

Dependence of Limiting Oxygen Index of Buoyant Turbulent non-premixed Flame on Fuel

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1 Introduction

The effectiveness of a gaseous agent on the fire suppression is quantified as the lowest oxygen concentration that will support combustion of a fuel, or limiting oxygen index (LOI). LOI has been measured for both the laminar and turbulent diffusion flames. For the laminar flame, different styles of flame was studied for their LOI. Shown in Table 1, opposed flow diffusion flames were used to assess the LOI [1-4]. Since a laminar counterflow diffusion flame can be established in the stagnation region, this approach can avoid thermal quenching of burner. Simmons and Wolfhard [1] investigated the LOI of diffusion flames of various fuels burning in oxygen/nitrogen mixture oxidized using an opposed flow, porous hemisphere burner, and showed that LOI reduces as the degree of unsaturation of fuel is increased. This suggests that the controlling factor of LOI may be the limiting flame temperature. Ishizuka and Tsuji [2], Puri and Seshadri [4], Pitts et al. [3] showed the similar findings using an opposed flow burner, and LOI increased with elevated strain rate of flame.

Table 1. Limiting Oxygen Index of Diffusion Flames Burning Different Fuels

	Methane	Propane	Ethylene	Reference
Opposed flow flame	0.139	0.127	0.105	[1]
	0.143			[2]
	0.139	0.127		[3]
	0.150	0.137		[4]
Coflow flame		0.141		[5]
		0.140		[6]
	0.153	0.140		[7]
	0.167	0.150		[3]
Turbulent flame (non-anchored)	0.152	0.139		[8]
Turbulent flame (anchored)	0.122	0.122		[8]

Cup burner was also widely used to examine LOI of fire-fighting agents [5-7]. Shown in Table 1, LOI of the same fuel measured using a cup burner is higher than those measured using an opposed flow diffusion flame, as a result of heat loss to burner rim. Therefore, LOI measured using a cup burner may be affected by the cup diameter, which changes the portion of heat loss to the burner [9]. What is more, different from an opposed flow diffusion flame, a flame generated from a cup burner is a co-flow system and the flame strain rate is difficult to evaluate. Nevertheless, LOI of methane is higher than those of propane, consistent with the measurements of the opposed flow diffusion flame. The measurements from a Santoro burner [3] are higher than those from cup burner, as a result of that the Santoro burner has a stainless steel tube body, and smaller diameter than that of cup burner. These factors potentially increased heat loss of the Santoro burner and contributed to a higher LOI [3].

Recently, White et al. [10] and White [8] extended the LOI measurement into turbulent flames generated from a turbulent line burner with a co-flow of air mixed with varying levels of nitrogen dilution. For the non-anchored condition, extinction of turbulent flame occurred from the burner rim blow-off. Therefore, the measured LOI values of methane and propane are similar to those from cup burner, see Table 1. In the anchored condition, turbulent flame was anchored by a surrounding oxygen flow anchor to prevent liftoff extinction. Therefore, the LOI measured in the anchored condition more closely reflects the global extinction limit of turbulent flame. The LOIs measured in this fashion are lower than those from unanchored condition and laminar flame.

The current study aims to expand LOI measurement of low strain, buoyant, turbulent flames of fuels with different saturation levels, including methane, propane, ethylene, and propylene. For this purpose, a newly-developed compartment facility provided a well-controlled burning environment. The characteristics of flame burning in the reduced oxygen environment leading to extinction condition were measured and reported.

2 Experimental

Global flame characteristics including combustion efficiency, LOI were measured on axisymmetric, buoyant, turbulent pool-like diffusion flames. A schematic of the experimental apparatus is shown in Figure 1. A water-cooled enclosure provided control of ambient O_2/N_2 concentration ratio and minimized the ambient draft disturbances that may contribute to a less quiescent environments. Air plus added nitrogen was supplied by gas reservoirs and controlled by rotameters at about 10 times the stoichiometric oxidant requirement of the flames. Air and nitrogen was mixed in a static mixer (Koflo 1.5-40-6-2) before being supplied to the enclosure. The enclosure has a cross section of $1.22 \times 1.22 \text{ m}^2$, and a height of 1.83 m. The mixed oxidizer was supplied to the lower chamber of enclosure through a distribution box. Uniform ambient flow was achieved by passing the oxidizer through a plenum followed by several screens and a layer of 25.4 mm fine sand. During a test, the air flow rate was fixed, the enclosure oxygen concentration was continuously monitored and controlled by adjusted nitrogen flow rate.

