Investigation on the Flame Tilt Characteristics of Hydrogen/Propane Mixture Diffusion Jets in Cross Flow: Parameter Analysis Based on the Hydrogen Blending Fraction

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ABSTRACT

An experimental study of hydrogen/propane mixture diffusion jets in cross flow has been performed to obtain the jet flame tilt characteristics when considering the combined effect of the cross flow and hydrogen blending fraction. The pipe nozzle with an inner diameter of 4 mm was employed in the experiments, using hydrogen and propane as the fuel jet velocity in the range of 11.06-49.76 m/s. The cross wind speed changed from 0.5 to 1.5 m/s. The experimental results showed that the hydrogen/propane mixed jet flame evolution was affected by the hydrogen blending fraction and cross flow wind. The flame trajectory length decreases with increasing the hydrogen fraction. The flame tilt angle decreases with the hydrogen blending fraction for a given mean jet velocity. Moreover, a simplified theoretical analysis was adopted to discuss the flame height and hydrogen blending fraction.

KEYWORDS: Jet diffusion flame, hydrogen/propane mixture, hydrogen blending fraction, flame tilt angle, cross wind.

NOMENCLATURE

A	area (m^2)
C	concentration of jet (-)
D	inner nozzle diameter (m)
d	diameter of nozzle (mm)
H	flame height (m)
K	stoichiometric ratio
L	flame length (m)
$\dot{m}$	mass flow rate (-)
R	momentum ratio
Q	heat release rate (kW)
u	velocity (m/s)
V	volume flow rate (m^3/s)
X	volume fraction (-)

Greek

α	flame tilt angle (-)
ρ	density (kg/m^3)

Subscripts

f	flame
j	jet
∞	air
v	velocity

INTRODUCTION

Jets in cross-flow (JICF) are an important problem with the rapid development of energy and petrochemical industry, and they have a wide variety of combustion applications, such as flares, air-

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breathing gas turbine engines, quench devices in RQL combustors, and fluidic flame stabilization[1]. Combustion in a flare or jet fire occurring in the form of a strong turbulent flame might be dominated by buoyancy or momentum. Such a flame presents a number of challenging phenomena for study, including the effect of crosswind on flame shape and size, radiation and formation, and dispersion of smoke and other gaseous pollutants [2].

Much work has been done on the characteristics of a jet flame in cross flow, and theoretical or empirical equations have been established to predict the shape, length, and tilt characteristics of such jets in cross flow [3-9]. Brzustoski [3] and Gollahalli [4] conducted a series of experiments and found that the initial effect of cross flow was to shorten the flame, after which increases in a cross-flow velocity caused increases in the flame height. Huang and Wang [5] made a division of the jet flame mode based on the flow field of wake-stabilized jet flames (R_M). Kalghatgi [6] developed correlations to determine the flame length scales based on experiments on the turbulent jet diffusion flames in cross winds. Majeski [7] pointed out that diluting the fuel only changed the timescale for the fuel to mix with the required amount of air and burn. Wang [8] investigated the evolution characteristics of turbulent jet diffusion flame, considering the effect of cross flow and sub-atmospheric pressures. Wang [9] investigated the tilt angle of turbulent jet diffusion flames in crossflow and proposed a global correlation with momentum flux ratio.

Hydrogen syngas is expected as the next generation of fuels for the engines and other power sources, with the rising global demand for stringent energy and emission regulations. Many researchers have studied the effect of the addition of hydrogen into natural gas on engine performances and emissions in recent years [10-12]. Practical studies of internal combustion engines and gas turbines combustors indicated that a blended fuel with a mixture of hydrocarbon and hydrogen syngas could improve the performance of the combustors [13]. However, relatively less work has been focused on the characteristics of mixed jet diffusion flames, especially the mixture of hydrocarbon and hydrogen fuel. In the present study, experiments were conducted in a wind tunnel with the hydrogen/propane diffusion jet flames to discover the flame tilt characteristics of the mixed jet diffusion flames in a cross wind. The effect of hydrogen blending fraction on the mixed jet flame lengths and tilt angles is discussed. Moreover, a simplified theoretical analysis was adopted to explain the flame tilt characteristics.

