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International Conference on Hydrogen Safety

Influence of initial pressure on hydrogen/air flame acceleration during severe accident in NPP

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Introduction

Hydrogen risk in NPP

- Severe accident with core uncovering
 - oxidation of fuel rod cladding by steam at high temperature and hydrogen production
 - **hydrogen release into the containment** of Light Water Reactor (Three Miles Island (1979) and Fukushima (2011) accidents).
- **Defense in depth philosophy:**
the reactor containment building is the last barrier preventing the release of radioactive material to the environment.
Its **structural integrity** must be ensured along with the **serviceability of those safety features** needed for accident mitigation.
- **Mechanical loads** and structural damage **depend strongly on flame propagation regimes** (the faster the flame/shock wave is, the more important the pressure loads become).

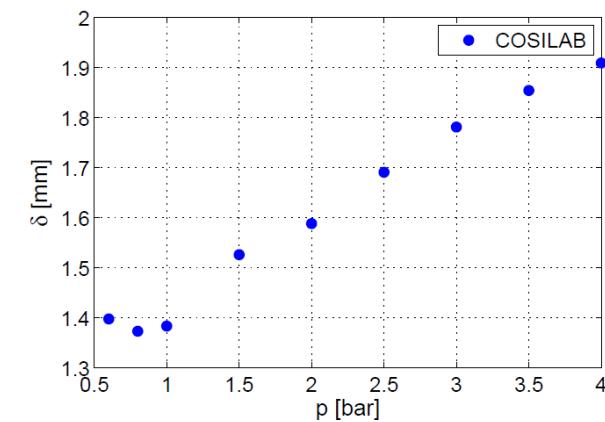
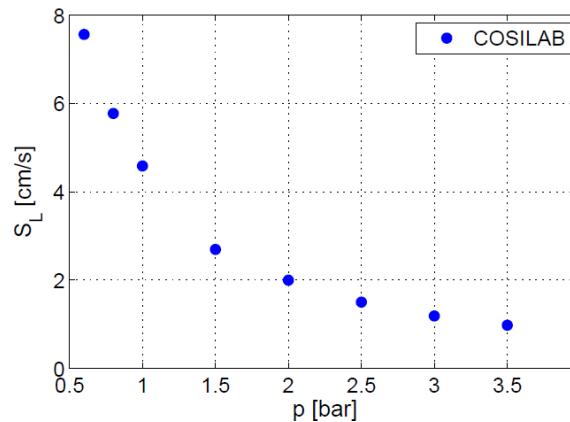
Objectives

- Early 2000s : experimental criteria for **Flame Acceleration (FA)** :
 - σ criterion (and further up-dates)
(Dorofeev1999; Kuznetsov1999; Dorofeev2001)
- Medium scale experiments within obstacles laden tubes and ducts (reproduction of reactor building compartmentalization). Most of the experiments were performed at $p_0 \leq p_{amb}$
- **In case of severe accident, reactor containment pressure increases up to 5 bar $\rightarrow p_0 > p_{amb}$**
- **Objective:** **experimental study on the influence of the initial pressure on flame acceleration for lean hydrogen/air mixtures.**
11 %vol hydrogen in air mixture was investigated
→ lower limit for flame acceleration

Influence of the initial pressure

■ Analytical models:

- (Mallard,LeChatelier1883): the laminar flame velocity depends on the pressure and the overall reaction order $S_L \propto p^{\frac{n-2}{2}}$ $n = n(p)$



$$\delta = \frac{\alpha(T_b)}{\sigma S_L}$$

11% H₂/air mixture: 1D flame propagation simulations with COSILAB® (detailed kinetic mechanism and transport properties of (Connaire2004))

- (Law, 2006): the activation energy and the Zeldovich number β increase as $p_0 \gg$

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

- $\beta(Le - 1) < -2$ criterion for the onset of cellular instabilities:**

For very lean H₂/air mixture: $Le(p) = Le_{H_2} = \text{const} < 1$

→ **as $p_0 \gg$, $\beta(Le - 1) \ll$ thus the flame is more thermally unstable,**

Influence of the initial pressure

- Numerical model: **EUROPLEXUS RDEM model** (Velikorodny2015)
(Large scale combustion model)

- Reactive Euler equations
- Conservation of the progress variable ξ

$$\frac{\partial}{\partial t}(\xi) + \vec{D} \cdot \vec{\nabla} \xi = 0$$

- Riemann solver: flame = propagating interface (Beccantini2009)
- Model for flame propagation

