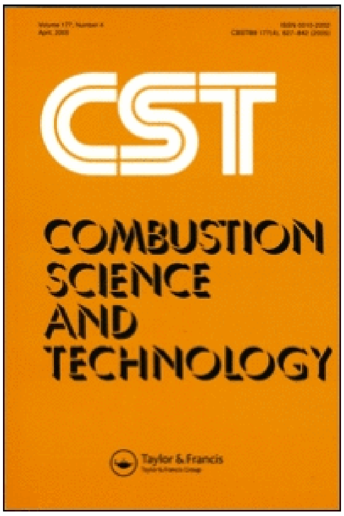

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Blow-Out Stability of Gaseous Jet Diffusion Flames. Part I: In Still Air

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Abstract—A universal non-dimensional formula that describes the blow-out stability limit of gaseous jet diffusion flames in still air has been found experimentally. Its validity has been established over a wide range of parameters that affect the blow-out limit. Its extrapolation to cases where the burner exit flow is choked suggests that for a given gas there is a critical burner diameter above which a stable flame can exist at any flow rate.

1 INTRODUCTION

A jet diffusion flame in still air will lift off the tip of the burner and form a stable lifted flame when the flow rate through the burner is increased beyond a limiting value known as the lift-off stability limit. If the flow rate is increased further, the flame is extinguished at some limiting rate known as the blow-out stability limit. The lift-off stability and the structure of the turbulent lifted diffusion flame in still air have received some attention in the past (*e.g.*, Wohl *et al.*, 1949; Vanquickenborne and Van Tiggelen, 1966; Scholefield and Garside, 1949). The stability of flames of co-flowing streams of hydrogen and air has been studied by Vranos *et al.* (1968). Takeno and Kotani (1975) conducted similar experiments but with the aim of understanding the effect of the temperature of the air stream on the stability of the flame. More recently, Baev and Yasakov (1976) and Annushkin and Sverdlov (1979) have published papers that concentrate on the blow-out stability of diffusion flames. In particular, Annushkin and Sverdlov (1979) propose a semi-empirical formula that can be used to calculate the burner exit velocity at blow-out for different burner diameters for propane, methane and hydrogen. However, the experimental verification provided by them for their predictions is rather limited. Moreover, their formula cannot be used to find the blow-out limits for fuels other than those used by them.

This paper describes the results of a systematic experimental study of the blow-out stability of jet diffusion flames in still air. The fuel gases used are methane, propane, ethylene, acetylene, commercial butanes and hydrogen. Burner diameters range from 0.2 mm to 12 mm. From dimensional analysis, it is possible to identify non-dimensional groupings of the various flow and gas parameters that affect blow-out. An empirical formula in terms of these non-dimensional groupings can be found to describe the blow-out stability limits of all the different gases used. The validity of such a "universal" formula is further confirmed by studying the blow-out of flames of mixtures of methane/air, methane/CO_2, propane/air and propane/CO_2. Finally, an attempt is made to extrapolate these results to cases where the flow at the burner exit is choked at blow-out, by taking into account the expansion of the gases in the supersonic plume that results from such under-expanded sonic jets.

2 THEORETICAL CONSIDERATIONS

At the base of a lifted diffusion flame, the local turbulent burning velocity, S_t, will be equal to the local flow velocity, U. If the flow rate through the burner is increased, U will increase and the base of the flame will be blown downstream to a new position where once again S_t will equal U. The flame will blow out when the change in S_t cannot keep up with the change in U anywhere in the jet as one moves downstream from the base of the flame.

Now let H be the distance along the burner axis where the mean fuel concentration falls to the stoichiometric level. It is very unlikely that the base of the stable, lifted flame will be downstream of this point. H is independent of the burner exit velocity and is given (Birch *et al.*, 1978) by

$$H = \left[4\frac{\bar{\theta}_e}{\bar{\theta}_s}\left(\frac{\rho_e}{\rho_\infty}\right)^{1/2} - 5.8\right] d_e \qquad (1)$$