EXPERIMENTAL APPARATUS

A 20.2 m total length wind tunnel with the cross sectional dimensions of 1.8 m height and 1.8 m width was employed for the experiments (Fig. 1). The detailed tunnel facility has been described in [14]. The cross flow speed changed in the range of 0.5-1.5m/s and was monitored by the vertically installed hot-wire anemometer (the fluctuation is under 2%). A 4.0 mm diameter nozzle was mounted at a height of 30 cm above the tunnel floor level. The stable hydrogen/propane mixture fuel was supplied from the mixing chamber with a 3m long gas pipe with a gas flow rate meter for each test. The volumetric flow rates of hydrogen and propane were in the range of 0.25-1.50 m^3/h and 0.25-0.75 m^3/h, respectively. Hence, the hydrogen blending fraction $X_{j,\mathrm{H_2}}$ in the experiments ranged from 0.25 to 0.86. The heat release rate was in the range of 6.61-21.29 kW. The experimental scenarios are listed in Table 1. All the tests were repeated three times to reduce the random errors.

We defined the hydrogen blending fraction, $X_{j,\mathrm{H_2}}$, of the mixed jet diffusion flames, as $X_{j,\mathrm{H_2}} = V_{j,\mathrm{H_2}} \big/ \left(V_{j,\mathrm{C_3H_8}} + V_{j,\mathrm{H_2}}\right)$, where $V_{j,\mathrm{H_2}}$ and $V_{j,\mathrm{C_3H_8}}$ are hydrogen and propane volumetric flow rates, respectively. Moreover, $u_{j,\mathrm{H_2}} = V_{j,\mathrm{H_2}} / A_{nozzle}$ and $u_{j,\mathrm{C_3H_8}} = V_{j,\mathrm{C_3H_8}} / A_{nozzle}$.

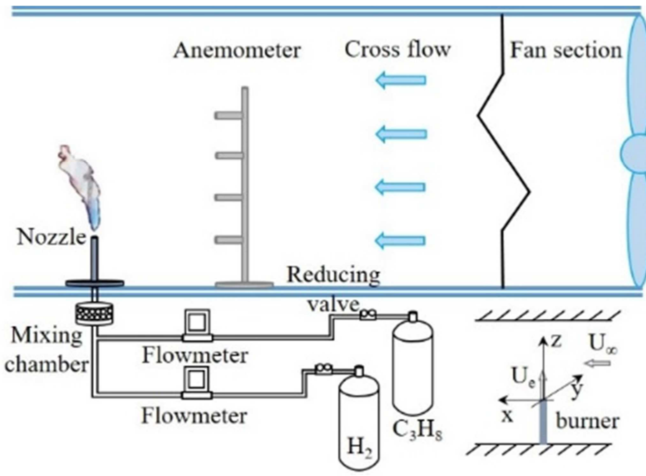

Fig. 1. Schematic diagram of experimental apparatus.

Table 1. Summary of experimental scenarios

u_∞ (m/s)	$u_{j,\ C_3H_8}$ = 5.53 m/s				$u_{j,\ C_3H_8}$ = 11.06 m/s				$u_{j,\ C_3H_8}$ = 16.59 m/s			
	$u_{j,\ H_2}$ (m/s)	u_j (m/s)	$X_{j,\ H_2}$ (-)	Q (kW)	$u_{j,\ H_2}$ (m/s)	u_j (m/s)	$X_{j,\ H_2}$ (-)	Q (kW)	$u_{j,\ H_2}$ (m/s)	u_j (m/s)	$X_{j,\ H_2}$ (-)	Q (kW)
0.5	5.53	11.06	0.50	6.61	5.53	16.59	0.33	12.53	5.53	22.12	0.25	18.46
	11.06	16.59	0.67	7.30	11.06	22.12	0.50	13.22	11.06	27.65	0.40	19.15
	16.59	22.12	0.75	7.99	16.59	27.65	0.60	13.91	16.59	33.18	0.50	19.83
	22.12	27.65	0.80	8.68	22.12	33.18	0.67	14.60	22.12	38.71	0.57	20.52
	27.65	33.18	0.83	9.37	27.65	38.71	0.71	15.29	27.65	44.24	0.63	21.21
	33.17	38.7	0.86	10.06	33.17	44.23	0.75	15.98	33.17	49.76	0.67	21.90
1.0	5.53	11.06	0.50	6.61	5.53	16.59	0.33	12.53	5.53	22.12	0.25	18.46
	11.06	16.59	0.67	7.30	11.06	22.12	0.50	13.22	11.06	27.65	0.40	19.15
	16.59	22.12	0.75	7.99	16.59	27.65	0.60	13.91	16.59	33.18	0.50	19.83
	22.12	27.65	0.80	8.68	22.12	33.18	0.67	14.60	22.12	38.71	0.57	20.52
	27.65	33.18	0.83	9.37	27.65	38.71	0.71	15.29	27.65	44.24	0.63	21.21
	33.17	38.7	0.86	10.06	33.17	44.23	0.75	15.98	33.17	49.76	0.67	21.90
1.5	5.53	11.06	0.50	6.61	5.53	16.59	0.33	12.53	5.53	22.12	0.25	18.46
	11.06	16.59	0.67	7.30	11.06	22.12	0.50	13.22	11.06	27.65	0.40	19.15
	16.59	22.12	0.75	7.99	16.59	27.65	0.60	13.91	16.59	33.18	0.50	19.83
	22.12	27.65	0.80	8.68	22.12	33.18	0.67	14.60	22.12	38.71	0.57	20.52
	27.65	33.18	0.83	9.37	27.65	38.71	0.71	15.29	27.65	44.24	0.63	21.21
	33.17	38.7	0.86	10.06	33.17	44.23	0.75	15.98	33.17	49.76	0.67	21.90

