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HYDROGEN NON-REACTING AND REACTING JETS IN STAGNANT AIR: OVERVIEW AND STATE-OF-THE-ART

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ABSTRACT

An overview and state-of-the-art of studies on non-reacting and reacting hydrogen jets submerged into stagnant air are presented. The similarity law by Chen and Rodi (1980) for calculation of axial concentration decay in non-reacting jets with modifications on the non-ideal behaviour of hydrogen at high pressures and presence of highly underexpanded jet structure is validated against large scale experiment by Shell and HSL (Shirvill *et al.,* 2006). A new dimensionless group to correlate 95 experimental data on jet flame length is derived by the similitude analysis to address the unresolved issue of flame length dependence on both nozzle diameter and mass flow rate. All data collapsed onto a single curve, with the best fit equation $L=76\cdot(\dot{m}\cdot D)^{0.347}$. The nomogram is developed as a tool for hydrogen safety engineering to assess the flame length by only nozzle diameter and storage pressure.

Keywords: hydrogen, dispersion, underexpanded jet, jet fire, flame length, correlation

INTRODUCTION

Hydrogen is an emerging energy carrier for vehicles, stationary fuel cell applications, etc. The development of infrastructure for hydrogen economy requires new safety codes and standards that establish guidelines for building the components of this infrastructure (Schefer *et al.*, 2007). However, before the standards are developed the underlying physical phenomena have to be understood, and reliable engineering tools developed. Hydrogen onboard vehicle tanks currently operate at pressures up to 700 bars, and unscheduled releases can create highly underexpanded turbulent jets. This will lead to formation of a flammable envelope in a case of unignited release, or a jet fire if hydrogen is ignited. Knowledge of flammable envelope size and jet flame length is needed to underpin set-back distances for hydrogen safety engineering. For example, the envelope with hydrogen concentration close to the lower flammability limit (4% by volume) must not reach locations with air intake into buildings, etc. Flame length, radiation and duration of jet fires should not pose unacceptable risk to people and structures.

In this paper the author overviews in a chronological order results of previous studies on non-reacting hydrogen jets and jet fires. Based on the analysis of theoretical results and experimental data on mixing and combustion in jets, new ideas are suggested and validated to address issues related to high pressure hydrogen storage. Engineering tools for prediction of safety or set-back distances are developed.

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Non-ideal behaviour of hydrogen and under expansion of flow in a nozzle at high pressures are accounted for.

NON-REACTING HYDROGEN RELEASES

In 1961 Ricou and Spalding demonstrated by means of dimensional analysis that when the fluid density is uniform, the Reynolds number is high, and the distance x from the nozzle is much larger the diameter of the orifice D, the mass flow rate, including entrained air across a section at right angle to the jet axis $m(x)$, is proportional to x

$$m(x) = K_1 M_0^{1/2} \rho_S^{1/2} x\,, \tag{1}$$

where the momentum flux of the jet at orifice is $M_0 = \rho_N U^2 \pi D^2 / 4$. It was found experimentally that: the equation for mass flow rate holds for non-uniform density without modification provided that buoyancy effects are negligible; a numerical constant K_1 has the value 0.282 irrespective of the density ratio; and the presence of combustion reduces K_1. The experimental data for isothermal injection of different gases (hydrogen, air, propane, carbon dioxide) into stagnant air can be held to obey the relation

$$\frac{m(x)}{m_N} = 0.32 \frac{x}{D} \sqrt{\frac{\rho_S}{\rho_N}}\,. \tag{2}$$

This coincides with the earlier suggestion by Thring and Newby (1953) that the characteristic length of a turbulent jet is not D but $D(\rho_N/\rho_S)^{1/2}$. Reciprocal to the left-hand side of equation (2) by Ricou and Spalding (1961) is a fuel mass fraction averaged through the jet cross-section

$$C_{av} = 3.1 \sqrt{\frac{\rho_N}{\rho_S}} \frac{D}{x}\,. \tag{3}$$

A fuel mean mass fraction on a jet axis is higher compared to a fuel mass fraction averaged through the jet cross-section and can be calculated by a similarity law by Chen and Rodi (1980) for round and plane jets respectively

$$\frac{C_{ax}}{C_N} = 5.4 \sqrt{\frac{\rho_N}{\rho_S}} \frac{D}{x} \text{ (round jet)}; \qquad \frac{C_{ax}}{C_N} = 2.13 \sqrt{\frac{\rho_N}{\rho_S}} \sqrt{\frac{D}{x}} \text{ (plane jet)}. \tag{4}$$

