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Prediction of Lift-Off Distance in Choked and Subsonic Hydrogen Jet Fires

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Highlights

- Review of past measurement of lift-off heights of hydrogen jet flames.
- Particular problems of hydrogen as a fuel.
- Proposed correlation in terms of fractional fuel requirements and normalized lift-off height.

Abstract

Hydrogen jet flames, as a consequence of their greater reactivity, have a number of characteristics that are different from other flames. These are reviewed, as are the various attempts that have been made to characterise, and generalise, the lift-off distance at the base of jet flames. There has been a consistent improvement in the accuracy of the expressions for the prediction of lift-off distance. In addition to the greater reactivity that creates a small laminar flame thickness, allowance must be made for the significantly smaller air requirement for each mole of hydrogen fuel. The evolution of an expression for the lift-off distance is discussed and a new expression is provided. Alongside the blow off data for lifted flame regimes, this enables hydrogen lifted flames to be fully characterised.

1. Introduction

Hydrogen jet flames arise in a number of contrasting circumstances. The high diffusion coefficient of hydrogen can generate significantly greater discharges from leaky pipelines than with other gases. In the case of such small leakages, close to the quench regime, the gas may ignite, yet remain undetected because a hydrogen flame is almost invisible [1]. In contrast, when excessively high temperatures are generated in nuclear reactors, metal can react with steam to generate hydrogen which, by some suitable means, must be vented for safety. More commonly, pressurised hydrogen containers may unintentionally be leaking and the jet may ignite to produce a large jet flame. The lift-off distance, L, from the burner exit plane to the leading edge of the flame is an important characteristic of those jet flames with higher jet velocities, u. At lower values of u, particularly with air cross flow, the flame can remain attached to the burner, at a burner leeward tip or at a turbulent recirculating wake. The evolution of our understanding of L is briefly traced. Within the lift-off distance, fuel and air are mixed. The strain rate is high enough to extinguish all but the more reactive embryonic laminar flamelets, and those associated with the maximum laminar burning velocity, S_L, preferentially survive. It is also within the lift-off distance that a cross wind can enhance the reactivity of the mixture.

Figure 1, from [2], indicates the limits within which hydrogen jet flames, in the form of lifted flames, are sustainable. In this figure, U_b^* is the value of the dimensionless flow number at

blow-off, as given in [2]. Its origins lie in computer studies of jet flames and the Karlovitz Stretch factor, a ratio of chemical to eddy liffetimes [3,4]. At high values of U^* flame quenching leads to blow-off, at U_b^*. The value of U^* is given by:

$$U^* = \left(u/S_L\right)\left(\delta/D\right)^{0.4}\left(P_i/P_a\right).$$
(1)

The pressure ratio is that of the initial stagnation presssure to the atmospheric pressure. This ratio increases with u. The smallest pipe diameter that can sustain a lifted flame at a given U^* is D_b and this is normalised by the laminar flame thickness, δ, of the premixed fuel/air flame at the maximum laminar burning velocity, given by the kinematic viscosity, ν, divided by S_L. Blow-off occurs when the high velocity fuel gas entrains more air than is necessary to sustain a flame, and flame quenching ensues. Values of U_b^* range from correspondingly low Reynolds number flows to a chocked flow regime, in which supersonic velocities can arise [5]. The region in which blow-off occurs with hydrogen is narrower than with hydrocarbons.

It is the aim of such correlations as appear in Fig. 1 to achieve the maximum generality, preferably covering all fuels. The vertical line, labelled CPR, indicates the location where the critical pressure ratio is attained. To the right of this, shock waves are generated that enhance the reactivity. This correlation has been reasonably successful in generalising δ/D_b plots against U_b^* for hydrocarbons, but less so for hydrogen for three reasons. The paper concentrates on these differences. First, it is more reactive with a high S_L and low δ. Furthemore, the expresssion for δ is an overestimate. This is because the high diffusion of hydrogen atoms reduces the thickness of the flame preheat zone and there is no effective way of allowing for this. This problem is explored in [2,6]. The background to the problem is illustrated in Fig. 2, which compares computed profiles of volumetric heat release rate, with the reaction progress variable, θ, for methane and hydrogen flames, taken from [7]. It shows the heat release developing much earlier in the H_2 flame. Nevertheless, somewhat arbitrarly, the expression $\delta = \nu/S_L$, will be employed. Thirdly, the air requirement for hydrogen combustion is significantly less than for hydrocarbons. As a result, it would be anticipated that lifted flames would have smaller lift off distances in the case of H_2.

