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Investigation of methane combustion flames diluted by carbon dioxide on non-premixed burner

M. Angsuchoti, A. Kaewpradap* and S. Jugjai

Department of Mechanical Engineering King Mongkut's University of Technology Thonburi, 126 Pracha Uthit Rd., Bang mod, Thungkru, Bangkok 10140 Thailand

* Corresponding Author: E-mail amornrat.kae@mail.kmutt.ac.th, Tel. (662) 4709267, Fax. (662) 4709111

Abstract. This study was investigated to obtain methane combustion flames diluted by carbon dioxide on non-premixed burner. The methane combustion characteristics were analyzed on axisymmetric jet (AJ) non-premixed burner. The investigated parameters consist of fuel velocity (U_f), air velocity (U_a), CH_4 concentration (% by volume) and firing rate (F.R.). The results showed that longer flame length and lower temperature were obtained when fuel velocity increased between 0.4-1.6 m/s. At the same fuel velocity, carbon dioxide was diluted in methane combustion from 30-70% by volume, flame length was decreased by much lower yellow tip flames and slightly higher blue flames due to well mixed between air and fuel. In addition, all blue flames could be found at CH_4 concentration less than 50% by volume and extinction limit was occurred at U_f=1.6 m/s and methane concentration less than 30%. However, this study also found that air velocity had slightly effects on flame length and flame temperature. It concluded that less than 70% of carbon dioxide dilution could be applicable to improve diffusion flame from methane combustion on AJ non-premixed burner.

1. Introduction

Nowadays, there are many types of burner used in the industrial part with premixed and non-premixed combustion. Even though, premixed burner was applied widely due to well-mixed combustion however it was known about risk from flashback flames [1]. In the past, flashback flame phenomena obtained from premixed combustion was studied with equivalence ratio more than unity with the variation of mass flow rates [2]. In order to operate gaseous combustion on burner with safety, the combustion flames on basic non-premixed burners, Axisymmetric Jet (AJ) burner, Wolfhard Parker (WP) burner and tubular burner, were investigated [3]. Hydrogen (H_2) diffusion flame diluted by inert gas, was also studied to obtain change of flame structure on AJ burner, WP burner and tubular burner as the basic of non-premixed burner [4]. In the past, fossil fuel applied for general combustion in heat process of industrial parts, emitted greenhouse gases such as carbon dioxide (CO_2) and oxide of nitrogen (NO_x) to environment and affected climate change. In this present, low carbon fuel such as natural gas, biogas was instead of fossil fuel to reduce emission [5]-[6]. As low emission and renewable fuel, the policy of biogas usage increased from 193 kW to 3600 kW was supported by Ministry of Energy, Thailand

during 2008-2013 [7]. The main compositions of biogas are methane (CH_4) and carbon dioxide (CO_2), which compositions of biogas are different because of gas production. The previous study showed the unstable premixed flames of synthetic biogas investigated with different compositions [8]. In order to operate burner with safety, non-premixed methane and hydrogen combustion was studied and longer flame length of methane combustion with increase of fuel velocity was obtained [9]-[10]. Moreover, mapping and structure flames were resulted from inverse diffusion flames of methane [11]. Thus, it is necessary to investigate CH_4 diluted with CO_2 combustion flames as the main compositions of biogas on AJ non-premixed burner to operate combustion devices for biogas with safety. Following variation of methane concentration, fuel velocity and air velocity, flame characteristics of methane diluted with CO_2 could be applicable to obtain smart operation range of non-premixed burner.

2. Nomenclature

U_f	Fuel-inert velocity (m/s)
U_a	Air velocity (m/s)
ρ	Density (kg/m^3)
c_p	Specific heat (J/kg•K)
k	Thermal conductivity (W/m•K)
$F.R.$	Firing rate (kW)
L	Flame length (mm)
A	Area (m^2)
$\dot{m}$	Mass flow rate (kg/s)
Q_a	Volume flow rate (m^3/s)
T	Flame temperature (°C)
LHV	low heating value (kJ/kg)

3. Experimental setup

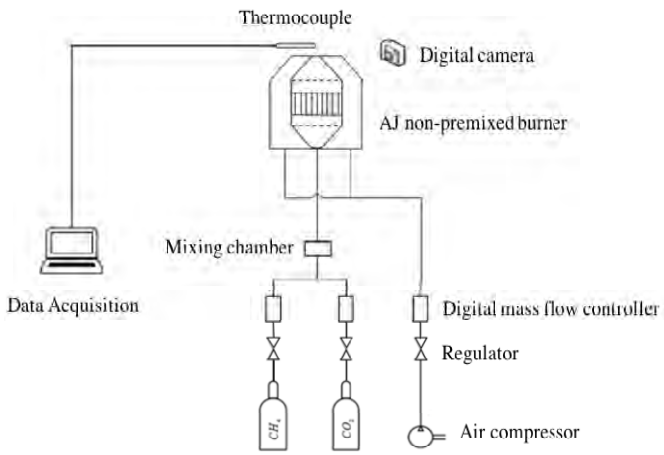

Fig.1 Experimental setup.