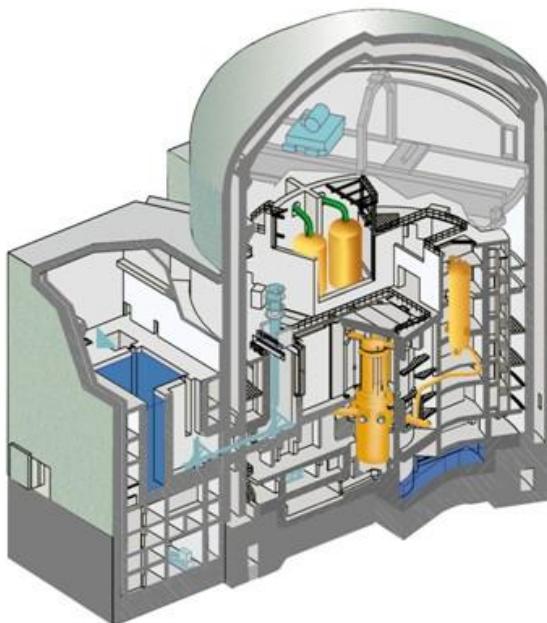
$$\vec{D} = \vec{U} + K_0 \vec{n} \quad \vec{U} = \text{Velocity of the unburnt gas}$$

$$K_0 = \text{Flame velocity} = S_L^0 \Theta_{TH} \Theta_{TURB}$$

$$\Theta_{TH} = \left(\frac{P}{P_0}\right)^{-0.5} \left(\frac{T}{T_0}\right)^\beta \quad (\text{Malet2004}) \quad (\rightarrow n = 1)$$

Experimental device

SSEXHY (Structure Subjected to an Exlosion of Hydrogen):
a medium scale facility for flame acceleration



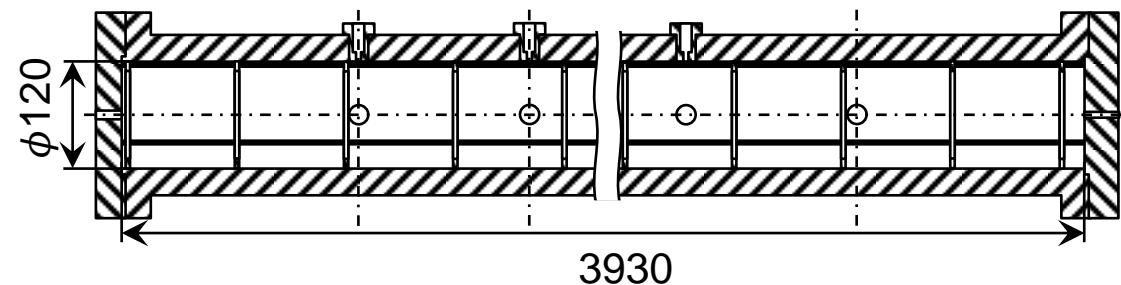
Transversal section of the EPR
(European Pressurized Reactor)



Simplified experimental device :

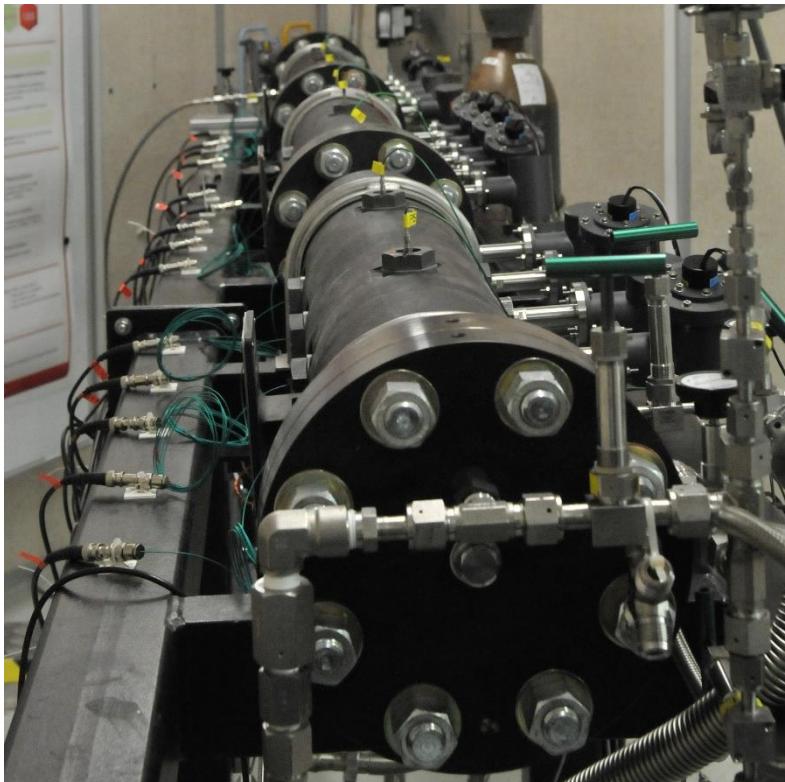
Pressure vessel (tube) equipped with annular obstacles uniformly distributed to

- 1) reproduce the compartmentalized inner structure of reactor building;
- 2) promote flame acceleration.



