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DETERMINATION OF THE STRAIN IN COUNTERFLOW DIFFUSION FLAMES FROM FLOW CONDITIONS

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Introduction

Opposed jet diffusion flames have long been used to test flammability of various fuel/oxidizer systems (e.g. [1]), and more recently to evaluate fire suppressants (e.g. [2]). An experimental configuration of fuel impinging upon air to which a suppression agent has been added is a good approximation of most types of fire suppression. Opposed jet flames constitute one of the simplest experimental configurations in which the extinction of nonpremixed flames can be measured. Extinction occurs when fuel and oxidant flow rates are increased above certain values. An intuitive interpretation of this phenomenon is that the flame is blown out when chemical reactions can not occur fast enough to maintain a sufficient pool of reactive species against the flow of incoming reactants The change of the extinction condition when a fire suppression agent is added is indicative of the degree to which the agent slows down the overall flame reaction rate by, for instance, cooling the flame or depleting the pool of radicals necessary for combustion.

The extinction condition may be characterized by the flow rates of fuel and oxidizer that cause the flame to extinguish. Such parameters, however, are not intrinsic properties of the fuel/oxidizer system under study, but are particular to a given experimental apparatus. A more fundamental quantity, the oxidant-side velocity gradient upstream of the flame, or strain, is used in order to facilitate comparisons between different laboratories using different experimental configurations. The inverse of the strain is a natural time scale for the flow in this configuration, and, under various assumptions, the strain at extinction can be shown to be proportional to the global reaction rate [3]. Thus, for example, the effectiveness of a suppressant additive in reducing the global reaction rate can be ascertained simply by observing the corresponding changes in the extinction strain.

The strain that is typically quoted for an opposed-jet flame is the maximum velocity gradient along the jet axis on the air side of the stagnation plane, which generally occurs just upstream of the flame. Strain is determined experimentally by mapping the velocity field of the jet using techniques such as laser-Doppler anemometry, and taking the derivative of the velocity along the jet centerline. The extinction strain can then be approximated by extrapolating measured strains to the extinction condition [2]. LDV measurements are quite time consuming, and for many fire suppressants, the presence of particulates or soot hampers optical diagnostics from being performed in the flame environment. Therefore, it is desirable to be able to determine the strain from the more easily measured fuel and oxidant flow rates.

Two expressions, corresponding to different assumptions about the jet exit velocity conditions, have been proposed to estimate the strain based on the compositions and flow rates of the two reactant streams. Such calculated strains neglect the effects of chemistry and temperature variation, and are referred to as "global strains." Two cases for the flow geometry are typically encountered experimentally. If the two jets are formed from long straight tubes with no obstructions, the axial velocity profile at the tube exit as a function of radial position follows a parabolic profile, which produces a radially diverging flow downstream of the tube exit. This configuration is often modeled by imposing a potential flow solution as the boundary condition. If on the other hand the axial velocity profile is radially uniform across the tube exit (usually achieved experimentally by screens or by converging nozzles), the flow does not diverge downstream of the tube exit, and is modeled as plug flow. In practice, flow fields have been found to be

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between these two idealizations for both converging nozzles and straight tubes[1,2].

Equation 1 gives an expression for strain for the parabolic flow case. This expression represents a potential-flow solution, in which the strain is uniformly distributed from the tube exit to the stagnation plane, whose position is given by the relative momenta of the two jets:

$$a_g = \frac{2V_{ox}}{L}\left(1 + \frac{V_f^2\rho_f}{V_{ox}^2\rho_{ox}}\right) \qquad (1)$$

where a is the strain, V the mean axial velocity at the tube exit (the centerline velocity is 2V), ρ the gas density, and L the tube separation. Subscripts g, f, and ox refer to global, fuel, and oxidant, respectively. In the case of plug flow, Seshadri and Williams[4] have derived the following expression for the velocity gradient near the stagnation plane:

$$a_g = \frac{2V_{ox}}{L}\left(1 + \left(\frac{V_f^2\rho_f}{V_{ox}^2\rho_{ox}}\right)^{1/2}\right) \qquad (2)$$

We compare the predictions of these formulas to experimental data in order to determine their accuracy and applicability for a variety of flow conditions.

Experimental Procedure

The opposed jet burner apparatus used for this study consists of two tubes with 1 cm ID, separated by 1 cm. The flow velocity profile at the tube exit is nearly parabolic in the absence of a flame, but is flattened somewhat when a flame is present. The fuel/oxidizer systems studied were methane/air and propane/air. The usual experimental protocol is to maintain the luminous zone midway between the tubes. Since the stoichiometric mixture is less that 0.5 for both fuels, the location of the flame is to the air side of the stagnation plane; the distance between the flame and stagnation plane diminishes as the strain rate increases.

All flames studied were at atmospheric pressure. The tubes are mounted vertically. For methane/air, the fuel enters through the top tube. The luminous zone of the methane/air flame is a nearly flat disc. For low-strain propane/air flames, using the bottom tube for the air flow produces a nearly flat flame, similar to that of methane. At high flow rates, however, the propane/air flame in this configuration tends to become unstable, possibly due to the relative buoyancies of the fuel and air tending to make the flame unstable. Flowing the air through the top tube generates a curved, bowl-like flame. Although this configuration is less one-dimensional, it is more stable at high strain rates. The methane flame with the air entering through the top tube has a similar appearance.

