Hydrogen Fires

Jennifer X Wen
Fire and Explosion Research Group
Faculty of Engineering, Kingston University
London, UK

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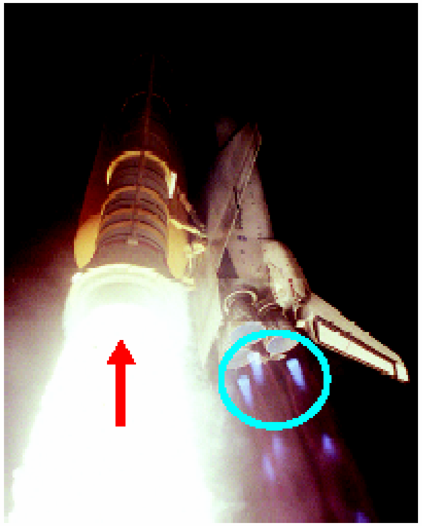
Outline (Lecture 1)

- **Basic characteristics of hydrogen fires**
- **Some fundamentals of fires**
- **Hydrogen jet fires**
  - Flame Length
  - Lift-off heights
  - Flame radiation
  - Horizontally oriented high pressure hydrogen jet flames
  - Ignition of Hydrogen Leaks

Basic characteristics of hydrogen fires

- Hydrogen fire burns quickly
- Hydrogen flames have low radiant heat
- Hydrogen fires are almost invisible



Basic characteristics of hydrogen fires

Table 3 Combustion time for 121 litres of fuel (reproduced from [1])

Fuel	Combustion time
Liquid hydrogen (LH_2)	27 sec
Propane	4 min
Petrol	5 min
Jet fuel (JP-4)	7 min

Comparison of fire from a leak in a gasoline engine car and the same kind of leak from a hydrogen car. Gasoline car to the right and hydrogen car to the left (reproduced from [2])

Table A7.1

Hydrogen Accidents - Industrial

Category	Number of Incidents	Percentage Total Accidents
Undetected Leaks	32	22
Hydrogen-Oxygen Off-gassing Explosions	25	17
Piping and Pressure Vessel Ruptures	21	14
Inadequate Inert Gas Purging	12	8
Vent and Exhaust System Incidents	10	7
Hydrogen-Chlorine Incidents	10	7
Others	35	25
Total	145	100

Zalosh, R. G., and T. P. Short. *Comparative Analysis of Hydrogen Fires and Explosion Incidents*. C00-4442-2, Factory Mutual Research Corp., Norwood, MA (1978).

Zalosh, R. G., and T. P. Short. *Compilation and Analysis of Hydrogen Accident Reports*. C00-4442-4, Factory Mutual Research Corp., Norwood, MA (1978).

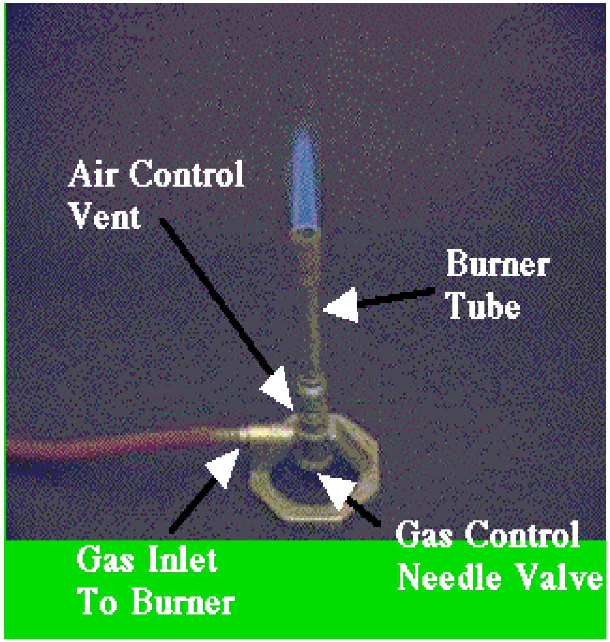
Hydrogen Fire Hazards

Table 11 Frequency of occurrence of ignition sources (reproduced from [47])

Ignition source	Hydrogen incidents		Non-hydrogen incidents	
	Number	%	Number	%
Arson	0	0	37	2.6
Collison	2	2.5	121	8.4
Flame	3	3.7	113	7.9
Hot surface	2	2.5	56	3.9
Electric	2	2.5	114	7.9
Friction spark	2	2.5	33	2.3
Not identified	70	86.3	942	64.5
Non-ignition	0	0	21	1.5
Total	81	100	1437	100

Some fundamentals of fires

- **Premixed combustion**



- **Non-premixed combustion**

Partially premixed combustion

Fireballs, jet, pool and flash fires

- A fireball results from the burning of fuel-air cloud
- Jet fires result from the combustion of a fuel released from a pressurized system or storage vessel.
- Pool fires are the result of surface burning of flammable or combustible liquid
- A flash fire is the non-explosive combustion of a vapour cloud resulting from a release of flammable or combustible material into the open air.