where d_e is the effective burner diameter, $\bar{\theta}_e$ is the fuel mass fraction at burner exit, $\bar{\theta}_s$ is the fuel mass fraction in the stoichiometric mixture of the fuel and ambient gas, ρ_e is the density of the burner gas at the burner exit and, ρ_∞ is the ambient density. All things being equal, the larger the value of H, the more scope there will be for the base of the flame to seek a new stable position as the burner exit velocity is increased, and the more difficult it will be to blow out the flame. By similar considerations the larger the value of the maximum laminar burning velocity, S_u, of the fuel in a mixture with the ambient gas, the more difficult it should be to blow out the flame, since the maximum turbulent burning velocity will depend on S_u. The turbulent burning velocity will also depend on the local turbulence parameters and the fuel concentration. These in turn will depend on the kinematic viscosity, ν_e, of the fuel gas and the ratio of densities, (ρ_e/ρ_∞), at the exit plane. Therefore, we can expect U_e, the burner exit velocity at blow-out, to depend on H, S_u, ν_e and (ρ_e/ρ_∞). Simple dimensional analysis (*e.g.*, Lydersen 1979) now tells us that

$$\frac{U_e}{S_u} = f\left(R_H, \frac{\rho_e}{\rho_\infty}\right) \qquad (2)$$

where $R_H = (H \cdot S_u/\nu_e)$ is the Reynolds number based on H. We now determine this functional relationship by experiment.

3 EXPERIMENTS

Each burner is a 65 mm long straight tube mounted at the end of a settling chamber whose internal diameter is 152 mm. The gases were supplied from cylinders to the settling chamber through appropriately calibrated rotameters. For high flow rates, these rotameters were bypassed and the pressure in the settling chamber was measured when the flame blew out, using either a water or a mercury manometer. This pressure was taken to be the stagnation pressure, and the Mach number, M, when the gas was expanded to atmospheric pressure was calculated from it. The stagnation temperature, T_0, was assumed to be equal to the ambient temperature, which was taken to be 290 K. In calculating the various flow parameters, the compressibility of the gases was taken into account. The results of experiments using pure fuels are described first.

3.1 *Results for Pure Fuels*

The fuels used, along with their properties, are listed in Table I. In Figure 1, the Mach number, M_b, at the burner exit when the flame blows out is plotted against the burner exit diameter, d_b, for different gases. Of course, M_b is the same as M for subsonic jets. It can be seen that M_b increases

TABLE I
Properties of the gases used in the study

Gas	Purity/ composition, %v	Molecular weight	Dynamic viscosity, μ, at 0° C, micropoises	Maximum burning velocity in air, S_u, m/s	Ratio of specific heats, γ	Mass fraction in stoichiometric mixture with air, θ_s
Methane	99	16	102.7	0.39	1.31	0.055
Propane	99	44	74	0.45	1.13	0.06
Ethylene	95	28	91	0.75	1.255	0.063
Acetylene	95	26	93.5	1.63	1.25	0.07
Hydrogen	99	2	84.2	3.06	1.4	0.028
Commercial butanes	28 isobutane, 42 *n*-butane, 26 propane, 4 other hydrocarbons	54.1	80	0.44	1.1	0.06

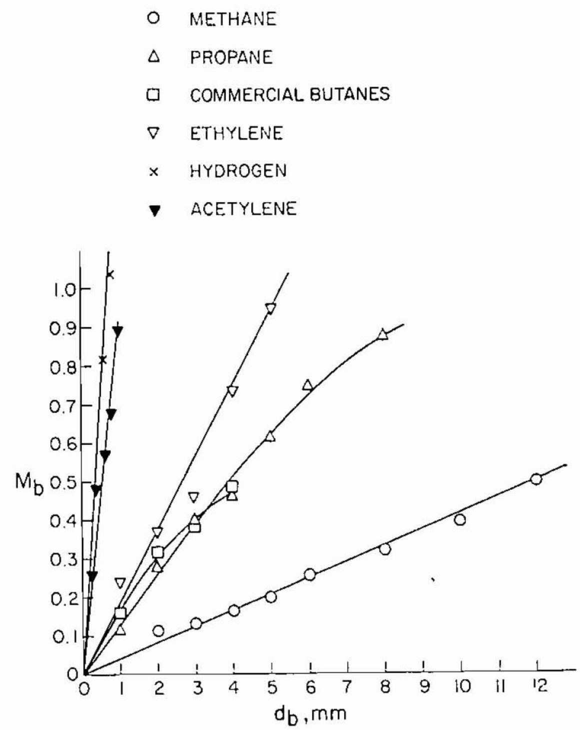

FIGURE 1 Mach number at the burner exit at blow-out.

