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## Lift-off Heights and Visible Lengths of Vertical Turbulent Jet Diffusion Flames in Still Air

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**Abstract**—The lift-off heights and visible-flame lengths of jet diffusion flames in still air have been determined for hydrogen, propane, methane and ethylene.

The flame lift-off height varies linearly with the jet exit velocity and is independent of the burner diameter for a given gas. The results support the assumption that if the burner exit flow is choked the burner can be approximated by an equivalent convergent-divergent nozzle at whose exit the flow has expanded to ambient pressure. The data for different gases can be collapsed onto a single curve if they are plotted in terms of the appropriate non-dimensional groupings. These results and previous results for blow-out stability suggest that diffusion flames blow out when the base is lifted to between 0.65 and 0.75 times the height at which stoichiometric concentration is reached at the jet axis. It can be deduced from the experimental results that, at the base of the flame, the ratio of turbulent burning velocity to laminar burning velocity varies as the square root of the local turbulence Reynolds number based on the integral length scale. The predicted correlation for the turbulent burning velocity agrees well with the experimental data presented in the literature.

The flame length results for different gases and burner diameters can be collapsed onto a single curve if plotted in terms of the non-dimensional groupings suggested by Becker and Liang (*Combust. Flame*, **32**, p. 115, 1978). The results near the forced convection limit are in line with the theoretical work presented by Becker and Liang but disagree with their final recommendation. Away from the forced convection limit, the flame length correlation is similar to that proposed by Becker and Liang.

### INTRODUCTION

A jet diffusion flame in still air lifts off the tip of the burner and forms a stable lifted flame when the flow rate through the burner is increased beyond a limit known as the lift-off stability limit. The flame will blow itself out if the flow rate is further increased beyond a limit known as the blow-out limit. The structure of the lifted diffusion flame has been studied by Vanquickenborne and Van Tiggelen (1966) Günther *et al.* (1981) and in the context of flame stability, by Annushkin and Sverdlov (1979) and Hall *et al.* (1980). The assumption that the fuel-air mixture is fully premixed at the base of the lifted flame is implicit in all these studies because the concept of a turbulent premixed flame travelling against the mean flow is used to explain the stabilization mechanism. This assumption has been questioned recently (*e.g.*, Janicka and Peters 1982, Peters and Williams 1983) and it has been suggested that the lift-off as well as blow-out characteristics of turbulent jet diffusion flames can be explained in terms of the extinction of laminar flamelets. However, in the present work we follow the traditional model proposed by Vanquickenborne and Van Tiggelen (1966) and find that it provides a reasonable explanation for all our experimental observations.

In particular, the present work describes a systematic study of the factors affecting lift-off height,  $h$ , the distance between the burner exit plane and the base of the lifted flame. Almost all the previously published results for  $h$ , have been for methane flames. In this work, we present results for flames of hydrogen, propane and ethylene as well as methane. For hydrogen, the results extend to the regime

where the flow at the burner exit is choked. These results suggest a method for extending the correlations describing flames from subsonic jets to those from under-expanded sonic jets; such flames can occur in practice during gas well blow outs or emergency gas ventings. It is possible to identify non-dimensional groupings of the various flow and gas parameters that affect  $h$ . A single empirical plot in terms of these non-dimensional groupings can be found to describe all the experimental observations. It is deduced, using this "universal" plot and the well established results describing the fluid mechanics of turbulent jets, that at the base of the lifted flame the ratio of turbulent burning velocity to laminar burning velocity varies as the square root of the local turbulence Reynolds number based on the integral length scale. The predicted correlation for the turbulent burning velocity is shown to agree well with the experimental data found in the literature.

The visible-flame length is an important parameter of a diffusion flame and as such has received considerable attention (*e.g.*, Günther 1966, Hawthorne *et al.* 1949). One of the most recent and perhaps the most comprehensive study of this kind is by Becker and Liang (1978). They have recommended, after a detailed consideration of entrainment and momentum growth in jet flames, non-dimensional parameters which can be used in flame length correlations. We interpret our data in terms of their study. Previously there have not been any experimental results for flames from very high speed jets—near what is known as the forced convection limit. We present such results in this paper. These results are in line with the theoretical work discussed by Becker and Liang (1978) but disagree with their final recommendations. Away from the forced convection limit the flame length correlation is similar to that proposed by Becker and Liang (1978).

