SUPPRESSION OF SOOT FORMATION AND SHAPES OF LAMINAR JET DIFFUSION FLAMES

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INTRODUCTION

Laminar nonpremixed (diffusion) flames are of interest because they provide model flame systems that are far more tractable for analysis and experiments than practical turbulent flames. In addition, many properties of laminar diffusion flames are directly relevant to turbulent diffusion flames using laminar flamelet concepts. Finally, laminar diffusion flame shapes have been of interest since the classical study of Burke and Schumann (ref. 1) because they involve a simple nonintrusive measurement that is convenient for evaluating flame shape predictions. Motivated by these observations, the shapes of round hydrocarbon-fueled laminar jet diffusion flames were considered, emphasizing conditions where effects of buoyancy are small because most practical flames are not buoyant.

Earlier studies of shapes of hydrocarbon-fueled nonbuoyant laminar jet diffusion flames considered combustion in still air and have shown that flames at the laminar smoke point are roughly twice as long as corresponding soot-free (blue) flames and have developed simple ways to estimate their shapes (refs. 2-5). Corresponding studies of hydrocarbon-fueled weakly-buoyant laminar jet diffusion flames in coflowing air have also been reported, see refs. 6 and 7 and references cited therein. These studies were limited to soot-containing flames at laminar smoke point conditions and also developed simple ways to estimate their shapes but the behavior of corresponding soot-free flames has not been addressed. This is unfortunate because ways of selecting flame flow properties to reduce soot concentrations are of great interest (refs. 8 and 9); in addition, soot-free flames are fundamentally important because they are much more computationally tractable than corresponding soot-containing flames. Thus, the objectives of the present investigation were to observe the shapes of weakly-buoyant laminar jet diffusion flames at both soot-free and smoke point conditions and to use the results to evaluate simplified flame shape models. The present discussion is brief, see refs. 9 and 10 for complete details.

SOOT FORMATION IN COFLOWING JET DIFFUSION FLAMES

Soot-free diffusion flames can be achieved by subjecting fuel jets to strong air coflow similar to air atomization processes (refs. 9 and 10). This can be seen from the sketch of a nonbuoyant coflowing laminar jet diffusion flame appearing in Fig. 1. The figure shows the flame sheet, the soot formation region at fuel-rich conditions, the soot oxidation region at fuel-lean conditions and flow streamlines. Later results will show that the length of the flame sheet is set by the fuel flow rate independent of coflow velocity at large coflows which implies that residence times for soot formation are inversely proportional to the air coflow velocity. Thus, increasing the coflow velocity inhibits soot formation and eventually leads to the soot-free flames that were sought during the present study.

EXPERIMENTAL METHODS

Measurements were carried out in a windowed chamber at low pressures to minimize effects of buoyancy. A coaxial tube burner was used, directed vertically upward, with fuel flow along the axis.

THEORETICAL METHODS

Simplified analysis of flame shapes for flames in still gases (ref. 4) was extended to treat coflow (ref. 7) assuming steady axisymmetric nonbuoyant flow, negligible radiation, thin flame sheet, equal mass diffusivities and specific heats of all species, boundary layer flow and constant properties. This yields the following expression for flame length, L_f, relative to a virtual origin, L_o (ref. 7):

$$(L_f - L_o)/d = C_f C_n Re\, Sc/Z_{st} \tag{1}$$

where d = burner diameter, Re = burner Reynolds number, Z_{st} = stoichiometric mixture fraction and C_n = 3/32 and 2/32 for weak and strong coflow and C_f = 1/2 and 1 for soot-free and laminar smoke point flames. See ref. 7 for the formulation for flame shape and the algorithm for computing flame properties.

RESULTS AND DISCUSSION

Laminar Soot Points. The variation of the laminar soot-point and lift-off conditions, as a function of fuel and air flow rates and pressure, are illustrated in Fig. 2 for ethylene/air flames; results for other fuels were similar. The results show that increasing the air coflow velocity progressively increases the laminar soot-point fuel flow rate until the lift-off limit is reached. Increasing pressure, however, reduces the effect of coflow velocity because effects of buoyancy intrude and modifies the flow to enhance soot formation. Increasing pressure also increases the coflow velocity at lift off. Taken together, it is clear that coflow extends the range of soot-free operation, particularly when effects of buoyancy are small.