almost linearly with d_b for all the gases. The same data are shown in Figure 2 as plots of a non-dimensional velocity,

$$\bar{U}_e = \frac{U_e}{S_u}\left(\frac{\rho_e}{\rho_\infty}\right)^{1.5}$$

against the Reynolds number, R_H. It can be seen that the data for different gases collapse onto a single curve given by

$$\bar{U}_e = 0.017 R_H(1 - 3.5 \times 10^{-6}\, R_H) \qquad (3)$$

The validity of this "universal" formula to describe the blow-out limit of jet diffusion flames was further tested by studying the stability of flames of mixtures of gases. These results are discussed below.

3.2 *Results for Mixtures of Gases*

The mixtures used were methane/air, methane/CO_2, propane/air and propane/CO_2. For a given burner diameter, as the concentration of the diluent in the burner gas is increased, the blow-out velocity decreases. This is illustrated in Figure 3, where U_e has been plotted against the concentration of the diluent for different mixtures, for the 5 mm

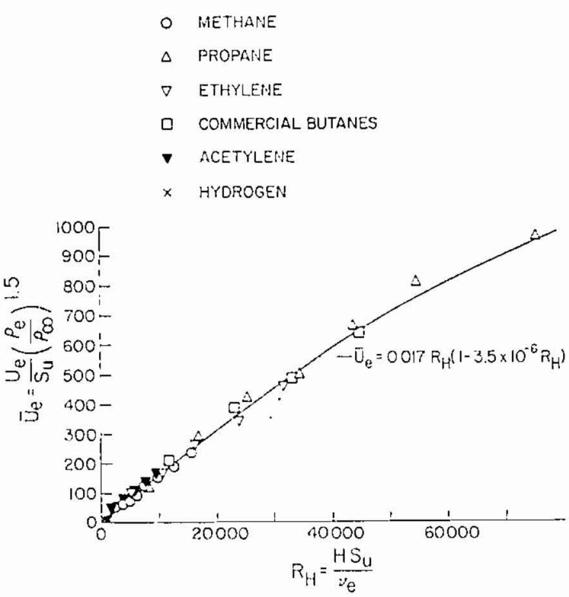

FIGURE 2 The universal blow-out stability curve.

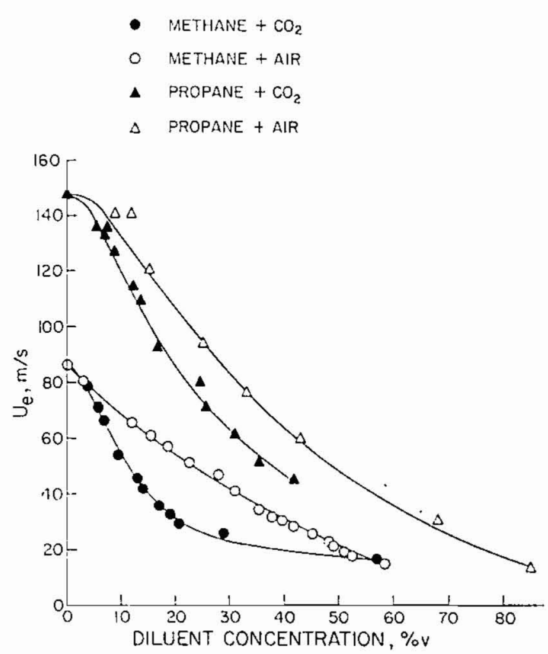

FIGURE 3 The effect of diluents on the burner exit velocity at blow-out. Burner diameter 5 mm.

