Blow-Off Velocities of Jet Flames

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ABSTRACT

There have been significant successes in the mathematical modelling of lift-off distances and plume heights of fuel jet flames, and in correlating these parameters experimentally. A dimensionless flow number, or jet velocity, has been developed, with which experimental dimensionless plume heights and flame lift-off distances have been successfully correlated. However, the prediction of blow-off heights presents significantly more difficulty. This is because of the strong non-linearities at blow-off, involving complexities of mixing, strain rates, flamelet burning velocities and curvatures, with localised flame extinctions. Because of these, it is difficult to obtain consistency in the measurement of blow-off heights. Consequently, the practice adopted by Kalghatgi of measuring dimensionless fuel jet velocities at blow-off was followed in the present study. Just before blow-off, strong instabilities and flame oscillations develop, and a correlation of blow-off is proposed in terms of the last stable dimensionless flow number, before blow-off occurs. The study covers acetylene, commercial butanes, ethylene, hydrogen, methane and propane. Blow-off is characterised from plots of the dimensionless flame lift-off distance against the flow number for each fuel, with identification of the last stable dimensionless flow number prior to blow-off. This enables the dimensionless flow numbers for blow-off to be identified for the different fuels, along with the associated dimensionless lift-off distance.

KEYWORDS: Blow-off, jet flame, lift-off distance, plume height.

NOMENCLATURE

D	pipe diameter (m)
f	ratio of fuel to air moles in fuel-air mixture for maximum burning velocity, S_L
L	flame lift-off distance (m)
P_a	atmospheric pressure (Pa)
P_i	initial stagnation pressure (Pa)
Re_L	Reynolds number based on S_L and D, (DS_L/ν)
S_L	maximum laminar burning velocity of the fuel-air mixture under conditions of ambient atmosphere (m/s)
t	time (s)
u	fuel flow mean velocity at the exit plane of pipe for subsonic flow. For ratios of atmospheric pressure to pipe pressure equal to, or less than, the critical pressure ratio, sonic velocity after isentropic expansion (m/s)
U^*	dimensionless flow number for choked and unchoked flow, $(u/S_L)Re_L^{-0.4}(Pi/Pa)$
U_b^*	dimensionless U^* reporting blow-off conditions
Greek	
δ	laminar flame thickness, under conditions of ambient atmosphere (ν/S_L) (m)
ν	kinematic viscosity, under conditions of ambient atmosphere (m^2/s)
Subscripts	
a	ambient conditions
i	initial stagnation conditions

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INTRODUCTION

In the cases of both controlled flaring, and jet flames generated by unintended blow-out, it is important to be able to predict flame lift-off distance, plume height and radiative emission. At both low and high jet velocities the flame can become unstable, in the latter case leading to flame blow-off. Whereas there are valuable correlations of plume heights and flame lift-off distances, there is much less guidance about the onset of flame blow-off. The increasing use of “fracking”, with its associated increased flaring, with possible associated incomplete combustion, and emission of a potent greenhouse gas, emphasises the importance of studies in this area. The present paper discusses data on blow-off and the problems of correlating it, for some of the more common fuels. All flames are located on a cylindrical pipe, vertically released, in the absence of any pilot flame.

There have been significant successes in the mathematical modelling of lift-off distances and plume heights [1, 2], but the prediction of blow-off conditions is more difficult. This is because of the strong non-linearities at blow-off, involving the complexities of mixing with high turbulence, strain rates, flamelet curvatures, and localised flame extinctions. Results from the stretched laminar flamelet modelling in [1], in conjunction with experimental jet flame data, have led to a practical correlation of the normalised flame lift-off distance, $(L/D)f$, where L is the flame lift-off distance, D the pipe diameter, and f the ratio of fuel to air moles in the fuel-air mixture for maximum laminar burning velocity, S_L, with a dimensionless flow number, U^*, given by

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

Here, u is the pipe flow mean velocity and sonic velocity for choked flow, δ the laminar flame thickness, at the ambient conditions, given by ν/S_L, with ν the gaseous mixture kinematic viscosity, under conditions of the ambient atmosphere, P_a, while P_i is the initial stagnation pressure [3].

