

SHAPES OF BUOYANT AND NONBUOYANT METHANE LAMINAR JET DIFFUSION FLAMES*

521-25
227358

PETER B. SUNDERLAND[†], Zeng-guang Yuan[†] and David L. Urban
NASA Lewis Research Center
Cleveland, Ohio

Introduction

Laminar gas jet diffusion flames represent a fundamental combustion configuration. Their study has contributed to numerous advances in combustion, including the development of analytical and computational combustion tools. Laminar jet flames are pertinent also to turbulent flames by use of the laminar flamelet concept.

Investigations into the shapes of noncoflowing microgravity laminar jet diffusion flames have primarily been pursued in the NASA Lewis 2.2-second drop tower, by Cochran and coworkers [1, 2] and by Bahadori and coworkers [3-6]. These studies were generally conducted at atmospheric pressure; they involved soot-containing flames and reported luminosity lengths and widths instead of the flame-sheet dimensions which are of greater value to theory evaluation and development.

The seminal model of laminar diffusion flames is that of Burke and Schumann [7], who solved the conservation of momentum equation for a jet flame in a coflowing ambient by assuming the velocity of fuel, oxidizer and products to be constant throughout. Roper and coworkers [8, 9] improved upon this model by allowing for axial variations of velocity and found flame shape to be independent of coflow velocity. Roper's suggestion that flame height should be independent of gravity level is not supported by past or present observations. Other models have been presented by Klajn and Oppenheim [10], Markstein and De Ris [11], Villiermaux and Durox [12] and Li et al. [13]. The common result of all these models (except [12] in the buoyant regime) is that flame height is proportional to fuel mass flowrate, with flame width proving much more difficult to predict. Most existing flame models [7, 9, 10, 12, 13] have been compared with shapes of flames containing soot, which is known to obscure the weak blue emission of flame sheets.

The present work involves measurements of laminar gas jet diffusion flame shapes. Flame images have been obtained for buoyant and nonbuoyant methane flames burning in quiescent air at various fuel flowrates, burner diameters and ambient pressures. Soot concentrations were minimized by selecting conditions at low flowrates and low ambient pressures; this allows identification of actual flame sheets associated with blue emissions of CH and CO₂. The present modeling effort follows that of Roper [8] and is useful in explaining many of the trends observed.

Experimental Methods

The experiments were conducted in a general-purpose combustion rig, consisting of a windowed pressure vessel, a fuel delivery system, an ignitor, a color CCD camera, a microprocessor controller and lead-acid batteries. The fuel jet issued vertically upward on the axis of the cylindrical chamber, whose diameter, length and volume were 25 cm, 53 cm and 27 l, respectively. The burners were straight stainless steel tubes with beveled outside edges and inside diameters of 0.42, 0.85, 1.70, 3.25 and 5.54 mm. The burners had length-to-diameter ratios of at least 40, which ensured fully-developed laminar discharge. The flames were ignited using spring-loaded retracting hot wires (Kanthal A, 0.36 mm) mounted in tension 3 mm above the burners. These wires were 12 mm long and were energized with 28 VDC, causing them to glow and rupture within 30 ms. Following ignition, the ruptured wires retracted symmetrically with minimal flow disturbance.

On-board methane (purity 99.99%) was stored in a 75 ml bottle and delivered to the burner via, in order, a pressure regulator, a solenoid valve, an orifice, a mass-flow meter, and a second solenoid valve. Orifice diameters were varied from 0.03-0.07 mm to ensure choked flow. Fuel flowrates were determined using the in-line mass flow meter (Omega FMA-5606-ST), which was calibrated for each fuel using a bubble meter. The pair of solenoid valves minimized diffusion of air into the fuel delivery plumbing prior to release into microgravity and allowed for optimization of the timing and volume of the initial fuel

* Presented at the Third International Microgravity Combustion Conference, May 19-21, 1997.

[†] National Research Council

[‡] NYMA Inc.

flow. Room air was used as the ambient for conditions at or below 1 atm; a mixture of 21.1% O₂, balance N₂, was used for the 2 atm flames.

The flames were imaged using a color CCD camera (Panasonic WV-CL352) mounted 27 mm from and perpendicular to the chamber axis. Fixed-iris lenses were used, with focal lengths (16-50 mm) chosen according to flame size, and f-numbers (1.4-6) chosen according to illumination levels. For flames containing soot, an additional camera was utilized behind a CH-line filter. Signals from the cameras were carried via fiber-optic cable to a stationary SVHS video recorder.