Laser-Doppler velocimetry (LDV) measurements using a QSP Digital instrument were performed on the air side of the propane/air flames in both configurations, and of the methane/air flame with the fuel entering through the top tube. Laser scattering was generated by 0.3 μm alumina particles seeded into the air stream. Measured velocity profiles were fit to a polynomial function. The derivative was determined analytically from the fitting function, and the maximum value of the derivative was taken as the experimental strain.

Comparison of Different Fuels

Fig. 1a shows the experimental strain as a function of the oxidizer volumetric flow rate. Plotted in the figure are data for methane and for propane in both configurations (fuel in top tube, air in bottom tube, and vice-versa). For all three sets of data, the relationship between the oxidizer flow rate and the strain is nearly identical. This is a useful result, since it says that flames of different fuels which have identical air stream flow rates will have nearly identical strains.

The nearly identical regression between the methane and propane data is probably a consequence of the mean molecular weight of the air stream and the location of the flame being identical for the two fuels. The flame position is slightly to the oxidant side of the stagnation plane; the offset will be a function of the strain (lower strain causes a bigger offset), and the diffusivity of the fuel (a lighter fuel with a higher diffusivity causes a bigger offset). Comparing methane and propane fuels, methane has a diffusivity about 60% higher. Keeping the reaction zone midway between the tubes, the diffusivity will tend to keep the stagnation plane farther from the air inlet for methane than for propane at

a given strain. On the other hand, the stoichiometric mixture fraction of propane in air is somewhat lower than that of methane. Assuming that the flame will be located near the position where the local mixture fraction is stoichiometric, we see that the two effects tend to cancel. In Fig. 1a, the net effect of these two factors is not distinguishable outside the uncertainty of the strain measurements in comparing the two fuels. For most other light hydrocarbons, one would expect the near cancellation of these two effects to also take place, resulting in very similar relationships between strain rate and flow rate. For fuels such as hydrogen, which has a dramatically different diffusivity, the relationship between oxidizer flow rate and strain rate may be quite different.

Correlation between Experimental Strain, Global Strain, and Oxidizer Flow Rate

In Figs. 1b and 1c, the experimental strain is plotted against the global strain calculated by Eqns. (1) and (2). Using either formula, the calculated strain is considerably lower than the experimental value. However, the relationship between measured strain and global strain calculated using Eqn. (2) has the merit of an intercept that is indistinguishable from zero to within the uncertainty of the fit. Thus, for Eqn. (2), we can write:

$$a_{actual} = 1.60\ a_{calc}. \qquad (3)$$

where the constant of proportionality was determined from a linear curve fit that passes through the origin (not shown). This proportionality makes Eqn. 2 very useful for comparing the effect of inhibitors. Because the ratio of inhibited to uninhibited global strain is the same as the same ratio for measured strain, it should be possible to dispense with velocity measurements in measuring the impact of an inhibitor on the global reaction rate.

Effect of Changing Composition of the Oxidizer Stream

In all of the data presented above, the mean molecular weight of the air stream was constant. Many fire suppression agents, however, are several times more dense than air. In the concentrations needed to extinguish a low strain flame (typically 5-10% by volume, depending on the agent), the effect of the agent on the relationship between flow rate and strain rate must be considered. Eqns. (1) and (2) take fluid densities into account, and thus relationships such as those shown in Figures 1b and 1c can be used with variable-composition air streams. In order to use a relationship between measured strain and oxidant flow rate, however, one must decide whether to express strain as a function of volumetric flow rate (as shown in Fig. 1a), mass flow rate, or momentum flux. As long as ρ_{ox} does not vary, the three formulations are equivalent. We have taken some preliminary data in methane/air flames inhibited with 1,1,1,2,3,3,3-heptafluoropropane in order to investigate which relationship gives the minimum error as the air stream gas density varies.

In Table 1 results are given for three flow conditions in flames containing 3.85% by volume heptafluoropropane. The three inhibited flames are compared to an uninhibited flame; the three sets of flow conditions were chosen to match the air stream volumetric flow rate, mass flow rate, and momentum flux, respectively, as the uninhibited flame. The flame with the same volumetric flow rate appears to give the value of strain that is closest to that of the uninhibited flame. However, the differences in strain for the three conditions are comparable to the repeatability of the measurements, as indicated by the three values obtained in the case in which momentum flux is matched. For many agents, particularly those which can extinguish the flame at fairly low concentrations, it thus appears that the effect of the variation of the air stream density is of marginal statistical significance. For agents such as SF_6 which have higher molecular weights but lower inhibition efficiencies, the variation is likely to be larger.

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Table 1. Strain measured in methane/air flames with and without 3.85% by volume heptafluoropropane in the air side.