Figure 1 shows the experimental setup to study characteristic of methane combustion flames diluted by CO_2. Following the experimental setup, CH_4 diluted with CO_2 fed to mixing chamber and AJ non-premixed burner which air was supplied separately as co-flow method. To study equivalence ratio

variations, air, CH_4 and CO_2 flows were measured by digital mass flow controllers. Table 1 and Table 2 show that CH_4 concentration was varied between 30%-100% with CO_2 dilution with variation of fuel velocity and air velocity. Moreover, variation of equivalence ratio, fuel and air velocity were also experimented. In order to obtain uniform flow fuel, muffler and 100 micron of mesh were installed in AJ non-premixed burner which was designed for 7.5 mm of nozzle fuel exit diameter with 75 mm of nozzle air exit diameter. When fuel and air flowed into burner then they ignited to observe combustion flame characteristics. Photographs of flame characteristics were taken by digital camera. However, forward looking infrared (FLIR) camera was used for in this study for investigate local temperature of diffusion flame by infrared radiation. In addition, thermocouple was installed to measure flame temperature and recorded by data logger (HIOKI LR8431-20 Memory HI Logger).

Table 1. Variation of CH_4 and CO_2 at U_a=cm/s for U_f=0.4, 1.0 and 1.6 m/s.

CH_4 [%]	CO_2 [%]	U_f [m/s]		
100	0	0.4	1.0	1.6
70	30	0.4	1.0	1.6
50	50	0.4	1.0	1.6
30	70	0.4	1.0	1.6

Table 2. Variation of CH_4 and CO_2 at U_f=0.6 m/s for U_a=4, 5 and 6 cm/s.

CH_4 [%]	CO_2 [%]	U_a [m/s]		
100	0	0.4	1.0	1.6
70	30	0.4	1.0	1.6
50	50	0.4	1.0	1.6
30	70	0.4	1.0	1.6

4. Methodology

4.1 Flame structure

For diffusion flame, fuel needs to diffuse to oxidizer then the reaction time is longer than premixed flame. Normally, heat released from premixed flame is greater than from diffusion flame. It was noted that yellow and blue flames were known as luminous and premixed zone, respectively [12].

4.2 Gas properties

As the gas properties of CH_4 and CO_2 at 25°C, density (ρ), heat capacity (c_p), thermal conductivity (k) and lower heating value (LHV) are shown in Table 3.

Table 3. CH_4 and CO_2 properties at 25°C.

Gas properties	CH_4	CO_2
ρ [kg/m3]	421	685
c_p [J/kg•K]	2260	6200
k [W/m•K]	0.035	0.078
LHV [kJ/kg]	50000	0

4.3 Fuel velocity

In this study, fuel velocity was varied to observe flame characteristics. Fuel velocity was calculated by ratio between volume air flow rate and nozzle fuel exit area as followed by Eq. (1)

$$U_f = Q_f / A \qquad (1)$$

4.4 Air velocity

In order to obtain combustion flames on AJ non-premixed burner which was designed for 75 mm of nozzle air exit diameter, thus it is necessary to find variation of air velocity. Air velocity in this experiment can be varying by volume flow rate as shown in Eq. (2).

$$U_a = Q_a / A \qquad (2)$$

4.5 Firing rate

Firing rate is applied to express the rate of power and it is the product of low heating value and mass flow rate as shown in Eq. (3)

$$F.R. = \dot{m}_f \times LHV \qquad (3)$$

4.6 Methane concentration

Methane concentration is the ratio between volume flow rate of methane and total flow rate as shown in Eq. (4)

