

IMPROVEMENT IN FLAME STABILITY OF DIFFUSION FLAME USING A BLUFF-BODY SWIRLING JET COMBUSTOR

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ABSTRACT

Based on past research, the flame stability of various combustion areas is being debated. However, the mechanism of flame stabilization is not yet fully understood, nor is there any systematic research being done into flame stabilization. Especially lacking is any research regarding hybrid combustion areas where swirl flow has been added to flames formed in bluff body type combustors. As a result of this knowledge regarding flame stability is sparse. With this research, an investigation has been carried out into the temperature fields, flow fields, and the flame characteristics formed in currently available bluff body combustors that have been induced with swirl flows and who's annular has been attached with a swirler. Also looked at is flame stability. In this study measurements were carried out on the special characteristics of flames in the case of a swirl flow being added to a diffusion flame using a bluff body combustor. Also measured were the flow fields and temperature fields; flame stability also being examined. The results are as follows. By conferring a swirl flow to a bluff body combustor, there was an improvement in flame stability. And In the flames formed by a bluff body combustor, the often observed hysteresis phenomenon could not be seen when a swirl flow was added. Addition, The improvement in stability achieved by adding a swirl flow to the combustion field is thought to be achieved by the air flow being extended to the radial by centrifugal force, causing near the flame surface, the formation of a velocity which balances a temperature field that maintains a high temperature range and combustion velocity.

INTRODUCTION

As the world is facing issues such as the exhaustion of fossil fuels due to a rapid increase in energy consumption, as well as environmental pollution on a global scale, more efficient combustion technology that makes effective use of limited resources is being sought after. Also, there is a call for the development of green combustion technology in order to avoid

further air pollution and global warming. However, on the other hand, it is also demanded that combustion technology must also be compatible with the diversification of fuels, the usage of fuels in accordance with combustion technology for the purpose of the diversification of usable technologies, while also possessing high stability, high capacity, high regulation, and low noise, etc.

Moreover, in recent years, due to economizing and regional decentralization, the developments of compact combustors that produce low levels of exhaust are also being sought after. In practical combustors, the majority of diffusion flames confer swirl flow to the flow of air in order to facilitate the mixture of fuel and air, as well as carrying out a means of establishing bluff body.

Previous research regarding swirling jet combustors has made clear flame structure by measuring velocity distribution, turbulence intensity, temperature and gas concentration in combustion fields [1-4]. Also, research [5] is being carried out regarding the flame stability of combustors which have had the shape of their fuel nozzle changed after adding swirl flow to the air flow of the annulus. Regarding research on bluff body combustors, Chen et al. [6] have conducted a systematic investigation into flame form and flame stability. This was done using a bluff body combustor with a fuel nozzle diameter of 3.5mm, and a bluff body diameter of 45mm. As a result, flame form was divided into the following 5 classifications: recirculation zone flame, central control flame, jet flame, local extinction flame and lift flame. They also made clear the relation of lift height with the speed of liquid fuel as a flame characteristic. They proved that lift height matches single jet flame regardless of annular air flow speeds, as well as the existence of a hysteresis region that shows traces of lift height when the fuel flow rate is reduced. This result differs when the fuel flow rate is increased. Dano et al. [7] point out that the ratio of fuel flow rate and air flow rate along with the bluff body form affects the process of flame stabilization. Moreover

Nishimura et al. [8,9] investigated the flame stability of annular air flow when it is at a low flow rate range, the relationship of hysteresis region with air flow velocity, and flame bifurcation phenomenon within the hysteresis region. In the area of research regarding spin flow being added to bluff body combustors, Huang et al. [10,11] are researching the flow structure and temperature range of non-combustion area and combustion area occurring in low flow rate range. Yasir et al. [12,13] are taking measurements of the flow area of the non-combustion area and combustion area of a high flow rate using a laser Doppler velocimeter. They are also using a Raman-Rayleigh-LIF to conduct spot measurements of chemical species concentration and the temperature within diffusion flame. They also classified flame formation of the swirl flow combustion area. The results of these experiments are made public on their respective websites [14] and are used as benchmarks.

Based on past research, the flame stability of various combustion areas is being debated. However, the mechanism of flame stabilization is not yet fully understood, nor is there any systematic research being done into flame stabilization. Especially lacking is any research regarding hybrid combustion areas where swirl flow has been added to flames formed in bluff body type combustors. As a result of this knowledge regarding flame stability is sparse. With this research, an investigation has been carried out into the temperature fields, flow fields, and the flame characteristics formed in currently available bluff body combustors that have been induced with swirl flows and who's annular has been attached with a swirler. Also looked at is flame stability.

