THE STRUCTURE AND FLAME PROPAGATION REGIMES IN TURBULENT HYDROGEN JETS

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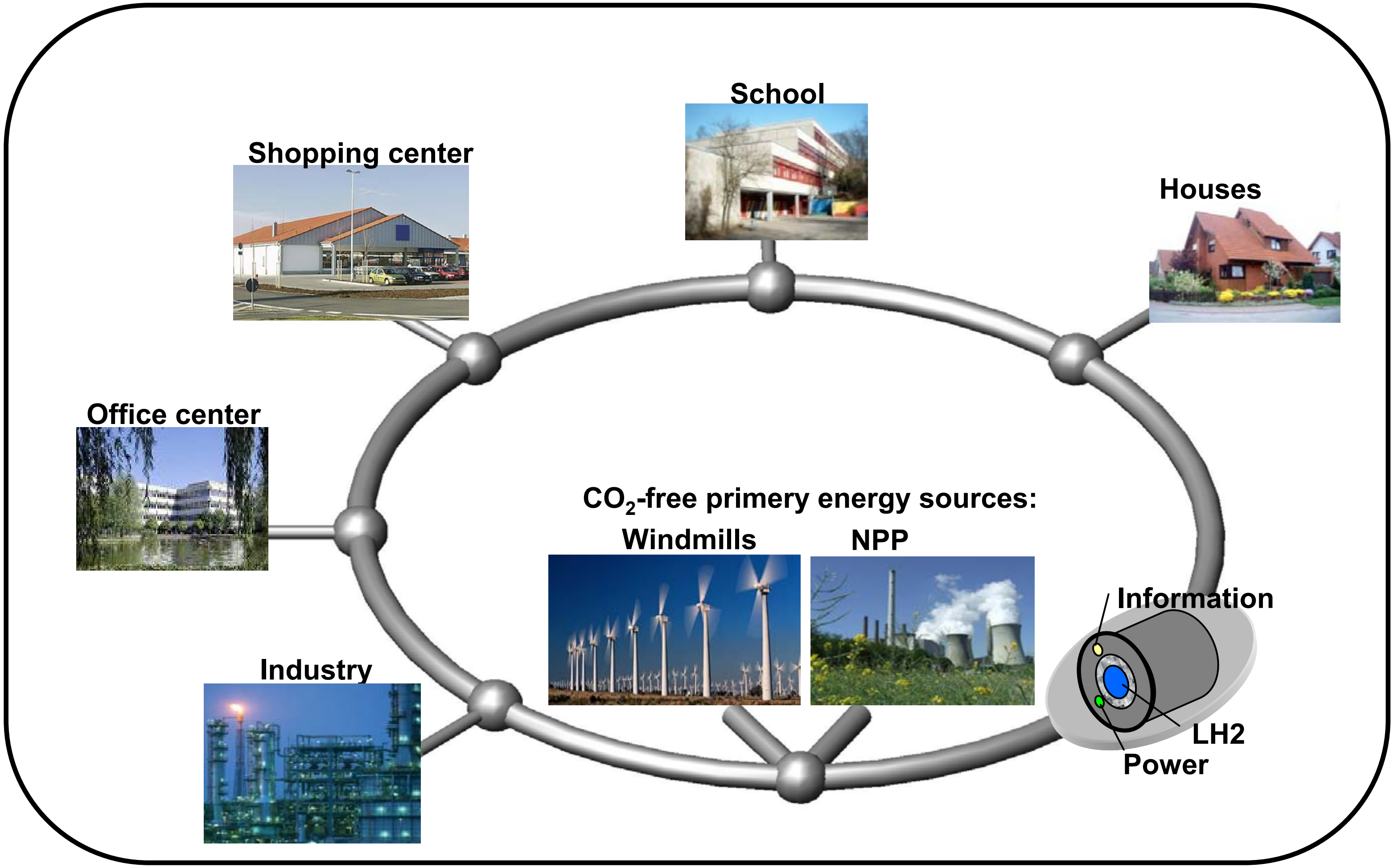
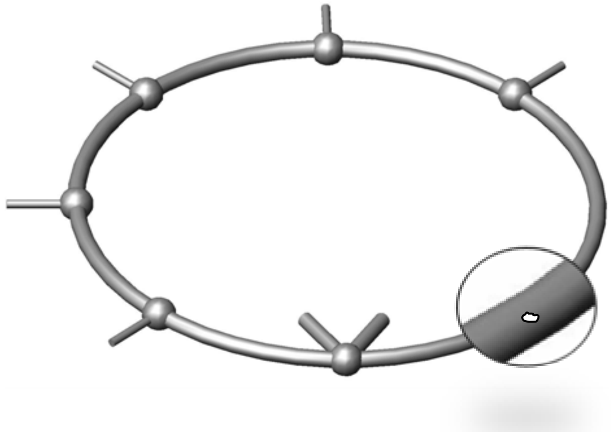
icefuel® **integrated cable energy system for fuel and power**
(R&D-Project)

