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Primer
“Hydrogen fires”

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are gratefully appreciated.

Outline

- Main safety concerns
- Types of hydrogen fires
- Microflames
- Jet fire basics
- The dimensional correlation for flame length
    - The nomogram
- The dimensionless correlation
- Hydrogen jet flame tip location (separation distance)
- Flame shape: round and plane jets
- Pressure effects of ignited jets
- Unattached versus attached jet fires
- Bonfire tests
- Pressure relief devices
- Fires in high pressure electrolysers (an issue)

Main safety concerns

Knowledge gaps (JRC-led gap analysis in CFD):

- Hydrogen releases and dispersion
- Spontaneous ignition of sudden releases
- **Fires: jet fires, self-extinction, microflames**
- Explosions: deflagrations, DDT, detonations

Safety strategies and systems:

- **Fire resistance of storage tanks *with*** pressure relief devices ***in*** garages, tunnels, car parks, etc.
- Indoor releases, fires, explosions
- Mitigation techniques

Hydrogen safety engineering:

- Need in a platform to consolidate fragmented safety codes and standards (produced by industry and for industry) into a safety framework for all stakeholders.

Types of hydrogen fires

Types of 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 jets
- Little knowledge of liquefied hydrogen (LH2) fires

… and questions:

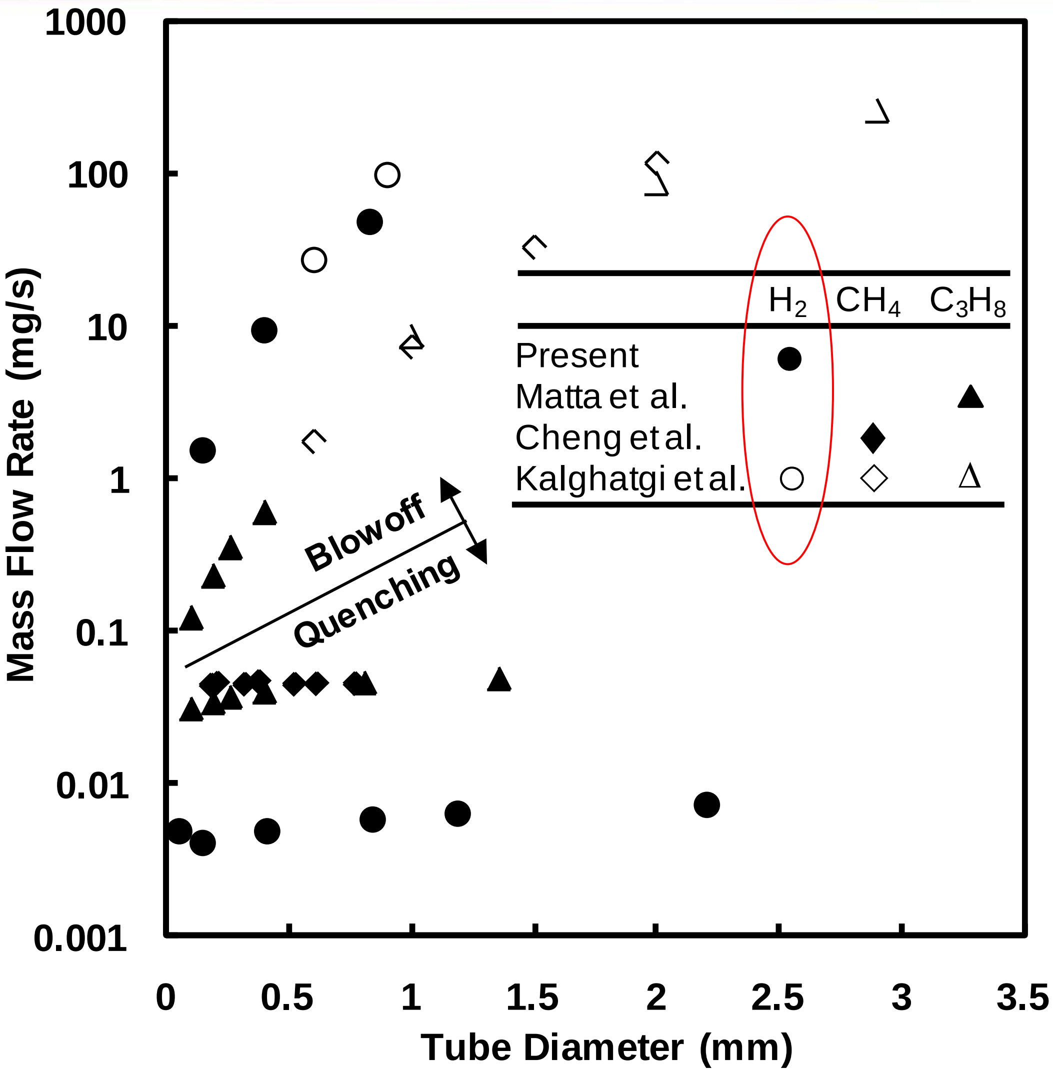
- Can all these types of compressed gaseous hydrogen (CGH2) jet fires be correlated?
- Can traditional L_F/d=f(*Fr*) correlations (*Fr*-based) be applied (ignoring dependence on *Re* and *M*!)?

Microflames
(P. Sunderland et al.)

Weakest flame

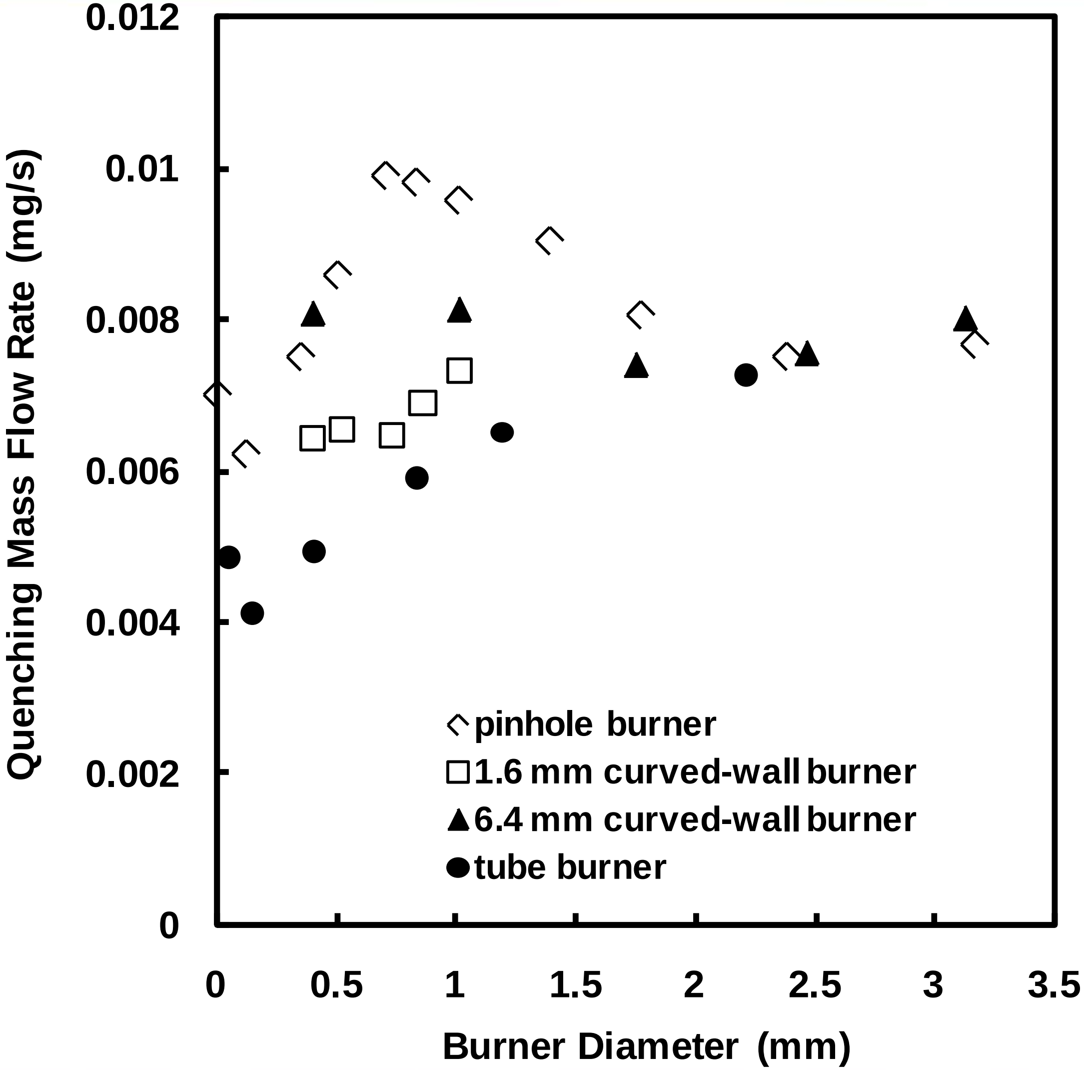
- **Hazard**: the small leak burns undetected for a long period, damaging the containment system and providing an ignition source for a subsequent large release.
- **Left**: hydrogen flowing downward into air (mass flow rate 3.9 μg/s, power 0.46 W).
- **Right**: hydrogen flowing downward into oxygen (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

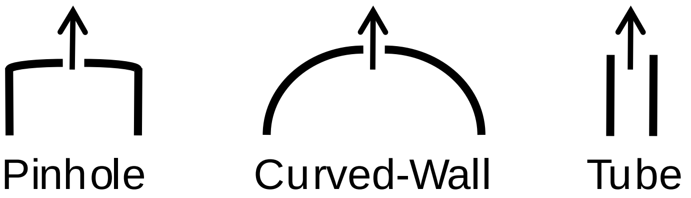


- Tube burner is used.
- **Quenching limits are nearly independent of diameter.**
- Hydrogen has the lowest quenching limit and the highest blowoff limit.