NOMENCLATURE

D_i	[mm]	Inner diameter of annular swirling jet exit
D_j	[mm]	Fuel nozzle exit diameter
D_o	[mm]	Outer diameter of annular swirling jet exit
H_L	[mm]	Lift height
L_F	[mm]	Flame length
Re_a	[-]	Exit Reynolds number of annular air flow ($= (D_o - D_i) \cdot U_a / \nu_a$)
Re_f	[-]	Exit Reynolds number of central fuel jet ($= D_j \cdot U_f / \nu_f$)
S	[-]	Swirl number ($= \frac{2}{3} \frac{1 - (D_i/D_o)^3}{1 - (D_i/D_o)^2} \tan \alpha$)
U_a	[m/s]	Volumetric mean axial velocity of annular swirling jet at exit
U_f	[m/s]	Volumetric mean axial velocity of central fuel jet at exit
U_{fc}	[m/s]	Volumetric mean axial transitional velocity of central fuel jet at exit
α	[deg]	Swirl angle
ν_a	[m ² /s]	Kinematic viscosity of air
ν_f	[m ² /s]	Kinematic viscosity of fuel

EXTERNAL BOUNDARY CONDITIONS

A schematic diagram of the burner and swirl generator used in these investigations are shown in Fig.1. The swirl generator can exchange the whole fuel nozzle part. The swirl generator is

attached to the annular part that an air flow passes, and this formed the direction board in the section of the 30mm upper stream part from the burner exit, and attached at the angle. Table 1 shows the swirl angle and swirl number which were used in this experiment. Furthermore, Table 2 shows the operation range of fuel flow and air flow in this experiment.

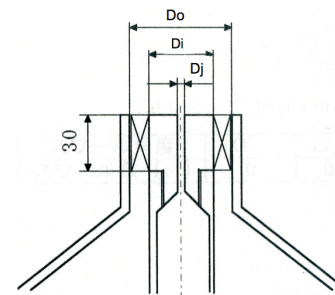
Table 1 Swirl angle and swirl number

Swirl angle α (deg)	0	22.5	33.75	45	60
Swirl number S [-]	0	0.35	0.56	0.83	1.45

Table 2 Experimental conditions

	Fuel (C ₃ H ₈)	Air
Flow rate Q(L/min)	0 - 30	0 - 120
Velocity U (m/s)	0 - 70.74	0 - 1.38
Reynolds number Re (-)	0 - 47687	0 - 1781

Commercial-grade propane was employed as the fuel gas. The diameters of the fuel nozzle D_j , the inner annulus D_i and the outer annulus D_o are 3mm, 36mm and 56mm, respectively. The streaklines are visualized by particle paths using green light scattered from Al₂O₃ particles, 3.5 μ m in mean diameter carried in the fuel and air flows. The light from a 2W Argon ion laser formed into a sheet is used for illumination. A high-speed particle image velocimeter (PIV) system is used to measure the unsteady flow structure in the flames. The system consists of an Nd:YLF pulsing laser, a high-speed camera, an electronic synchronizer, and desktop computer installed with the sequence control, image acquire, and PIV analysis software. The men temperature is measured a thermocouple of Pt-Pt/Rh 13%, 75 μ m in diameter.



(b) Appearance photograph of combustor

Figure 1 Combustor

RESULTS OF THE EXPERIMENT AND CONSIDERATIONS

For the purposes of this research, flame stabilization is defined by the existence of depression effect caused by the blowing about and rising (lift flame) of flames. I will especially be focussing on the phenomenon of lift flame and will analyse flame stability.

Flame Formation

Generally, flames formed in a bluff body type combustor are greatly transformed by the interaction of fuel flow and air flow. Flame forms are also categorized into “fuel penetration form”, fuel flow that has been formed in the bluff body background penetrating the recirculation zone, and “fuel non-penetrated form”, fuel flow which has been suppressed by air flow. These flame forms observed in combustion areas are also further categorized into four larger groups: flame base that clings to the inner edge of the bluff body known as “inner flame”; flame base that clings to the outer edge of the bluff body known as “outer flame”; “recirculation zone flame”, which are flames that have been caught up in the recirculation whirl formed in the bluff body; and finally “lift flame” defined as flame base that has separated from the bluff body and has stagnated after coming to a raised state.