The nominal value of δ for hydrogen is in practice less than a fifth of that of methane and, as explained, because of the high diffusion of H atoms, this further reduces the thickness of the flame preheat zone. As a result of these factors, values of D_b for hydrogen jet flames are about 25 times smaller than for methane. Although the repercussions for blow-off of hydrogen flames are well appreciated, there is less understanding of the effect on flame lift-off distances of the high reactivity of hydrogen jet flames. The purpose of the present paper is to trace the development of a number of proposals for expressions for this lift-off distance in hydrogen jet flames, and propose a new one.

2. Expressions for the Lift-off Distance

All the correlations shown are for hydrogen lifted jet flames in subsonic and choked regimes [8-11]. Amongst the earliest attempted correlations for L proposals are those of Broadwell et al. [12], shown in Fig. 3, and of Miake-Lye and Hammer [13] in Fig. 4. In both papers the height is expressed in metres and in the latter case the pipe diameter does not feature. Neither does it feature in the correlation of Kalghatgi [9], who stated that the diameter had no influence on the lift-off. The only distance scaling in this correlation is the laminar flame thickness. His correlation for subsonic and choked flows is shown in Fig. 5. It is entirely based on dimensionless groups and it shows less scattering of data.

The absence of the f factor is only important for comparisons between different fuels. There remains the problem of selecting the best normalising length scale for L. The same thickness, δ, is embodied in U*, as a parameter relevant to flame structure. It is also a scaling parameter for D_b, that determines the minimum value of D for a lifted flame, in the correlation in Fig. 1. It was concluded that D would provide a better length scale correlating parameter, providing a geometric description of the system, and with the inclusion of the f factor.

These correlations for a single fuel, not surprisingly, are better than a generalised correlation of all fuels, even when hydrogen is excluded. The general correlation of measured lift off distances in [14] was improved by the introduction of f, the ratio of fuel moles to air moles for S_L. These values are shown for a variety of fuels at S_L in Table 1. With the inclusion of the f factor, subsonic and supersonic correlations are shown in Fig. 6, involving $f^{0.2}$ for the latter. The uniqueness of H_2 lies, not only in its active preheat zone, but also in its exceptionally high values of both S_L and f. The f parameter was introduced in the general correlation for all fuels in [14]. This correlation is shown, but for H_2 only, in Fig. 6. In this figure L is normalised by the pipe diameter, D. The choked and supersonic regimes are corrrelated separately and the correlations are good.

Figure 6 is of interest in that it shows in more detail how the the subsonic and choked flow regimes are clearly differentiated. Figure 7 combines the two regimes, with the same f factor. The correlation is better than in Fig. 6. Figure 8 shows the relationship with L normalised by δ is not satisfactory, particularly in the subsonic regime, where there is a large scatter in the values. The two regimes are clearly diferentiated.

3. Discussion and Conclusions

Both Figs. 6 and 7 show a levelling off of the dimensionless lift-off distance with increasing U*. This is attributable to localised supersonic flows and to the complex generation of shock waves in the highly choked regime, with an associated enhancement of chemical reaction rates. Such a complex choked flow structure is a severe challenge for mathematical modelling. Subsonic lifted jet flame mathematical modelling can be much more reliable than for the shocked flow regime. It is rather surprising that Figs. 1, 6 and 7 suggest consistent sructures in the different regimes, particularly in the choked flow regime.

That Lf^n/D. might give a better correlation than Lf/δ is confirmed by Figs 6 to 8. Consequently, Figs. 6 and 7 fully characterise hydrogen lifted jet flames. From Fig. 6 the lift-off distance is given by:

$$(L/D)f = -0.0003U*^2 + 0.21U* - 2.83, \tag{2}$$

for the subsonic regime, and by

$$(L/D)f^{0.2} = -0.0002U*^2 + 0.23U* - 0.91, \tag{3}$$

for the choked/supersonic regime.

