# The Correlation for Non-Premixed Hydrogen Jet Flame Length in Still Air

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**ABSTRACT**

The experimental data on the hydrogen flame length normalized by the nozzle diameter are correlated with the dimensionless product of the density ratio (hydrogen density in the nozzle exit to the density of surrounding air) and the Mach number to the power of three. The current up-to-date experimental data on hydrogen flame length are used to build the correlation that covers laminar and turbulent flows, buoyancy- and momentum-dominated releases, subsonic, sonic and highly under-expanded supersonic jets. The density and velocity of hydrogen in the nozzle are taken either directly from experiments or calculated by the under-expanded jet theory published elsewhere. The correlation is validated in the range of hydrogen storage pressures from nearly atmospheric up to 90 MPa and nozzle diameters from 0.4 to 51.7 mm. The predictive capability of this dimensionless correlation exceeds that of previously published work based on the Froude number only.

**KEYWORDS:** hydrogen jet fire, flame length, under-expanded jet.

**NOMENCLATURE LISTING**

| | | | |
|---|---|---|---|
| $b$ | hydrogen co-volume ($m^3$/kg) | $T$ | temperature (K) |
| $C$ | speed of sound (m/s) | $U$ | velocity (m/s) |
| $d$ | diameter (m) | **Greek** | |
| $Fr$ | Froude number | $\gamma$ | specific heats ratio |
| $g$ | acceleration of gravity (9.81 m/$s^2$) | $\pi$ | Pi (3.14) |
| $K_{Suth}$ | Sutherland constant (K) | $\rho$ | density (kg/$m^3$) |
| $L_F$ | hydrogen flame length (m) | $\mu$ | dynamic viscosity (Pa·s) |
| $\dot{m}$ | mass flow rate (kg/s) | **subscripts** | |
| $M$ | Mach number | $_F$ | flame |
| $M_{H2}$ | hydrogen molecular weight (kg/mol) | $_N$ | nozzle |
| $Re$ | Reynolds number | $_S$ | surroundings |
| $R_{H2}$ | hydrogen gas constant (J/kg·K) | | |

**INTRODUCTION**

Emerging hydrogen and fuel cell technologies and infrastructures, including storage at up to 100 MPa, pose new challenges to fire safety. One of them is the prediction of hydrogen flame length from highly under-expanded jets. Experimental data published decades ago are mainly for subsonic releases of hydrogen or at pressures far below 100 MPa. Dimensionless flame length correlations suggested at that time were based on the use of the Froude number (*Fr*) in one or another form [1–3].

Recently *Fr*-based correlations [4,5] were expanded to high pressure hydrogen jet fires. The general idea of this technique is to correlate experimental data with the modified *Fr* number that is built on a so-called notional or effective nozzle diameter instead of the real nozzle diameter. However, the size of the notional nozzle diameter depends on the theory applied to calculate it including a number of simplifying assumptions. For example, a constant flow velocity is assumed at the notional nozzle while in fact at high pressures there is a strong supersonic flow on the periphery immediately downstream of the Mach disk and a practically stagnant flow in the middle of the jet. Besides, only a limited number of their own experimental data were used by authors to support their correlations.

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In 2009 the dimensional correlation for a hydrogen jet flame length in still air was published [6]. The flame length of 95 hydrogen jet fires was correlated with a new similarity group that includes the product of mass flow rate and nozzle diameter to exclude dependence on the model-dependent notional nozzle parameters. The original under-expanded jet theory [7] was used to calculate mass flow rate in the nozzle based on hydrogen storage pressure and temperature. The correlation [6] was updated in 2010 to include 123 experimental hydrogen flame length data points [8]. It demonstrates better predictive capability in the momentum-controlled regime, which is the most appropriate for hydrogen leaks from high pressure equipment, compared to the *Fr*-based approach [4].

The aim of this paper is to improve our understanding of underexpanded hydrogen jet fires and develop a correlation for the non-premixed flame length in a dimensionless form. The correlation should cover the whole spectrum of hydrogen releases including laminar and turbulent jets, buoyant and momentum jets, and expanded and under-expanded jets.

## DIMENSIONLESS CORRELATION

### Dimensionless Groups

Previous flame length correlations were based on *Fr* number and validated mainly against experimental data on subsonic buoyant jet fires with a limited number of data on momentum-dominated jets at moderate pressures at the source. However, experimental data indicate that the flame length has to be a function of not only the *Fr* number but also the Reynolds (*Re*) number and the Mach (*M*) number. It is impossible to build a universal correlation based on only one of these dimensionless numbers. Indeed, the simple idea that an experimental jet flame length can only be correlated by the *Fr* number [1–4] does not work well in the momentum-controlled regime when more experiments have been recently analyzed [8]. The recent correlation [6] reproduces experimental data for momentum-dominated highly under-expanded jets within 20 % and drops the predictive accuracy to 50 % for subsonic jets. Thus, both types of correlations are not closing the problem for the whole range of jet conditions. There is a need for a dimensionless group that would better predict hydrogen jet fire length for various conditions and flow regimes.

It follows from the dimensional correlation $L_F = 76 \cdot (\dot{m} \cdot d_N)^{0.347}$ [6] that the dimensionless flame length $L_F/d_N$ is practically independent of the physical nozzle diameter $d_N$ and depends on density $\rho_N$ and velocity $U_N$ of hydrogen in the nozzle. Thus, the following dimensionless group is suggested in this study to correlate with the dimensionless flame length $L_F/d_N$

$$\frac{\rho_N}{\rho_S} \cdot \left(\frac{U_N}{C_N}\right)^3, \qquad (1)$$

where the speed of sound for non-ideal gas was corrected as a function of temperature in the nozzle using Eq. 2, where $\gamma$ is the hydrogen specific heats ratio (1.41), $R_{H2}$ is the hydrogen gas constant (4124 J/kg·K) and $b$ the hydrogen co-volume ($7.69 \times 10^{-3}$ m$^3$/kg)

$$C_N = \sqrt{\frac{\gamma \cdot R_{H2} \cdot T_N}{(1 - b \cdot \rho_N)}}\ . \qquad (2)$$

The form of dimensionless group given in Eq. 1 suggests for subsonic flows ($M < 1$) the dependence of the non-dimensional flame length on the nozzle Mach number only. Indeed, the hydrogen density in the nozzle $\rho_N$ is a constant for subsonic flows (with the assumption of constant temperature). Hence, the ratio of hydrogen density in the nozzle exit to the density of surrounding air $\rho_N/\rho_S$ is a constant too. For choked flows ($M = 1$) the dimensionless flame length depends only on the hydrogen density in the nozzle $\rho_N$ that increases with the storage pressure.