In this research on the flame formation of combustion areas where swirl flow has been added to a bluff body combustor, two forms have been observed: inner flame (adhesion flame) and lift flame. In Fig.2 directly observable is a flame where the swirl angle α has been transformed, with air flow rate at $U_a=1.04\text{m/s}$, and fuel flow rate at $U_f=37.73\text{m/s}$. Also the distance from the burner rim to the flame base is defined as the lift height. Both are noted in Fig. 2. In fig. 2 (a), swirl angle $\alpha=0\text{deg}$ the flames are lift flames which have risen up from the burner rim by approx. 40mm and are violently oscillating in the flow direction. Also, in the vicinity of the flame base, the formation of non-luminous flame (blue cone) caused by the onset of premixing can be seen; the lower flow section is formed by luminous flame which is a characteristic of diffusion flame. In fig. 2 (a) (b) where swirl angle α has been increased, it can be seen that lift height is gradually decreasing while on the contrary the flame base is extending to the radial while vibrating greatly. However in fig. 2 (d) $\alpha=45\text{deg}$, the flame base becomes an inner flame adhering to the burner rim. In the vicinity of the outer edge of the flame base, there was an outbreak of spiral shaped wrinkles; while in fig. 2 (e) $\alpha=60\text{deg}$, it was observed that the disturbance of these wrinkle formations became even greater.

Next I set the air flow at a constant rate, and examined the effects of swirl angle when the fuel flow rate is changed. Fig. 3 shows flames with a swirl angle of $\alpha=0\text{deg}$, 60deg , with $U_a=1.0\text{m/s}$ being set as a constant, and $U_f=18.80\text{m/s}$ being changed to 37.73m/s . In fig. 3 (a), in comparison with flame formation which is adhesive flame being inner flame at $\alpha=0\text{deg}$ and $U_f=18.86\text{m/s}$, when it becomes $U_f=37.73\text{m/s}$ the flames make the transition to lift flames. However in fig 3 (b) $\alpha=60\text{deg}$ and $U_f=18.86\text{m/s}$, the flames become inner flames as in the case of fig. 3 (a) $\alpha=0\text{deg}$. Also, it can be seen that the luminous flame area that forms in the lower flow section, tends

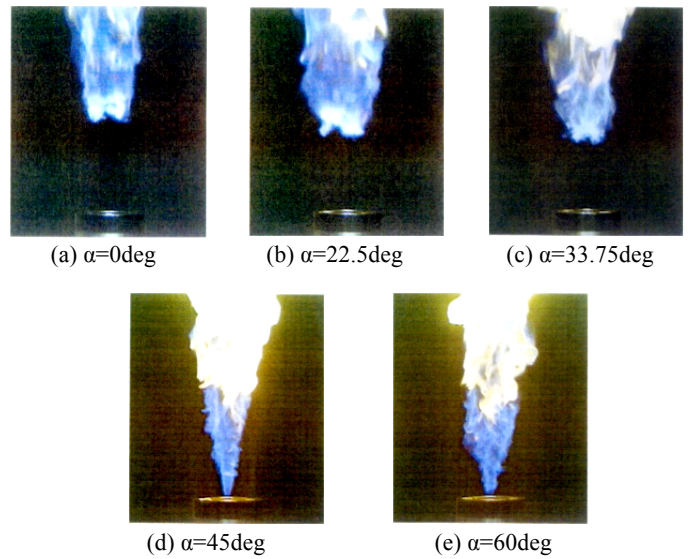


Figure 2 Direct photograph of flame ($U_a=1.04\text{m/s}$, $U_f=37.73\text{m/s}$)

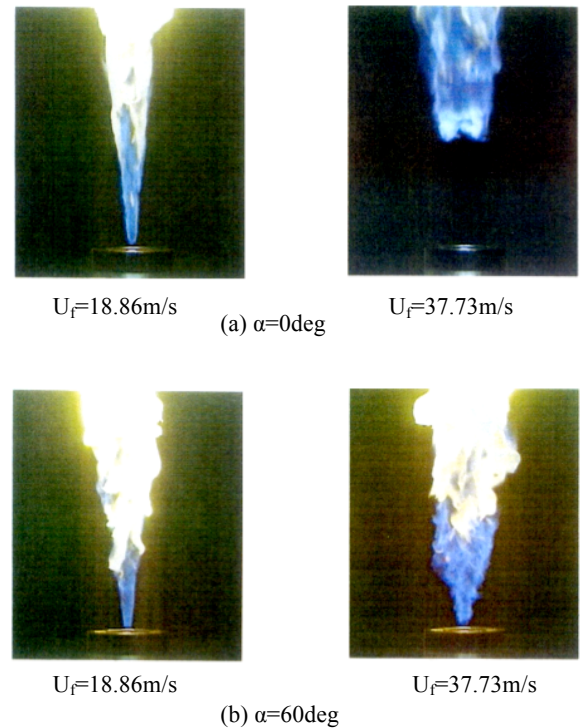


Figure 3 Direct photograph of flame ($U_a=1.04\text{m/s}$)

to form in the upper flow area compared when to when at $\alpha=0\text{deg}$. In fig. 3 (b), when it becomes $U_f=37.73\text{m/s}$, differing from the lift flame that forms at $\alpha=0\text{deg}$, adhesive flame (inner flame) forms, and the flame surface greatly expands toward the lower flow section.