For the combined correlation of Fig. 7:

$$(L/D)f = -0.0002U*^2 + 0.19U* - 3.3, \tag{4}$$

Because the present study is focused just on hydrogen, it does not fully scrutinise the roles of f and δ, both of which remain unchanged. Although the f factor is important in generalising characteristics over a wide range of hydrocarbons, for the reasons given, this generalisation does not extend to hydrogen, and this is the reason for treating hydrogen separately. Interest-

ingly, the f factor suggests that a jet of air in an ambient atmosphere of gaseous fuel would have an air jet f factor that is the reciprocal of the fuel f factor. The consequence would be significantly smaller values of L/D for air jets. Because of the high f value for hydrogen such a jet reversal role would have less effect on L/D. It would seem that a decision on the optimal correlation can only be resolved by a study of the degree of generalisation that is possible over a wide range of different fuels.

In general terms, although most jet fires may not be included among major accidents, due to their relatively small size and reach, they have nevertheless often been a first step in triggering a domino effect sequence, in a number of accidents. It they impinge on other equipment, with very high heat fluxes, this situation can initiate catastrophic consequences in a very short time. Therefore, account must be taken of their potential effects, requiring fundamental study of all the factors affecting their height and lift-off distance, i.e., their range. The present study is also relevant to the venting of hydrogen from malfunctioning nuclear reactors and to the design of hydrogen fuelled domestic heating systems, which have been proposed, using, pipe-distributed, hydrogen, produced from the steaming of methane. The present paper has chronological reviewed the key equations which mark the stepping stones along the route of continuing improvement of our understanding of flame lift-off, for the unique fuel, hydrogen. Both blow off and lift off data have been presented and dicussed.

