Liftoff of Propane - Air Diffusion Flames By Axis Symmetric Co-flow Air Injection

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ABSTRACT

Combustion of gas with diffusion system is widely used in many residential gas appliances like stove, engine furnaces and industrial furnaces. Phenomenon of lifted flame is often happened at diffusion flame where the stream of fuel and air into combustor flow separately. Hence the combustion process needs time so that mixing of air and fuel reach the condition ready for burnt. This condition make the burner tip protected from high thermal load and more safe to operate.

In this paper, propane was ejected into quiescence air through nozzle having 1.8 mm holes diameter. Fuel flow rate was increased until liftoff conditions exceed; hereinafter flow rate of fuel was made constant at 69 ml/s and air was ejected around of fuel with axis symmetric flow. Liftoff behavior of diffusion flames was investigated for various air flow rate: 17.9 ml/s – 89.9 ml/s. Lifted distance decreased from 130 mm to 90 mm when air was injected with flow rate of 19.1 ml/s, however, it increased to 100 mm when air flow rate increased to 35.9 ml/s.

Cold-flow simulation showed the moderate air flow rate give a faster density degradation at axial line compared to larger air flow rate. It means moderate flow rate of air support a better air-fuel mixing than faster one.

Key words: diffusion, combustion, lifted-flame, lifted-distance

I. INTRODUCTION

Combustion is a process to convert chemical energy contained in the fuel to thermal energy and in most cases accompanied by light. There are two kinds of combustion process: premixed combustion where fuel and oxidizer are mixed completely before entering the combustion chamber and non-premixed or diffusion combustion where fuel and oxidizer flow in to the combustion chamber separately.

Generally, diffusion combustion process is preferred to be applied in industries for safety and reliability reasons, because in a diffusion flame, lifted phenomena often takes place early. With the base of flame separates from burner tip, the flame gives an advantage of avoiding thermal contact between the flame and the nozzle which would lead to erosion of the burner material. However, the disadvantage of this flame stabilization technique is that lifted flame blow off more easily than attached flame and therefore must continuously be controlled [1].

Liftoff distance is defined as the distance between burner tip and base of flame. It will increase with additional velocity until the flame blows out [2]. The criteria for establishing the liftoff height are different for each theory and can be given as follows:

1. The local flow velocity at the position where the laminar flame speed is a maximum and matches the turbulent burning velocity of a premixed flame.
2. The local strain rates in the fluid exceed the extinction strain rate for laminar diffusion of flame let.
3. The time available for back mixing by large scale

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flow structures of hot products with fresh mixture is less than a critical chemical time required for ignition.

Liftoff heights for free and confined jets at propane diffusion combustion have investigated by Cha M.S and Chung S.H. [3] and they found that the ratio of the liftoff height at blowout to the nozzle diameter maintains a near-constant value of 50 for free and confined jets. Result of observation indicates that liftoff heights x_f for free jets are proportional to the nozzle exit mean velocity u_i and are independent of the nozzle diameter and the data can be fit to equation [(1)]:

$$\bar{x}_f = 0{,}002245 u_i - 0{,}01663 \qquad (1)$$

While liftoff height for confined jets the data can be fit to equation (2).

$$\frac{\bar{x}_f}{d_i} = u_i \left(1{,}02 + \frac{0{,}0976}{d_d - 0{,}35} \right) \qquad (2)$$

where d_i = nozzle diameter, d_d = shroud diameter.

L.K. Su et al. [4] investigated lifted jet diffusion flame by planar laser-induced fluorescence and particle image velocimmetry. They delineate that there is high temperature region at the base of lifted flame.

Watson et al. [5] performed simultaneous result of combustion of Hydrogen which not yet stabilized (CH) and result of combustion of Carbon of which not yet stabilized OH planar laser-induced fluorescene (PLIF) measurements at the flame base. The CH radical is short-lived and is thought to mark the instantaneous reaction zone, while OH is removed by slower three-body reactions and marks regions containing hot combustion products. Maurey, et al.[6] also observed high-temperature region outside and upstream of the reaction zones.