From these results, it can be thought that the increase of swirl angle and air flow is effective in helping to promote flame stability.

Flame Characteristics

For the purposes of investigating in detail the effects that changes in swirl angle and air flow have on flame stability, We examined the flame characteristics of the lift height of lift flame and also flame length. Because of the large vibrations of the flame base and flame head, filming was carried out with a digital video camera and an averaged value of a ten second image was used for the measurement value of lift height and flame length.

In fig 4., air flow velocity was set at $U_a=1.04\text{m/s}$ and 1.38m/s , and shows lift height when fuel flow velocity is changed. Lift height becomes dimensionless with the fuel nozzle diameter D_j . As a parameter, the value of swirl angle change has been shown, and the values of the increase/decrease seen in fuel flow velocity have also been noted. Fig. 4 (a) $U_a=1.04\text{m/s}$, with a setting of $\alpha=0$, adhesive flame forms in the vicinity of $U_f=21\text{m/s}$, however above $U_f=21\text{m/s}$ there is a sudden transition to lift flame. After this, in conjunction with the increase in fuel flow velocity, the often seen change in lift height is not observed. When the values exceed $U_f=40\text{m/s}$ however, there is a re-increase, and finally it is extinguished at $U_f=65\text{m/s}$. Next, when reducing fuel flow velocity, up until $U_f=21\text{m/s}$ the reaction is the same as when the fuel flow velocity was increased, however below $U_f=21\text{m/s}$ again there is the onset of an increase in lift height. These results show that compared with an increase/decrease in fuel flow velocity, the situation where lift height doesn't follow the same course, hysteresis phenomenon is observed even at $\alpha=22.5^\circ$, although the region is small. At $\alpha=33.75\text{deg}$, lift height is almost 0 up to $U_f=28\text{m/s}$. At this level adhesive flames form, however any further than this and they make the transition to lift flames. Under these same conditions, conversely reducing fuel flow velocity, the hysteresis phenomenon observed at $\alpha=0\text{deg}$, 22.5deg does not appear. Again, if the swirl angle is increased to $\alpha=45\text{deg}$, 60deg , fuel flow velocity U_f of the transition to lift flame becomes greater and the Hysteresis phenomenon does not emerge. Furthermore, with the increase of U_f , the flames at $\alpha=0\text{deg}$, 22.5deg , 33.75deg are finally extinguished in the vicinity of $U_f=68\text{m/s}$. The flames at $\alpha=0\text{deg}$ with an air flow velocity of $U_a=1.38\text{m/s}$ in fig. 4 (b), maintain an inner flame at a vicinity of up to $U_f=21\text{m/s}$, however if this is exceeded they become extinguished. The cause of this will not be discussed here. A lift height change of $\alpha=22.5\text{deg}$ show the same results as fig.4(a). Namely the appearance of the Hysteresis phenomenon, the range and size as well as the lift height value being mostly the same. Also, when it is $\alpha=33.75\text{deg}$, 45deg the same trend can be seen as when it is $U_a=1.04\text{m/s}$. However at $\alpha=60\text{deg}$ the lift height is 0 and maintains an inner flame. Moreover, it has been verified that the flame extinction observed at the time of fig. 4's $\alpha=22.5\text{deg}$, 33.75deg fuel flow velocity increase, does not occur with the increase of air flow velocity.

Fig. 5 shows lift height when a change has been made to fuel flow velocity at $\alpha=0\text{deg}$, 60deg . As a parameter, the value of the change in air flow velocity will be shown. In the case of fig 5 (a) $\alpha=0\text{deg}$, at $U_a=0\text{m/s}$ lift flame transition begins when U_f are approx. 10m/s . From the fact that adhesion flame forms