The conditions for the present flames are summarized in Table 1. Nomenclature is as follows: p is ambient pressure, d is burner diameter, L is the distance from the burner lip to the flame sheet intersection with the axis and w is the maximum flame width. Reynolds number is defined as $Re = \rho_0 v_0 d / \mu_0 = 4 \dot{m} / \mu_0 d$, where ρ is density, v is average velocity, μ is dynamic viscosity, $\dot{m}$ is fuel mass flowrate and subscript 0 refers to fuel-inlet conditions. The normal-gravity flames were restricted to steady-state, nonflickering conditions. The microgravity flames were ignited immediately following release into microgravity. Uncertainties in the measurements are estimated to be 5% for fuel flow rate and for dimensions of the small or low-pressure flames and 20% for the dimensions of the other flames, which contained soot and required judicious estimation of flame sheet locations.

Analytical Model

The Roper model [8] was selected here because of its unique attributes, specifically its pertinence to noncoflowing conditions, its lack of assumptions regarding buoyancy levels and its ability (demonstrated here for the first time) to predict full shapes. Seeking generality, Roper used Cartesian coordinates. We briefly present the derivation in cylindrical coordinates since the present flames are axisymmetric. Roper [8] invokes several assumptions, including: axial diffusion may be neglected, temperature, velocity and mass diffusivity (T , v and D) may vary with height but are uniform at any given height, and combustion causes no change in number of molecules. Conservation of species then yields:

$$v_r(r, z) \frac{\partial C(r, z)}{\partial r} + v_z(z) \frac{\partial C}{\partial z} - \frac{D}{r} \frac{\partial}{\partial r} \left(r \frac{\partial C}{\partial r} \right) = 0 \quad (1)$$

where r , z , v_r and v_z are the radial and axial coordinates and velocities, D is mass diffusivity, $C = (f - f_a) / (f_0 - f_a)$, $f = nX_f - X_{O_2}$, subscripts a and 0 indicate ambient and initial fuel conditions, X is mole fraction, and n moles of O₂ react stoichiometrically with one mole of fuel (F). The boundary conditions on Eq. 1 are $C(r, 0) = 1$ for $r < d/2$, where d is the burner diameter, $C(r, 0) = 0$ for $r > d/2$, and $C \rightarrow 0$ in the far field. The following transformation is now introduced to convert r and z to the new coordinates η and θ :

$$t(z) = \int_0^z \frac{dz}{v_z}; \quad \eta(r, z) = \frac{r}{r_D(z)}; \quad \frac{d \ln r_D}{dt} = \frac{v_r}{r}; \quad \theta(t) = D \int_0^t \frac{dt}{r_D^2} \quad (2)$$

Variables t and r_D are the elapsed residence time on the flame axis and the characteristic scale of diffusion. Eq. 1 becomes:

$$\frac{\partial C(\eta, \theta)}{\partial \theta} = \frac{1}{\eta} \frac{\partial}{\partial \eta} \left(\eta \frac{\partial C}{\partial \eta} \right) \quad (3)$$

subject to boundary conditions $C(\eta, 0) = 1$ for $\eta < 1$ and $C \rightarrow 0$ in the far field. The solution to Eq. (3) is:

$$C(\eta, \theta) = \frac{e^{-\frac{\eta^2}{4\theta}}}{4\theta} \int_0^1 e^{-\frac{\eta_1}{4\theta}} I_0 \left(\frac{\eta \sqrt{\eta_1}}{2\theta} \right) d\eta_1 \quad (4)$$

where I_0 is the modified Bessel function of first kind of order 0. This equation is called the P-function [13, 14]. Note that buoyancy, fuel flowrate, pressure and burner diameter do not appear in Eq. 4, thus permitting integration prior to specification of these quantities. We have solved Eq. 4 numerically using Romberg integration and Newton-Raphson root-finding, and contours for $C = 0.095$, 0.056 and 0.040 (corresponding to CH₄, C₂H₆ and C₃H₈ stoichiometric locations) are shown in Fig. 1. Although these curves bear resemblance to laminar jet diffusion flame shapes, determination of true shapes requires converting η and θ to real-world coordinates using the relations [8]:

$$r_D = \frac{d}{2} \left(\frac{v_0 T_f}{v_z T_0} \right)^{1/2} = \left(\frac{\dot{m} T_f}{\pi \rho_0 v_z T_0} \right)^{1/2}; \quad \theta = \frac{4 D T_0}{d^2 v_0 T_f} z \quad (5)$$

where T_f is the temperature at which diffusion is assumed to occur. This conversion requires knowledge of flame temperatures and axial velocity profiles. The above relations for r_D lend valuable insight into flame width behavior, as discussed below.