Flame height measurement based on luminous soot by planar laser-induced fluorescence was done [7]. Chumber et al. calculates flame length structure by CFD framework [8]. Flame height measurements have been used to test models of flame structure and to calculate residence times of soot particles. The most commonly accepted definition of flame height is the distance from tip burner to the position on centerline where the fuel and oxidizer are in stoichiometric proportions.

Some of research results suggested that at the base flame has high brightness besides high temperature; hence determination of base flame from flame photograph is determined as the position with the highest brightness level.

II. EXPERIMENT

The research investigated the effect of air injection on alteration of lifted distance of propane diffusion flame. Figure1 showed the schematic of experimental set-up. At liftoff condition flame was reached, flow rate of propane was made constant, and then air with variable flow rate was introduced around of propane. The experiment was divided in two steps; 1. Propane was combusted in quiescence air; 2. Air was injected coaxially at the outer to propane flows.

Combustion in Quiescence Air

The combustion experiments with propane in quiescence air was done to know the influence of Reynolds number at nozzle exit on lifted-distance, flame height flame length, temperature at nozzle tip, and then investigate the burning velocity. Propane was introduced into quiescence air by nozzle burner with 1.8 mm of holes diameters. The flame was captured by video camera during 8 – 10 second, and then with computer software lifted the distance, flame length and flame height can be measured. Figure 2 show propane flame which was introduced by cone nozzles at Bunsen’s burner tip (a) and form of propane diffusions flame at quiescence air (b).

The result of lifted distance measurement to propane flow rate is showed at Figure 3. When propane flow rate is less than 29 ml/s the flame is attached at burner tip. Furthermore, when the flow rate reaches 29 ml/s the flame begins lift from burner tip. Lifted

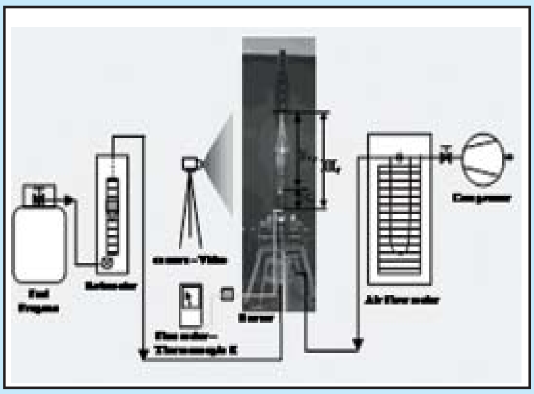

Figure 1
Schematics of experimental set-up

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distance increases linearly with propane flow rate increase until 69 ml/s of propane flow rate. At this flow rate, for the addition of propane flow rate does not alter the lifted-distance until blow-off is reached.

Injected Air around Propane Stream

The second experiment was done with injected air around propane stream at the initial condition of liftoff condition. Flow rate of propane was made constant to 69 ml/s through cone nozzle with hole diameters 1.8 mm, while air was injected with varied flow rate through a gap with inner diameters 6 mm and outer diameters 10 mm. Figure 4 show the channel of propane and air flows. The alteration of lifted distance resulted by co-axially air injection to propane flow is showed at Figure 5.

III. RESULT AND DISCUSSION

Diffusion Flame without Injection Air

Figure 3 show that lifted-flame begin at propane flow rate of 0.029 l/s. Furthermore lifted distance increased linearly with the addition of fuel flow rate until it reached liftoff condition (Q_f = 0.065 l/s). Lifted distance becomes constant when fuel flow rate exceed 0.065 l/s and blow-off occurs when fuel flow rate over 0.089 l/s.