Jet Fires

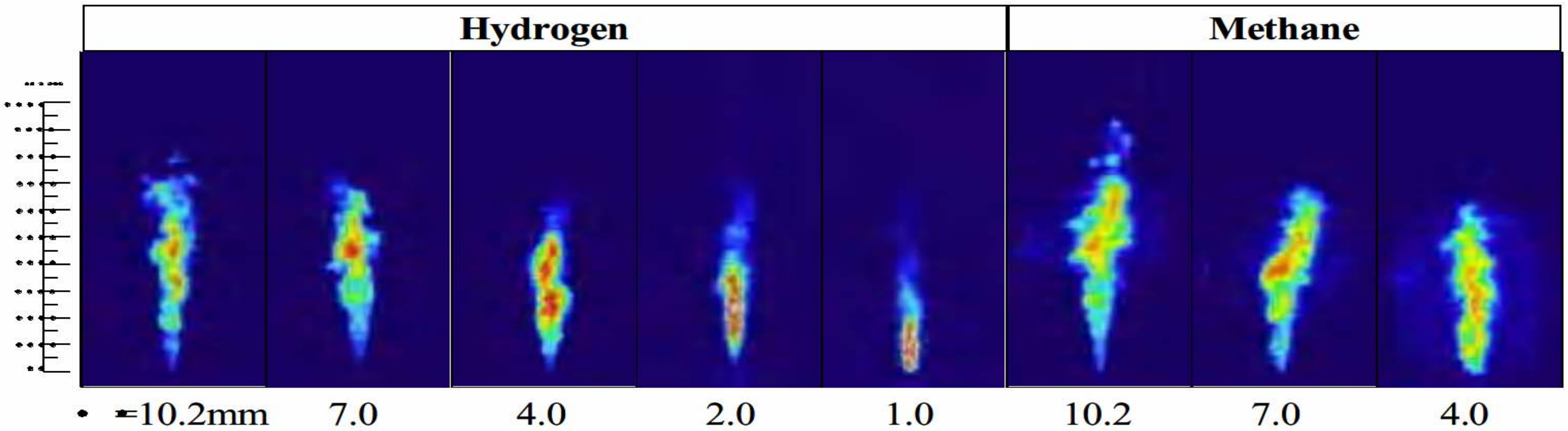


Figure 6 The infrared pictures of hydrogen and methane flames in relation to gas nozzle diameter.

Table 1 Comparison of hydrogen and methane flame

		Hydrogen	Methane
Upward Release	Maximum Flame Temperature Nozzle Dia. Φ4.0mm	1,171• •	928• •
	Flame Size Nozzle Dia. Φ10.2mm	Length: 710mm Width: 120mm	Length: 830mm Width: 150mm
	Maximum Heat Release	1.6kW/m^2	1.8kW/m^2

Fireball

A

Liquid Hydrogen and Oxygen Fireball 230 kg (500 lb) Test

Hydrogen jet fires - Flame Length

- **Delichatsios's correlation**
  - Nondimensional Froude number

$$Fr_f = \frac{u_e f_s^{3/2}}{(\rho_e/\rho_\infty)^{1/4}[\frac{\Delta T_f}{T_\infty} g d_j]^{1/2}}$$