Experimental set-up

- Material: SS X2CrNi 18-9
- $l_t = 3930 \text{ mm}$ (3 modules with $l_m = 1310 \text{ mm}$), $\emptyset_i = 120 \text{ mm}$
- $p_{\max} = 100 \text{ bar}$
- 32 annular obstacles: $BR = 0.3$, $D = \emptyset_i$
- 42 instrumentation ports



Photomultiplier tubes

14 tubes to detect OH* radical ($\lambda_{OH^*} = 310 \text{ nm}$)



Pressure sensors

9 KISTLER piezoelectric sensors



Shock sensors

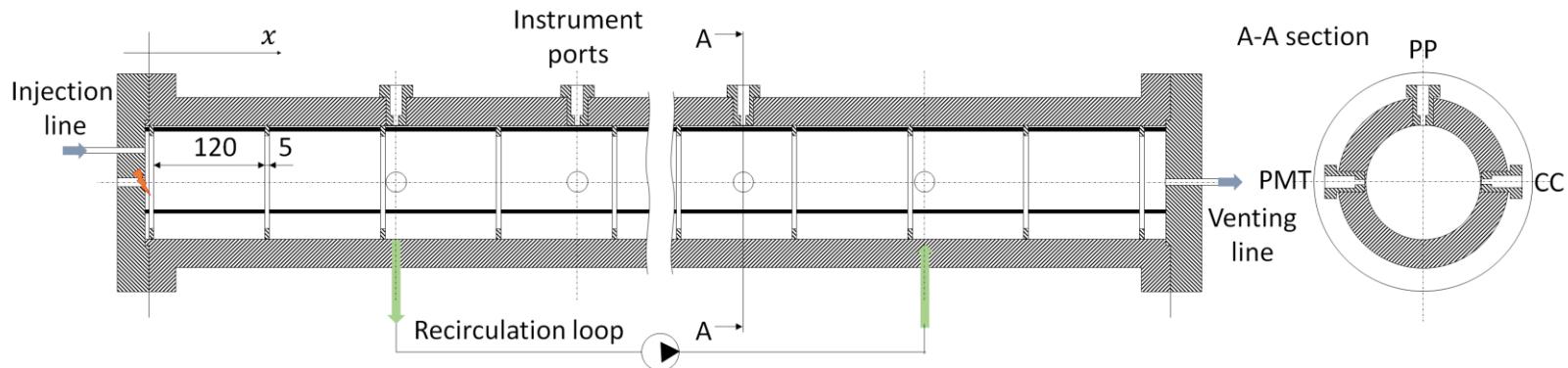
14 CHIMIE METAL piezoelectric sensors



Data acquisition unit NI PXIe-1078

5 cards with 8 channels each one
(Analog Input – 7,5MHz/Ch)

Experimental set-up



Single shot preparation

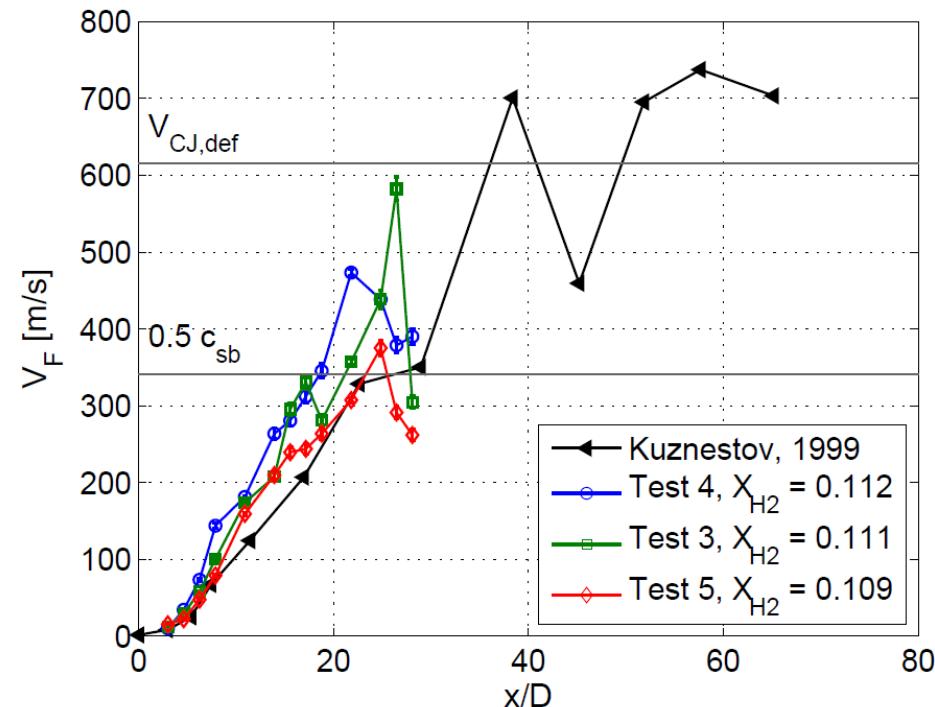
- First, the combustion tube is set under primary vacuum. Then a flammable mixture is injected. Hydrogen/air mixtures are prepared with the method of the partial pressures:
$$\chi_{\text{H}_2} = \frac{p_{\text{H}_2}}{p_{\text{tot}}} = 1 - \chi_{\text{air}}$$
- The mixture is forced to recirculate in an external loop to promote mixture homogenization. Gas-chromatographic analysis on mixture samples are then performed;
- The mixture is ignited by automotive spark plug;
- Signals acquisition is triggered (acquisition triggering and cards synchronization are managed in LabView environment);
- Once the experiment is over, the combustion tube is inerted with nitrogen and vented.