- **ICEFUEL – Energy System of the Future:**



Accident scenarios

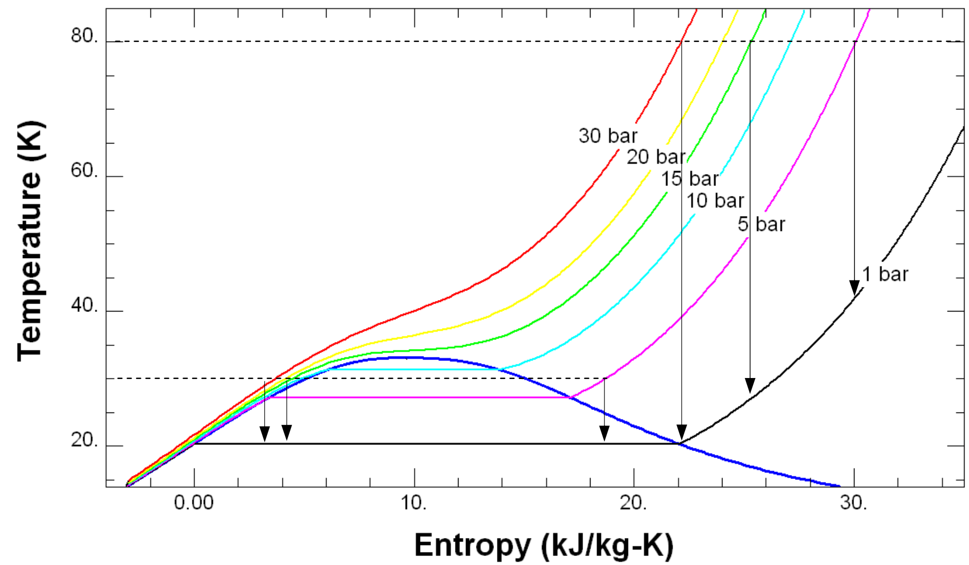
- **Free release from Icefuel - cable**

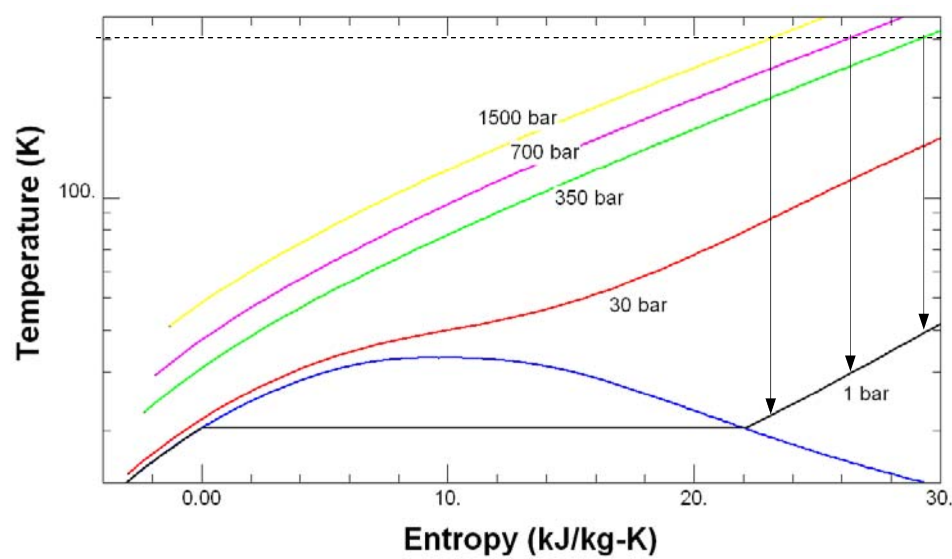


Effective leak diameter 1-4 mm

- Proposed operating conditions of the Icefuel-cable: p = 15-30 bar, T = 20-33K
- Depending on the initial hydrogen state we will have two phase flow, one phase liquid flow or one phase gas flow under iso-entropic hydrogen release
- Simplest case of high pressure hydrogen release at temperature T = 293K has to be investigated as a reference scenario

- **Diagram of state of para-H2**





Objectives

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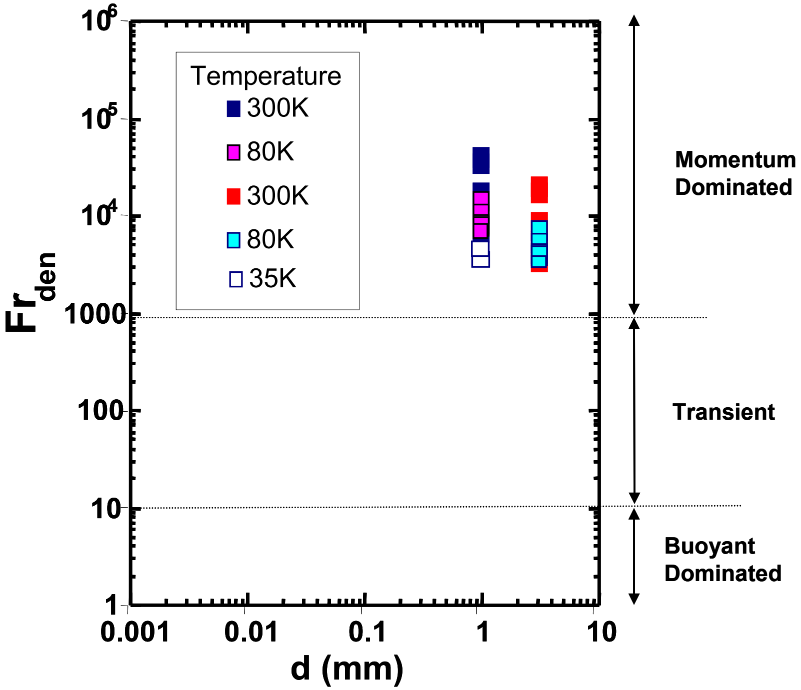
- In current work we consider an accident scenario in which the hydrogen pipeline is broken and the released hydrogen jet is ignited
- In order to estimate the hazard potential we have to study the properties of unburned and burned hydrogen jets released from a pressurized pipeline at an ambient temperature to compare in further work the same properties for a hydrogen jet at cryogenic temperatures 30K and 80K

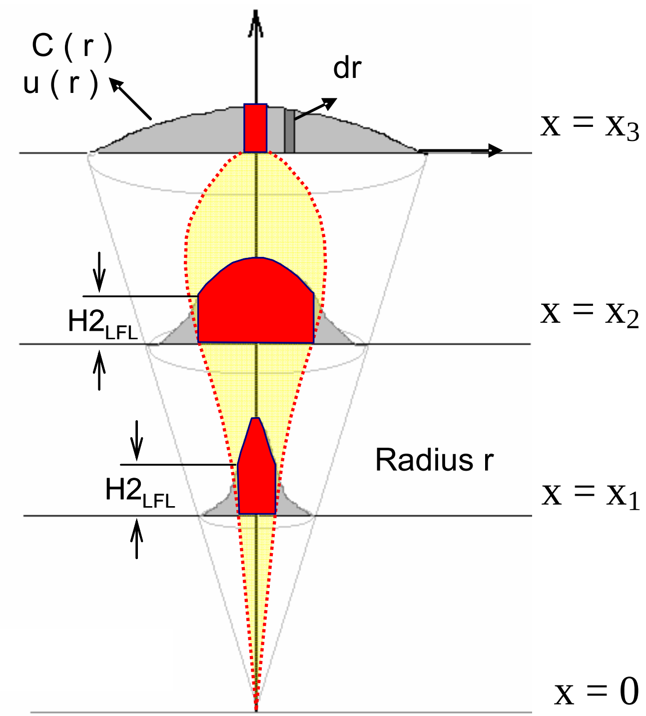
High momentum jet characteristics



- The buoyancy to inertia ratio is expressed by densimetric Froude number:

$$Fr = \frac{\rho_0 \cdot u_0^2}{(\rho_\infty - \rho_0) \cdot g \cdot d_0}$$

- We can use Chen-Rodi correlations for high momentum jet:



- Axial concentration:

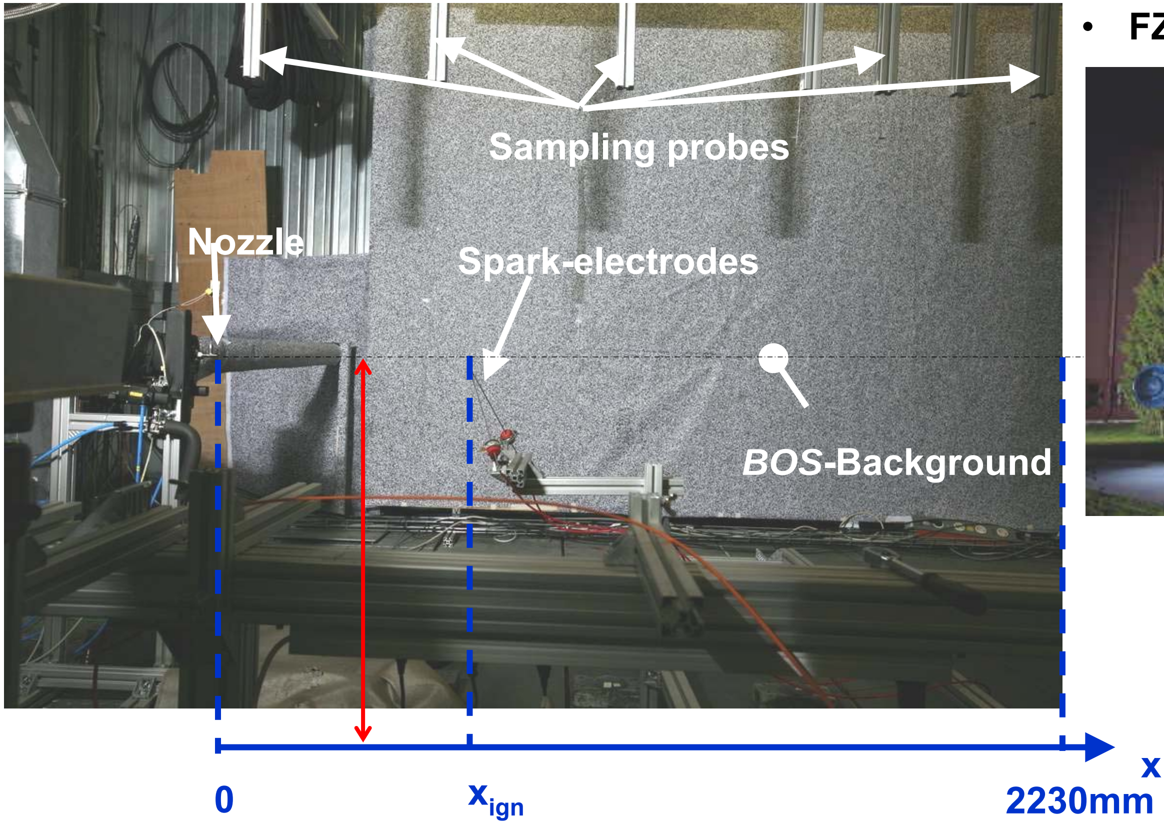
$$C(x) = A \cdot C_0 \cdot \frac{d_{ef}}{x + x_0} \left(\frac{\rho_a}{\rho_{H_2}} \right)^{1/2}$$

- Axial velocity:

$$u(x) = u_0 \cdot B \cdot \left(\frac{x + x_0}{d_0} \right)^{-1}$$

Experimental set-up and variables

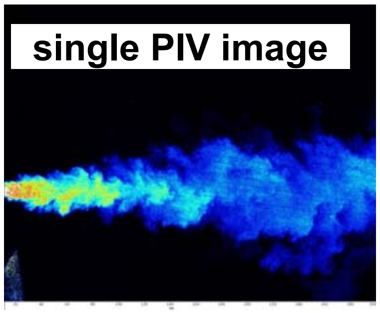
- Pressure 5-60 bar
- Temperature 30-298 K
- Nozzle diameter 0.5, 1, 2 and 4 mm
- Hydrogen mass flow rate 0.3 – 6.5 g_{H2}/s
- Ignition positions 0-2.5 m from the nozzle

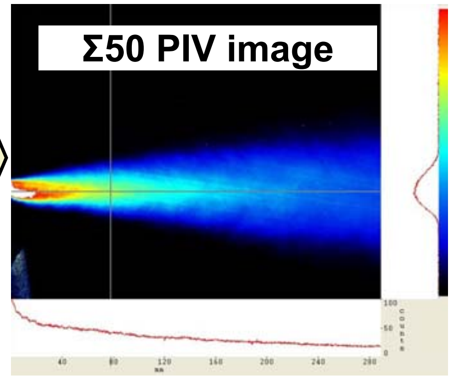


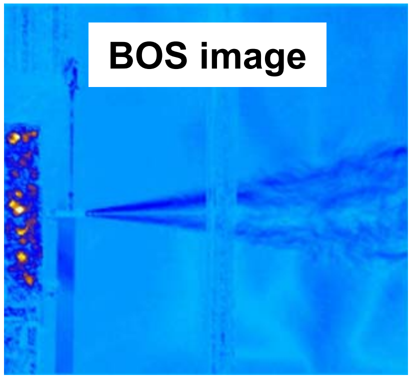
- **FZK experimental test site HYKA**

- **Room dimensions: 5.5 x 8.5 x 3.4 m ($V = 160\ m^3$)**

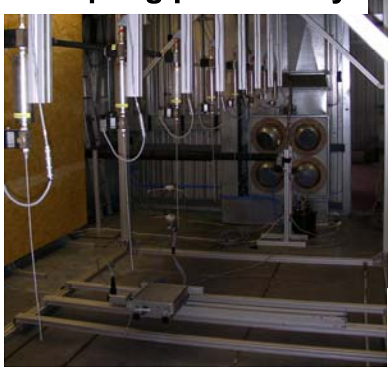
- **Structure and characteristics of free hydrogen jet:**
  - Laser velocimetry - PIV (Particle Image Velocimetry - tracer: oil drops Ø2 µm
  - H_2 distribution - Background Oriented Schlieren (BOS) up to 1000 fr.p.s
  - Hydrogen concentration (sampling probes)