## EXPERIMENTAL DETAIL

The gases used were hydrogen, methane, propane and ethylene and their properties are listed in Table I. The burner diameter,  $d_b$ , ranged from 1.08 mm to 10.1 mm. Each burner is a straight tube mounted at the end of a settling chamber of internal diameter 152 mm. The pressure in the settling chamber was measured using either a mercury or a water manometer for low pressures and a pressure gauge for high pressures. The pressure drop coefficient for each burner was evaluated separately by using nitrogen and measuring the reservoir pressure and the pitot pressure at the axis of the burner near the exit plane simultaneously; it was found to be negligibly small. Hence the settling chamber pressure was taken to be the flow stagnation pressure,  $P_{st}$ . The Mach number, velocity, temperature and density— $M$ ,  $U_e$ ,  $T_e$  and  $\rho_e$  respectively—when the gas expands fully to atmospheric pressure,  $P_{at}$ , are calculated from isentropic equations of one dimensional gas dynamics (*e.g.*, Liepman and Roshko 1957).

For each operating condition, three still photographs of the flame were taken with an exposure time of 1/30 s. Both the flame length,  $L$ —the distance between the tip of the visible flame and the burner exit plane—and  $h$  were measured from each photograph and averaged. In some cases, schlieren photographs of the base of the flame were also taken.

For subsonic jets, the Mach number,  $M_b$ , at the burner exit plane is the same as  $M$ . However, for many of the cases involving hydrogen, the flow at the burner exit plane was choked. In such cases, the Mach number at the burner exit plane is unity, the pressure is greater than atmospheric and the flow will immediately

TABLE I  
Properties of the gases used in the study

Gas	Maximum laminar burning velocity, $S_u$ , $m\ s^{-1}$	Ratio of specific heats, $\gamma$	Dynamic viscosity, <sup>a</sup> $\mu P$ $\mu = bT^{1.5}/(S + T)$ , where $T$ is temperature in		Stoichiometric fuel mass fraction, $W_1$	Gas constant, $R$ , $m^2\ s^{-2}\ K^{-1}$	Fuel mass fraction when laminar burning velocity is maximum, $W_s$
			$b$	$S$			
Hydrogen	3.06	1.4	6.5	67	0.0284	4157	0.076
Methane	0.39	1.31	10	168	0.0549	520	0.058
Propane	0.45	1.13	8.6	241	0.06	189	0.068
Ethylene	0.75	1.255	10.4	225	0.0632	297	0.073

<sup>a</sup>Lydersen (1979)

<sup>b</sup>Defined in Becker and Liang (1978)

expand to atmospheric pressure in a supersonic plume. We acknowledge this expansion by replacing the burner with an equivalent convergent-divergent nozzle at whose exit the flow has expanded to atmospheric pressure. The diameter,  $d_e$ , of such a nozzle is greater than  $d_b$  and can again be calculated from standard equations.

## RESULTS

### *Lift-off Height, $h$*

In Figure 1a,  $h$  is plotted against  $U_e$  for hydrogen. The velocity when the exit flow first gets choked is also marked. It can be seen that  $h$  is independent of  $d_b$  and that it increases linearly with  $U_e$  except near the lift-off limit. This has also been noted by Annushkin and Sverdlov (1979) and their results for hydrogen agree well with those shown in Figure 1a. The method outlined above for handling under-expanded sonic jets seems to be justified since even in these cases ( $M > 1$ ) the data are in line with those for subsonic cases. Results for methane, propane and ethylene are shown in Figures 1b, 1c and 1d, respectively. In these experiments the burner flows were limited to subsonic flows. Again,  $h$  is independent of burner diameter and increases linearly with  $U_e$  except near the lift-off limit. There is reasonable agreement between our methane results and those given by Vanquickenborne and Van Tiggelen (1966). However, for both methane and propane, the lift-off heights measured in the present work are, in general, larger than those given by Annushkin and Sverdlov (1979).

The flame will be stabilized in a premixed region in the outer edge of the turbulent jet mixing layer and at the stabilization ring we should expect the local mean flow velocity,  $\bar{U}$ , to be equal to the local turbulent burning velocity,  $S_t$ , as discussed by Vanquickenborne and Van Tiggelen (1966). The two velocity profiles plotted at height  $h$  would be as in Figure 2, where  $y$  is the radial coordinate. We assume that the flame stabilizes where the value of  $S_t$  is maximum. At the lean and rich limits,  $S_t$  will be zero and we can expect the maximum value of  $S_t$  to occur at a distance of  $y_s$  where the mean fuel concentration,  $W_s$ , is such that the laminar burning velocity has its maximum value,  $S_u$ . For hydrocarbons,  $y_s$  is almost equal to the radial distance at which the mixture is stoichiometric. The maximum value of  $S_t$  depends on  $S_u$  as well as on the local turbulence parameters. These and the local mean flow velocity in the outer region of the jet mixing layer will depend on the velocity  $U_e$ , the kinematic viscosity  $\nu_e$  at the jet exit, and the density ratio  $\bar{\rho} = \rho_e/\rho_\infty$ , where  $\rho_e$  is the density of the burner gas at the jet exit and  $\rho_\infty$  is the density of the ambient gas (air). Hence we can expect  $h$  to be a function of  $S_u$ ,  $U_e$ ,  $\nu_e$  and  $\bar{\rho}$ . From simple dimensional analysis (*e.g.*, Lydersen 1979) we can expect:

$$R_h \equiv \frac{h \cdot S_u}{\nu_e} = f\left(\frac{U_e}{S_u}, \bar{\rho}\right) \quad (1)$$