The gaseous fuel was supplied from a steel round burner of 15.2 cm in diameter; uniform exit velocities over the burner surface were ensured by using two layers of coarse and fine sand (2.54 and 5.08 cm thickness, respectively). The fuel flow rate was maintained constant by a mass flow controller (Sierra C100M-DD-3-OV1-SV1-PV2-S0). With the reduction of ambient oxygen concentration, the flame with a relatively small heat release rate tends to blow off before the global extinction, as a result of heat loss to the burner. Such extinction is not desirable as it does not represent the typical extinction behavior encountered in large-scale fire suppression. Therefore, the flame base near burner needs to be compensated for such a heat loss, e. g. White et al. [10] used the oxygen injection near the burner rim. In

the current work, the flame was anchored by 36 pre-mixed ethylene/air pilot flames surrounding the burner. Each premixed flame was adjusted to be approximately 2.5 cm long. The total heat release rate of pilot flames is approximately 1 kW.

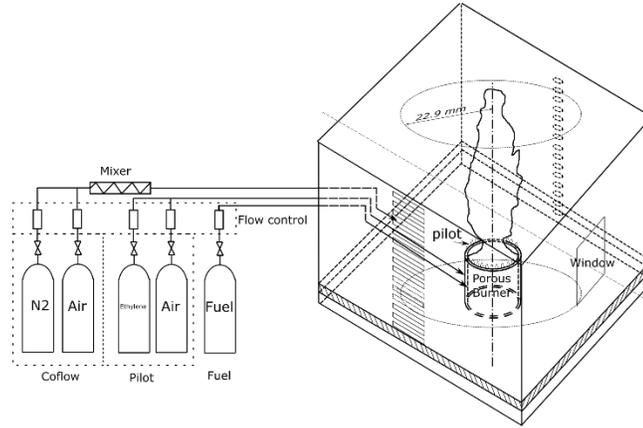


Figure 1. Schematic of the apparatus and instrumentation.

A characterization test was conducted to verify that the oxygen concentrations of co-flow surrounding the flame were maintained at the prescribed level. The oxygen concentration at the heights above the burner of 5.1, 30.5, 55.9, and 81.3 cm, and the radial distance of 22.9 cm from burner axis was measured for a steady state flame similar to those examined in the test. The sampling locations virtually encapsulated the largest size of flames encountered in the study and represented the co-flow environment of flame. The steady state oxygen concentrations of these locations were consistent, within a 1.3% difference from the corresponding oxygen concentration in the inlet condition. This indicated that the co-flow and enclosure system effectively controlled the oxidizer environment and that ambient air infiltration had a negligible effect on flame.

The water-cooled enclosure was positioned under a fire products collector (FPC). The calorimetry measurements were conducted in the same fashions as those in the Fire Propagation Apparatus test [11, 12]. The combustion efficiency is evaluated by:

$$\chi = \frac{\dot{Q}_c}{\dot{m}_f \Delta H_c} \quad (1)$$

where \dot{m}_f is the fuel flow rate (g/s), ΔH_c is the theoretical heat of combustion (kJ/g), and \dot{Q}_c is the chemical heat release rate (kW),.

3 Results and Discussion

The experimental results are reported and discussed here. Variation of combustion efficiency and LOI with oxygen concentration in oxygen/nitrogen environment are first reported. The combustion efficiency of four gaseous fuels shows a slow reduction with a decreased oxygen concentration in the co-flow environment, then quickly reduces in the global extinction stage. A comparison of the LOIs of these fuels shows: $CH_4 > C_3H_6 > C_3H_8 > C_2H_4$. This trend is rationalized using the opposed-flow diffusion flames calculation results.

The left panel of Figure 2 shows the variation of combustion efficiency (χ) of buoyant turbulent ethylene diffusion flames with decreased oxygen concentrations in the oxygen/nitrogen mixture environment. The theoretical heat release rate of all test conditions were maintained at 10 kW. For ethylene, χ is 0.86 in air environment. χ decreases slightly from 0.86 to 0.8 on average when the oxygen concentration decreases from air condition to 11 vol%. The further decrease of oxygen concentration is accompanied by a drastic reduction of χ . During this stage, the flame becomes increasingly unstable and the upper part of flame shows the extinction behavior. The error bar shown in Figure 2 is the standard deviation of time series of χ , which increases in the global extinction stage as a result of unstable flame. χ reduces to 0.12 at the oxygen concentration of 8.2 vol%, which is lower than the LOI values of the other fuels, as shown in the right panel of Figure 2. The LOI values based on the χ trend with oxygen concentration, are 12.1, 11.2, 10.3, and 8.2 vol% for CH_4 , C_3H_6 , C_3H_8 , and C_2H_4 respectively. For all the fuels examined herein, χ values show a similar trend with that of ethylene that χ reduces slowly before quickly decrease when the oxygen concentration reaches close to the LOI value.