Results and discussion

Tests matrix

Test #	p_0 [mbar]	χ_{H2} [%]
1	600	10.9
2	800	11.1
3	1000	11.1
4	1000	11.2
5	1003	10.9
6	1501	11.1
7	1502	10.9
8	2000	11.1
9	4002	11.1

Reproducibility at $p = 1$ bar



- 11 %vol hydrogen in air mixture
→ lower limit for flame acceleration
→ quite unstable mixture

- A slight change in the mixture composition results in a variation of the maximum velocity.

Flame propagation

$x - t$ diagram of flame propagation

3 modules configuration

$BR = 0,3$

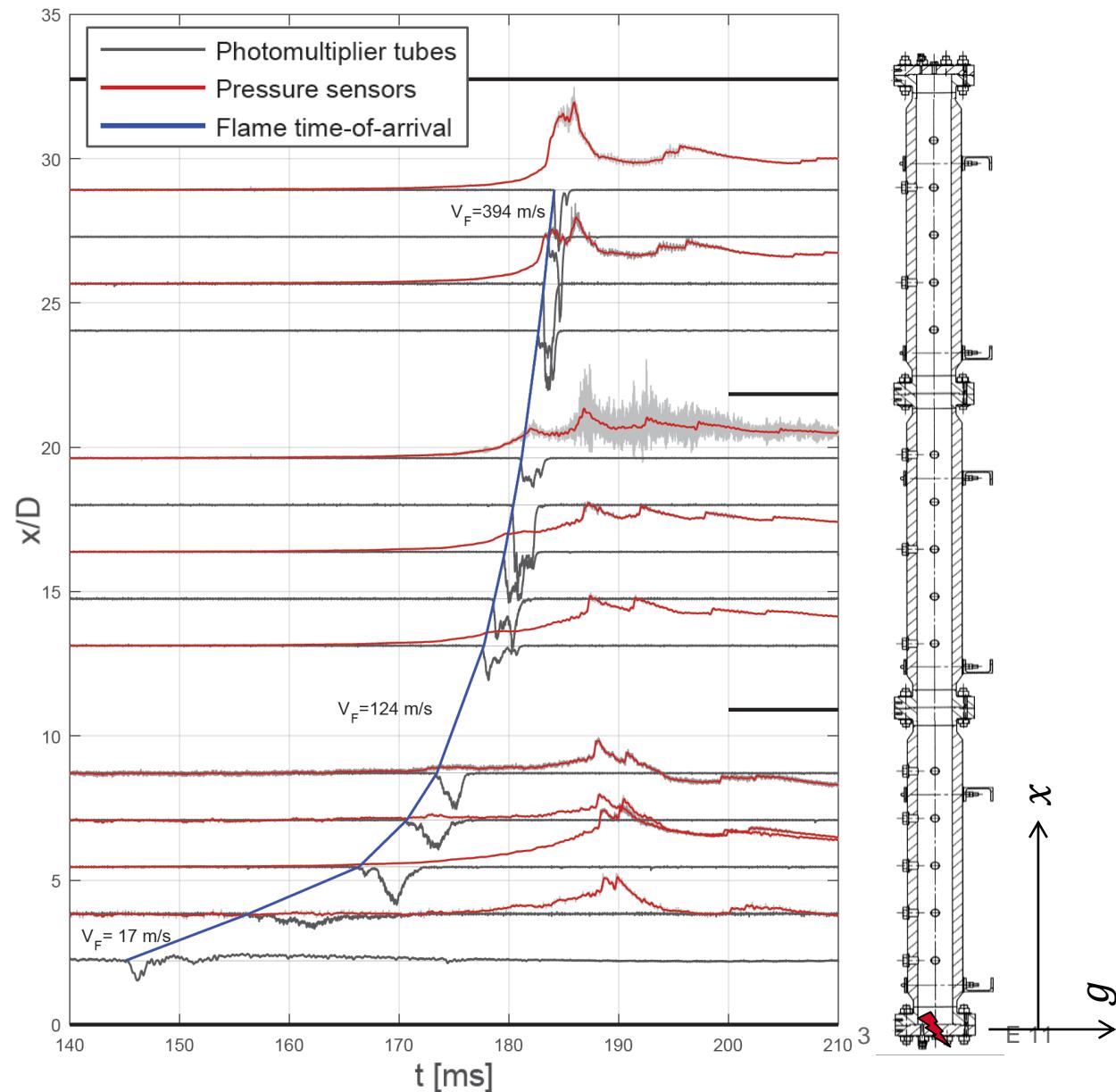
$\chi_{H2} = 10.9 \%$

$p_0 = 600 \text{ mbar}$

14 Photomultiplier tubes

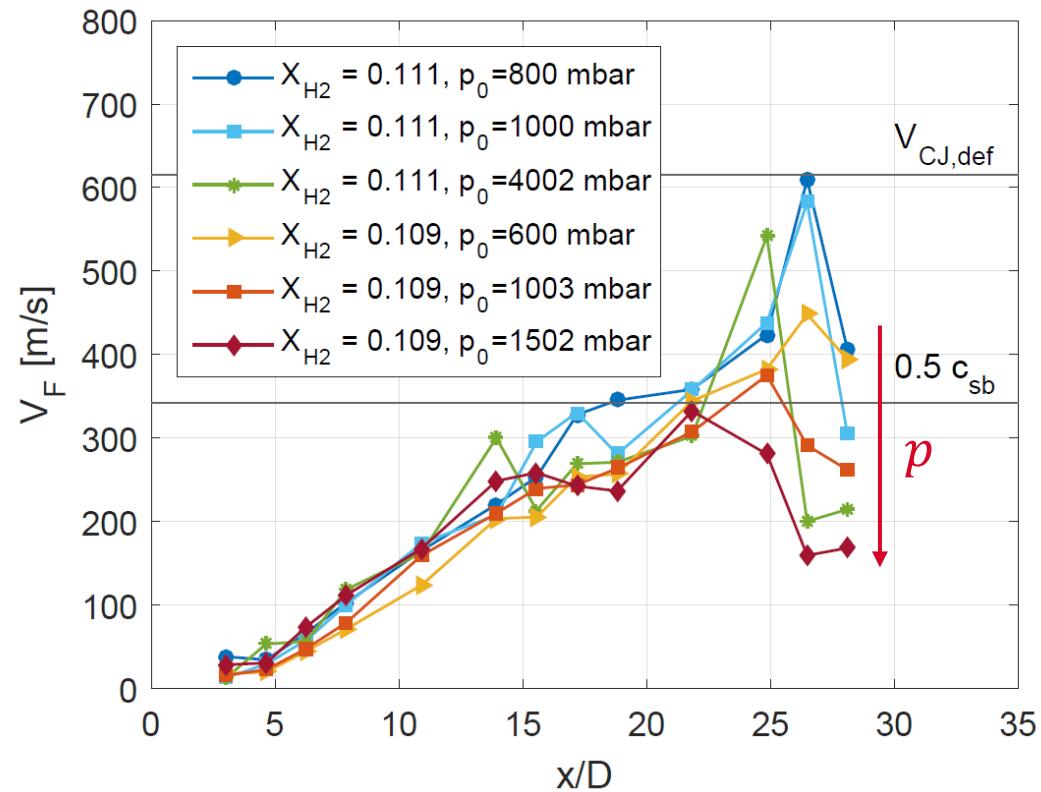
9 Pressure sensors

14 Shock sensors



Flame speed

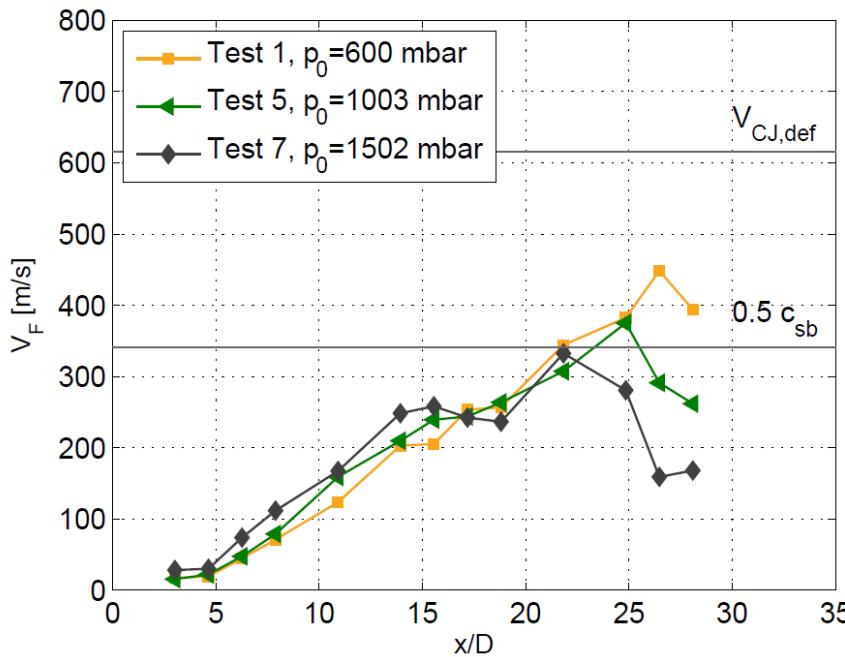
$$V_F = f(p)$$



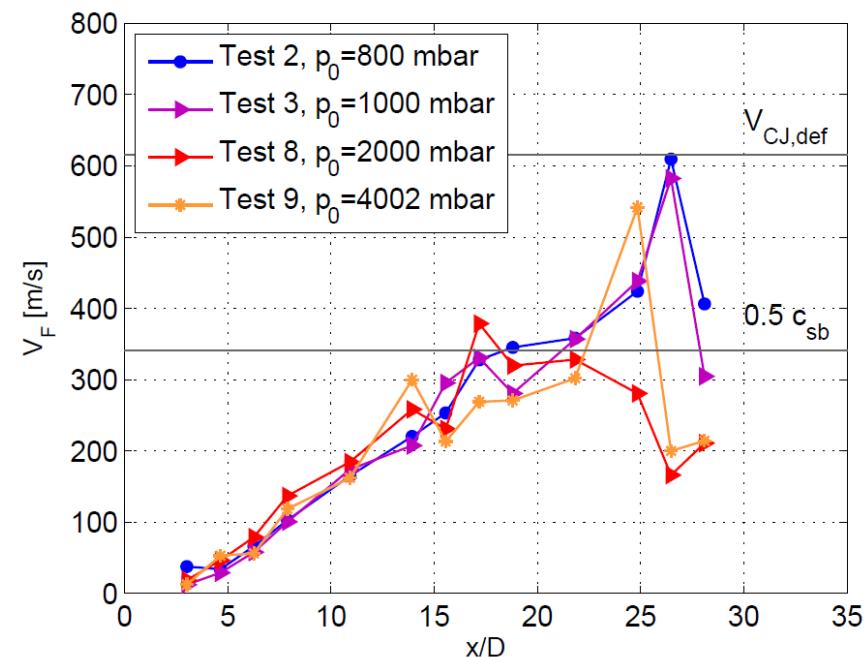
- No effects in the early stages of flame acceleration
- Flame slowdown at the end of the tube (interaction between the flame and the reflected shock)

Flame speed