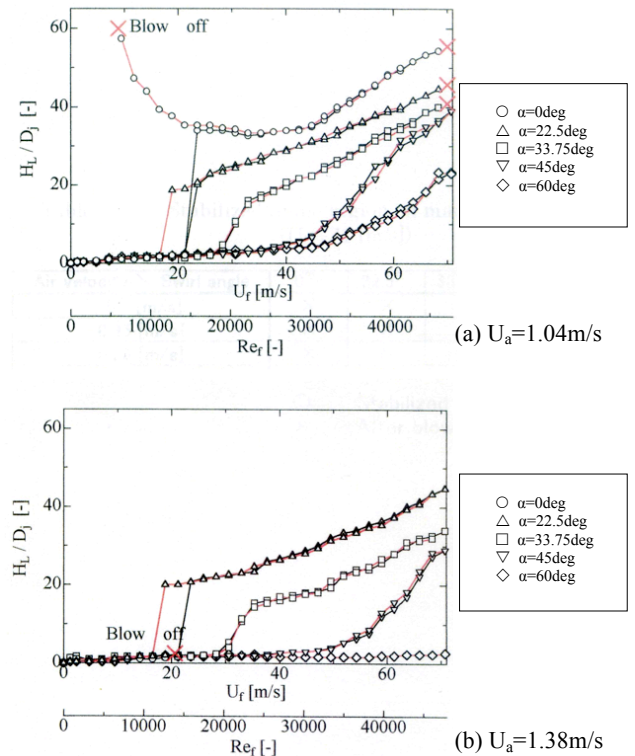


Figure 4 Relationship between fuel flow rate and lift height ($U_a=104\text{m/s}$ and 1.38m/s)

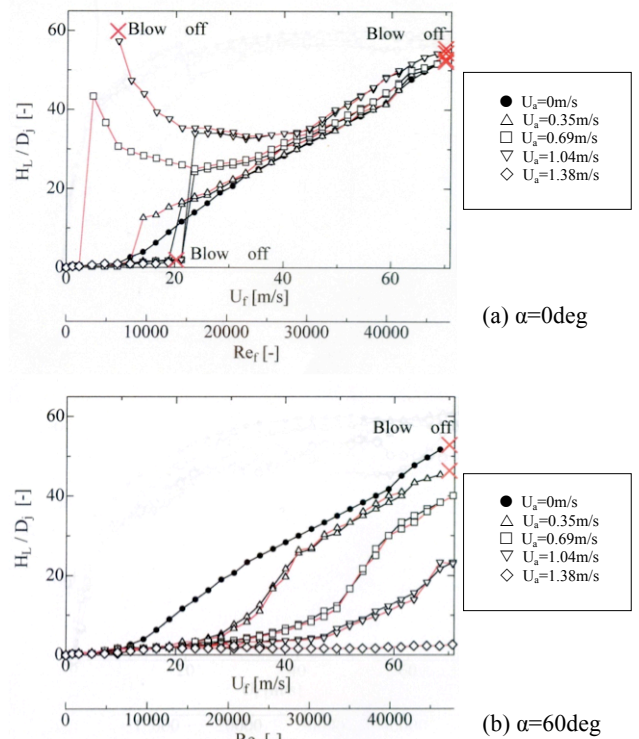


Figure 5 Relationship between fuel flow rate and lift height ($\alpha=0\text{deg}$ and 60deg)

up to $U_f=24\text{m/s}$, we can know that if U_a is increased, the specific effect of suppressing the transition to lift flame is achieved due to the action of the air flow. Also, if the air flow velocity is increased, the Hysteresis region undergoes expansion. Moreover, accompanying the increase of U_f , lift height approaches the value when air flow isn't added, and ultimately extinguishes in the vicinity of $U_f=70\text{m/s}$. In the case of fig. 5 (b), when $\alpha=60\text{deg}$ is reached, the Hysteresis phenomenon observed at $U_a=0.35\text{m/s}$, 0.69m/s , 1.04m/s does not appear. With the addition of air flow, at the value of $U_a=0.35\text{m/s}$ the U_f value of fuel flow velocity making the transition to lift flame is 25m/s , at $U_a=0.69\text{m/s}$ it is $U_f=30\text{m/s}$, at $U_a=1.04\text{m/s}$ it becomes larger at $U_f=42\text{m/s}$, and at $U_a=1.38\text{m/s}$ inner flames are formed up to $U_f=70\text{m/s}$ with flame stability being maintained. Moreover, in fig. 5 (a), the dispelling of the flame seen in the vicinity of $U_f=70\text{m/s}$ does not occur when air flow is increased. From the above, it has been proven that adding a swirl flow to a bluff body burner increases the effect of suppressing lift flame and the occurrence of flames being dispelled.

Flow Field

As has been described above, it is proven that flame stability improves when swirl flow is added to a bluff body burner. The improvement of flame stability is thought to be due to the great change that occurs in the flow field and temperature field which form a combustion field. We shall now look at flow fields in the vicinity of bluff bodies.

