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Hydrogen fires

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Outline

- Introduction to hydrogen fire
- Types of hydrogen fires
- Microflames
- Jet fire basics – what do we know?
- The dimensional correlation for flame length
  - Worked example
- Harm criteria
- Unattached versus attached jet fires
- A note on indoor fires

Types of hydrogen fires

- From micro- (10^{-9} kg/s) to high debit flames (10 kg/s)
- Laminar diffusion and turbulent non-premixed flames
- Buoyancy- and momentum-dominated jets
- Subsonic, sonic and highly under-expanded supersonic jet flames
- Little knowledge of liquefied hydrogen (LH2) fires
- Impinging flames will not be discussed here but also important
- Jet flames in the presence of obstacles, surfaces and in confinement

Hydrogen fire: some facts

- Hydrogen burns with an invisible flame (Video 1 & 2)
- The main product of hydrogen combustion is water
  - No soot – hence the radiation is less (twice) than a hydrocarbon flame!

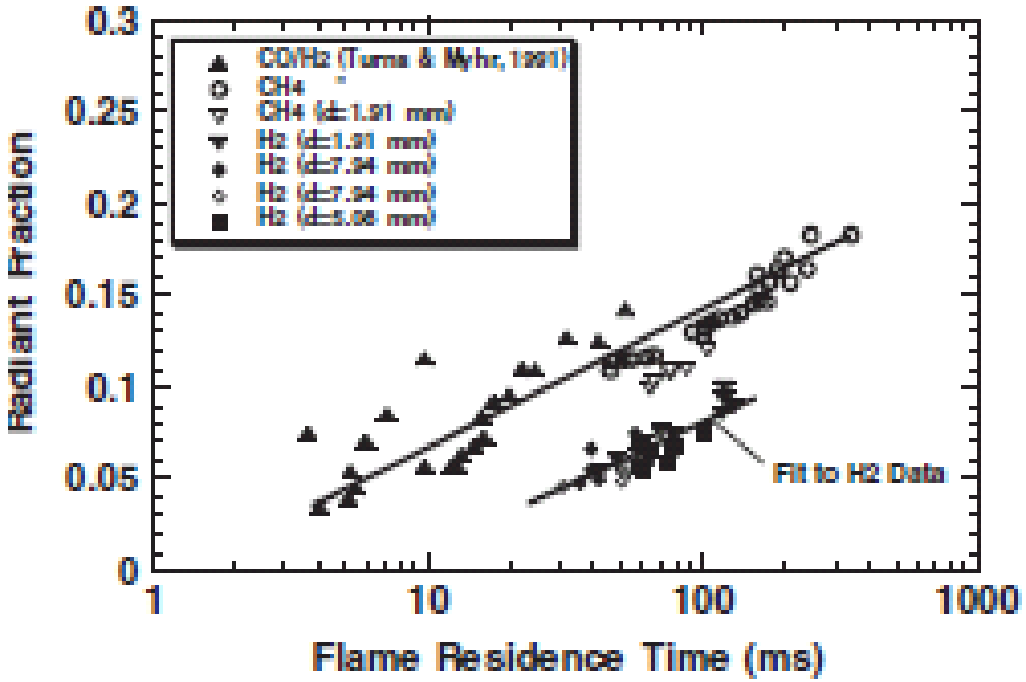
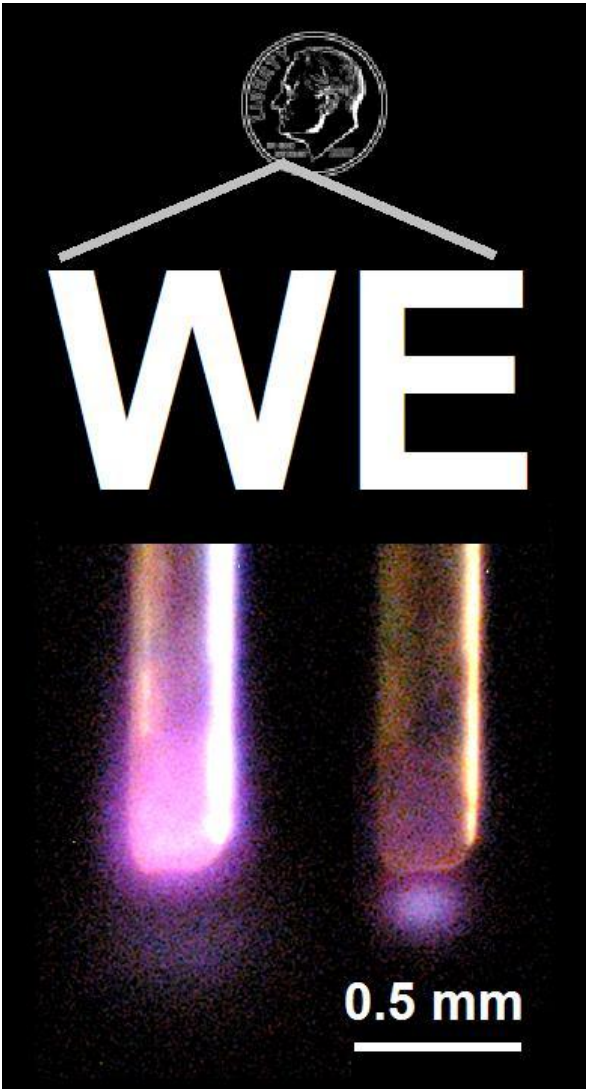


Figure source: Predicting radiative heat fluxes and flammability envelopes from unintended releases of hydrogen William Houf, Robert Schefer, International Journal of Hydrogen Energy 32 (2007) 136 – 151

The radiant fraction, X_{rad}, is defined as the fraction of the total chemical heat release that is radiated to the surroundings and is given by an expression of the form $X_{rad} = S_{rad}/m_{fuel}H_c$.

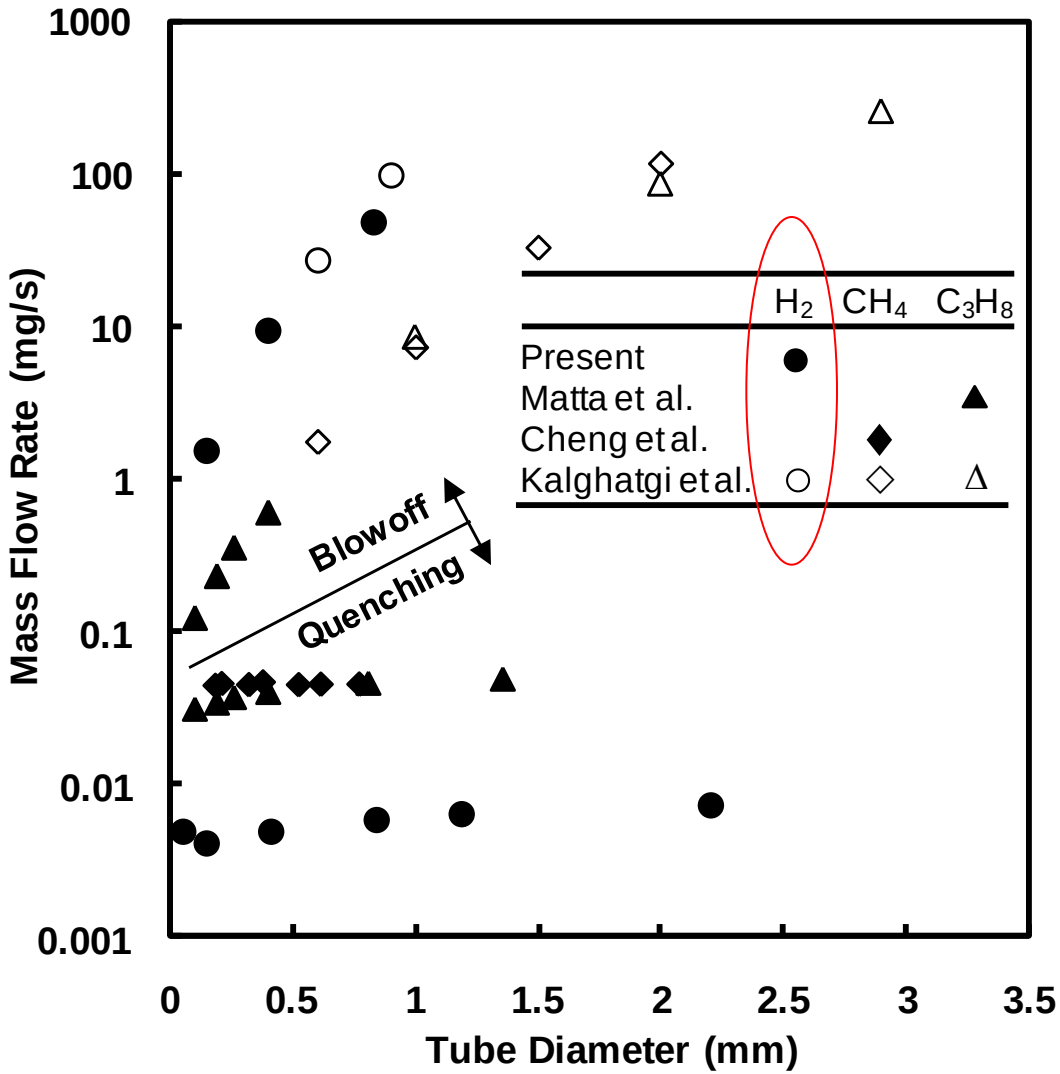
Microflames
(P. Sunderland et al.)