Results and Discussion

Figs. 2a and 2c show one buoyant and one nonbuoyant methane flame at otherwise identical conditions. The normal-gravity flame is a nonflickering flame shown in steady state; the microgravity flame, typical of those in this study, is nearly steady at the end of its 2.2-second duration. The color video from which these images was produced reveals a familiar appearance in the buoyant flame; it has a bright blue flame sheet, a dim blue interior and a small yellow tongue of soot just inside the flame tip. The nonbuoyant flame in Fig. 2c is longer, broader and dimmer than its buoyant counterpart. A faint blue flame sheet is barely visible on its periphery, but the flame is generally violet. This violet coloration is attributed to combined blue emissions from CH and CO₂ and dim orange emissions from low concentrations of soot at low temperatures.

Lengths of the present buoyant and nonbuoyant flames are normalized by burner diameter and plotted versus Re in Fig. 3. The buoyant and present nonbuoyant flames exhibit best-fit slopes of 1.06 and 0.86, respectively, but are fit here with unit-slope lines in accordance with theory [8, 10, 11, 13]. This unit slope reflects the observation that for both buoyant and nonbuoyant flames, $L \sim \dot{m}$ with a negligible dependence upon pressure and diameter. The nonbuoyant flames are generally longer than corresponding buoyant flames, but the two regimes converge at the large Re because nonbuoyant flame development time increases with Re and thus the present high-Re microgravity flames are smaller than their steady-state shapes.

The shown fit of present nonbuoyant flames is 64% higher than the normal-gravity fit, and the Roper model is useful in explaining this. Although the model predicts length to be independent of axial velocity for fixed $\dot{m}$ (leading Roper to question the model's ability to explain the observed difference in lengths) it also predicts that lengths scale with $T_f^{-0.67}$. Thus the considerably lower temperatures of nonbuoyant flames [6] reduce diffusion rates and are responsible for the increased lengths. The fits shown in Fig. 3 correspond to the Roper prediction using T_f values for the buoyant and nonbuoyant flames of 2690 K and 1370 K (in contrast to the 1500 K initially used in Ref. 9). Here we have invoked the relation $D \sim T_f^{1.67}/p$, where $D=20 \text{ mm}^2/\text{s}$ at 1 atm and 300 K [9]. Although these derived temperatures are a crude representation of actual flame temperatures, they are reasonable in light of the assumptions in the model.

Also shown in Fig. 3 are previous measurements [2, 4, 5] of microgravity methane flames. Reynolds numbers for these data have been corrected to the d length scale considered here. Note that these flames are at relatively high pressure and Re and thus contain significant amounts of soot; this, and the fact that only luminosity lengths were reported, explains why the unit-slope fit through these data lies 25% above the fit of present nonbuoyant lengths.

Widths of the present flames are shown in Fig. 4, including least-squares fits (with slopes of 0.52 and 0.22) of the present buoyant and nonbuoyant flames. The previous data shown [2, 5] agrees with present nonbuoyant observations because even in sooty flames, maximum luminous widths nearly coincide with maximum flame-sheet widths. Widths of both buoyant and nonbuoyant flames increase with Re, in contrast to past predictions of constant widths [10] and of widths that decrease with Re [3]. The fit of the buoyant flames yields $L/w \sim \text{Re}^{0.5}$, which is Blasius boundary-layer behavior. The slope of the nonbuoyant-flame fit is lower, possibly another indication of underdeveloped shapes at the highest Re. The relation in Fig. 4 of $w/d \sim \text{Re}^n$, where n is between 0 and 1, captures the increase in w with $\dot{m}$ and d that is observed for both buoyant and nonbuoyant flames. However, additional correlations are being sought because this relation fails to reflect the decrease of widths with pressure in buoyant flames that has been observed here and elsewhere [15].

