) reduces the needed time to propagate from the top to the bottom, compared to the dry case (blue curve).

With a spray flowrate of 100 ml/min, the flame reaches the PM at 0.58 m in 0.13 s instead of 0.36 s of the dry case. The slope of the curve decreases slightly during the propagation in the dome

but the decrease is not as marked as in the dry case. The curve slope increases slightly due to the entry in the acceleration tube and then it decreases until the obstacles region. When the flame interacts with the obstacles, the slope of the curve increases and the flame reaches the last PM in 0.43 s which is almost 10 times faster than the case without water spray.

The spray injection with a flowrate of 50 ml/min has a similar impact on the flame position trajectory. The flame is just slightly delayed compared to the injection with 100 ml/min. The first PM detects the flame after 0.15 s from the ignition time (instead of 0.35 of the dry case). The propagation in the dome takes 0.30 s and it induces a slight decrease of the curve slope. The entry in the acceleration tube accelerates slightly the flame which reaches the obstacles region at 3.3 m from the top in 0.45 s. The obstacles accelerate the flame which takes 0.54 s to reach the last PM instead of 1.42 s in the case without water spray.

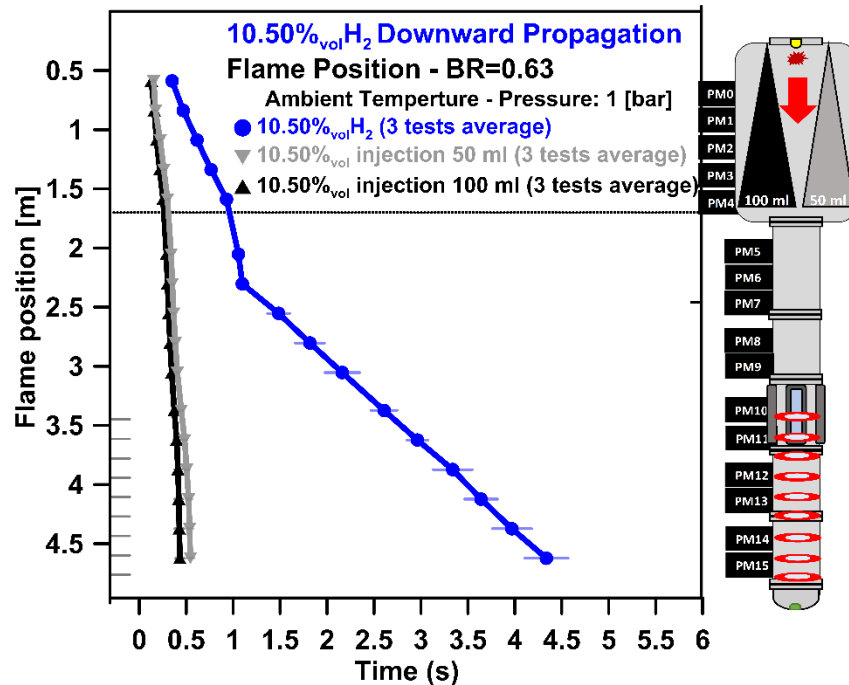


Figure 151: Impact of the water flow rate on 10.50%_{vol} H₂ Flame Position Wet Mixtures – Downward Propagation – BR=0.63. $t=0$ s : Spark Ignition; blue: dry case at 10.5%_{H₂} + 89.5%_{Air}; grey :spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome.

5.2 Impact of the water flowrate on the downward Flame Propagation Speed in presence of obstacles

This paragraph presents the results concerning the impact of the water spray injection on the flame speed for downward propagation in presence of obstacles.

Figure 152 shows the impact of the water spray flowrate on the downward flame speed in case of 13%_{vol}H₂.

The black curve is the averaged flame speed in case of a spray injection with a flowrate of 100 ml/min. The initial flame speed at 0.83 m is 13.2 m/s which is almost 2 times higher than the corresponding velocity in dry case (7 m/s). The flame speed decreases slightly during the propagation in the dome up to 11.7 m/s at 1.33 m from the ignition point. The entry in the acceleration tube leads to an acceleration of the flame which reaches a value of 67.8 m/s at 2.55 m from the ignition point which is almost 17 times higher than the reached value in the dry case at the same position. The flame speed, before to enter in the obstacles region, decreases up to 26 m/s at 3.3 m and then it starts to increase rapidly until the end of the acceleration tube. The final value of flame speed is around 350 m/s which is 2 orders of magnitude higher than the final speed value observed in the dry case (2 m/s).

The grey curve is the case in which is injected the water spray with a flow rate of 50 ml/min. The initial flame speed is 11.5 m/s almost 2 times the corresponding value in the dry case and it decreases slightly during the dome propagation until 10.8 m/s. The entry of the flame in the acceleration tube corresponds to an increase of the speed up to 58 m/s which is one order of magnitude higher than the case without water spray (3.9 m/s). After 2.5 m from the ignition point the flame speed decreases to reach 27 m/s before the obstacles region. The velocity increases strongly up to a final value of 375 m/s which is 2 order of magnitude higher than the dry case.

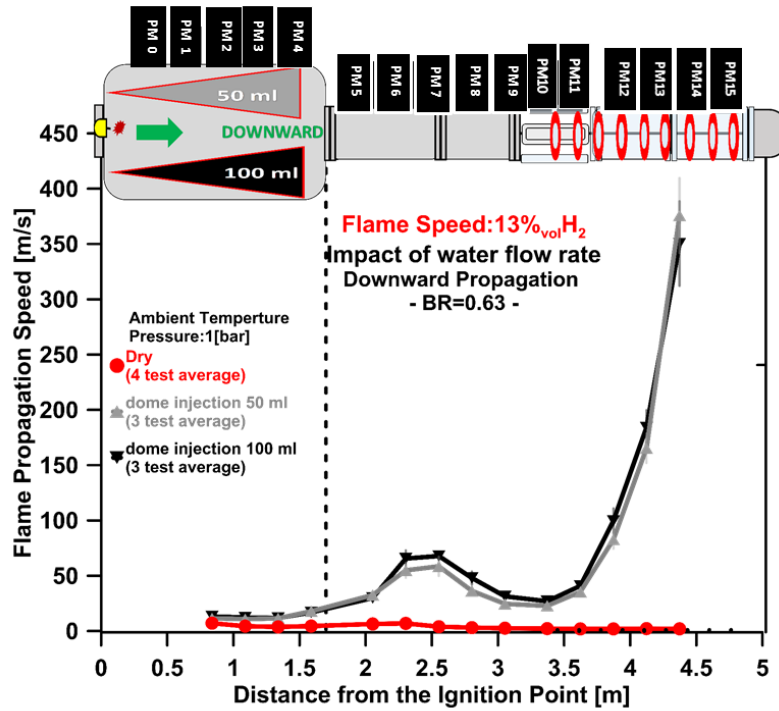


Figure 152: Impact of the water flow rate on 13%vol H₂ on the Flame Speed in Downward Propagation – BR=0.63. $t=0$ s : Spark Ignition; red: dry case at 13% H_2 + 87% Air ; grey :spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome.

Figure 153 shows the impact of the water spray flowrate on the downward flame speed in case of 11%vol H_2 .

The black curve is the average flame speed in case of a spray injection with a flowrate of 100 ml/min. The initial speed is 8.3 m/s which is 4 times higher than the corresponding dry case (2.6 m/s). The flame velocity decreases to 1 m/s during the propagation in the dome. The variation of the internal diameter from the dome to the acceleration tube (from 750 mm to 150 mm) induces an increase of the velocity up to 24 m/s at 2.55 m from the ignition point. The flame speed decreases until to the entry in the obstacles region where it accelerates from 26 m/s at 3.3 m to 127 m/s at 4.3 m from the ignition point. The final flame speed, with a flowrate of 100 ml/min of water spray, is 2 order of magnitude higher than the corresponding one in the dry case.

The impact of the spray injection with a flowrate of 50 ml/min, in the flame propagation speed is represented by the grey curve. The initial value of the flame speed is 8.3 m/s, almost 4 times higher than the initial one in the case without spray injection. The flame speed exhibits a slight decrease during the propagation in the dome and it starts to accelerate before the entry in the acceleration tube. The velocity increases up to 21.5 m/s at 2.3 m from the ignition point. After that

point, the speed decreases until the entry in the obstacles region where it increases from 15 m/s at 3.3 m to 196 m/s at 2.4 m from the ignition.

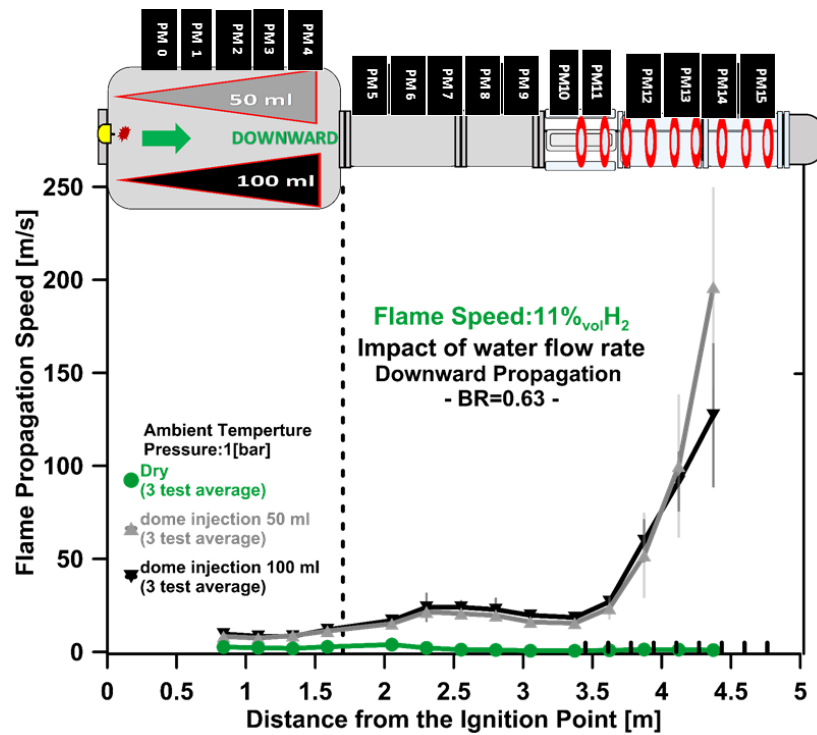


Figure 153: Impact of the water flow rate on 11%vol H₂ on the Flame Speed in - Downward Propagation – BR=0.63. $t=0$ s : Spark Ignition; green: dry case at 11% H_2 + 89% Air ; grey :spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome.