Indeed, if we plot  $R_h$  against  $\bar{U}_e$ , where

$$\bar{U}_e = \frac{U_e}{S_u} \cdot g(\bar{\rho})$$

and the function  $g$  is defined by:

$$g(\bar{\rho}) = 0.04 + 0.46\bar{\rho} + 0.5\bar{\rho}^2 \quad (2)$$

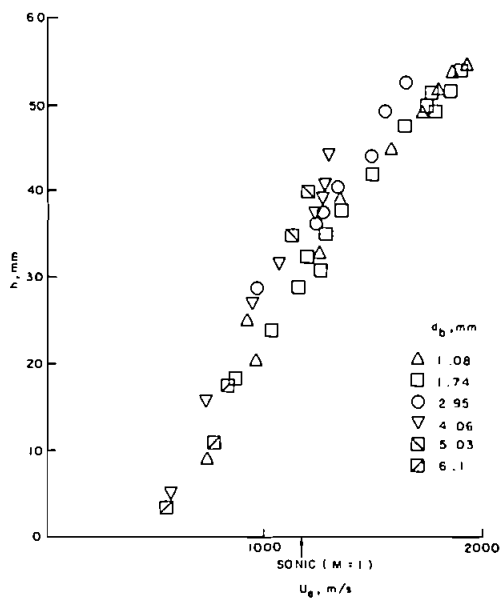


FIGURE 1(a) Hydrogen

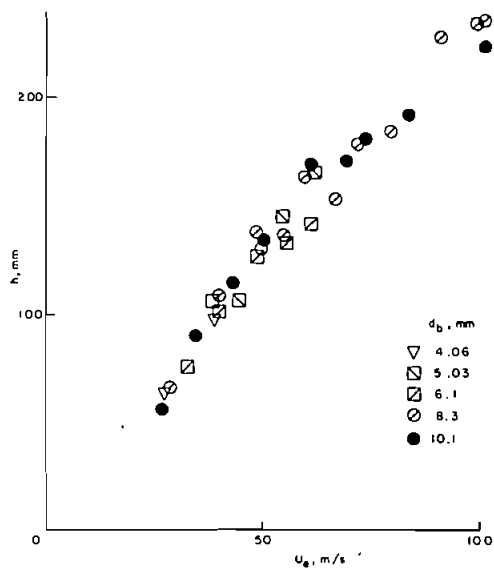


FIGURE 1(b) Methane.

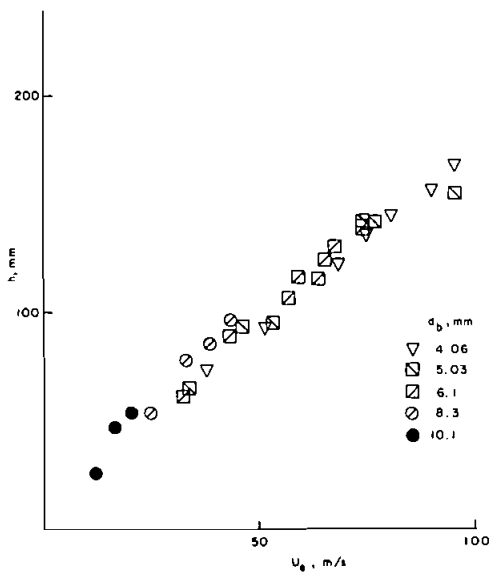


FIGURE 1(c) Propane.

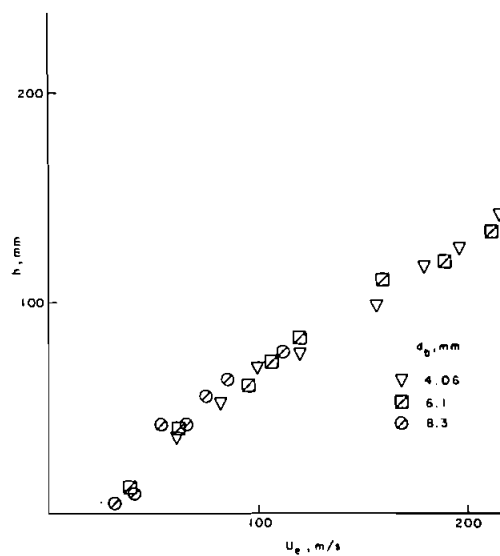


FIGURE 1(d) Ethylene.