Luminous Flame Lengths. Measurements and predictions of luminous flame lengths for weakly-buoyant flames in strong coflow and for nonbuoyant flames in still air are illustrated in Fig. 3. Results are shown for both soot-free and smoke-point flames. It is clear that Eq. (1) provides excellent correlations of flame lengths conditions that are considered.

Shapes of Soot-Free Flames. Some measured and predicted luminous flame shapes in strong coflow are illustrated in Fig. 4. Two sets of measurements are shown: (1) colored photographs of the outer boundary of the strong blue reaction zone (involving CO_2 and OH emissions at fuel-lean condition), and (2) colored photographs taken with a filter for the CH line whose outer boundary should be close to the flame sheet. Both measurements yield similar results which are in remarkably good agreement with predictions. Similar results were obtained at other flame conditions, see ref. 10.

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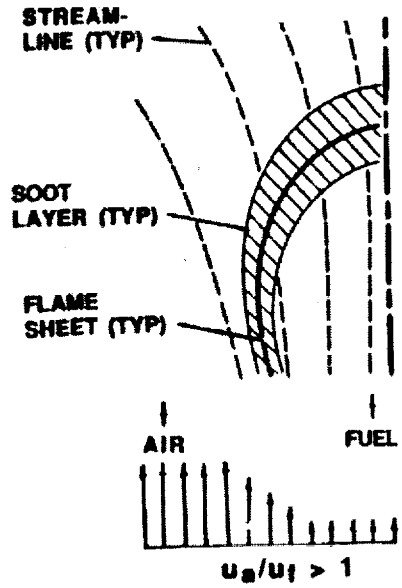

Fig. 1. Effect of reactant stream velocities on soot properties in laminar coflowing jet diffusion flames having uniform initial air and fuel velocities.

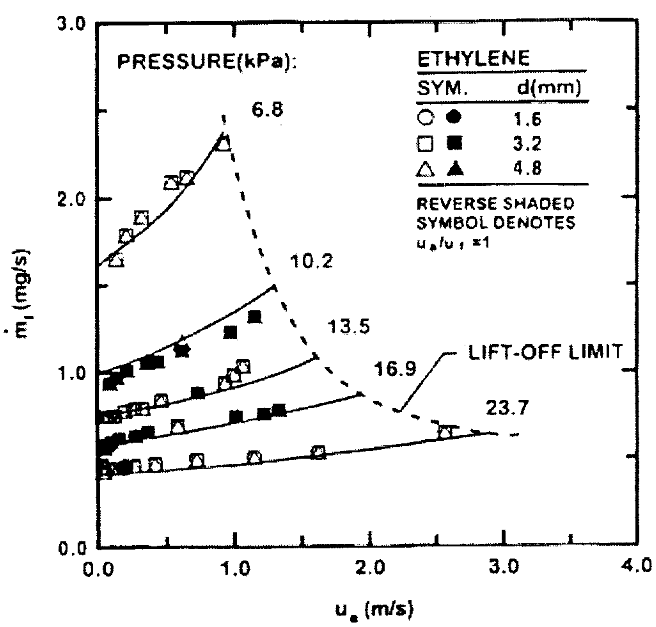

Fig. 2. Fuel flow rates at laminar soot-point and lift-off conditions for ethylene-fueled laminar jet diffusion flames in coflowing air.