Figure 154 reports the results about the impact of the water flowrate on the downward flame speed in case of 10.50%vol H_2 .

The black curve represents the averaged value of the flame speed versus the distance from the ignition in case of a spray injection with a water flowrate of 100 ml/min. The initial flame speed, at 0.58 m from the ignition point, it is 9.2 m/s which is almost 4 times higher than the corresponding dry case (2.3 m/s). The velocity decreases slightly during the propagation in the dome up to 7.3 m/s at 1.3 m/s. After this point the flame speed increases, due to the entry in the acceleration tube and it reaches a value of 20 m/s which is 3 times higher than the one reached at the same point in the dry case. The velocity decreases until the obstacles region where it increases strongly from 12 m/s at 3.3 m to 55 m/s in the final part of the tube. The final velocity is one order of magnitude higher than the dry case in which it is less than 1 m/s.

The grey curve is the averaged flame propagation speed in case of an injection with a flowrate of 50 ml/min. Even in this case, the presence of the spray increases the flame speed but its impact is slightly less important than in the case with higher flowrate (black curve). The initial flame speed is 7.6 m/s which is almost 3 times higher than for the dry case (1.9 m/s). The flame velocity decreases slightly during the propagation in the dome and it starts to accelerate with the entry in the acceleration tube where it reaches 20 m/s at 2.3 m/s instead of 1.2 m/s of the dry case. The flame speed decreases up to 7 m/s before the entry of the flame in the obstacle region. The obstacles increase strongly the flame speed which reach a final value of 42 m/s which is almost 2 order of magnitude higher than the dry case.

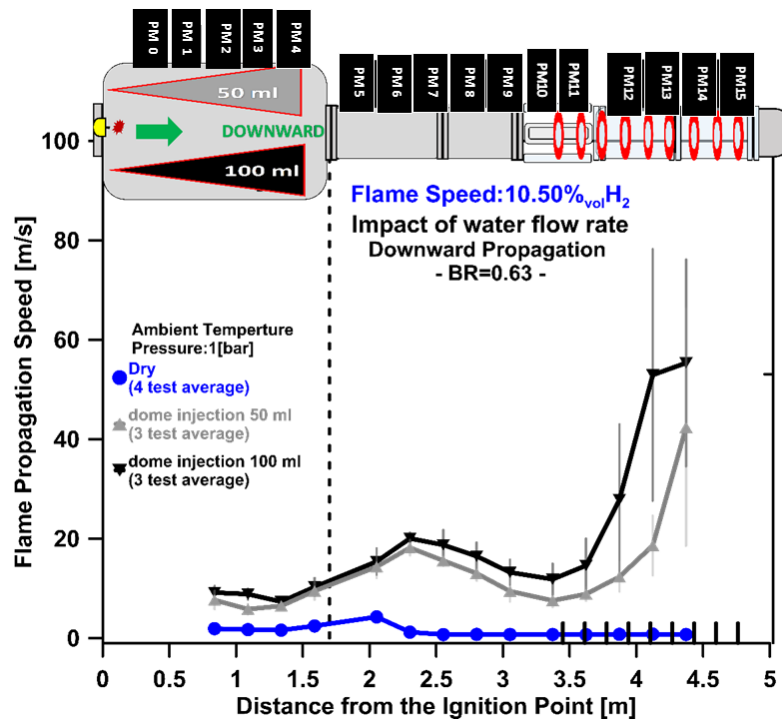


Figure 154: Impact of the water flow rate on 10.50%vol H_2 on the Flame Speed in Downward Propagation – $BR=0.63$. $t=0$ s : Spark Ignition; blue: dry case at 10.5% H_2 + 89.5%Air; grey :spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome.

Figure 155 shows the comparison between the flame speed in downward propagation and the speed of sound in the burned gases, as a function of the normalized distance (X/D).

The dash lines represent the case of a spray injection with a flowrate of 100 ml/min. The dot lines represent the case of a spray injection with a flowrate of 50 ml/min.

By considering the acceleration criteria, it is possible to observe that only at 13%vol H_2 , the flame has to be considered accelerated. In both spray injection cases, the flame speed, exceeds half of the

speed of sound of the burned gases. This occurs only in the last part of the acceleration tube but for the rest of the propagation, the velocity remains in the range of 10% of the half speed of sound values.

In case of 11%_{vol}H₂ and 10.50%_{vol}H₂, the flames do not accelerate even in the last part of the acceleration tube where the obstacles are placed.

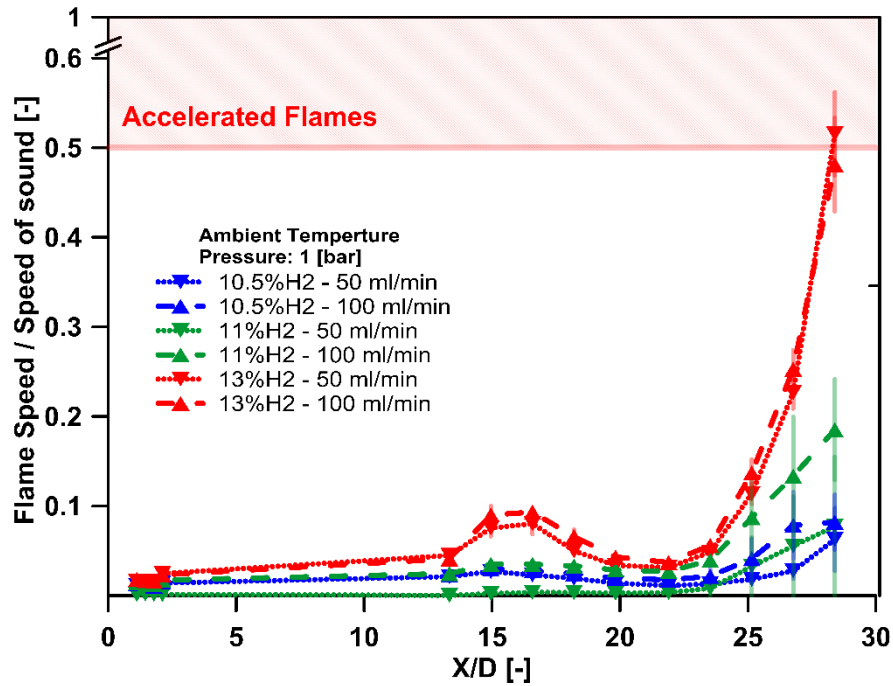


Figure 155: Acceleration Criteria Wet Mixture in Downward propagation BR=0.63

5.3 Impact of the water flowrate on the downward flame Pressure Evolution in presence of obstacles

This paragraph reports the results concerning the impact of the spray flowrate on the pressure evolution in downward propagation in presence of obstacles (BR=0.63).

Figure 156 shows the impact of the water spray flowrate on the pressure evolution in case of an initial hydrogen concentration of 13%_{vol}. The red curve represents the case without water spray, the black line is the case of a spray injection with a flowrate of 100 ml/min and the grey line is the case in which is injected water spray with a flowrate of 50 ml/min. The dot lines are the corresponding P_{AICC} calculated by using the initial condition for each showed test. The presence of the spray injection reduces significantly the time of combustion.

Indeed, for the dry case, when P_{max} is reached, the flame still propagates (not all the volume is burnt). On the contrary, in case of water spray injection, the total volume is burnt after the maximum. The decrease of the slope corresponds to the cooling phase due to the heat losses to the wall.

In case of a spray injection with a flowrate 100 ml/min (the black curve), the averaged time to reach the peak is 0.22 s instead of 0.55 s in absence of water spray. It is possible observe an important peak of over pressure which is on average 23.5 bar which is almost 5 times higher than the corresponding P_{AICC} (4.9 bar). After the peak, the signal exhibits a transient time in which there are important oscillations and the pressure evolution decreases faster than the dry case.

The grey curve is obtained in case of water spray injection with 50 ml/min. Even in this case, the averaged time to reach the peak is 0.24 s which is half of the needed time to reach the peak without water spray. P_{max} exhibits an important increase which is on average more than 5 times the P_{AICC} calculated in the same initial conditions (4.92 bar). After the peak, the signal is characterized by important oscillations and the pressure decrease is faster than the case without spray.