Reynolds number of propane flows when leaving the nozzle's burner can be expressed by equation [3] as follow:

$$\mathrm{Re} = \frac{\rho . u_i . d}{\mu} = \frac{u_i . d}{\nu} \qquad (3)$$

For nozzle exit mean velocity of propane, u_i, can be expressed by $u_i = Q_f/A$ or $u_i = 4Q_f/ðd^2$, so Reynolds number can be expressed as:

$$\mathrm{Re} = \frac{4}{\pi}\frac{Q_f}{\nu . d} \qquad (4)$$

Where Q_f is propane's flow rate, í is kinematics viscosity and d is holes diameter of nozzle exit. The kinematics viscosity of propane is given in Table 1. By linear interpolation kinematics viscosity of propane at 25 ^{0}C was 4.6 .10^{-4} m^2/s. Furthermore the relation between lifted distance and Reynolds number at nozzle exit as is presented at Table 2.

Table 2 indicates that the flame attached at the burner tip for Reynolds number of propane less than 44.5, at higher Re the flame began to lift with linear increase as Re increases to 100. For Re higher than 100, the flame reaches liftoff condition, and lifted-distance stays at constant value until Re reaches 137. Furthermore higher flow rates of propane make the flame comes to blow-off condition. Figure 6 show the relation between lifted distance and the fuel flow rate at lifted condition, the relation can be expressed as equation (5) where lifted distance, x_f in mm and fuel flow rate, Q_f in l/s.

$$x_f = 2598.5.Q_f - 53.629 \qquad (5)$$

Alternatively, the lifted distance can be presented in equation (6) where x_f in m and nozzle exit velocity of

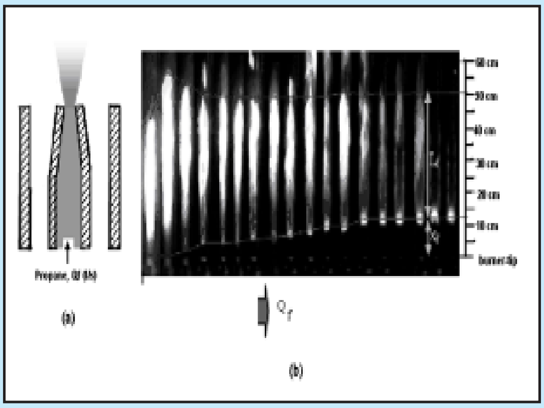

Figure 2
(a) Propane flows through cone-nozzles at burner tip
(b) Shapes of propane diffusion flame for various flow rates of propane

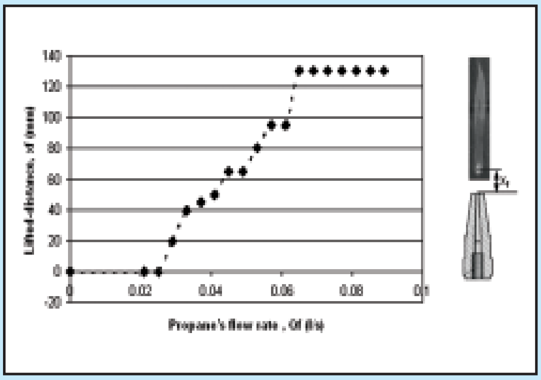

Figure 3
Alteration of lifted-distance resulted by change of propane flow rates

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Table 1
Kinematics viscosity of propane

t, ^{0}C	v.10^4 , m^2/s
0	3.81
100	6.94
200	10.9

Table 2
Lifted-distance for various flow rate of propane's

Qf (ml/s)	Re_f	X_f (mm)
0.021	32.309	0
0.025	38.463	0
0.029	44.617	20
0.033	50.771	40
0.037	56.925	45
0.041	63.079	50
0.045	69.233	65
0.049	75.387	65
0.053	81.541	80
0.057	87.695	95
0.061	93.849	95
0.065	100.003	130
0.069	106.157	130
0.073	112.311	130
0.077	118.465	130
0.081	124.619	130
0.085	130.773	130
0.089	136.927	130

Propane u_i in m/s.

$$x_f = 0.0066.u_i - 0.0536 \qquad (6)$$

Liftoff condition started when propane flow rate exceed 65 ml/s.