  - Nondimensional flame length

$$L^* = \frac{L f_s}{d_j (\rho_e/\rho_\infty)^{1/2}} = \frac{L f_s}{d^*}$$

  - In the buoyancy-dominated regime,

$$L^* = \frac{13.5 Fr_f^{2/5}}{(1+0.07 Fr_f^2)^{1/5}}$$

for $Fr_f < 5$

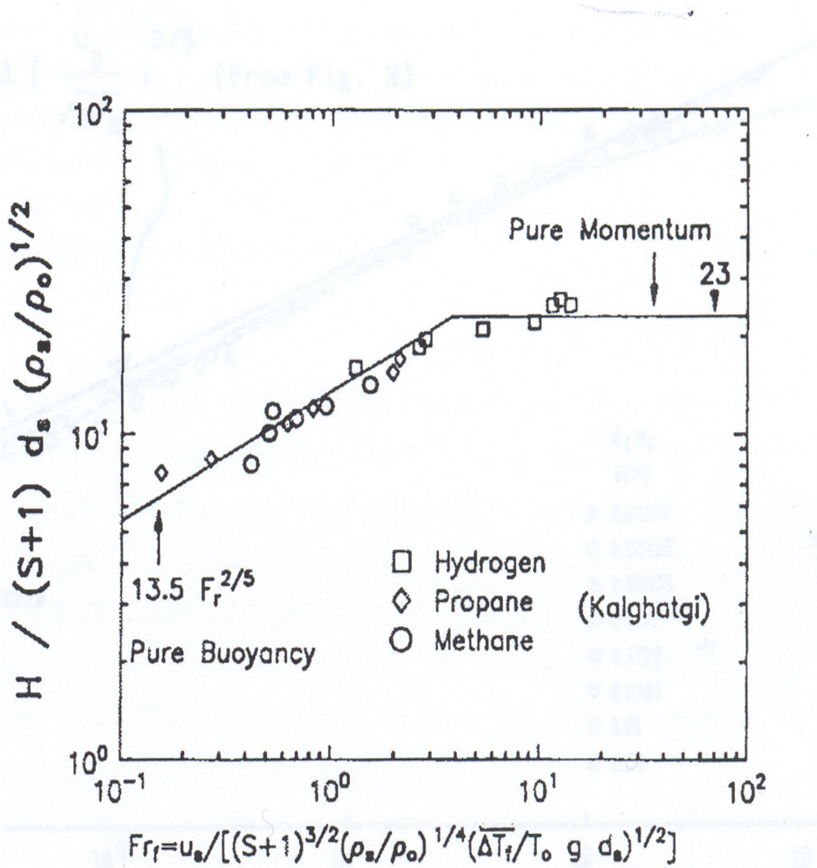
  - In the momentum-dominated regime,

$$L^* = 23$$

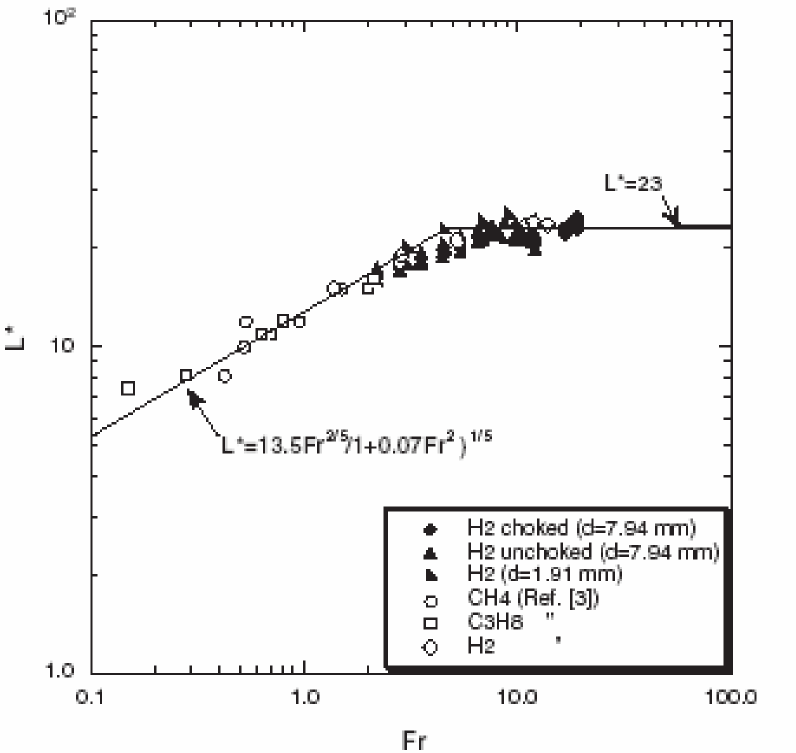
for $Fr_f < 5$

Hydrogen jet fires - Flame Length

- **Delichatsios' correlation**

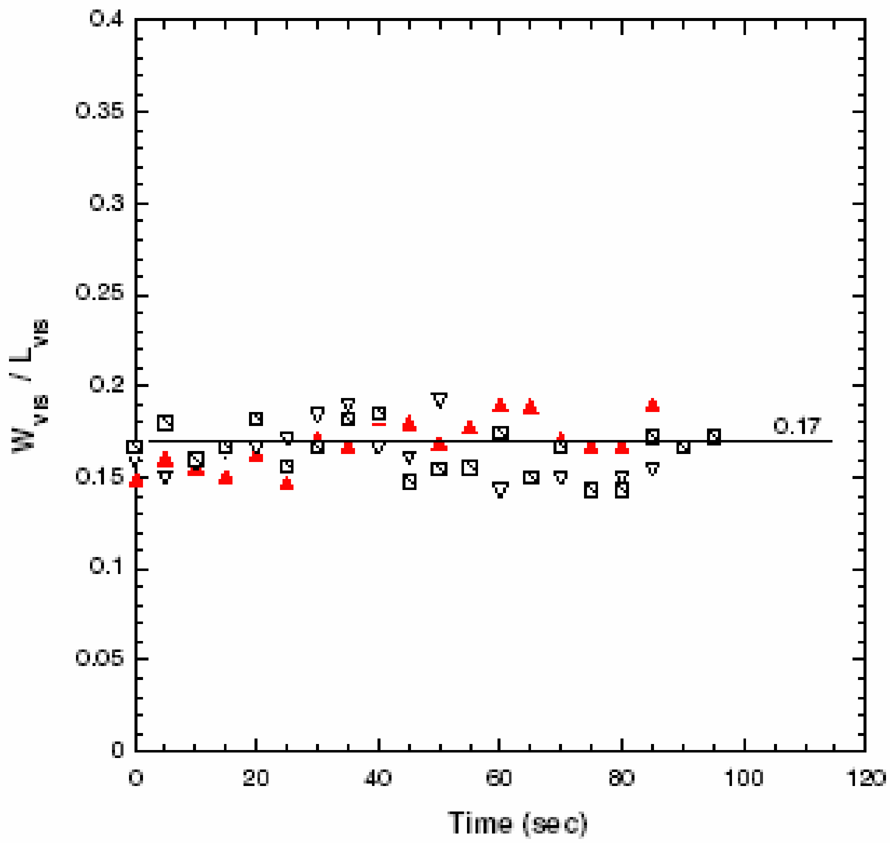


- **With Sandia vertical hydrogen flame data**



Hydrogen jet fires - Flame Width

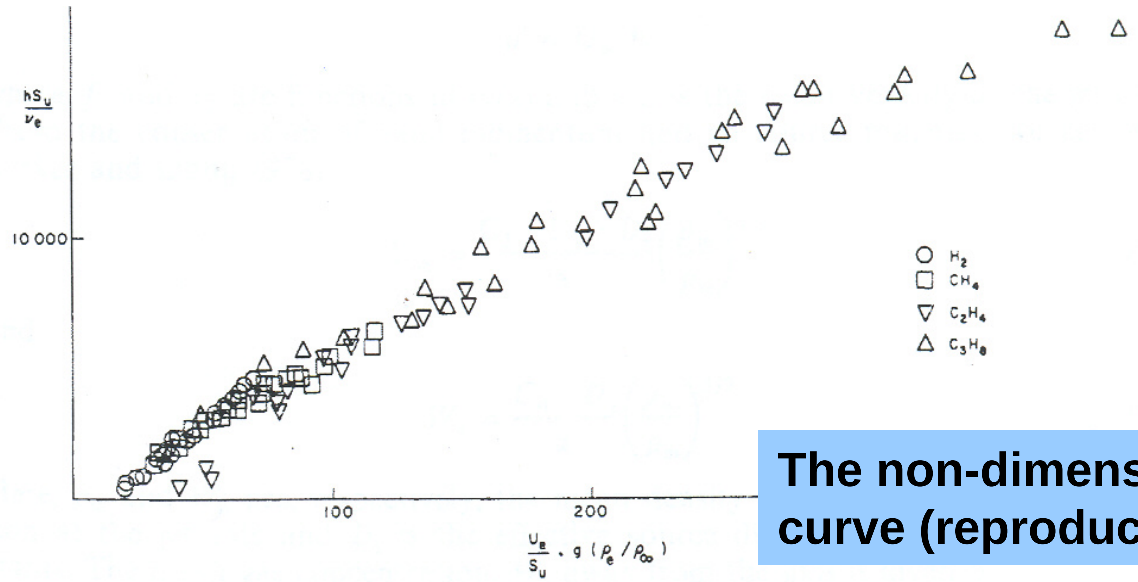
Variation of visible flame width with Froude number. Data Ratio of maximum flame width to flame length determined from visible flame emission (reproduced from [20).