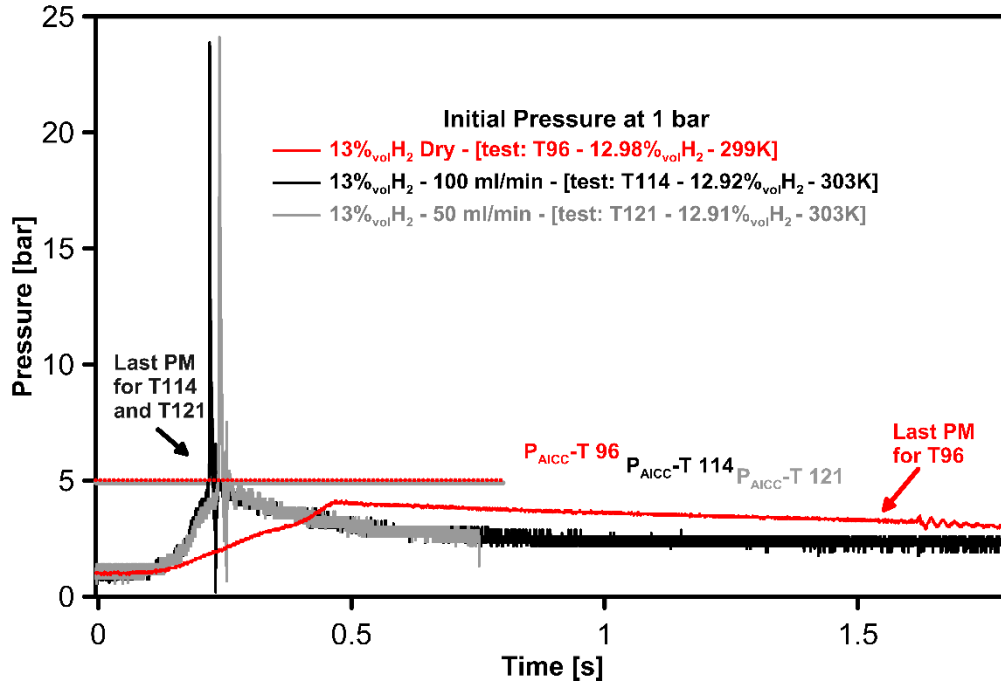


Figure 156: Pressure Evolution at 13%volH₂- Impact of the water flowrate-Downward - BR=0.63. $t=0$ s : Spark Ignition; red: dry case at 13%H₂ + 87%Air; grey :spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome.

Figure 157 shows the impact of the water spray flowrate on the pressure evolution in case of an initial hydrogen concentration of 11%vol.

The spray injection with a flowrate of 100 ml/min (black curve) reduces the time to reach the peak from 0.96 s of the dry case to 0.39 s. $P_{\max}$ is on average 3 times higher than the P_{AICC} calculated by using the same initial conditions (4.4 bar). After the peak, there is an oscillatory transient which is followed by a pressure decrease faster than the one observed in the dry case.

The grey curve is representative of the pressure evolution in the case of a spray injection of 50 ml/min. The time to reach the peak is reduced from 0.96 s of the dry case to 0.39 s. $P_{\max}$ is on average 3 times higher than the P_{AICC} calculated in the same initial conditions. The decrease of the pressure signal is characterized by a short oscillatory transient and after that, the signal decreases faster than the case without water spray.

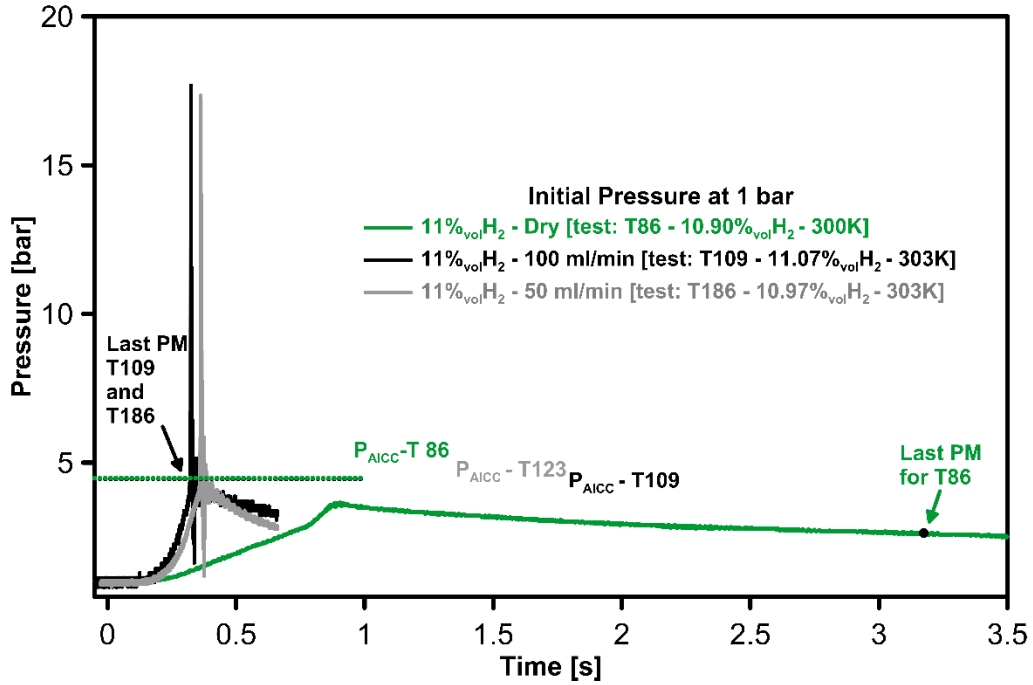


Figure 157: Pressure Evolution at 11%_{vol}H₂- Impact of the water flowrate-Downward - BR=0.63, t=0 s : Spark Ignition; green: dry case at 11%H₂ + 89%Air; grey :spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome.

Figure 158 shows the impact of the water spray flowrate on the pressure evolution in case of an initial hydrogen concentration of 10.50%_{vol}.

The black curve represents the case of a spray injection with a flowrate of 100 ml/min. It is possible to observe that the spray injection reduces the time to reach the maximum peak compared to the dry case (blue curve). The pressure signal reaches the peak in 0.35 s which is at least 3 times smaller than the needed time to reach the maximum peak in the corresponding dry case (1.2 s). P_{max} is on average 5.8 bar which is almost 1 bar more the corresponding P_{AICC} (4.3 bar). The decreasing of the pressure result is faster than the dry case.

The grey curve is the pressure evolution in case of a spray flowrate of 50 ml/min. The time to reach the peak is on average 0.55 s which is half of the time to reach the peak in the dry case (1.2 s). P_{max} is on average almost 2 times higher than the P_{AICC} (4.31 bar). After the peak, the signal shows some oscillations which are rapidly smoothed. The pressure decrease is faster than the observed one in the dry case.

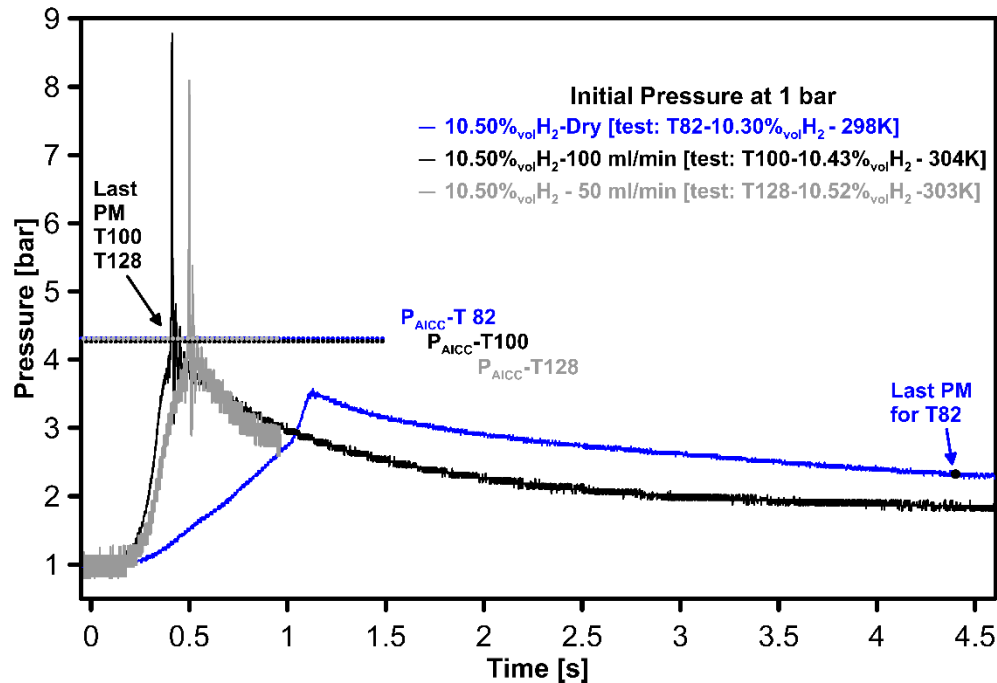


Figure 158: Pressure Evolution at 10.50%_{vol}H₂- Impact of the water flowrate-Downward - BR=0.63. . $t=0$ s : Spark Ignition; blue: dry case at 10.5%H₂ + 89.5%Air; grey :spray injection 50 ml only in the dome; black: spray injection 100ml only in the dome.

Figure 159 shows the impact of the water flow injection on explosion parameters in downward propagation with a blockage ration of 0.63. The results show that the spray injection in downward propagation condition, increases the severity of explosion. In presence of spray injection, the pressure evolution is characterized by a strong impulse corresponding to P_{max} which is more than 5 times higher than the one reached in absence of spray.

P_{max} reached with a water spray injection of 50 ml/min, it is slightly higher than the one reached with an injection of 100 ml/min. Anyway by considering the related error bars, it is not possible to consider it is significant.

The time to reach the peak is reduced by the spray injection and the injection of 100 ml/min has an effect slightly more important, in terms of combustion time reduction than the injection with a flowrate of 50 ml/min.

The dP/dt_{max} is increased by the spray injection:

- 3 order of magnitude at 13%_{vol}H₂ and 11%_{vol}H₂
- 2 order of magnitude at 10.50%_{vol}H₂

The K_G index with spray injection is in the domain of the strong explosion.