Thus, for jets in stagnant air the distance to particular concentration expressed in percents by volume linearly depends on nozzle diameter L/D=const. According to the similarity laws (4) the decay of nozzle gas concentration in a round jet is essentially faster with distance compared to a plane jet. The constant's value calculated by (4) for round (plane) jet is (with density ratio ρ_S/ρ_N=14.45 in the approximation of fully expanded flow in the nozzle): $(L/D)_{30\%}$=49.3 (379); $(L/D)_{8.5\%}$=222 (7689); $(L/D)_{4\%}$=493 (37854); $(L/D)_{2\%}$=1008 (157926); $(L/D)_{1\%}$=2029 (640760). It is worth noting that correlations (4) by Chen and Rodi (1980) were validated by concentration measurements in vertical jets up to value L/D=50 only and their applicability above this range should be validated. The following formula was used to calculate the mass fraction by the volumetric (mole) fraction: $1/C_{M\text{-}ax}=1+(1/C_{V\text{-}ax}-1)M_S/M_N$ (mass fraction 0.0288 corresponds to 30% by volume, 0.00639 - 8.5%, 0.00288 - 4%, 0.00141 - 2%, 0.0007 - 1%).

In 1980 Shevyakov *et al.* published results on unignited hydrogen jets in air. In particular, they showed that at high Froude numbers Fr>10^5 the dimentionless distance to 30% by volume of hydrogen

$(L/D)_{30\%}$ is a constant 47.9. This is in an excellent agreement with published independently at the same year work by Chen and Rodi (1980). Similarly, the theoretical formula derived by Shevyakov and Saveleva (2004) gives close to Chen and Rodi (1980) estimate for the flammable envelope $(L/D)_{4\%}$=410.

Hydrogen onboard storage pressure is up to 700 bars. Many of leaks would form underexpanded jet. Jet is considered underexpanded if the pressure at the end of a nozzle has not fully dropped to the atmospheric pressure. At high pressures the exit velocity remains locally sonic, but the exit pressure rises above ambient with the result that expansion down to ambient conditions takes place outside the nozzle (Birch *et al.*, 1984). The theoretical critical pressure ratio for sonic hydrogen flow is about 1.9 according to well-know formula for choked flow conditions $p_N / p_R = \left(2/(\gamma+1)\right)^{\gamma/(\gamma-1)}$. Jets exhausted from the open end of the experimental geometry studied by Ishii *et al.* (1999) tend to be subsonic matched jets for ratios of pressure in high-pressure and low-pressure chambers (the only parameter controlling the jet strength) between 1 and 4.1, sonic underexpanded jets for pressure ratios in the range from 4.1 to 41.2, and supersonic underexpanded jets for pressure ratios above 41.2. Repeating barrel shocks and Mach disks structures downstream of the first Mach disk appear intermittently at pressure ratios below 20. For typical hydrogen storage pressures we could expect a short structure with only one Mach disk. Thring and Newby (1953) were probably the first to introduce the pseudo-diameter (or notional source/nozzle diameter) concept. They suggested that the pseudo-diameter $D_{eff} = D\sqrt{\rho/\rho_{eff}}$, where D_{eff} is the aperture of a jet through which the same mass flow rate of nozzle fluid would have emerged with the same jet momentum but with density ρ_{eff} instead of ρ. However, the relationship is valid only if flow velocity at real and notional nozzles are equal, which is not an obvious assumption.

In 1984 Birch *et al.* suggested that the similarity law by Chen and Rodi (1980) works also for underexpanded jets. The behaviour of underexpanded jets was shown to be similar to classical free jets provided that an appropriate scaling factor is employed to describe the effective size of the jet source. The resultant concentration field behaves as if it was produced by a larger source than the actual nozzle. Birch *et al.* (1984) found that for a 2.7 mm diameter round nozzle and pressures from 3.5 to 71 atm the mean concentration of natural gas decay along the centreline when plotted against the non-dimensional coordinate $x/(D\sqrt{p_t/p_S})$, where p_t is the pressure in storage tank, all the data collapsed onto a single curve. The range of validation was L/D=30-170. Birch *et al.* (1984) underlined that the notional nozzle does not necessarily exist in the physical sense – it is merely postulated to agree with chosen definition. They used the ideal gas law, the equation for conservation of mass between choked flow through actual nozzle and a sonic flow through notional nozzle. Other assumptions used: uniform sonic velocity after jet expansion to ambient pressure, and expanded flow temperature equal to initial temperature in the reservoir.

Unfortunately, Birch *et al.* (1984) used incorrect form of the Chen and Rodi (1980) correlation, in particular the volumetric fraction was used in their equation instead of the mass fraction as in the original correlation (Chen and Rodi, 1980; Wang *et al.*, 2008), etc. By these reasons their results are questionable. The conclusion by Birch *et al.* (1984) about the universal character of Chen and Rodi's correlation (1980) still has to be validated. Then the estimation of set-back distances for non-reacting hydrogen jets would be straight forward as follows from equations (4) with a density of nozzle gas, ρ_N, calculated by a justified method. There are other reasons by which Birch *et al.* (1984) and similar approaches can not be applied for high pressures gas storage, e.g. due to limitations on the ideal gas law at high pressures. This is an essential issue: the ideal gas law overestimates the hydrogen released mass from 700 bar storage by about 45% (Tchouvelev *et al.*, 2007).