The dimensionless group given in Eq. 1 can be rewritten in terms of *Re* and *Fr* numbers as follows

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

where *Re* and *Fr* are determined through parameters of hydrogen flow in the nozzle

$$\mathrm{Re} = \frac{\rho_N \cdot d_N \cdot U_N}{\mu_N} \quad \text{and} \quad Fr = \frac{U_N^2}{d_N \cdot g} \, , \tag{4}$$

and the hydrogen dynamic viscosity (Sutherland constant for hydrogen was chosen as $K_{Suth}$ = 72 K and the dynamic viscosity $\mu_{293} = 8.76 \times 10^{-6}$ Pa·s)

$$\mu_N = \mu_{293} \cdot \left( \frac{293 + K_{Suth}}{T_N + K_{Suth}} \right) \cdot \left( \frac{T_N}{293} \right)^{3/2} . \tag{5}$$

From Eq. 3 it follows that at a constant temperature of hydrogen in the nozzle the dimensionless flame length depends on both *Re* and *Fr* numbers not only the nozzle *Fr* number as in former correlations.

**Description and Interpretation of Experiments**

Some of the experiments described in this section do not provide all the necessary information for our calculations. For instance, only in a few experiments was the container temperature history during blow-down provided [4,9]. In order to calculate flow parameters in cases when experimental temperature was not provided, it was assumed that the initial temperature in the container was 273 K. The temperature in the nozzle was then calculated using the under-expanded jet theory [7] for under-expanded jets and taken equal to storage temperature 273 K for subsonic releases. Calculations using the under-expanded jet theory [7] showed that a decrease of hydrogen temperature in a tank by 50 K would increase the density in the nozzle by only 10 %.

Hawthorne et al. [10] in 1949 reported results of two experiments with vertical subsonic hydrogen jet fires: one with 4.76 mm diameter rounded nozzle gave $L_F/d_N$ = 134 (*Re* = 2,870; *Fr* = 92,000); another with 4.62 mm diameter sharp-edged nozzle had $L_F/d_N$ = 147 (*Re* = 3,580; *Fr* = 158,000). The velocity at the nozzle was calculated using the values given for *Fr*. The density at the nozzle was assumed to be 0.0899 kg/m$^3$ and the temperature 273 K.

In 1977 Shevyakov and Komov [2] published a study on hydrogen subsonic flames in tubular burners of 1.45–51.7 mm diameter. The visual length of on-port flames was measured in a darkened room. The correlation $L_F/d_N(Fr)$ was developed to cover both buoyancy- and momentum-controlled regimes. For each experimental point, the diameter, flame length and flow velocity were provided. The hydrogen density of 0.0899 kg/m$^3$ and the hydrogen temperature of 273 K were assumed in the nozzle.

In 1984 Kalghatgi [11] published jet flame lengths for more than 70 tests with subsonic and sonic releases of hydrogen into still air through nozzles with diameter from 1.08 to 10.1 mm. Each burner was a straight tube mounted at the end of a settling chamber of internal diameter 152 mm. The mass flow rate was provided for each measurement and exit flow parameters (Mach number, velocity, temperature and density) were calculated by Kalghatgi using the Liepman and Roshko approach [12]. In this study we assumed that hydrogen temperature in a tank was 273 K and that the density in the nozzle was 0.0899 kg/m$^3$ for subsonic flows. The flow velocity at the nozzle was calculated from the experimental mass flow rate provided using the equation $U_N = (4 \cdot \dot{m}_N)/(\rho_N \cdot \pi d_N^2)$. For under-expanded jets an initial temperature in the container was assumed to be 273 K and the hydrogen density at the nozzle was calculated using the under-expanded jet theory [7].

In 2005 Mogi et al. [13] published experimental data for horizontal hydrogen jet flames from convergent nozzles of 0.1–4 mm diameter and spouting pressures 0.01–40 MPa. The release from four compressed hydrogen storage tanks with internal volume of 0.046 $m^3$ each, was done 1 m above the floor and 1 m away from a wall. For each test, the hydrogen mass flow rate and spouting pressure were provided. The temperature in the tank was assumed to be 273 K. Then, hydrogen density and flow velocity in the nozzle were calculated using the under-expanded jet theory [7].

Schefer et al. [4] published in 2006 a study on spatial and radiative properties of open vertical hydrogen jet flames for subsonic and high pressures releases up to 17.2 MPa. They performed a blow-down of two cylinders of 0.049 $m^3$ each with initial pressure 17.2 MPa, through a 7.6 m straight section stainless steel tubing of 7.94 mm diameter. The blow-down time was about 100 s. There was a 3.175 mm diameter manifold orifice near the cylinder outlets. Shocked flow conditions were reached at the exit of the 7.94 mm diameter tube early in the blow-down. The tank pressure had dropped sufficiently to have a subsonic flow 40 s after the start of the release. Two sets of data were presented for the flame length:

- Releases performed using a blow-down at an initial pressure of 17.2 MPa through 7.94 mm diameter tubing. Transients of data during the blow-down at the tubing exit were provided for the 7.94 mm test: pressure, mass flow rate, and jet velocity. The temperature in the container was assumed to be 273 K. The under-expanded jet theory [7] was then used to calculate hydrogen density and temperature at the nozzle exit. For the subsonic release at the end of the blow-down, the hydrogen density at the nozzle was assumed to be 0.0899 $kg/m^3$. For this particular set of data, $M \neq 1$ for under-expanded releases. This could be explained by an inaccuracy in data provided on the jet exit velocity and/or by the assumption of constant temperature at 273 K in the tank.
- In the same paper, subsonic releases from 1.91 mm were presented and the mass flow rate and exit velocity were given along with the flame length. The density of the hydrogen at the nozzle was assumed to be 0.0899 $kg/m^3$.

In 2007 Schefer et al. [14] measured hydrogen jet flame lengths in tests at pressures up to 43.1 MPa and for a nozzle diameter of 5.08 mm. Their own notional nozzle theory [14] accounting for departures from the ideal gas behavior was applied to ensure the applicability of lower-pressure engineering correlations based on the *Fr* number and a dimensionless flame length, when substituting flow parameters and diameter in the nozzle by those at the notional nozzle. The experimental set-up was composed of eight cylinders of volume 0.617 $m^3$ each and filled at 43.1 MPa. A stagnation chamber located between cylinders and exit was used to maintain a low exit flow Mach number. The experimental data provided, i.e. stagnation chamber pressure and temperature history, exit mass flow rate, flow velocity at the nozzle, were used in this study to calculate the hydrogen density at the nozzle using the under-expanded jet theory [7].