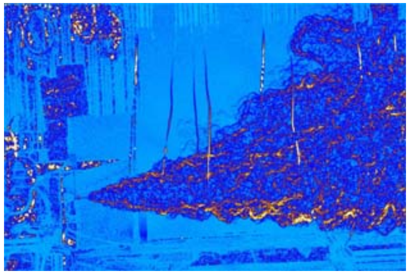




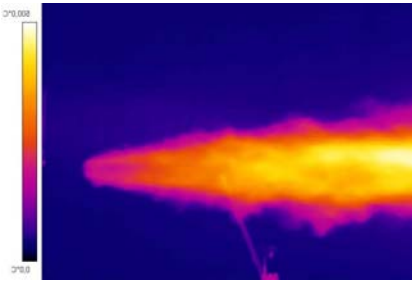
Sampling probe array



- **Ignition and flame propagation regimes:**
  - Ignition position
  - flame velocity (BOS up to 1000 fr.p.s)
  - flame temperature (IR camera 25 fr.p.s)
  - pressure



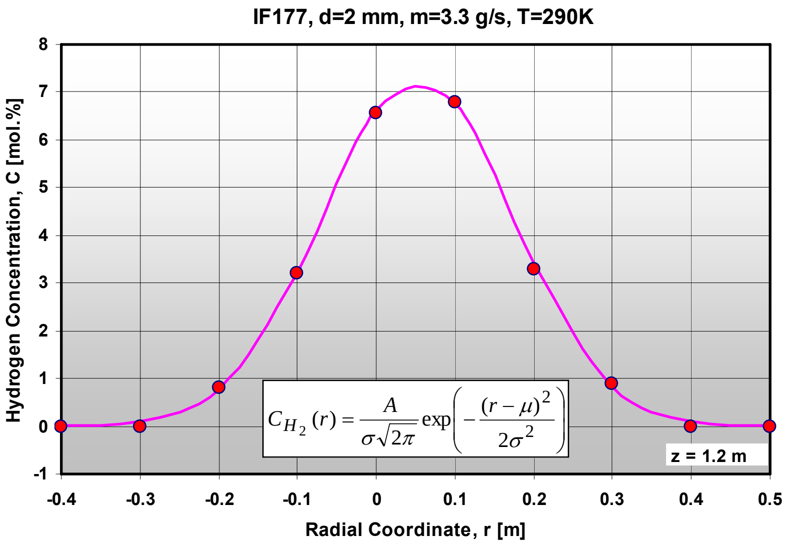
BOS image

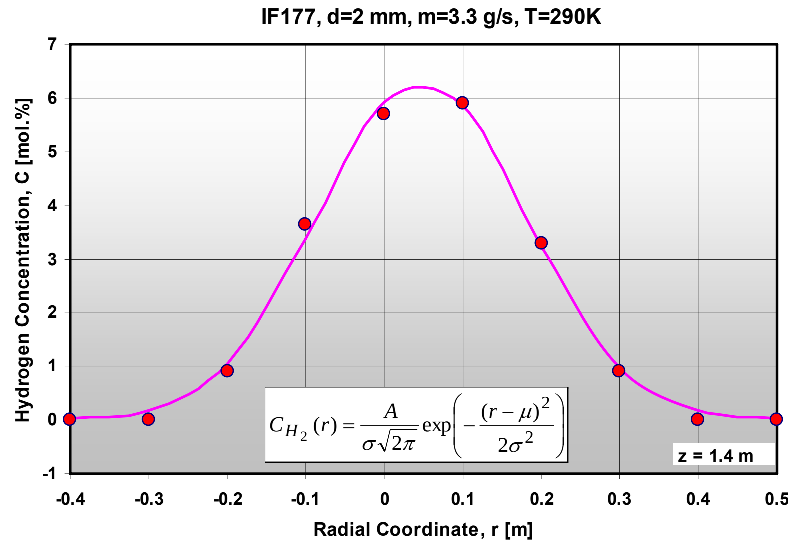


IR image

Radial hydrogen concentration profile $C_{H2}(r)$

Sampling probes - measurements



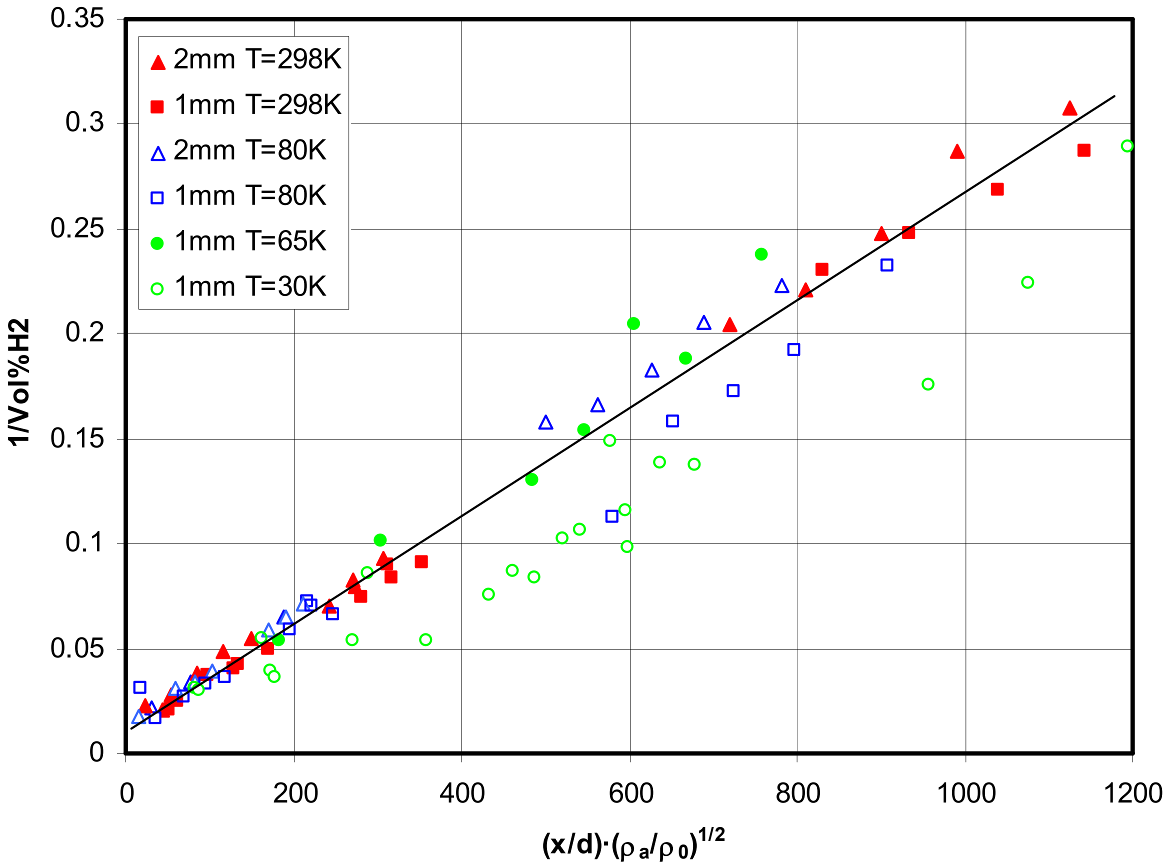