Weakest flame



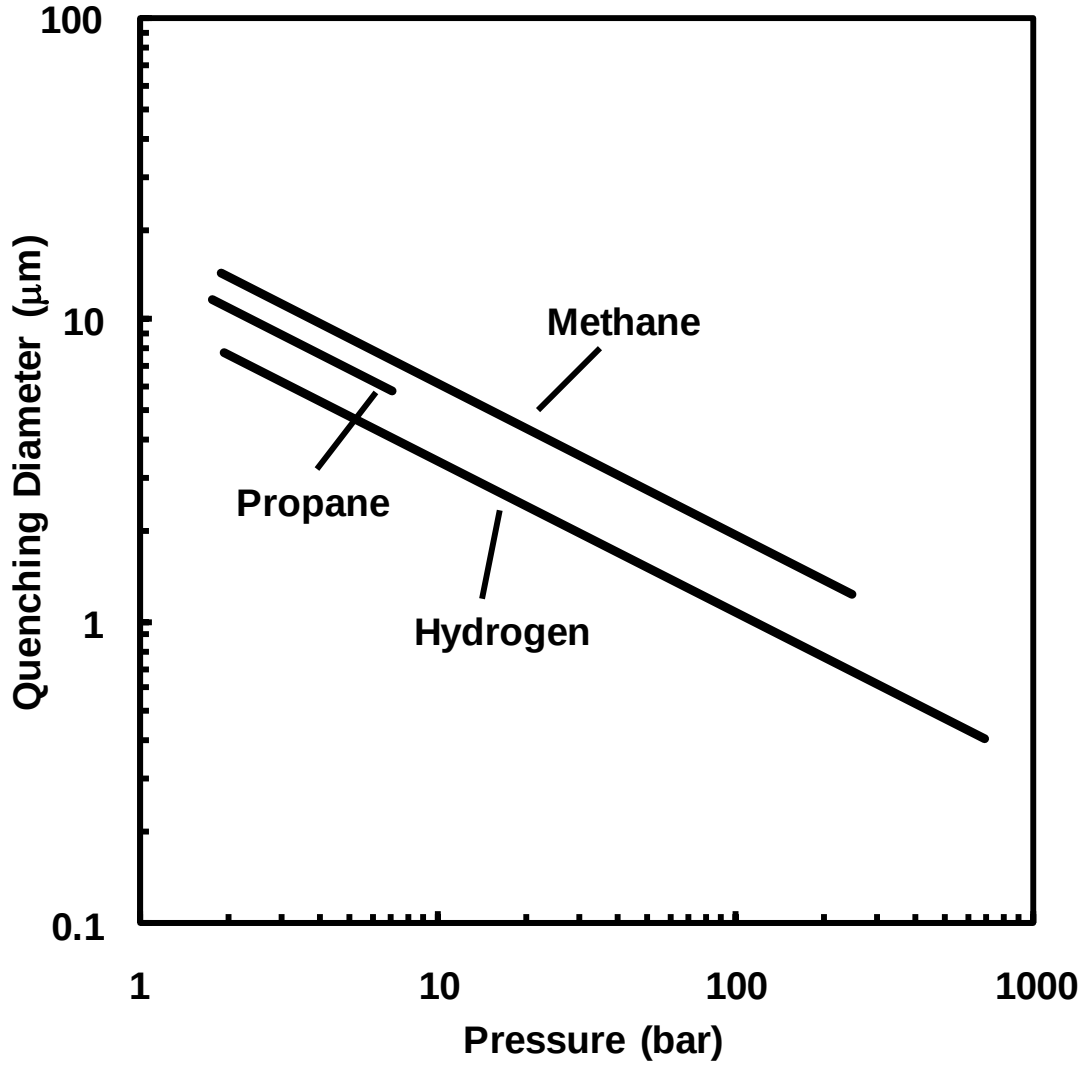
- **Hazard**: the small leak burns undetected for a long period, damaging the containment system and providing an ignition source for a subsequent large release.
- **Left**: hydrogen flowing downward into air (mass flow rate 3.9 μg/s, power 0.46 W).
- **Right**: hydrogen flowing downward into oxygen (2.1 μg/s, 0.25 W).
- The tube inside and outside diameters are 0.15 and 0.30 mm respectively. The exposure time 30 s (required to register).
- The previous record for hydrogen flame balls was 0.5-1.0 W (Ronney et al., 1998).
- SAE J2600 permits hydrogen leak rates below **200 mL/hr (0.46 μg/s) – no flame!**

