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Brief Communications

Quenching limits of inverse diffusion flames with enriched oxygen

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ABSTRACT

Quenching limits of laminar axisymmetric inverse diffusion flames were observed. Oxygen/nitrogen mixtures were injected into hydrocarbons at 1.01 bar. The limits are correlated with scaling that includes the premixed flame quenching distance and the proportionality between diffusion flame length and oxidizer flow rate. The quenching limit flow rates scale approximately with oxygen mole fraction raised to the −1.53 power and increase slightly with burner diameter. The quenching limit heat release rates are on average twice those of corresponding normal flames.

1. Introduction

Firefighters that carry enriched oxygen in their breathing apparatus benefit from longer working times and improved physical performance [1–3]. However, this introduces the hazard that enriched oxygen could leak into an underventilated fire. Personnel injury and equipment damage may occur if a leak can support a flame.

An inverse diffusion flame involves an oxidizer jet surrounded by fuel. These flames have unusual sooting behavior [4–7] and shapes [4,5,7–9]. Spherical inverse flames have yielded insight into soot formation and flame quenching [10,11].

A quenching limit is the condition of a gas jet diffusion flame whereby any reduction in flow rate causes extinction. Extensive quenching limits of normal flames are available [12–16] and have applications to fuel system safety [17] and microcombustor design [13,18–20]. Only one past study, of limited scope, has reported quenching limits of inverse flames [21].

2. Scaling model

Past studies proposed that normal diffusion flames quench when the stoichiometric flame length, L_{st}, decreases to half the associated premixed flame quenching distance, L_q [15], or to the flame standoff distance [13]. Ref. [15] proposed

$$\dot{m}_q = L_q/2A, \quad (1)$$

where $\dot{m}$ is the burner mass flow rate, subscript q denotes quenching, and A is the coefficient of proportionality between L_{st} and $\dot{m}$.

Quantity L_q is the minimum separation between parallel walls for which a flame can propagate [22–24]. Quenching diameters in round tubes are typically 50% larger [25]. The dead space (the closest approach of a premixed flame to a wall) is about $0.1L_q$ [26,27]. The available measurements in both air and enriched oxygen were correlated here to obtain $L_q = 0.267X_{O2}^{-1.258}$, $L_q = 0.190X_{O2}^{-1.207}$, and $L_q = 0.218X_{O2}^{-1.324}$, for methane [28,29], ethylene [25], and propane [29,30], respectively, where X_{O2} is oxygen mole fraction in the oxidizer.

Several measured L_{st} of inverse diffusion flames are available, but generalized correlations do not exist. Thus published L_{st} for 21 inverse flames were correlated here with $\dot{m}$, for methane [5], ethane [4], and ethylene [5], obtaining $A = 0.550$ m s/g. The inclusion of the available measurements [4] involving enriched oxygen is noteworthy. Past work found L_{st} for normal flames to be independent of the flow rate of diluent into the fuel [31–33], but did not consider the high temperatures and mass diffusivities of Ref. [4].

3. Experimental

Oxidizer was supplied via round stainless steel burners with inside diameters of 0.75, 1.53, 3.02, and 4.56 mm and outside diameters of 1.6, 1.97, 4.04, and 6.38 mm, respectively. The burners had blunt ends, except that the 0.75 mm burner had a knife edge. Fuel was supplied via a concentric 100 mm honeycomb port. The fuel was then confined by a 155 mm long cylindrical glass chimney with a diameter of 100 mm. The chimney top was sealed with aluminum foil with a 13 mm round hole on axis. The oxidizers were O_2/N_2 mixtures with X_{O2} of 0.21–1 and the fuels were methane, ethylene, and propane. The reactant flow rates were controlled

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with metering valves and measured with calibrated rotameters. Ambient conditions were 1.01 bar and 25 °C. A still digital camera recorded color images.

The fuel flow rate (4 mg/s) was 5–10 times stoichiometric at the quenching limits, and its variation had a negligible effect on the limits. Ignition was with a retracting hot wire. The oxidizer flow rate was reduced gradually until quenching was detected visually in the darkened laboratory, and was then increased to confirm extinction. At least four repeats were averaged at each condition. The estimated uncertainty in the quenching flow rates is ±10%. Additional details are in Zhang [34].

4. Results and discussion

Figure 1 shows representative flames slightly above their quenching limits. Figure 1a illustrates the effect of burner diameter, *d*. For these reactants $L_q = 0.68$ mm, yielding an expected 1.0 mm quenching diameter [25]. Figure 1b illustrates the effect of increasing X_{O2}. Figure 1c illustrates the effect of fuel type. The relatively short L_q for ethylene/air [25] explains why here only the ethylene flame descends into the burner.