Source type effect

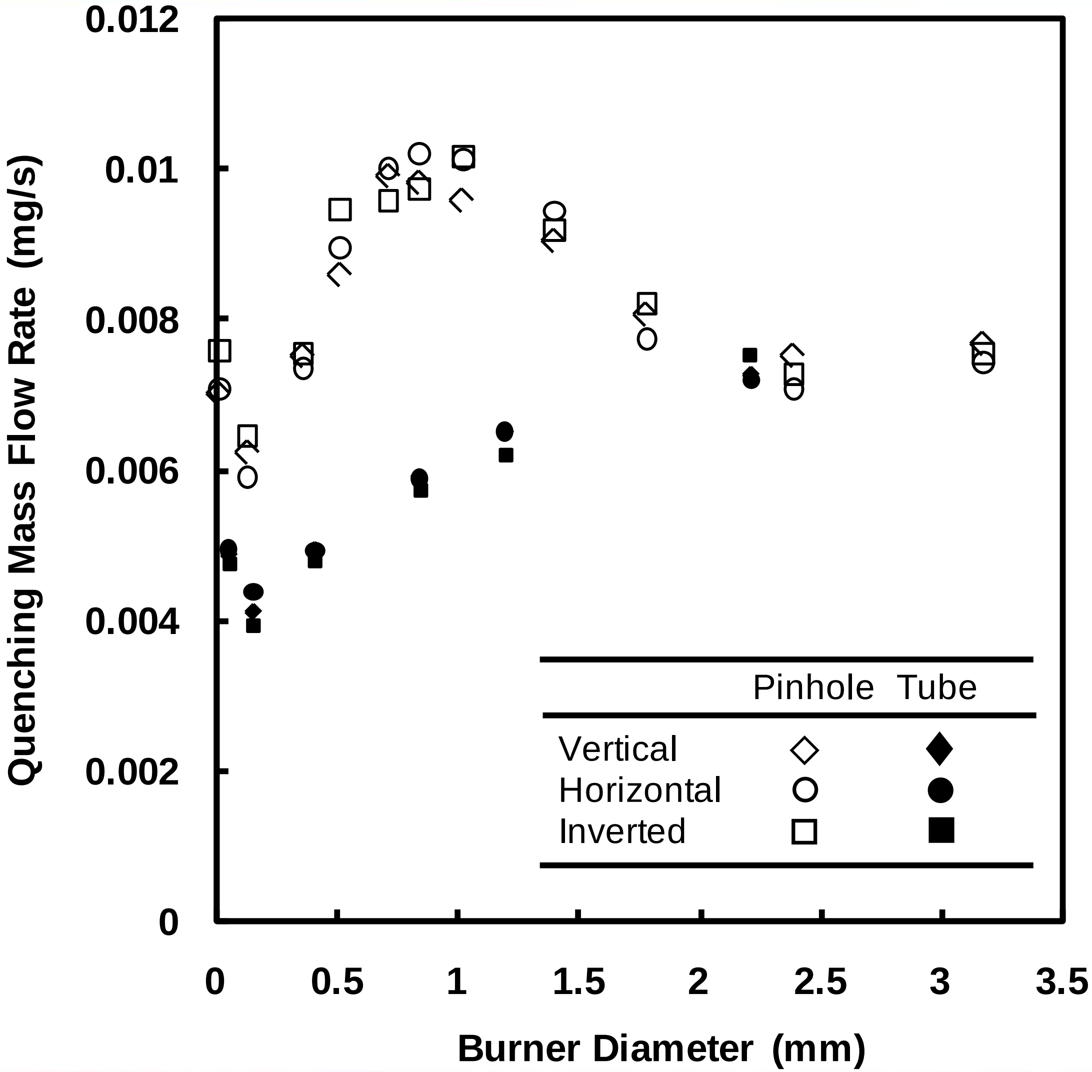


- Three burner types



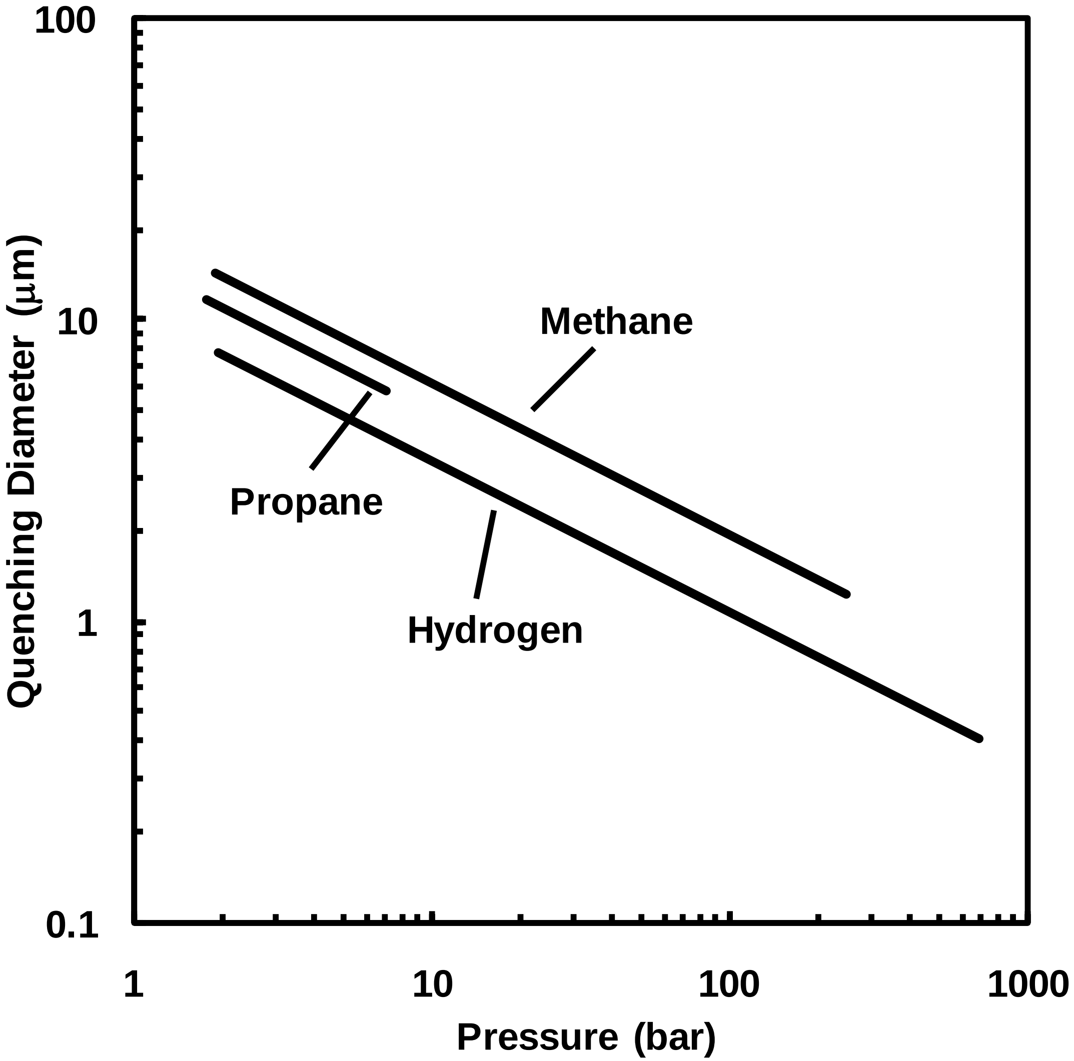
- For large diameters the limits converge.
- Heat losses are highest for pinholes, lowest for tube burners.

Orientation effect



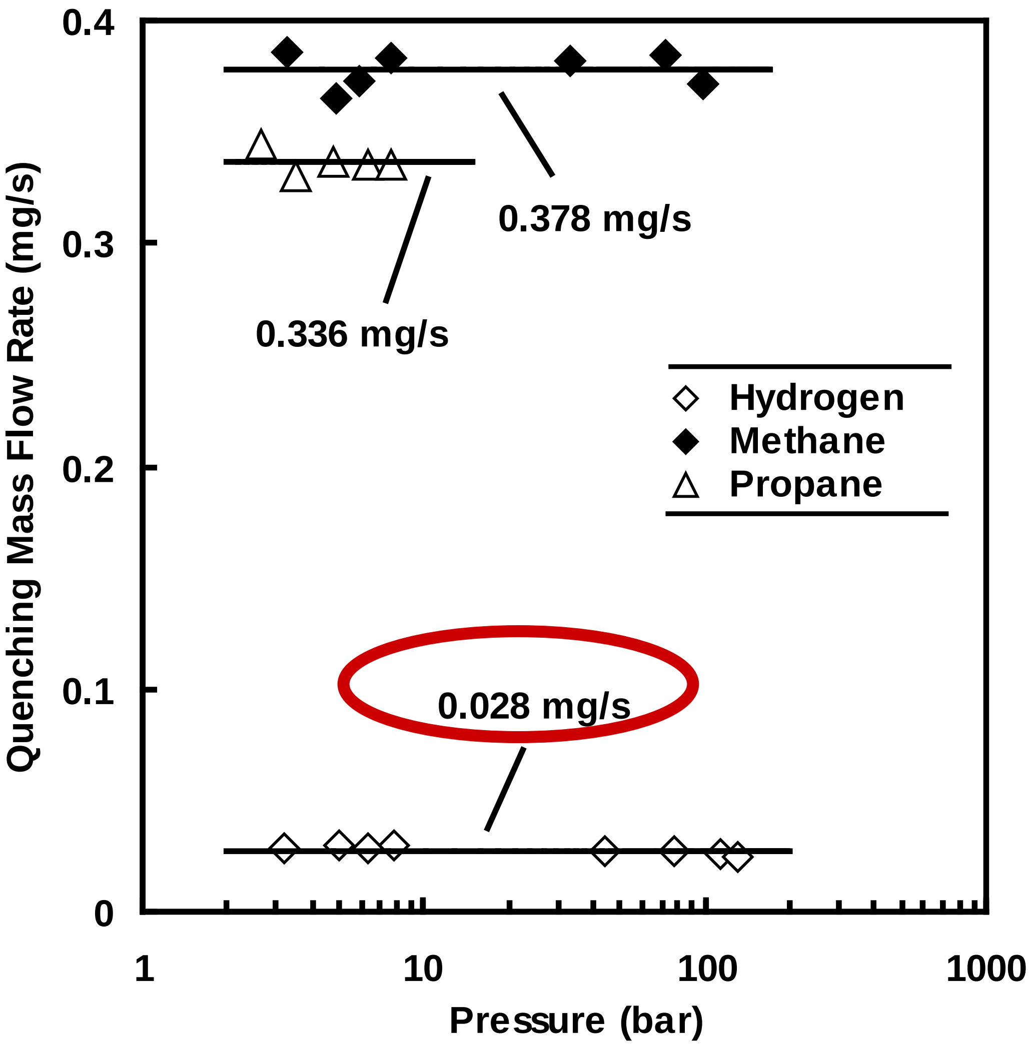
Burner type has more effect than burner orientation