Schefer *et al.* (2007) the first calculated a notional nozzle diameter taking into account the non-ideal behaviour of hydrogen at high pressures. Their approach is entirely analogous to Birch *et al.* (1984) and is based on the conservation of mass and momentum, assumes no viscous forces, the ambient pressure and uniform velocity profile across the notional nozzle cross section, sonic (choked with M=1) flow at the jet exit, and isentropic flow relations. It allows calculation of sought jet conditions at the nozzle. Similar approach has been developed by Molkov *et al.* (2009) based on the application of mass and energy conservation equations. Comparison between axial measured (Shirvill *et al.,* 2006) concentration for horizontal jet escaping through 3 mm diameter orifice from 100 bar storage (initial temperature 14 C) and concentration calculated by equation (4) with values ρ_N determined by the model (Molkov *et al.*, 2009) is shown in Table 1.

Table 1. Measured (Shirvill *et al.,* 2006) and calculated axial hydrogen concentration

Concentration, % by volume	Distance from the nozzle, m								
	3	4	5	6	7	8	9	10	11
Measured	9.95	7.73	6.12	4.94	4.41	4.04	3.49	2.85	2.69
Calculated	13.8	10.7	8.74	7.38	6.39	5.63	5.04	4.56	4.16

The calculated concentrations are conservative through the whole range of validation L/D=1000-3700, which is essentially beyond the maximum validation limit in previous studies, e.g. L/D=170 in (Birch *et al.*, 1984). From author's point of view there are at least three possible reasons for higher calculated concentrations. The first is absence of losses in the applied model (Molkov *et al.*, 2009). The second is a possible decrease of initial pressure 100 bar immediately after the start of release as observed in some experiments of such kind (Schefer *et al.,* 2007). The third reason is horizontal direction of jet whereas correlation is originally for vertical jets. The last is supported by some increase of the deviation between measured and calculated values with a distance from the nozzle. More research is needed to clarify the role of these reasons and validate the method further. In a meantime this conservative method can be recommended for hydrogen safety engineering.

HYDROGEN JET FIRES

The classic theoretical consideration of mixing and combustion in turbulent gas jets by Hawthorne *et al.* (1949) is the first used for assessment of turbulent flame lengths. The qualitative agreement between theory and experimental flame length and axial concentration pattern indicated that the process of mixing is the controlling factor in determining progress of the combustion. The authors reported flame heights as (L_F-s), where L_F was "the highest point to which the flickering tip reached" and s was the "distance from the break point to nozzle", a generally short length of non-turbulent flame. Transition from laminar diffusion to turbulent flames commences for hydrogen release into still air at Reynolds number around 2000 (Hottel and Hawthorne, 1949). The relation for free turbulent flame jets was developed (Hawthorne *et al.*, 1949)

$$\frac{L_F - s}{D} = \frac{5.3}{C_{st}} \sqrt{\frac{T_{ad}}{\alpha_T T_N}\left[C_{st} + (1 - C_{st})\frac{M_S}{M_N}\right]}\,. \tag{5}$$

Hawthorne *et al.* (1949) derived by simple scaling technique that flame length L is proportional to diameter D only and concluded that fuel gas flow rate is no factor, as long as it is great enough to produce a fully developed turbulent flame. They showed also that the actual variation of hydrogen concentration (normalised by axial concentration) over a cross-section of jet fire (normalised by a jet width where concentration is half of maximum concentration) is independent of distance from the nozzle. For free turbulent hydrogen flames in air in which the effects of buoyancy are small, i.e. high orifice velocity and small diameter (i.e. in the momentum limit, characteristic for hydrogen high pressure releases, with negligible value of parameter *s*), and with α_T=1.173, T_{ad}/T_N=8.04, C_{st}=0.296, M_S/M_N=14.45 (Hawthorne *et al.,* 1949) above equation casts as L_F/D=152, i.e. turbulent flame length is 152 nozzle diameters.

In 1972 Golovichev and Yasakov theoretically calculated the maximum length to diameter ratio as L/D=220, and the maximum measured value for a subsonic release with velocity 365 m/s was L/D=205. In 1974 the first systematic attempt to investigate hydrogen flame length over the whole range of operation from forced convection (jets) to natural convection (plumes) was undertaken by Baev and colleagues (1974a, 1974b). Becker and Liang (1978) stated that basic flame-length equation by Baev *et al.* resembles that of Hawthorne *et al.* (1949) but is more general in that it allows for effects of compressibility (Mach number), etc. More than 70 experiments were performed by Baev and colleagues with nozzle diameters from 1 to 16.65 mm, with subsonic jets and supersonic jets with Mach number from 0.25 to 3.08 (outflow velocities from 0 to 2600 m/s).

