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A FLOW-FIELD STUDY OF LIFTED FLAMES IN LOW-SWIRL COMBUSTOR

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ABSTRACT

This article describes an investigation of preliminary combustion characteristics with various thermal powers and equivalence ratio in low-swirl combustor. The most significant feature of low-swirl combustion is lifted flame. This lifted flame happened to combine feature propagating flame of premixed combustion with swirl flow. The swirl number as a main parameter in this work was from 0.42 to 0.49. It is confirmed that this low-swirl combustor had a wide turndown ratio of about 11:1 and was operated within thermal power of 2 - 21kW for our laboratory scale. The attempt is made to confirm the generation of uniform velocity profiles near exit nozzle without the inner recirculation zone. For this, the PIV system, hot wire anemometer and pitot tube measuring were employed in this work. It is also confirmed that the flashback didn't occur since over 4kW in this experimental thermal power range.

KEYWORDS: Lean premixed, Low swirl, Divergent flow, Swirl number, Flashback, PIV measurement

1. INTRODUCTION

Principal combustion technology of low emission combustion is lean premixed combustion. This technology has been applied in many combustion systems. Also, swirl is the predominant flow mechanism found in premixed and non-premixed combustion systems because it provides an effective means to control flame stability as well as the combustion intensity. Most practical systems have been utilized high swirl in which the swirling motion is sufficiently intense to generate a large and stable internal recirculation zone (IRZ) that is also known as the toroidal vortex core. As it well known, the mechanism of NOx formation is mainly a function of local flame temperature and residence time of the generated species within the reaction zone. By the way, the disadvantage of swirl induced premixed combustion, especially high swirling flames, is attributed to the hot spots with long residence time due to the recirculation zone, which acts as thermal NOx production source. Low swirl combustion has been designed by R. K. Cheng et al. in order to eliminate the recirculation zones of the traditional stabilization method. As the regulation of NOx advances daily, it is proposed that the low swirl combustion is available technology and shows similar emission performance compared with high swirl combustion or even lower NOx without hot spots like high swirling flames. The low swirling combustion is also the verified technology which is always able to sustain stable combustion without flame blow-off despite of tolerable disturbance. Also, it rarely happens the flashback because of their self-similarity characteristics. The lifted flame in low swirl burner can be sustained at constant position regardless of mixture velocity due to the restructured uniform flows newly themselves by diverging flow. It has been known that the key point of low swirl combustion is using propagation characteristics of turbulent premixed flame. And, the typical characteristics of low swirl flame is that the turbulent-mixing flame always lift-off from nozzle exit. Therefore, the concept of low swirl combustion differs radically from high swirl combustion that has always a strong and robust inner recirculation zone.

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2. EXPERIMENTAL SYSTEM

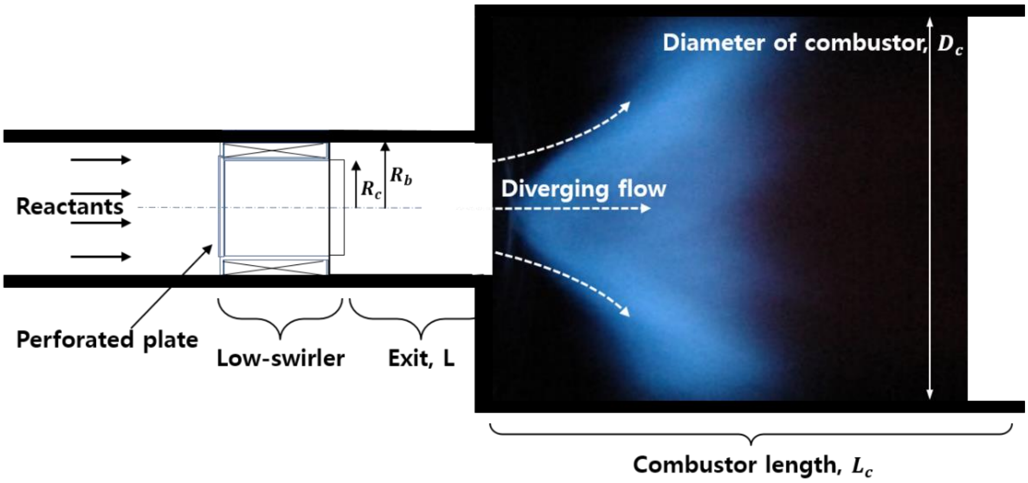

Fig 1 Schematic of nozzle head parts for the low-swirl combustor

The experimental setup is shown in Fig. 1. In low swirl combustion, there are generally the swirler angle (α), nozzle recess length (L), thermal power (Q), equivalence ratio (∅) as main parameter that influenced flame shape and behavior of low swirling flames.