Hydrogen jet fires – Lift-off height

- **Kalghatgi's correlation from subsonic jets to those from under-expanded sonic jets:**

$$\left(\frac{h\rho_e S_{L\max}}{\mu_e}\right) = C\left(\frac{U_e}{S_{L\max}}\right)\left(\frac{\rho_e}{\rho_\infty}\right)^{1.5}$$



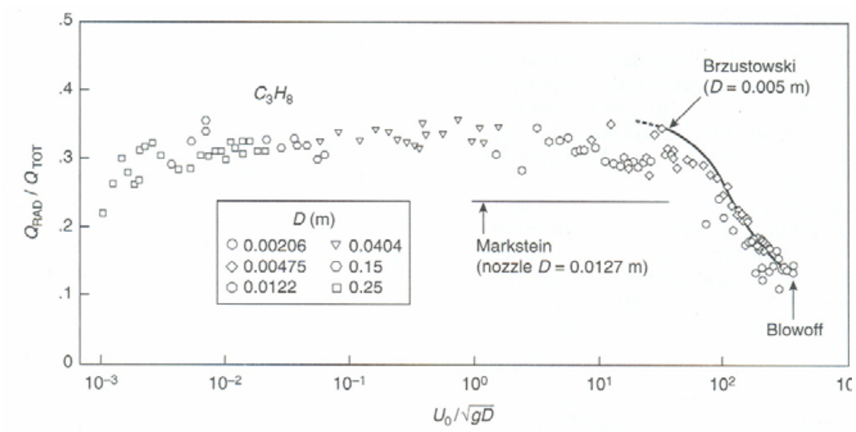
The non-dimensional lift-off height curve (reproduced from [12])

Radiation from jet flame

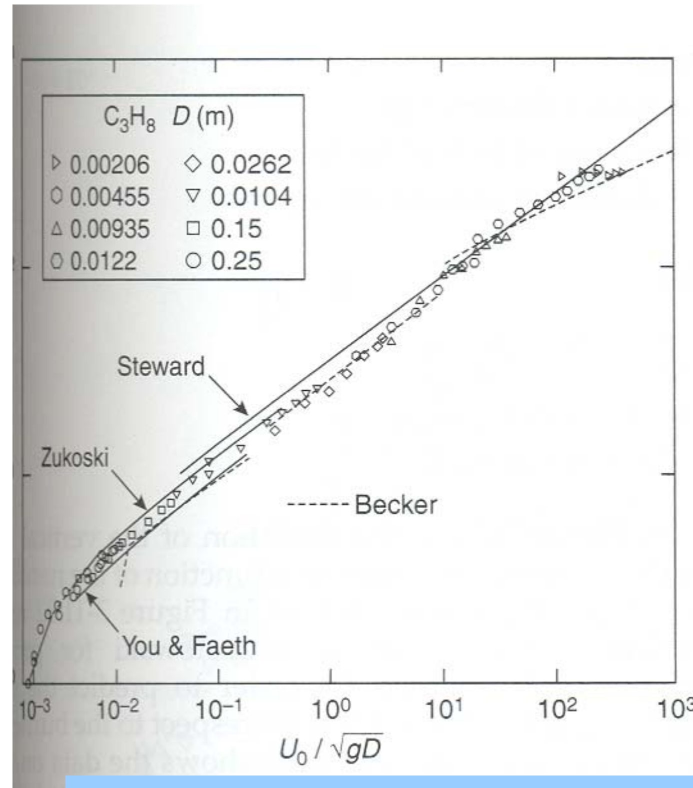
Table 7 Comparison of radiative fraction, χ_r , of various fuels (reproduced from [30])

Fuel	f_s	χ_r Brzustowski [34]	χ_r Burgess and Hertzberg [33]	χ_r Tan [35]	χ_r Kent [36]	χ_r McCaffrey [33]
Hydrogen	1.0	0.2	0.17	-	-	-
Methane (C_1)	0.189	0.2	0.23	0.20	0.19	0.22
Ethylene (C_2)	0.170	0.25	0.36	0.26	0.25	0.38
Propane (C_3)	0.176	0.30	-	0.32	0.32	0.302
Butane (C_4)	0.175	0.30	0.30	0.37	0.37	-
C_5 and higher	-	0.40	-	-	-	-

Radiation from jet flame



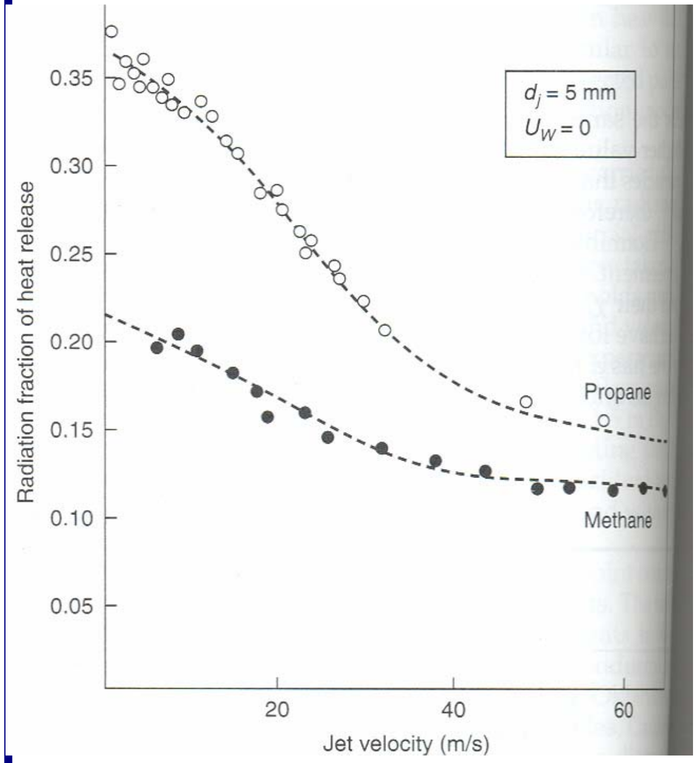
Radiative fraction measured by McCaffrey [33].