$$\chi_{\text{H}2} = 10.9 \%$$



$$\chi_{\text{H}2} = 11.1 \%$$



- **1st phase of FA ($x/D < 15$):**
no significant differences;
- **2nd phase of FA ($x/D > 15$):**
for $\chi_{\text{H}2} = 10.9 \%$ $V_F \ll V_{\text{CJ,def}}$

Note that:

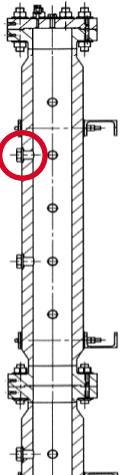
$V_F = 0.5 c_{sb}$ criterion for FA (Doorofeev1999)

$V_F = V_{\text{CJ,def}}$ criterion for chocked flame regime (Chue1993)

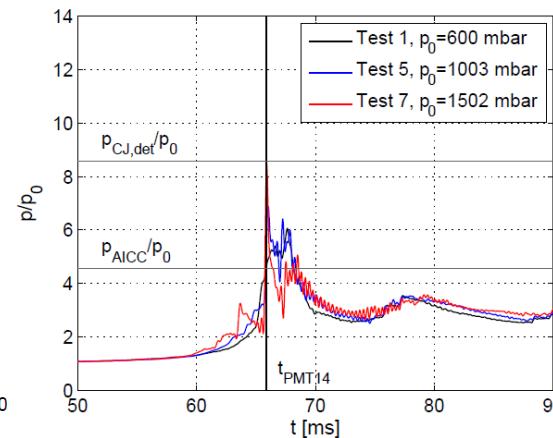
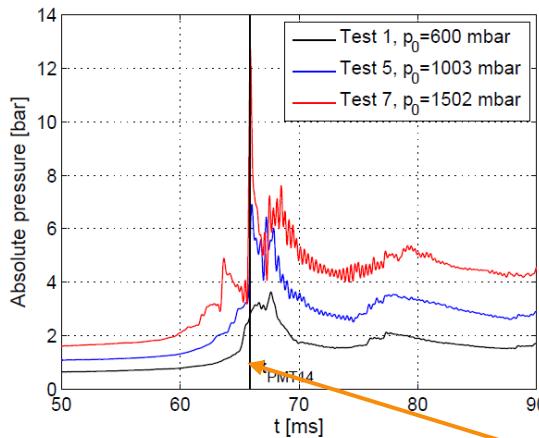
Pressure records