$$[CH_4] = Q_{CH4} \times 100\% / (Q_{CH4} + Q_{CO2}) \qquad (4)$$

5. Result and discussions

5.1. Flame structure

Figure 2 shows flame structure with variation of CH_4 and CO_2 at U_a =cm/s for U_f=0.4, 1.0 and 1.6 m/s. When CH_4 concentration was lower, the yellow flame shown in luminous zone was minimized due to dilution of CO_2. For CH_4 concentration less than 50%, higher blue flames in premixed zone was observed when fuel velocity was higher. It was caused by decrease of fuel instead of CO_2 and air could be entrained to fuel [12]. However, the extinction flame was observed at 30% of CH_4 concentration and U_f=1.6 m/s. Moreover, flame structure with variation of CH_4 and CO_2 at U_f =0.6 m/s for U_a=4, 5 and 6 cm/s were illustrated in Fig.3. Figure 4 shows the relation between CH_4 concentration and U_f at U_a=4 cm/s. At U_f=0.6 m/s, yellow flame was found for fuel velocity between 0.4-1.6 m/s and pure blue flame was found at less than 30% of CH_4 concentration between fuel velocity 0.4-1.0 m/s.

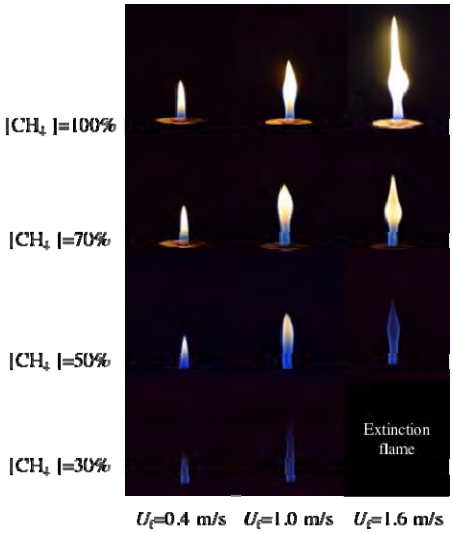

Fig.2 Flame structure with variation of CH_4 and CO_2 at U_a = 0.4 cm/s for U_f = 0.4, 1.0 and 1.6 m/s.

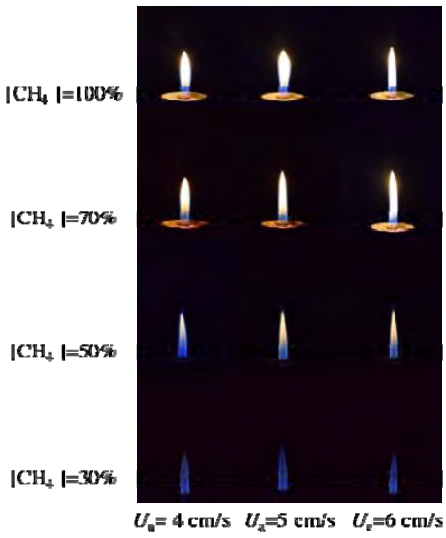

Fig.3 Flame structure with variation of CH_4 and CO_2 at U_f = 0.6 m/s for U_a = 4, 5 and 6 cm.

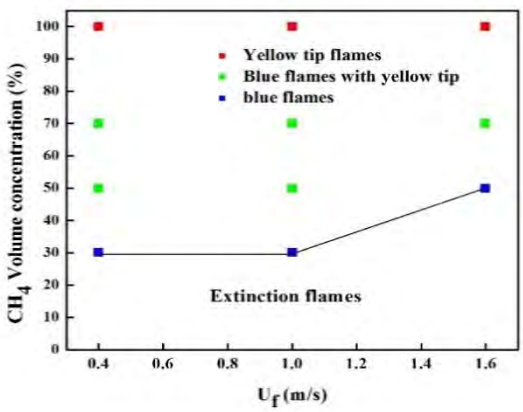

Fig.4 Relation between CH_4 concentration and U_f at U_a = 4 cm/s.

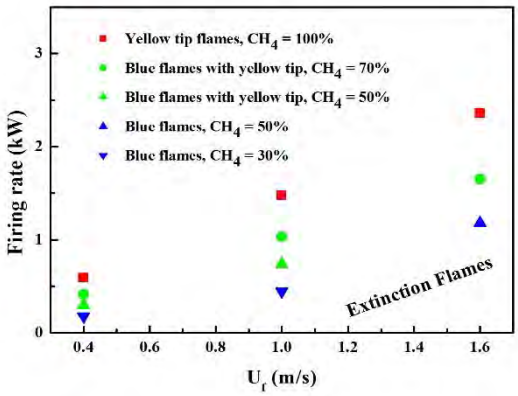

Fig.5 Relation between firing rate and fuel velocity at U_a = 4 cm/s.