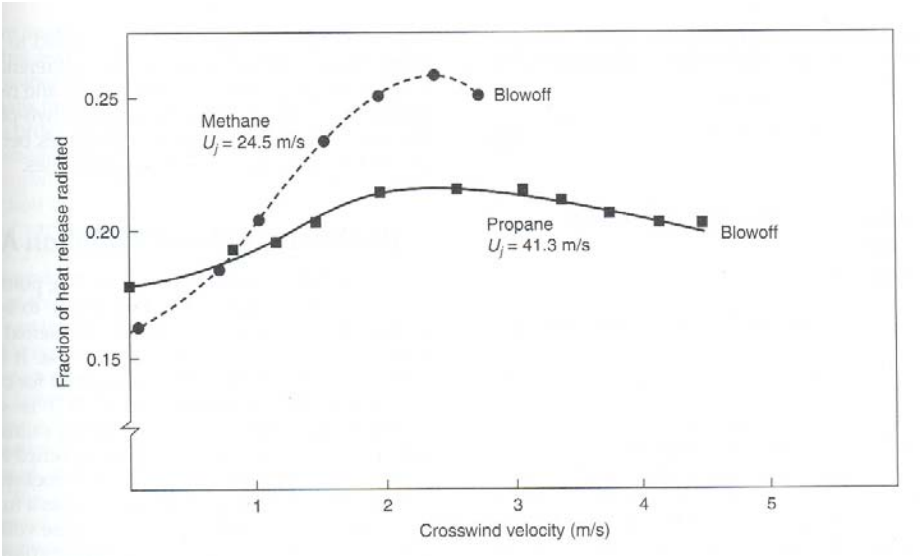


Radiative fraction is constant in the buoyancy-controlled regime, but for momentum-controlled jet flames, the radiative fraction decreases until blow-off occurs.

Flame height per nozzle diameter as a function of (reproduced from [30]).

Radiation from jet flames





Effect of crosswind on the radiant energy

Radiation fraction χ_r decreases with increasing jet velocity

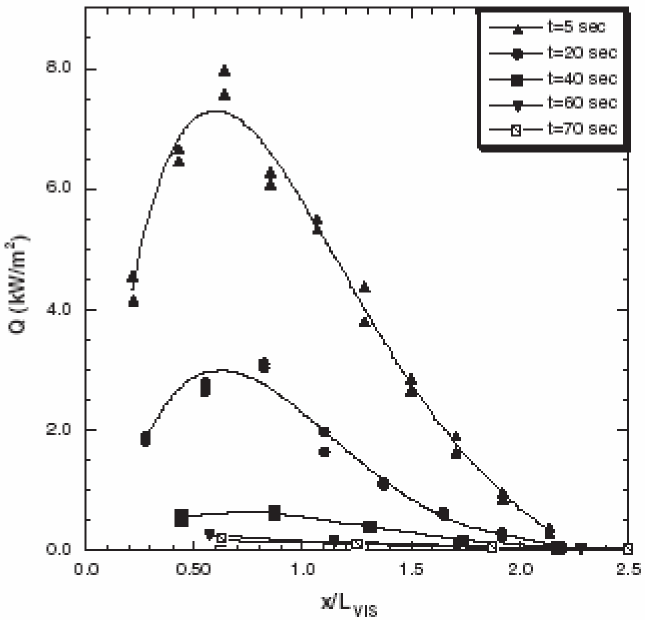
Radiative properties of hydrogen jet fires - (Schefer et al. [20], Molina and Schefer [21] and Schefer et al. [22])

Table 8 Flame conditions (reproduced from [20])

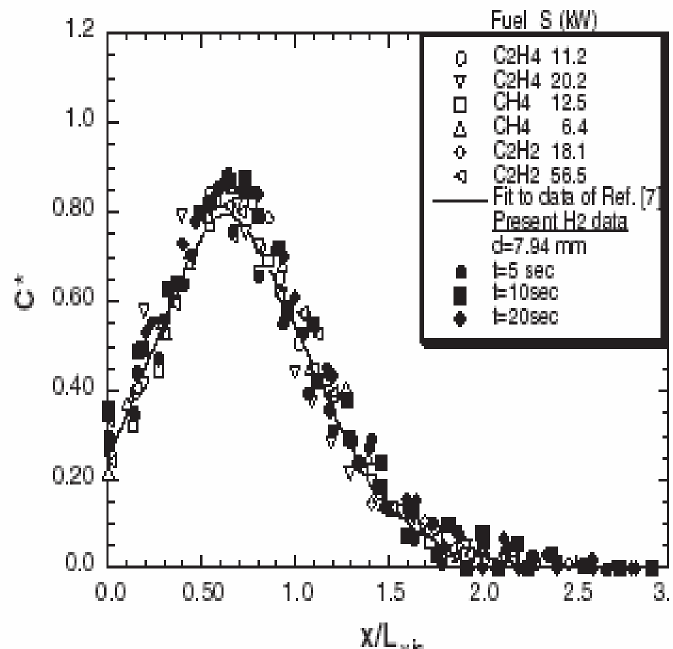
Flame	d_J (mm)	u_J (m/s)	Q (slm)	Re	m (g/s)	$m\Delta h_c$[a] (kW)
Lab flame	1.91	87.7	15	1569	0.021	2.64
	"	116.3	20	2081	0.028	3.34
	"	174.5	30	3123	0.042	5.01
	"	261.6	45	4686	0.062	7.52
	"	349.0	60	6247	0.083	10.0
SRI flame (s)	7.94					
$t = 5$	"	1233	41,026	9.8×10^5	57.3	6874
$t = 20$	"	1231	16,589	3.9×10^5	23.17	2779
$t = 40$	"	1078	4954	1.2×10^5	6.92	830
$t = 60$	"	644	1482	4.2×10^5	2.07	248
$t = 70$	"	446	810	1.9×10^5	1.13	135

[a] $\Delta h_c = 119,962$ kJ/kg for hydrogen heat of combustion. $\tau\ (\rho_f W_f^2 L_{vis} f_s)/(3\rho_0 d^2 u_J)$ [11].