H_2-free jet, 290K, distances from the nozzle x = 1.2 and x =1.4 m

- Gaussian profile of radial hydrogen concentration

Axial hydrogen concentration profile u(x)

H_2- jet (30K, 80K, 298K)
Sampling probes – measurements



- Hyperbolic decay of axial H2 concentration with distance
- Dependence can be easily linearized in consistency with Chen-Rodi correlation
- 30K data deviate from higher temperature data due to two-phase flow effect

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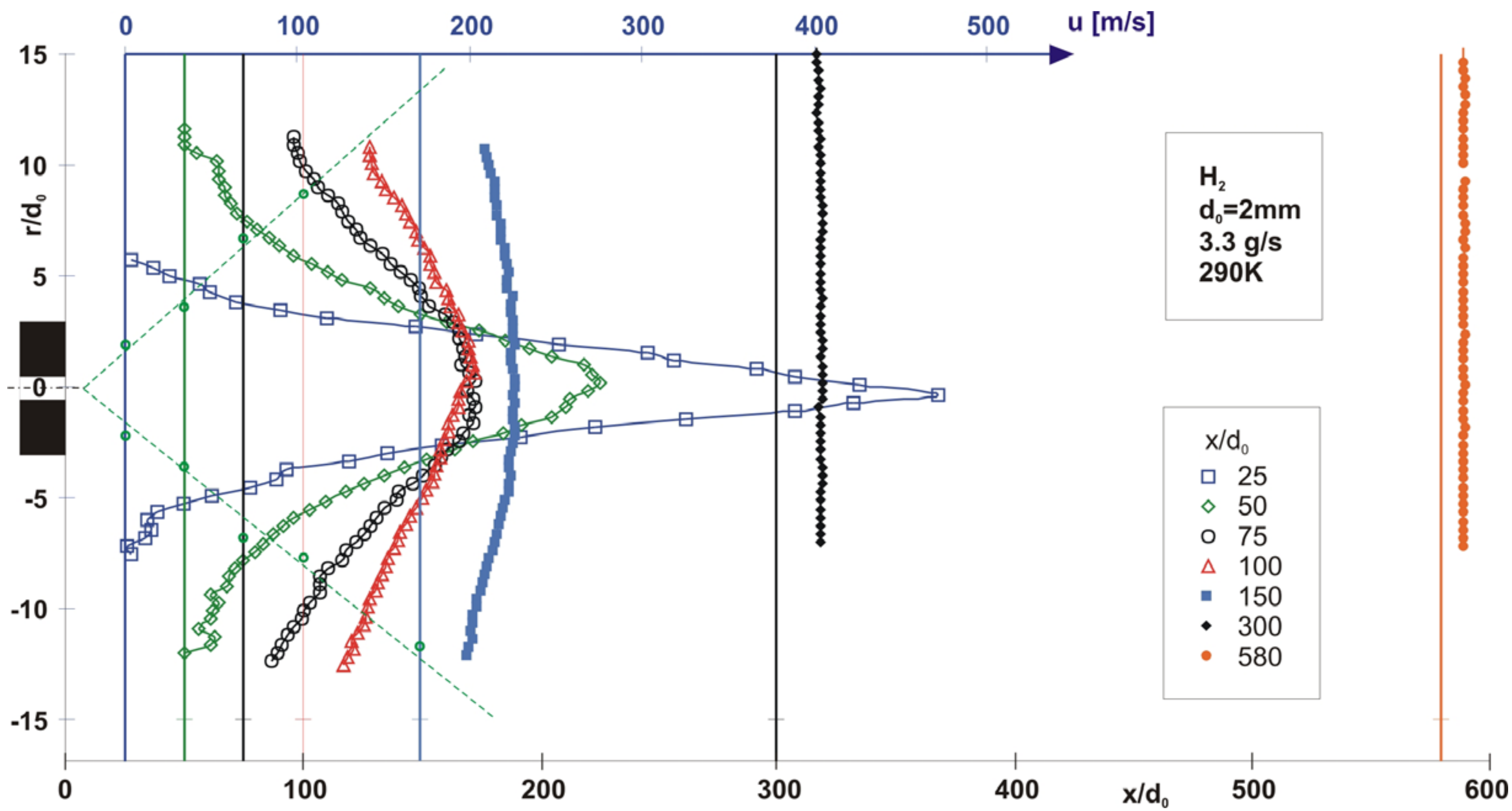
PIV - measurements



