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Improvement of IDF Burner Effects on Lean Non-Premixed Synthetic Thai Natural Gas Flames

Kaewpradap A.* **and Jugjai S.**

Combustion and Energy Research Laboratory (CERL), Department of Mechanical Engineering, King Mongkut's University of Technology Thonburi, Thailand

* corresponding author: amornrat.kae@kmutt.ac.th

Abstract. The combustion characteristics of lean non-premixed Thai synthetic natural gas on improved inverse diffusion flame (IDF) burner were investigated. Air and fuel nozzles were improved from normal diffusion flame burner (NDF) and set as inside and outside exits on burner, respectively. The combustion flames were studied with variations of fuel and air velocity. The luminous flame length was lower and premixed flame length was higher by designed IDF burner due to enhance of mixing between inside air and ambient air. When the equivalence ratio decreased, lower flame length and flame temperature were obtained. Moreover, the highest premixed combustion flames and the maximum temperature were observed equivalence ratio between $\Phi = 0.76\text{-}0.80$ on lean non-premixed synthetic Thai natural gas flames with designed IDF burner.

1. Introduction

Basically, the combustion flames were categorized as premixed and non-premixed flames. However, disadvantages of premixed flame such as flashback and easy blow off were considered [1]. Thus, diffusion flame as non-premixed flame was applied to operate safely without flashback. In the past, normal diffusion flame (NDF) was improved by inverse diffusion flame (IDF). The effect of air flow rate variation on methane and ethylene using soot laser-induced incandescence and hydroxyl laser-induced fluorescence [2]. As the previous study, methane combustion diluted by carbon dioxide on NDF burner was investigated [9]. In order to study methane flame structure, OH-PLIF was applied and analysed [3]. The effect of nozzle length from LPG combustion on IDF was studied. The flame structure and CO emission were resulted [4]. The comparison of LPG combustion on IDF burner between backstep and coaxial burner was investigated. The compact flame with less luminosity was shown in the backstep burner [5]. The appearance and emission characteristics of LPG IDF with swirl were investigated. The adequate entrainment and swirl effect induced low CO and NO_x [6]. The effect of IDF burner diameter on flame characteristics and emission was studied. The smaller nozzle diameters affected to higher flame temperature [7]. The characteristics and structure of natural gas IDF were studied. Following the variations of discharge nozzle and ratio of inner air jet and outer fuel jet velocities, flame length, temperature distribution and stability limit were resulted [8].

In Thailand, natural gas was applied widely in both industrial and transportation sectors [10]. There are many sources of natural gas in Thailand and it can be categorized by location as eastern and western sources. However, the average composition of natural gas consists of methane (CH_4 = 89%) and carbon dioxide (CO_2 = 11%) [11]. Nowadays, the consumption of natural gas significantly grows

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especially in the part of industry. For industrial sector, non-premixed burner was used widely to be safety. However, the natural gas combustion on non-premixed burner should be improved for energy conservation and environment. Consequently, this study focuses on improvement of NDF to IDF burner for natural gas combustion. The flame characteristics and flame temperature are observed with variation of air and fuel velocity on designed IDF burner.

2. Nomenclature

A_a	Air nozzle area (m^2)
A_f	Fuel nozzle area (m^2)
D_a	Air nozzle diameter (mm)
D_f	Fuel nozzle diameter (mm)
c_p	Specific heat (J/kg•K)
k	Thermal conductivity (W/m•K)
F.R.	Firing rate (kW)
L_f	Flame length (mm)
LHV	low heating value (kJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
Q_f	Fuel volume flow rate (m^3/s)
Q_a	Air volume flow rate (m^3/s)
T_f	Flame temperature (°C)
U_a	Air velocity (cm/s)
U_f	Fuel-inert velocity (m/s)
ρ	Density (kg/m^3)

3. Experimental apparatus

Figure 1 shows the experimental apparatus to study characteristic of natural gas combustion by using simulated gas with composition of CH_4 = 89% and CO_2 = 11% as called synthetic natural gas. Following the experimental apparatus, inverse diffusion flame (IDF) burner consists of air and fuel supplied separately as co-flow method. In order to study equivalence ratio variations, air, CH_4 and CO_2 flows were measured by digital mass flow controllers. Table 1 shows nozzle area of NDF and IDF burners. The IDF burner was designed with the same area between the fuel and air nozzle area (44.16 mm^2). Moreover, variation of equivalence ratio by decrease of fuel velocity (U_f) at U_a = 13.4 m/s and increase of air velocity (U_a) at U_f =1.59 m/s were also experimented as shown in table 2 and 3. When fuel and air flowed into burner and ignited, the combustion flame characteristics were observed. Photographs of flame characteristics were taken by digital camera. In addition, thermocouple was installed to measure flame temperature and recorded by data logger (HIOKI LR8431-20 Memory HI Logger).