The graph of the $dp/dt_{\max}$ and of the K_G reports also the values related to the condition before to reach the maximum peak (grey and black symbols) which are already higher (at least 5 times) than the ones in dry case. Anyway the explosion severity is to be considered still in the domain of the weak explosion.

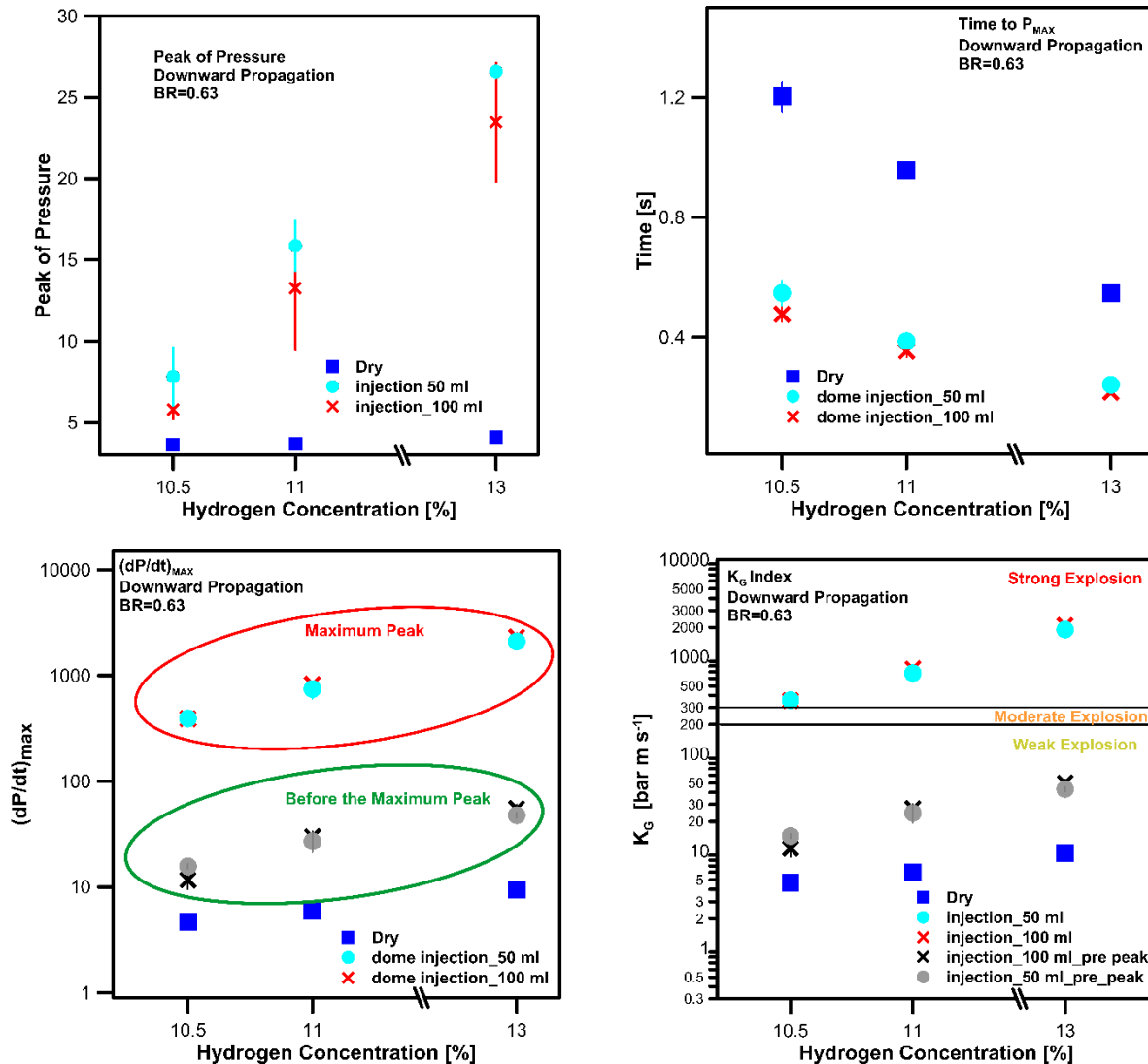


Figure 159: Explosion Parameters summary-Downward Propagation-BR=0.63

5.3.2 Consideration on the pressure evolution

The pressure evolution exhibits a strong peak when the flame reaches the end of the acceleration tube. Figure 160 shows an example of pressure evolution over the time (Test T114). The time zero is the time at which the spark ignition system is triggered.

The green symbols represent the flame arrival in front of the photomultipliers systems. The flame propagation in the dome takes almost 0.16 s and it corresponds to the red zone in the graph. The other 11 PMs describe the flame propagation in the acceleration tube which correspond to the green zone in graph.

It is possible to notice that when the flame enters in the acceleration tube, the pressure starts to increase and the last PM (at 4.6 m) detects the flame slightly before the occurrence of the $P_{\max}$.

$P_{\max}$ occurs when the flame is propagating between the last PM position at 4.6 m and the location of the pressure sensor at 4.75 m from the ignition.

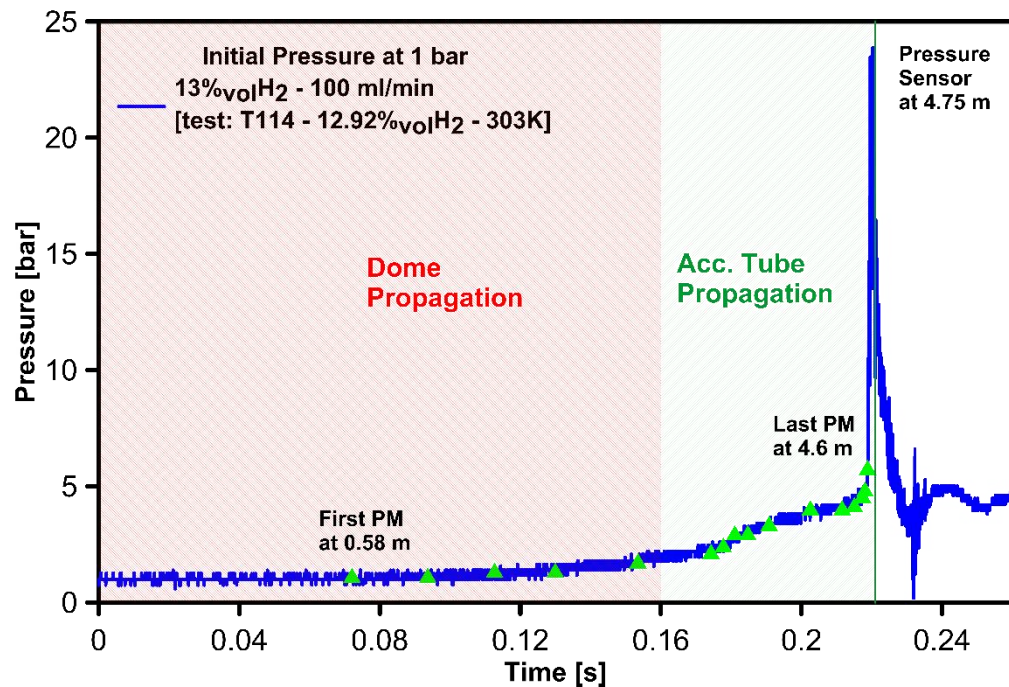


Figure 160: Flame Position on the pressure evolution signal in downward propagation with $BR=0.63$ in presence of water spray. $t=0$: Ignition Spark; Blu: pressure profile test: T114; green symbols: PM signal of test T114.

In order to explain the pressure dynamic, it is important to keep in mind that in downward propagation condition, the propagation, in the acceleration tube, occurs in a compressible mixtures.

When the flame reaches the obstacles region, the velocity increases significantly. The interaction between flame and obstacles create pressure waves which sum up and form a shock wave at the end of the tube leading to an auto-ignition of the fresh gases behind this shock in the bottom cap (Figure 47).

5.3.3 Pre-Compression Conditions

The first part of the pressure evolution is analysed in order to provide more information about the impact of the spray injection. For each experiments the Chapman-Jouguet pressure is calculating considering the pressure achieved by each experiment before P_{max} as showed in Figure 161. The temperature, corresponding to the pressure before P_{max} , It is calculated by using the initial temperature and pressure, assuming an isentropic transformation as showed in Equation 41:

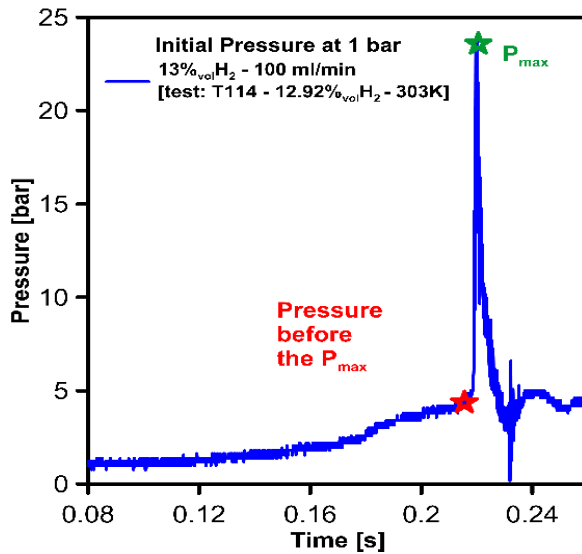


Figure 161: Example of pressure evolution signal

$$T_2 = T_1 \cdot \left(\frac{P_2}{P_1} \right)^{\frac{1-\gamma}{\gamma}}$$

Equation 41: Calculation of the temperature T with Isoentropic transformation

All the initial input data and the results are listed in the following Table 1.