Baev *et al.* (1974a) theoretically derived that at the momentum controlled limit a flame length $L_F \sim Re$, or $L_F/D \sim u\rho/\mu$, i.e. the dimensionless flame length is practically constant for sonic releases. In the presence of lifting forces $L_F \sim Re^{2/3}Fr^{1/3} \sim u^{4/3}D^{1/3}$. They concluded that depending on *Fr* number there will be a characteristic peak in $L(Re)$ dependence, as described by Hottel and Hawthorne (1949), or there will be no peak for nozzles of larger diameter with increase of *Re* (three years later this was confirmed in experiments by Schevyakov and Komov (1977)). The largest experimental ratio observed was about L_F/D=230 for subsonic laminar jets and a limit L_F/D=190 for turbulent jets. Data on flame lengths were presented as dependence on the Froude number $Fr=U^2/gD$ and demonstrated saturation on the flame length dependence with increase of *Fr* number. In 1975 Bilger and Beck conducted experiments for a vertical jet diffusion hydrogen flame into still air (*Fr*: $0.6 \cdot 10^6$, $1.5 \cdot 10^6$, and $5.2 \cdot 10^6$). They found similar to Baev *et al.* (1974a) tendency of flame length saturation with *Fr* increase above $1.5 \cdot 10^6$.

In 1977 Shevyakov and Komov published their probably the only one paper in English on hydrogen releases. More results for hydrogen jet fires were reported in 2004 by Shevyakov and Saveleva. In (Shevyakov and Komov, 1977) a dependence of dimensionless flame length L_F/D on Reynolds number up to *Re*=20,000 is given for nine stainless steel tubular burners of diameter from 1.45 mm to 51.7 mm (ratio of burner length to diameter was changing from 50 for smaller diameter burners to 10 for largest one). The dependence $L_F/D(Re)$ for small burners with diameter up to 6 mm has a characteristic peak of decreasing with diameter magnitude in the area of transition from laminar to turbulent flow (Re<2,300). Then L_F/D increases with *Re* approaching a limit L_F/D=220-230 for high Reynolds numbers. For the same Reynolds number L_F/D decreases with diameter increase. This is in line with previously obtained results by Baev *et al.* (1974a, 1974b).

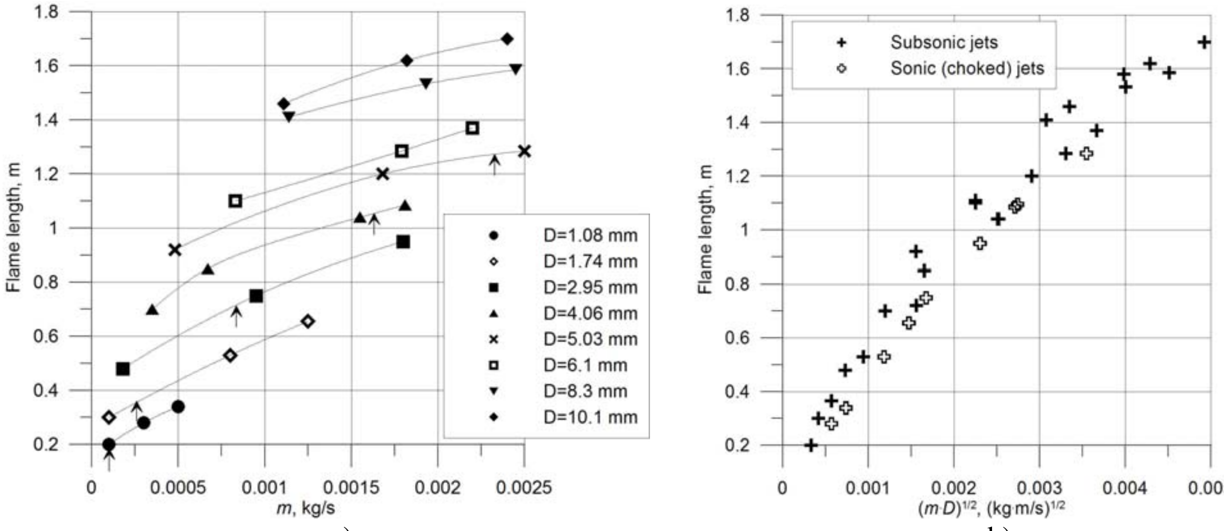
Schevyakov and Komov (1977) performed and summarised results of more than 70 experiments on subsonic hydrogen jet fires in still air. Results are presented in coordinates L_F/D versus $Fr=U^2/gD$. The momentum controlled limit L_F/D=220-230 for hydrogen jet fires was reached for $Fr>2 \cdot 10^6$. This is 50% above the value L_F/D=152 reported in the basic study by Hawthorne *et al.* (1949). However, there is no contradiction between these results. Indeed, two experiments reported by Hawthorne *et al.* (1949) were performed with nozzle diameter 4.62 and 4.76 mm (*Re*=2,870-3,580). For the same experimental conditions, the dimensionless flame length L_F/D in Hawthorne *et al.* (1949) tests was exactly reproduced in experiments by Schevyakov and Komov (1977) and can be calculated by their formulas.