In 2008 Imamura et al. [15] conducted a series of experiments to understand the thermal hazards of hydrogen jet flames and more specifically temperature field of hot currents in the downstream region. They used hydrogen release system composed of a hydrogen cylinder, a stop valve, a regulator, an air-operated ball valve and a nozzle located 1 m above ground. Experiments investigated the dependence of flame shape on the spouting conditions: nozzle diameters were 1, 2, 3 and 4 mm and spouting pressures 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 MPa. The hydrogen flame was visualized by spraying NaCl aqueous solution. Experimental measurements of jet flame length as a function of diameter were provided. The given spouting pressure was measured at the pressure transducer close to the nozzle. With the assumption about the temperature in the container to be equal to 273 K, the underexpanded jet theory [7] was applied to calculate flow parameters, i.e. velocity and density, at the nozzle.

In 2009 Studer et al. [16] published results of their experimental study on hydrogen jet fires. Hydrogen was stored in a 0.025 $m^3$ Type IV tank at 10 MPa and released horizontally through a 5 m long flexible pipe with internal diameter of 15 mm. The pipe was mounted 1.5 m above the ground and the hydrogen was ignited immediately after release by an electric spark. Pressure and temperature were recorded in the pipe just prior to the nozzle but were not given in the publication [16]. The authors investigated releases through orifices of 4, 7 and 10 mm. The experimental data on pressure history, jet flame length and time of sampling were published elsewhere [17]. With assumption of hydrogen temperature in the tank of 273 K it was possible to calculate the flow parameters at the real nozzle using the under-expanded jet theory [7].

In 2009 Proust et al. [9] used a Type IV tank with 0.025 $m^3$ capacity pressurized up to 90 MPa to study hydrogen jet fires. Hydrogen was released horizontally 1.5 m above ground via a 10 m long pipe with internal diameter 10 mm, and ignited by a continuous propane-air burner. The pressure was measured at the head of the tank, the temperature was measured inside the tank using K-Type thermocouples and the mass flow rate was deduced from measurements of a numerical weighting device where the tank was located. The jet flame length was measured for orifice diameter 1, 2 and 3 mm. The experimental set up was similar to [16] and there were some doubts about the accuracy of the mass flow rate provided. By this reason the experimental data on pressure and temperature were used in this study to calculate the mass flow rate and other flow parameters at the nozzle by use of the under-expanded jet theory [7]. It was found that calculated mass flow rates were in an excellent agreement with the experimental data provided.

The correlation in coordinates the dimensionless flame length, $L_F/d_N$, and the similarity group $(\rho_N/\rho_S)\cdot(U_N/C_N)^3$ is shown in Fig. 1. The summarized experimental and calculated data are presented in Table 1. Experimental data used to build Table 1 include: container or spouting pressure, when applicable, real nozzle diameter, flame length, mass flow rate or velocity in a nozzle. Other parameters in Table 1 were calculated based on the experimental data with use of the under-expanded jet theory [7], when applicable, and the described above assumptions.

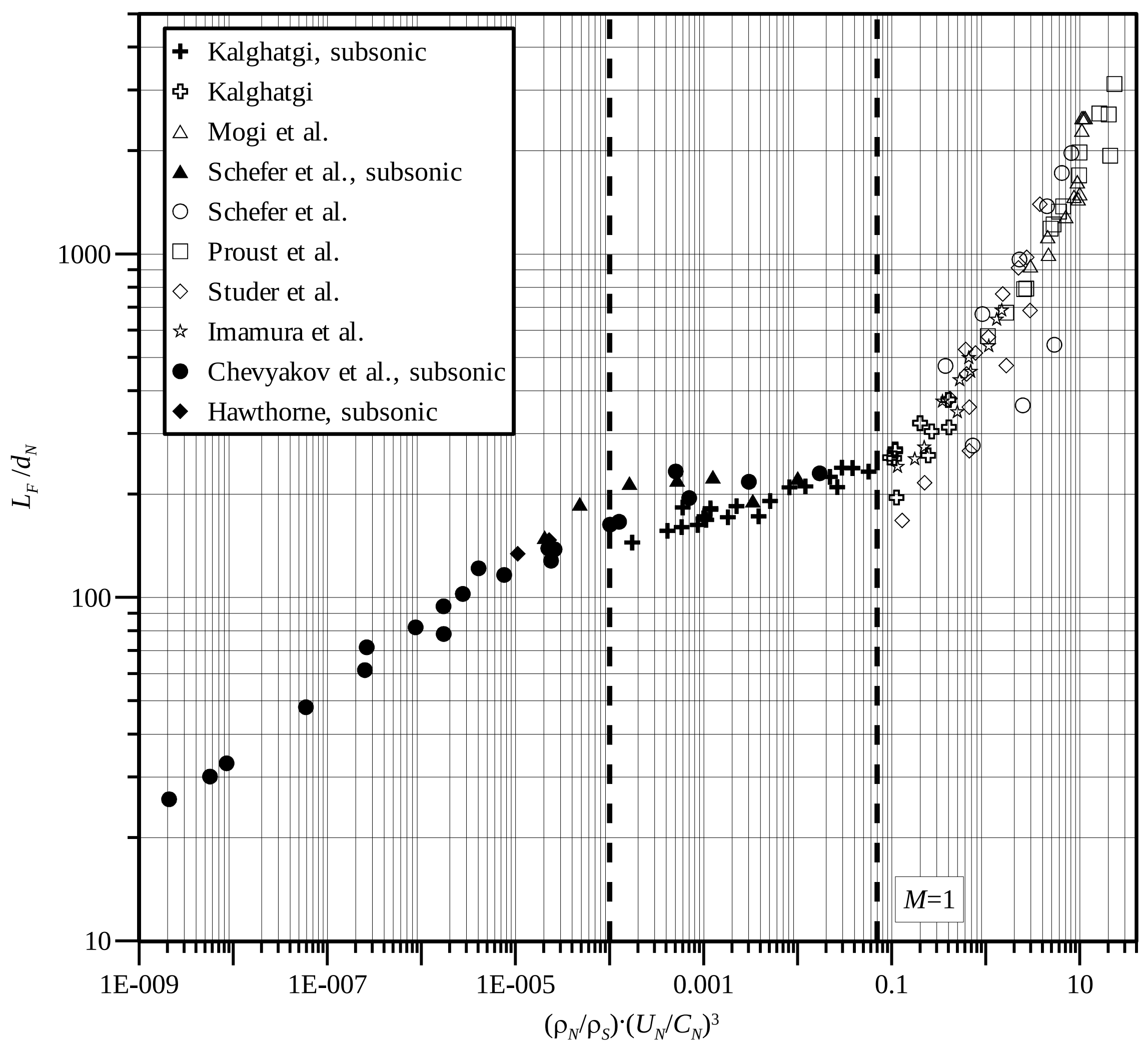


Fig. 1. The dimensionless correlation for hydrogen jet flame length.