Quenching and blowoff



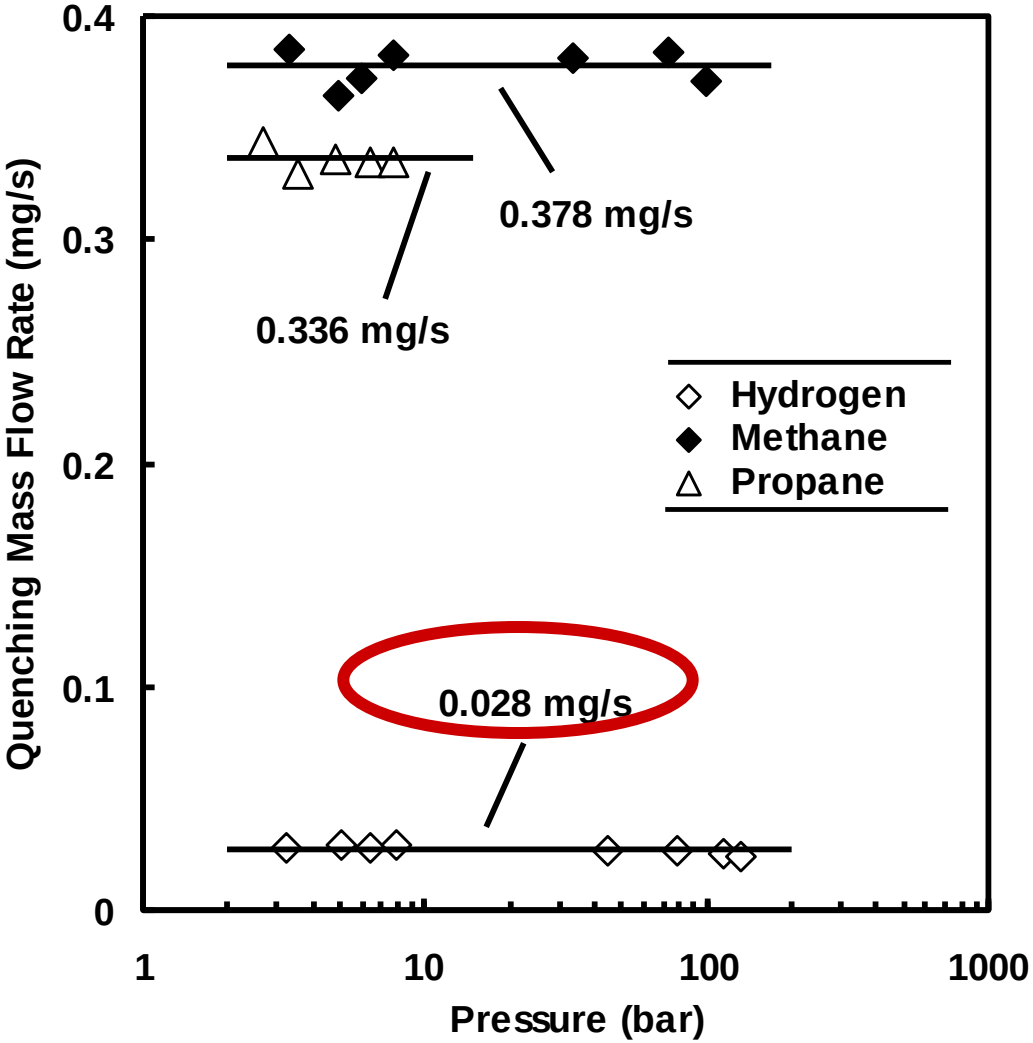
- Tube burner is used.
- **Quenching limits are nearly independent of diameter.**
- Hydrogen has the lowest quenching limit and the highest blowoff limit.
- Source orientation and geometry examined but not shown here

Quenching diameter

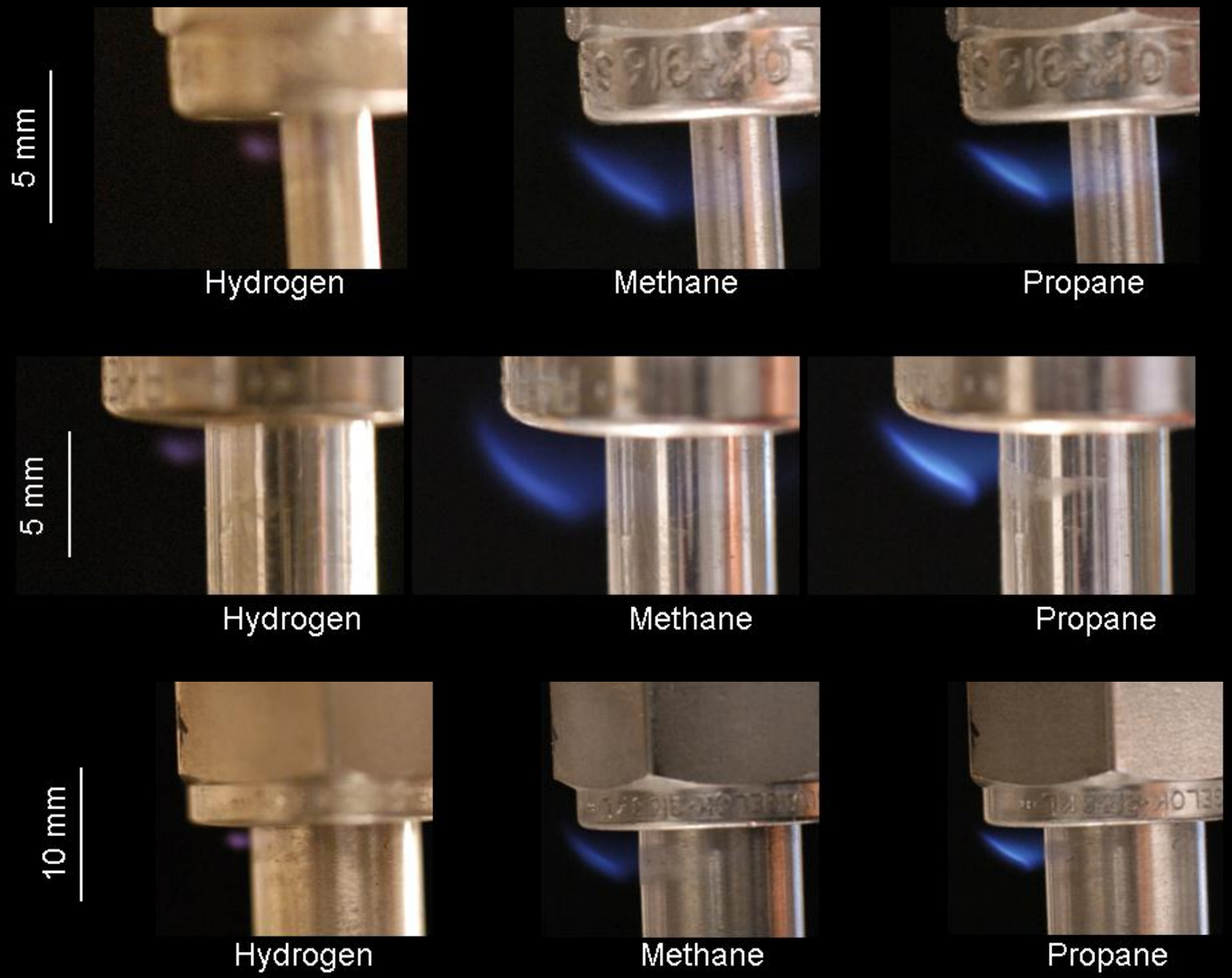


- Upstream pressure required for 5.6 μg/s hydrogen isentropic choked flow is shown.
- For hydrogen at 690 bar, **any hole larger than 0.4 μm will support a stable flame**.