The major phenomenological findings of present flame widths are: nonbuoyant flames are wider than their buoyant counterparts; widths increase with $\dot{m}$ and d ; and buoyant flame widths decrease with pressure whereas nonbuoyant flame widths show no statistically significant variation with pressure. The analysis of Roper [8] is of assistance in interpreting many of these observations, referring to Eq. 5. Note that width is proportional to r_D and that these quantities are referred to interchangeably in this discussion. For changes in buoyancy, $r_D^2 \sim T_f/v_z$; the reduced velocities in microgravity flames more than compensate for the reduced temperatures to yield flames which are wider than in normal gravity. For pressure variations, $r_D^2 \sim v_0/v_z$, which explains observed width behavior; for buoyant flames this ratio increases as pressure decreases, and it is feasible that for nonbuoyant flames v_0/v_z is nearly independent of pressure. For changes in burner diameter, $r_D^2 \sim 1/v_z$; increasing burner size increases width via an decrease in v_z for both buoyant and nonbuoyant flames. An explanation for the increase of width with fuel flowrate is not as readily provided by Eq. 5. This issue, and quantitative explanation of the other width observations, may be possible following implementation of axial velocity profiles into the Roper model.

As mentioned earlier, we have used the Roper model to predict entire flame shapes, and predictions corresponding to the buoyant and nonbuoyant flames of Figs. 2a and 2c are shown in Fig. 2b. These contours were obtained using the same D as

before and T_f of 2690 K and 1370 K for the buoyant and nonbuoyant flames. These temperatures were obtained in the above discussion of Fig. 3 and ensured that the predicted buoyant and nonbuoyant heights would roughly agree with observations. For the normal-gravity prediction, it was assumed $v_z=v_0$ at all locations in the flame. This is a reasonable approximation of axial velocities in low-pressure flames that first decrease and later increase via buoyancy [16]. For the microgravity prediction, it was assumed that $v_z=v_0/8$ since this best matched the observed flame width. It is expected that $v_z<v_0$ in microgravity flames but no measurements are available to validate the ad hoc divisor of 8 adopted here. Unrestrained variation of T_f and v_z allows the Roper model to match any observed flame shape; although the choices made here are reasonable, an improved determination of values for these parameters is being sought.

Acknowledgments

This work was aided by helpful discussions with G. M. Faeth, H. R. Ross, V. Nayagam and I. Wichman. This work was supported under a NASA/NRC postdoctoral fellowship and was performed at NASA Lewis. The drop tests were conducted by B. M. Mendelson.

References

1. Haggard, J. B. and Cochran, T. H., *Combust. Sci. Technol.* 5:291 (1972).
2. Cochran, T. H., "Experimental Investigation of Laminar Gas Jet Diffusion Flames in Zero Gravity," NASA TN D-6523, (1972).
3. Edelman, R. B. and Bahadori, M. Y., *Acta Astronautica* 13:681, (1986).
4. Bahadori, M. Y. and Stocker, D. P., "Oxygen-Concentration Effects on Microgravity Laminar Methane and Propane Diffusion Flames," Combustion Institute Eastern States Meeting, 1989.
5. Bahadori, M. Y., Edelman, R. B., Stocker, D. P. and Olson, S. L., *AIAA J.* 28:236 (1990).
6. Bahadori, M. Y., Stocker, D. P., Vaughan, D. F., Zhou, L. and Edelman, R. B., in *Modern Developments in Energy, Combustion and Spectroscopy*, (F. A. Williams et al., eds.), Pergamon Press, 1993, p. 49.
7. Burke, S. P. and Schumann, T. E. W., *Ind. Eng. Chem.* 20:998 (1928).
8. Roper, F. G., *Combust. Flame* 29:219 (1977).
9. Roper, F. G., Smith, C. and Cunningham, A. C., *Combust. Flame* 29:227 (1977).
10. Klajn, M. and Oppenheim, A. K., *Nineteenth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, 1982, p. 223.
11. Markstein, G. H. and De Ris, J., *Twentieth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, 1984, p. 1637.
12. Villiermaux, E. and Durox, D., *Combust. Sci. Technol.* 84:279, (1992).
13. Li, S. C., Gordon, A. S. and Williams, F. A., *Combust. Sci. Technol.* 104:75 (1995).
14. Masters, J. I., *J. Chem. Phys.* 23:1865 (1955).
15. Yuan, T., Durox, D. and Villiermaux, E., *Combust. Sci. Technol.* 92:69, (1993).
16. Sunderland, P. B. and Faeth, G. M., *Combust. Flame* 105:132 (1996).