RESULTS AND DISCUSSION

Flame configurations

The hydrogen/propane flame evolution in the cross wind, under increasing hydrogen flow is illustrated in Fig. 2, with a propane flow velocity of 5.53 m/s and a cross wind speed and hydrogen flow velocity in the range of 0.5-1.5 m/s and 5.53-33.17 m/s, respectively. It can be seen from the figures that the flame trajectory length increases with the cross wind speed, as well as the flame tilt characteristics. Previous work [2] had found that the initial effect of cross flow was to shorten the flame, after which an increase in cross-flow velocity increased the flame length. The tails of the jet flame body become smooth and an axisymmetric tail flame can be observed as the cross wind speed increases. It may be suppressed by the vorticity circulation at the flame edge, and the counter-rotating vortex pair exits in the flame edge [15-16]. The similar qualitative trend of the diffusion jet flame has been discussed by the previous studies [8, 15]. It also can be seen that with the fuel jet velocity increasing, the jet flame tilt becomes less pronounced and both the flame height in the cross wind direction and flame trajectory length become shorter. In addition, as the hydrogen flow velocity increases, the jet flame body becomes less luminance and the blue flame area at the base becomes enlarged. The flame body area becomes smaller and the tail of the jet flame presents much less wrinkled as the hydrogen blending fraction increases.

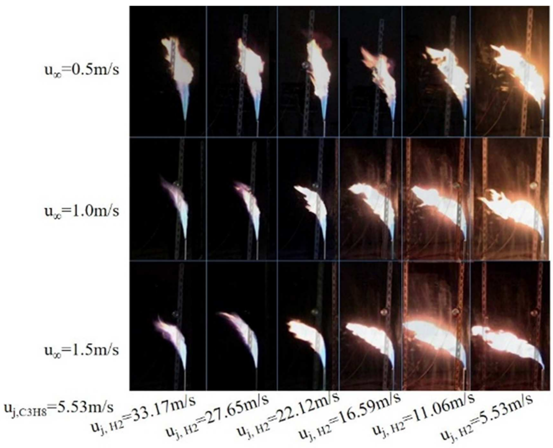

Fig. 2. Flame evolution in the cross wind with increasing hydrogen flow velocity.

Flame length and flame tilt angle

Each recorded image of the hydrogen/propane mixture jet flame was converted to binary images by the Otsu method [17], and the flame intermittency distribution was obtained by averaging the values of these consecutive binary images in each pixel position. Fig. 3 illustrates the determination of flame trajectory-line length, L_f, flame height, H_f, and flame tilt angle, α and α_B, from the recorded flame images. As can be seen, the flame trajectory-line length L_f is the distance between the nozzle exit and flame tip along the flame tilt trajectory, and the flame height H_f is the perpendicular distance from the flame tip to the nozzle exit. The flame tilt angle α_B is the angle between the jet exit axis and the line joining the flame tip to the nozzle tip, while α is the included angle between the tangent line of the flame trajectory line and the jet exit axis.