FIGURE 1 Variation of lift-off height ( $h$ ) with exit velocity ( $U_e$ ).

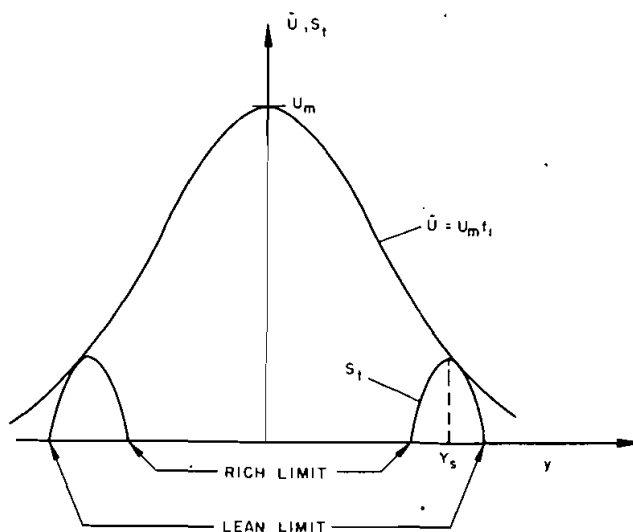


FIGURE 2 Sketch of the radial profiles of mean velocity and turbulent burning velocity.

we find that all the results in Figures 1a to 1d can be collapsed onto a single curve as shown in Figure 3. In the range  $0.5 < \bar{\rho} < 2$ , which covers hydrocarbon gases from methane to butane,  $g(\bar{\rho}) \approx \bar{\rho}^{1.5}$ . It was found in a previous study (Kalghatgi 1981) that at the blow-out stability limit, the velocity  $U_e$  could be described by a function of the form:

$$\left(\frac{U_e}{S_u}\right)(\bar{\rho})^{1.5} = C_1 \cdot \left(\frac{HS_u}{\nu_e}\right) \quad (3)$$

where  $H$  is the distance from the exit plane at which the mean gas concentration falls to stoichiometric on the jet axis, and  $C_1$  is a constant between 0.013 and

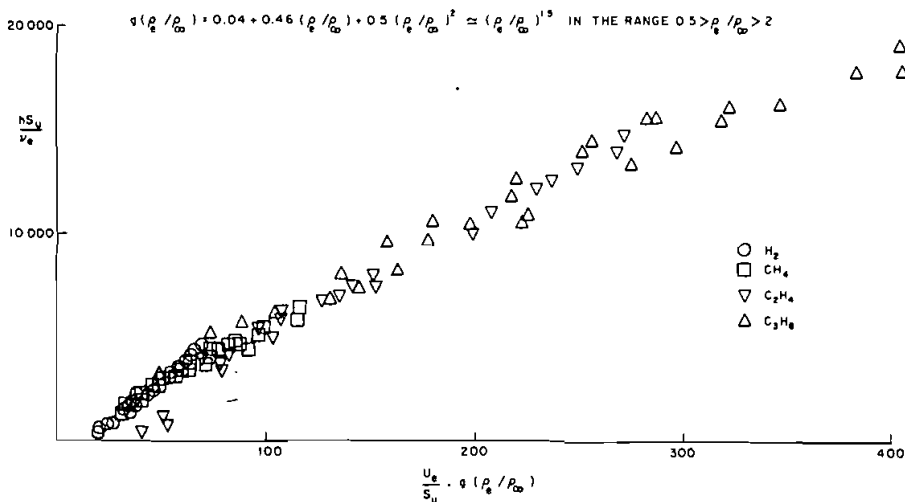


FIGURE 3 The non-dimensional lift-off height curve.

0.015. We now find from Figure 3 that for hydrocarbon gases, to a fairly good approximation:

$$\left(\frac{hS_u}{v_e}\right) = C_2 \left(\frac{U_e}{S_u}\right) (\bar{\rho})^{1.5} \quad (4)$$

with  $C_2$  about 50. Hence we can deduce that diffusion flames will be blown out when  $h/H$  reaches a value between 0.65 and 0.75. This is consistent with the proposition of Hall *et al.* (1980) that blow out occurs when the base of the flame reaches the axial position where the radial coordinate of the stoichiometric concentration profile is maximum.