TABLE 1

Summary of Test Flames

Buoyancy	p, bar	d, mm	Re	L, mm	w, mm	# Flames
Nonbuoyant	0.25	1.7	28-116	9-45	14-25	3
	0.49	0.85-1.7	28-123	11-53	10-23	5
	0.98	0.42-3.3	15-601	9-51	5-20	18
Buoyant	0.25	1.7-5.5	8-233	6-60	7-15	11
	0.49	0.85-5.5	5-152	3-27	4-12	19
	0.98	0.42-5.5	3-358	1-36	2-8	24
	1.97	0.42-5.5	2-472	1-30	1-5	19

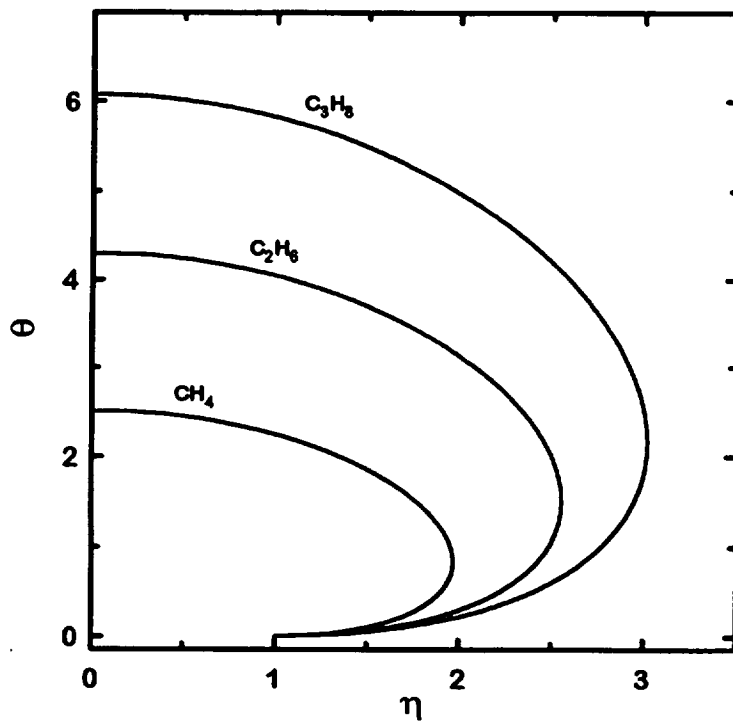


Fig. 1. C contours from Eq. 4.

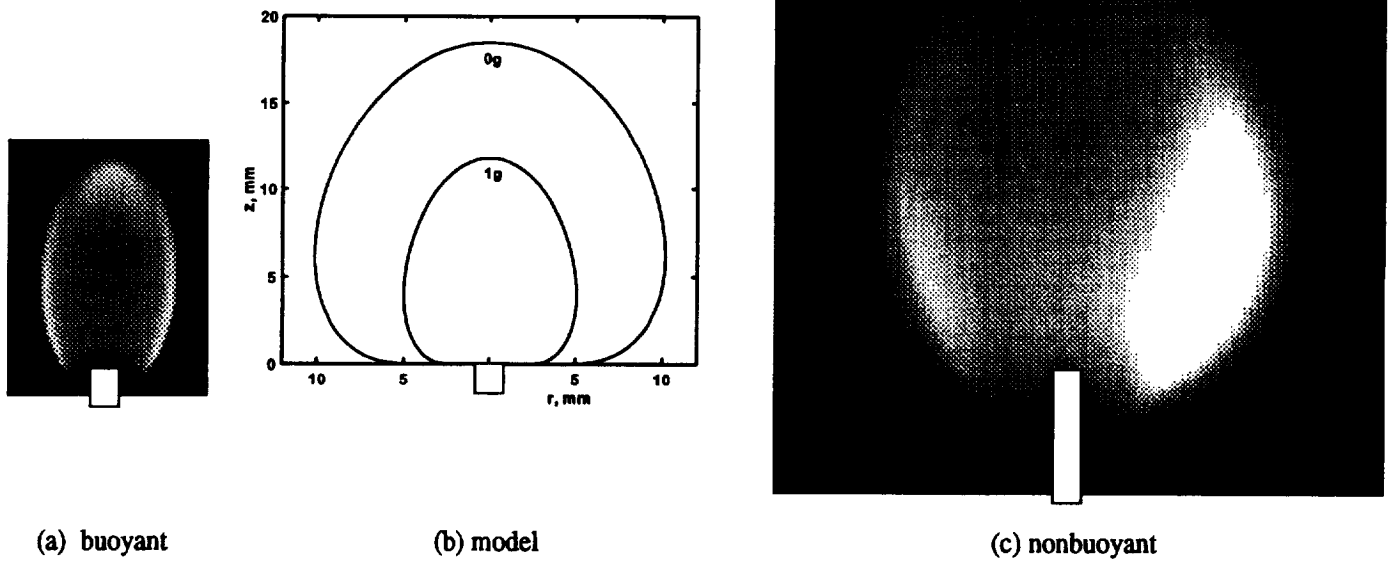


Fig. 2. Images of buoyant and nonbuoyant flames and model results. All images are at the same scale, with burner locations shown. Conditions are methane fuel, $\dot{m} = 0.83$ mg/s, $d = 1.7$ mm, $p = 0.25$ atm and $Re = 56$.