100 ml/min	H₂ tube	T_{ini} [K]	P_{CJ} (1 bar)	P_{precomp.} [bar]	T_{precomp.} [K]	P_{CJ} (P_{precomp.})
13%	12.87 ± 0.04	304 ± 0.7	9.2 ± 0.03	4.38 ± 0.18	464 ± 7	28.1 ± 0.9
11%	10.94 ± 0.1	304 ± 1.1	8.2 ± 0.04	3.74 ± 0.18	445 ± 4	22.5 ± 0.8
10.5%	10.46 ± 0.07	302 ± 1.8	8.0 ± 0.05	3.67 ± 0.22	437 ± 9	21.8 ± 0.9
50 ml/min	H₂ tube	T_{ini} [K]	P_{CJ} (1 bar)	P_{precomp.} [bar]	T_{precomp.} [K]	P_{CJ} (P_{precomp.})
13%	12.91 ± 0.03	304 ± 0.7	9.2 ± 0.03	4.14 ± 0.24	457 ± 8	27.6 ± 0.8
11%	10.91 ± 0.04	304 ± 1.1	8.2 ± 0.04	3.78 ± 0.05	447 ± 1	22.6 ± 0.3
10.5%	10.51 ± 0.02	302 ± 1.8	8.0 ± 0.02	3.66 ± 0.17	439 ± 5	21.7 ± 0.8

Table 36: Initial Condition for Chapman-Jouguet Condition Calculation

Figure 162 shows the comparison between the measured $P_{\max}$ and the calculated P_{CJ} as a function of the initial hydrogen concentration.

By comparing the reached $P_{\max}$ and the P_{CJ} (calculated in pre-compressed conditions), it is possible to observe that in case of 13%_{vol}H₂, they are very close for both the spray injections cases.

At 13%_{vol}H₂, in the case of a spray injection of 100 ml/min, the $P_{\max}$ is on average 83% of the P_{CJ} and in case of a spray injection of 50 ml/min, the $P_{\max}$ is on average 96% of the P_{CJ} . At 11%_{vol}H₂, the $P_{\max}$ is the 59% of the P_{CJ} in case of 100 ml/min and 70% in case of 50 ml/min. At 10.50%_{vol}H₂, the ratio between P_{CJ} and $P_{\max}$ is 26% in case of an injection with a flowrate of 100 ml/min and it is 36% in case of 50 ml/min of spray injection.

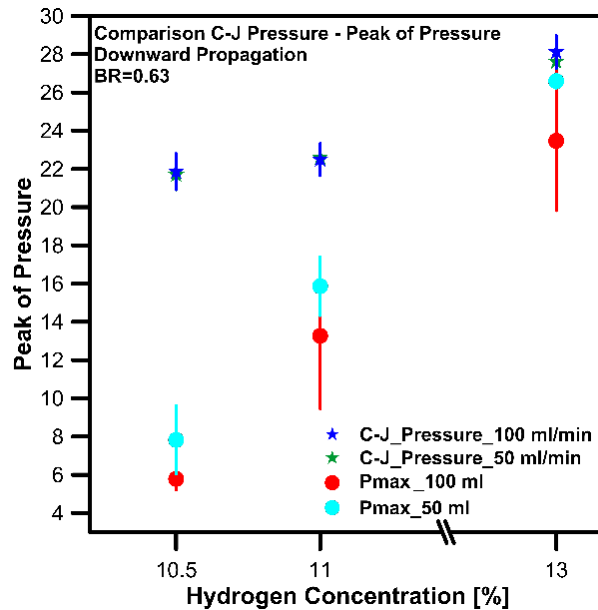


Figure 162: Comparison Maximum Peak of pressure with Chapman-Jouguet Pressure

6 Conclusions on the Downward Flame Propagation in presence of Obstacles

In absence of water spray injection, the downward flame propagation is not affected by the presence of the obstacles. The obstacles configuration and their position are not able to accelerate the flame which is slowed down by the condensation of the burned gases. When the flame reaches the obstructed region, it is energetically weak. The interaction with the annular obstacles, do not lead to an increase of the turbulence necessary to enhance the speed propagation. The resulting severity of the deflagration is in the domain of weak explosions and it is clearly comparable with the one observed in downward propagation without obstacles.

The activation of the water spray in presence of obstacles represents the strongest aggravation of the explosion observed during our experimental campaign. The combustion time is strongly reduced by the water injection and it decreases as the water flowrates increases.

The flame propagation speed exhibits a slight dependence on the water flowrate and it increases as the water flow increases. In the last part of the acceleration tube, the speeds are accelerated by 2 orders of magnitude at 13%_{vol}H₂ and 11%_{vol}H₂ and of 1 order of magnitude at 10.50%_{vol}H₂.

The resulting effect is an auto-ignition of the fresh mixture in the bottom cap of the facility which provides $P_{\max}$ higher than the one achievable by the P_{AICC} .

At 13%_{vol}H₂, the flame propagation speed exceeds the acceleration criteria based on the speed of sound in the burned gases and furthermore $P_{\max}$ is close to the Chapman-Jouguet pressure corresponding to the pre-compressed conditions.

This outcome defines the flame propagation at 13%_{vol}H₂ in air as the worst case of our experimental study because the resulting deflagration has the requirements to transit eventually toward a detonation event.

Propagation de la flamme vers le bas

Ce chapitre est consacré à la propagation vers le bas de la flamme pour un mélange d'hydrogène de 10,50, 11, 13 % vol H₂. La propagation de la flamme a été étudiée dans un tube lisse (BR=0) et en présence d'obstacles annulaires (BR=0.63). En considérant le cas sans injection d'eau pulvérisée, on constate que le phénomène de déflagration est fortement influencé par les effets de flottabilité qui agissent comme inhibiteurs de propagation de la flamme. La configuration géométrique de l'appareil d'essai et les faibles vitesses de la flamme, conduisent à un temps de combustion plus lent qui est en concurrence avec le temps de condensation des gaz brûlés. La propagation de la flamme est influencée par la condensation des gaz brûlés qui empêche l'augmentation de la pression pendant le phénomène de combustion. La P_{max} résultante est significativement inférieure à celle que l'on peut obtenir dans des conditions adiabatiques. La sévérité de l'explosion est significativement inférieure à celle correspondant au cas sec en propagation ascendante. L'activation du jet introduit de la turbulence dans les gaz frais à la fois à cause du moment transféré (effet bulk) et à cause de l'évaporation des gouttes (dans le front de flamme et/ou en amont de celui-ci). La vitesse de la flamme dans le tube d'accélération augmente fortement par rapport au cas sec ainsi que la gravité de l'explosion. Les résultats des vitesses de flamme montrent un plus grand effet de promotion lorsque le débit d'eau pulvérisée augmente. Cependant, en raison de la présence de l'effet de condensation, les paramètres d'explosion ne confirment pas clairement une dépendance à la quantité d'eau injectée. La propagation vers le bas, dans des conditions tubulaires lisses, souligne l'importance de la direction de propagation pour l'étude de ce phénomène et montre un exemple d'une nette aggravation de la gravité de l'explosion induite par l'activation du jet. En l'absence d'injection d'eau pulvérisée, la propagation de la flamme vers le bas n'est pas affectée par la présence des obstacles. La configuration des obstacles et leur position ne permettent pas d'accélérer la flamme qui est ralentie par la condensation des gaz brûlés. Lorsque la flamme atteint la région obstruée, elle est énergétiquement faible. L'interaction avec les obstacles annulaires, n'entraîne pas une augmentation de la turbulence nécessaire pour améliorer la propagation de la vitesse. La sévérité de la déflagration qui en résulte est dans le domaine des faibles explosions et elle est clairement comparable à celle observée en propagation descendante sans obstacles. L'activation de la pulvérisation d'eau en présence d'obstacles représente la plus forte aggravation de l'explosion observée lors de notre campagne expérimentale (Figure 6). Le temps de combustion est fortement réduit par l'injection d'eau et diminue à mesure que le débit d'eau augmente. La vitesse de propagation de la flamme dépend légèrement du débit d'eau et augmente à mesure que le débit d'eau augmente. Dans la dernière partie du tube d'accélération, les vitesses sont accélérées de 2 ordres de grandeur à 13%volH₂ et 11%volH₂ et de 1 ordre de grandeur à 10,50%volH₂. L'effet qui en résulte est une auto-inflammation du mélange frais dans le bouchon inférieur de l'installation qui fournit une P_{max} supérieure à celle pouvant être obtenue par le P_{AICC} . A 13%volH₂, la vitesse de propagation de la flamme dépasse les critères d'accélération basés sur la vitesse du son dans les gaz brûlés et de plus P_{max} est proche de la pression Chapman-Jouguet correspondant aux conditions pré-comprimées. Ce résultat définit la propagation de la flamme à 13 % volH₂ dans l'air comme le pire cas de notre étude expérimentale parce que la déflagration résultante a les exigences pour passer éventuellement vers un événement de détonation.

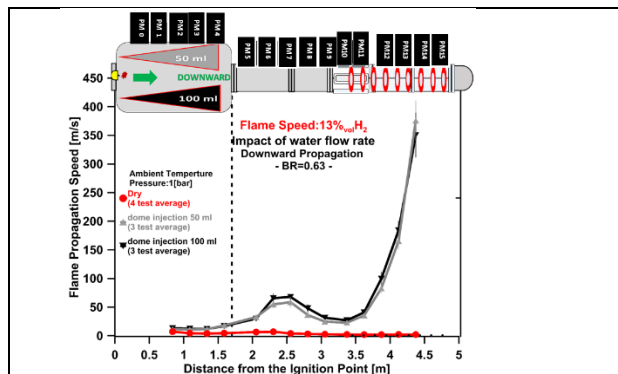


Figure 6 : Impact du débit d'eau sur 13%vol H₂ sur la vitesse de la flamme en propagation descendante - BR=0.63. t=0 s : Allumage par étincelle ; rouge : boîtier sec à 13%H₂ + 87%Air ; gris : injection par pulvérisation 50 ml seulement dans le dôme ; noir : injection par pulvérisation 100 ml seulement dans le dôme.