Effect of Air Injection on Liftoff Behaviors

When the flame at liftoff condition and the flow rate or propane was kept constant at 69 ml/s, the air

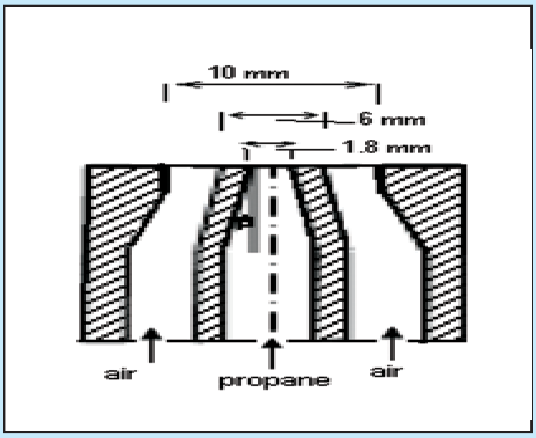

Figure 4
Channel of Propane and air flows

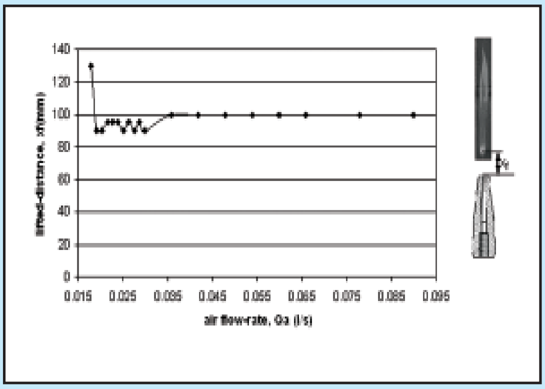

Figure 5
Alteration of lifted distance by air injected coaxially propane flows

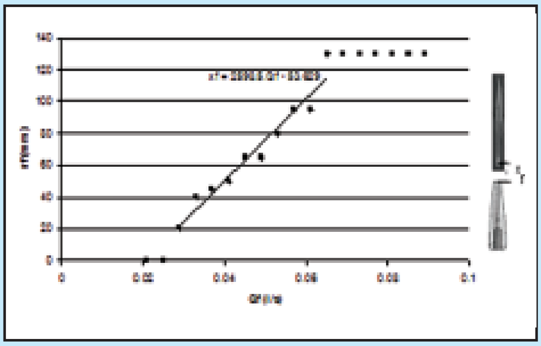

Figure 6
Lifted-distance increased linearly with fuel flow rate before liftoff condition

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is injected co-axially around the propane's flow with various flow rates. Figure 5 showed the alteration of lifted distance due to the air injection. Measurement of lifted-distance for various air injections is presented at Table 3.

Air-fuel ratio in volume is the ratio between air flow rate and fuel flow rate. The existence air injected becomes lifted-distance of flame to become shorter. AFR less than 0.52 gives bigger alteration of lifted distance, on the contrary alteration of lifted distance lower for AFR value more than 0.52.

Flammability Limits for Propane Mass Fraction

Combustion process for air-propane follows the reaction formulas as shown as formula (7).

$$C_3H_8+5(O_2+3.76N_2) \rightarrow 3CO_2+4H_2O+18.8N_2 \quad (7)$$

Air-Fuel Ratio of stoichiometric reaction for propane is 23.8 by volume-ratio or 15.6 by mass-ratio. Flammability limits for various fuel was showed at Table 4. Propane has equivalence ratio 0.51 for lean mixture and 2.83 for rich mixture [2]