H_2-free jet, 290K, different axial positions x/d_0

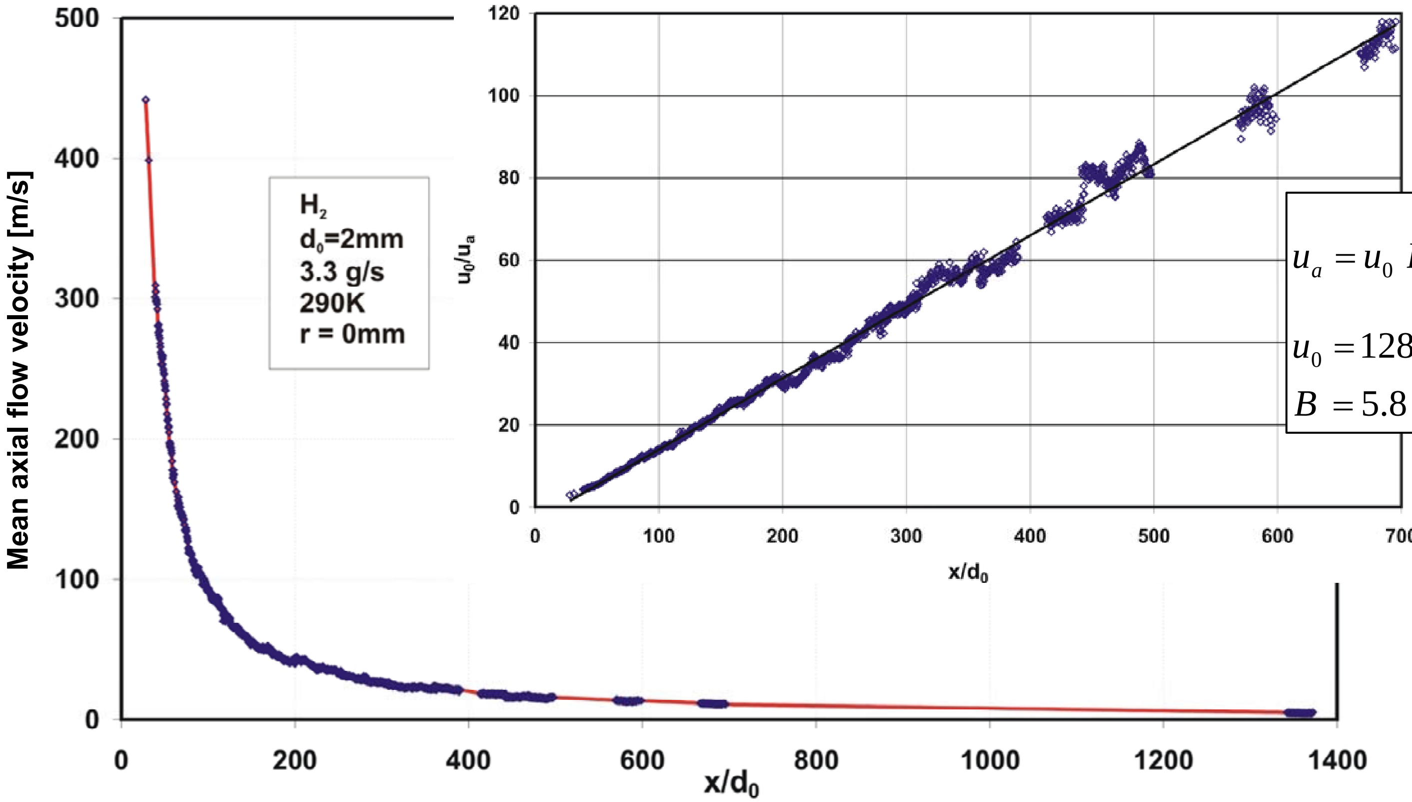
- Practically ideal Gaussian profile of radial flow velocity
- Flow opening angle is about 22° - 25°

Axial velocity in free hydrogen jet

2D-PIV measurements of flow velocity at 290 K

$$\vec{v} = \begin{pmatrix} u \\ v \end{pmatrix}$$

Hyperbolic decay of axial flow velocity with distance



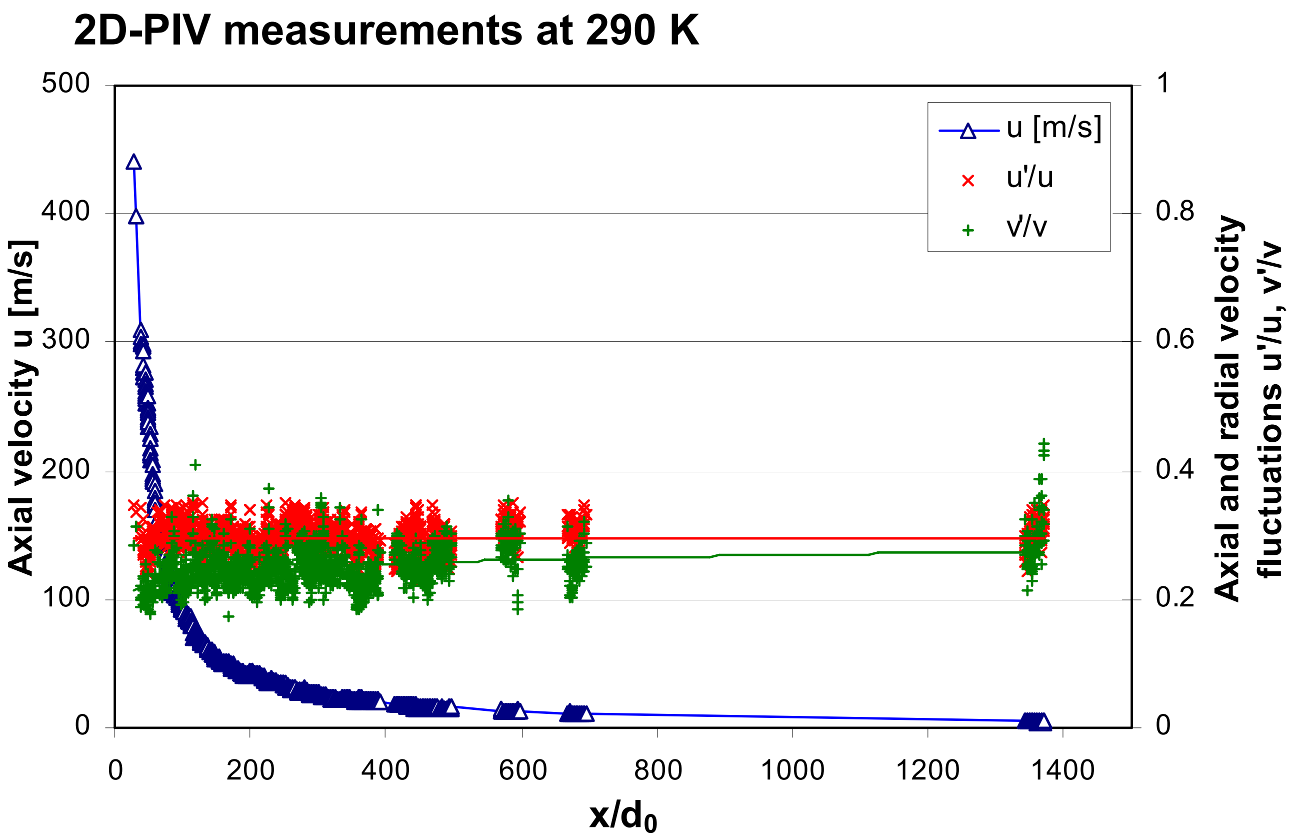
$$u_a = u_0 \, B \left(\frac{x - x_0}{d_0} \right)^{-1}$$