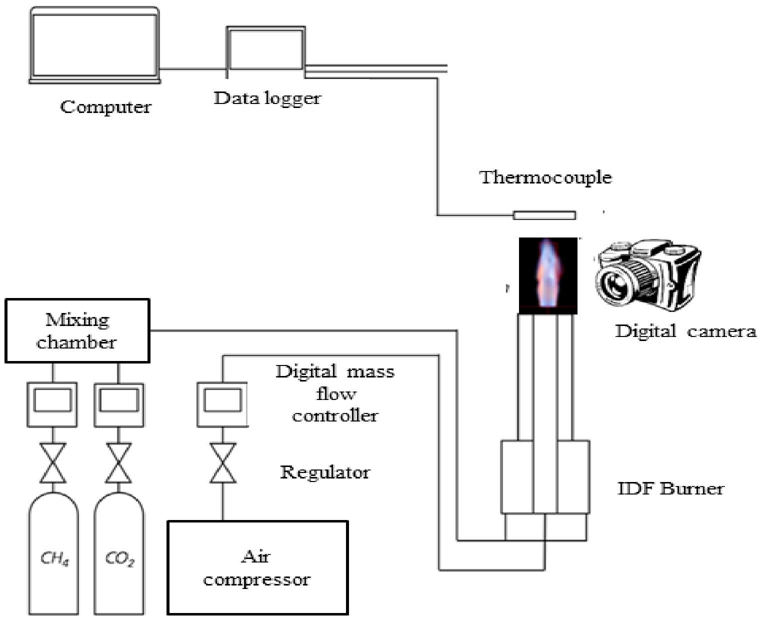

Figure 1. Experimental apparatus.

Table 1. Nozzle diameter and area of NDF and IDF burners.

Burner	Nozzle area (mm^2)	
	A_f	A_a
NDF[8]	44.16	4415.63
IDF	44.16	44.16

Table 2. Variation of air velocity for equivalence ratio between 0.72-1.00 at U_f = 1.59 m/s.

Φ [-]	U_a [m/s]	U_f [m/s]
1.00	13.14	1.59
0.96	13.66	1.59
0.92	14.26	*1.59*
0.88	14.94	*1.59*
0.84	15.62	*1.59*
0.80	16.45	*1.59*
0.76	17.28	*1.59*
0.72	18.26	*1.59*

Table 3. Variation of fuel velocity for equivalence ratio between 0.72-1.00 at U_a = 13.4 m/s.

Φ [-]	U_a [m/s]	U_f [m/s]
1.00	13.14	1.59
0.98	13.14	1.53
0.96	13.14	1.47
0.94	13.14	1.*40*
0.92	13.14	1.34
0.90	13.14	1.28
0.88	13.14	1.21
0.86	13.14	1.15
0.84	13.14	*1.08*

0.82	13.14	*1.02*
0.80	13.14	*0.96*
0.78	13.14	*0.89*
0.76	13.14	*0.83*
0.74	13.14	*0.77*
0.72	13.14	*0.70*

Table 4. Properties of CH_4 and CO_2 at 25°C.

Gas properties	CH_4	CO_2
ρ [kg/m^3]	421	685
c_p [J/kg•K]	2260	6200
k [W/m•K]	0.035	0.078
LHV [kJ/kg]	50000	0
Thai Natural Gas composition [%]	89	11

4. Methodology

4.1. Gas properties

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 4.

4.2. Flame structure analysis

Figure 2 shows diffusion flame structure that consists of flame length, luminous and blue zones [6]. As the diffusion flame, fuel needs to diffuse to oxidizer then the reaction time is longer than premixed flame. Heat released from premixed flame is greater than from diffusion flame. Following the diffusion flame structure, blue zone and luminous zones reflected to premixed and non-premixed zones.