Table 1. Experimental and calculated data.

| Experiment | ***P*** (MPa) | $d_N^a$, (mm) | $\left(\frac{L_F}{d_N}\right)^a$ | $m_N$ (g/s) | $\rho_N$ (kg/s) | $T_N$ (K) | $U_N$ (m/s) | $C_N$ (m/s) | $\mu_N$ (Pa·s) | ***Fr*** | ***Re*** | ***M*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hawthorne, 1949 | – | 4.76 | 134 | 3.0E-02 | 0.090 | 273 | 66[a] | 1261 | 9.39E-06 | 4.96 | 3.48 | 0.05 |
| Hawthorne, 1949 | – | 4.62 | 147 | 4.0E-02 | 0.090 | 273 | 85[a] | 1261 | 9.39E-06 | 5.20 | 3.57 | 0.07 |
| Shevyakov, 1977 | – | 51.70 | 26 | 2.3E-01 | 0.090 | 273 | 4[a] | 1261 | 9.39E-06 | 1.46 | 3.28 | 0.00 |
| Shevyakov, 1977 | – | 51.70 | 30 | 3.2E-01 | 0.090 | 273 | 5[a] | 1261 | 9.39E-06 | 1.75 | 3.42 | 0.00 |
| Shevyakov, 1977 | – | 51.70 | 33 | 3.7E-01 | 0.090 | 273 | 6[a] | 1261 | 9.39E-06 | 1.86 | 3.48 | 0.00 |
| Shevyakov, 1977 | – | 21.00 | 48 | 1.2E-01 | 0.090 | 273 | 12[a] | 1261 | 9.39E-06 | 2.82 | 3.37 | 0.01 |
| Shevyakov, 1977 | – | 21.00 | 61 | 1.9E-01 | 0.090 | 273 | 19[a] | 1261 | 9.39E-06 | 3.24 | 3.58 | 0.01 |
| Shevyakov, 1977 | – | 21.00 | 78 | 3.6E-01 | 0.090 | 273 | 36[a] | 1261 | 9.39E-06 | 3.79 | 3.86 | 0.03 |
| Shevyakov, 1977 | – | 15.30 | 72 | 1.0E-01 | 0.090 | 273 | 19[a] | 1261 | 9.39E-06 | 3.39 | 3.45 | 0.02 |
| Shevyakov, 1977 | – | 15.30 | 82 | 1.5E-01 | 0.090 | 273 | 28[a] | 1261 | 9.39E-06 | 3.73 | 3.62 | 0.02 |
| Shevyakov, 1977 | – | 15.30 | 102 | 2.2E-01 | 0.090 | 273 | 42[a] | 1261 | 9.39E-06 | 4.07 | 3.79 | 0.03 |
| Shevyakov, 1977 | – | 10.75 | 94 | 9.0E-02 | 0.090 | 273 | 36[a] | 1261 | 9.39E-06 | 4.08 | 3.57 | 0.03 |
| Shevyakov, 1977 | – | 10.75 | 116 | 1.5E-01 | 0.090 | 273 | 59[a] | 1261 | 9.39E-06 | 4.51 | 3.78 | 0.05 |
| Shevyakov, 1977 | – | 10.75 | 138 | 2.3E-01 | 0.090 | 273 | 89[a] | 1261 | 9.39E-06 | 4.87 | 3.96 | 0.07 |
| Shevyakov, 1977 | – | 6.00 | 122 | 4.0E-02 | 0.090 | 273 | 48[a] | 1261 | 9.39E-06 | 4.59 | 3.44 | 0.04 |
| Shevyakov, 1977 | – | 6.00 | 128 | 7.0E-02 | 0.090 | 273 | 86[a] | 1261 | 9.39E-06 | 5.10 | 3.69 | 0.07 |
| Shevyakov, 1977 | – | 6.00 | 163 | 1.1E-01 | 0.090 | 273 | 139[a] | 1261 | 9.39E-06 | 5.52 | 3.90 | 0.11 |
| Shevyakov, 1977 | – | 4.00 | 139 | 3.0E-02 | 0.090 | 273 | 84[a] | 1261 | 9.39E-06 | 5.26 | 3.51 | 0.07 |
| Shevyakov, 1977 | – | 4.00 | 166 | 5.0E-02 | 0.090 | 273 | 150[a] | 1261 | 9.39E-06 | 5.76 | 3.76 | 0.12 |
| Shevyakov, 1977 | – | 4.00 | 195 | 1.0E-01 | 0.090 | 273 | 265[a] | 1261 | 9.39E-06 | 6.25 | 4.01 | 0.21 |
| Shevyakov, 1977 | – | 1.45 | 233 | 1.0E-02 | 0.090 | 273 | 238[a] | 1261 | 9.39E-06 | 6.60 | 3.52 | 0.19 |
| Shevyakov, 1977 | – | 1.45 | 217 | 2.0E-02 | 0.090 | 273 | 432[a] | 1261 | 9.39E-06 | 7.12 | 3.78 | 0.34 |
| Shevyakov, 1977 | – | 1.45 | 230 | 4.0E-02 | 0.090 | 273 | 771[a] | 1261 | 9.39E-06 | 7.62 | 4.03 | 0.61 |
| Kalghatgi, 1984 | – | 1.74 | 210 | 1.9E-01[a] | 0.090 | 273 | 954 | 1261 | 9.39E-06 | 7.67 | 4.17 | 0.71 |
| Kalghatgi, 1984 | – | 2.95 | 233 | 6.7E-01[a] | 0.090 | 273 | 1147 | 1261 | 9.39E-06 | 7.66 | 4.51 | 0.91 |
| Kalghatgi, 1984 | – | 6.10 | 182 | 8.3E-01[a] | 0.090 | 273 | 339 | 1261 | 9.39E-06 | 6.22 | 4.27 | 0.25 |
| Kalghatgi, 1984 | – | 4.06 | 238 | 1.2E+00[a] | 0.090 | 273 | 1079 | 1261 | 9.39E-06 | 7.40 | 4.59 | 0.80 |
| Kalghatgi, 1984 | – | 10.10 | 156 | 1.6E+00[a] | 0.090 | 273 | 238 | 1261 | 9.39E-06 | 5.70 | 4.33 | 0.18 |
| Kalghatgi, 1984 | – | 1.08 | 171 | 3.0E-02[a] | 0.090 | 273 | 391 | 1261 | 9.39E-06 | 7.10 | 3.58 | 0.29 |
| Kalghatgi, 1984 | – | 1.74 | 172 | 1.0E-01[a] | 0.090 | 273 | 502 | 1261 | 9.39E-06 | 7.11 | 3.89 | 0.37 |
| Kalghatgi, 1984 | – | 2.95 | 163 | 1.8E-01[a] | 0.090 | 273 | 306 | 1261 | 9.39E-06 | 6.45 | 3.91 | 0.23 |
| Kalghatgi, 1984 | – | 4.06 | 172 | 3.5E-01[a] | 0.090 | 273 | 323 | 1261 | 9.39E-06 | 6.36 | 4.07 | 0.24 |
| Kalghatgi, 1984 | – | 4.06 | 209 | 7.0E-01[a] | 0.090 | 273 | 646 | 1261 | 9.39E-06 | 6.96 | 4.37 | 0.48 |
| Kalghatgi, 1984 | – | 4.06 | 238 | 1.2E+00[a] | 0.090 | 273 | 1079 | 1261 | 9.39E-06 | 7.40 | 4.59 | 0.80 |
| Kalghatgi, 1984 | – | 5.03 | 183 | 4.5E-01[a] | 0.090 | 273 | 270 | 1261 | 9.39E-06 | 6.11 | 4.08 | 0.20 |
| Kalghatgi, 1984 | – | 5.03 | 239 | 1.7E+00[a] | 0.090 | 273 | 991 | 1261 | 9.39E-06 | 7.24 | 4.65 | 0.73 |
| Kalghatgi, 1984 | – | 6.10 | 180 | 8.3E-01[a] | 0.090 | 273 | 339 | 1261 | 9.39E-06 | 6.22 | 4.27 | 0.25 |
| Kalghatgi, 1984 | – | 6.10 | 211 | 1.8E+00[a] | 0.090 | 273 | 735 | 1261 | 9.39E-06 | 6.89 | 4.60 | 0.54 |
| Kalghatgi, 1984 | – | 6.10 | 225 | 2.2E+00[a] | 0.090 | 273 | 899 | 1261 | 9.39E-06 | 7.07 | 4.69 | 0.66 |
| Kalghatgi, 1984 | – | 8.30 | 170 | 1.5E+00[a] | 0.090 | 273 | 320 | 1261 | 9.39E-06 | 6.04 | 4.37 | 0.24 |
| Kalghatgi, 1984 | – | 8.30 | 185 | 1.9E+00[a] | 0.090 | 273 | 419 | 1261 | 9.39E-06 | 6.27 | 4.49 | 0.31 |
| Kalghatgi, 1984 | – | 8.30 | 191 | 2.5E+00[a] | 0.090 | 273 | 552 | 1261 | 9.39E-06 | 6.51 | 4.61 | 0.41 |