Leaky fittings

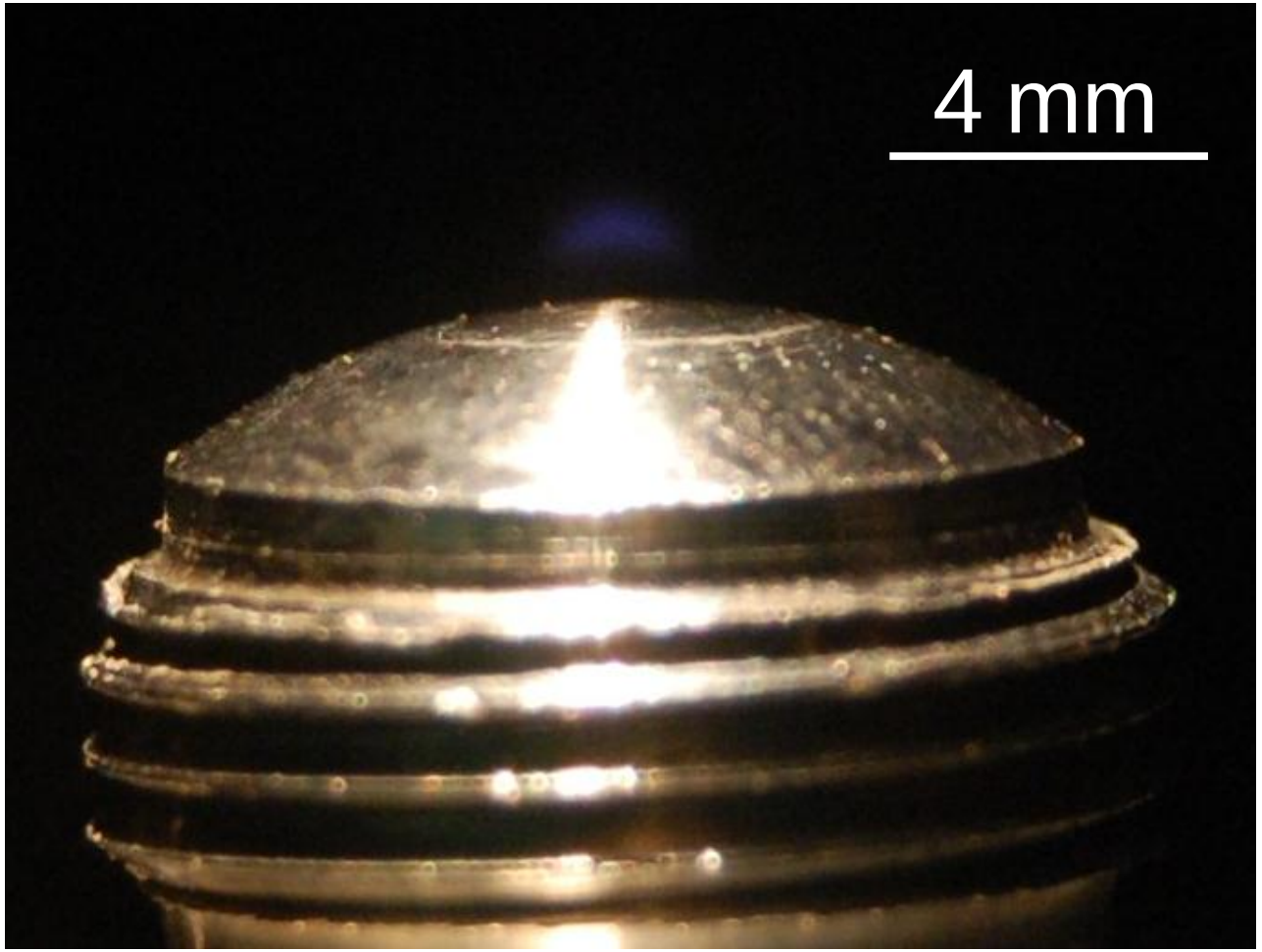


- Quenching limits for a 6 mm compression fitting are shown.
- Limits are independent of pressure.
- **Limits are about 10 times of those of tube burners.**
- Hydrogen limits are the lowest.


5 mm
Hydrogen
Methane
Propane
5 mm
Hydrogen
Methane
Propane
10 mm
Hydrogen
Methane
Propane

Microflame length

- Test 1 (picture): L_F=**1 mm**, m=7.5 μg/s, D=0.36 mm Stand-off height is 0.25 mm.
- Test 2: L_F=**0.4 mm**, m=3.9 μg/s, D=0.15 mm



What we can and cannot do?

We can:

- Predict flame length of free jets
- Predict temperature decays with length
- Estimate radiation from a free fire
- Reduce the length with innovative PRDs
- Compare the jet flame tip location with a corresponding unignited jet concentration

We cannot:

- Describe all possible regimes of indoor hydrogen fires, including self-extinction and re-ignition
- Predict flame length in vitiated atmosphere
- Predict quantitatively surface effect on flame length
- Predict accurately transition from momentum- to buoyancy controlled fires

Estimating flame length

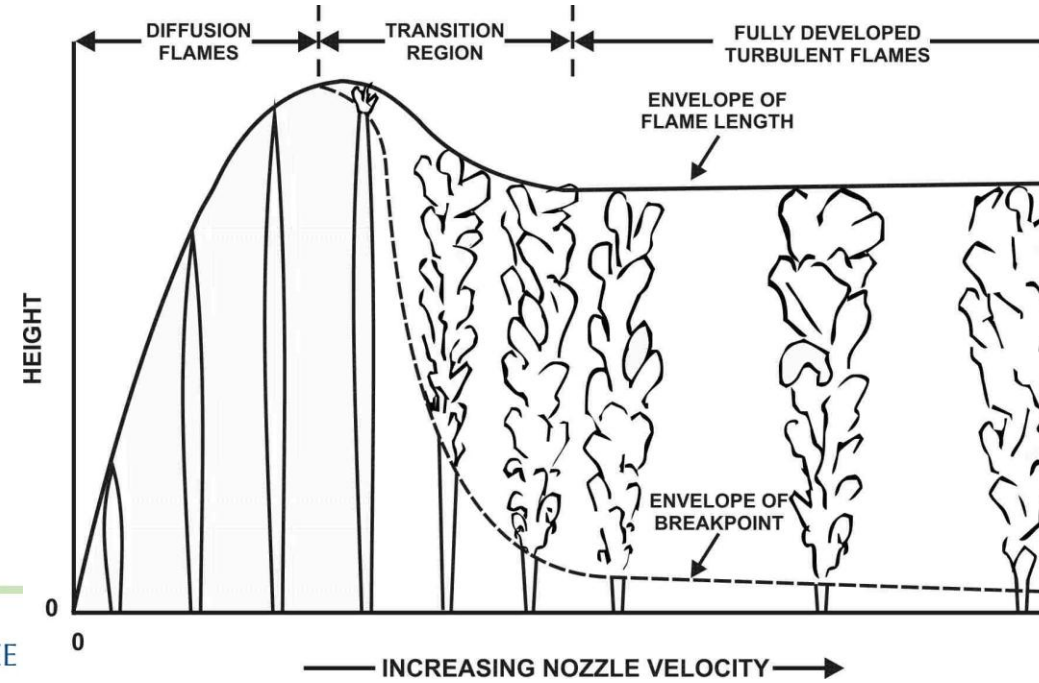
(UU correlation)

Laminar vs turbulent

- The classic theoretical consideration of mixing and combustion in turbulent gas jets by Hawthorne, Weddell, Hottel (HWH, 1949).
- "**The process of mixing is the controlling factor** in determining progress of the combustion".
- **Transition from laminar diffusion to turbulent flames** commences for release of hydrogen into still air at **Reynolds number around 2000** (Hottel, Hawthorne, 1949).

Flame types (terms):

- Laminar diffusion
- Turbulent non-premixed



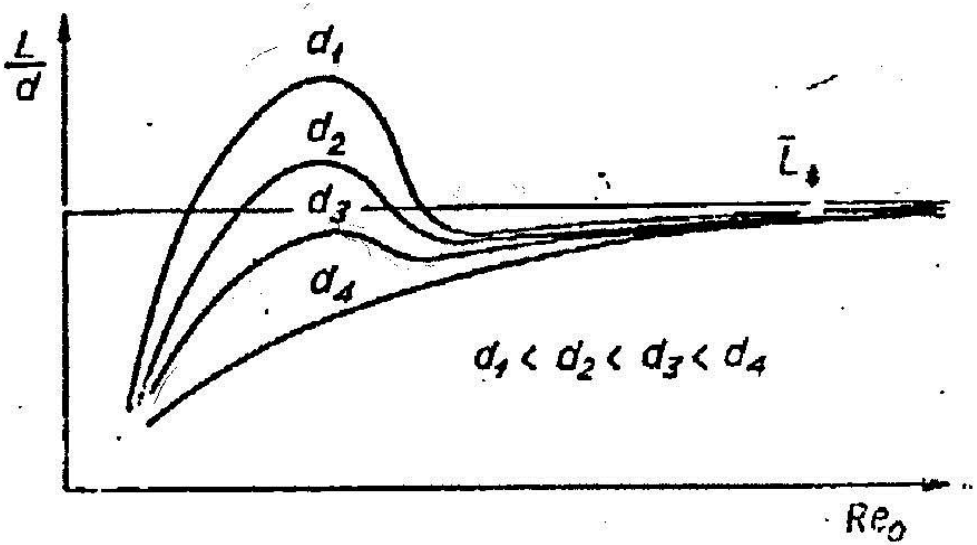
Dimensionless numbers

- The Froude number, ***Fr=U²/gd***, where *U* - velocity, *d* – characteristic size, *g* – acceleration of gravity, is a ratio of **inertial to gravity** force (then multiplied by the product of density by area ρA).
- The Reynolds number, ***Re=Ud*ρ/μ**, where ρ – density, μ – viscosity, is a ratio of **inertial to viscous** force.
- The Mach number, ***M=U/C***, where *C* – speed of sound, is a ratio of **inertial force to inertial force at sonic flow**. The speed of sound in gas is