Radiative properties of hydrogen jet fires - (Schefer et al. [20], Molina and Schefer [21] and Schefer et al. [22])



Profiles of radiative heat flux along the centreline of a turbulent, hydrogen-jet flame. Jet diameter is 7.94 mm. Jet orientation is vertical (reproduced from [20]).



Profiles of normalized radiative heat flux along the centreline of a turbulent, hydrogen-jet flame. Jet diameter is 7.94 mm. Jet orientation is vertical (reproduced from [20]).

Radiative properties of hydrogen jet fires - (Schefer et al. [20], Molina and Schefer [21] and Schefer et al. [22])

The radiative fraction for H2 flames is nearly a factor of two lower than non-sooting hydrocarbon flames

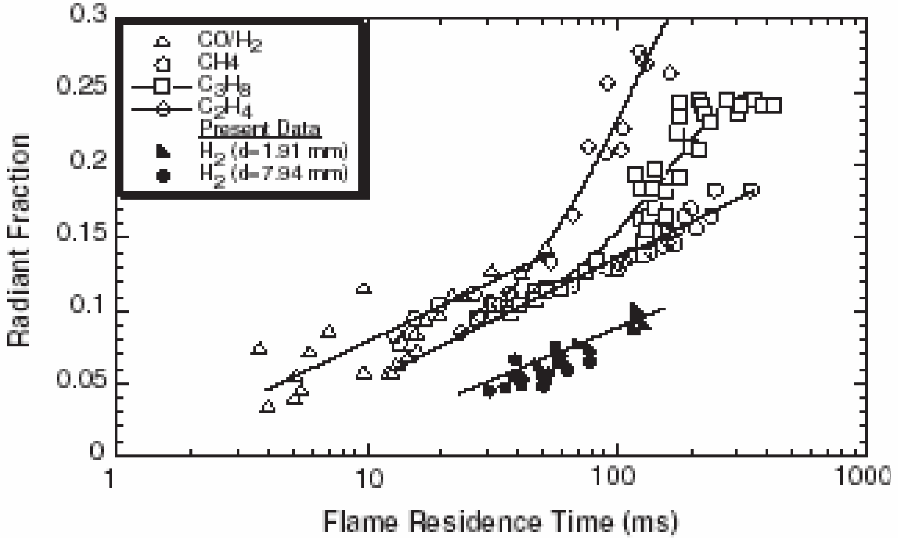


Fig. 24 Radiant fraction as a function of flame residence time (reproduced from [20]).

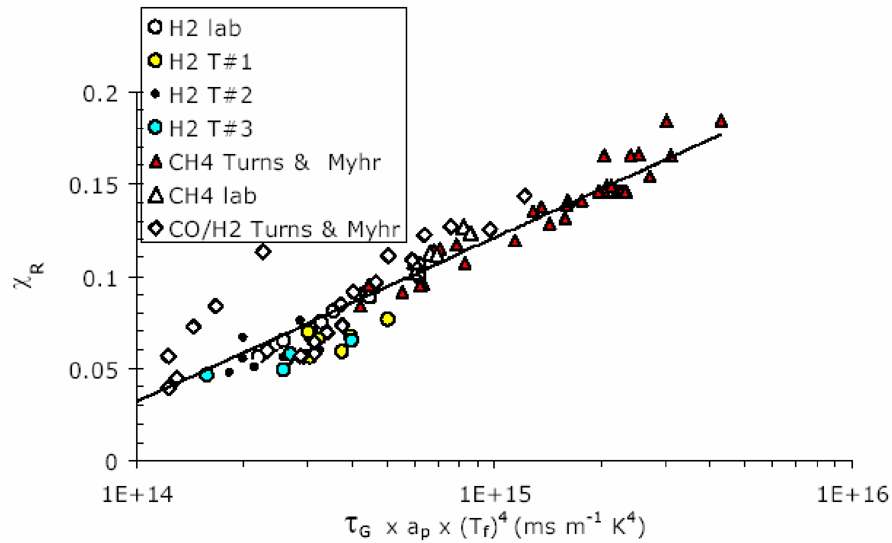


Fig. 25 Variation of radiative fraction (χ_{rad}) with the factor $\tau_G \times a_p \times T_{ad}^4$ for the gas mixtures in Fig. 24 (reproduced from [21]).

Radiative properties of hydrogen jet fires - (Schefer et al. [20], Molina and Schefer [21] and Schefer et al. [22])

Radiative fraction of large-scale jet flames was smaller than that predicted by the correlation obtained for laboratory-scale flames.

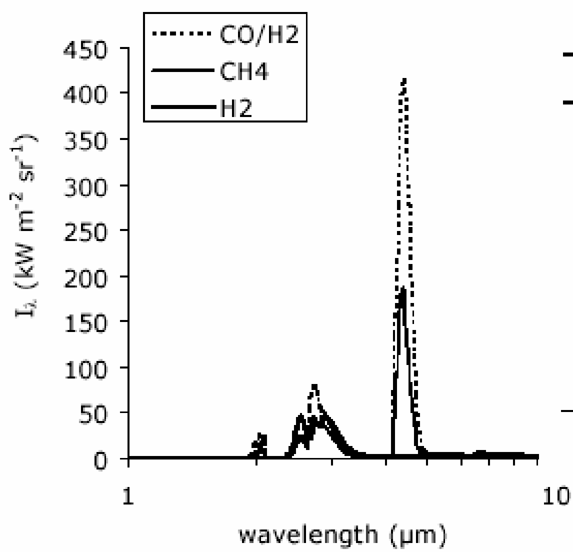


Table 10 Flame width and optical thickness ($\kappa = a_p \times W_f/2$) for the different gas mixtures (reproduced from [21])