$$\chi_{H2} = 10.9 \%$$

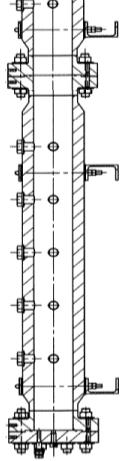
PP9



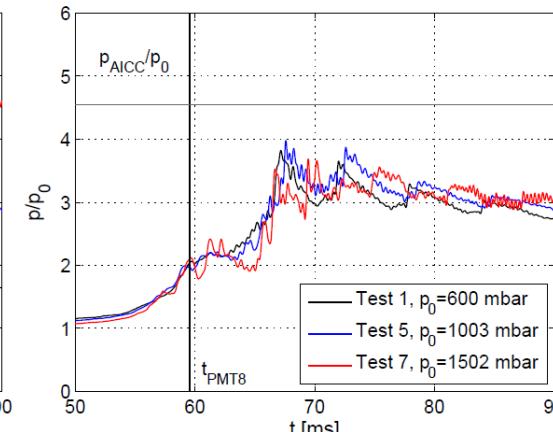
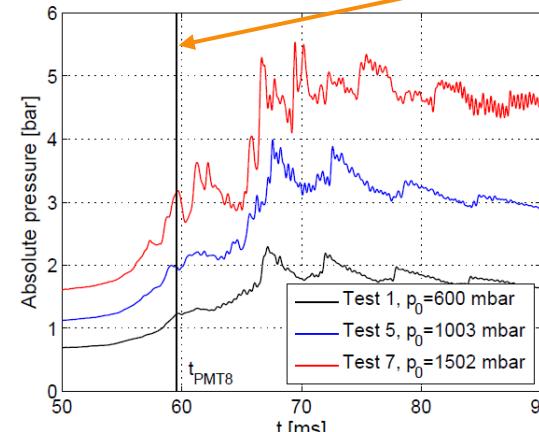
Capteur de pression PP9 ($x = 3470$ mm)



PP6



Capteur de pression PP6 ($x = 1965$ mm)



Flame time-of-arrival

Combustion pressure

$$p \propto p_0$$

- The leading shock wave ahead of the flame is more energetic as the initial pressure increases;

- Two consecutive reflected waves appear due to
 - (1) leading shock
 - (2) reaction front.
 As $p_0 \gg$ the magnitude of the shock reflected wave increases.

Conclusions and perspectives

- The effect of initial pressure on hydrogen/air flame acceleration was experimentally investigated. The **initial pressure was varied in the range 0,6 – 4 bar** for a lean mixture with $\chi_{\text{H}_2} = 11 \%$.
- Experiments showed:
 - **Early stages of flame acceleration are mostly unaffected by pressure variation:** the decrease of the laminar velocity is probably compensated by the increase of the cellular structures on the flame front;
 - The pressure evolution is proportional to the initial pressure: $p \propto p_0$;
 - In the **late stage** of flame propagation, **the flame tends to slow down**; this effect is more pronounced for higher initial pressure. The reason is mainly due to the interaction of the reflected shock wave with the flame front.
- Since $\chi_{\text{H}_2} = 11 \%$ corresponds to a quite unstable mixture, close to the lower limit for flame acceleration, **we foresee to test more reactive mixtures.**
- **The comparison with numerical simulation is ongoing.**

Acknowledgements

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Introduction

- Pressure ratio across a shock wave

$$\frac{p_2}{p_1} = \frac{2\gamma_1 \left(\frac{U_1}{c_{s1}} \right)^2 - (\gamma_1 - 1)}{(\gamma_1 + 1)}$$