Displayed in fig. 6, are the results of a flow field in the vicinity of a combustor that has had its fuel flow velocity changed at a constant of $U_a=0.69\text{m/s}$. These results have been visualized according to the laser sheet method. Firstly in fig.6 (a) $\alpha=0\text{deg}$, in the inner flame forming $U_f=18.86\text{m/s}$, directly above the bluff body there exists a pair of recirculation whirls sandwiching the flame base. As shown in fig. 5, flames immediately transform into lift flames as they approach $U_f=21\text{m/s}$, however the height of the recirculation whirls compared to inner flames are $2/3$ s smaller. The whirl also moves closer to the center of the bluff body. Moreover, if the fuel flow velocity is increased, the recirculation whirl gradually retracts. This type of flow field continues until the flames are dispelled. The reason that recirculation whirls' retraction accompany an increase in fuel flow velocity is because of the difference in pressure resulting from the difference in velocity between fuel flow and air flow that becomes larger with the increase of fuel flow velocity. It is also thought that due to the air flowing through the annular being absorbed toward the central axis where the fuel flow is flowing, recirculation whirls become smaller. Comparing the inner flame $U_f=18.86\text{m/s}$ with lift flame flow field $U_f=37.73\text{m/s}$, 56.59m/s , in the case of the inner flame, the main part of the air flow follows the outer part of the flame surface and flows in the axial direction. However in the case of lift flame, it was observed that all of the air flow flows down to the flame base and accompanied the fuel flow.

As displayed in fig.6 (b), the adverse flow observed when no swirl flow had been induced in the results shown in fig. 6 (a), as well as a recirculation whirl do not exist when a swirl flow of $\alpha=60\text{deg}$ is induced. Next, similar to the case where no swirl

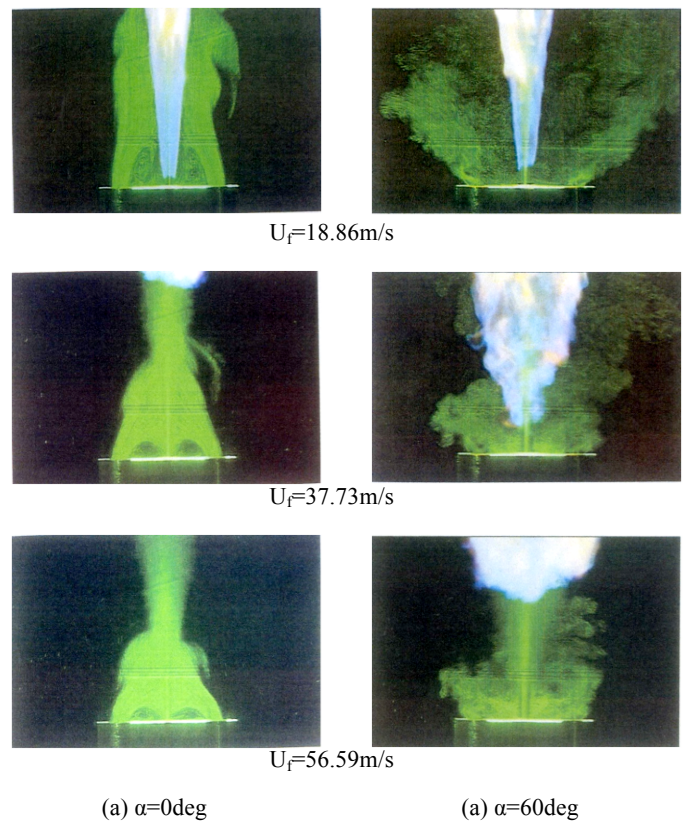


Figure 6 Laser-sheeted photographs nearby combustor ($U_a=0.69\text{m/s}$)

flow was induced in fig. 6 (a), comparing the flow field with the inner flame and the lift flame, in the inner flame of $U_f=18.86\text{m/s}$ the majority of the air flow extends largely to the outer part of the flame; however in the lift flame with an increased fuel flow velocity of $U_f=56.59\text{m/s}$, the observation was made that almost all of the air flow flows down to the flame base. This result proves similar to $\alpha=0\text{deg}$. From the fact that air flow velocity is fixed, it is thought that the accompanying amount of air flow on the side of the fuel affects the change in flame formation in some kind of way.

Fig. 7 shows time-averaged velocity distribution based on the PIV in each swirl angle at $U_a=1.04\text{m/s}$, $U_f=18.86\text{m/s}$. From the results of this experiment, it is confirmed that the flow of air flow that was observed in the flow visualization test in fig. 2, extends to the radial following an increase in swirl angle. Again, as shown in fig. 7, the flow of the stagnation area in the recirculation area, which was even observed when swirl flow was not induced in the visualization test, has a tendency to expand along with the flame surface, which in turn follows an increase in swirl angle.