The variations of flame trajectory lengths with the hydrogen blending fraction at different cross wind speeds are illustrated in Fig. 4. The flame trajectory lengths for the different cross wind speeds have a decreasing trend with increasing hydrogen blending fraction. The flame trajectory lengths range from 46.7 to 61.7 cm under a cross wind of 0.5 m/s, the values range from 30.9 to 60.4 cm under across wind of 1.0 m/s, and from 31.27 to 57.9 cm under the cross wind of 1.5 m/s. The flame trajectory length could decrease with an increase in air entrainment and mixing with fuel due to the strong vorticity circulation. However, as the cross flow becomes stronger, the vorticity circulation may be suppressed at the flame edge, which presents the smooth flame edge as shown in Fig. 2.

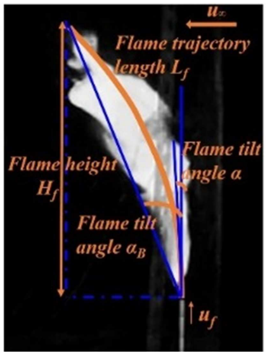

Fig. 3. Determination of flame trajectory-line length L_f, flame height H_f, and flame tilt angles α and α_B from flame images (d = 4 mm, u_j = 38.70 m/s, u_∞ = 1.0 m/s).

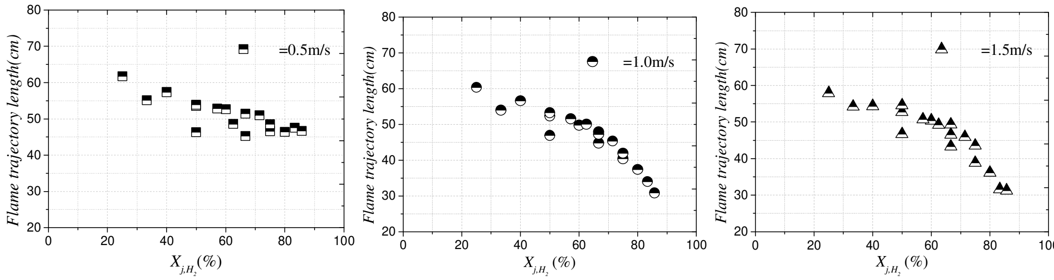

Fig. 4. Flame trajectory length versus hydrogen blending fraction at different cross wind speeds.

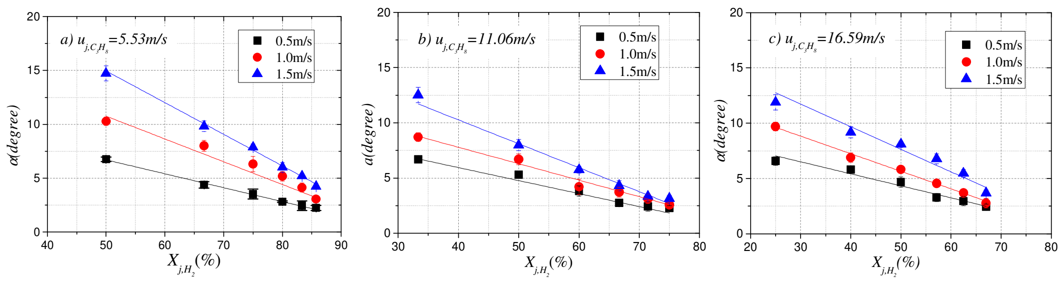

Fig. 5. Variation of flame tilt angle (α) with hydrogen blending fraction under different cross wind speeds (where α is the including angle between the tangent line of the flame trajectory line and the jet exit axis).

Figure 5 illustrates the flame tilt angles α for the propane jet flow velocity of 5.53 m/s (a), 11.06 m/s (b) and 15.59 m/s (c) with increasing the hydrogen fraction under different cross wind speeds where α is the angle between the tangent line of the flame trajectory line and the jet exit axis. A significant trend observed in Fig. 5 is that the flame tilt angle α becomes smaller with increasing hydrogen addition. For the same hydrogen blending fraction, α becomes smaller as the cross wind speed increases. It is evident from Fig. 5 (a), (b) and (c) that the flame tilt angle α for the propane jet flow of 5.53 m/s varies from 2.1 to 14.95, whereas the variations in the flame tilt angle α for the greater propane jet flow of 11.06 m/s and 16.59 m/s are 2.28-12.51 and 2.49-11.89, respectively. The linear curves of α fit well with the hydrogen blending fraction. We can see that the flame tilt angles α_B also linearly correlate with the hydrogen blending fraction for the different propane jet flow velocities (Fig. 6) where α_B is the angle between the burner axis and the connecting line of the flame tip and the burner exit. It can also be seen from Fig.6 (a), (b) and (c) that the flame tilt angles α_B present a decreasing trend, with the hydrogen blending fraction increasing for the different cross wind speeds. It can be seen that the flame tilt angle α_B of 0.5 m/s cross wind speed is smaller than that of the 1.0 and 1.5 m/s cases.