Table 1 Experimental conditions

Parameters	Range
Fuel	CH_4
Oxidizer	Air
Swirl number	$0.42 < S < 0.49$
Dia. of nozzle($d_0 = 2R_b$)	28mm
Dia. of combustor(D_c)	74mm
Thermal power(kW)	2.0 - 8.0
Equivalence ratio(∅)	0.6 – 1.3

Experimental conditions in this work are listed in Table 1. The combustor chamber is simulated using a fused quartz with 74mm inner diameter and 350mm long. Equivalence ratio was adjusted from 0.6 to 1.3 with intervals of 0.1 through the method of altering air flow rates in fixed state of fuel flow rates to identical thermal power. It was confirmed that the flames could sustain up to 21kW in our laboratory scale, however, the thermal power range was from 2.0 to 8.0kW in this study. As a preliminary study, this work was conducted at fixed parameter that had swirl angle of 37°, perforated plate porosity of 29.6% and recess length of 33.5mm, separately. Fuel and the oxidizer are methane and air.
Swirl number of swirler employed in this study is defined as following formula:

$$S = \frac{\int_0^{R_b} UWr\,dr}{R\left(\int_{R_c}^{R_b} U^2 r\,dr + \int_0^{R_c} U^2 r\,dr\right)} = \frac{\frac{2}{3}tan\alpha(1-R^3)}{(1-R^2+\frac{U_c^2 R^2}{U_a^2})} = \frac{2}{3}tan\alpha\,\frac{1-R^3}{1-R^2+\left[m^2\left(\frac{1}{R^2}-1\right)^2\right]R^2} \quad (1)$$

and

$$R = R_c/R_b \quad (2)$$

and

$$m = \dot{m}_c/\dot{m}_a \quad (3)$$

R_c is radius of portion unswirled flow passages, R_b is radius of burner nozzle. U_c is axial direction velocity as bypassed reactant in center swirler, $U_a$is average axial direction velocity of swirler outside annulus. M means mass flow ratio, $\dot{m}_c$ is mass flow rate that passed center of swirler, and $\dot{m}_a$ is mass flow rate that passed swirler outside annulus. Hence, the swirl number in this study has range of 0.42 < S < 0.49.

3. RESULTS AND DISCCUSSION

Figure 2 shows direct photo that appeared different shapes of flame according to the variation of the equivalence ratios and the thermal powers each for 3kW ~ 7kW. At all thermal power, it is confirmed that the lifted flame heights were decreased with increase of equivalence ratio until near 1.0 and then were increased again over equivalence ratio of 1.1. Which phenomenon is coincided with flame speed trend with respective to the equivalence ratio. In other words, we had recognized that the propagation velocity characteristics of premixed flame in low swirl combustion were appearing with diverging flow.