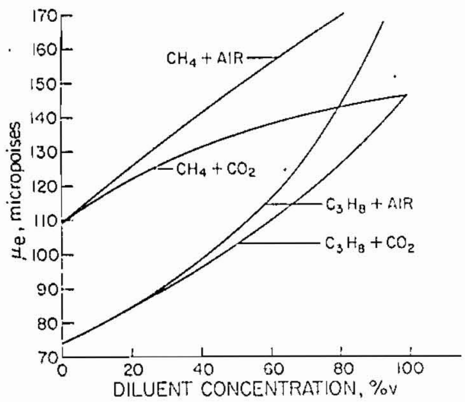

FIGURE 4a Variation of dynamic viscosity (μ_e) with diluent concentration.

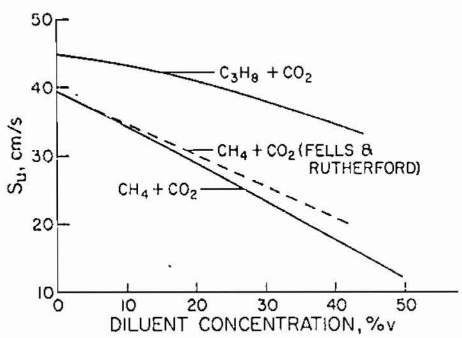

FIGURE 4b Variation of maximum laminar burning velocity (S_u) with diluent concentration.

diameter burner. Similar experiments with mixtures were also conducted using the 3 mm, 4 mm and 6 mm burners.

When air is used as a diluent, the gas properties that change are ρ_e, $\bar{\theta}_e$ and the dynamic viscosity, μ_e. With CO_2 as the diluent, in addition to these properties, S_u also changes. Of these, ρ_e and $\bar{\theta}_e$ can be easily determined as functions of the diluent concentration. μ_e was calculated using the method outlined in Strehlow (1968) and is shown as a function of the diluent concentration in Figure 4a. S_u was calculated for mixtures with CO_2 by the method proposed by Spalding (1956) and Yumlu (1968) and is shown in Figure 4b. Also shown for comparison in Figure 4b is the straight line with the slope proposed by Fells and Rutherford (1969) for methane/CO_2 mixtures based on their experiments, which, it should be pointed out, were done

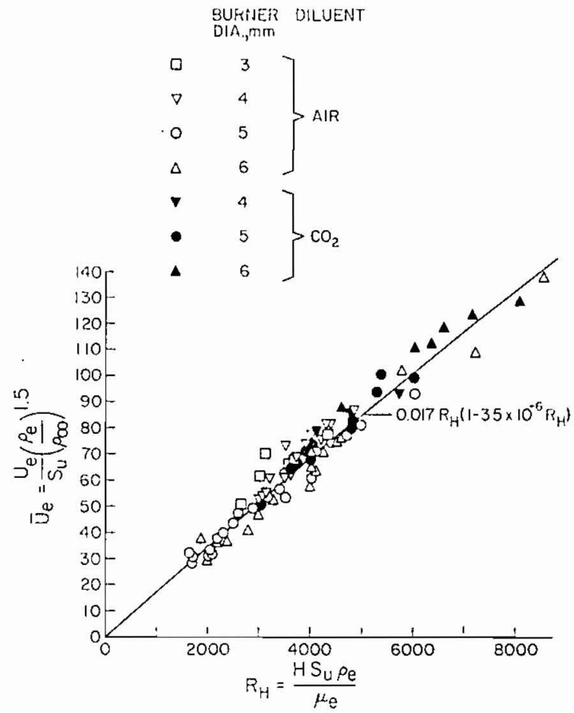

FIGURE 5 The non-dimensional blow-out stability curve for mixtures with methane as the fuel.

for CO_2 concentrations of less than 15 percent. We can now express the results such as those in Figure 3 in terms of $\bar{U}_e$ and R_H. In Figure 5, $\bar{U}_e$ has been plotted against R_H for methane/air and methane/CO_2 mixtures, from which it can be seen that Eq. (3) describes the blow-out limit for these cases, where R_H varies between 1000 and 9000, reasonably accurately. Similarly from Figure 6, where $\bar{U}_e$ has been plotted against R_H for propane/air and propane/CO_2 mixtures, it can be seen that Eq. (3) is valid for $10{,}000 > R_H > 40{,}000$.