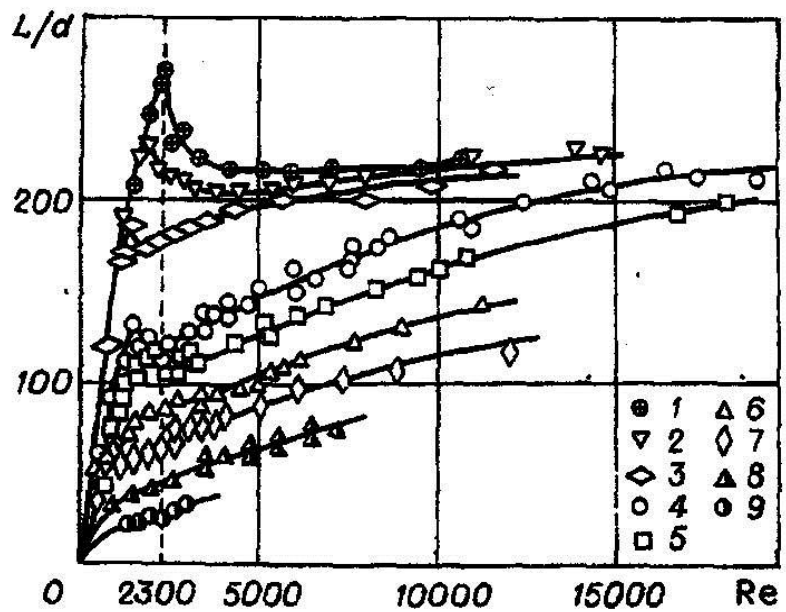
$$C = \sqrt{\gamma \frac{RT}{M}}$$

Flame length to diameter $L_F/d=f$ (*Re*)

- Dependence of the flame length to diameter ratio (L_F/d) on Reynolds number for different nozzle diameters, i.e. *Fr*
- Turbulent flame length limit L_t



Baev, Yasakov (1974, theory)



Shevyakov, Komov (1977): 1 – 1.45 mm; 9 – 51.7 mm.

Can all these scattered data be correlated by one curve?

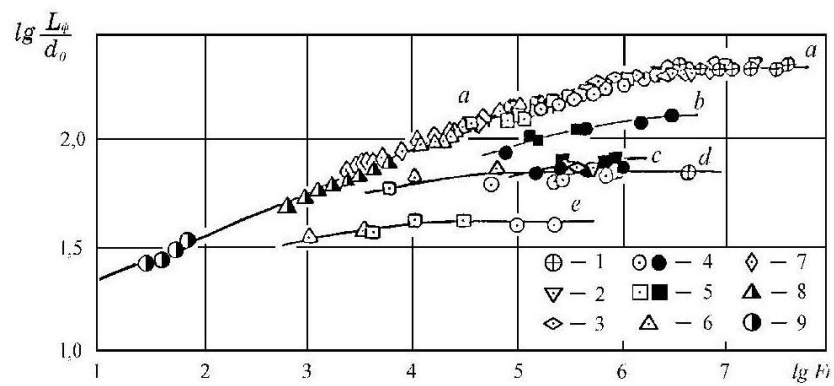
Flame length to diameter, L_F/d, data

- 1949, Hawthorne et al.: L_F/d=**134** (*Re*=2,870; *Fr*=92,000)
- 1972, Golovichev, Yasakov: **220** (theory), max **205** (365 m/s)
- 1974, Baev et al.: **230** (subsonic laminar), **190** (turbulent limit) L_l/L_t=**1.74** (theory), i.e. expected scattering **±30%**.
- 1977, Shevyakov et al.: momentum controlled limit **220-230**
- 1993, Delichatsios: **210**
- 1999, Heskestad: **175**
- 2005, Mogi et al.: $L_F/d=524\cdot P^{0.436}$ (**200**, 0.11 MPa; **254**, 0.19)
- Modified Shevyakov's correlation:

$$L_F/d = 15.8\cdot Fr^{1/5}\ (Fr = U^2/gd < 10^5);$$

$$L_F/d = 37.5\cdot Fr^{1/8}\ (10^5 < Fr < 2\cdot 10^6);$$

$$L_F/d = 230\ \ (Fr > 2\cdot 10^6).$$

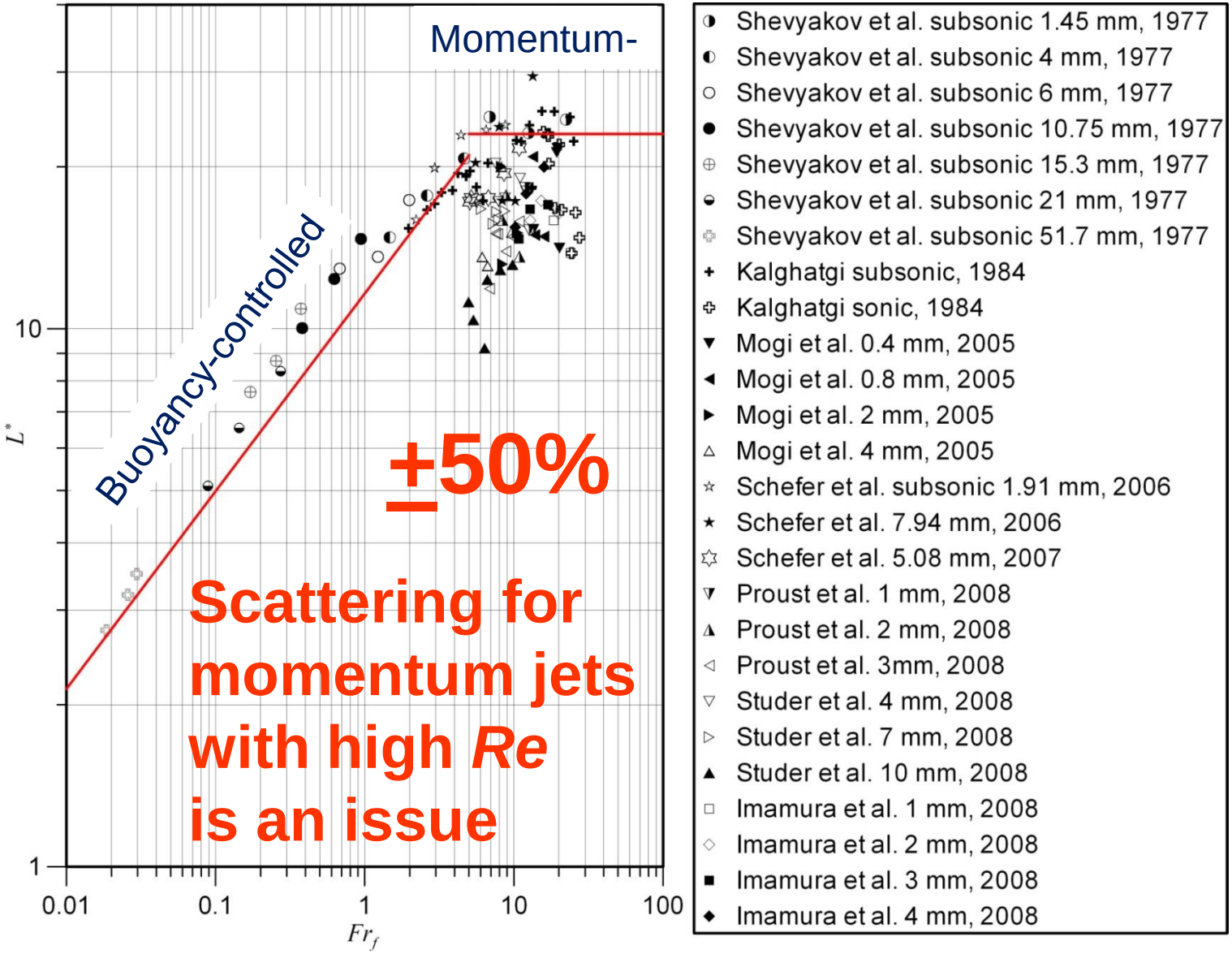


Expanded sub-sonic and sonic jets only!