Notes: [a] - experimental data.

Table 1 (continued). Experimental and calculated data.

| Experiment | **$P$** (MPa) | $d_N^a$, (mm) | $\left(\frac{L_F}{d_N}\right)^a$ | **$m_N$** (g/s) | **$\rho_N$** (kg/s) | **$T_N$** (K) | **$U_N$** (m/s) | **$C_N$** (m/s) | **$\mu_N$** (Pa·s) | ***Fr*** | ***Re*** | ***M*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kalghatgi, 1984 | – | 10.10 | 145 | 1.2E+00[a] | 0.090 | 273 | 179 | 1261 | 9.39E-06 | 5.45 | 4.21 | 0.13 |
| Kalghatgi, 1984 | – | 10.10 | 160 | 1.8E+00[a] | 0.090 | 273 | 268 | 1261 | 9.39E-06 | 5.80 | 4.38 | 0.20 |
| Kalghatgi, 1984 | – | 10.10 | 168 | 2.0E+00[a] | 0.090 | 273 | 298 | 1148 | 8.21E-06 | 5.89 | 4.49 | 0.24 |
| Kalghatgi, 1984 | – | 1.08 | 313 | 5.0E-01[a] | 0.486 | 226 | 1151 | 1151 | 8.20E-06 | 8.10 | 4.87 | 1.00 |
| Kalghatgi, 1984 | – | 1.74 | 376 | 1.3E+00[a] | 0.478 | 226 | 1151 | 1151 | 8.20E-06 | 7.89 | 5.07 | 1.00 |
| Kalghatgi, 1984 | – | 2.95 | 322 | 1.8E+00[a] | 0.240 | 226 | 1150 | 1150 | 8.20E-06 | 7.66 | 5.00 | 1.00 |
| Kalghatgi, 1984 | – | 4.06 | 270 | 1.9E+00[a] | 0.130 | 226 | 1149 | 1149 | 8.21E-06 | 7.52 | 4.87 | 1.00 |
| Kalghatgi, 1984 | – | 1.08 | 259 | 3.0E-01[a] | 0.292 | 226 | 1150 | 1150 | 8.20E-06 | 8.10 | 4.65 | 1.00 |
| Kalghatgi, 1984 | – | 1.74 | 195 | 3.5E-01[a] | 0.134 | 226 | 1149 | 1149 | 8.21E-06 | 7.89 | 4.51 | 1.00 |
| Kalghatgi, 1984 | – | 1.74 | 305 | 8.3E-01[a] | 0.318 | 226 | 1150 | 1150 | 8.20E-06 | 7.89 | 4.89 | 1.00 |
| Kalghatgi, 1984 | – | 1.74 | 376 | 1.3E+00[a] | 0.478 | 226 | 1151 | 1151 | 8.20E-06 | 7.89 | 5.07 | 1.00 |
| Kalghatgi, 1984 | – | 2.95 | 254 | 9.5E-01[a] | 0.127 | 226 | 1149 | 1149 | 8.21E-06 | 7.66 | 4.72 | 1.00 |
| Kalghatgi, 1984 | – | 2.95 | 322 | 1.8E+00[a] | 0.240 | 226 | 1150 | 1150 | 8.20E-06 | 7.66 | 5.00 | 1.00 |
| Kalghatgi, 1984 | – | 4.06 | 267 | 1.9E+00[a] | 0.130 | 226 | 1149 | 1149 | 8.21E-06 | 7.52 | 4.87 | 1.00 |
| Kalghatgi, 1984 | – | 5.03 | 255 | 2.5E+00[a] | 0.115 | 226 | 1149 | 1149 | 8.21E-06 | 7.43 | 4.91 | 1.00 |
| Mogi, 2005 | 10.1[a b] | 0.40 | 1475 | 1.2E+00[a] | 10.344 | 220 | 1228 | 1228 | 8.02E-06 | 8.58 | 5.80 | 1.00 |
| Mogi, 2005 | 12.5[a b] | 0.40 | 2500 | 2.5E+00[a] | 12.650 | 218 | 1248 | 1248 | 7.98E-06 | 8.60 | 5.90 | 1.00 |
| Mogi, 2005 | 13.0[a b] | 0.40 | 2500 | 5.0E+00[a] | 13.125 | 218 | 1252 | 1252 | 7.97E-06 | 8.60 | 5.92 | 1.00 |
| Mogi, 2005 | 5.0[a b] | 0.80 | 1125 | 2.7E+00[a] | 5.450 | 223 | 1189 | 1189 | 8.12E-06 | 8.26 | 5.81 | 1.00 |
| Mogi, 2005 | 10.6[a b] | 0.80 | 1625 | 5.5E+00[a] | 11.220 | 219 | 1236 | 1236 | 8.01E-06 | 8.29 | 6.14 | 1.00 |
| Mogi, 2005 | 13.0[a b] | 0.80 | 2500 | 2.0E+01[a] | 13.590 | 217 | 1256 | 1256 | 7.96E-06 | 8.30 | 6.23 | 1.00 |