Thus the validity of Eq. (3) in describing the blow-out limit of diffusion flames in still air has been established over a wide range of conditions (Figures 2, 5 and 6).

4 EXTRAPOLATION OF THE RESULTS TO CASES WHERE THE BURNER EXIT FLOW IS CHOKED

It can be seen from Figure 1 that as the burner diameter is increased (beyond 5.3 mm for ethylene, for example) the burner exit flow could be choked

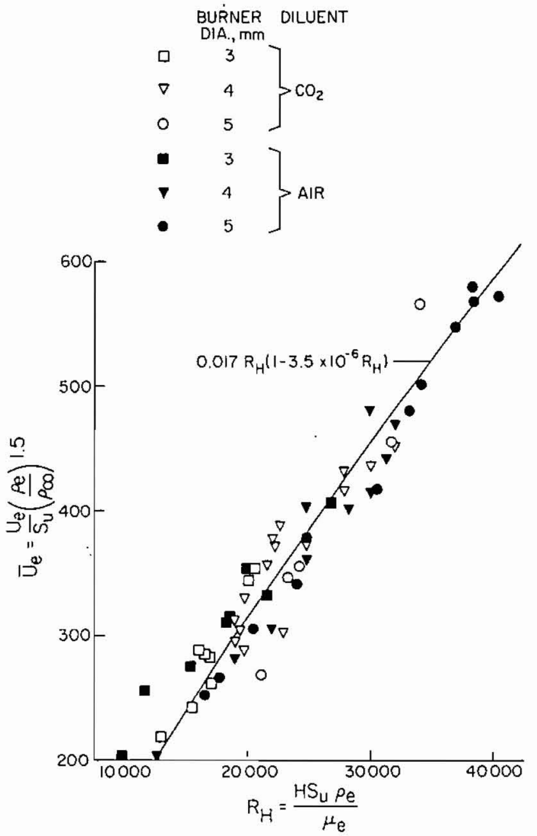

FIGURE 6 The non-dimensional blow-out stability curve for mixtures with propane as the fuel.

and we could still get a stable flame. The structure of the supersonic plume that results from such under-expanded sonic jets has been studied extensively and is rather complicated. However, we assume, as in Annushkin and Sverdlov (1979), that in such cases the burner can be simply replaced by an equivalent convergent-divergent nozzle at whose exit the gas has fully expanded to ambient pressure. The actual burner diameter, d_b, can be related to the diameter, d_e, and the Mach number, M, at the exit of such a nozzle. The result of using this equivalent diameter, d_e, in Eq. (3) is illustrated in Figure 7, where the velocity, U_e, at blow-out at the exit of the equivalent burner is plotted against d_b for acetylene. The point where sonic velocity is reached at the actual burner exit is also marked on the plot, which is a stability envelope outside which stable flames can exist. Thus it can be seen that if d_b is larger than a critical diameter, d_{cr}, which is 1.57 mm for acetylene, this extrapolation predicts that a diffusion flame would be stable at all flow rates. It also shows that for a burner diameter near d_{cr}, stability is restored on increasing the flow rate continuously as we cross the upper branch of the stability envelope. These predictions were first made by Annushkin and Sverdlov (1979) and stem mainly from the fact that the ratio (d_e/d_b) increases with flow rate once the burner exit flow is choked.

Curves similar to that for acetylene have also been plotted for methane, propane and ethylene in Figure 7. The change in the scale on the abscissa is to be noted. For these cases, the computation breaks down if we use Eq. (3) for $R_H>75{,}000$, and in any case, Eq. (3) has only been tested for R_H

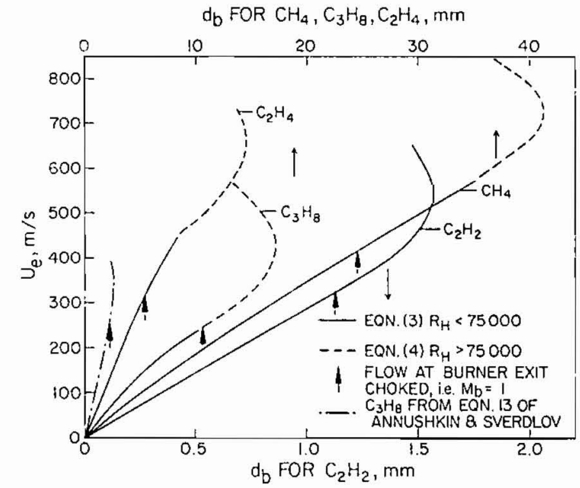

FIGURE 7 Extrapolation of the stability curve to cases where the nozzle exit flow is choked at blow-out.