#### *Turbulent Burning Velocity at the Base of the Lifted Flame*

Though turbulence and turbulent burning were invoked in the previous section, turbulence parameters did not enter the discussion explicitly. In this section, we use the well established results for jet mixing along with the experimental results shown in Figure 3 to try to deduce a relationship between  $S_t$ ,  $S_u$  and a turbulence Reynolds number based on local turbulence parameters at the base of the flame. The object is to explore the links between the global approach based on dimensional analysis, which has been shown to be valid, and the more fundamental principles that govern the problem rather than to derive any "universal" law to describe turbulent combustion.

We have said (Figure 2) that at the base of the lifted diffusion flame:

$$S_t = \bar{U} \quad (5)$$

Now, in axisymmetric turbulent jets (*e.g.*, Abramovich 1963, Hinze 1975) at any point  $(x, y)$  in the jet, where  $x$  is the distance along the axis measured from the jet exit plane:

$$\bar{U} = U_m f_1 \quad (6)$$

and the root mean square fluctuation velocity,  $u'$ , is given by (*e.g.*, Wygnanski and Fiedler 1969)

$$u' = U_m f_2 \quad (7)$$

where  $f_1$  and  $f_2$  are functions of  $(y/x)$  and  $U_m$  is the mean velocity at the jet axis. From the conservation of axial momentum and jet source material, we get (*e.g.*, Becker and Liang 1978)

$$U_m = \frac{C_3 \cdot U_e \cdot D_s}{x} \left(\frac{\rho_\infty}{\rho_m}\right)^{1/2} \quad (8a)$$

and

$$W_m = \frac{C_4 \cdot D_s}{x} \left(\frac{\rho_\infty}{\rho_m}\right)^{1/2} \quad (8b)$$

Here,  $\rho_m$  and  $W_m$  are, respectively, the mean density and the mean gas mass fraction at the jet axis and  $D_s$  is the effective source diameter.  $C_3$  and  $C_4$  are constants. The mean gas concentration,  $W$ , away from the axis is given by

$$W = W_m \cdot f_3 \quad (9)$$



where  $f_3$  is a function of  $y/x$ . Then, from Eqs. 6, 8 and 9:

$$\frac{\bar{U}}{U_e} = \frac{C_3 f_1}{C_4 f_3} W \quad (10)$$

and from Eqs. 6 and 7,

$$\frac{\bar{U}}{u'} = \frac{f_1}{f_2} \quad (11)$$

The turbulent integral length scale,  $l$ , in the jet mixing layer at an axial distance,  $x$ , is given by (e.g., Abramovich 1963, Davies *et al.* 1963)

$$l = C_5 x \quad (12)$$

We have found experimentally (Figure 3, Eq. (4)) that

$$\frac{1}{S_u^2} = \frac{h \rho_e}{\mu_e C_2 U_e g(\bar{\rho})} \quad (13)$$

At the base of the flame  $x = h$  and  $W = W_s$ . Multiplying each side of Eq. (13) by  $S_t \cdot \bar{U} \cdot u'$  we get after substitution from Eqs. (5), (10), (11) and (12) and some rearrangement,

$$\frac{S_t^2}{S_u^2} = \frac{C_3 f_1^2 l \rho_e u'}{C_4 f_2 f_3 C_5 \mu_e C_2 g(\bar{\rho})} \cdot W_s \quad (14)$$

One can find a range of values in the literature for the various constants describing jet mixing, which occur in Eq. (14). For instance the value of  $C_4$  appears to range from 4 to 6 (Birch *et al.* 1978). We shall take the values for  $C_3$  and  $C_4$  to be those suggested by Becker and Liang (1978)—6.2 and 5.4 respectively. Similarly from the results and discussion presented in Wygnanski and Fiedler (1969) and Birch *et al.* (1978),  $C_5$  can be judged to be 0.07 and  $(f_1^2/f_2 f_3)$  to range from 1.7 to 4 for  $0.05 < y/x < 0.2$  which is the range of  $y/x$  encountered in our experiments. As mentioned in the last section  $C_2$  is approximately 50. All these numerical values can be grouped together in  $K$  whose value ranges from 0.56 to 1.3 and we can write Eq. (14) as

$$\frac{S_t^2}{S_u^2} = \frac{u' l \cdot \rho_e W_s}{\mu_e g(\bar{\rho})} K \quad (15)$$