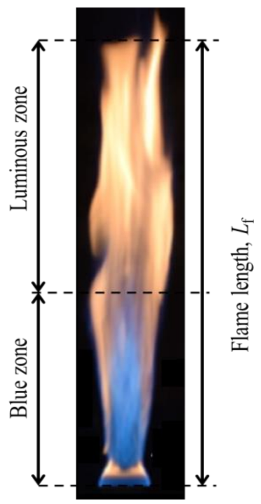

Figure 2. Diffusion flame structure [6].

4.3. Flow velocity

In order to obtain combustion flames on IDF burner which was designed for 7.5 and 10.6 mm of air and fuel nozzle diameter, thus it is necessary to find variation of air and fuel velocity. Fuel and air velocity were calculated by ratio between volume flow rate and nozzle exit area as followed by equation (1) and (2).

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

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

5. Methodology

5.1. Flame structure

Figure 3 shows diffusion flame on NDF burner with variation of fuel velocity for methane concentration between 30-100% [8]. In order to improve natural gas flame combustion, IDF burner was designed with air nozzle as inner exit and fuel nozzle as outer exit. The diffusion flames on IDF burners with variation of fuel and air velocity were observed. At U_a = 13.4 m/s, the fuel velocity decreases, luminous zone becomes less and flame length is lower as shown in figure 4. It is because of rich combustion with inadequate air at U_f = 1.59 m/s. Figure 5 illustrates the air velocity decreases with U_f = 1.59 m/s and slightly luminous zone was shown at U_a = 13.14 and 13.66 m/s due to less air effect with incomplete combustion. However, the results shows much premixed zone of diffusion flames obtained from IDF burner compared to diffusion flames from NDF [8].

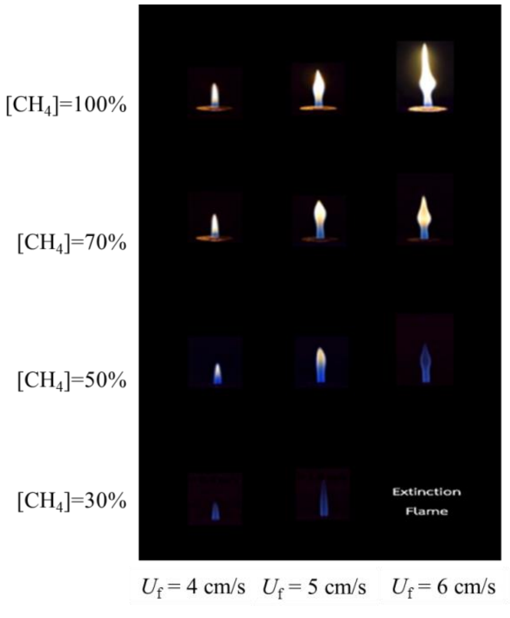

Figure 3. Diffusion flame on NDF burner with variation of fuel velocity for methane concentration between 30-100% [8].

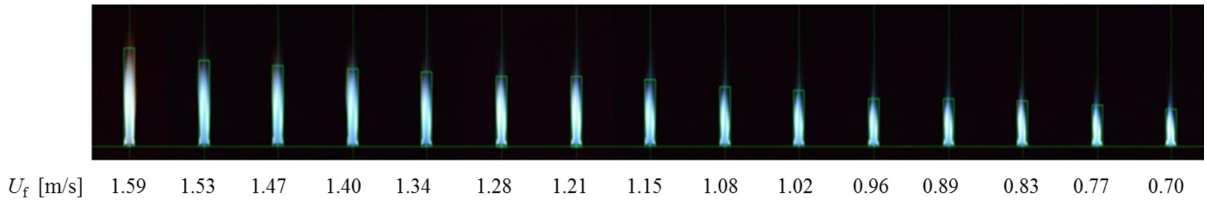

Figure 4. Diffusion flame on IDF burner with variation of fuel velocity at Ua = 13.4 m/s.