$u_0 = 1282 \frac{m}{s}$ $\quad d_0 = 2\ mm$

$B = 5.8$ $\quad x_0 = 38.4\ mm$

- Hyperbolic decay of axial flow velocity with distance
- Dependence can be easily linearized in consistency with Chen-Rodi correlation

Axial and radial fluctuations of flow velocity

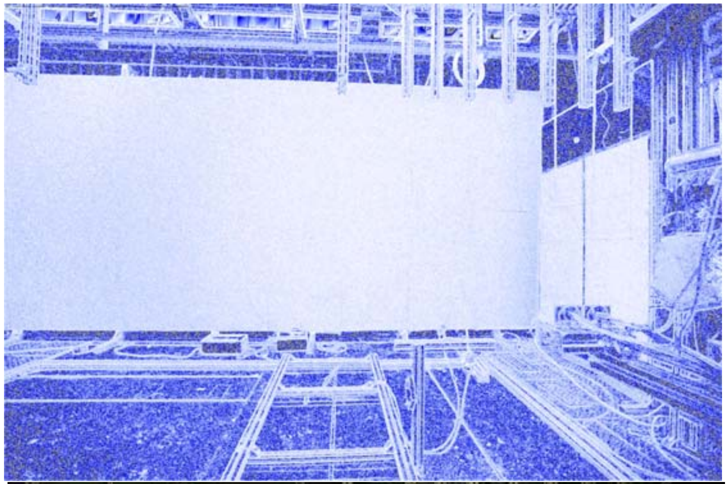


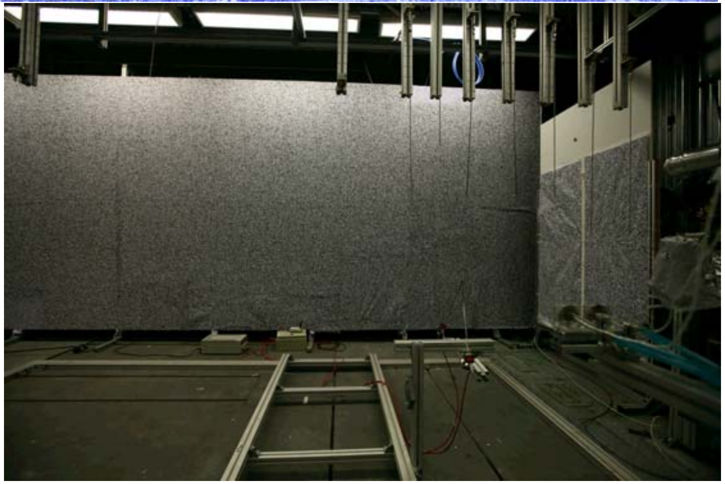
- The measured mean axial velocity fluctuations at the center line are remains practically constant $u_{rms}/\bar{u}$ ~30% for all measured positions along the jet axis up to the distance of 25 d_0
- The averaged radial turbulence level $v_{rms}/\bar{v}$ increases from 22% at 25d_0 to 30% at 1400d_0

Flame propagation regimes

30K experiments
d=0.5 mm
P=30 bar

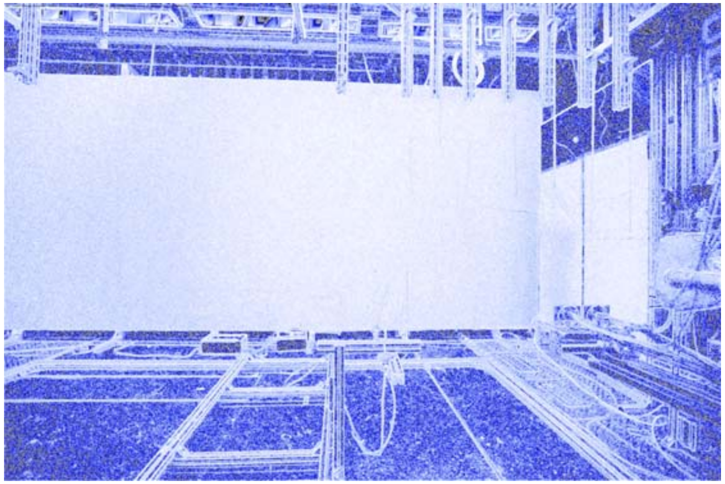
Fast flame





x = 1.5 m

Slow flame



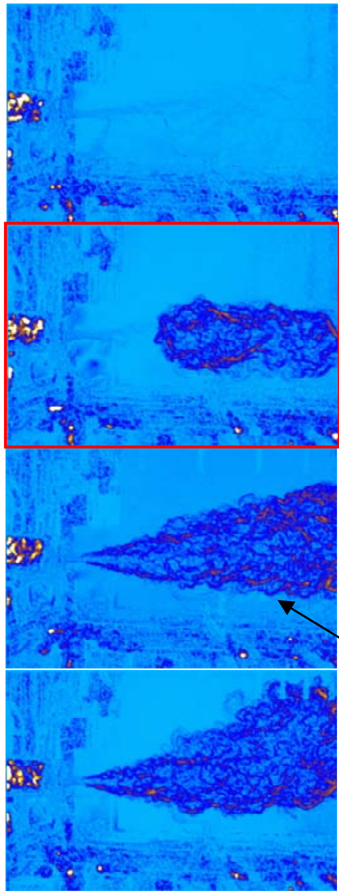
x = 1. 6 m

- Distance :
  - no ignition
  - slow flames and local quenching
  - fast flame acceleration