5.2. Combustion diagram

The relation between firing rate and fuel velocity at U_a=4 cm/s is shown in Fig.5. Firing rate was higher when fuel velocity increased for CH_4 concentration incapable less than 30%.The diffusion flame of methane diluted by CO_2 could be operated on this AJ non-premixed burner more than 2 kW at U_f=1.6 m/s.

5.3 Flame length

Flame length could be longer by increasing of fuel velocity as shown in Fig.6 and 7. For CH_4 concentration was less than 70%, carbon dioxide affected on flame length and yellow flame was decreased obviously. However, flame length was slightly wider by variation of air velocity.

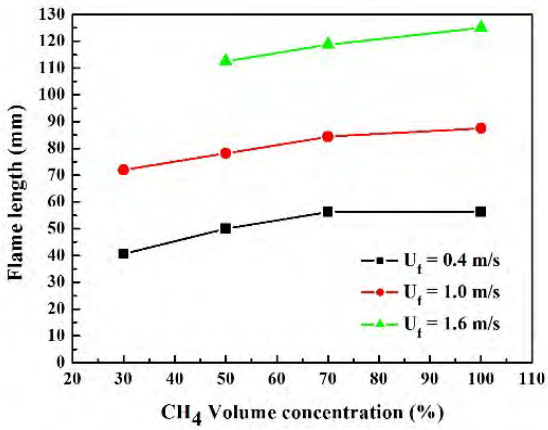

Fig.6 Flame length at U_a = 4 cm/s by varying U_f and %CH_4.

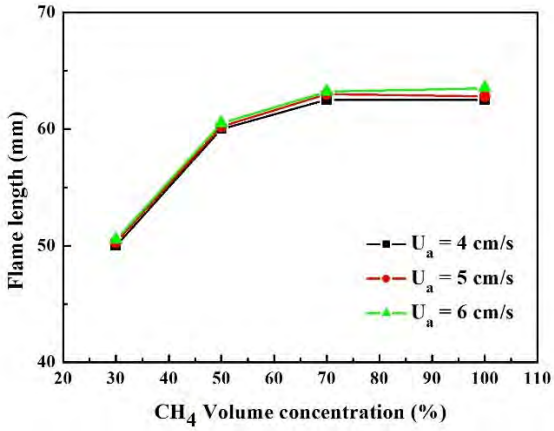

Fig.7 Flame length U_f = 0.6 cm/s with variation of U_a and CH_4 concentration.

5.4 Flame Temperature

Flame temperature of diffusion flame photos taken by FLIR camera was shown in Fig.8. As this result, temperature around cone of flame is highest because reaction area is around nozzle exit. However, higher flame temperature was obtained with lower fuel velocity and CH_4 concentration as illustrated in Fig.9.

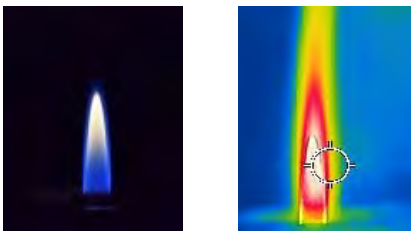

Fig.8 Comparison between flames taken by digital camera and FLIR camera

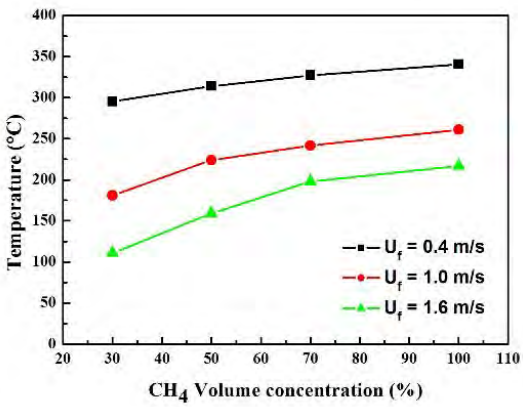

Fig.9 Relation between flame temperature and CH_4 concentration with variation of U_f.

6. Conclusions

This study was experimented with variation of fuel velocity, air velocity, CH_4 concentration and firing rate. As the results, wider flame length and lower temperature were obtain when fuel velocity increased between 0.4-1.6 m/s At the same fuel velocity, carbon dioxide was diluted in methane combustion from 30-70% by volume, flame length was decreased by much lower yellow flames and slightly higher blue flames due to well mixed between air and fuel flow rate. In addition, all blue flames could be found at less than 50% of methane concentration by volume and extinction limit was occurred at U_f = 1.6 m/s and CH_4 concentration less than 30%. It concluded that less than 70% of carbon dioxide dilution could be applicable to improve diffusion flame from methane combustion on AJ non-premixed burner.

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