In the subsonic regime the relationship is

$$(L/D)f = 0.11\,U^* - 0.2\,. \qquad (2)$$

Further details of the correlation of flame lift-off distance with flow number are given in [3], but blow-off is not considered.

Significantly fewer measurements have been made of blow-off than of lift-off distances. Sometimes, as in [4], blow-off points have been obtained on the basis of semi-theoretical assumptions, such as, in this case, that blow-off occurs when the change in burning velocity “cannot keep up with” the change in local flow velocity downstream from the base of the flame.

DEVELOPING INSTABILITIES

Because of the complex non-linearities, there are considerable theoretical difficulties in predicting blow-off using mathematical modelling and in generalising practical correlations. Localised premixed flamelets only become established when they are reactive enough and the strain rates are low enough. As blow-off is approached, with increasing U^*, an initial stable, steady increase in lift-off distance accelerates increasingly and then, even more rapidly, the flame becomes unstable and blows off. This is illustrated in Fig. 1 by the increase in $(L/D)f$ with U^* for a methane flame, that unlike all other flames in the study was aerated.

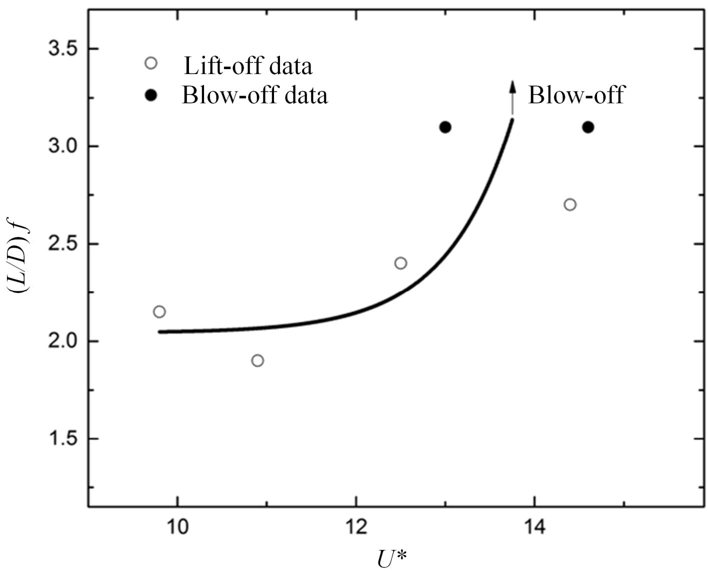

Figure 1. Normalised lift-off distances, *(L/D)f*, as a function of *U** for aerated subsonic methane jet flames (fuel/air ratio of 35.7).

In the final stage, just prior to blow-off, unstable oscillatory fluctuations in lift-off distance are generated. Fig. 2 shows such fluctuations, on the threshold, and at the occurrence of blow-off, for an aerated methane flame. Directly measured values of *L* are plotted against time. Prior to blow-off, at the base of the flame, there are strong fluctuations in localised equivalence ratios, and near-extinction, strain rates. High amplitude oscillations finally culminate in blow-off.

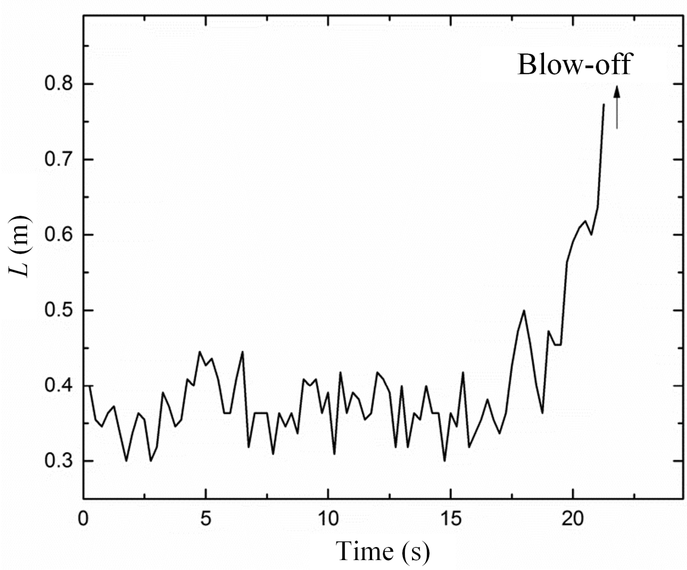

Figure 2. Oscillatory aerated methane jet flame (fuel/air ratio = 50) prior to blow-off. Lift-off distances leading up to blow-off. Time interval between successive data points is 0.25 s.