Acknowledgements

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Table and Figures

Fuel	ϕ	Max S_L (m/s)	f
CH_4	1.02	0.39	0.116
C_2H_2	1.4	1.57	0.092

C_4H_{10}	1.1	0.41	0.035
C_2H_4	1.1	0.72	0.077
C_3H_8	1.1	0.41	0.046
H_2	1.8	3.07	0.756

Table 1. Values of f and ϕ at maximum laminar burning velocity.
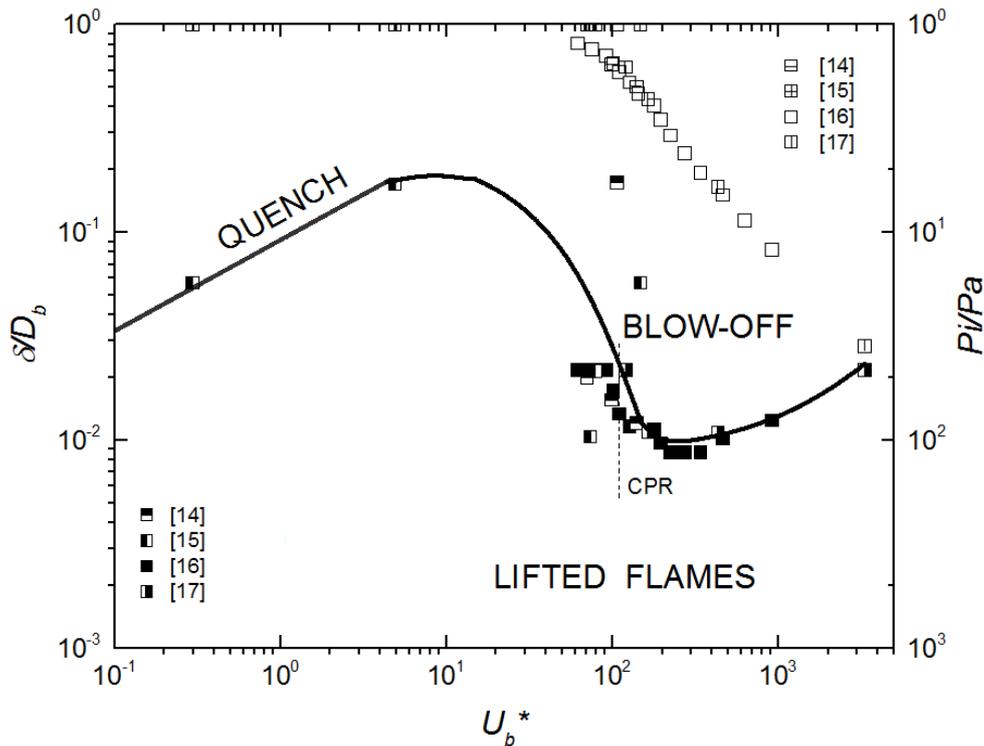
Figure 1. Hydrogen Jet Flame Blow-off Boundaries. Increasing δ/D above $(\delta/D)_b$ leads to blow-off. Dashed vertical line shows Critical Pressure Ratio conditions. U* is the