The reason why air flow gradually extends to the radial when swirl flow is increased is because of the action of a large centrifugal force due to air flow. Because of this, the inflow of excessive air flow in the vicinity of the flame base ($h=0\sim 50\text{mm}$) is suppressed, thereby preventing temperature reduction on the flame surface, which leads to the reduction of combustion velocity. Also, in the flow of the vicinity of the

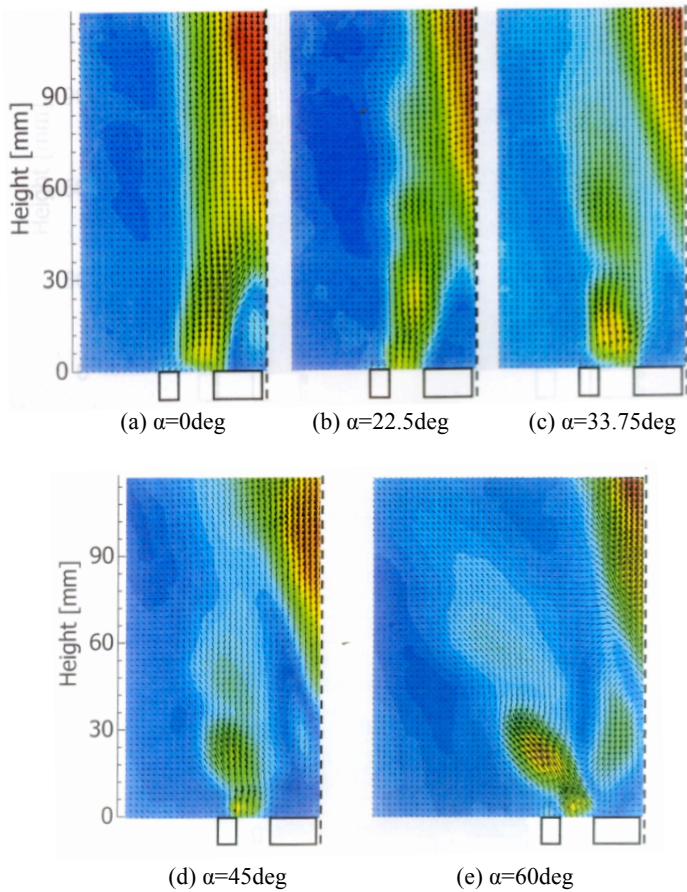


Figure 7 Time-averaged velocity field by PIV measurement in the vicinity of the combustor (Attached flame $U_a=1.04\text{m/s}$, $U_f=18.86\text{m/s}$)

flame surface that exists between air flow and fuel flow, by forming an area of low flow velocity, and with the suppression of the transition from inner flame to lift flame, it is thought that improvements can be made in flame stability.

Next, with fuel flow velocity at the time when inner flame has made a complete transition to lift flame being defined as U_{fc} ; we shall consider the changes in swirl number that produce an effect in the transition to lift flame. Fig.8 compares swirl number with the fuel flow velocity that has made the transition to lift flame. As a parameter values that changed air flow velocity are displayed. The transition flow velocity (U_{fc}) that accompanies an increase in swirl numbers display a slight increase up to $S=0.56$; however once it increases to above $S=0.83$ there is a sharper increase. Again, once $S=1.45$ is reached, conversely at all air flow velocities, transition flow velocity (U_{fc}) only slightly increases. From the above, it is thought that in-between the change from 0.56 to 0.83, the structure of the flow field undergoing combustion is also undergoing a great transformation.

Temperature Field

Finally, combustion fields, following the changes in flow structures their temperature fields fluctuate greatly. It is thought changes in the swirl angle and air flow velocity on the

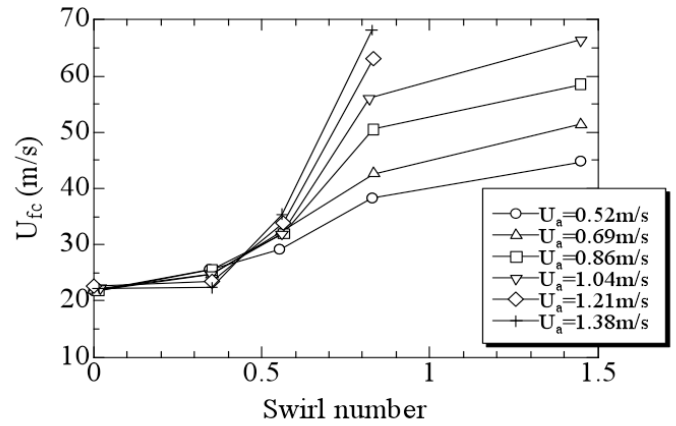


Figure 8 Relationship between transition velocities to lifted flame and swirl number

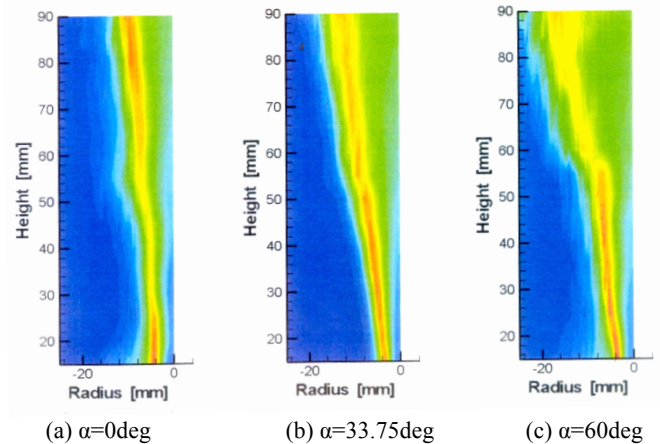


Figure 9 Time-averaged temperature contours in the vicinity of the combustor

temperature field undergoing combustion.