Fr-based flame length correlations

- Dimensionless flame length correlations suggested previously are based on the use of the Froude number (*Fr*) only in one or another form.
- Recently *Fr*-based correlations were expanded to high pressure hydrogen jet fires (**under-expanded jets**). The general idea of this technique is to correlate experimental data with the **modified *Fr* number** that is built on so-called notional or **effective nozzle diameter** instead of real nozzle diameter. However, the size of the notional nozzle diameter and the velocity in the notional nozzle are dependent on the theory applied, including a number of simplifying assumptions.

Fr-based correlation example



Under-expanded jets are included!

The dimensional correlation

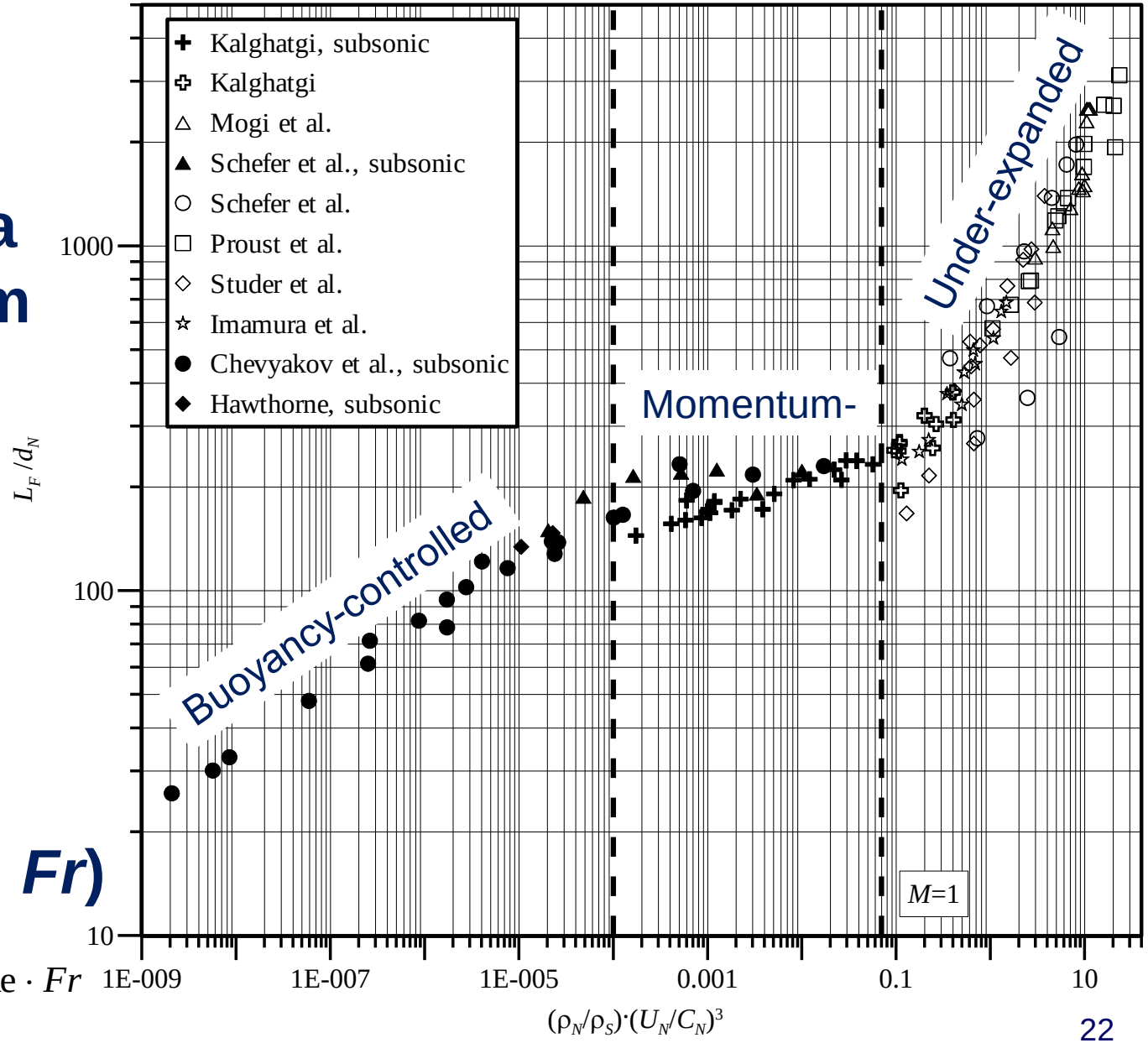
- In **2009** the dimensional correlation for hydrogen jet flame length in still air was published (95 points), and updated in **2010** (123 points).
- Data on flame length were correlated with a new similarity group, $\boldsymbol{L_F \sim (m \cdot d)^{1/3}}$, where ***m* is mass flow rate** and ***d* is nozzle diameter** (real – to exclude d_{eff}).
- The original under-expanded jet theory is applied to calculate the mass flow rate in the nozzle.
- This correlation demonstrates better predictive capability (compared to *Fr*-based correlations) **in the momentum-controlled regime**, which is the most appropriate for hydrogen leaks from high pressure equipment (see next slide).

Dimensionless correlation…?

- The **dimensional** correlation for flame length is $L_F \sim (m \cdot d)^{1/3}$
- Mass flow rate is proportional to the actual nozzle diameter squared $m \sim d^2$
- This implies that **dimensionless flame length L_F/d** is then an exponent function of **only density, ρ_N, and velocity, U_N, in the nozzle**
- The dimensionless density and velocity can be introduced: ρ_N/ρ_S and U_N/C_N, $C_N = \sqrt{\dfrac{\gamma \cdot R_{H2} \cdot T_N}{(1 - b \cdot \rho_N)}}$
- The correlation (next slide) is **validated:**
  - hydrogen storage pressures **up to 90 MPa;**
  - **nozzle diameters from 0.4 to 51.7 mm**.

The dimensionless correlation

Validation:
P **=0.1-90 MPa**
d**=0.4-51.7 mm**
L/T; SS/S/SS



Line *M*=1
(choked flow)

M **(*M*<1)-> (*Re, Fr*)**

$$\frac{\rho_N}{\rho_S}\cdot\left(\frac{U_N}{C_N}\right)^3 = \frac{g\cdot\mu_N}{\rho_S\cdot C_N^3}\cdot \mathrm{Re}\cdot Fr$$

How do we use this correlation?