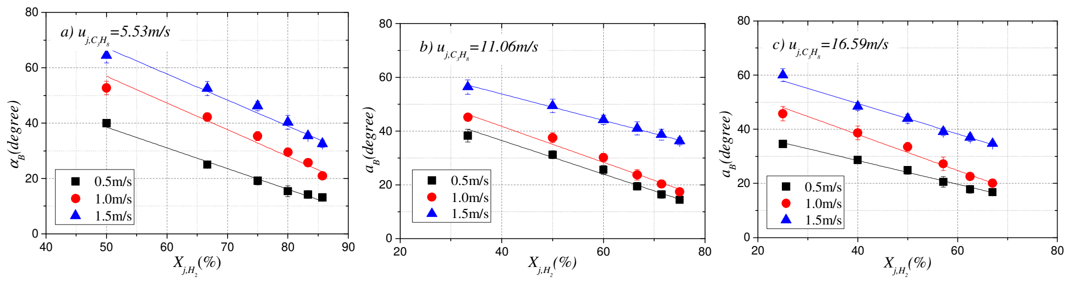

Fig. 6. Variation of flame tilt angle (α_B) with hydrogen blending fraction. (α_B is the angle between the jet exit axis and the line joining the flame tip to the nozzle tip).

Simplified theoretical analysis

Kalghatgi [6] developed correlations to determine the flame height scales based on experiments on the turbulent jet diffusion flames in the cross wind. The expression for flame height is:

$$\frac{H_f}{D_s} = 6 + \frac{2.35}{R_v} + 20R_v . \tag{1}$$

Here H_f is the flame tip from the plane of the burner (m), $D_s = D\left(\rho_j/\rho_\infty\right)^{0.5}$ is the effective source diameter, and $R_v = u_\infty / u_j$ is the non-dimensional velocity, where D is the inner nozzle diameter(m), ρ_j is the density of the mixed jet fuel (kg/m^3), $\rho_j = X_{j,\mathrm{H_2}}\rho_{j,\mathrm{H_2}} + \left(1 - X_{j,\mathrm{H_2}}\right)\rho_{j,\mathrm{C_3H_8}}$, ρ_∞ is the density of the cross wind (kg/m^3), u_∞ is the cross wind speed (m/s), u_j is the jet fuel velocity (m/s).

The comparison between the predicted and measured flame height is shown in Fig 7. The theoretical values calculated in Kalghatgi's model are lower than the measured values. Kalghatgi [6] also pointed out that the range of validity of these correlations is for values of R_v greater than 0.02 and less than 0.25, while for $R_v < 0.02$, the wind-free data may be used to determine the flame heights and the tilt may be assumed to be zero. However, for the hydrogen/propane mixture diffusion jet flame in this experiment, the measured values of H_f / D_s under the cross flow of 0.5m/s are almost concentrated in the range of $R_v < 0.02$.

A relationship is presented in the normalized form of flame height and velocity in Fig.8, and the experimental results are well fitted with the related coefficient being greater than 0.90 in the following:

$$\frac{H_f}{D_s} = \exp(5.2 - 10.4R_v). \tag{2}$$

Substituting $D_s = D(\rho_j/\rho_\infty)^{0.5}$ in Eq.(2) yields

$$\frac{H_f}{\exp(5.2 - 10.4R_v)D} = \left(\frac{\rho_j}{\rho_\infty}\right)^{0.5}. \tag{3}$$

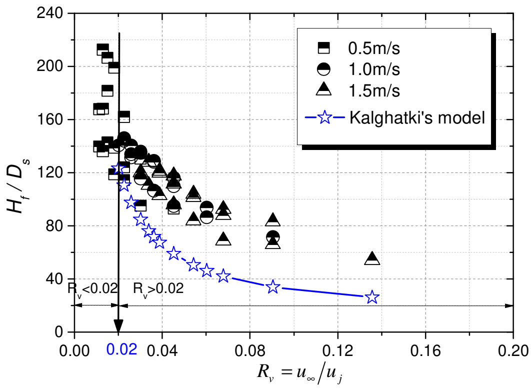

Fig. 7. Variation of between predicted and measured flame height with velocity ratio