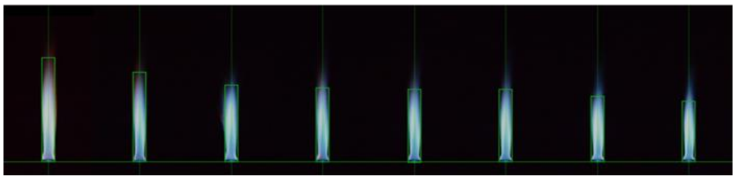

Figure 5. Diffusion flame on IDF burner with variation of air velocity at Uf = 1.59 m/s.

5.2. Flame length
Figure 6 shows flame length (L_f) on IDF burner with variation of equivalence ratios. Following variation in table 2 and 3, the equivalence ratio becomes lower when air velocity increases and fuel velocity decreases. When equivalence ratio decreased, flame length was lower owing to exceed air and less fuel in lean combustion.

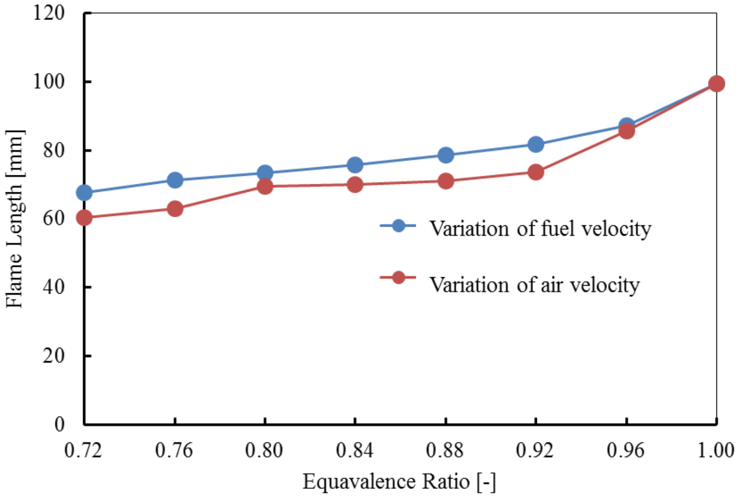

Figure 6. Flame length (L_f) on IDF burner with variation of equivalence ratios.

5.3. Flame temperature
Figure 6 shows flame temperature (T_f) on IDF burner with variation of equivalence ratios. When the equivalence ratios were decreased by decrease of fuel velocity and increase of air velocity, flame temperatures became lower. For Φ = 0.76-0.80, maximum flame temperature was observed because only appearance of premixed zone was shown.

6. Conclusion
In this study, IDF burner was designed with the same area of air and fuel nozzle (A_a:A_f, 1:1) to improve natural gas combustion by using simulating gas with composition of CH_4 = 89% and CO_2 = 11% as called synthetic natural gas. The results are concluded as this followings.

1. The lower flame length and much premixed zone were obtained from IDF burner compared to NDF burner. The results reflected that the combustion was improved
2. When the equivalence ratio decreased during lean combustion, flame length and luminous zone were lower.

When the equivalence ratio decreased during lean combustion, flame temperature was lower. However, the maximum flame temperature was observed between Φ = 0.76-0.80.

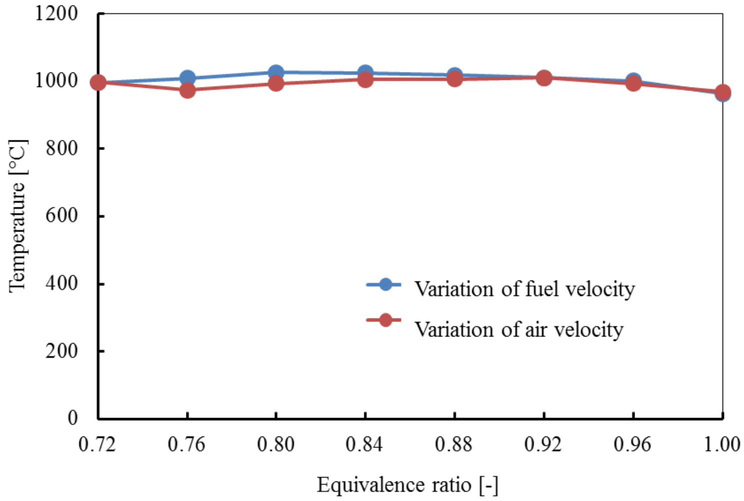

Figure 7. Flame temperature (T_f) on IDF burner with variation of equivalence ratios.

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