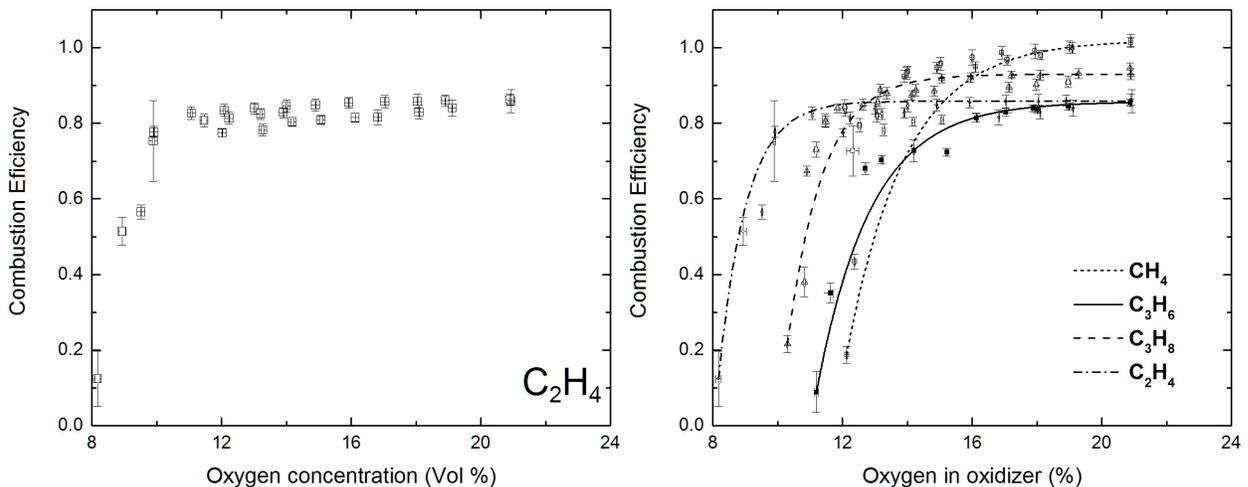


Figure 2. Left: combustion efficiency of buoyant turbulent ethylene diffusion flame under different oxygen/nitrogen mixture environment; right: comparison of combustion efficiency of four gaseous fuels.

Flame extinction of diffusion flame can be attributed to 1. Dilution of thermal agent; 2. Heat loss such as convective or radiative heat loss; 3. Stretch or compression of flame sheet due to varying local strain rate [13]. The heat loss or added thermal agent can cause the chemical reactions to slow down and ultimately unable to sustain flaming condition. Flame with a lower strain rate has a thicker fuel/oxidizer interface and therefore more residence time that can result in a more sustainable flame. Inversely, a higher strain rate diffusion flame reduces the interface thickness and leads to a weaker flame more prone to extinct. The effect of dilution and strain rate on extinction can be illustrated using the laminar diffusion flame

calculation results in the similar fashion with Pitts et al. [3]. The simulation was carried out using the Cantera opposed-flow diffusion flame model [14]. A detailed reaction kinetic mechanism, GRI-Mech 3.0 [15], was applied for CH_4 , C_3H_8 , and C_2H_4 fuels in the simulation. The detailed reaction mechanism from Qin et al. [16] was applied for C_3H_6 . The left panel of Figure 3 shows the maximum flame temperature of C_2H_4 diffusion flame in oxygen/nitrogen opposed flow with different oxygen concentrations and strain rates. The strain rate on the x-axis is evaluated with the mean axial velocity gradient. Oxygen concentration was varied from 21 vol% to 8 vol% with 1 vol% resolution. For each oxygen concentration condition, strain rate was increased by increasing both the oxidizer and fuel mass flow rates until flame extinction was predicted. In the current simulation, flame heat loss is assumed to be zero. Therefore, the variation of maximum flame temperature between different oxygen concentration and same strain rate conditions is attributed to dilution effect of additional nitrogen. For a fixed oxygen concentration level, the peak flame temperature reduces with the increased strain rate. At the higher oxygen concentration level, the flame extinction occurs at relatively larger strain rate compared to those with a lower oxygen concentration. The smallest oxygen concentration for ethylene without extinction is 9 vol%, lower than 12, 10 and 11 vol%, the oxygen concentrations of CH_4 , C_3H_8 , and C_3H_6 respectively calculated in the same fashion. The minimum temperature at extinction of ethylene is 1325 K, lower than those of CH_4 , C_3H_8 , and C_3H_6 , 1512 K, 1340 K, and 1468 K respectively. The right panel of Figure 3 shows the dependence of extinction temperature on strain rates of opposed-flow flame of four fuels. Ethylene flame can exist at relatively larger strain rate, and methane flame can exist at much lower strain rate compared to the other fuels. Both the effect of strain rate and extinction temperature is consistent with the LOI trend observed in Figure 2. Therefore, the LOI values of the four gaseous fuels can be mainly explained based on the kinetic analysis. Due to the relatively low strain rate of the buoyant turbulent flame, it can be inferred that heat loss may play an important role in the current experimental results, which requires a comprehensive computational fluid dynamic study to further interpret the experimental result.