Flame condition	measured strain (s^{-1})
Uninhibited	115
Match mass flow rate to uninhibited case	103
Match momentum flux to uninhibited case	97, 99, 115
Match volumetric flow rate to uninhibited case	123

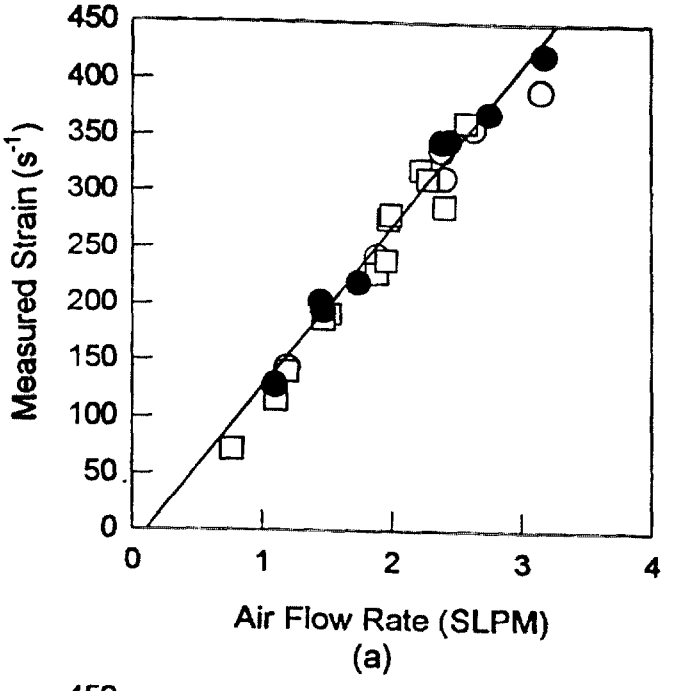
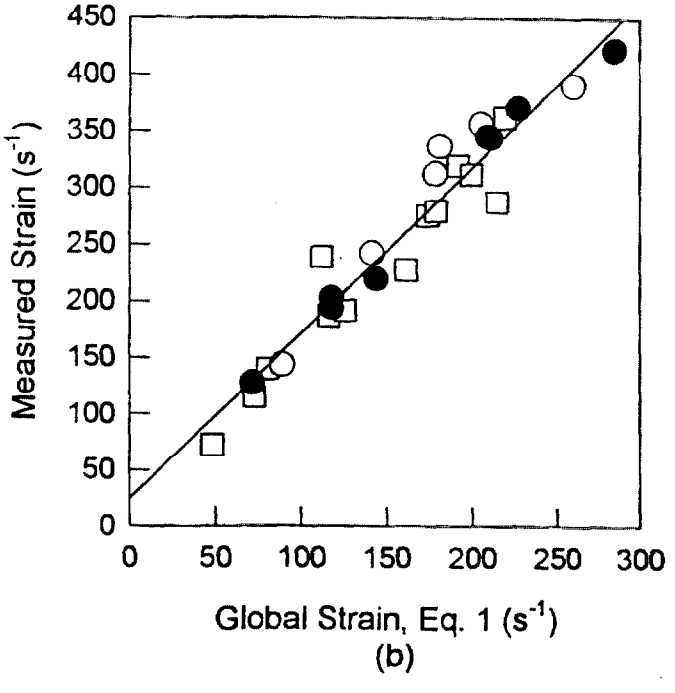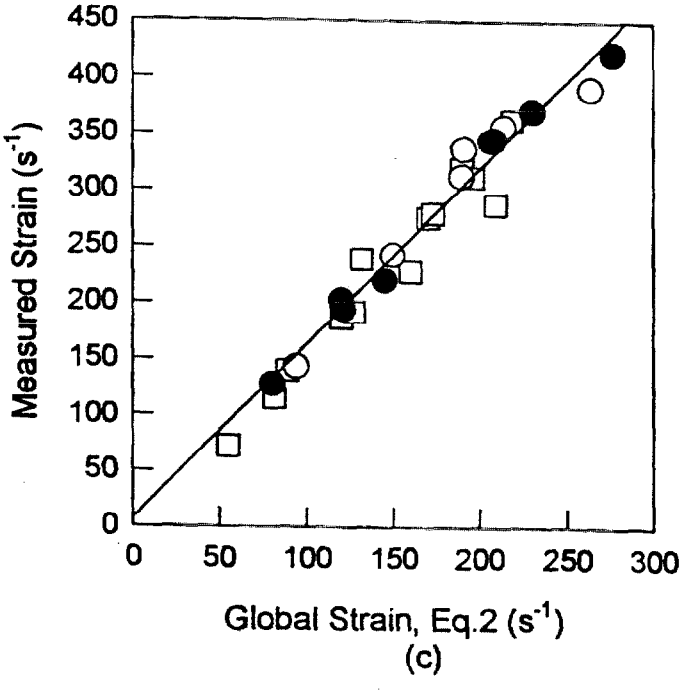
Figure 1. Measured strain as a function of (a) oxidant volumetric flow rate, (b) global strain, Eqn. 1, and (c) global strain, Eqn. 2. Squares represent methane/air flames with methane on the top; closed circles represent propane/air flames with propane on the top; open circles represent propane/air flames with air on the top.