Quenching diameter

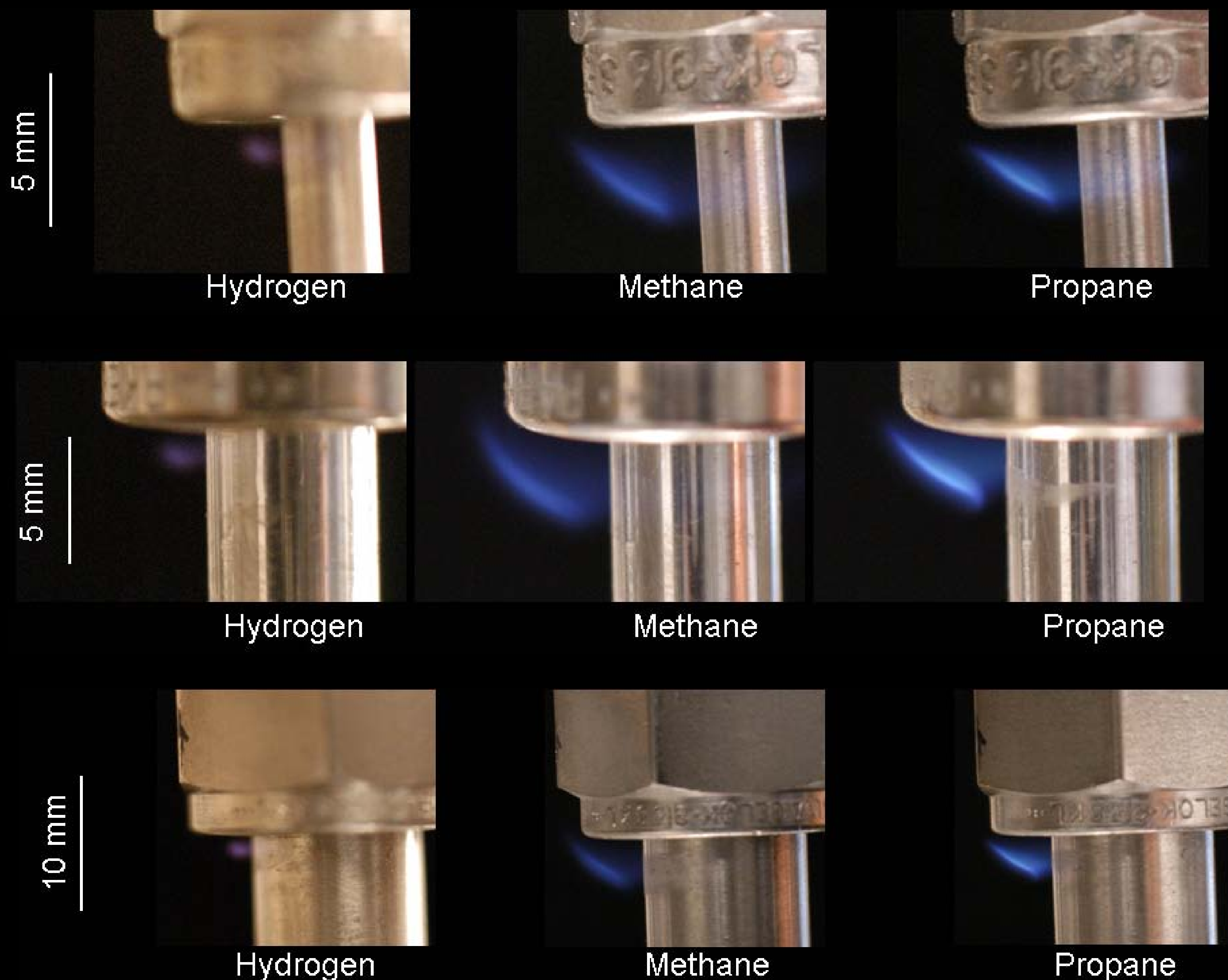


- Upstream pressure required for 5.6 μg/s hydrogen isentropic choked flow is shown.
- For hydrogen at 690 bar, **any hole larger than 0.4 μm will support a stable flame**.

Leaky fittings

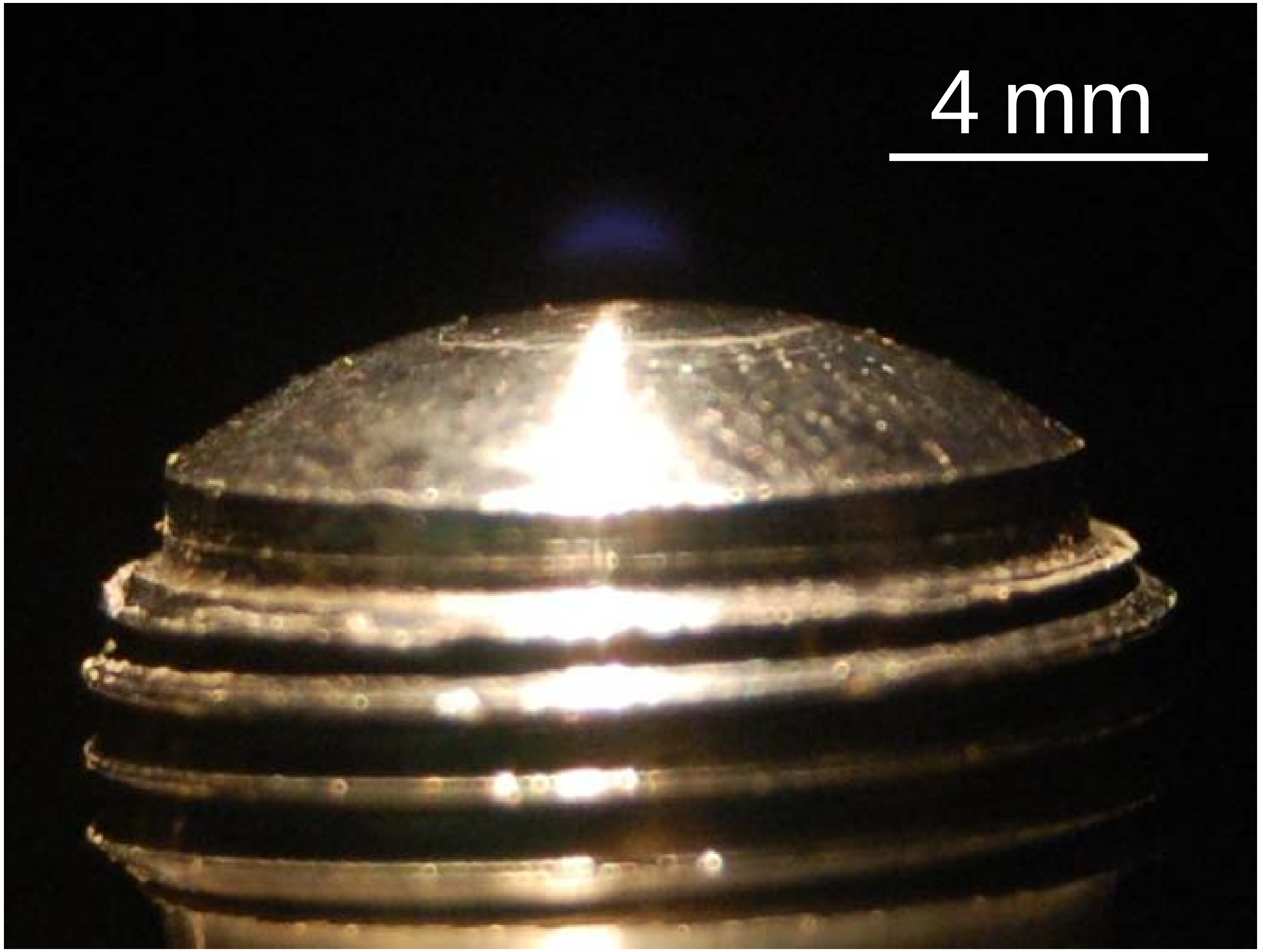


- Quenching limits for a 6 mm compression fitting are shown.
- Limits are independent of pressure.
- **Limits are about 10 times of those of tube burners.**
- Hydrogen limits are the lowest.


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

Microflame length

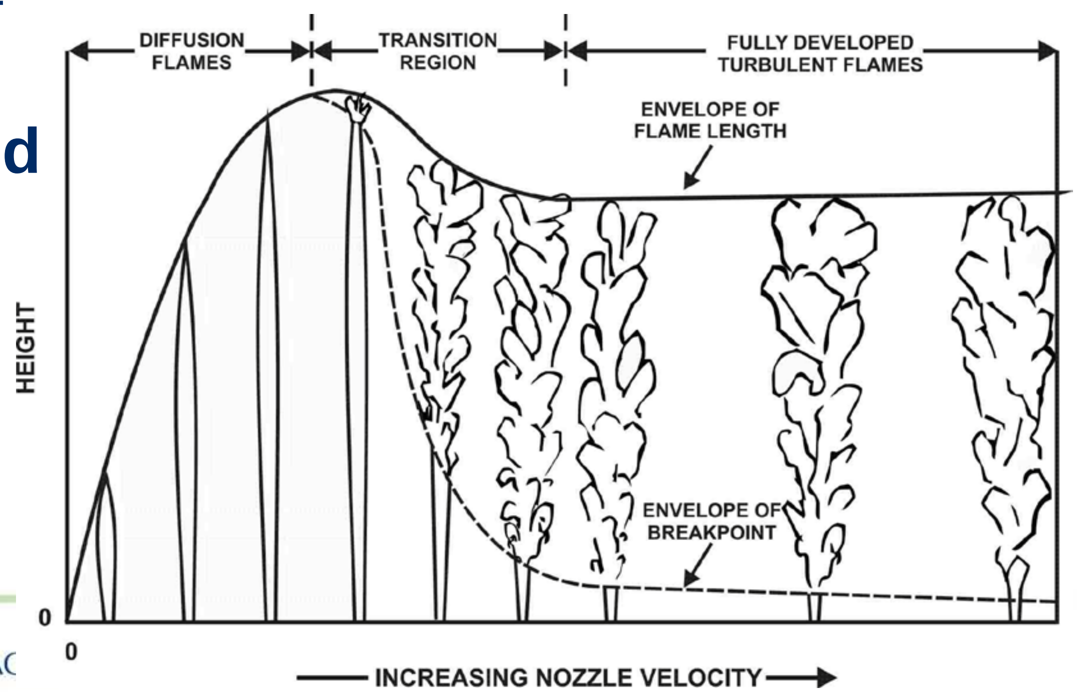
- Test 1 (picture): L_F=**1 mm**, m=7.5 μg/s, D=0.36 mm Stand-off height is 0.25 mm.
- Test 2: L_F=**0.4 mm**, m=3.9 μg/s, D=0.15 mm



Jet fire basics

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

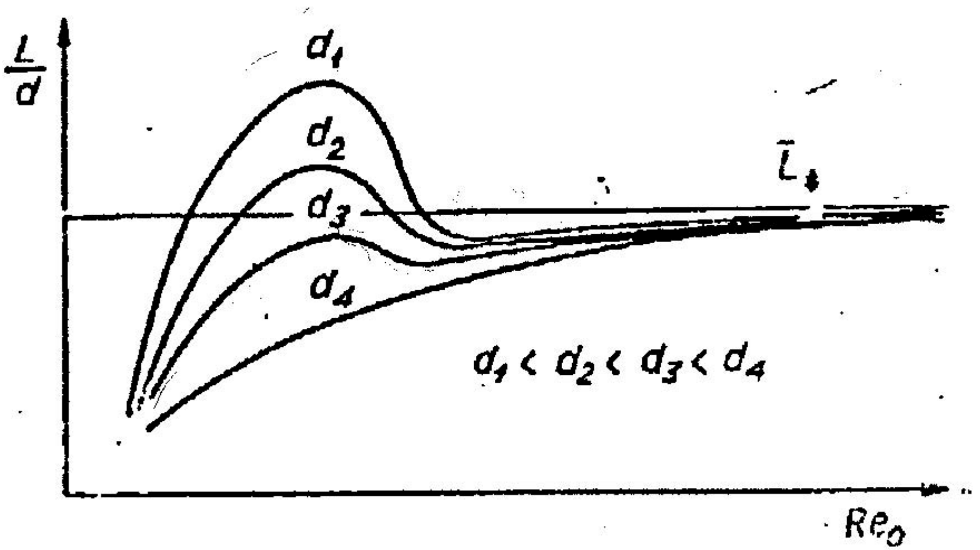
Dimensionless numbers

- 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

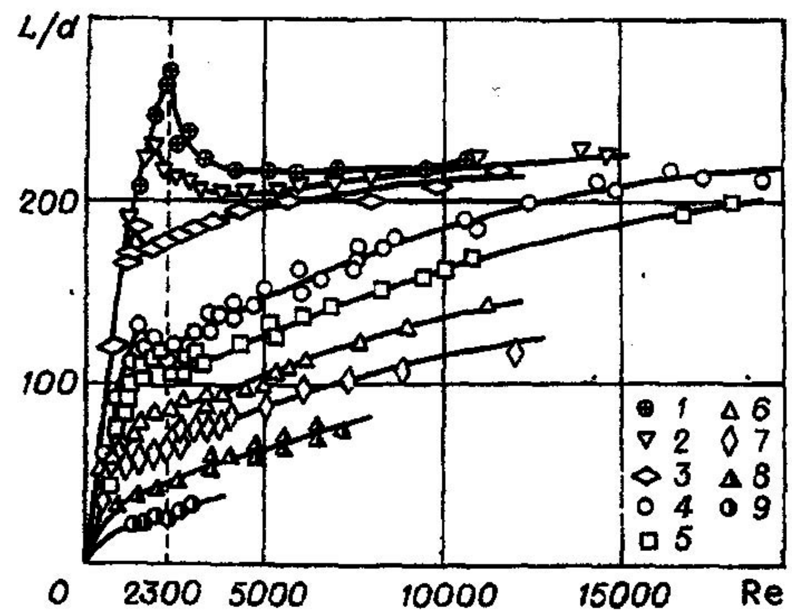
$$C = \sqrt{\gamma \frac{RT}{M}}$$

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?