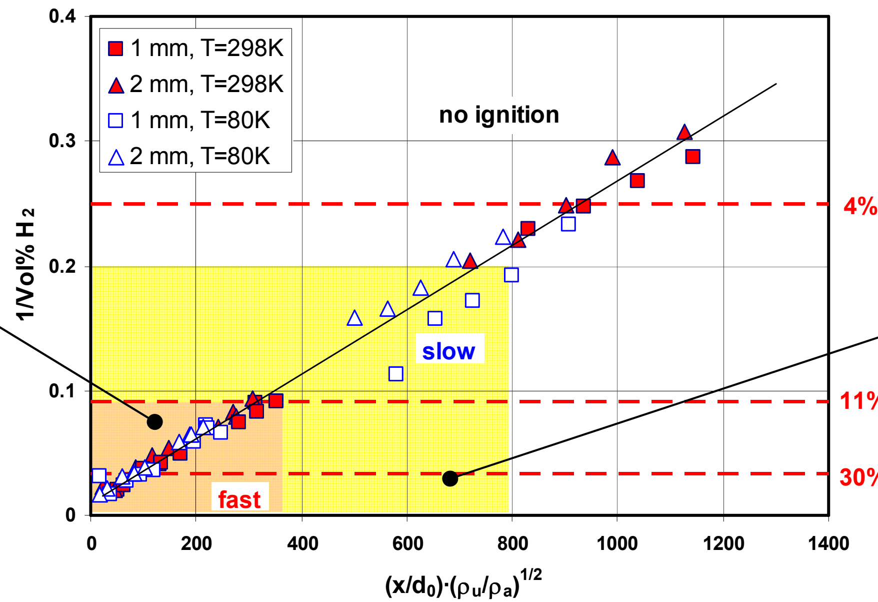
Flame propagation regimes in hydrogen jet

- Flame propagation regimes in H_2-jet:
  - no ignition
  - slow flames and local quenching
  - fast flame acceleration

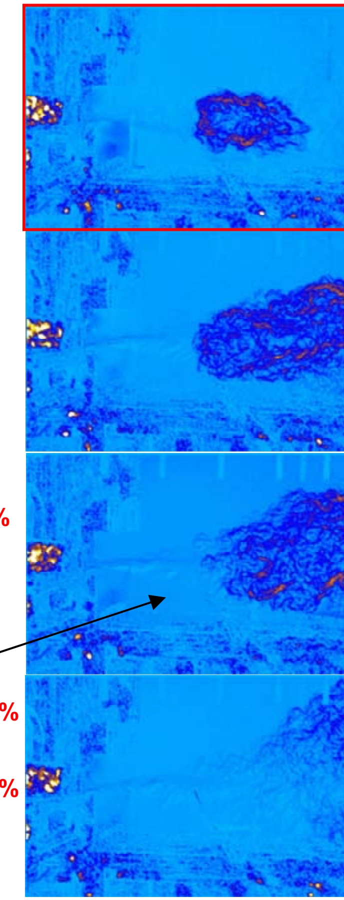
x_{ign} = 800 mm



H_2-jet (5 bar, 290K),
Ønozzle = 4 mm,
t_{inj}=3s (3.5 g/s),
framing time step = 300ms



x_{ign} = 900 mm

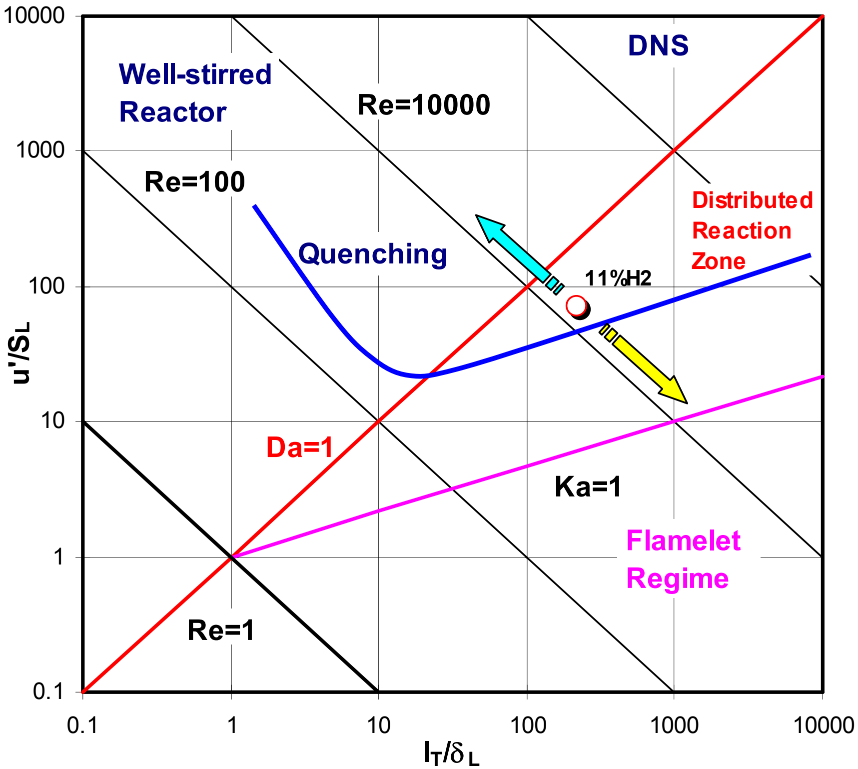


Flame

Jet flow

Flame propagation regimes in hydrogen jet

Phase diagram of turbulent flame propagation regimes



- **Laminar flamelet regimes** (Ka<1, Da >1) Typical for highly reactive laminar or quasi-laminar flames ($t < t_K$). Thin flames zone. Maximum what turbulence can achieve is to wrinkle the flame
- **Distributed reaction zone** (Ka>1, Da >1) Typical for thick flames. Small eddies already can penetrate into the flame brush to make it thicker ($t_T > t > t_K$). Wrinkled or corrugates flames. Above the quenching line local quenching can occur.
- **Well stirred reactor zone** (Ka>1, Da <1) Turbulence destroy flame brush ($t_T < t$). Global quenching can occur.

Critical point characteristics (C_{H2} = 11%):

- Turbulent pulsations and flow velocity: u'/u = 25%; u = 57 m/s
- Laminar velocity and flame thickness: S_L= 0.2 m/s, δ_L = 0.23 mm
- Integral scale (large eddies size): l_T >= 5 cm (conservative) ➔ l_T / δ_T~ 200
- Dimensionless turbulent pulsations : ➔ u'/S_L = 70

Conclusions

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- Horizontal quasi-stationary high-momentum hydrogen jets with different temperatures, nozzle diameters and different mass flow rates in the range from 0.3 to 6.5 g/s have been investigated
- An optical PIV method and sampling probe techniques combined with a gas analyzer have been used for jet structure investigation. It was shown that the experimental data are in good consistency with Chen - Rodi scale correlation
- Combustion experiments with variable ignition points showed that stable flame with maximum flame velocity can only occur if the hydrogen concentration at the ignition point exceeds 11% of hydrogen. In this case the flame propagates up- and downstream the jet, whereas in case of less than 11% of hydrogen the flame propagates only downstream or quenches
- The data on hydrogen jet combustion are in good consistency with our previously proposed expansion ratio- or σ-criterion as a flame acceleration potential

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