Because of the nature of the physicochemical complexities just prior to blow-off, it is unlikely that blow-off data can be correlated in a generalised way. Furthermore, there is no stabilised blow-off height, due to the very rapid rate of change in lift-off distance as blow-off occurs. The stable value of U^* just prior to blow-off is a possible correlating parameter, but it seems clear that this must be found for each fuel separately. The procedure adopted is to attempt to ascertain values of U^* at blow-off for six different jet fuels.

BLOW-OFF DATA FOR DIFFERENT FUELS

For each fuel, the normalised lift-off distances, $(L/D)f$, drawn from the data bank [3] are plotted against U^* for subsonic jet flames, and indicated by open symbols. The values of U^* for the reported diverse blow-off conditions, designated by U_b^*, are indicated by different black-filled symbols.

In several instances dimensionless flame heights have been reported for values of U^* that are greater than U_b^*. In such cases, the highest values of U^* are shown by a vertical dashed line. The fuels studied are methane, propane, hydrogen, ethylene, acetylene, and butane. Data are drawn from 576 measurement sets from seventeen sources [3], with 11 measurement sets for blow-off [4-7].

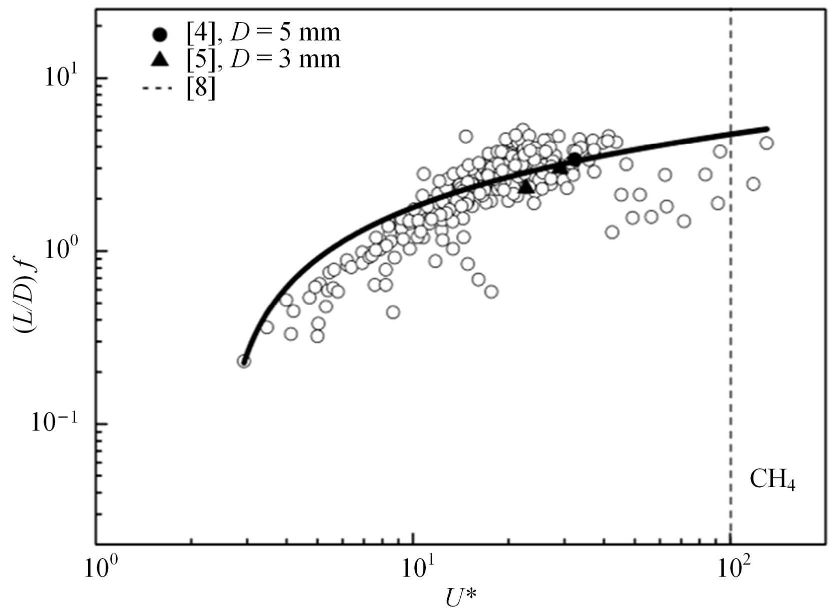

Figure 3. Normalised methane flame lift-off distances, modified, from [3]. Black-filled circles and triangles indicate blow-off data [4, 5]. Vertical dashed line indicates highest U^* value reported for plume height [8].

Fig. 3 shows the normalised flame lift-off distances for methane jet flames. The best fit relationship of $(L/D)f$, with U^*, is indicated by the bold curve. Open circles indicate lift-off distance data, filled black circles values of U^*, namely U_b^*, at blow-off, from [4, 5]. The vertical dashed line indicates the highest U^* value reported for plume height measurements. Clearly, stable subsonic jet flames have been reported beyond the blow-off regimes found by several authors [4, 5] with a maximum U^* value of 100 [8]. Interestingly $(L/D)f$ is relatively small in the regime between measured blow-off and maximum measured plume height.