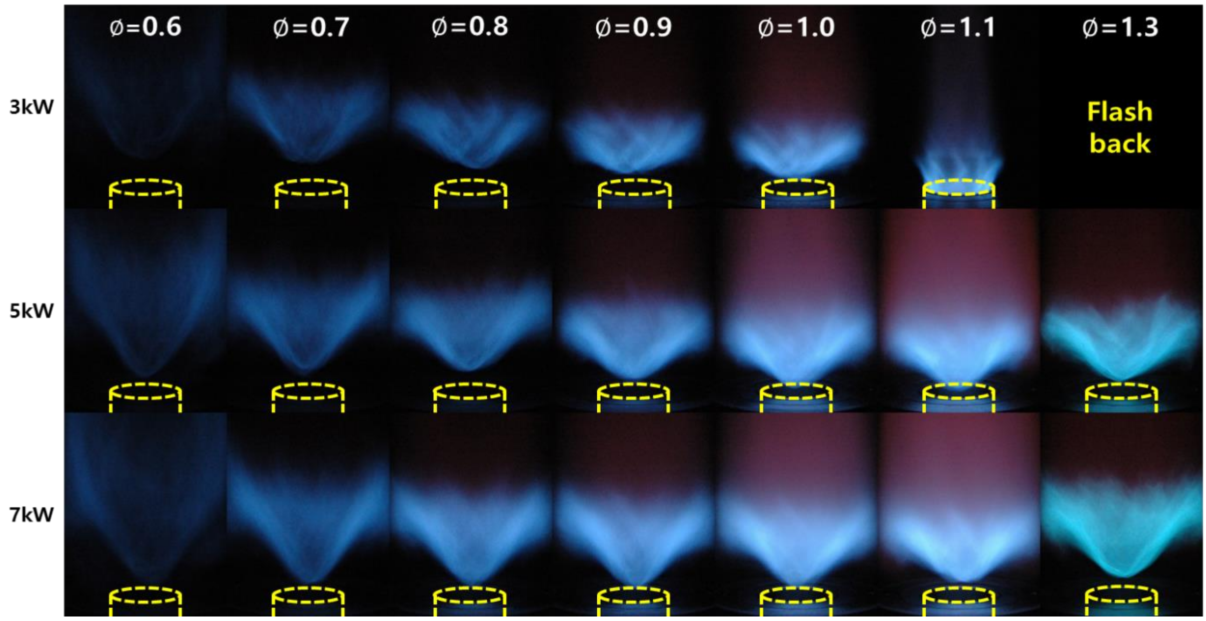

Fig.2 Direct flame photo of low-swirl combustion with different thermal power and equivalence ratio

As can be seen from the Figure 2, the flame shows sucked back into the burner at thermal power 3kW and equivalence ratio 1.1. This is that due to low flow rates, the exit velocity of burner is slower than propagation velocity of turbulent flame, so that the flash-back has occurred with in-burning flames. Occasionally, the flash-backed flame would be formed on perforated plate. However, we confirmed that the flash-back seldom occurred since over the 4kW thermal power in this study because the burner exit velocity correspond to over 4kW flow rates was always faster than the propagation velocity of turbulent flame. Such this phenomenon could be explained with self-similarity, which is defined as following equation (4).

$$U_0 - \frac{dU}{dx}\left(x_f - x_0\right) = S_T \quad (4)$$

and

$$\text{Damköhler model}: \frac{S_T}{S_L} = 1 + \frac{Ku\prime}{S_L} \quad (5)$$

Where, U_0 ,S_T, S_L are the axial velocity of mixture, the turbulent and the laminar burning velocity, respectively. x_f, x_o represent the virtual position of linear velocity origin and the position of the flame front.

The equation was arranged as equation (6) using model equation of Damköhler that the turbulent burning velocity is linearly dependent on the rms velocity of the turbulence intensity, u' such as equation (5).

$$1 - \frac{dU}{dx}\frac{(x_f - x_0)}{U_0} = \frac{S_L}{U_0} + \frac{Ku'}{U_0} \tag{6}$$

$where,\ u'$ is rms velocity value, K is an empirical correlation constant that is 2.16 for case of methane. Hence, $[(dU/dx)/U_0]$ value and Ku'/U_0 value are a regular constant, S_L/U_0 is very small value relatively. Therefore, the equation (6) say why the lifted flame position in low swirling flames is always maintained at a constant lift-off height above nozzle exit without blow-off. Equation (6) also informs that the flame moves closer to the burner exit with decreasing U_0 until the flash-back occurs when $x_f - x_0 = 0$.

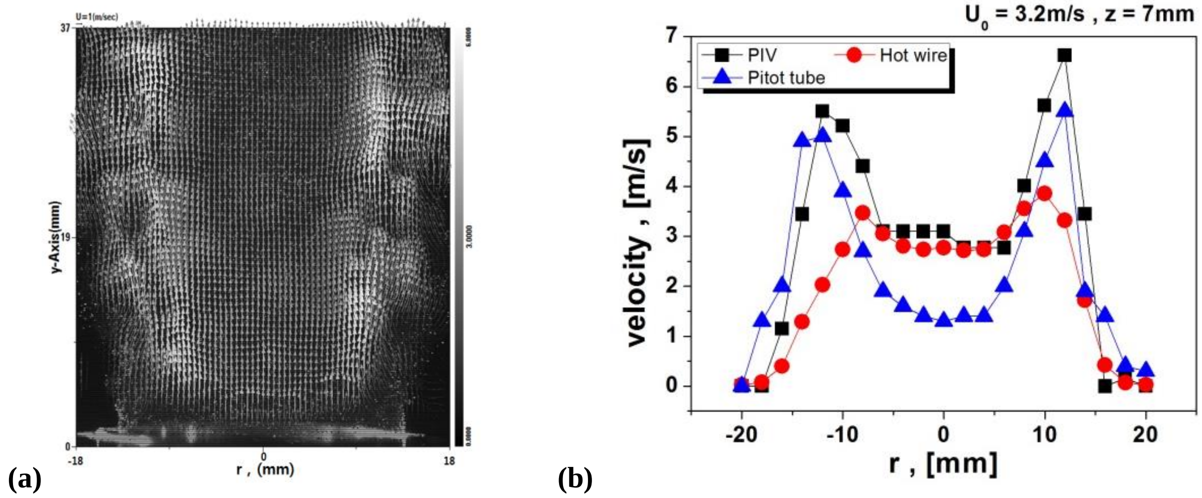

Fig. 3 (a) PIV result of low-swirl combustion with thermal power 5kW and equivalence ratio ∅ = 0.8 (U_0 = 3.2m/s) **(b)** Comparison PIV, Hot wire and Pitot tube measurements