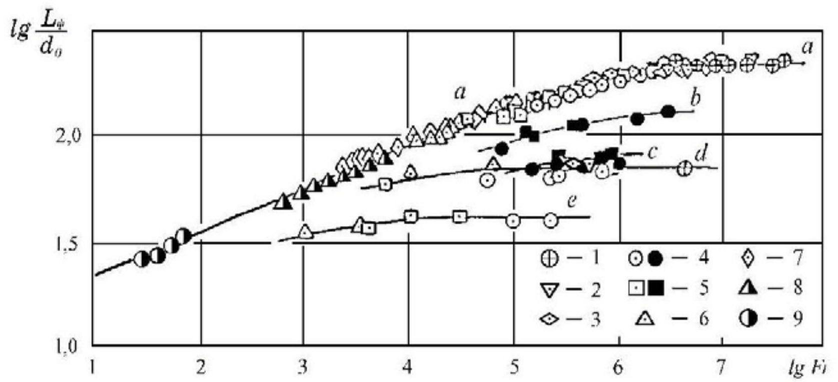
Flame length to diameter, L_F/d, data

- 1949, Hawthorne et al.: $\boldsymbol{L_F/d}$=**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 **$\pm$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:

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

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

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

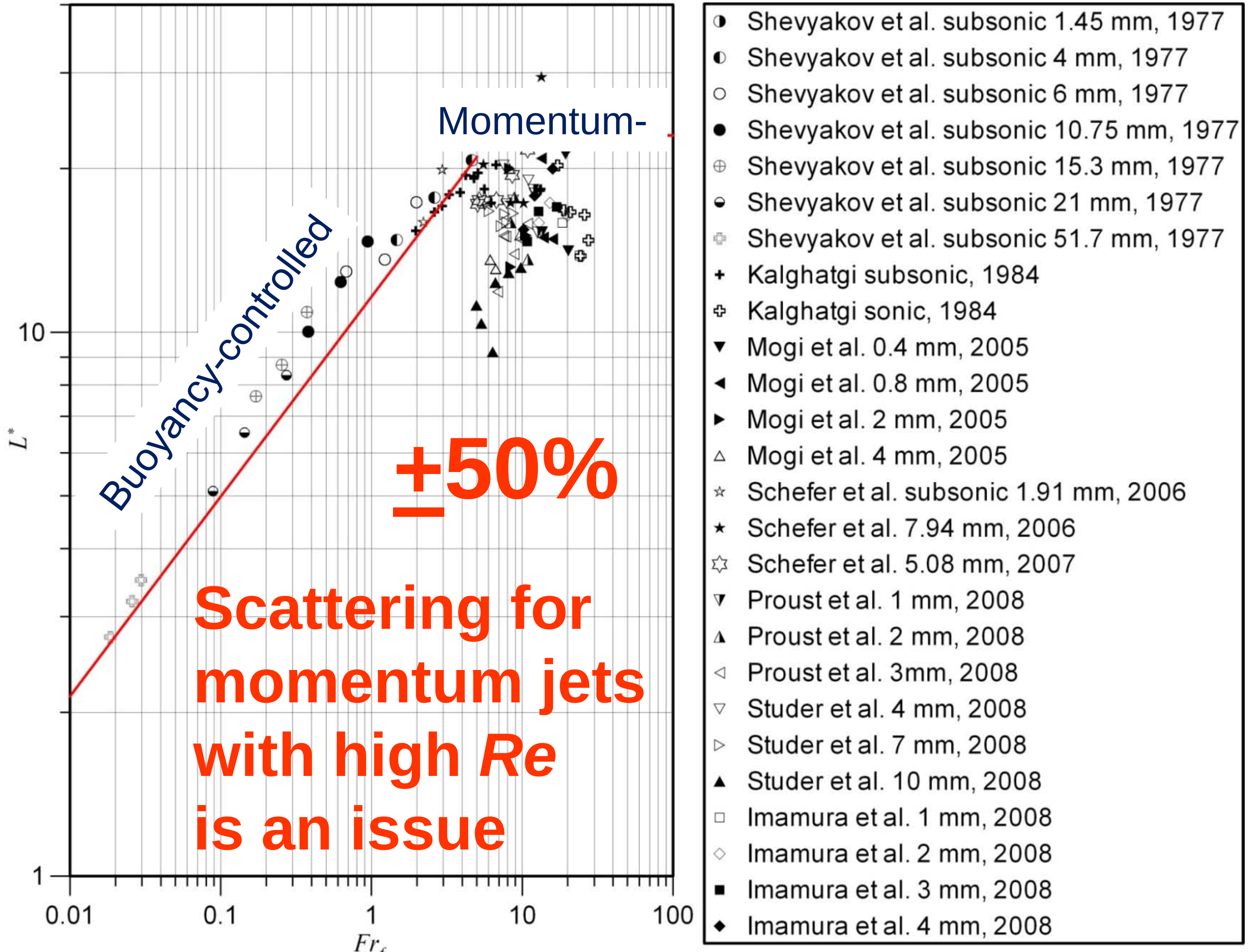


Expanded sub-sonic and sonic jets only!

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).

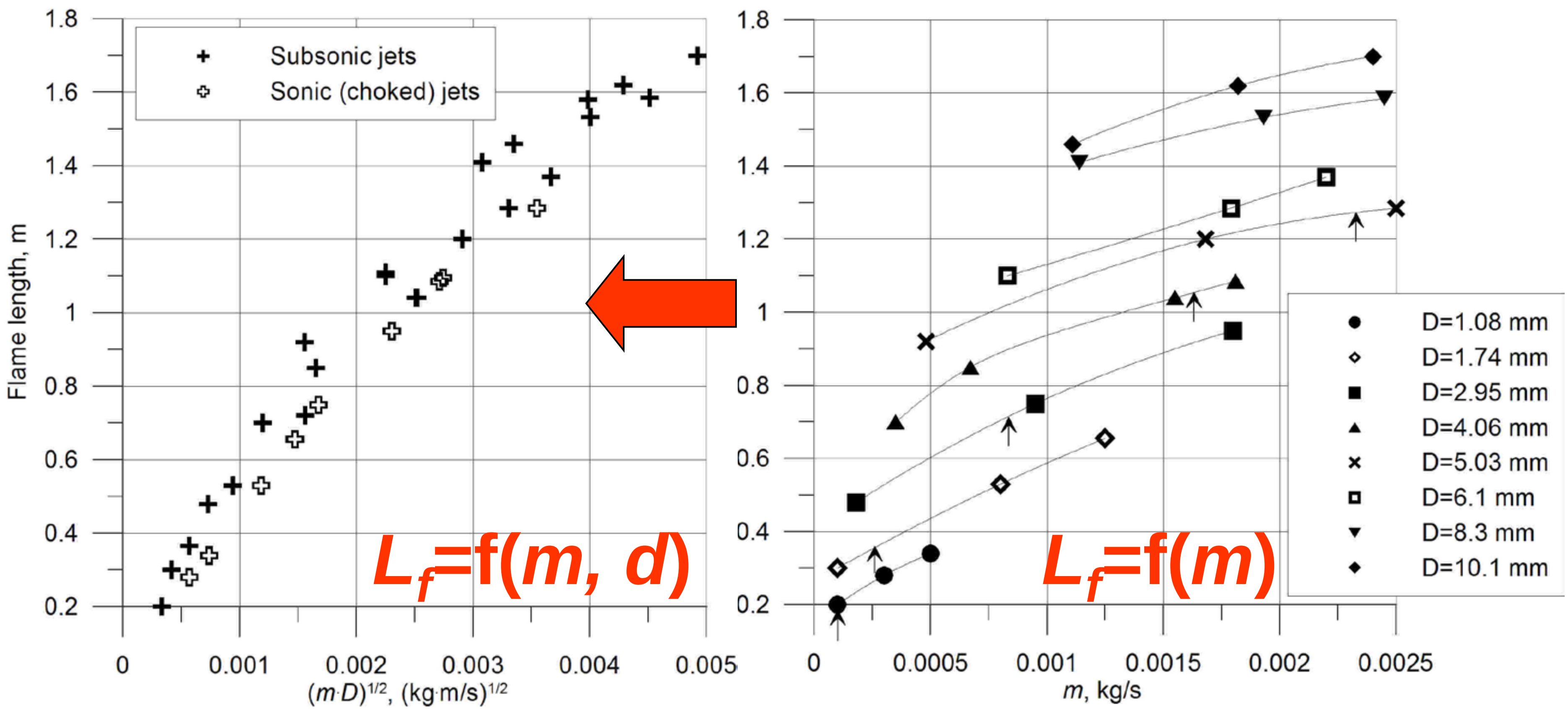
Similitude analysis

- Let us apply dimensional analysis to correlate a **flame length, L_F**, with a **nozzle diameter, d**, **densities of hydrogen in the nozzle, ρ_N**, and **density of surrounding air, ρ_S**, **viscosity, μ,** and hydrogen **velocity in the nozzle, U**. The Buckingham Π theorem (6-3=3: ratio of densities, velocities, and the third Π number).
- An attempt was made to correlate Kalghatgi data on L_F with new similarity group ***m·d**, where **m** is* **mass flow rate** from the nozzle (not just with ***m*** as in work by Mogi et al., 1995, $L_F = 20.25 \cdot m^{0.53}$)