An engineering correlation for calculation of the dimensionless flame length of vertical hydrogen jet fire was developed by Shevyakov *et al.* (1977, 2004). The correlation covers the whole range of conditions from buoyancy controlled (lower *Fr*) to momentum controlled (higher *Fr*) jet fires. To account for a conservative increase of the limit for momentum controlled jet fire regime from L_F/D=220 (Schevyakov and Komov, 1977) to L_F/D=230 (Shevyakov and Saveleva, 2004), and to achieve continuous piecewise linearity of the correlation in the whole range of Fr the following modification of the original correlation by Schevyakov and Komov (1977) is obtained by linear regression analysis in this study

$$\frac{L_F}{D} = 15.8 \cdot Fr^{1/5}\,(Fr < 10^5);\; \frac{L_F}{D} = 37.5 \cdot Fr^{1/8}\,(10^5 < Fr < 2 \cdot 10^6);\; \frac{L_F}{D} = 230\,(Fr > 2 \cdot 10^6). \qquad (6)$$

In 1976 Bilger with a reference on the pioneering work of Hawthorne *et al.* (1949) wrote that for reaction rates limited by diffusion the flame problem is analogous to an equivalent non-reacting mixing problem with the reaction zone appearing at the contour where the nozzle fluid concentration has been diluted to stoichiometric. However, comparison between the similarity law by Chen and Rody (1980) for non-reacting jets (4) and the correlation by Schevyakov *et al.* (1977, 2004) for subsonic jet flames at forced convection limit (6) shows that the concentration of hydrogen in non-reacting jet at a distance equal to the flame tip location is essentially less, i.e. about 8.5%. This is in line with the Hawthorne *et al.* (1949) idea of 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 for non-reacting jet. This our result surprisingly corresponds to 8.5-9.5% limit for downward and spherically propagating premixed hydrogen-air flames (Molkov, 2007).

In 1984 Kalghatgi published experimental results for more than 70 tests with subsonic and supersonic releases of hydrogen into still air through nozzles with diameter from 1.08 to 10.1 mm (Figure 1a). The maximum measured flame length for subsonic releases agree well with experimental data and recommendations of Shevyakov *et al.* (1977, 2004) and both are below recommendations by Becker and Liang (1978). Kalghatgi clearly stated that his results disagree with Becker and Liang's predictions L_F/D=310. He also showed that lift-off height varies linearly with the jet exit velocity and is independent of the burner diameter for a given gas.



a) b)

Fig. 1. Experimental data by Kalghatgi (1984): a) scattered original data – dependence on mass flow rate for different nozzle diameters (arrows indicate transition to sonic flow); b) converged data in this study – dependence on the similarity group (*m·D*)

An important conclusion that can be drawn from the study by Kalghatgi (1984) is that flame length grows with mass flow rate for a constant diameter, and flame length grows with diameter for a constant mass flow rate. This means that attempts to correlate the flame length with only diameter, similar to an approach for non-reacting jets (Birch *et al.*, 1984), are inappropriate. Moreover, it indicates that flame length correlations with only mass flow rate, as in recent publications of Japanese researchers (Mogi *et al.*, 2005), would give a priori poor prediction accuracy in a whole range of mass flow rates. A similarity group $(\dot{m} \cdot D)$ derived later in this study decreases the scattering of original experimental data of Kalghatgi (1984, Figure 1a) drastically (see Figure 1b).

In 1993 Delichatsios studied flame height relationships in the range from momentum to buoyancy-controlled turbulent jet diffusion flames with use of the "fire Froude number" for reacting flows in the form similar to used by Ricou and Spalding (1961). For the momentum limit he obtained $L_F/D=23(S+1)(\rho_N/\rho_S)^{1/2}$, where S is air to fuel mass stoichiometric ratio. This gives value $L_F/D=210$ ($S=33.72$ for 30% hydrogen-air mixture). This is slightly below the value by Shevyakov *et al.* (1977).

Blake and McDonald (1995) reported that in the momentum limit, length of horizontal flames is identical to the length of vertical flames, while in the buoyancy limit, vertical size of horizontally directed jet flame approaches the length of vertical flames. In 1998 Cheng and Chiou observed that an increase of the liftoff velocity increases the liftoff height without significant altering the flame height. Their data on flame height are around Schevyakov's limit $L_F/D=230$ within the experimental scattering.

In 1999 Heskestad published paper on consolidation of flame height data for turbulent jet diffusion flames. Assuming subsonic discharge Heskestad found for hydrogen in the momentum limit $L_F/D=175$ (230 for methane, 350 for propane, 50 for carbon monoxide). This is above theoretical value $L_F/D=152$ by Hawthorne *et al.* (1949), but less than $L_F/D=210$ by Delichatsios (1993), $L_F/D=230$ by Shevyakov *et al.* (1977), and $L_F/D=310$ by Becker and Liang (1978).