dimensionless flow number, $(u/S_L)(\delta/D)^{0.4}(P_i/P_a)$. Unfilled square markers indicate the pressure ratio. Taken from [2].
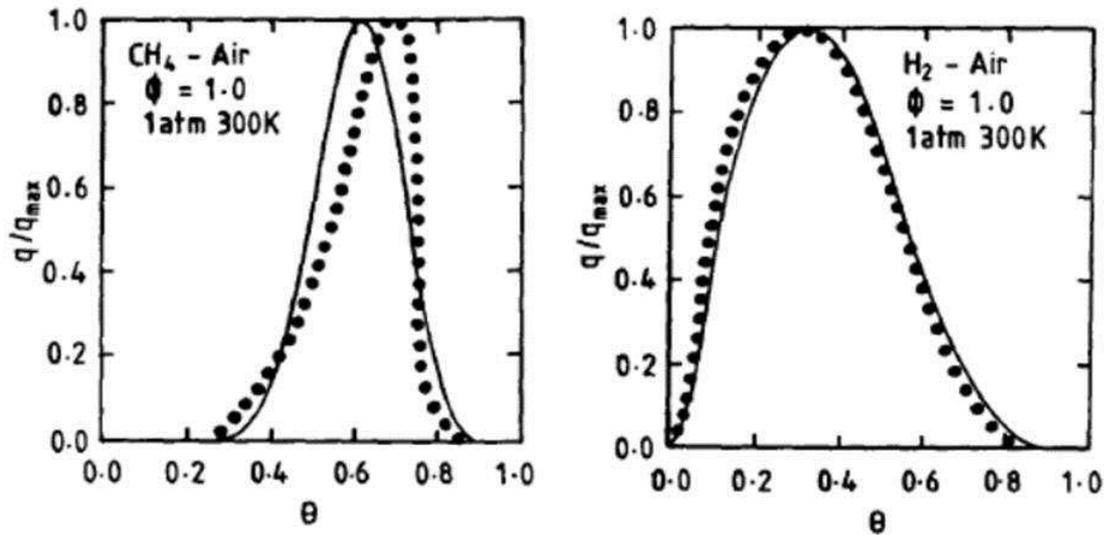
Figure 2: Dotted curves show volumetric heat release rate profiles from detailed chemical kinetics, for CH4/air and H2/air mixtures from [3]. θ is the reaction progress variable. The full line curve is a more approximate algebraic fit. From [7].
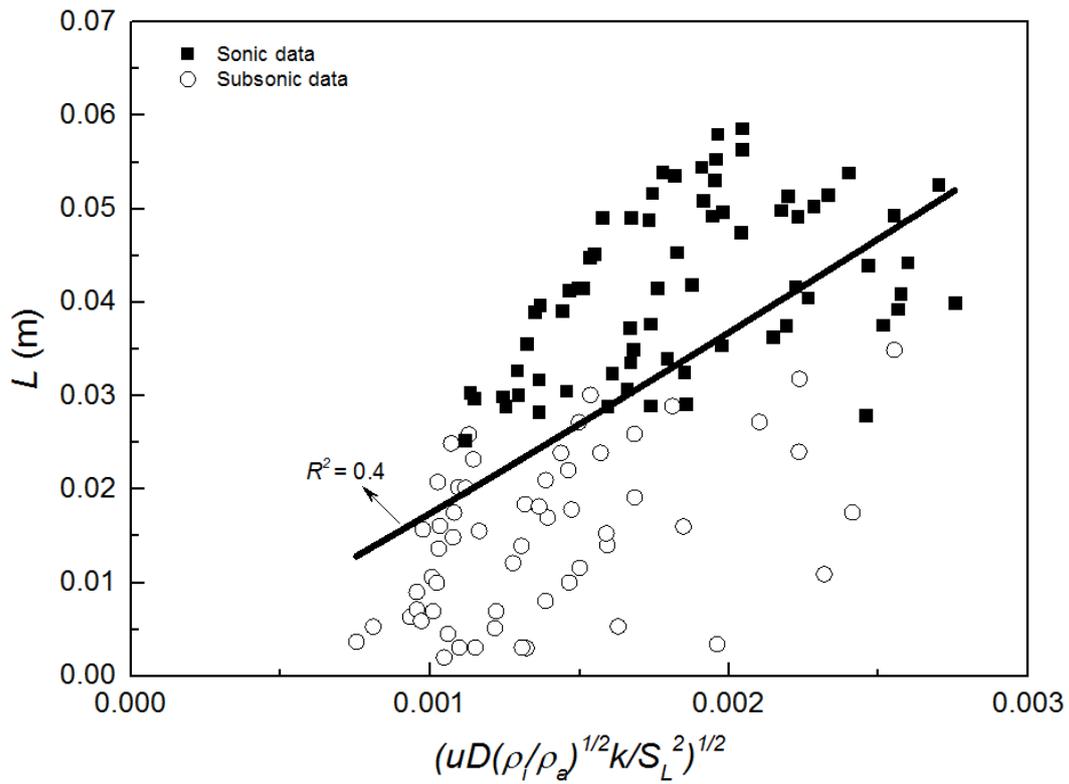