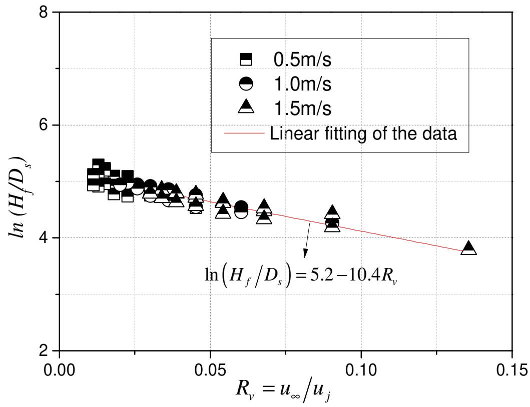

Fig. 8. Normalized flame height versus non-dimensional velocity ratio

Majeski [7] introduced the stoichiometric ratio K_s to discuss the mean flame height when considering the effect of fuel dilution,

$$H_f \propto K_s^{1/2}, \tag{4}$$

where $K_s = \dot{m}_{O_2}/C_f\dot{m}_j$, $\dot{m}_{O_2}$ is the total supply of oxygen to the flame, and $\dot{m}_j$ is the total mass flow rate of the jet, and C_f is the concentration of fuel in the jet, $C_f = \rho_f V_{j,f}/\rho_j V_j$, $V_{j,f}$ and V_j are the volume flow rate of the jet and fuel component, respectively. Hence, Eq. (3) could be revised as

$$\frac{H_f}{\exp(5.2 - 10.4R_v)D} \sim K_s^{1/2}\left(\frac{\rho_j}{\rho_\infty}\right)^{0.5}, \tag{5}$$

Using

$$\rho_j = X_{j,\mathrm{H_2}}\rho_{j,\mathrm{H_2}} + (1 - X_{j,\mathrm{H_2}})\rho_{j,\mathrm{C_3H_8}} \text{ and } K_s = \frac{X_{j,\mathrm{H_2}}\rho_{j,\mathrm{H_2}}\frac{32}{4} + (1 - X_{j,\mathrm{H_2}})\rho_{j,\mathrm{C_3H_8}}\frac{160}{44}}{X_{j,\mathrm{H_2}}\rho_{j,\mathrm{H_2}} + (1 - X_{j,\mathrm{H_2}})\rho_{j,\mathrm{C_3H_8}}},$$

calculated for the mixture of hydrogen and propane, in Eq. (5). Eq. (5) can be represented as:

$$\frac{H_f}{\exp(5.2 - 10.4R_v)D} \sim \left(\frac{X_{j,\mathrm{H_2}}\rho_{j,\mathrm{H_2}}\frac{32}{4} + (1 - X_{j,\mathrm{H_2}})\rho_{j,\mathrm{C_3H_8}}\frac{160}{44}}{\rho_\infty}\right)^{1/2}. \tag{6}$$

Substituting ρ_{j,C_3H_8} = 1.84 kg/m^3, ρ_{j,H_2} = 0.09 kg/m^3, ρ_∞ = 1.189 kg/m^3 at normal temperature and pressure and D = 0.004 m into Eq. (6), gives the correlation in Fig. 9. This illustrates the flame height versus the hydrogen blending fraction in the modified model. As can be seen in Fig. 9, the flame height presents the linear correlation with hydrogen blending fraction for the different cross flow velocities.

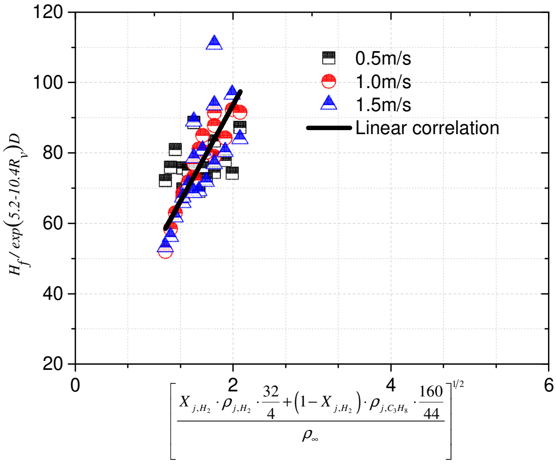

Fig. 9. Comparison of simplified model (Eq.(6)) with experimental results of flame height and hydrogen blending fraction for different cross flow velocity.