In 2005 Mogi *et al.* published data, including horizontal flame lengths, for hydrogen releases at overpressures 0.1-400 bar from convergent nozzles of diameter 0.1-4 mm. The convergent nozzle is characterised by comparatively small hydraulic losses and consequently larger flame lengths can be expected. The nozzle was 1 m above the floor and 1 m from a wall. Proximity of floor and the wall could affect the flame length through change of air entrainment. It is known that fire plume along a wall, due to change in entrainment, has longer decay of temperature in the plume along the axis compared to the free plume. No stable flames were observed for nozzle diameters 0.1 and 0.2 mm – flame blew off although the spouting pressure increased up to 400 bar. The dimensionless flame length increases with the spouting pressure, measured close to the nozzle, as $L_F/D=524.5 \cdot P^{0.436}$, where pressure is in MPa (Mogi *et al.*, 2005). Based on this equation the maximum dimensionless flame length for subsonic flows ($p_R=0.19$ MPa) can be estimated as $L_F/D=254$ which is 10% above the value $L_F/D=230$ (Shevyakov and Komov, 1977). The equation of Mogi *et al.* (2005) gives essentially higher flame length $L_F/D=3344$ at pressure 700 bar characteristic for onboard gaseous hydrogen storage. Mogi *et al.* (2005) correlated the flame length to the mass flow rate regardless of the nozzle diameter as $L_F=20.25 \cdot m^{0.53}$. However, it is easy to see from Figure 8 in (Mogi *et al.*, 2005) that experimental data scattering is affected by the nozzle diameter dependence in absolutely the same manner as in Kalghatgi's work (1984). Both sets of experiments line up when the flame length is plotted against the similitude group $(\dot{m} \cdot D)$ derived in next section (see Figure 2).

In 2006 Schefer *et al.* published a study on spatial and radiative properties of open-flame hydrogen vertical jet, both subsonic and sonic (choked), at pressures up to 172 bar. The conclusion by Kalghatgi (1984) that flame length increases with both the total mass flow rate and the jet nozzle diameter was confirmed. Two sets of data are presented for flame length: for subsonic laboratory scale hydrogen releases (*Fr* from transitional $4.1\cdot10^5$ to momentum-controlled $6.5\cdot10^6$, *Re* from laminar 1569 to transitional/turbulent 6247) from 1.91 mm diameter nozzle, and for a blowdown at initial pressure 172 bar through 7.94 mm diameter stainless steel tubing (*Fr* in the momentum controlled region from $2.6\cdot10^6$ to $1.9\cdot10^7$, turbulent $Re=(1.9\text{-}9.8)\cdot10^5$). Both series of experimental results are presented in Figure 2 along with data by other authors. It worth noting that there was 3.175 mm diameter manifold orifice near the cylinder outlets to the 7.6 m straight section tubing of 7.94 mm diameter. The blowdown time of two cylinders of 49 litres each from initial 172 bar through described hydraulic system was about 100 s. Schefer *et al.* (2006) compared infrared, visible, and ultraviolet flame lengths. They concluded that $L/L_{IR}=0.88$, $L/L_{UV}=0.78$. For turbulent jet flames the flame width is approximately $0.17\cdot L$.

In 2007 Schefer *et al.* carried out experiments at higher pressures up to 413 bar, where departures from ideal gas behaviour become important, and a nozzle diameter of 5.08 mm. It was stated that lower-pressure engineering correlations based on the Froude number and a dimensionless flame length also apply to releases up to 413 bar, when the notional nozzle diameter and flow properties at the notional nozzle are substituted in the correlation for flame length.

Similitude analysis

Let us derive a correlation between flame length, L_F, 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, by the similitude analysis. The Buckingham Π theorem proves that for the problem which 6 quantities and 3 dimensions involved (mass, length and time), the quantities can be arranged into (6-3)=3 independent dimensionless parameters. These three parameters can be easily determined as $\Pi_1=D/L_F$, $\Pi_2=\rho_N/\rho_S$, and $\Pi_3=\rho_N DU/\mu$. It is convenient to invert some of the parameters and to take some square roots to form $\Pi_1 \text{x} \Pi_3^{1/2} \text{x} \Pi_2^{-1/4}$ and derive a function which includes both mass flow rate and diameter

$$L_F = f\left(\dot{m}^{1/2}\cdot D^{1/2}\cdot\sqrt{\frac{4}{\pi\mu}}\cdot\sqrt[4]{\frac{\rho_S}{\rho_N}}\right). \tag{7}$$