$$L_F \propto \sqrt{\frac{\dot{m} \cdot d}{\mu}} \quad (\mu = const)$$

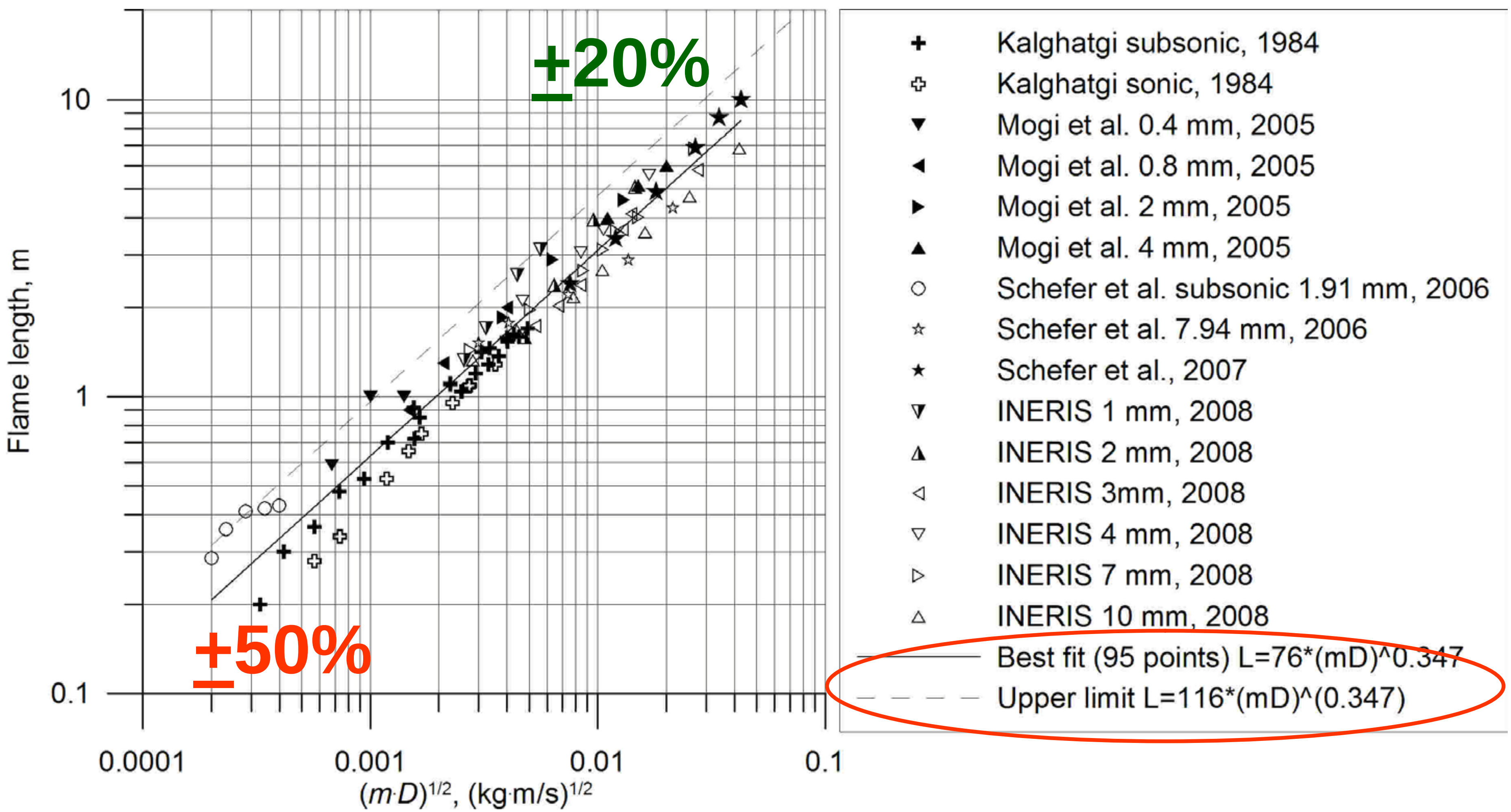
New similarity group (*m·d*)

m – mass flow rate; *d* – real nozzle diameter



Kalghatgi (1984) data are converged

The dimensional correlation



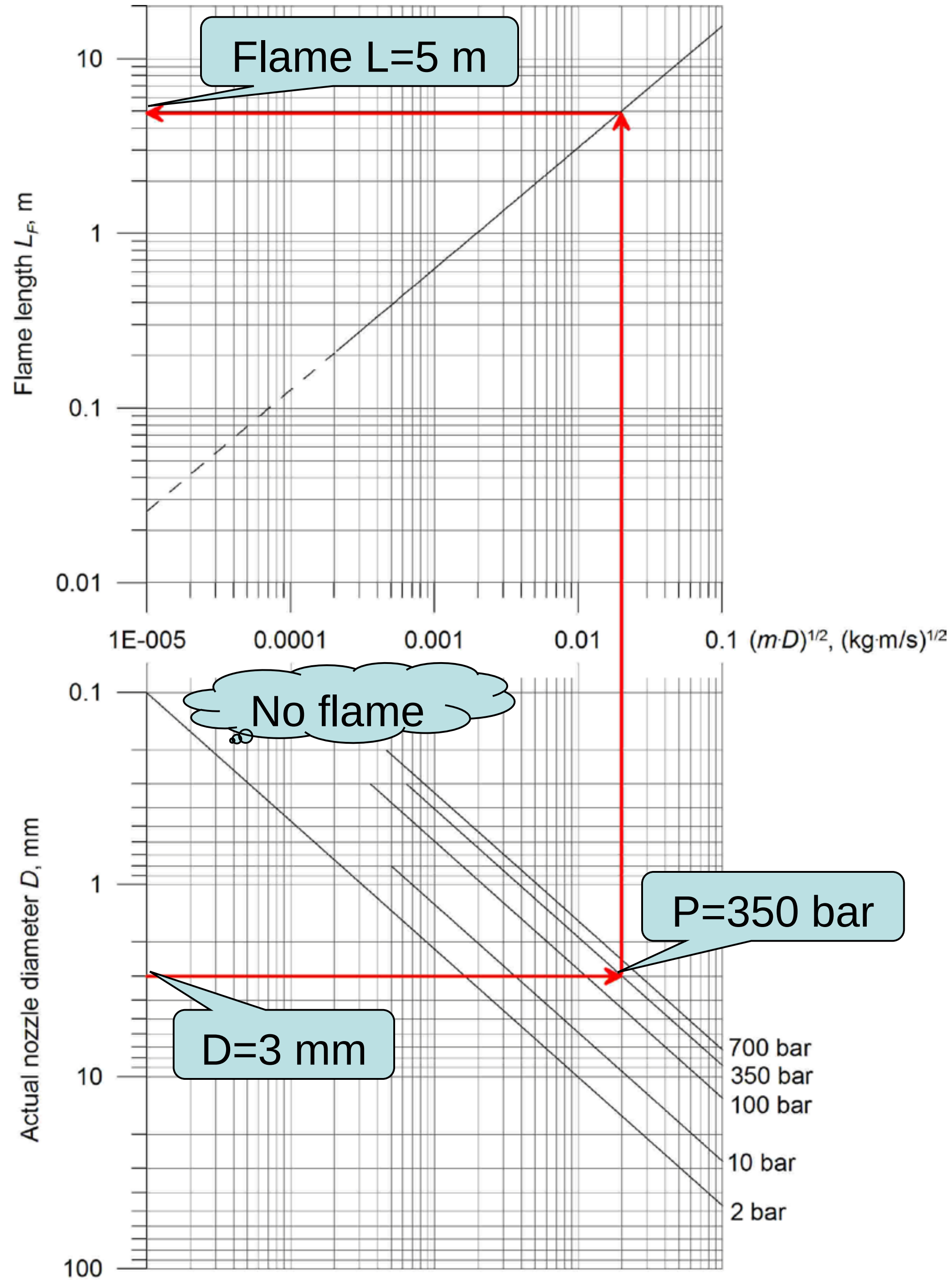
Good prediction for high and poor for small debit jets

The nomogram

Derived from the jet flame length correlation (best fit curve; please multiply by 1.5 for a conservative estimate).

Special feature:

No stable flames (**“non-combustible”** hydrogen) were observed for nozzle diameters 0.1-0.2 mm – flame blew off although the spouting pressure increased up to 400 bar.



Dimensionless correlation…?