| Mogi, 2005 | 3.0[a b] | 2.00 | 925 | 7.3E+00[a] | 3.570 | 224 | 1174 | 1174 | 8.15E-06 | 7.85 | 6.01 | 1.00 |
| Mogi, 2005 | 10.0[a b] | 2.00 | 1450 | 2.0E+01[a] | 11.456 | 219 | 1238 | 1238 | 8.00E-06 | 7.89 | 6.55 | 1.00 |
| Mogi, 2005 | 110[a b] | 2.00 | 2300 | 8.5E+01[a] | 12.530 | 218 | 1247 | 1247 | 7.98E-06 | 7.90 | 6.59 | 1.00 |
| Mogi, 2005 | 4.5[a b] | 4.00 | 1000 | 3.0E+01[a] | 5.540 | 223 | 1190 | 1190 | 8.11E-06 | 7.56 | 6.51 | 1.00 |
| Mogi, 2005 | 7.0[a b] | 4.00 | 1288 | 5.6E+01[a] | 8.496 | 221 | 1213 | 1213 | 8.06E-06 | 7.57 | 6.71 | 1.00 |
| Mogi, 2005 | 10.0[a b] | 4.00 | 1500 | 1.0E+02[a] | 11.920 | 219 | 1241 | 1241 | 7.99E-06 | 7.59 | 6.87 | 1.00 |
| Schefer, 2006 | – | 1.91 | 150 | 2.0E-02[a] | 0.090 | 273 | 88[a] | 1261 | 9.39E-06 | 5.55 | 3.17 | 0.06 |
| Schefer, 2006 | – | 1.91 | 187 | 3.0E-02[a] | 0.090 | 273 | 117[a] | 1261 | 9.39E-06 | 5.80 | 3.30 | 0.09 |
| Schefer, 2006 | – | 1.91 | 215 | 4.0E-02[a] | 0.090 | 273 | 175[a] | 1261 | 9.39E-06 | 6.15 | 3.47 | 0.13 |
| Schefer, 2006 | – | 1.91 | 220 | 6.0E-02[a] | 0.090 | 273 | 258[a] | 1261 | 9.39E-06 | 6.49 | 3.64 | 0.19 |
| Schefer, 2006 | – | 1.91 | 225 | 8.0E-02[a] | 0.090 | 273 | 346[a] | 1261 | 9.39E-06 | 6.74 | 3.77 | 0.26 |
| Schefer, 2006 | 11.2[a] | 7.94 | 544 | 5.7E+01[a] | 5.790 | 223 | 1233[a] | 1192 | 8.11E-06 | 7.29 | 6.84 | 1.03 |
| Schefer, 2006 | 4.7[a] | 7.94 | 363 | 2.3E+01[a] | 2.520 | 225 | 1231[a] | 1167 | 8.17E-06 | 7.29 | 6.48 | 1.06 |
| Schefer, 2006 | 1.9[a] | 7.94 | 277 | 6.9E+00[a] | 1.070 | 226 | 1078[a] | 1156 | 8.19E-06 | 7.17 | 6.05 | 0.93 |
| Schefer, 2006 | 1.2[a] | 7.94 | 223 | 2.1E+00[a] | 0.090 | 273 | 644[a] | 1261 | 9.39E-06 | 6.73 | 4.69 | 0.51 |
| Schefer, 2006 | 0.1[a] | 7.94 | 191 | 1.1E+00[a] | 0.090 | 273 | 446[a] | 1261 | 9.39E-06 | 6.41 | 4.53 | 0.35 |
| Schefer, 2007 | 26.2[a] | 5.08 | 1969 | 3.6E+02 | 12.380 | 215[a] | 1140[a] | 1236 | 7.90E-06 | 7.42 | 6.96 | 0.92 |
| Schefer, 2007 | 16.6[a] | 5.08 | 1722 | 2.3E+02[a] | 9.190 | 195[a] | 1079[a] | 1145 | 7.32E-06 | 7.37 | 6.84 | 0.94 |
| Schefer, 2007 | 9.7[a] | 5.08 | 1378 | 1.4E+02[a] | 5.940 | 187[a] | 1056[a] | 1092 | 7.09E-06 | 7.35 | 6.65 | 0.97 |
| Schefer, 2007 | 4.5[a] | 5.08 | 965 | 6.4E+01[a] | 2.880 | 189[a] | 1052[a] | 1071 | 7.14E-06 | 7.35 | 6.33 | 0.98 |
| Schefer, 2007 | 1.7[a] | 5.08 | 669 | 2.8E+01[a] | 1.120 | 192[a] | 1059[a] | 1066 | 7.24E-06 | 7.35 | 5.92 | 0.99 |
| Schefer, 2007 | 0.7[a] | 5.08 | 472 | 1.1E+01[a] | 0.450 | 196[a] | 1067[a] | 1070 | 7.35E-06 | 7.36 | 5.52 | 1.00 |

Notes: [a] - experimental data; [b] - spouting pressure.

Table 1 (continued). Experimental and calculated data.