For 18 of the tests the flames remained attached above the burner before quenching. These generally involved burners with inside diameters below $1.5L_q$. In the other 10 tests, the flames descended into the burner before quenching.

Figure 2a shows that $\dot{m}_q$ scales approximately with $X_{O2}^{-1.53}$. This does not quantify the effect of *d*, collapse the fuels, or test Eq. (1). This is addressed in Fig. 2b, whose axes come from Eq. (1). The prediction of Eq. (1), also shown, overpredicts the measurements by an average factor of 1.8 but captures the overall trend. A similar overprediction was found for normal flames [15]. These overpredictions arise because *A* increases near quenching [13,14] and because dead space (if available) would decrease the predicted L_{st} at quenching.

The 10 descended flames are indicated with arrows in Fig. 2b. These correlate with the attached flames, as was previously observed for normal flames [15]. The scaling of Eq. (1) reasonably captures the behavior of descended flames, probably because the oxidizer leakage fraction exceeds that required for combustion [11,35] when the descended flame extent (represented by $A\,\dot{m}_q$) matches the quenching distance (represented by $L_q/2$).

The ability of Eq. (1) to account for X_{O2} and *d* was evaluated by correlating $\dot{m}_q\,A/L_q$ with X_{O2} and *d*. Eq. (1) fully accounts for the decrease of $\dot{m}_q$ with X_{O2}. There was a small increase in $\dot{m}_q\,A/L_q$ with increasing *d*, as was observed for normal diffusion flames [13,15]. This is attributed to increased heat losses with larger burners [15].

Lecoustre et al. [16] observed quenching limits of normal hydrogen diffusion flames issuing into oxygen with heat release rates as low as 0.25 W. The range of heat release rates for the quenching limits of Fig. 2 are 0.8–5.3 W. These average twice those of corresponding normal flames [15], which is attributed to the increased stoichiometric lengths of inverse flames for corresponding reactants and heat release rates.

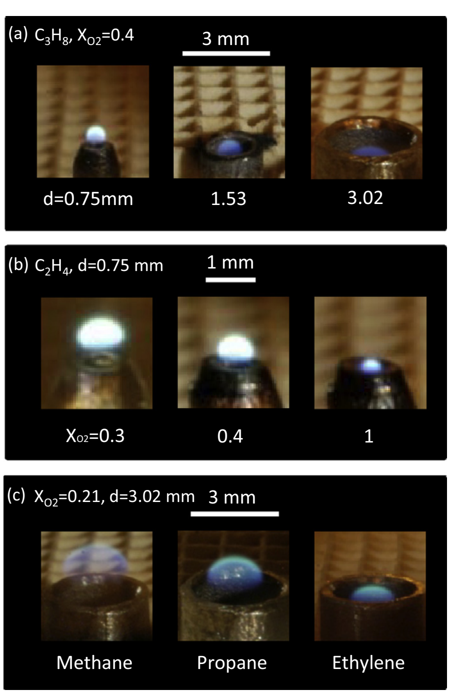

Fig. 1. Color images of inverse flames slightly above their quenching limits.

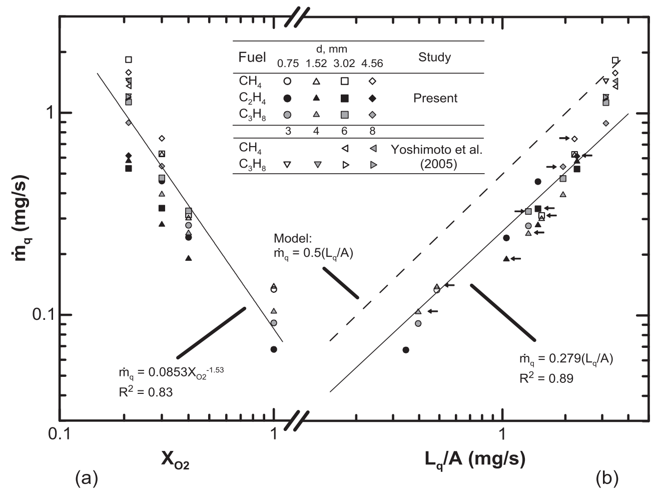

Fig. 2. (a) Quenching mass flow rate plotted with respect to X_{O2} for the 28 present measurements and the 6 measurements of Ref. [21]. (b) Quenching mass flow rate plotted with respect to L_q/A, where $A = 0.550$ m s/g. Arrows denote flames that descended into the burner before quenching.

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