Worked example

The dimensionless correlation

- Y axis: L_f/d_n where L_f = flame length, d_n= nozzle diameter
- X axis: $(\rho_N/\rho_S)(U_N/C_N)^3$ where
- ρ_N = density at the nozzle exit,
  find the same way as with similarity law for unignited jets
  equal to 0.0838 kg/m^3 at normal temperature and pressure (NTP) for <u>sub-sonic and expanded sonic jets</u>
  IF the jet is underexpanded then the density is calculated by an **under-expanded jet theory** developed at the University of Ulster
- ρ_S =density of the surroundings = 1.205 kg/m^3 for air
- C_N = is the speed of sound in hydrogen at the nozzle exit,

$$C = \sqrt{\gamma \frac{P}{\rho}} = \sqrt{\gamma \frac{RT}{M}}$$

- U_N = the velocity of the hydrogen at the jet exit
  $U_N = C_N$ for sonic and supersonic jets,
  for subsonic jets:

$$U_N = \sqrt{2 \frac{\Delta P}{\rho}}$$

Example: 200 bar, 1mm orifice

- Take storage temperature = 288 K
- ρ_N = 9.287 kg/m^3 (underexpanded jet theory- pressure ratio >1.9 bar)
- ρ_s = density of the surroundings, 1.205 kg/m^3 for air
- d_n = diameter = 0.001 (make sure in m, SI units)
- Imagine an unignited jet – then the distance to the LFL is:

$$C_{ax}^{m} = 5.4\sqrt{\frac{\rho_N}{\rho_S}}\frac{D}{x} \qquad x = 5.4\sqrt{\frac{\rho_N}{\rho_S}}\frac{D}{C_{ax}^{m}}$$

x= 5.20 m

How does the flame length compare??