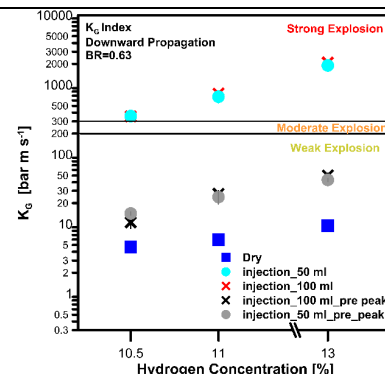


Figure 7: Paramètre d'explosion - impact du débit d'eau dans la propagation descendante BR=0.63. Bleu : Cas sec ; Rouge : Injection par pulvérisation 100ml seulement dans le dôme ; bleu clair : injection par pulvérisation 100ml seulement dans le dôme

Conclusions and Perspectives

This work has been within the framework of the MYTHIGENE project which is a project being carried out by IRSN, the CEA, the ICARE Institute and various industrial - primarily EDF, Air Liquide and Areva - and academic partners, including the Jülich Research Institute of Germany (ANR-PIA-RSNR). The aim is to improve the knowledge related to the Hydrogen Risk during the development of a severe accident in a nuclear power plant. The objective of this work is to identify the conditions for which the activation of the Containment Spray System (CSS) affects the propagation of the hydrogen-air-vapor flame. In terms of nuclear safety, this work can assist in the crucial challenge of the development and validation of flame propagation models in diphasic mixture conditions for large volumes.

The first chapter concerns the state of art about the interaction between the hydrogen-air-vapor flame and the water droplets. It has highlighted the importance of the spray characteristic parameters as: droplets sizes, spray density and spray momentum and how they impact on the different aspects of the combustion. Part of the scientific literature has showed the possibility to mitigate the explosion severity by using low momentum spray with higher spray density [48] and small droplet sizes [46] [47]. Other scientific works instead highlight the enhancing explosion effect of the spray due to the spray generated turbulence [57] [58] [61]. The most part of the scientific works are performed in small explosion chambers with a low spray momentum and they do not take into account the impact of the flame propagation direction compared to the spray injection direction. By starting from this lack of information, our experimental study was defined.

The second chapter concerns the description of ENACCEF1 and the related diagnostics. This vertical facility has an internal volume of 720 l and it is composed by an acceleration tube and a dome which is designed to reproduce the explosion dynamic occurring in a nuclear containment building. The apparatus was equipped to study the impact of the spray injection on the flame in upward and downward propagation direction, with different spray locations and water flowrate.

The third chapter presents the results about the thermodynamic equilibrium calculation and the laminar flame speed calculation. This study was performed in order to identify the impact of the water vapor content on the fundamental parameters of the combustion. It was highlighted the role of the initial temperature increase, in case of dry and humid hydrogen-air mixture and how, the latter case, it reduces the T_{ad} and P_{AICC} due to the higher water vapor content. The study of the laminar flame speed and thickness has allowed to identifying the experimental conditions in terms

of initial mixture conditions (range from 10.5 to 13%_{vol}H₂) and the water spray parameters (size of water droplets) interesting for our purpose.

The fourth chapter concerns the characterization of two sprays produced by two mono-fluid high pressure with an orifice diameter of 100 μm and 200 μm . The characterization was performed by using a laser particle sizer and laser extinction measurement but firstly, it was necessary to optimize the experimental conditions in order to define numbers of tests to perform and measurements location. The results show that the two nozzles produces: similar droplets size in terms of Mean Sauter Diameter but, allowing two different water loading (50 and 100 ml/min), leading to two different spray densities.

The results of the experimental study show that a small quantity of injected water (0.01% compared to the entire volume) can impact the flame differently according to: the propagation flame direction, the blockage ratio and initial hydrogen content.

The chapter 5 concerns the result in case of upward flame propagation, both in smooth and obstructed tube conditions. A slight explosion mitigation effect is observed which is more marked as the H₂ content is lowered and as the quantity of injected water increases. In case of 10.50%_{vol}H₂ and 11%_{vol}H₂, the flame propagation speed can be increased by injecting water spray but given the geometry of our facility (acceleration tube and dome), it does not result in an increase of the explosion severity. At 13%_{vol} H₂, the mitigation effect on the severity of the explosion depends on the propagation condition and it is not possible to observe it in case of accelerated flames.

Chapter 6 concerns the result in case of downward propagation, both in smooth and obstructed tube conditions. In smooth and in obstructed tube conditions, in absence of water spray, the combustion is strongly affected by the condensation of the burned gases which reduce the severity of the explosion. The water spray injection increases the severity of the explosion both in smooth and in obstructed tube conditions. The presence of obstacles worsens it dramatically the scenario leading to an increase of the K_G index (2 order of magnitude higher) and creating favorable conditions for DTT phenomena at 13%_{vol}H₂. The water spray does not reduce the flame speed propagation but it pushes downward the flame, by enhancing strongly its speed. The impact of the spray injection shows a slight dependency on the water flowrate.

In terms of perspectives, visualization techniques could be useful to characterize the initial turbulence induced by the spray injection and to visualize the impact of the water droplets on the flame propagation in the tube and in the dome. A heating system could be used, in order to investigate the role of the initial temperature of the water. In downward propagation, the impact of

bigger water droplets, with a lower tendency to fully evaporate in order to discriminate the role of the water evaporation in the flame propagation could be studied. The impact of the spray on higher initial hydrogen concentrations could be studied in order to clarify the impact on flames which are more stable (higher Lewis number) by increasing the N₂ dilution in order to obtain lower peak of pressure. From the point of view of the nuclear safety, this work allows to highlight that in the field of the hydrogen risk, it is crucial the ignition source location and the flame propagation direction. By considering, its huge impact on the explosion severity, it is advisable to conduct furthermore investigations focused on the downward flame propagation conditions.

It could be interesting to do the experimental investigation by using higher droplets size and a simpler facility geometry in order to reduce the difference, in terms of propagation regime due to our experimental facility, between upward propagation and downward propagation. A new facility has been built at ICARE laboratory which a vertical tube highly equipped with several diagnostics that would allow a detailed study of the interaction between the flame and a water spray both in downward and upward directions: ENACCEF II. This facility can be heated up to 200°C which would allow these studies with different initial temperatures

Conclusion and Perspectives (Français)

Ces travaux s'inscrivent dans le cadre du projet MYTHIGENE qui est un projet mené par l'IRSN, le CEA, l'Institut ICARE et divers partenaires industriels - principalement EDF, Air Liquide et Areva. L'objectif est d'améliorer les connaissances relatives au risque hydrogène lors du développement d'un accident grave dans une centrale nucléaire. L'objectif de ce travail est d'identifier les conditions dans lesquelles l'activation du système de pulvérisation du confinement (CSS) affecte la propagation de la flamme hydrogène-air-vapeur. En termes de sûreté nucléaire, ces travaux peuvent aider à relever le défi crucial du développement et de la validation de modèles de propagation de la flamme dans des conditions de mélange diphasique pour de grands volumes.

Les résultats du calcul de l'équilibre thermodynamique et du calcul de la vitesse de flamme laminaire ont été réalisés afin d'identifier l'impact de la teneur en vapeur d'eau sur les paramètres fondamentaux de la combustion. Il a été souligné le rôle de l'augmentation initiale de la température, dans le cas d'un mélange hydrogène-air sec et humide et comment, dans ce dernier cas, elle réduit le T_{ad} et le P_{AICC} en raison de la teneur plus élevée en vapeur d'eau. L'étude de la vitesse et de l'épaisseur de la flamme laminaire a permis d'identifier les conditions expérimentales en termes de conditions de mélange initial (de 10,5 à 13% volH₂) et les paramètres de pulvérisation d'eau (taille des gouttelettes d'eau) intéressants pour notre application. Les résultats de l'étude expérimentale montrent qu'une petite quantité d'eau injectée (0,01 % par rapport au volume total) peut avoir un impact différent sur la flamme en fonction de la direction de propagation de la flamme, du rapport de blocage et de la teneur initiale en hydrogène.