Now we want to express  $\rho_e$  and  $\mu_e$  in terms of the parameters at the base of the flame. If  $\rho_s$  is the density at the base of the flame, then:

$$\rho_s = \frac{\rho_e}{W_s + (1 - W_s)\bar{\rho}} \quad (16)$$

The viscosity,  $\mu_s$ , at the base of the flame will also be a function of  $W_s$ ,  $\mu_e$  and  $\bar{\rho}$  and can be found from the procedure outlined in Strehlow (1978). Hence, we can briefly write

$$\frac{W_s}{g(\bar{\rho})} \cdot \frac{\rho_e \mu_s}{\rho_s \mu_e} = f_4(W_s, \bar{\rho}) \quad (17)$$

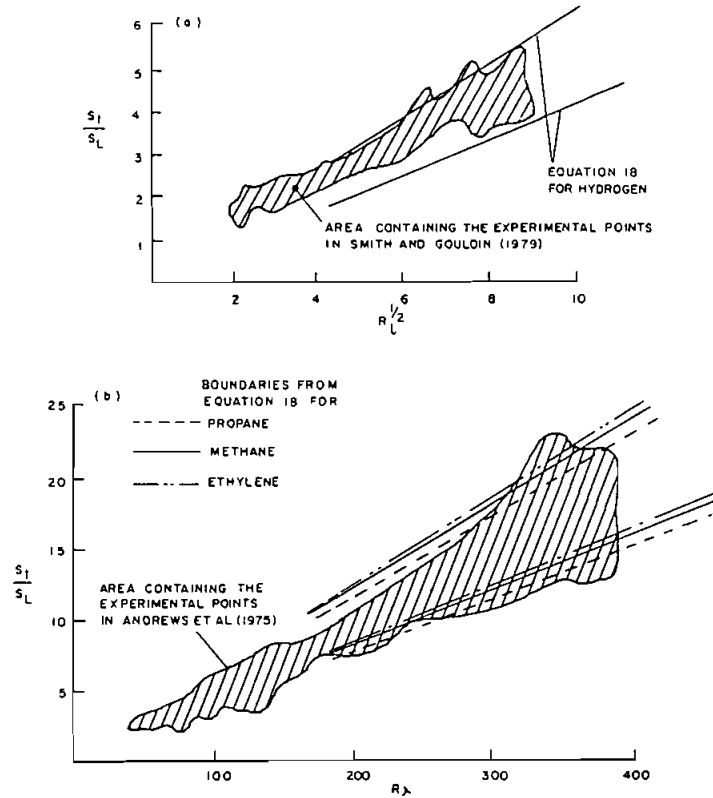


FIGURE 4 Comparison of Eq. (18), the deduced correlation for turbulent burning velocity, with experimental results of (a) Smith and Gouldin (1979), (b) Andrews *et al.* (1975).

Using Eq. (17), Eq. (15) can be written as:

$$\frac{S_t^2}{S_u^2} = R_t \cdot f_4(W_s, \bar{p}) \cdot K \quad (18)$$

where  $R_t$  is the turbulence Reynolds number given by

$$R_t = \frac{u'l}{\mu_s} \rho_s$$

The value of  $f_4$ , for hydrogen, methane, propane and ethylene is respectively, 0.3, 0.138, 0.123 and 0.14. For hydrogen in the present experiments, from Eq. (12),  $l$  can be expected to range from 0.7 mm to 3.5 mm because  $h$  varies between 10 mm and 50 mm. The kinematic viscosity at the base of the flame,  $\nu_s$ , will be about  $2.3 \times 10^{-5} \text{ m}^2/\text{s}$ . Assuming that  $u'$  is of the order of 1 m/s,  $R_t$  for hydrogen flames in the present case can be expected to be between 30 and 150. This range of  $R_t$  overlaps the range of  $R_t$  considered by Smith and Gouldin (1979) who have plotted the experimentally determined ratio of turbulent burning velocity  $S_t$ , to laminar burning velocity,  $S_L$ , against  $R_t^{1/2}$  for premixed methane-air flames stabilized in grid turbulence. Equation (18) predicts that when  $S_t/S_u$  is plotted against

$R_t^{1/2}$ , for hydrogen, the points should fall between the two straight lines shown in Figure 4a. These lines neatly bracket the shaded area in which all the experimental points of Smith and Gouldin (1979) fall.

For the hydrocarbon jet flames considered in this work,  $R_t$  is expected to be larger than 500. Andrews *et al.* (1975) have considered cases where the turbulent Reynolds number is large and have plotted  $S_t/S_L$  against the turbulent Reynolds number  $R_\lambda$  based on the Taylor microscale  $\lambda$ . From their Eq. (6), we can deduce that

$$R_\lambda = 7R_t^{1/2} \quad (19)$$

In Figure 4b, the shaded area is the region where the experimental points in Figure 2 of Andrews *et al.* (1975) fall. The straight lines are the predicted boundaries from Eqs. (18) and (19) above for propane, methane and ethylene and can be seen to be consistent with the results of Andrews *et al.* (1975).