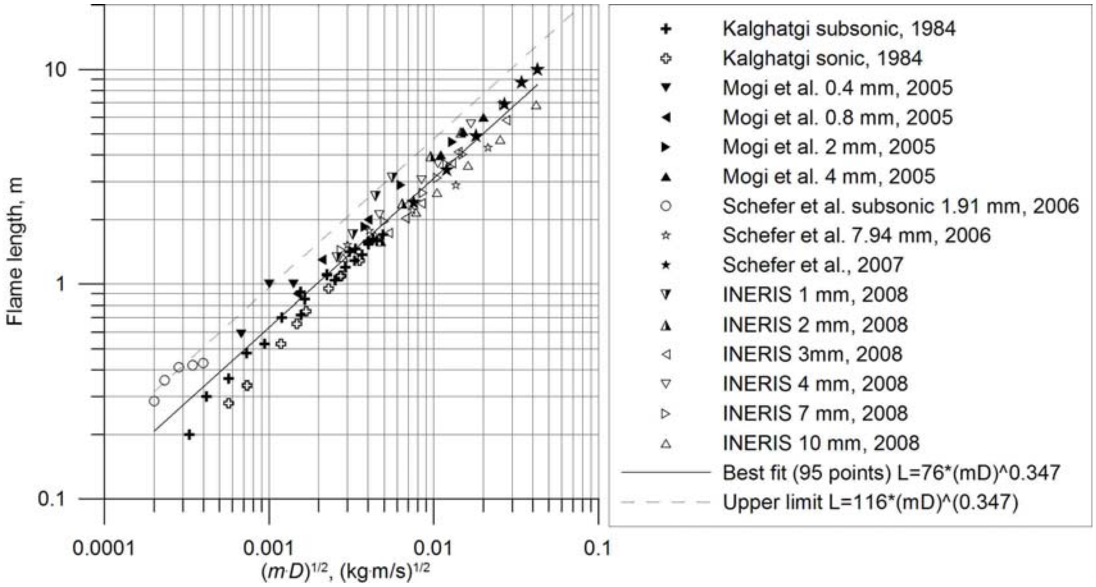


Fig. 2. Experimental data and the correlations for hydrogen jet flame length

Scattered original data on flame length (Kalghatgi, 1984, Figure 1a) collapses to the same curve when the derived similitude group $(\dot{m} \cdot D)$ is applied (Figure 1b). However, use of this correlation for the jet flame length assessment requires a method of mass flow rate calculation for non-ideal gas and highly underexpanded jet. The method has been recently developed, applied in this study, and to be presented in detail in (Molkov *et al.*, 2009).

Experimental data for jet flame length of high pressure hydrogen releases versus the similarity group $\dot{m} \cdot D$ are shown in Figure 2 for tests performed by Kalghatgi (1984), Mogi *et al.* (2005), Schefer *et al.* (2006, 2007), and INERIS group (Proust *et al.,* 2009). The best fit equation for 95 experimental points is $L=76 \cdot (\dot{m} \cdot D)^{0.347}$, and the upper limit equation is $L=116 \cdot (\dot{m} \cdot D)^{0.347}$. It is envisaged that the data scattering will reduce further if density of hydrogen in the nozzle, ρ_N, is included when developing the graph in Figure 2.