Dans le cas de propagation de la flamme vers le haut, aussi bien dans des conditions de tube lisse que dans des conditions de tube obstrué, on observe un léger effet d'atténuation de l'explosion qui est plus marqué lorsque la teneur en H₂ diminue et que la quantité d'eau injectée augmente. Dans le cas de 10,50%volH₂ et 11%volH₂, la vitesse de propagation de la flamme peut être augmentée en injectant de l'eau pulvérisée, mais étant donné la géométrie de notre installation (tube d'accélération et dôme), il n'en résulte pas une augmentation de la sévérité de l'explosion. A 13%vol H₂, l'effet d'atténuation sur la gravité de l'explosion dépend des conditions de propagation et il n'est pas possible de l'observer en cas de flammes accélérées. Dans le cas de propagation vers le bas, dans des conditions de tubes lisses ou obstrués, en l'absence d'eau pulvérisée, la combustion est fortement affectée par la condensation des gaz brûlés qui réduit la gravité de l'explosion. L'injection d'eau pulvérisée augmente la gravité de l'explosion aussi bien dans des conditions lisses que dans des conditions de tube obstrué. La présence d'obstacles l'aggrave considérablement le scénario conduisant à une augmentation de l'indice KG (2 ordre) et créant des conditions favorables aux phénomènes de la DTT à 13%volH₂. Le jet d'eau ne réduit pas la propagation de la vitesse de la flamme, mais il pousse la flamme vers le bas, en augmentant fortement sa vitesse. L'impact de l'injection de pulvérisation montre une légère dépendance au débit d'eau. En termes de perspectives, les techniques de visualisation pourraient être utiles pour caractériser la turbulence initiale induite par l'injection de pulvérisation et pour visualiser l'impact des gouttelettes d'eau sur la propagation de la flamme dans le tube et dans le dôme. Un système de chauffage pourrait être utilisé pour étudier le rôle de la température initiale de l'eau. En propagation descendante, l'impact de gouttelettes d'eau plus grosses, avec une tendance plus faible à s'évaporer complètement afin de discriminer le rôle de l'évaporation de l'eau dans la propagation de la flamme pourrait être étudié. L'impact de la pulvérisation sur des concentrations initiales d'hydrogène plus élevées pourrait être étudié afin de clarifier l'impact sur des flammes plus stables (indice de Lewis plus élevé) en augmentant la dilution N₂ afin d'obtenir un pic de pression inférieur. Du point de vue de la sûreté nucléaire, ce travail permet de souligner que dans le domaine du risque hydrogène, il est crucial l'emplacement de la source d'inflammation et le sens de propagation de la flamme. En tenant compte de son impact considérable sur la sévérité de l'explosion, il est recommandé de mener des investigations supplémentaires axées sur les conditions de propagation de la flamme vers le bas. Il pourrait être intéressant de faire l'étude expérimentale en utilisant des gouttelettes plus grosses et une géométrie d'installation plus simple afin de réduire la différence, en termes de régime de propagation due à notre installation expérimentale, entre la propagation ascendante et la propagation descendante. Une nouvelle installation a été construite dans

le laboratoire d'ICARE, dont un tube vertical équipé de plusieurs diagnostics permettant une étude détaillée de l'interaction entre la flamme et un jet d'eau dans les deux sens, vers le bas et vers le haut : ENACCEF II. Cette installation peut être chauffée jusqu'à 200°C ce qui permettrait ces études avec des températures initiales différentes.

Bibliography

- [1] D. Leteinturner Chaumont, Manuel, Vendel, Bentaib, Paihories, Sabroux, *IRSN - Nuclear Safety - Scientific and Technical Report 2002*, vol. IRSN-Scientific and Technical Report 2002. 2002.
- [2] A. Bentaib, D. Jacquemain, et Institut de radioprotection et de sûreté nucléaire (France), *Nuclear power reactor core melt accidents: current state of knowledge*. 2015.
- [3] A. Bentaib, H. Bonneville, G. Cénérino, B. Clément, F. Corenwinder, M. Cranga, G. Ducros, F. Fichot, D. Jacquemain, C. Journeau, V. Koundy, D. Leteinturier, D. Magallon, R. Meignen, F. Chaumont et Durin, Chaumont, Manuel, Vendel, Bentaib, Paihories, Sabroux, Leteinturner, *IRSN research and Development on hydrogen risk during severe pressurized water reactor accidents*. EDP Sciences, 2015.
- [4] IAEA, International Atomic Energy Agency, *Mitigation of Hydrogen Hazard in Severe Accident in Nuclear Power Plants*. 2011.
- [5] Veine Gustavsson, E. Moller, « Study on hydrogen Deflagration for Selected Severe Accident Sequences in Ringals 3 ». 2002.
- [6] Rapport IRSN-2007/83 , Rapport CEA-2007/351, « Research and development with regard to severe accidents in pressurised water reactors: Summary and outlook », 2007.
- [7] H. Cheikhravat H. , Goulier J., Bentaib A., Meynet N. , et Chaumeix N., Paillard C., « Effects of water sprays on flame propagation in hydrogen/air/steam mixtures », *Elsevier*, vol. Proceedings of the Combustion Institute, n° 35, p. 2717-2718, 2014.
- [8] A. Bentaib, N. Meynet, A. Bleyer, « Overview on Hydrogen risk research and development activities: methodology and opened issues », vol. 47, p. 26-32, 2015.
- [9] S. Hermsmeyer *et al.*, *Review of current Severe Accident Management (SAM) approaches for nuclear power plants in Europe*. Luxembourg: Publications Office, 2015.
- [10] A. Foissac, « Modélisation des interactions entre gouttes en environnement hostile », IRSN-PhD Thesis, 2011.
- [11] D.R. Guideldenbecher, C. Lopez Rivera, P.E. Sojka., *Handbook of Atomization and Sprays*, vol. 6. Springer Science and Business Media, 2011.
- [12] A. H. Lefebvre et V. G. McDonell, *Atomization and sprays*, Second edition. Boca Raton London New York: CRC Press, Taylor & Francis Group, 2017.
- [13] T.D. Fansler, S.E. Parrish, « Spray measurement technology: a review », *Measurement Science and Technology*, vol. 26, p. 34, 2015.
- [14] Z. Liu, A.K. Kim, « A review of water mist fire suppression system: -Fundamental Studies », *Journal of Fire Protection Engineering*, p. 32-50, 2000.
- [15] Mark Linne, « Imaging in the optically dense regions of a spray: A review of developing techniques », *Progress in Energy and Combustion Science*, p. 403-440, 2013.

- [16] N. Ashgriz, Éd., *Handbook of atomization and sprays: theory and applications*. New York, NY: Springer, 2011.
- [17] P. Krawczyk, K. Badyda, S. Młynarz, « Effect of the air to water ratio on the performance of internal mixing two-fluid atomiser », *Chemical and Process Engineering*, p. 461-471, 2016.
- [18] M.J. Sapko, A.L. Furno, J.M. Kutcha, « Quenching methan-air ignitions with water spray », Bureau of Mines Report RI-8214, 1977.
- [19] D.B. Spalding, « The Combustion of liquid fuels », *4th Symposium of Combustion*, p. 847-864, 1953.
- [20] G.A.E. Godsave, « Studies of the combustion of drops in a fuel spray -The burning of singles drops of fuel », *4th Symposium of Combustion*, p. 818-830, 1953.
- [21] G. CHEN et A. GOMEZ, « Co-Flow Laminar Diffusion Flames of Monodisperse Sprays: Structure, Evaporation and Microgravity Effects », *Combustion Science and Technology*, vol. 115, n° 1-3, p. 177-201, juin 1996.
- [22] C. K. Law, *Combustion physics*. Cambridge: Cambridge University Press, 2010.
- [23] I. Glassman et R. A. Yetter, *Combustion*, 4. ed. Amsterdam: Elsevier/Acad. Press, 2008.
- [24] M. Kuznetsov, S. Kobelt, J. Grune, T. Jordan, « Flammability limits and laminar flame speed of hydrogen air mixtures at sub-atmospheric pressures », p. 8-9, 2012.
- [25] H. Cheikhvat, N. Chaumeix, A. Bentaib, C.-E. Paillard, « Flammability Limits of Hydrogen-Air Mixtures », *Nuclear Technology*, p. 5-16, 2012.
- [26] R.K. Kumar, « Flammability Limits of Hydrogen-Oxygen diluent mixtures », *Journal of Fire Sciences*, p. 278-254, 1985.
- [27] R. G. Abdel-Gayed, K. J. Al-Khishali, D. Bradley, « Turbulent burning velocities and flame straining in explosions », *Proceeding Royal Society London*, vol. 391, p. 393-414, 1984.
- [28] Goulhier J., « Comportements aux limites de flammes de prémélange hydrogène/air. Étude de la transition flamme laminaire-flamme turbulente », Orléans, 2015.
- [29] G. Ciccarelli, S. Dorofeev, « Flame acceleration and transition to detonation in ducts », vol. 34, p. 499-550, 2008.
- [30] T. Poinso et D. Veynante, *Theoretical and numerical combustion*, 2. ed. Philadelphia: Edwards, 2005.
- [31] R. Mével, S. Javoy, F. Lafosse, N. Chaumeix, G. Dupré, C.-E. Paillard, « Hydrogen-nitrous oxide delay times: Shock tube experimental study and kinetic modelling », vol. Volume 32, n° Issue 1, p. 359-366, 2009.
- [32] F. Tamanini, J.L. Chahaffee, « Turbulent vented gas explosions with and without acoustic waves », vol. 42, p. 1845-1851, 1992.
- [33] A. Teodorczyk, J. H. S. Lee, « Detonation attenuation by foams and wire meshes lining the walls », vol. Shock Waves, n° 4, p. 225-236, 1995.
- [34] C. Bruno, L. Crocco, et C. Casci, Éd., *Recent Advances in the aerospace sciences: In honor of Luigi Crocco on his 75. birthday*. New York u.a: Plenum Pr, 1985.