Gas mixture	W_f (m)	κ (-)
H_2 lab [17]	0.059 - 0.085	0.01 - 0.02
H_2 T#1 [16]	0.363 - 1.555	0.04 - 0.18
H_2 T#2 [16]	0.246 - 0.705	0.03 - 0.08
H_2 T#3 [17]	0.374 - 0.806	0.04 - 0.09
CH_4 lab [17]	0.086 - 0.098	0.02
Turns CH_4 [14, 27]	0.114 - 0.255	0.03 - 0.07
Turns CO/H_2 [14, 27]	0.030 – 0.098	0.01 – 0.04

Radiative properties of hydrogen jet fires - (Schefer et al. [20], Molina and Schefer [21] and Schefer et al. [22])

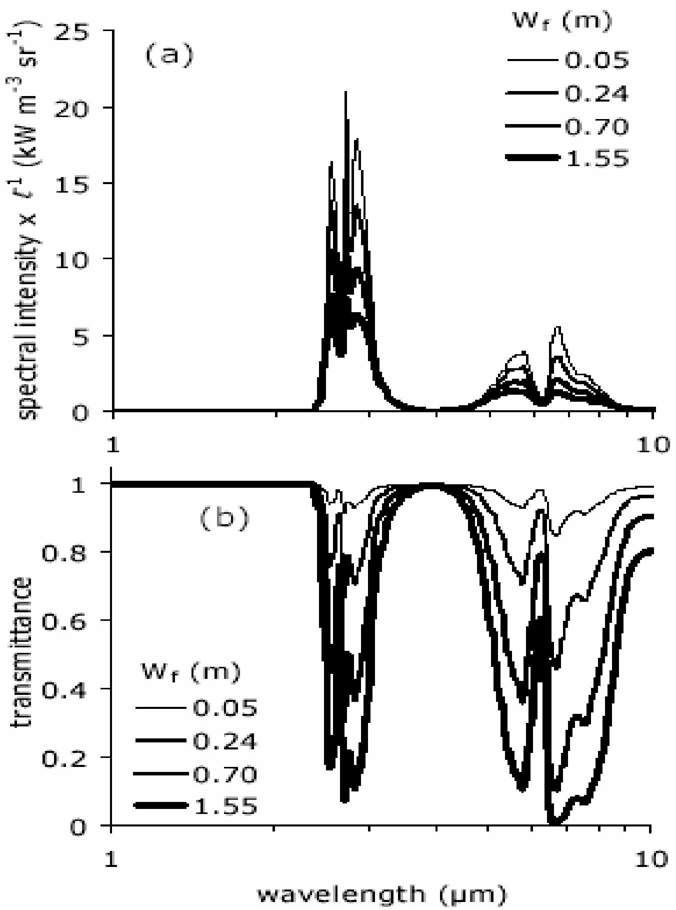


Fig. 27 Line-of-sight calculations (RADCAL [40]) of (a) spectral intensity divided by pathlength (ι) and (b) transmittance for flame A of the TNF Sandia database [43-45] (Wf = 0.05 m) and for flames scaled with dj to obtain different values of Wf. Predictions are for x/Lf = 0.7. (reproduced from [21])

Horizontally oriented high pressure hydrogen jet flames

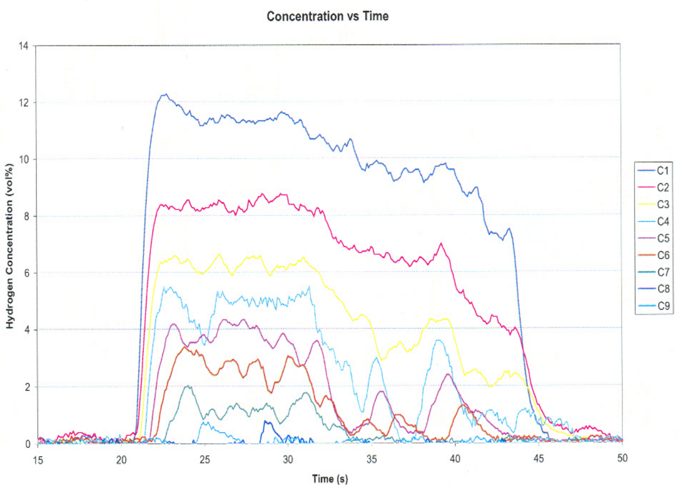


Fig. 29 Hydrogen concentrations at positions: 3, 4, 5, 6, 7, 8, 9 and 10 m downstream from the release point for the 135 barg release from a 3 mm orifice (reproduced from [38])