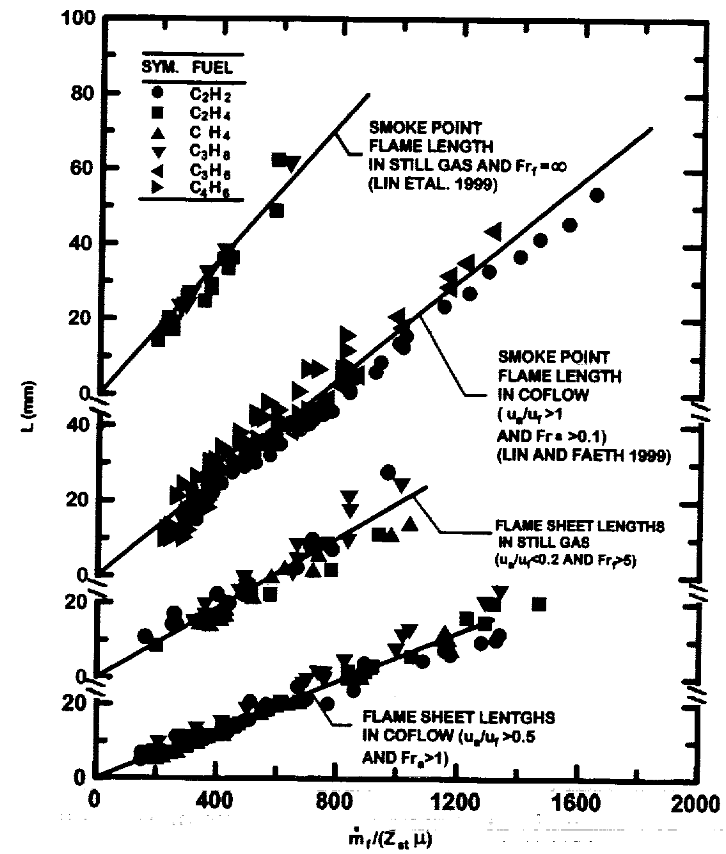

Fig. 3. Flame-sheet and luminous flame lengths (the latter at the laminar smoke point) of laminar jet diffusion flames in still air and in coflowing air.

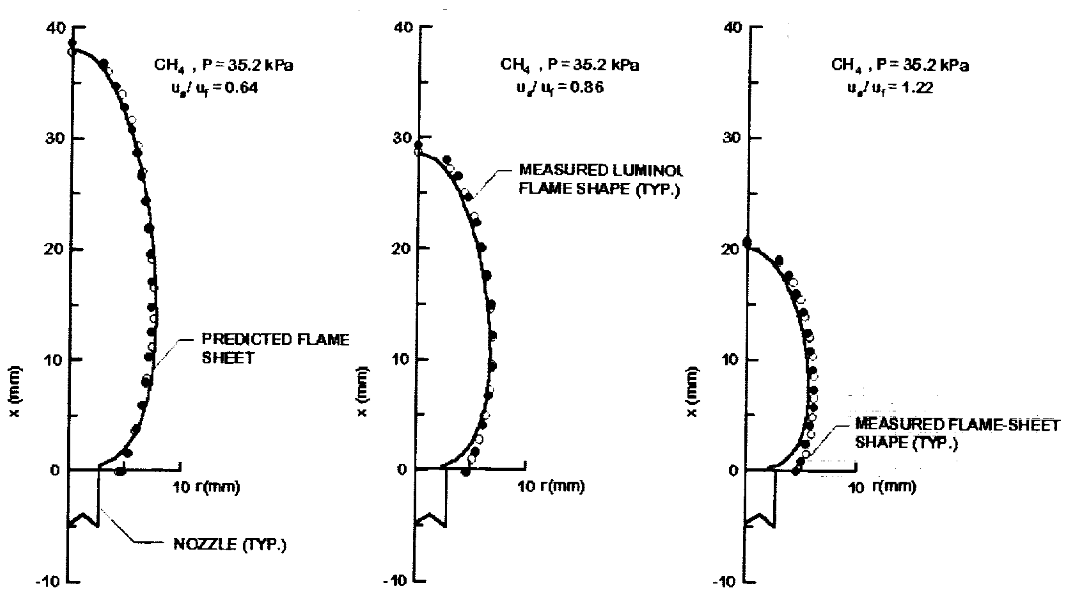

Fig. 4. Measured flame-sheet and luminous flame shapes and predicted flame-sheet shapes for soot-free methane-fueled laminar jet diffusion flames having a burner diameter of 4.3 mm for various air coflow velocity ratios.