Figure 3. Subsonic data taken from [8-11], and sonic data taken from [8,9,11]. L correlation, using parameters of Broadwell et al. [8] for both regimes. u is pipe flow velocity, D, pipe diameter, ρ_i/ρ_a, ratio of densities, k thermal diffusivity, and S_L laminar burning velocity. Straight line is best linear fit.
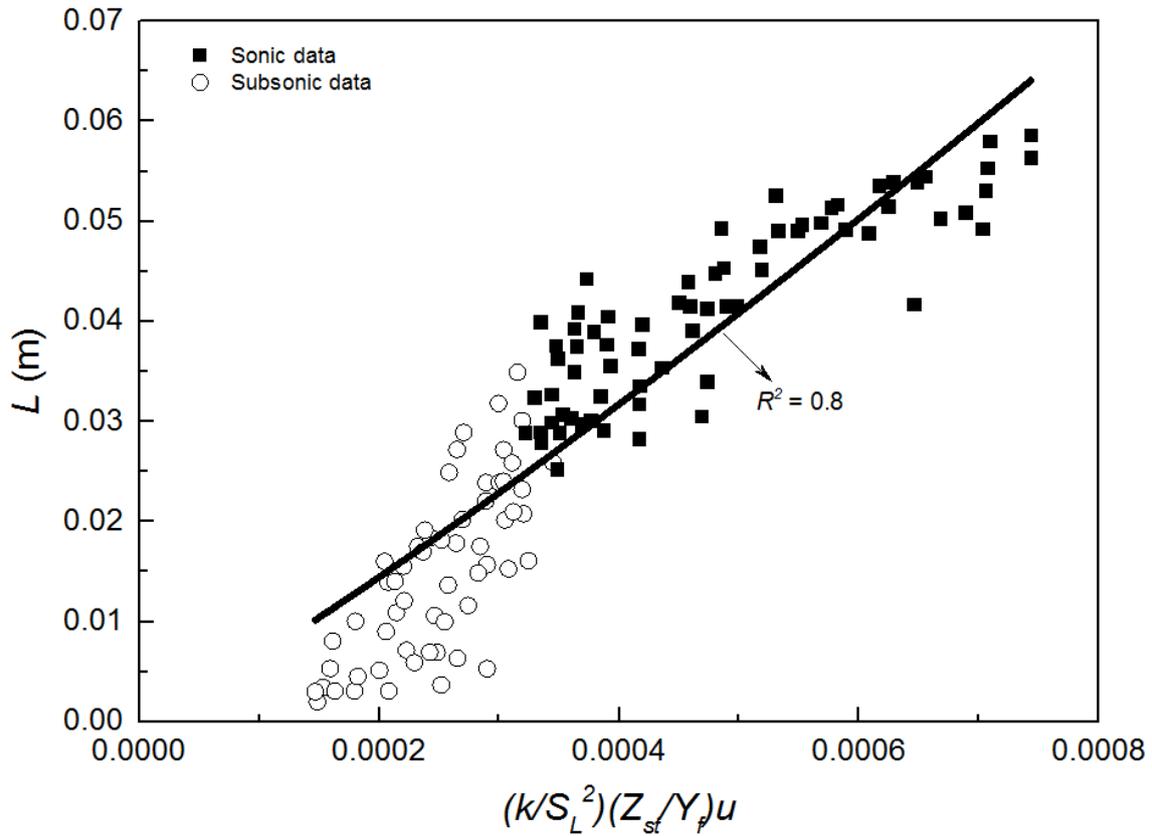
Figure 4. Subsonic data taken from [8-11], and sonic data taken from [8,9,11], L correlation, using parameters of Miake-Lye and Hammer [9] for both regimes. u is pipe flow velocity, k thermal diffusivity, S_L laminar burning velocity, Y_f mass