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

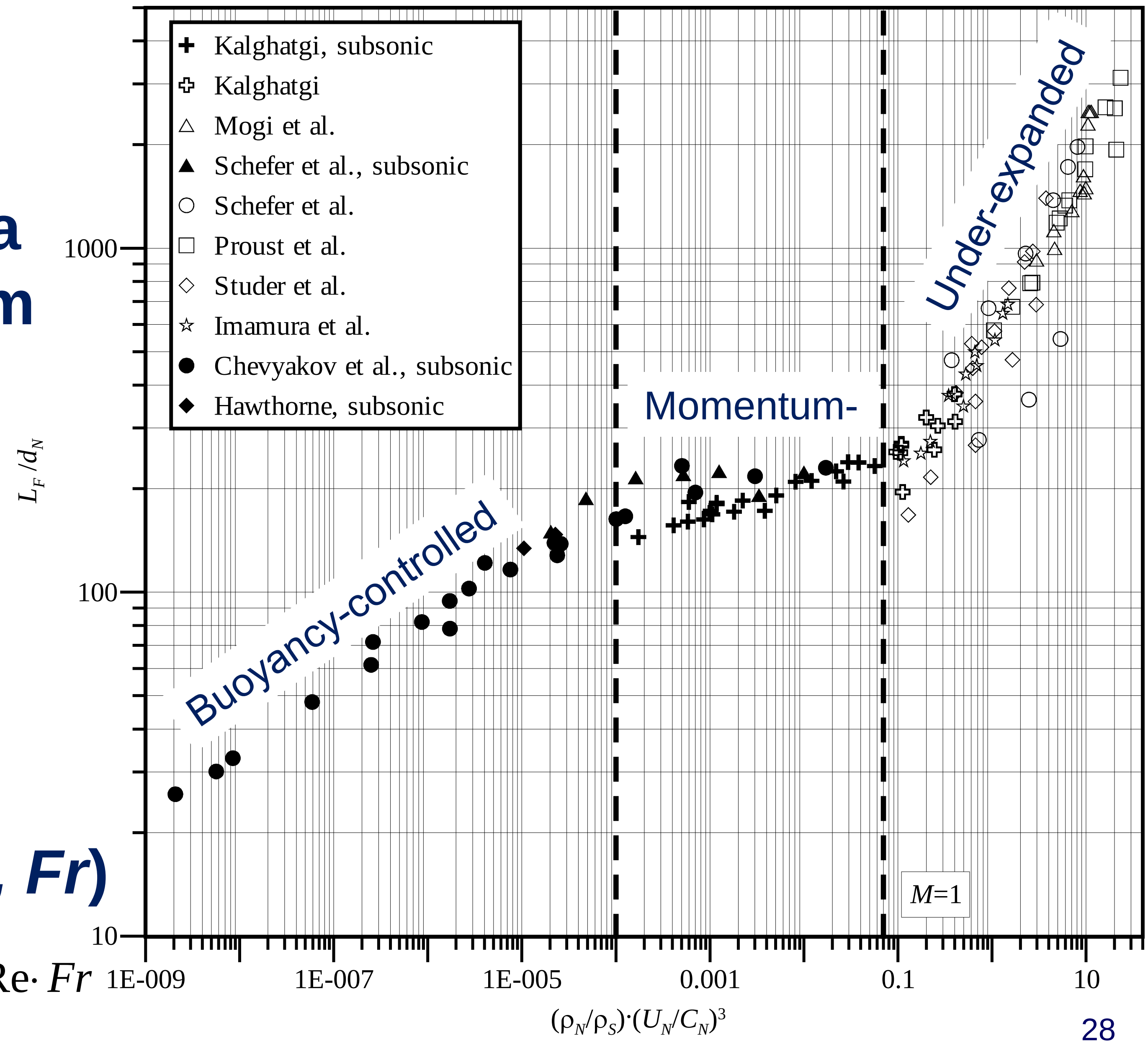
The dimensionless correlation

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*)**

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



Change of *Fr, Re, M*

$$M = \frac{U_N}{C_N}$$

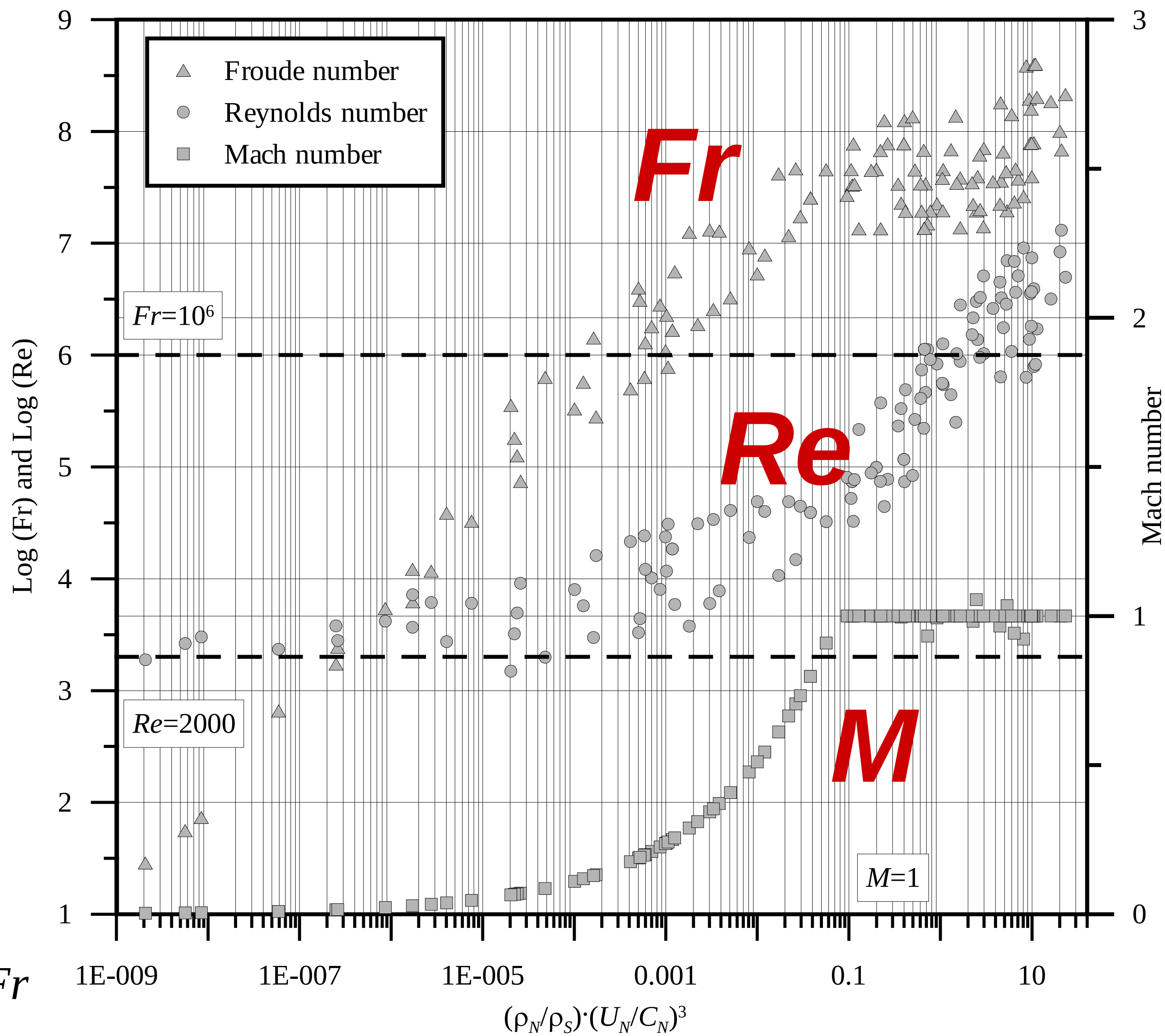
$$\mathrm{Re} = \frac{\rho_N \cdot d_N \cdot U_N}{\mu_N}$$

$$Fr = \frac{U_N^2}{d_N \cdot g}$$

***Re*=2000:**
Laminar to turbulent

***Fr*=10⁶:**
Buoyancy to Momentum

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



Conclusions (correlations)

- ***Fr*-based correlations** are not as general is it was thought – **inapplicable to under-expanded jet fires**.
- The dimensionless correlation for non-premixed hydrogen jet flame length in still air is developed in coordinates L_F/d_N - $(\rho_N/\rho_S)\cdot(U_N/C_N)^3$.
- The correlation is validated for storage pressures **0.1-90 MPa** and nozzle diameters **0.4-51.7 mm** (**laminar/turbulent, subsonic/sonic/supersonic, etc.**)
- Traditional **"buoyancy"**-controlled and **"momentum"**-dominated regimes are added by new **"inertial"** regime (power law for dependence of the flame length on the *Re* number for under-expanded high momentum jets).
- The correlation requires knowledge of **hydrogen density and velocity in the nozzle** (calculated using the under-expanded jet theory published elsewhere).

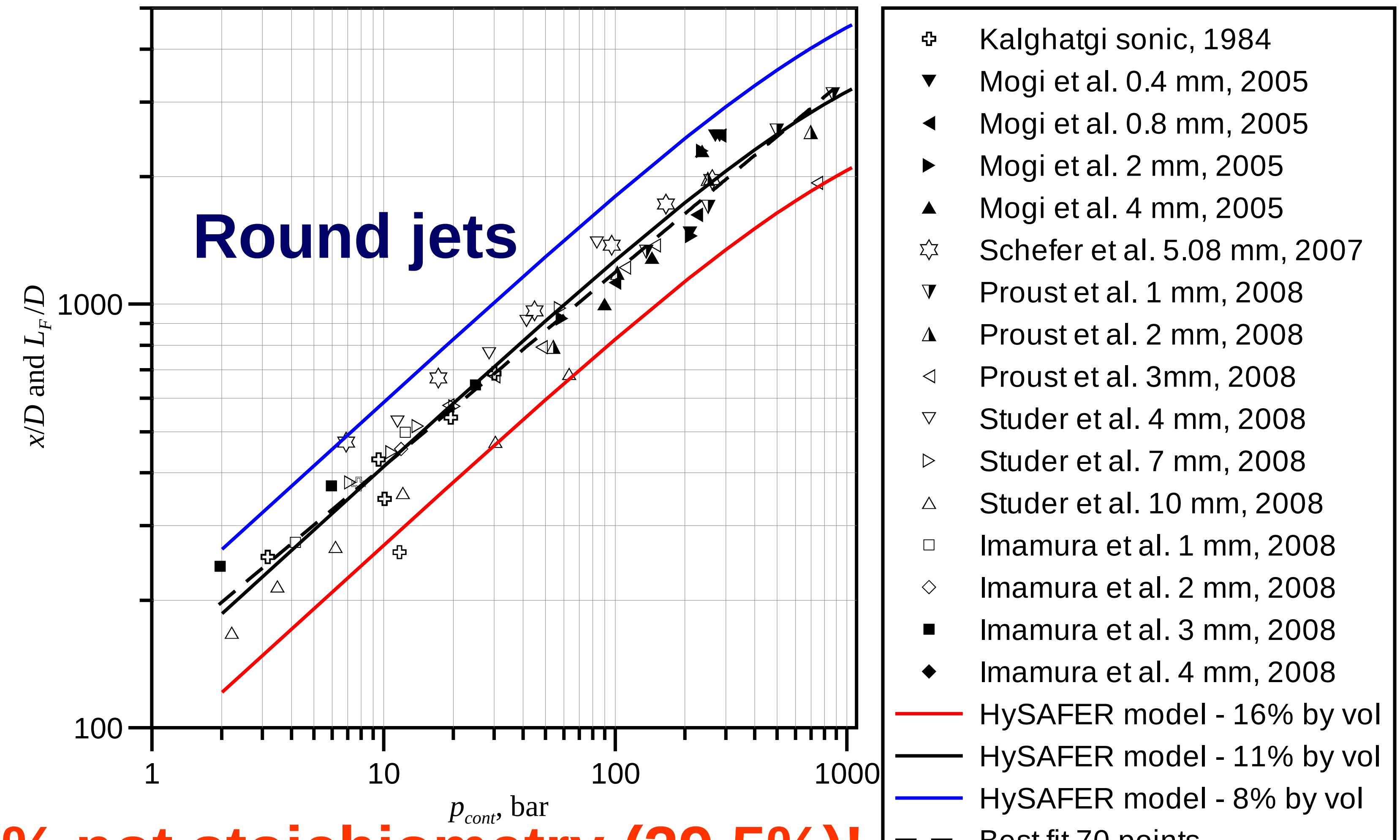
Hydrogen jet flame tip location (separation distance)

Right (+) and wrong (-) statements

- **(+) Hawthorn et al., 1949:** pointed out that it does not follow that burning will proceed as far as ideal mixing would allow. Concentration fluctuations **in turbulent flame** or local "**unmixedness**", producing a statistical smearing of reaction zone and a consequent lengthening **beyond the point where the mean composition of mixture is stoichiometric.**
- **(-) Sunavala, Hulse, Thring, 1957**: "Calculated flame length may be obtained by substitution the concentration corresponding to the **stoichiometric** mixture in equation of axial concentration decay for non-reacting jet"
- **(-) Bilger and Beck, 1975:** flame length is defined "for convenience" as the length on the axis to the point having a mean composition which is **stoichiometric** (hydrogen concentration is twice that of oxygen).
- **(-) Bilger, 1976:** the calculated flame length may be obtained by substitution the concentration corresponding to the **stoichiometric** mixture in the equation of axial concentration decay for a non-reacting jet.

Separation distance – one language

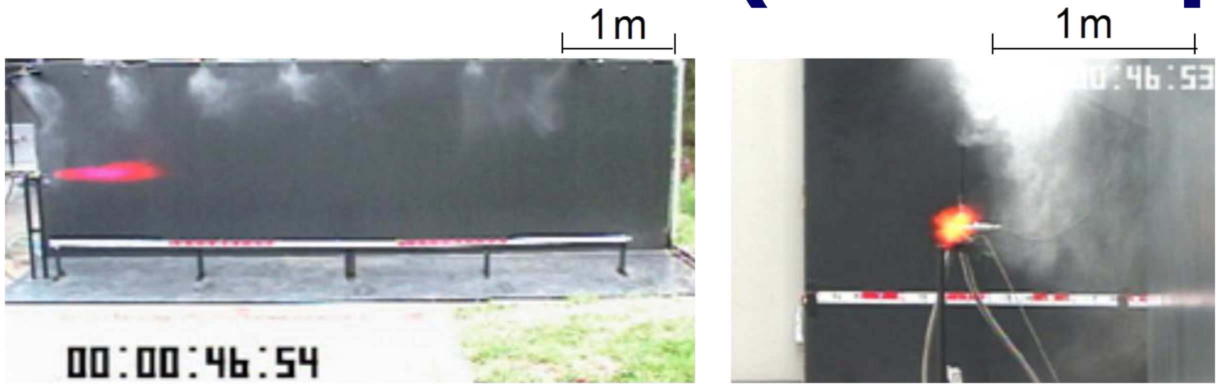
- **Flammable envelope** – 4% by volume (LFL)
- **Jet flame tip location** – 11% in unignited jet (8-16%)



11% not stoichiometry (29.5%)!

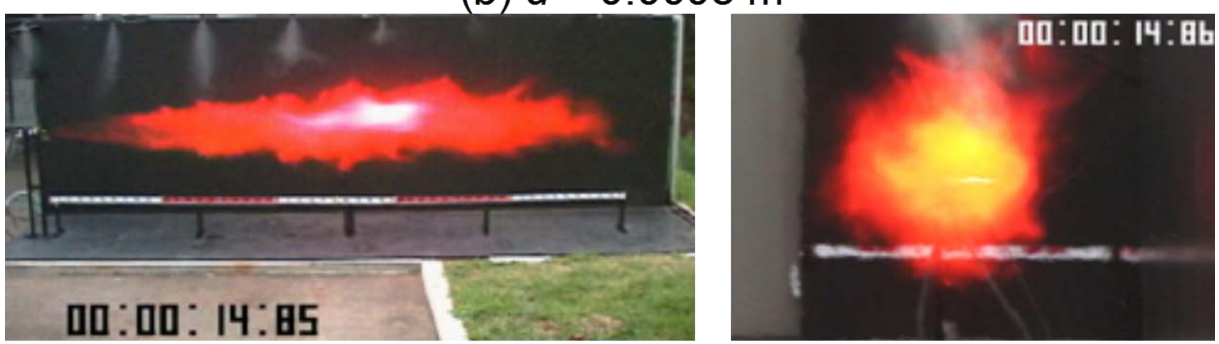
Flame shape: round and plane jets (Mogi et al.)