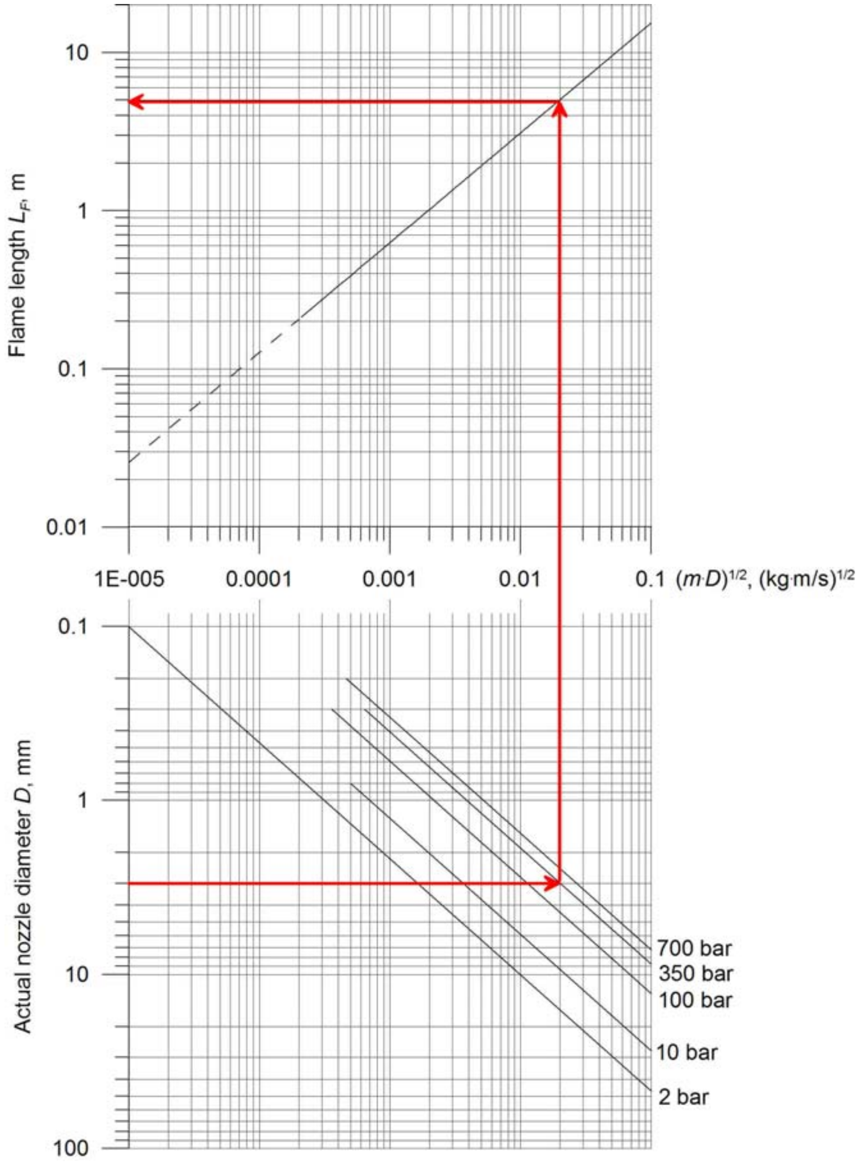


Fig. 3. The nomogram for hydrogen jet flame length

The nomogram for hydrogen safety engineering

The nomogram for calculation of hydrogen jet flame length is shown in Figure 3. This is based on the experimental correlation for flame length on the similarity group $\dot{m} \cdot D$ (Figure 2), $L=76^{\cdot}(m^{\cdot}D)^{0.347}$, and the method of mass flow rate calculation for non-ideal gas escaping from high pressure storage through underexpanded jet (Molkov *et al.*, 2009).

This simple engineering nomogram requires knowledge of only an orifice diameter and a storage pressure to determine the flame length. A special feature of the nomogram is accounting for pressure limit of flame existence at small size orifices (Okabayashi *et al.*, 2007). For example, a stable jet flame can exist at pressure 350 bar if only the orifice diameter is above 0.3 mm. It should be noted that the nomogram doesn’t account for situations when flow losses are essential. In such cases the nomogram gives a conservative result. The correlation in Figure 2 should be applied in such cases as an alternative tool with a condition that a method used for calculation of mass flow rate accounts for flow losses.

CONCLUSIONS

The review of mixing and combustion of hydrogen jet studies starting from the pioneering work by Hawthorne *et al.* (1949) is performed. The expansion of the similarity law by Chen and Rodi (1980) to non-ideal gas and underexpanded jets is validated with use of the original model for calculation of hydrogen density in the nozzle (Molkov *et al.*, 2009). The new dimensionless group for hydrogen jet flame length correlation is derived. 95 experimental data on hydrogen subsonic, sonic, and supersonic jet flames at pressures up to 413 bar are collapsed onto the same curve $L=76^{\cdot}(m^{\cdot}D)^{0.347}$. The nomogram for hydrogen jet flame length determination by only a nozzle diameter and a storage pressure is developed. The nomogram accounts for absence of stable combustion for small orifices (Okabayashi *et al.*, 2007).

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NOTATION

a	sound velocity, m/s
b	co-volume constant for Abel-Noble equation, b=0.007691 m^3/kg
C_{st}	mole fraction of nozzle fluid in the stoichiometric mixture with surrounding fluid (air)
C	volumetric or mass fraction
D	nozzle/orifice diameter, m
D_F	theoretical lateral flame dimension, m
Fr	Froude number, U^2/gD
g	acceleration of gravity, m/s^2
K	numerical constant
K_p	ratio of vent pressure to atmospheric pressure
L	visible flame length or axial distance to given concentration, m
m	mass flow rate across a section at right angle to the jet axis, kg/s
M	Mach number
M_N	molecular mass of nozzle fluid (hydrogen), g/mol
M_S	molecular mass of surrounding fluid (air), g/mol
M_0	momentum flux of the jet at orifice, kg·m/s^2
p	pressure, Pa
Re	Reynolds number
S	air to fuel mass stoichiometric ratio
s	distance from the break point to nozzle, m
T_{ad}	adiabatic flame temperature, K
T_N	temperature of fluid in the nozzle, K
u	flow velocity, m/s
U	gas velocity in the nozzle, m/s
W	flame width, m
x	axial distance from the nozzle/orifice, m
x_0	virtual jet origin displacement, m

Greek

α_T	ratio of reactants moles to products moles for the stoichiometric mixture
γ	specific heat ratio
ρ	density, kg/m^3

Subscripts

1	reservoir
av	averaged
ax	axial
eff	effective diameter (pseudo-diameter, notional nozzle diameter)
F	flame
l	laminar
M	mass
N	nozzle/orifice
R	reservoir
S	surrounding fluid
t	turbulent
V	volumetric