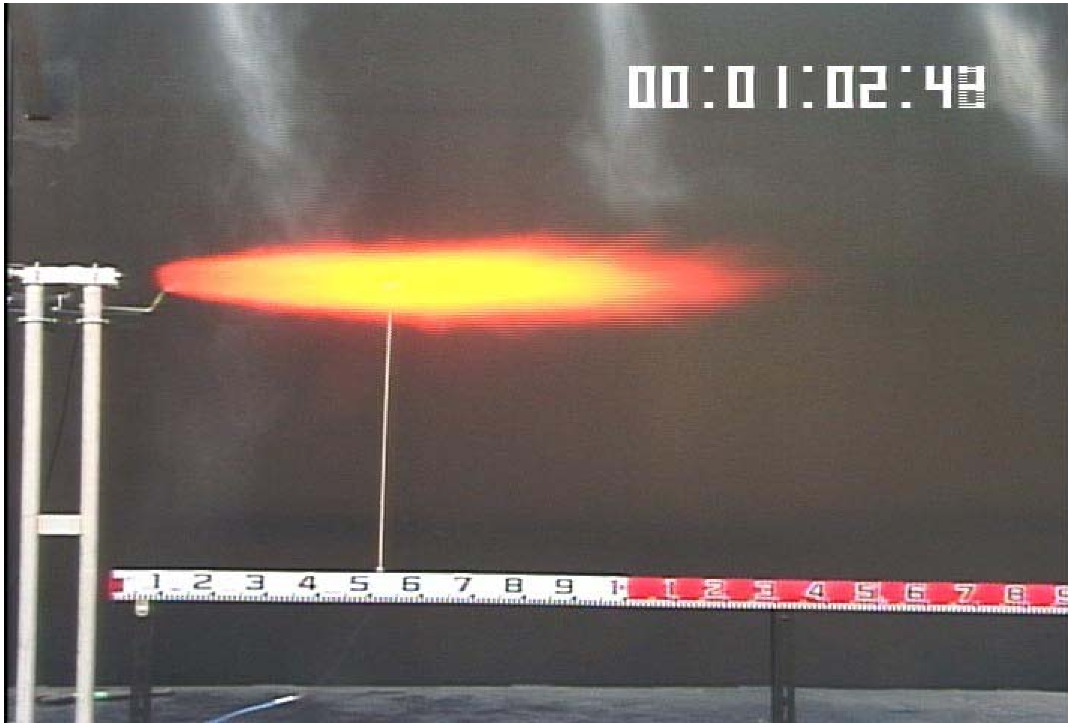


Fig. 31 Jet flame of 40 MPa high-pressure hydrogen (reproduced from [69]).

Ignition of Hydrogen Leaks

- **Astbury and Hawksworth [47]**

Table 11 Frequency of occurrence of ignition sources (reproduced from [47])

Ignition source	Hydrogen incidents		Non-hydrogen incidents	
	Number	%	Number	%
Arson	0	0	37	2.6
Collison	2	2.5	121	8.4
Flame	3	3.7	113	7.9
Hot surface	2	2.5	56	3.9
Electric	2	2.5	114	7.9
Friction spark	2	2.5	33	2.3
Not identified	70	86.3	942	64.5
Non-ignition	0	0	21	1.5
Total	81	100	1437	100

Hydrogen releases

81 incidents all led to ignition

4 cases with delay between release and ignition

11 cases where the sources of ignition

86.3% of incidents source not identified

No-hydrogen releases

1.5% did not ignite

64.5% of ignition sources were not identified.

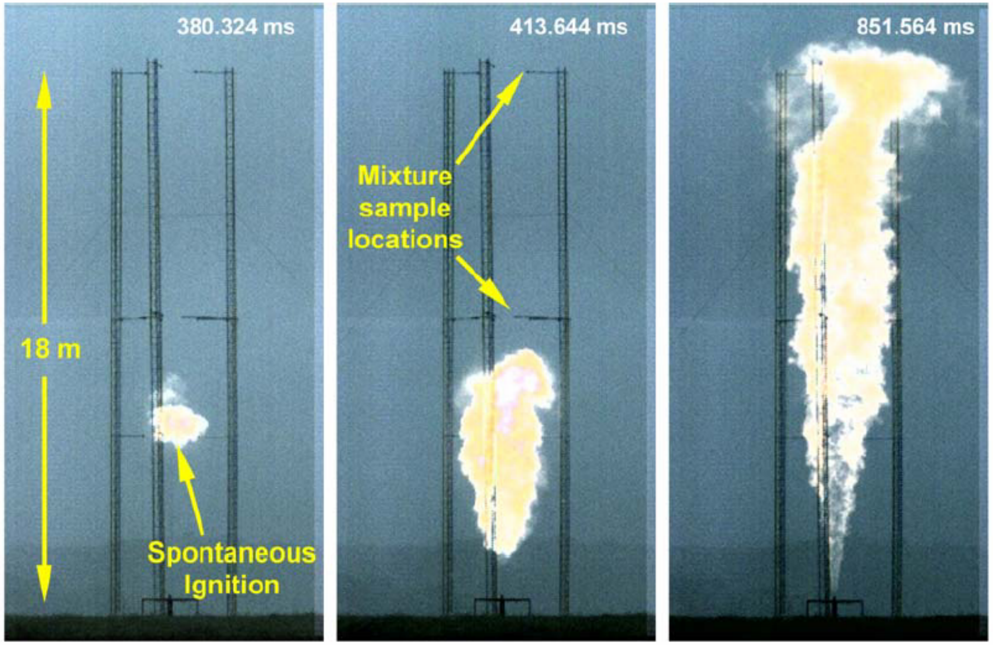
Several mechanisms which could ignite accidentally released hydrogen

- Reverse ~~Joule-T~~homson effect
- Electrostatic ignition
- Spark discharges from isolated conductors
- Brush discharges
- Corona discharges
- ~~Diffusion ignition~~
- Sudden ~~adiabatic~~ compression
- Hot ~~surface ignition~~

Some form of electrostatic charging is a possible mechanism where spontaneous ignition of hydrogen leaks from high pressure occurred at ambient temperature

Several mechanisms which could ignite accidentally released hydrogen

Fig. 32 High speed video frames from large-scale release experiments (reproduced from [46])



Summary

- **Hydrogen fire burns quickly**
- **Hydrogen flames have low radiant heat**
- **Hydrogen fires are almost invisible**
- **Vertically oriented hydrogen jet fires**
  - Flame length: Delichatsios's correlation is valid for vertical turbulent hydrogen jets, both subsonic and choked (validation up to 172 bar)
  - Lift-off height: Kalghatgi's correlation can cover flames from subsonic jets to those from under-expanded sonic jets.
  - Radiative properties of hydrogen jet fires
    - the functional dependence for radiative heat flux established previously for a range of hydrocarbon flames is also applicable to hydrogen-jet flames.
    - the radiative fraction of large-scale jet flames is smaller than that predicted by the correlation obtained for laboratory-scale flames.
    - the optical thickness increases with the flame size
    - the radiative fraction for H2 flames is nearly a factor of two lower than non-sooting hydrocarbon flames

Summary

- **Horizontally oriented high pressure hydrogen jet flames**
  - Some tests have been carried out and some are still ongoing.
  - Little quantified information can be found in the public domain.
  - It needs to be verified whether the aforementioned findings on vertically oriented jet flames are applicapable to horizontal flames.

- **Ignition of hydrogen leaks**
  - Some form of electrostatic charging is a possible mechanism where spontaneous ignition of hydrogen leaks from high pressure occurred at ambient temperature.