fraction of fuel in the jet fluid, Z_{st}, elemental mass fraction of pure fuel in air at stoichiometric conditions. Straight line is best linear fit.
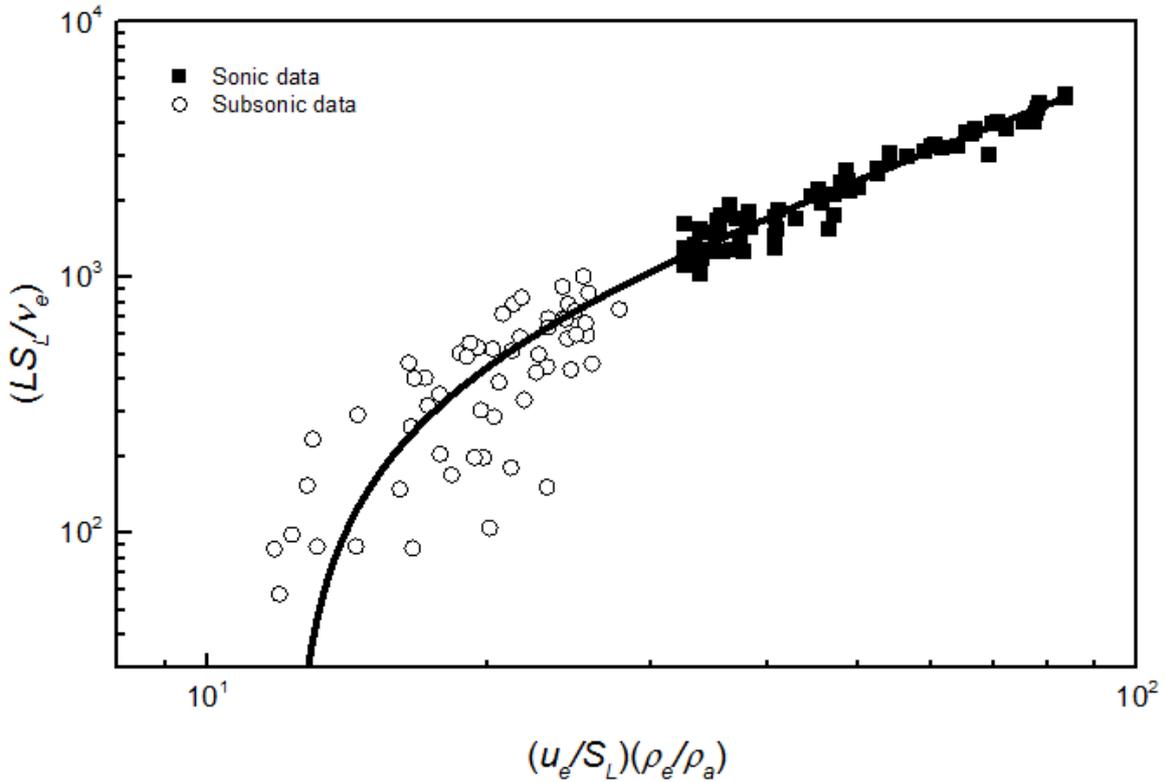
Figure 5. Subsonic data taken from [8-11], and sonic data taken from [8,9,11], being predicted by the dimensionless suggested correlation by Kalghatgi [5]. Filled markers indicate choked flow. The subscript e means expanded conditions.
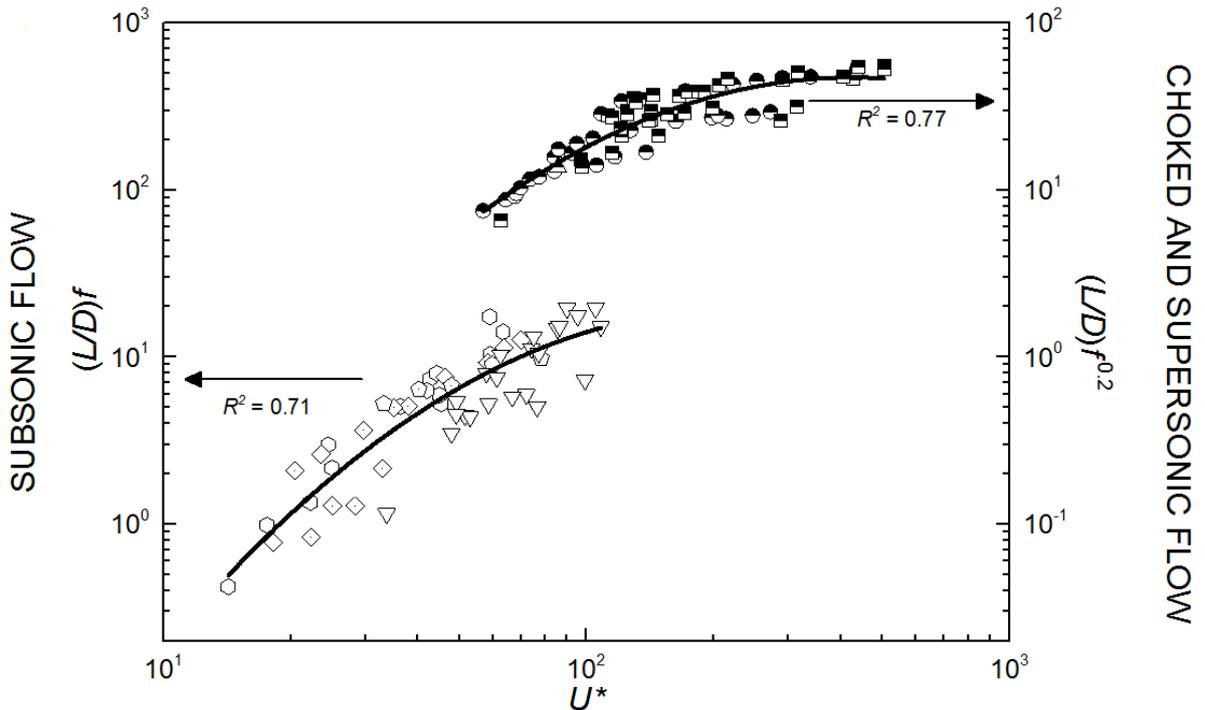