- [35] H.N. Phylaktou, G.E. Andrews, P.Herath, « Fast flame speeds and rates of pressure rise in the initial period of gas explosions in large L/D cylindrical enclosures », vol. Volume 3, n° Issue 4, p. 355-364, 1990.
- [36] N. Lamoreux, « Explosives properties of low hydrocarbons and natural gas mixtures. Flame propagation analysis of these mixtures in the presence of repeated obstacles », Université d'Orléans, 1995.
- [37] I.O.Moen, M.Donato, R.Knystautas, J.H.Lee, « Flame acceleration due to turbulence produced by obstacles », vol. 39, n° Issue 1, p. 21-32, 1980.
- [38] C.T. Johansen, G. Ciccarelli, « Visualization of the unburned gas flow field ahead of an accelerating flame in an obstructed square channel », *Combustion and Flame*, vol. 156, p. 405-416, 2009.
- [39] S.B. Dorofeev, M.S. Kuznetsov, V.I. Alekseev, A.A. Efimenko, W. Breitung, « Evaluation of limits for effective flame acceleration in hydrogen mixtures », *Journal of Loss Prevention in the Process Industries*, vol. 14, p. 583-589, 2001.
- [40] F. Malet, « Etude expérimentale et numérique de la propagation de flammes prémélangées turbulentes dans une atmosphère pauvre en hydrogène et humide », 2005.
- [41] E. Salzano, A. Di Benedetto, « Inherently Safe Index for Explosions in the Process Industry », vol. 37, p. 73-78, 2012.
- [42] J.-L. GUSTIN, « Risques d'explosion de poussières Caractérisation », *Techniques de l'ingénieur Risques d'explosion*, vol. base documentaire : TIB157DUO., n° ref. article : se5030, 2004.
- [43] S.J. Jones, A.F. Averill, J.M. Ingram, P.G. Holborn, P. Battersby, P.F. Nolan, et I.D. Kempell, M.J. Wakem, « Mitigation of hydrogen-air explosions using fine water mist spray », IChemE, 2006.
- [44] P.N. Battersby, A.F. Averill, J.M. Ingram, P.G. Holborn, P.F. Nolan, « Suppression of hydrogen-oxygen-nitrogen explosions by fine water mist: Part 2. Mitigation of vented deflagrations », *International Journal of Hydrogen Energy*, p. 19258-19267, 2012.
- [45] P.G. Holborn, P.N. Battersby, J.M. Ingram, A.F. Averil, P.F. Nolan, « Modeling the effect of water fog on the upper flammability limit of hydrogen-oxygen-nitrogen mixture », *International Journal of Hydrogen Energy _ Elsevier*, 2013.
- [46] W. Yang, R.J. Kee, « The Effect of Monodispersed Water Mists on the Structure, Burning Velocity, and Extinction Behavior of Freely Propagating, Stoichiometric, Premixed, Methane-Air Flames », p. 322-335, 2002.
- [47] A.U. Modak, A. Abbud-Madrid, J.-P. Delplanque, R. J. Kee, « The effect of mono-dispersed water mist on the suppression of laminar premixed hydrogen-, methane-, and propane-air flames », *Combustion and Flame*, p. 103-111, 2006.
- [48] P.G. Holborn, P. Battersby, J.M. Ingram, A.F. Averill, P.F. Nolan, « Modeling the mitigation of lean hydrogen deflagration in a vented cylindrical rig with water fog », p. 15406-15422, 2012.

- [49] MM.H.. Feng, Q.-W. Li, J. Qin, « Extinguishment of hydrogen diffusion flames by ultrafine water mist in a cup burner apparatus - A numerical study », vol. International Journal of the Hydrogen Energy, n° 40, p. 13643-13652, 2015.
- [50] P.G. Holborn, P. Battersby, J.M. Ingram, A.F. Averill, P.F. Nolan, « Estimating the effect of water fog and nitrogen dilution upon the burning velocity », p. 6882-6895, 2012.
- [51] P.G. Holborn, P. Battersby, J.M. Ingram, A.F. Averill, P.F. Nolan, « Modelling the mitigation of a hydrogen deflagration in anuclear waste silo ullage with water fog », p. 476-482, 2013.
- [52] J.R. Butz, P. French, « Application of Fine Water Mists to Hydrogen Deflagrations », *Proceeding , Halon Options Techincal Working Conference*, p. 345-355, 1993.
- [53] J.M. Ingram, A.F. Averill, P.N. Battersby, P.G. Holborn, P.F. Nolan, « Suppression of hydrogen-oxygen-nitrogen explosions by fine water mist: Part 1. Burning velocity », p. 19250-19257, 2012.
- [54] L.R. Boeck, A. Kink, D. Oezdin, J. Hasslberger, T. Sattelmayer, « Influence of water mist on flame acceleration, DDT and detonation in H₂-air mixtures », p. 6995-7004, 2015.
- [55] M. Gieras, « Flame Acceleration due to water droplets action », *Journal of Loss Prevention in the Process Industries*, vol. 21, p. 472-477, 2008.
- [56] G.O.Thomas, « On the conditions required for explosion mitigation by water sprays », *Istitution of Chemical Engineering*, p. 339-354, 2000.
- [57] K. van Wingerden, B. Wilkins, « The influence of water-spray on gas explosions.Part 1: water-spray-generated turbulence », *Journal of Loss Prevention in the Process Industries*, p. 53-59, 1995.
- [58] K. van Wingerden, B. Wilkins, « The influence of water-spray on gas explosions.Part 2: mitigation », *Journal of Loss Prevention in the Process Industries*, p. 61-70, 1995.
- [59] P. Zhang, Y. Zhou, X. Cao, X. Gao, B. Minshu, « Enhancement effects of methane/air explosion caused by water spraying in a sealed vessel », *Journal of Loss Prevention in the Process Industries*, p. 313-318, 2014.
- [60] K.C. Adiga, H. D. Willauer, R. Anath, F. Williams, « Droplet breakup energies and formation of ultrafine mist. », Nano Mist System and The Navy Tecnology Center for Safety and Survivability, Washington, DC, 2006.
- [61] « Attenuation of a shock wave passing through a cloud of water droplets », p. 285-296, 2009.
- [62] H. Cheikhravat, « Experimental Study of Hydrogen combustion in a flammable atmosphere in presence of water drops », IRSN-CNRS (ICARE) PhD Thesis, Université d'Orléans, CNRS-Orléans, 2009.
- [63] Romain Grosseuvres, « Analyse de propagation de flamme hydrogène-air-vapeur en milieu confiné », IRSN Thesis, 2018.
- [64] R. Grosseuvres, N. Chaumeix, A. Bentaib, « Pressure Profiles Measurements in ENACCEF Facility for Fast Flame Propagation », Xi'an, China, 2017.

- [65] R. Grosseuvres, A. Comandini, A. Bentaib, N. Chaumeix., « Combustion properties of H₂ /N₂ /O₂ /steam mixtures », *Proceedings of the Combustion Institute*, 2017.
- [66] A. Vesper, W. Breitung, B. Dorofeev, « Run-up distance to supersonic flames in obstacle laden tubes », p. 333-340, 2002.
- [67] D. Valiev, V. Bychkov, V. Akkerman, C.K. Law, L.E. Eriksson, « Flame Acceleration in channels with obstacles in the deflagration to detonation transition », p. 1012-1021, 2010.
- [68] Christopher E. Brennen, *Cavitation and Bubble Dynamics*. Oxford University Press, 1995.

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Propagation de la flamme d'hydrogène- air- vapeur d'eau en présence de gouttelettes d'eau

L'accident de Fukushima en 2011 a remis en évidence les graves conséquences qu'une explosion d'un mélange gazeux à base d'hydrogène induit sur les installations et l'environnement. Lors de cet accident, la destruction complète du réacteur 2 a entraîné un rejet important de poussières radioactives dans l'atmosphère avec de graves conséquences environnementales qui sont encore à l'étude. Une connaissance approfondie de la propagation d'une flamme d'hydrogène dans un environnement confiné est essentielle pour comprendre les conditions de transition entre les régimes de déflagration et de détonation de la flamme qui peuvent compromettre l'intégrité du bâtiment réacteur. Un aspect des aspects qui a été très peu étudié concerne l'impact que l'activation des jets d'eau de refroidissement peut avoir sur la gravité d'une explosion. Le but de ce travail de thèse est de mieux comprendre le rôle de l'injection d'eau pulvérisée sur les régimes de combustion de mélanges hydrogène-air (vitesses de propagation et chargement en pression) dans un espace confiné. Ce travail de recherche a débuté par une étude préliminaire afin d'évaluer l'impact de la présence de vapeur d'eau sur la vitesse laminaire et sur l'épaisseur de flamme. Par la suite, une étude expérimentale a été menée, au laboratoire ICARE-CNRS Orléans, dans un tube d'accélération vertical ENACCEF 1 (volume interne 720 l). Pour mener cette étude, différents mélanges hydrogène/air ont été choisis, représentatifs de différents régimes de combustion, afin d'investiguer l'impact de la pulvérisation d'eau sur une flamme ascendante et descendante. L'ensemble du travail constitue une base de données expérimentale utile pour la validation de codes CFD utilisés dans l'évaluation de la sûreté des installations nucléaires.

Mots clés : hydrogène, explosion, gouttelettes, sûreté nucléaire

Propagation of Hydrogen Air Vapour Flame in presence of Water Droplets

The Fukushima accident in 2011 highlighted the serious consequences that an explosion of a hydrogen-based gas mixture has on installations and the environment. In this accident, the complete destruction of Reactor 2 resulted in a significant release of radioactive dust into the atmosphere with serious environmental consequences that are still under investigation. A thorough knowledge of the propagation of a hydrogen flame in a confined environment is essential to understand the transition conditions between deflagration and flame detonation regimes that can compromise the integrity of the reactor building. One aspect of the aspects that has been little studied concerns the impact that the activation of cooling water jets can have on the severity of an explosion. The purpose of this thesis work is to better understand the role of water spray injection on the combustion regimes of hydrogen-air mixtures (propagation rates and pressure loading) in a confined space. This research work began with a preliminary study to evaluate the impact of the presence of water vapour on laminar velocity and flame thickness. Subsequently, an experimental study was carried out at the ICARE-CNRS Orléans laboratory in an ENACCEF 1 vertical acceleration tube (internal volume 720 l). To conduct this study, different hydrogen/air mixtures were selected, representative of different combustion regimes, to investigate the impact of water spray on an ascending and descending flame. All the work constitutes a useful experimental database for the validation of CFD codes used in the safety assessment of nuclear installations.

Keywords : Hydrogen, explosion, water spray, nuclear safety



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