Thus Eq. (18), the derived correlation for turbulent burning velocity is fully consistent with the results in the literature. Günther *et al.* (1981) have obtained similar results. They started with the assumption of a linear relationship between  $S_t/S_L$  and  $R_\lambda$  and demonstrated, after detailed measurement of flow properties, that at the base of the lifted flame,  $S_t = \bar{U}$ .

#### Flame Lengths

Lengths of jet diffusion flames in still air are estimated from empirical correlations such as those suggested by Becker and Liang (1978). Their work has shown that flame length correlations in non-dimensional terms are expected to be of the form:

$$\psi \equiv \left( \frac{D_s \beta}{L W_1} \right)^{2/3} = \psi(\xi_L) \quad (20)$$

We assume that the burner exit conditions are uniform. Then:

$$D_s = d_e \bar{p}^{0.5} \quad (21)$$

$L$  is the flame length,  $W_1$  is the mass fraction of fuel in a stoichiometric mixture with air,  $\beta$  is a constant for a given gas (see Becker and Liang 1978, for details) and  $\xi_L$  is the Richardson number defined as:

$$\xi_L = \left( \frac{g}{D_s^2 U_e^2} \right)^{1/3} L \quad (22)$$

where  $g$  is the acceleration due to gravity.

In Figure 5,  $L$  has been plotted against the mass flow rate,  $\dot{m}$ , for hydrogen; the flow rate at which the burner exit flow is first choked is marked for each burner. It can be seen that for a given burner diameter, flame length increases with mass flow rate and for a given mass flow rate, the flame length increases with burner diameter. Similar results were obtained for methane, propane and ethylene; the flow at the burner exit was limited to subsonic for these gases. The results in Figure 5 as well as those for other gases are plotted in terms of  $\psi$  and  $\xi_L$  in Figure 6. It can be seen that all the results collapse round a single curve as shown by Becker and Liang (1978). The curve is adequately described in the region  $2 < \xi_L < 11$  by

$$\psi = 0.2 + 0.024\xi_L \quad (23)$$

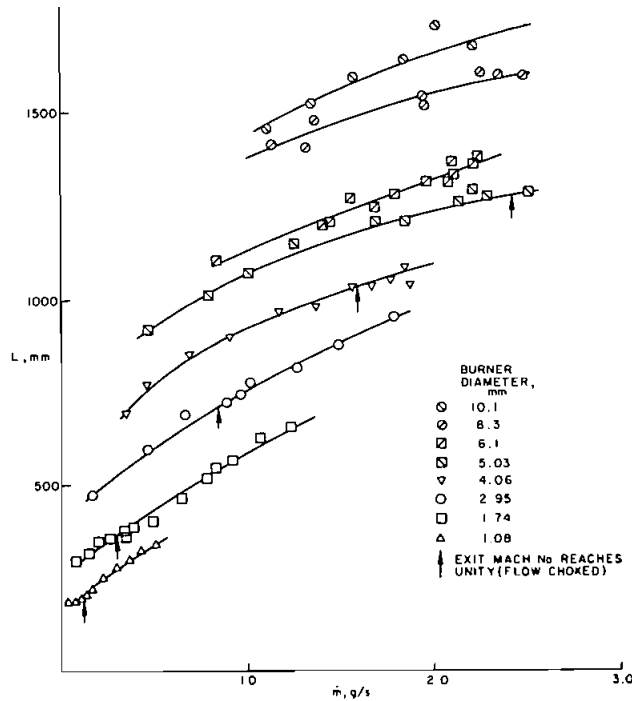


FIGURE 5 Variation of Flame Length ( $L$ ) with mass flow rate ( $\dot{m}$ ) for hydrogen.

whereas Becker and Liang (1978) suggested that for  $1 < \xi_L < 20$  and  $Re_L > 8000$ :

$$\psi = 0.18 + 0.022\xi_L \quad (24)$$

$Re_L$  is the Reynolds ratio at the flame tip and is defined by Becker and Liang (1978). In our experiments it was greater than 15000 in all cases. It can be seen from Figure 6 that the observed value of  $\psi$  is generally greater than the value predicted by Eq. (24). Thus for  $\xi_L > 2$  our flame lengths are shorter than those predicted by Eq. (24) by up to 15%. This may be because of the way the flame lengths were measured. Becker and Liang (1978) took the position of the flame tip to be "the furthest point at which flaming gas was seen to dwell with an appreciable frequency," whereas we identified the tip on still photographs. It could also be due to the difference in entrainment in the near field (Brzustowski 1980) of an attached flame, the case considered by Becker and Liang (1978), and a lifted flame.