Y axis: L_f/d_n we know d_n , we need to find L_f

X axis: $(\rho_N/\rho_S)(U_N/C_N)^3$ ….. ρ_N = 9.287 kg/m^3 as above,

ρ_s = 1.205 kg/m^3 for air

jet is underexpanded so we don't need to calculate U_N and C_N

Therefore x axis = (9.287/1.205)*1 = 7.707

Example: 200 bar, 1mm orifice

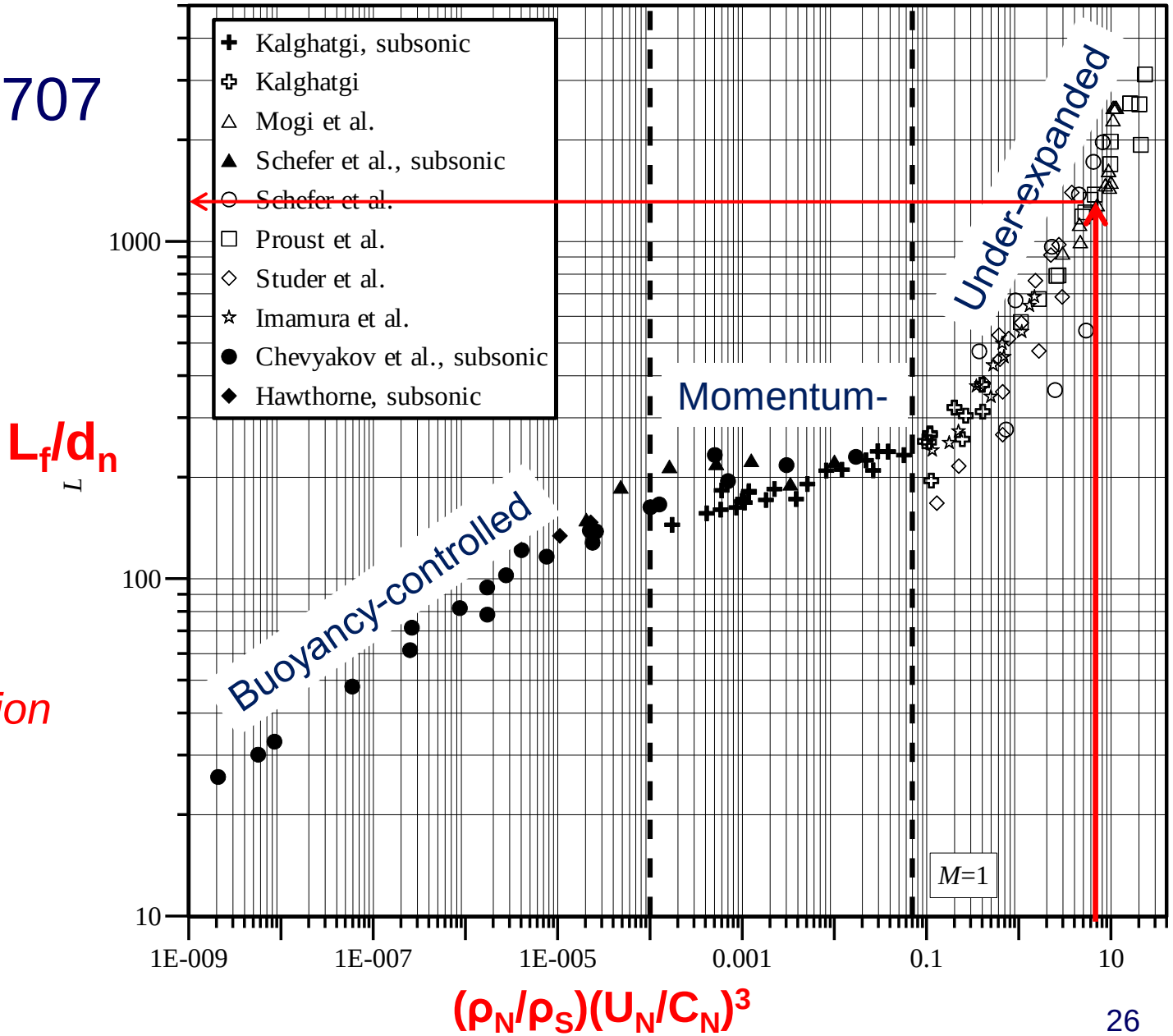
x axis = 7.707

y axis ~ 1500

L_f/d_n ~ 1500

For 1mm
Flame length is in
region of 1.5m

Note: W:L is in region of 0.17

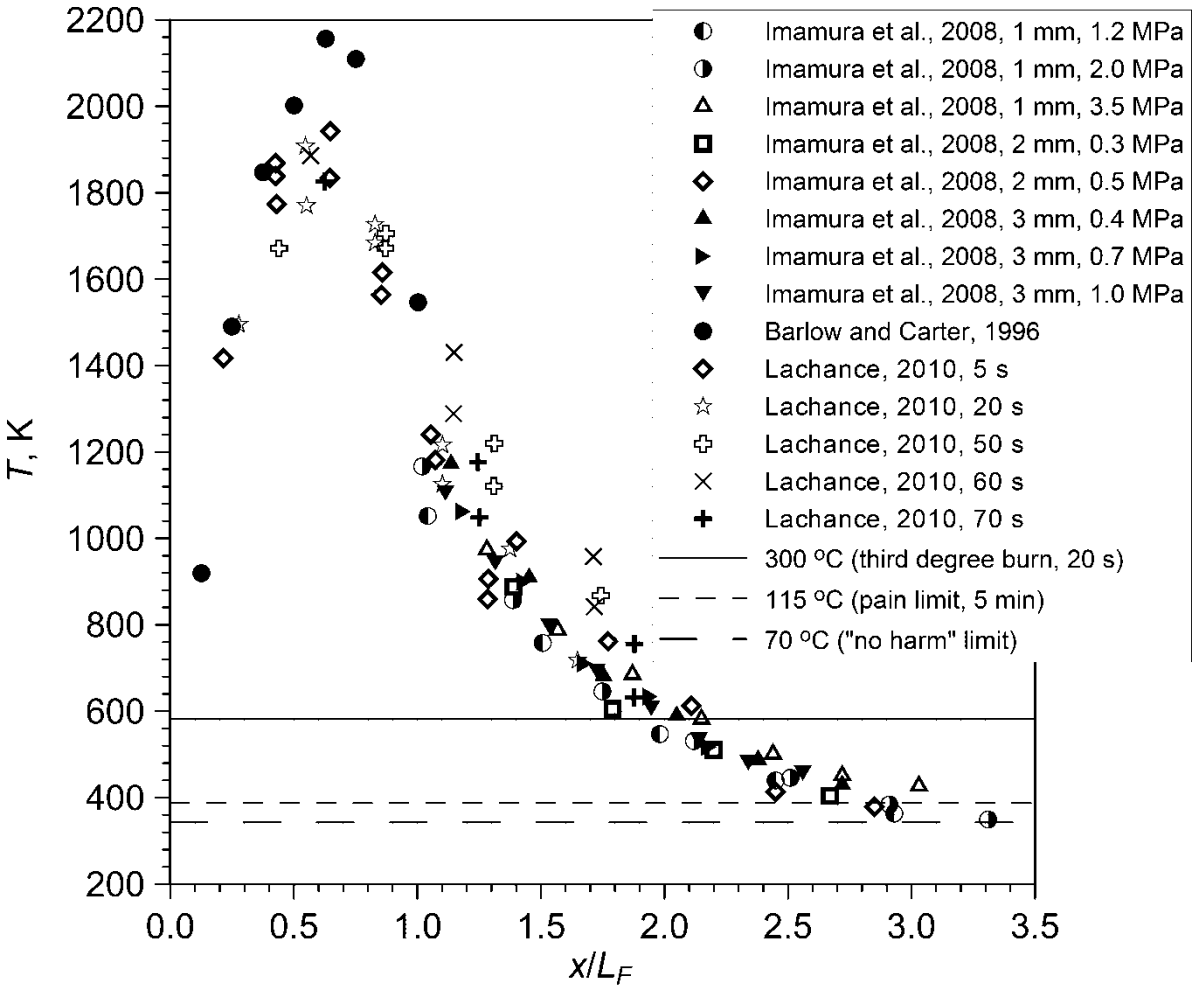


Temperature decay in a jet fire

Harm criteria

- Before calculating a safety distance it is necessary to consider what you would like to protect against
- In the case of free fires this would be heat flux and temperature (in the case of enclosure fires asphyxiation and over pressure may also be relevant
- For people direct flame contact as a result of a jet fire is generally assumed to result in third degree burns
- For people not in the flame, there is still potential for exposure to high radiation heat fluxes
- Molkov & Saffers: 70°C - “no harm” limit; 115°C - pain limit for 5 min exposure; 309°C - third degree burns for 20 s (“death” limit).

Normalised temperature profile



- Molkov & Saffers, Hydrogen Jet Flames, submitted to IJHE

Unattached versus attached jet fires

(205 bar, 800 ms ignition delay)

Attachment effect on jet flame length

205 bar, ignition delay 800 ms.

Attached jets – 0.11 m above the ground.

Unattached jets – 1.2 m above the ground.

Orifice diameter, mm	Flame length, m Attached jets	Flame length, m Unattached jets	Flame length increase, times
1.5	5.5	3	x1.83
3.2	9	6	x1.50
6.4	11	9	x1.22
9.5	13	11	x1.18

Conclusion:

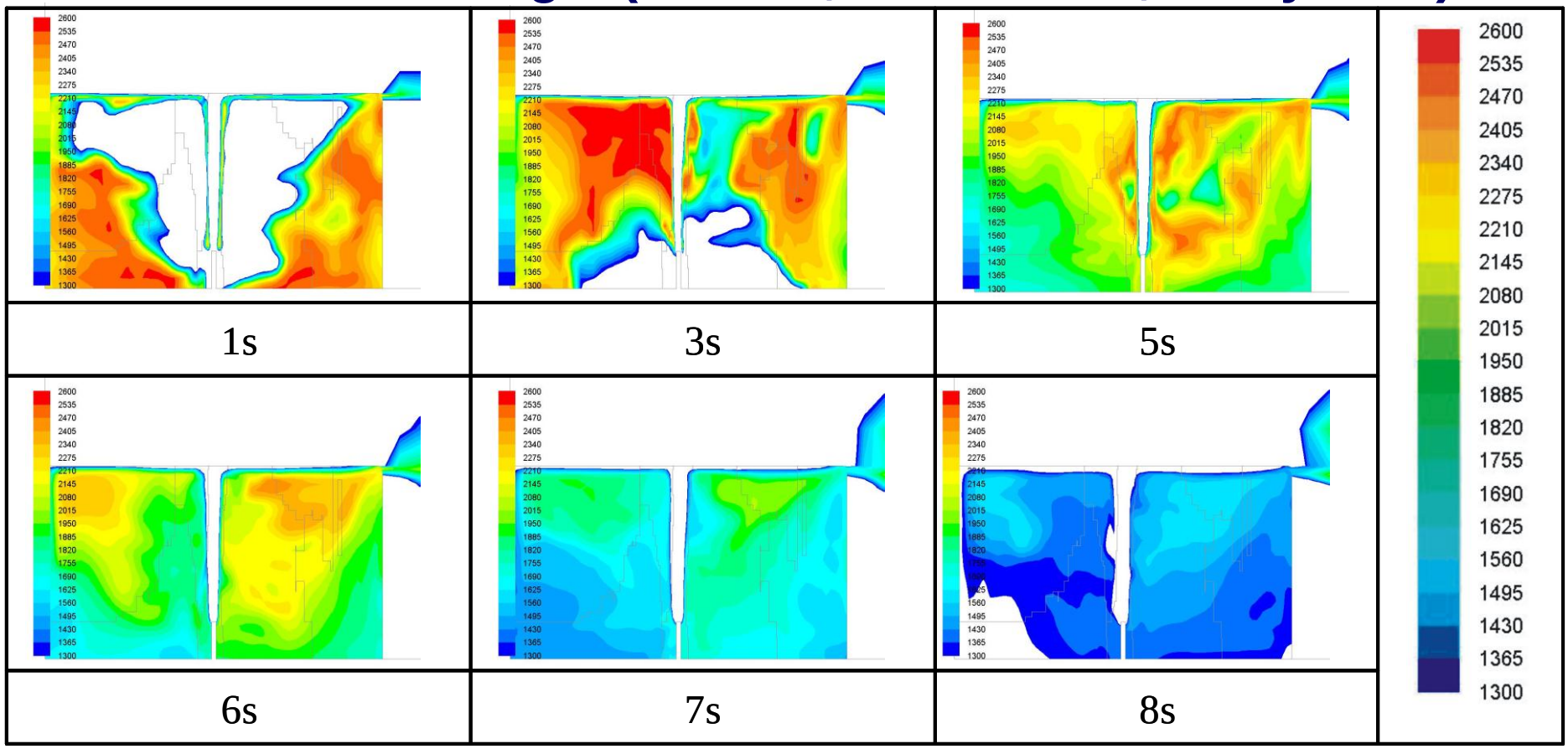
- *Release along ground or walls in proximity to them can increase flame length.*

Hydrogen Jet Fire in an Enclosure

- Important to understand for practical applications
- Behaviour of fire dependent on release conditions <u>and</u> geometry of enclosure
- Three regimes well ventilated, under ventilated and extinguishment
- In all cases we need to understand pressures, temperatures and heat fluxes
- Goal within HyIndoor project is to understand all the phenomena and to develop simple tools to predict relationship between e.g. gas release rate, ventilation and flame behaviour
- If we understand the phenomena we can improve design, provide guidance and inform RCS

Indoor car jet fire

Small garage LxWxH=4.5x2.6x2.6 m (“brick” vent).
Mass flow rate **390 g/s (350 bar, *D*=5.08 mm, today cars)**.



Self-extinction in seconds

Summary

- Introduction to types of hydrogen fires
- Overview of existing knowledge on free fires and summary of harm criteria
- Tool presented to estimate flame length
- Introduction to knowledge gaps
  - ❖indoor fires (self-extinction and re-ignition)
  - ❖Predict flame length in vitiated atmosphere
  - ❖surface effect on flame length etc.

Any Questions?