Round nozzles (*P*=35 Mpa)



(a) d = 0.0004 m

(b) d = 0.0008 m

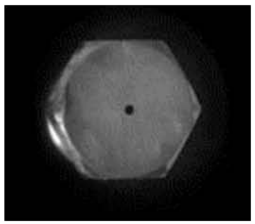
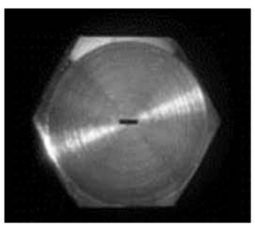
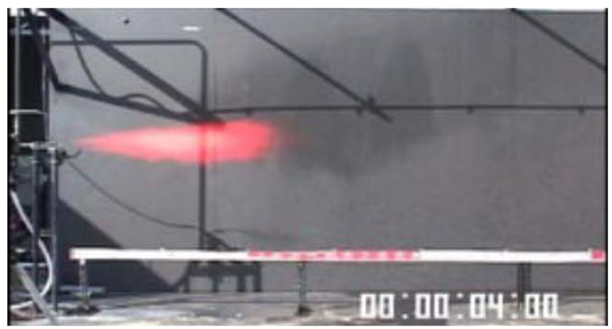
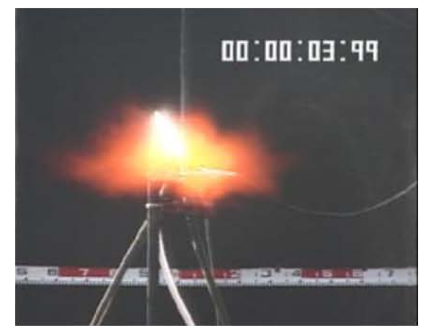
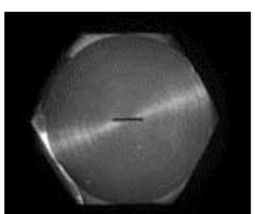


(c) d = 0.002 m

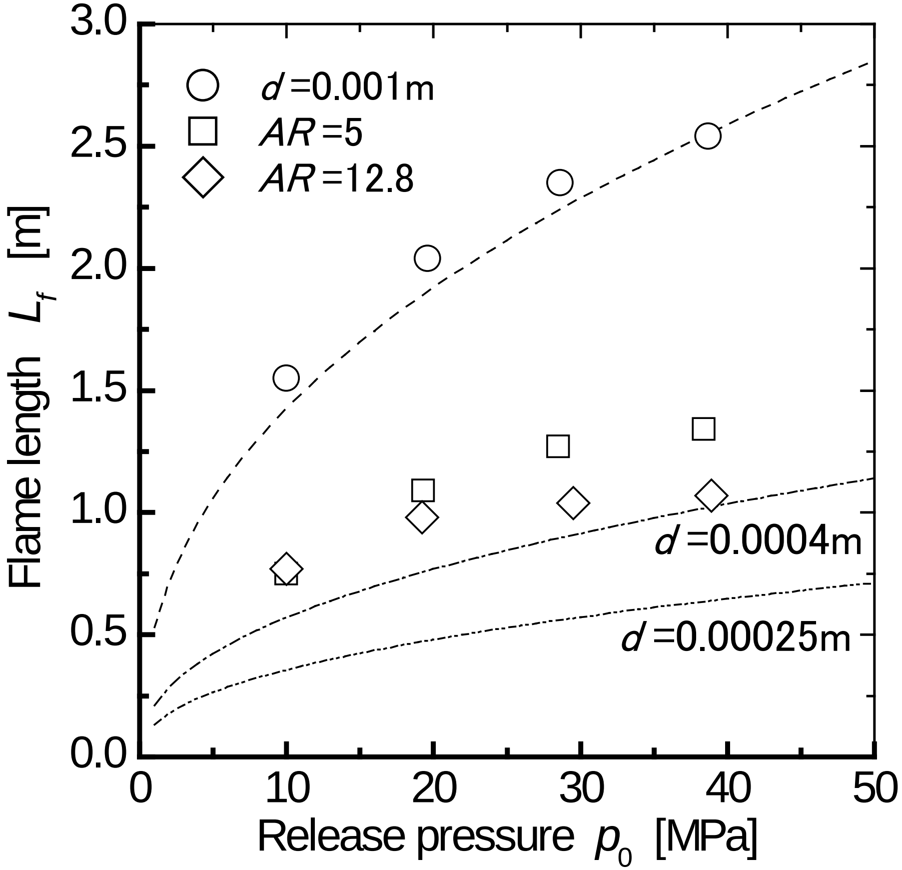
Flame length is proportional to nozzle diameter.

Round and plane nozzles (*A*=const)

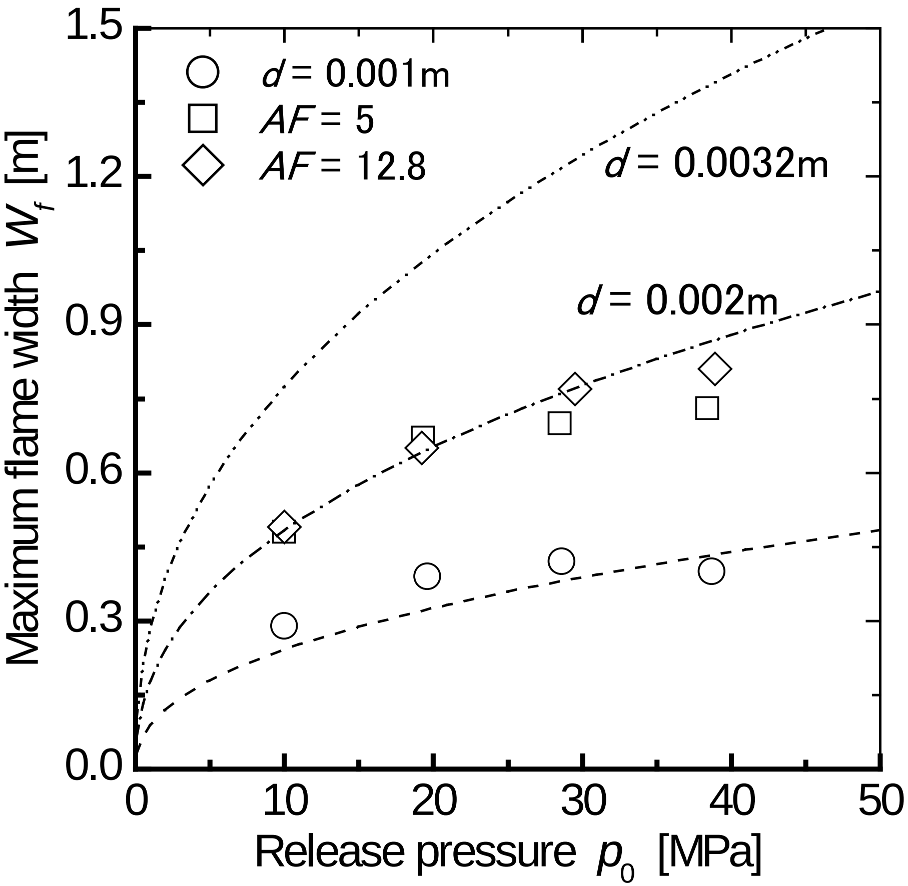
P=40 MPa (constant nozzle area 0.8 mm^2).

Nozzle	Side view	Front view
 d = 0.001 m		
 0.0004 × 0.002 m (*AF* = 5)		
 0.00025 × 0.0032 m (*AF* = 12.8)		

Nozzle shape effect on flame length



Length



Width

Pressure effects of ignited jets

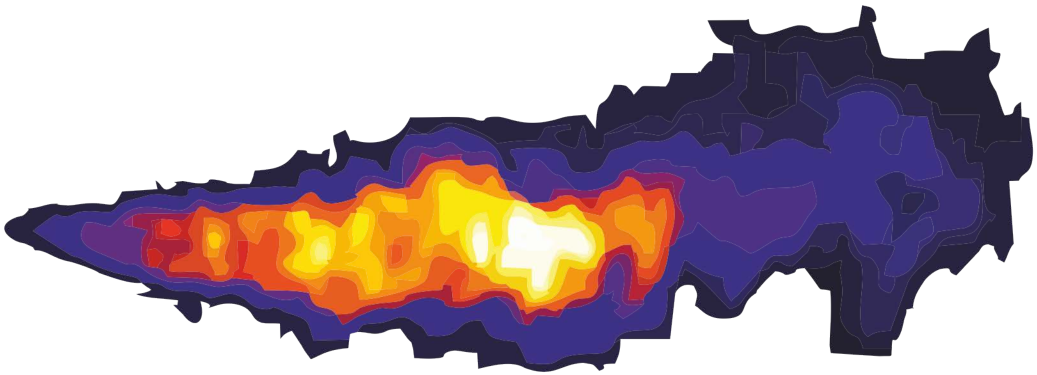
HSL tests

Test conditions

- Storage pressure: **205 bar** (two 50 litre cylinders).
- Stainless steel tubing ID=11.9 mm, a series of ball valves with internal bore of **9.5 mm**. Restrictors of 2 mm length and diameter: **1.5, 3.2, 6.4 mm**.
- Ignition by a match head with small amount of pyrotechnic material. Ignition **1.2 m** above the ground.
- The release point is **1.2 m** above the ground.
- Ignition point is located **2-10 m** from the release point.
- Piezo-resistive transducers pointed our upwards (except for wall mounted). Sensors are located at **axial distance 2.8 m** from the nozzle, **1.5 m** (then +1.1 m and +1.1 m) perpendicular to the axis, at height **0.5 m**.
- 260 ms to fully open the valve, 140 ms for hydrogen to reach 2 m, i.e. **400 ms is shortest ignition delay**.

Free jet fire: 9.5 mm, 800 ms, visible (16.5 kPa)

Infrared 4.1-5.3 microns (16.5 kPa)



Effect of orifice diameter on ΔP

Orifice diameter, mm	Ignition delay, ms	Max overpressure, kPa
1.5	800	Not recordable
1.5	400	Not recordable
3.2	**800**	**3.5**
3.2	**400**	**2.1**
6.4	800	15.2
6.4	400	2.7-3.7
9.5	**800**	**16.5**
9.5	**400**	**3.3-5.4**

Conclusion:

❖ Reduce orifice diameter ALARP to reduce overpressure following ignition

Effect of ignition delay on ΔP

Orifice d=6.4 mm. Ignition 2 m from the orifice.

Ignition delay, ms	Max overpressure, kPa
400	3.7
500	18.4
600	**19.4**
800	15.2
1000	11.7
1200	12.5
2000	9.5

Conclusion:

- Spontaneous ignition should reduce overpressure of self-ignited release (no SI observed with valve use).

Effect of ignition location on ΔP

Orifice d=6.4 mm. Fixed ignition delay 800 ms.