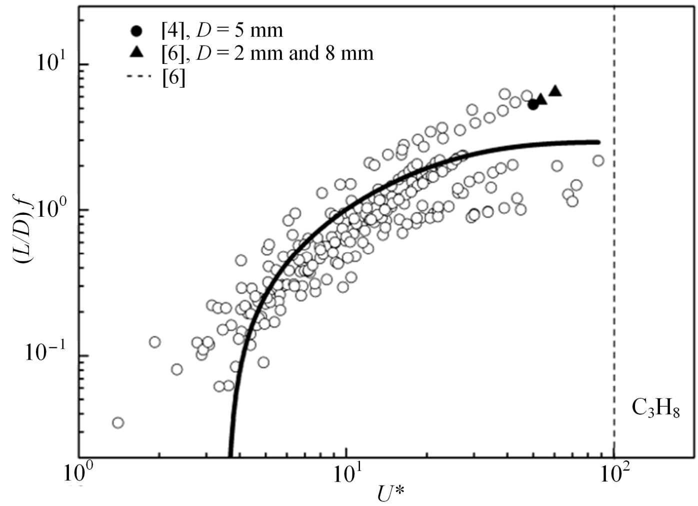

Figure 4. Normalised propane flame lift-off distances, modified from [3]. Black-filled circles and triangles indicate blow-off data [4, 6]. Vertical dashed line indicates highest U^* value reported for plume height [6].

Fig. 4 shows the normalised flame lift-off distances for propane jet flames, again with the best fit relationship of $(L/D)f$, indicated by the bold curve, and the same convention for the symbols and dashed line as in Fig. 3. Stable subsonic propane jet flames have been reported just beyond reported blow-off regimes found in [4, 6] with a maximum U^* value of 100 [6].

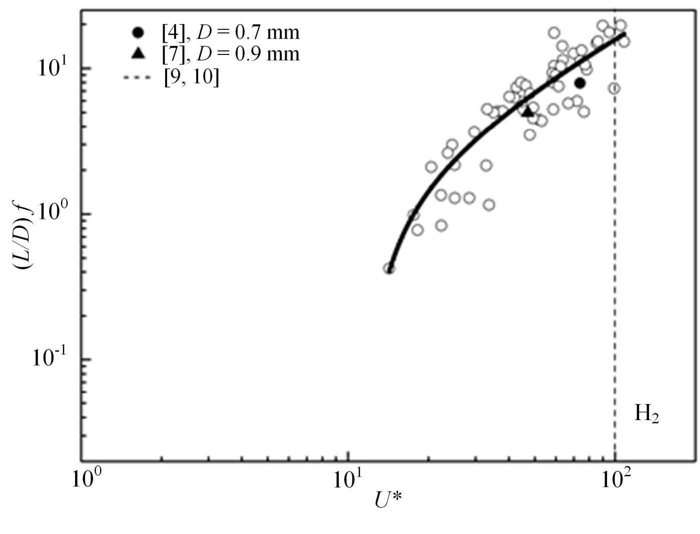

Figure 5. Normalised hydrogen flame lift-off distances, modified from [3]. Black-filled circles and triangles indicate blow-off data [4, 7]. Vertical dashed line indicates highest U^* value reported for plume height [9, 10].

Fig. 5 shows the normalised flame lift-off distances for hydrogen jet flames, again with the best fit relationship of $(L/D)f$, indicated by the bold curve, and the same convention for the symbols and dashed line as in Figs. 3 and 4. Stable subsonic hydrogen jet flames have been reported just beyond the blow-off regimes found in [4, 7] with a maximum U^* value of 100 [9, 10].