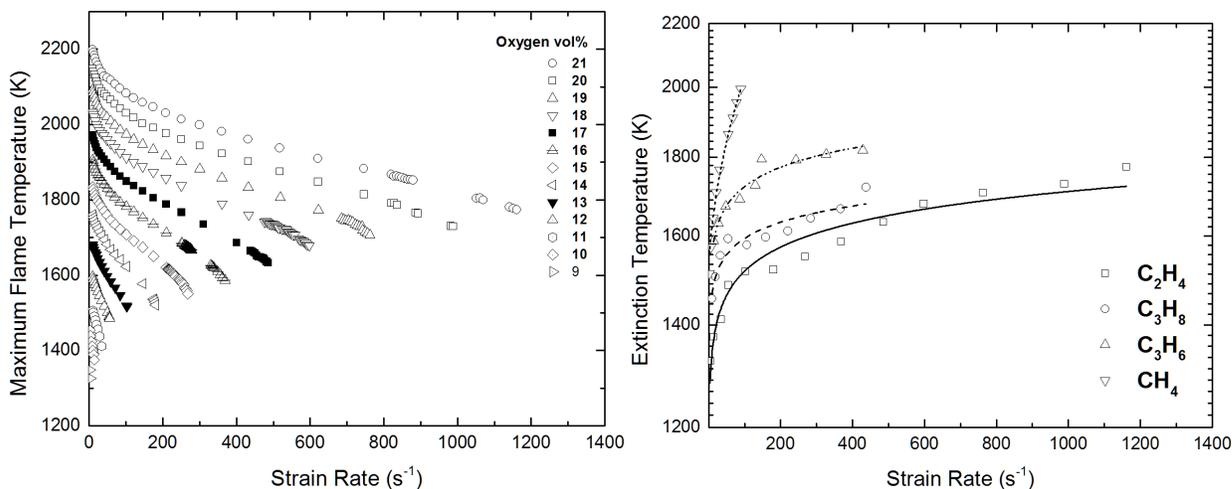


Figure 3. Left: Values of maximum flame temperatures calculated against mean strain rate; right: maximum flame temperature at extinction limit of different mean strain rates.

The two different extinction regimes shown in Figure 2 include: 1. When oxygen concentration is higher than that of global extinction stage, combustion efficiency reduces but chemical reactions still achieve completion, as evidenced of negligible production of CO in the over-fire region; 2. When oxygen concentration is in the range of the global extinction stage, global extinction occurs and CO production increases drastically. With the increase of nitrogen diluent fraction in the co-flow, the overall temperature

of diffusion flames decreases. For flamelets with lower temperature, the chemical reaction rates slow down and this prompts CO production. However, the temperature of flame downstream is sufficiently high to support the oxidation reactions of CO, which results in negligible CO production in the over-fire region, this was shown in the measurement of CO mass flow rate of propane pool-like flame through flame height by Santo and Delichatsios [17]. When oxygen concentration reaches the global extinction stage, the further reduced temperatures slow down the reaction steps and cannot fully oxidize CO, which results in increased CO emission in the over-fire region.

3 Conclusions

Effect of nitrogen diluent on the flame characteristics especially combustion efficiency and LOI were investigated for four gaseous fuels. For this purpose, a water-cooled compartment was developed to generate a controlled atmosphere for turbulent diffusion flame experiment. Combustion efficiency reduces slowly with a decreased oxygen concentration in co-flow, then quickly decreases when the oxygen concentration reached close to LOI value, or in the global extinction stage. The LOI values show that $CH_4 > C_3H_6 > C_3H_8 > C_2H_4$, which is consistent with those from laminar flame measurement. This trend can be reasonably explained by the kinetic simulation of opposed-flow flames, which shows that fuel with smaller LOI has the lower minimum extinction temperature and higher strain rate limit.

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