up to 75,000. Hence we make a further assumption that for $R_H>75{,}000$, the plot in Figure 2 can be extrapolated by a straight line whose slope is the same as that of the curve at $R_H = 75{,}000$, *i.e.*, for $R_H>75{,}000$

$$\bar{U}_e = 335+0.00807\, R_H \qquad (4)$$

With this additional assumption, it can be seen from Figure 7 that d_{cr} for ethylene, propane and methane is, respectively, 14.5 mm, 17.2 mm and 41.4 mm.

Also shown in Figure 7 is the stability curve for propane calculated from Eq. (13) of Annushkin and

Sverdlov (1979), using the values for the gas parameters listed in Table I. It can be seen that it differs considerably from the stability curve for propane, whose validity has been extensively tested in the present work. There is much better agreement for methane between the present work and that of Annushkin and Sverdlov (1979).

It must be emphasized that the extrapolation attempted here is intended to give only a qualitative picture of what to expect regarding the blow-out stability of diffusion flames for large burners. It becomes increasingly difficult to test the curves in Figure 7, especially for methane and propane, after the nozzle exit flow is choked, since the flow rates needed are too large for laboratory-scale experiments. However, there is some anecdotal evidence in the oil and gas industry that for large burner diameters, stable flames can exist for very large flow rates indeed. For instance, a stable flame was observed on top of a 10 cm diameter pipe that was directly connected to a natural gas reservoir with an internal pressure of at least 85 atmospheres.

5 CONCLUSIONS

A universal formula that describes the blow-out stability limit of gaseous jet diffusion flames in still air has been found experimentally. Its validity has been established over a wide range of parameters that affect the blow-out limit. Extrapolation of this formula to cases where the burner exit flow is choked suggests that for a given gas there is a critical burner diameter, d_{cr}, beyond which a stable flame can exist at any flow rate.

NOMENCLATURE

d_b Burner exit diameter.

d_{cr} Critical burner diameter beyond which stable flames can exist for all flow rates

d_e Effective burner diameter
$d_e = d_b$ for subsonic jets

$$d_e = d_b \left[\frac{2+(\gamma-1)M^2}{\gamma+1}\right]^{(\gamma+1)/4(\gamma-1)} M^{-1/2}$$

for choked jets

H Distance along burner axis at which mean fuel concentration falls to stoichiometric level. Equation (1).

M_b Mach number at burner exit at blow-out

M Mach number at effective exit at blow-out. $M = M_b$ for subsonic jets. For choked jets, M, is the Mach number after expansion of the gas to ambient pressure.

R Gas constant

R_H Reynolds number based on H
$\equiv H \cdot S_u/\nu_e$

S_u Maximum laminar burning velocity for a mixture of the burner gas with ambient gas (air).

T_0 Stagnation temperature. Taken to be 290 K, *i.e.*, ambient temperature in this work

$U_e \equiv \sqrt{(\gamma R T_0)} \cdot M(1+(\gamma-1)/2M^2)^{-1/2}$, velocity at effective burner exit at blow-out.

$\bar{U}_e \equiv U_e/S_u(\rho_e/\rho_\infty)^{1.5}$, non-dimensional velocity at blow-out

γ Ratio of specific heats

μ_e Dynamic viscosity at jet exit

$\nu_e \equiv \mu_e/\rho_e$, kinematic viscosity

$\rho_e \equiv \rho_0(1+(\gamma-1)/2M^2)$, density of jet gas at effective jet exit

ρ_0 Density of jet gas at temperature, T_0 and ambient pressure

ρ_∞ Density of ambient gas (air)

$\bar{\theta}_e$ Fuel mass faction at burner exit

$\bar{\theta}_s$ Fuel mass fraction in the stoichiometric mixture of the fuel and ambient gas

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