However, near the forced convection limit (*i.e.*,  $\xi_L \rightarrow 0$ ) where  $\xi_L < 2$ ,  $\psi$  increases with decreasing  $\xi_L$ . The minimum value of  $\psi$  is about 0.24. In plotting Figure 6, when the burner exit flow is choked, the burner has been replaced by an equivalent convergent-divergent nozzle as indicated in section 2. However, even if we take flow parameters before expansion in such cases (*i.e.*,  $M = 1$  and  $d_e = d_b$ , etc.) to calculate  $\psi$  and  $\xi_L$ , the results are very similar to those plotted in Figure 6 for  $\xi_L < 2$ . Becker and Liang's (1978) theoretical work (see their Eq. (33)) suggests that  $\psi \approx 0.35$  in the forced convection limit. They have also shown that the flame length equations of Hawthorne *et al.* (1949) as well as those of Günther (1966) give  $\psi \approx 0.33$  in the forced convection limit. Our results (Figure 6) are in line with both

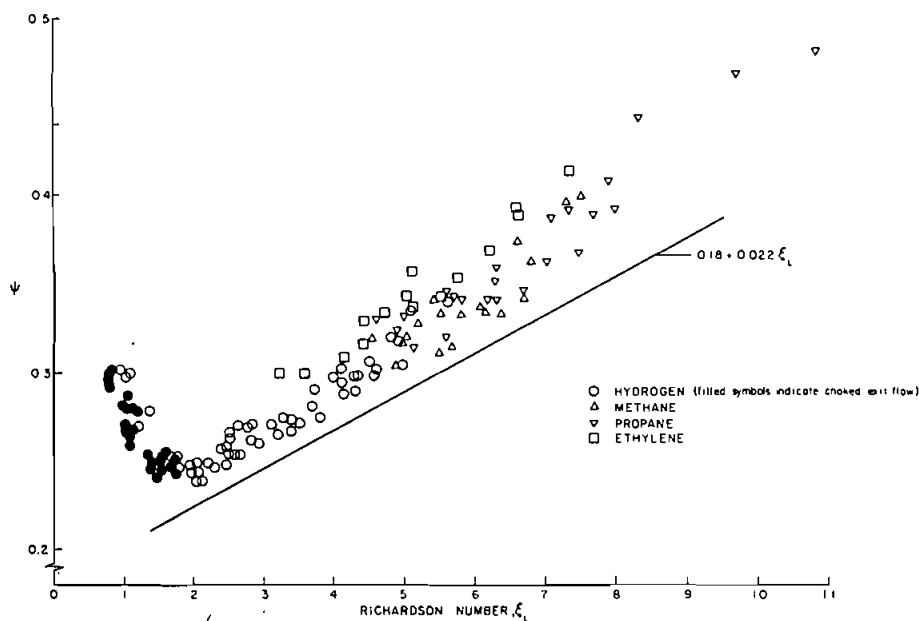


FIGURE 6 Non-dimensional flame length curve for hydrogen, methane, propane and ethylene.

these conclusions. However, Becker and Liang have argued that these equations significantly underestimate flame lengths in the forced convection limit and suggest in their final recommendations that  $\psi \approx 0.2$ , i.e.,  $L \approx (11D_s \beta/W_1)$  in this limit. Our results disagree with this prediction.

## CONCLUSIONS

Experimental results for lift-off heights and visible-flame lengths of jet diffusion flames in still air for hydrogen, propane, methane and ethylene have been presented. The flame lift-off height varies linearly with jet exit velocity and is independent of burner diameter for a given gas. The results support the assumption that if the burner flow is choked, the burner can be approximated by an equivalent convergent-divergent nozzle at whose exit the flow has expanded to ambient pressure. The data for different gases can be collapsed onto a single curve if they are plotted in terms of the appropriate non-dimensional groupings. These results, together with previous results for blow-out stability, suggest that diffusion flames blow out when the base is lifted to between 0.65 and 0.75 times the height at which stoichiometric concentration is reached at the jet axis. It has been deduced that at the base of the flame, the ratio of turbulent burning velocity to laminar burning velocity varies as the square root of the local turbulence Reynolds number based on the integral length scale. The predicted correlation for turbulent burning velocity agrees well with the data presented by Smith and Gouldin (1979) and Andrews *et al.* (1975).

Results for flame length near the forced convection limit are in line with the theoretical work discussed in Becker and Liang (1978), but disagree with their final

recommendations. The results for different gases can be collapsed onto a single curve if they are plotted in terms of the non-dimensional groupings suggested by Becker and Liang (1978).

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