Ignition delay, ms	Max overpressure, kPa
400	3.7
500	18.4
600	**19.4**
800	15.2
1000	11.7
1200	12.5
2000	9.5

Conclusion:

- Spontaneous ignition could increase overpressure of self-ignited release (more research is needed)

Barrier 90º: 9.5 mm, 800 ms (42 kPa)

Barrier 60^{o}: 9.5 mm, 800 ms (57 kPa)

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 Unttached 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:

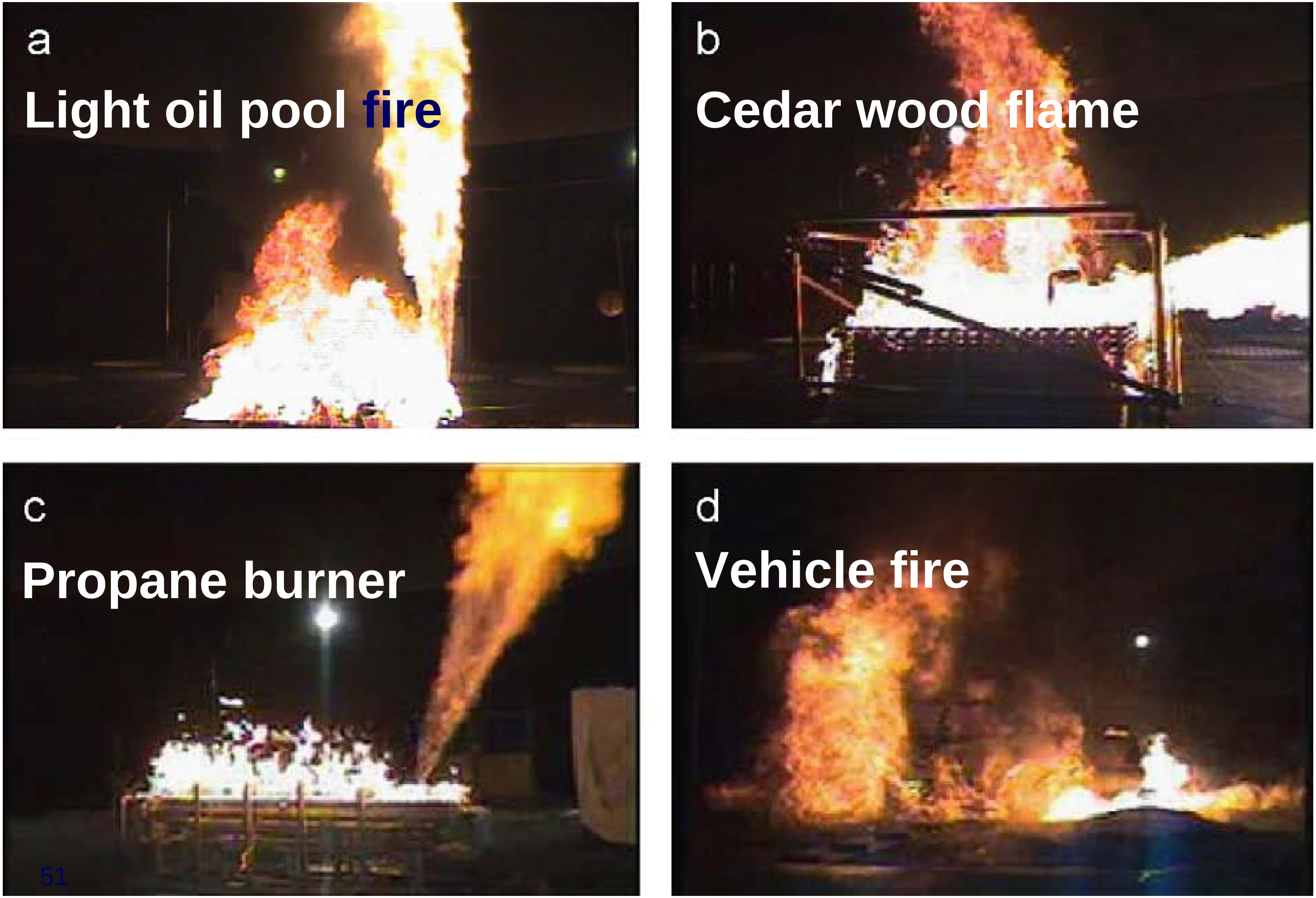
- Release along ground or walls in proximity to them can increase flame length.

Bonfire test: Type 4 tank (no PRD)

"Fire resistance" 1-6 minutes.
No combustion contribution to the blast.

Bonfire test (no PRD)

External fire tests to initiate PRD



Upward release from current PRD

Vehicle equipped with two 34 L capacity cylinders at 350 bar and **“normal” PRD** (IJHE, 2007, v.32).

Do we accept 10-15 m flame from a car?
No harm distance is 25-40 m (plus jet noise)!

Downwards release from PRD

Fire was initiated on the instrumentation panel ashtrays. The PRD was actuated 14 min 36 s (upward scenario) and 16 min and 16 s (downward). **Blowdown < 5 min** (**no tank failure – acceptable?**).

What if car is indoor…?

Garage problem solution

- **Mass flow rates from PRD must be reduced** to increase the hydrogen tank blowdown time (indoor).
- At the same time a **fire resistance of a system storage-PRD should be increased**, e.g. to R30.
- Probably Type 4 tanks (current fire resistance is few minutes) to be redesigned and tested (intumescent coating, etc.). Back to Type 1 or 2? Cryo-compressed storage (see test on next slide)?
- Pressure relief devices (PRD) with **shorter flame length at the same mass flow rate** to be tested and implemented (e.g. UK Patent Applications No.1005376.7 and No.1106812.9)

Cryo-compressed storage tests

Fire resistance (LLNL): 20 minutes

Innovative short flame PRD

Work-in-progress (Invest NI funding)

Current PRD

Current PRD

Short flame PRD

Short flame PRD

Innovative PRD1 (350 bar)

Flame length reduction: 7.5 –> 1.8 m

Innovative PRD2 (350 bar)

Flame length reduction: 6.1 –> 1.8 m

Fires in high pressure electrolysers (new safety issue)

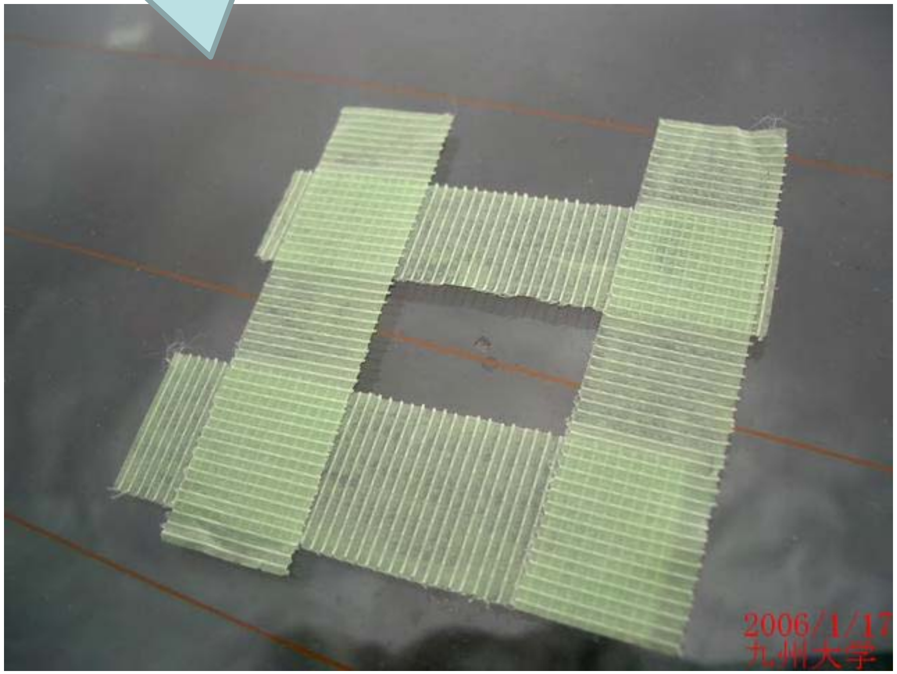
400 bar electrolyser (Japan)

Titanium electrolyser before and after the combustion in oxygen

http://www.nsc.go.jp/senmon/shidai/kasai/kasai004/ssiryo4-1.pdf

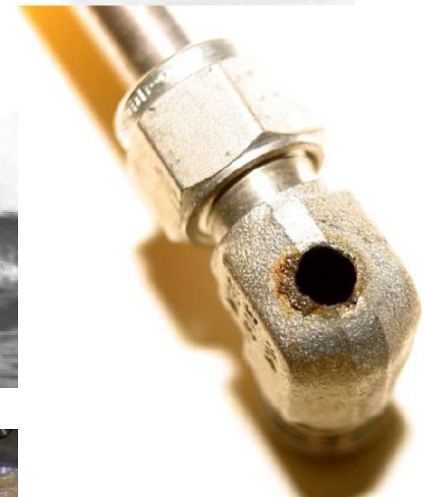
400 bar electrolyser (Japan)

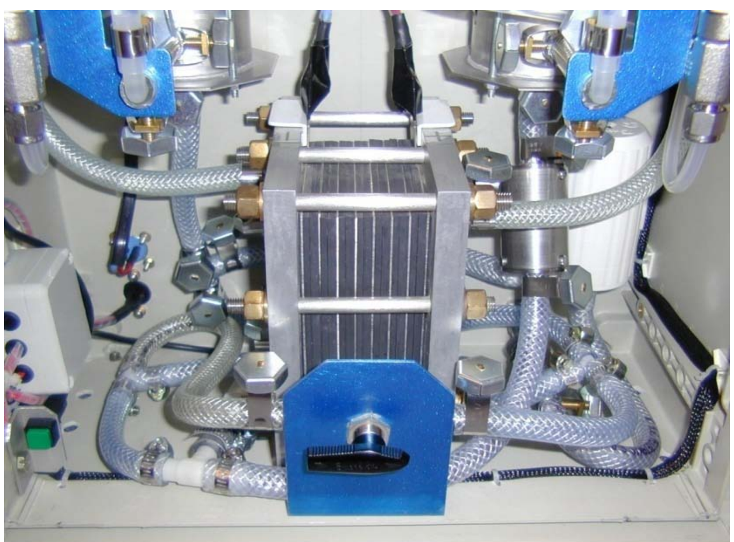
Titanium electrolyser materials were dispersed into surroundings: car windshield before and after (few days) the accident

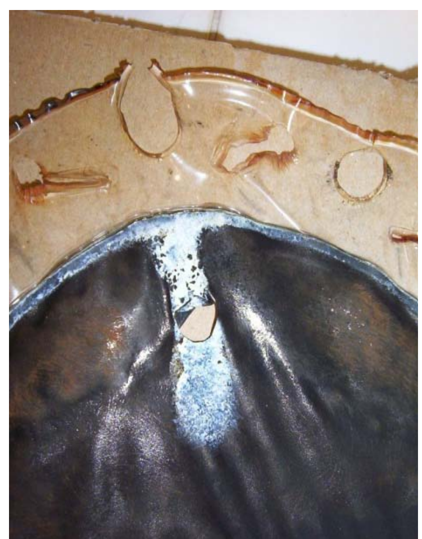


Electrolyser (France-Russia)

Cell failure mechanism at pressures above 50 bar.







There are more gaps in H2 safety…

…under scrutiny by:

- FCH JU (various consortiums);
- FP7 (different mechanisms: infrastructure, MCA);
- International Association for Hydrogen Safety;
- IEA Hydrogen Implementation Agreement (Task 31).

Safety is a main “non-technical” barrier to the hydrogen economy.

MSc in Hydrogen Safety Engineering (distance learning course):

http://campusone.ulster.ac.uk/potential/postgraduate.php?ppid=24