| Experiment | *P* (MPa) | $d_N^a$, (mm) | $\left(\frac{L_F}{d_N}\right)^a$ | $m_N$ (g/s) | $\rho_N$ (kg/s) | $T_N$ (K) | $U_N$ (m/s) | $C_N$ (m/s) | $\mu_N$ (Pa·s) | *Fr* | *Re* | *M* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Imamura, 2008 | 1.0[a b] | 1.00 | 347 | 5.3E-01[a] | 0.596 | 226 | 1152 | 1152 | 8.20E-06 | 8.13 | 4.92 | 1.00 |
| Imamura, 2008 | 3.0[a b] | 1.00 | 686 | 1.6E+00[a] | 1.766 | 225 | 1161 | 1161 | 8.18E-06 | 8.14 | 5.40 | 1.00 |
| Imamura, 2008 | 0.3[a b] | 3.00 | 253 | 1.6E+00[a] | 0.210 | 226 | 1149 | 1149 | 8.20E-06 | 7.65 | 4.95 | 1.00 |
| Imamura, 2008 | 0.9[a b] | 3.00 | 430 | 4.7E+00[a] | 0.630 | 226 | 1152 | 1152 | 8.20E-06 | 7.65 | 5.42 | 1.00 |
| Imamura, 2008 | 1.9[a b] | 3.00 | 540 | 9.6E+00[a] | 1.282 | 226 | 1157 | 1157 | 8.19E-06 | 7.66 | 5.74 | 1.00 |
| Imamura, 2008 | 0.4[a b] | 2.00 | 274 | 9.0E-01[a] | 0.265 | 226 | 1150 | 1150 | 8.20E-06 | 7.83 | 4.87 | 1.00 |
| Imamura, 2008 | 1.2[a b] | 2.00 | 499 | 2.7E+00[a] | 0.787 | 226 | 1154 | 1154 | 8.19E-06 | 7.83 | 5.35 | 1.00 |
| Imamura, 2008 | 2.5[a b] | 2.00 | 645 | 5.3E+00[a] | 1.562 | 226 | 1159 | 1159 | 8.18E-06 | 7.84 | 5.65 | 1.00 |
| Imamura, 2008 | 0.2[a b] | 4.00 | 241 | 1.8E+00[a] | 0.138 | 226 | 1149 | 1149 | 8.21E-06 | 7.53 | 4.89 | 1.00 |
| Imamura, 2008 | 0.6[a b] | 4.00 | 373 | 5.4E+00[a] | 0.414 | 226 | 1151 | 1151 | 8.20E-06 | 7.53 | 5.37 | 1.00 |
| Imamura, 2008 | 1.2[a b] | 4.00 | 455 | 1.1E+01[a] | 0.823 | 226 | 1154 | 1154 | 8.19E-06 | 7.53 | 5.67 | 1.00 |
| Proust, 2009 | 1.9[a] | 3.00 | 577 | 9.0E+00[a] | 1.259 | 189[a] | 1057 | 1057 | 7.14E-06 | 7.58 | 5.75 | 1.00 |
| Proust, 2009 | 74.2[a] | 3.00 | 1933 | 2.5E+02[a] | 25.120 | 225[a] | 1418 | 1418 | 8.17E-06 | 7.83 | 7.12 | 1.00 |
| Proust, 2009 | 14.8[a] | 3.00 | 1377 | 6.6E+01[a] | 7.960 | 206[a] | 1166 | 1166 | 7.64E-06 | 7.66 | 6.56 | 1.00 |
| Proust, 2009 | 4.8[a] | 3.00 | 791 | 2.3E+01[a] | 3.058 | 190[a] | 1077 | 1077 | 7.19E-06 | 7.60 | 6.14 | 1.00 |
| Proust, 2009 | 11.0[a] | 3.00 | 1220 | 5.0E+01[a] | 6.271 | 201[a] | 1135 | 1135 | 7.49E-06 | 7.64 | 6.45 | 1.00 |
| Proust, 2009 | 3.0[a] | 3.00 | 675 | 1.5E+01[a] | 1.968 | 188[a] | 1062 | 1062 | 7.13E-06 | 7.58 | 5.94 | 1.00 |
| Proust, 2009 | 69.8[a] | 2.00 | 2551 | 1.1E+02[a] | 24.280 | 224[a] | 1402 | 1402 | 8.13E-06 | 8.00 | 6.92 | 1.00 |
| Proust, 2009 | 25.1[a] | 2.00 | 1977 | 4.6E+01[a] | 11.837 | 218[a] | 1238 | 1238 | 7.97E-06 | 7.89 | 6.57 | 1.00 |
| Proust, 2009 | 10.2[a] | 2.00 | 1186 | 2.1E+01[a] | 5.830 | 202[a] | 1134 | 1134 | 7.52E-06 | 7.82 | 6.25 | 1.00 |
| Proust, 2009 | 5.4[a] | 2.00 | 794 | 1.2E+01[a] | 3.215 | 197[a] | 1099 | 1099 | 7.40E-06 | 7.79 | 5.98 | 1.00 |
| Proust, 2009 | 86.9[a] | 1.00 | 3129 | 3.2E+01[a] | 27.790 | 222[a] | 1446 | 1446 | 8.09E-06 | 8.33 | 6.70 | 1.00 |
| Proust, 2009 | 49.8[a] | 1.00 | 2567 | 2.0E+01[a] | 19.300 | 226[a] | 1346 | 1346 | 8.19E-06 | 8.27 | 6.50 | 1.00 |
| Proust, 2009 | 25.2[a] | 1.00 | 1696 | 1.1E+01[a] | 11.730 | 221[a] | 1247 | 1247 | 8.06E-06 | 8.20 | 6.26 | 1.00 |
| Proust, 2009 | 13.6[a] | 1.00 | 1329 | 6.6E+00[a] | 7.170 | 213[a] | 1178 | 1178 | 7.84E-06 | 8.15 | 6.03 | 1.00 |
| Studer, 2009 | 8.3[a] | 4.00 | 1397 | 7.0E+01[a] | 4.490 | 224 | 1182 | 1182 | 8.13E-06 | 7.55 | 6.42 | 1.00 |
| Studer, 2009 | 4.1[a] | 4.00 | 912 | 2.8E+01[a] | 2.660 | 225 | 1168 | 1168 | 8.16E-06 | 7.54 | 6.18 | 1.00 |
| Studer, 2009 | 2.9[a] | 4.00 | 765 | 1.8E+01[a] | 1.810 | 225 | 1161 | 1161 | 8.18E-06 | 7.54 | 6.01 | 1.00 |
| Studer, 2009 | 1.1[a] | 4.00 | 528 | 5.4E+00[a] | 0.728 | 226 | 1153 | 1153 | 8.20E-06 | 7.53 | 5.61 | 1.00 |
| Studer, 2009 | 5.8[a] | 7.00 | 979 | 1.0E+02[a] | 3.260 | 225 | 1172 | 1172 | 8.15E-06 | 7.30 | 6.52 | 1.00 |
| Studer, 2009 | 2.0[a] | 7.00 | 574 | 3.2E+01[a] | 1.272 | 226 | 1157 | 1157 | 8.19E-06 | 7.29 | 6.10 | 1.00 |
| Studer, 2009 | 1.4[a] | 7.00 | 515 | 2.1E+01[a] | 0.927 | 226 | 1155 | 1155 | 8.19E-06 | 7.29 | 5.96 | 1.00 |
| Studer, 2009 | 1.1[a] | 7.00 | 447 | 1.6E+01[a] | 0.748 | 226 | 1153 | 1153 | 8.20E-06 | 7.29 | 5.87 | 1.00 |
| Studer, 2009 | 0.7[a] | 7.00 | 379 | 1.1E+01[a] | 0.498 | 226 | 1151 | 1151 | 8.20E-06 | 7.29 | 5.69 | 1.00 |
| Studer, 2009 | 6.3[a] | 10.00 | 685 | 1.8E+02[a] | 3.540 | 224 | 1174 | 1174 | 8.15E-06 | 7.15 | 6.71 | 1.00 |
| Studer, 2009 | 3.0[a] | 10.00 | 474 | 6.4E+01[a] | 1.973 | 225 | 1162 | 1162 | 8.18E-06 | 7.14 | 6.45 | 1.00 |
| Studer, 2009 | 1.2[a] | 10.00 | 358 | 2.6E+01[a] | 0.799 | 226 | 1154 | 1154 | 8.19E-06 | 7.13 | 6.05 | 1.00 |
| Studer, 2009 | 0.6[a] | 10.00 | 267 | 1.1E+01[a] | 0.800 | 226 | 1154 | 1154 | 8.19E-06 | 7.13 | 6.05 | 1.00 |
| Studer, 2009 | 0.3[a] | 10.00 | 216 | 6.1E+00[a] | 0.267 | 226 | 1150 | 1150 | 8.20E-06 | 7.13 | 5.57 | 1.00 |
| Studer, 2009 | 0.2[a] | 10.00 | 168 | 2.0E+00[a] | 0.154 | 226 | 1149 | 1149 | 8.20E-06 | 7.13 | 5.33 | 1.00 |

Notes: [a] - experimental data; [b] - spouting pressure.