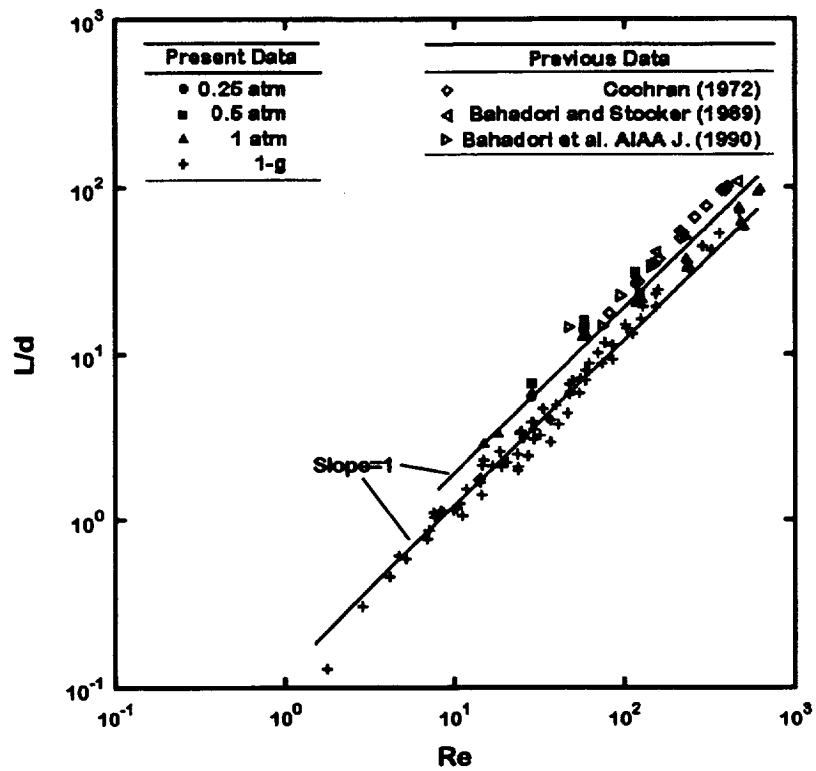


Fig. 3. Methane flame lengths.

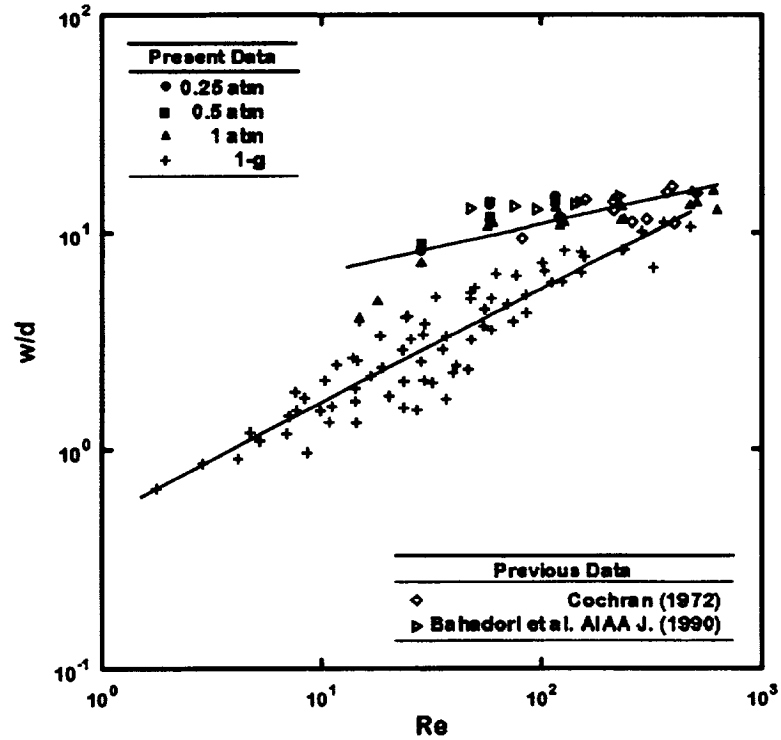


Fig. 4. Methane flame widths.