Rich mixture or upper flammability limit for propane (AFR-rich)
AFR-volume ratio

$$AFR - rich = \frac{AFR_{stoic}}{\Phi_{maks}} = \frac{23.8}{2.83} = 8.4$$

AFR-mass ratio

$$AFR - rich = \frac{AFR_{stoic}}{\Phi_{maks}} = \frac{15.6}{2.83} = 5.51$$

Where :

$$AFR = \frac{m_{air}}{m_{fuel}} \quad (8)$$

Mass fraction of propane for rich mixture of flammability limit can calculated as bellow:

$M_{Propane} = M_{air}$ / AFR-rich

$$f_{mass-rich} = \frac{M_{Propane}}{M_{Propane} + M_{air}}$$

$$f_{mass-rich} = \frac{M_{Propane}}{M_{Propane} + 5.51 M_{Propane}} = 0.154$$

With the same ways, mass fraction of propane for lean mixture is: $f_{mass-lean} = 0.0327$.

Table 3
Lifted distance for C_3H_8 is 69 ml/s

Q_{air} (l/s)	AFR-volume	X_f (mm)
0.0179	0.25942	130
0.0191	0.276812	90
0.0203	0.294203	90
0.0215	0.311594	95
0.0227	0.328986	95
0.0239	0.346377	95
0.0251	0.363768	90
0.0263	0.381159	95
0.0275	0.398551	90
0.0287	0.415942	95
0.0299	0.433333	90
0.0359	0.52029	100
0.0419	0.607246	100
0.0479	0.694203	100
0.0539	0.781159	100
0.0599	0.868116	100
0.0659	0.955072	100
0.0779	1.128.986	100
0.0899	1.302.899	100

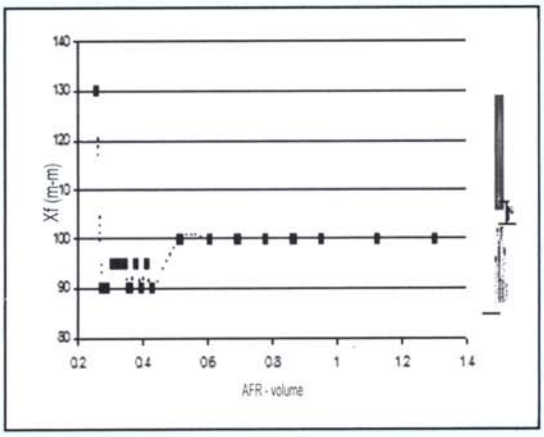

Figure 7
Effect of air injected co-axially to propane flow for lifted distance alteration

So the mass fraction of propane for flammability limits is: 0.0327 - 0.154. The value is assumed that the air is dry.

For air that contains vapor with relative humidity, RH= 41 % and temperature, T_{air} = 29 °C so 1 kg air is contain 0.026 kg vapor and equation (7) becomes :

$$C_3H_8 + 5(O_2 + 3.76N_2 + 0.082H_2O) \rightarrow$$
$$3CO_2 + 4.082H_2O + 18.8N_2$$

With the real condition above, flammability limit of Propane have mass fraction range : 0.031 – 0.152

Cold Flow Simulation by CFD

Figure 8 and 9 show simulation resulted for propane flow rate 69 ml/s through nozzles diameter 1.8 mm, and air injected co-axially outer the propane