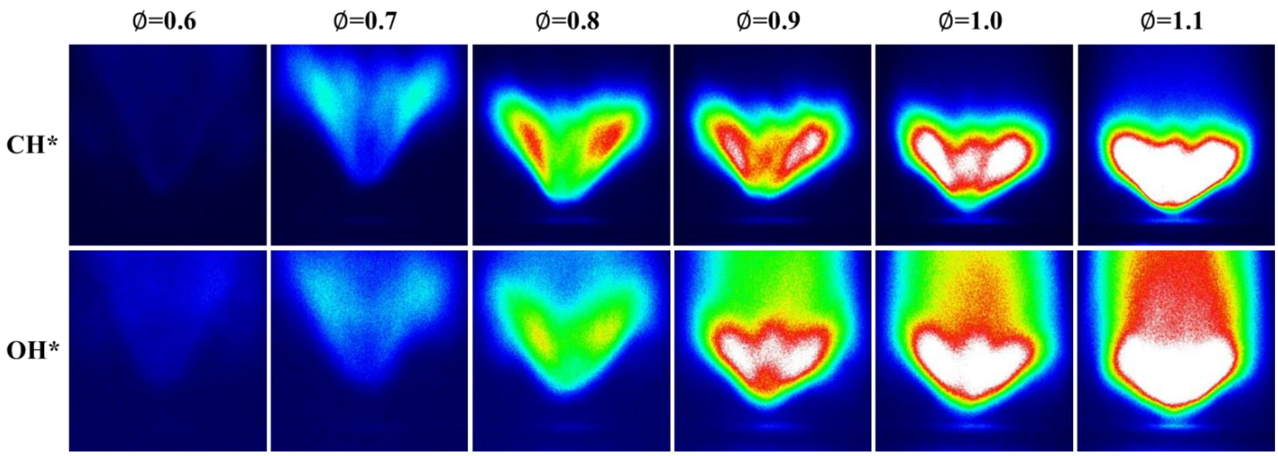

Fig 4 CH* and OH* radical images for 5kW

Figure (3-a) shows the visualized uniform flow field using PIV measurements. This picture was shown about flow field of non-reacting state at Q = 5kW, ∅ = 0.8. As you can see in the figure (3-a), it is confirmed that the flow field at center part of diverging flow is uniform. We compared measure result with figure (3-b) using PIV system, hot wire anemometer and pitot tube to verify the flow uniformity. When we measured the velocity profiles with three instruments, the results were for open flame without quartz glass tube. As is shown in Fig. 3 (b), there were a little difference depending on the employed measure equipment. Nevertheless, Fig. 3 (b) shows the velocity profiles are relatively uniform flow field at for all of 3 measuring results. Therefore, it was confirmed that the low swirl burner in present study was well designed to study continuously on low swirl combustion. Figure 4 shows the CH^* and OH^* images taken a flame picture using ICCD camera. At thermal power 5kW, we had photographed CH* radical and OH* radical chemiluminescence image adopted optical filter at front of the camera. The characteristics of radical chemiluminescence in fla me generally gave an insight into the combustion state within the reaction field. In generally, the C H* radical represents a barometer of reaction front, while the OH* radical concentration is usually d istributed along the heat release place. And, it is well known that the distribution of OH* radical concentration has a strong correlation with flame temperature, and the CH* is deeply correlated to form the rapid NO mechanism. Therefore, they will have very important roles on NOx generation. From the radical visualizations of Figure 4, we could identify the decrease of radical intensities as flames moved into more lean condition.

4. CONCLUSIONS

In this study, it was conducted a study on the velocity profiles and flame chemiluminescence as the preliminary work to confirm the flow uniform capacity in our low-swirl burner. Especially, the aim is made to confirm the generation of uniform velocity profiles from exit nozzle without the inner recirculation zone like high swirl burner. For this, the PIV, hot wire and pitot tube instruments were employed in this work. And, from analyzing characteristics of flame chemiluminescence with CH* and OH* radical using ICCD camera, the heat release uniformity could be shown. Through these results, it is confirmed that the uniform flow field, which is a core technology, has to be generated if low swirl combustion can be available. Also, we could consider that our low swirl burner from present study was well designed to study continuously on low swirl combustion in the future.

ACKNOWLEDGMENT

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NOMENCLATURE

Q	thermal power	(kW)	ϕ	equivalence ratio	
U_0	mean velocity	(m/s)	m	mass flow ratio	
S_T	turbulence burning velocity	(m/s)	S_L	laminar burning velocity	(m/s)

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