## DISCUSSION

There are three distinguished parts in the dimensionless correlation in Fig. 1 from the left to the right: ‘traditional’ buoyancy-controlled part that is represented by data on subsonic releases of Shevyakov et al. [2] and Hawthorne et al. [10]; ‘saturated’ momentum-dominated part represented by subsonic release tests by Kalghatgi [11] and Schefer et al. [4] where dimensionless flame length is essentially a constant; and finally a third part that stands for choked and under-expanded jet fires.

It is clear that there is no saturation of dimensionless flame length at value $L_F/d_N$ = 230 observed in numerous previous studies with expanded jets. Currently reported experiments exhibit much higher values, e.g. $L_F/d_N$ = 3000 [9]. Analysis of change in dimensionless groups (*Re, Fr, M*) value shows that for under-expanded jets, the dimensionless flame growth depends practically on *Re* number only as flow is choked and thus nozzle Mach number $M$ = 1 and nozzle *Fr* number is constant also for fixed diameter (Fig. 2).

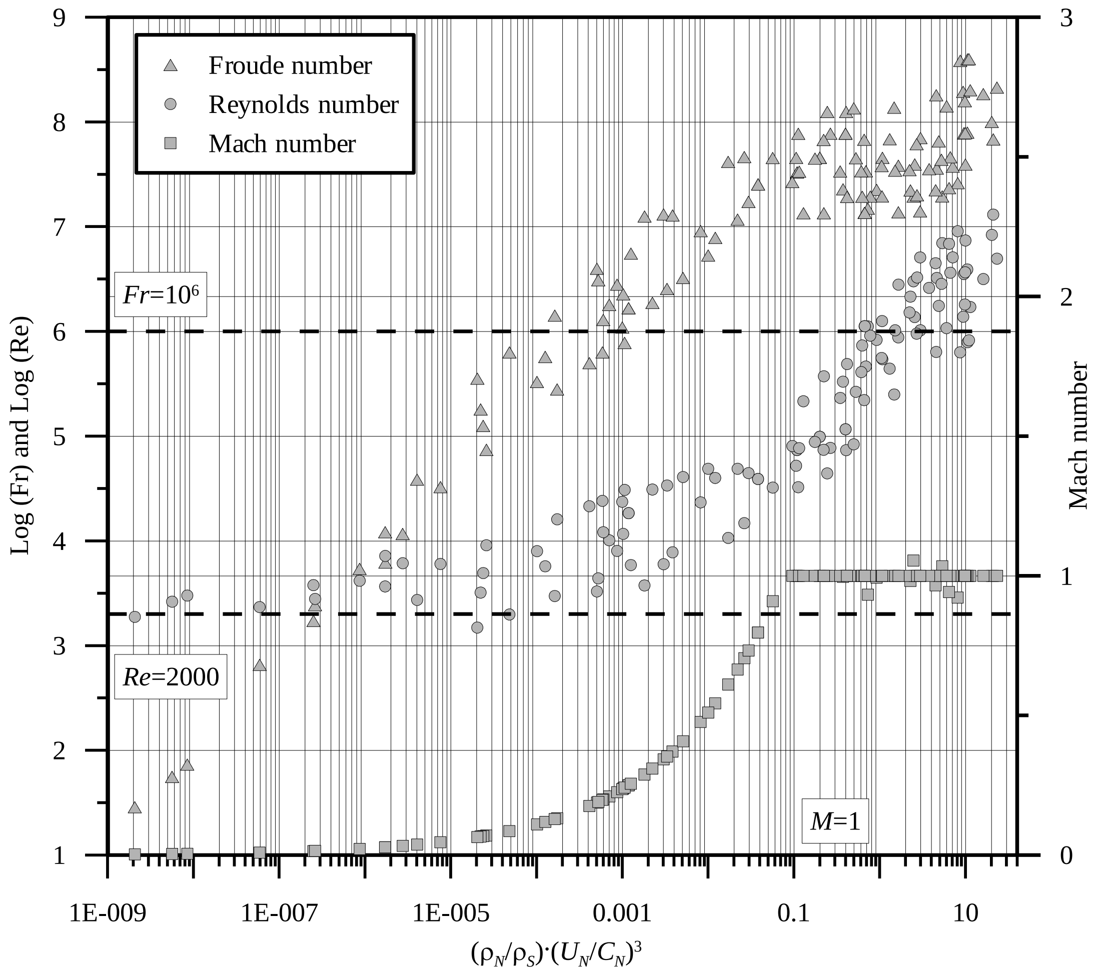


Fig. 2. Dimensionless numbers *Re, Fr, M* as a function of the new similarity group for experiments used for the correlation.

There are three lines in Fig. 2. Line $Re$ = 2000 separates laminar and turbulent jets. Prevailing majority of experiments used to validate the correlation were carried out for turbulent releases. Line $Fr = 10^6$ is indicative for transition from buoyancy- to momentum-dominated jets. Finally, line $M$ = 1 separates subsonic jets from choked in the nozzle flows. This explains the shape of the correlation (Fig. 1).

## CONCLUSIONS

The dimensionless correlation for non-premixed hydrogen jet flame length in still air in coordinates $L_F/d_N$ against $(\rho_N/\rho_S)\cdot(U_N/C_N)^3$ is developed. It is thoroughly validated by the experimental data on flame length for laminar and turbulent hydrogen flames, buoyancy- and momentum-dominated flows, expanded and highly under-expanded hydrogen jet fires. Numerous experimental data obtained by different authors collapsed into the same curve. The correlation follows previously established pattern with “traditional” buoyancy- and momentum-controlled parts, and incorporates power law for dependence of the flame length on the *Re* number for under-expanded high momentum jets. The correlation can be recommended for use by fire safety engineers and requires knowledge of only hydrogen density and velocity in the nozzle that can be calculated using the under-expanded jet theory published elsewhere.

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