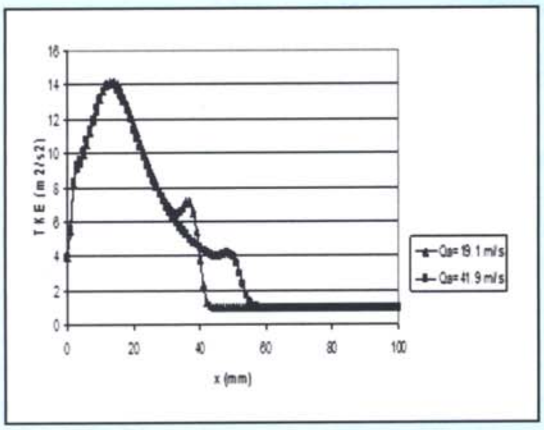

Figure 9
TKE distribute as long as the centerline

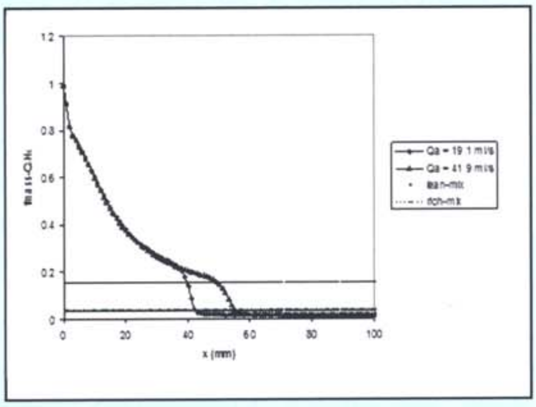

Figure 8
Mass-fraction of Propane distribute as long as axis above burner tip

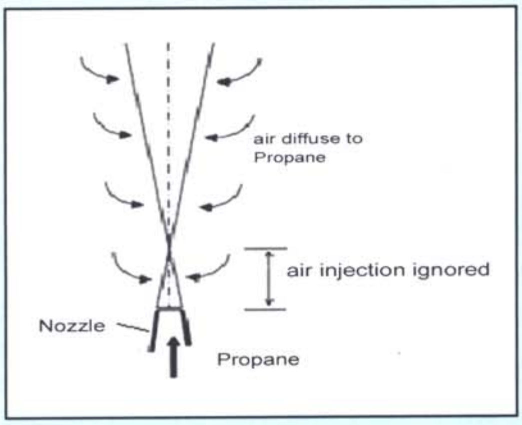

Figure 10
Conical flow of Propane near burner tip

Table 4
Flammability limits for various fuels.

Fuel	Φ_{min} (Lean or lower limit)	Φ_{maks} (Rich or upper limit)	Stoichiometric mass air-fuel ratio
Acetylene, C_2H_2	0.19	?	13.3
Methane, CH_4	0.46	1.64	17.2
Hydrogen, H_2	0.14	2.54	34.5
Propane, C_3H_8	0.51	2.83	15.6

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stream with flow rate 19.1 ml/s and 41.9 ml/s. The numerical model solver is steady-state, axis symmetric, viscous model is k-epsilon and species transport model inlet diffusion.

Distribution of mass fraction C_3H_8 at the centerline is showed in Figure 8. It indicates that air injected at 19.1 ml/s around propane stream causes earlier mixture to fall with in the range for C_3H_8 mass fraction is 0.0327 – 0.154. It demonstrates air injection at lower flow rate mix faster than higher flow. Distribution of turbulence kinetic energy (TKE) at centerline flow is presented at Figure 9. TKE as long as axis below 30 mm of burner tip for both cases are similar. Above 30 mm, injection with 19.1 ml/s air flow rate causes flow field to have higher TKE than 41.9 ml/s air flow rate. We proposed this condition was caused by fuel flow near burner tip has conical flow shape as illustrated in Figure 10. Near burner tip, fuel flow has inner direction so air can not mix easily. Far from burner tip, fuel flow has outward direction, this gives high probability for air and fuel to mix easily.

IV. CONCLUSIONS

We get conclusions based on the experiment that injections of air around of flow to make base flame closer to burner tip. Higher injection of air or higher AFR do not cause the lifted flame to be stabilized, on the contrary lifted distance is shorter at lower air flow rate. Moderate air injection makes mixing of air and fuel better near the burner tip, but higher air injection gives better mixing air and fuel at higher position. As indicated by TKE distribution at lower position TKE for lower air injection has higher value than at higher air flow rate. It showed that moderate air flow give mixture that is ready to burn at lower position than higher air flow.

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