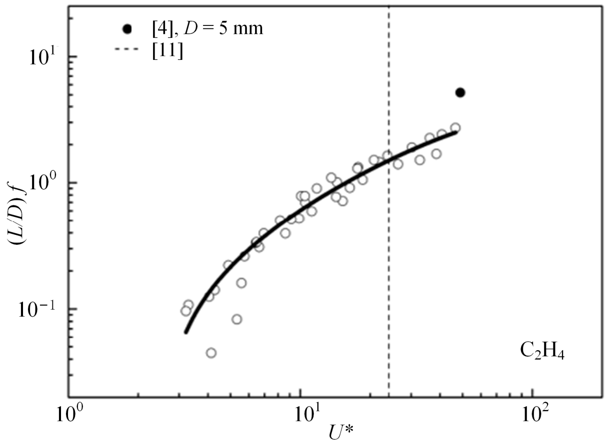

Figure 6. Normalised ethylene flame lift-off distances, modified from [3]. Black-filled circles indicate blow-off data [4]. Vertical dashed line indicates highest U^* value reported for plume height measurement [11].

Fig. 6 shows the normalised flame lift-off distances for ethylene jet flames, again with the best fit relationship of $(L/D)f$, indicated by the bold curve, and the same convention for the symbols and dashed line as in Figs. 3-5. In this instance, no plume heights have been reported at U^* values above the highest U_b^*.

Fig. 7, below, shows normalised flame lift-off distances for acetylene jet flames. Although there has been much interest in soot formation in acetylene flames, there are few data on its blow-off characteristics. The blow-off implied by [4] is at flow numbers in excess of those for plume height measurements in [12], with a U_b^* value of 31. Lift-off distances and flame heights were measured at a lower flow number of 6.5 in [12].

In addition, an attempt was made to study blow-off of butane flames. Blow-off data were only available from [4] and this gave a mean value of U_b^* of 32. The highest U^* value reported for butane plume height measurement was 0.5 from [13]. In this instance, no plume heights have been reported at U^* values above the highest U_b^* of 32 [4].

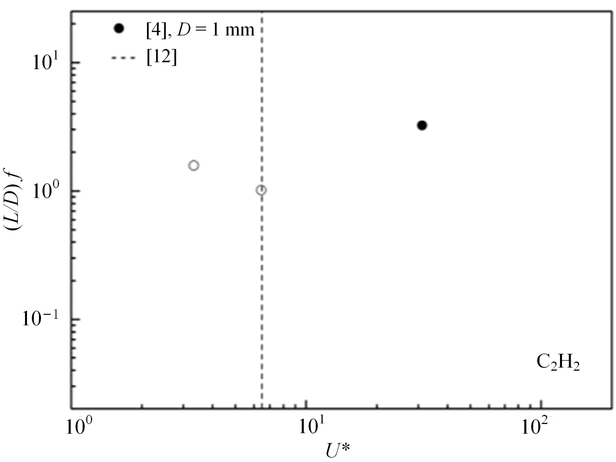

Figure 7. Normalised acetylene flame lift-off distances from [12]. Black-filled circles indicate blow-off data [4]. Vertical dashed line indicates highest U^* value reported for plume height measurement [12].

CONCLUSIONS

Table 1 shows the range of blow-off values, U_b*, averaged for each fuel in the study, in ascending order of U_b*.

Table 1. Range of blow-off values for each fuel in present study.

Fuel	U_b*	f	(L/D)	$(L/D)f$
CH_4	28	0.116	25	2.9
C_2H_2	31	0.092	35.9	3.3
C_4H_{10}	32	0.035	94.3	3.3
C_2H_4	49	0.077	67.5	5.2
C_3H_8	55	0.046	126.1	5.8
H_2	61	0.756	8.6	6.5

The results confirm that, although there might have been some success in generating generalised correlations of flame height and lift-off distance, the same cannot be said of blow-off conditions, which are shown to be fuel specific. A contradictory aspect of the study is that flame height measurements have been reported at values of U* in excess of U_b*. This might be attributed to both insufficient data and, insufficient measurement accuracy, combined with inadequate correlation laws.

The lowest value of U_b* is that of methane and the highest, that of hydrogen.

A significant influence is the value of the f factor. It is relatively high for hydrogen and, not surprisingly for the fuel that requires the least air, it has the smallest value of L/D at blow-off. Conversely, propane, with the smallest value of f has the largest value of L/D at blow-off.

It can be seen from the Table 1 that, very approximately, $L/D = U_b^*/(10f)$.

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