CONCLUSION

This paper experimentally investigates the hydrogen/propane mixture diffusion jets in cross flow. The cross wind speed and fuel jet velocity range from 11.06 to 49.76 m/s and from 0.5 to 1.5 m/s. Several flame tilt characteristic parameters were obtained considering the combined effect of the cross flow and hydrogen blending fraction. Major findings include:

(1) The flame trajectory length presented a decreasing trend with increasing hydrogen blending fraction and was approximately in the range of 30 cm – 60 cm for the different cross wind speeds.

(2) The flame tilt angle (α and α_B) decreased with the hydrogen blending fraction and ranged from 2-15 degree for a given mean jet velocity.

(3) A simplified theoretical analysis on the basis of stoichiometric ratio K_s proposed by Majeski, was adopted to discuss the flame height and the hydrogen blending fraction.

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REFERENCES

[1] A.R. Karagozian, The jet in crossflow, Phys. Fluids 26(10) (2014) 1-47.

[2] C.L. Beyler, Fire hazard calculations for large, open hydrocarbon fires. In The SFPE Handbook of Fire Protection Engineering, (5th Edn), J.H. Morgan, M.J. Hurley (Eds). National Fire Protection Association, Quincy MA, 2016.

[3] T.A. Brzustowski, A new criterion for the length of a gaseous turbulent diffusion flame, Combust. Sci. Technol. 6 (1973) 313-319.

[4] T.A. Brzustowski, S.R. Gollahalli, H.F. Sullivan, The turbulent hydrogen diffusion flame in a cross-wind, Combust. Sci. Technol. 11 (1975) 29-33.

[5] R.F. Huang, S.M. Wang, Characteristic flow modes of wake-stabilized jet flames in a transverse air stream, Combust. Flame 117 (1999) 59-77.

[6] G.T. Kalghatgi, The visible shape and size of a turbulent hydrocarbon jet diffusion flame in a cross-wind, Combust. Flame 52 (1983) 91-106.

[7] A.J. Majeski, D.J. Wilson, L.W. Kostiuk, Predicting the length of low-momentum jet diffusion flames in crossflow, Combust. Sci. Technol. 176 (2004) 2001-2025.

[8] Q. Wang, L.H. Hu, X.C. Zhang, et al., Turbulent jet diffusion flame length evolution with cross flows in a sub -pressure atmosphere, Energy Conv. Manag. 106 (2015) 703-708.

[9] J. Wang, J. Fang, S. Lin, et al., Tilt angle of turbulent jet diffusion flame in crossflow and a global correlation with momentum flux ratio, Proc. Combust. Inst. 36 (2017) 2979-2986.

[10] H. Ozcan,. Hydrogen enrichment effects on the second law analysis of a lean burn natural gas engine, int. J. Hydrogen Energy 35 (2010) 1443-1452.

[11] E. Porpatham, A. Ramesh, B. Nagalingam, Effect of hydrogen addition on the performance of a biogas fuelled spark ignition engine, Int. J. Hydrogen Energy 32 (2007) 2057-2065.

[12] C. Ji, S. Wang, Effect of hydrogen addition on combustion and emissions performance of a spark ignition gasoline engine at lean conditions, Int. J. Hydrogen Energy 34 (2009) 7823-7834.

[13] L. Pan, E. Hu, F. Deng, et al., Effect of pressure and equivalence ratio on the ignition characteristics of dimethyl ether-hydrogen mixtures, Int. J. Hydrogen Energy 39 (2014) 19212-19223.

[14] X. Chen, Q. Wang, S. Lu, et al., Investigation on the size and trajectory of mixed jet diffusion flames in cross wind, Energy Procedia 142 (2017) 1516-1521.

[15] A.R. Karagozian, Transverse jets and their control, Progr. Energy Combust. Sci. 36 (2010) 531-553.

[16] M.S. Lawal, M. Fairweather, P. Gogolek, S.R. Gubba, D.B. Ingham, L. Ma, M. Pourkashanian, A. Williams, Large eddy simulations of wake-stabilised flares, Fuel Proc. Technol. 112 (2013) 35-47.

[17] N. Otsu, A threshold selection method from gray-level histograms, IEEE Transactions on Systems, Man, and Cybernetics 9 (1979) 62-66.