Figure 6. Correlation for normalised lift off using different f factor weightings for the two regimes. Subsonic data taken from [8-11], and sonic data taken from [8,9,11].
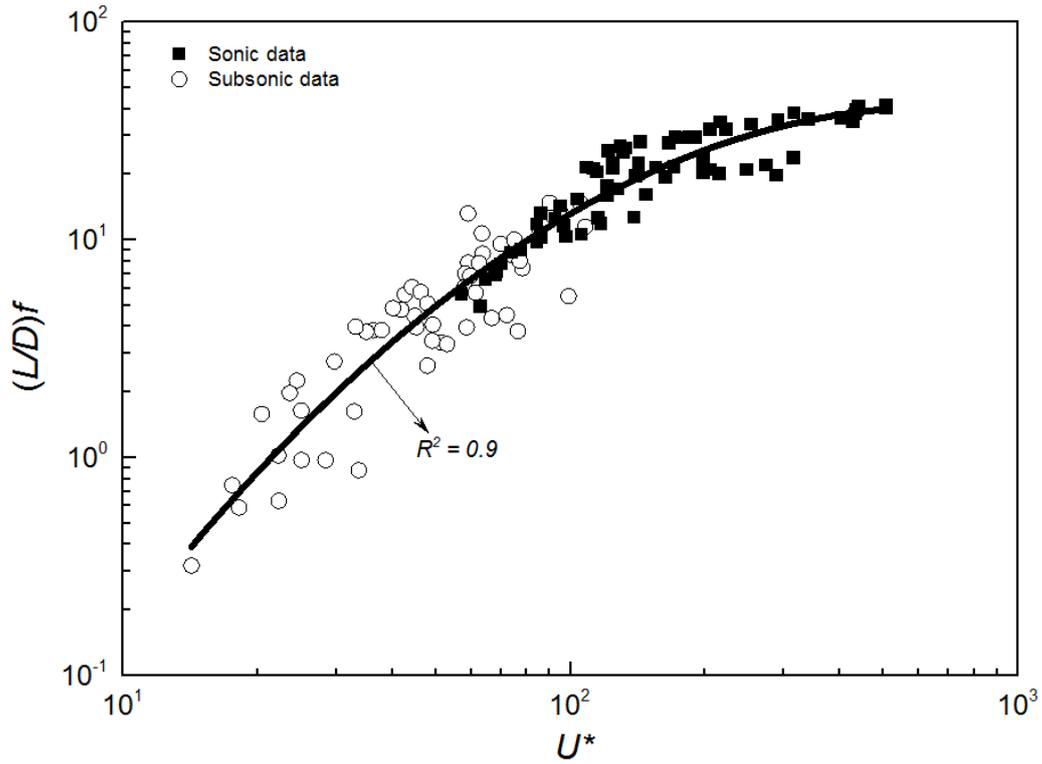
Figure 7. Correlation using the same f factor weighting for both regimes. Subsonic data taken from [8-11], and sonic data taken from [8,9,11].
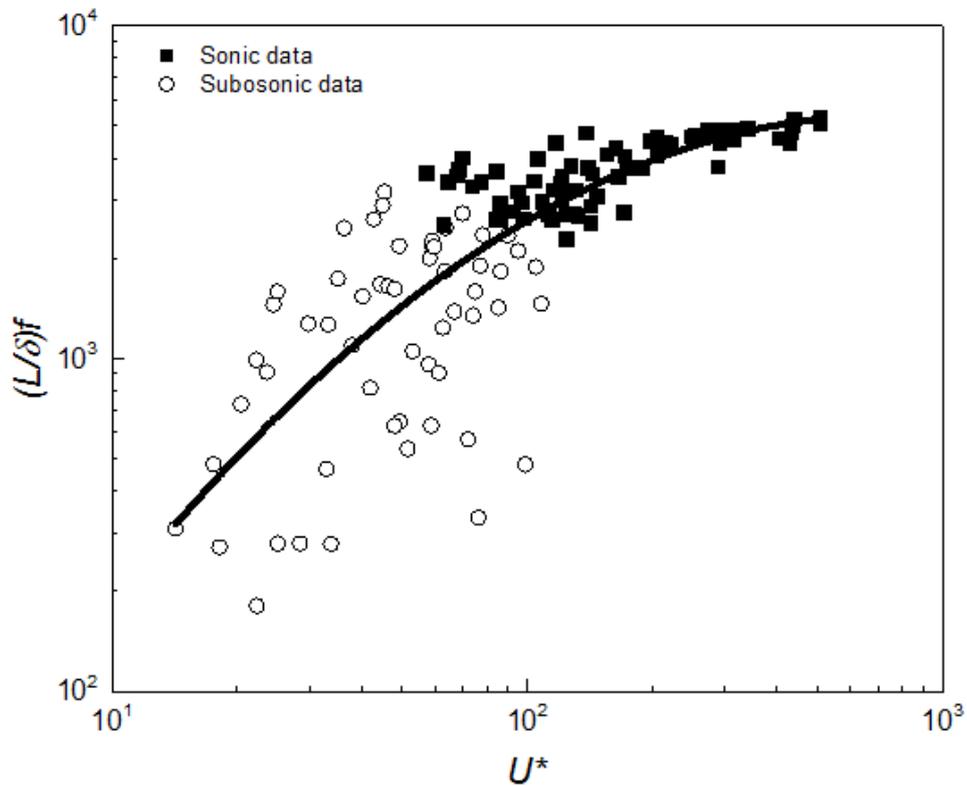
Figure 8. Recent correlation, incorporating f factor and normalisation of lift-off distance with flame thickness, for both regimes. Subsonic data taken from [8-11], and sonic data taken from [8,9,11].