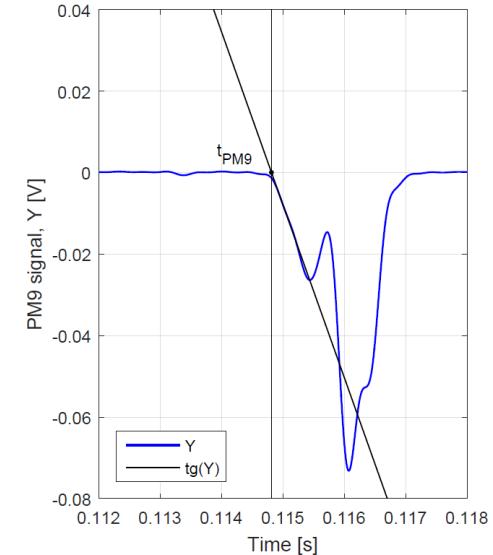
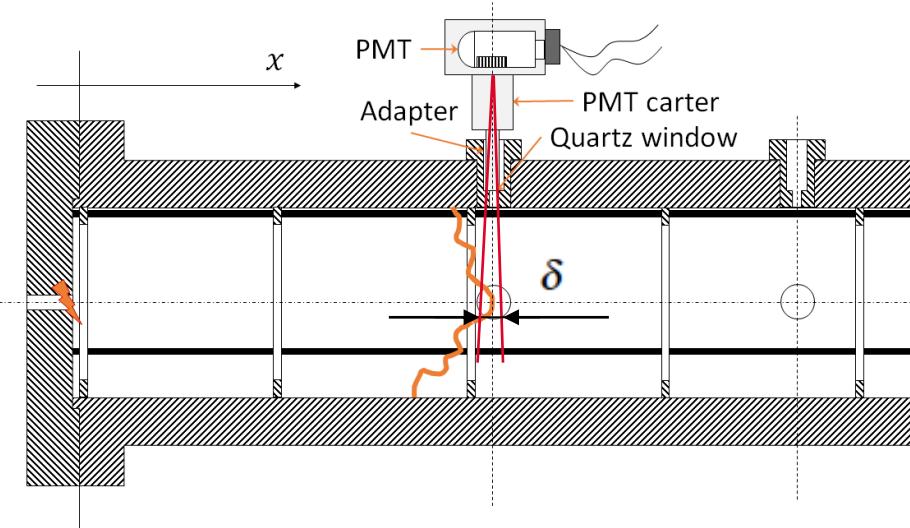
- Hydrodynamic force acting on a free-standing object:

$$\begin{aligned}
 F_H &= \frac{1}{2} C_d A \rho |U(t)| U(t) + && \text{Drag force} \\
 &+ (\rho V + m_a) \frac{\partial}{\partial t} (U(t)) + && \text{Inertia (buoyancy + added mass)} \\
 &+ V U(t) \frac{\partial \rho}{\partial t} + && \text{Change of mass per unit volume} \\
 &+ F_{DP} + && \text{Differential pressure, } f(\text{Ma}) \\
 &+ F_{HE} && \text{Hydro-elasticity (FSI)}
 \end{aligned}$$

- The **faster the flame/shock wave** is, the more important the **structural damage** becomes.

Flame tip velocity

- Determination of flame time-of-arrival with photomultiplier tubes:



- Average flame velocity between PMT^n and PMT^{n+1} :

$$\bar{V}(x) = \frac{\Delta x^{n+1}}{\Delta t^{n+1}} = \frac{x^{n+1} - x^n}{t^{n+1} - t^n} = V^{n+\frac{1}{2}}$$

- Uncertainty:

$$u^2(V^{n+\frac{1}{2}}) = \frac{2u^2(x)}{(\Delta t^{n+1})^2} + (\Delta x^{n+1})^2 u^2(t) \left(\frac{1}{(t^{n+1})^4} + \frac{1}{(t^n)^4} \right)$$

$$\frac{u(V)}{V} < 5\%$$

$u(x) \simeq \delta$
Uncertainty on the flame position (PMT solid angle)

$u^2(t) = u^2(\text{TTS}) + u^2(t_{\text{PM}\#})$ → Signal post-processing method
Sensor response time ($\approx \text{ns}$)

RDEM model

- Velikorodny et al. (2015) Combustion modeling in large scale volumes using EUROPLEXUS code :

Reactive Euler equations

$$\begin{cases} \frac{\partial}{\partial t} \rho + \vec{\nabla} \cdot (\rho \vec{U}) = 0 \\ \frac{\partial}{\partial t} (\rho \vec{U}) + \vec{\nabla} \cdot (\rho \vec{U} \otimes \vec{U} + P) = 0 \\ \frac{\partial}{\partial t} (\rho \tilde{e}_t) + \vec{\nabla} \cdot (\rho \vec{U} \tilde{h}_t) = 0 \\ \frac{\partial}{\partial t} (\xi) + \vec{D} \cdot \vec{\nabla} \xi = 0 \quad \text{Progress variable} \end{cases}$$

Riemann solver: flame = propagating interface
 (Beccantini A., Studer E. (2009) The reactive Riemann problem for thermally perfect gases at all combustion regimes)

Model for flame propagation

$$\vec{D} = \vec{U} + K_0 \vec{n} \quad \vec{U} \text{ Velocity of the unburnt gas}$$

K_0 Flame velocity

$$K_0 = S_L^0 \Theta_{TH} \Theta_{TURB}$$