Fig.9 shows the time averaged temperature distribution at $U_a=1.04\text{m/s}$, $U_f=18.86\text{m/s}$. Swirl angle α was adjusted to 0deg, 33.75deg, 60deg. At $\alpha=0\text{deg}$ shown in fig.9 (a), at the axial height of the combustor exit $h=30\sim 50\text{mm}$, seeing the temperature distribution of the range at which local extinction phenomenon is observed, compared to the temperature at a different height, a low value of approx. 200K was displayed. Because of this, it is thought that air flow creates a cooling effect on the surface of the flame, with the reduction of local combustion velocity giving rise to local quenching. Next, in considering the influence of swirl flows on combustion fields, the position that displays the highest temperature of the radial of each cross section is at the flame base vicinity ($h=15\text{mm}$), fig. 9(b)'s $\alpha=33.75\text{deg}$ and fig.9(c)'s $\alpha=60\text{deg}$ are almost at the same position.

Maintaining a high temperature area, the reduction of combustion temperature as observed in fig.9 (a) is unseen. Furthermore, at the lower side, it is seen that temperature distribution is being extended toward the radial, and that heat delivery is being carried out toward the outer part of the flame.

From this result, by adding swirl flow to a combustion field, there is no great change of the temperature field at the vicinity of the flame base. However more than at the flame base, in the case of a swirl flow not being induced, a reduction in heat that brings about local extinction doesn't exist in the lower reaches. Also from these results it is understood that in the lower section, there is acceleration in the diffusion of heat to the radial. From the above it has been shown that the temperature field of the flame base exerts a strong influence on flame stability, and that the induction of a swirl flow leading to the disappearance of low temperature fields creates the effect of an even more stable flame.

CONCLUSION

In this study measurements were carried out on the special characteristics of flames in the case of a swirl flow being added to a diffusion flame using a bluff body combustor. Also measured were the flow fields and temperature fields; flame stability also being examined. The results are as follows:

- (1) By conferring a swirl flow to a bluff body combustor, there was an improvement in flame stability.
- (2) In the flames formed by a bluff body combustor, the often-observed hysteresis phenomenon could not be seen when a swirl flow was added.
- (3) The improvement in stability achieved by adding a swirl flow to the combustion field is thought to be achieved by the air flow being extended to the radial by centrifugal force, causing near the flame surface, the formation of a velocity which balances a temperature field that maintains a high temperature range and combustion velocity.

REFERENCES

- [1] Okamoto T., and Takagi T., "Structure and NO_x formation characteristics of swirling jet flame", *Transactions of the Japan Society of Mechanical Engineers, (in Japanese)*, Vol.47, No.419 (1981), pp.1380-1389
- [2] Takagi T. and Okamoto T., and Kitaya K., "Study on Structure of Swirling flame", *Transactions of the Japan Society of Mechanical Engineers, (in Japanese)*, Vol.49, No.414 (1983), pp.1078-1086
- [3] Okamoto T., and Takagi T., "Formation and flow of recirculation zone, mixing and prediction of combustion in a swirling turbulent flame", *Transactions of the Japan Society of Mechanical Engineers, (in Japanese)*, Vol.54, No.508 (1988), pp.3533-3541
- [4] Chao Y.C., Leu J.H., and Hung Y.H., "Downstream boundary effects on the spectral characteristics of a swirling flowfield", *Experimental in Fluids* 10 (1991), pp.341-348
- [5] Christopher O. Iyogun, Madjid Birouk and Janusz A. Kozinski, "Experimental investigation of the effect of fuel nozzle geometry on the stability of a swirling non-premixed methane flame", *Fuel* 90 (2011), pp.1416-1423
- [6] Yung-Cheng, C., Chia-Chi, C., Kuo-Long, P. and Jing-Tang, Y., "Flame lift-off and stabilization mechanisms of non-premixed jet flames on a bluff-body burner", *Combustion and flame*, 115 (1998), pp.51-65
- [7] Esqiva-Dano, I., Ngyen, H.T. and Escudie, D., "Influence of bluff-body's shape on the stabilization regime of non-premixed flames", *Combustion and flame*, 127 (2001), pp.2167-2180
- [8] Nishimura T, Kunitsugu K, and Morio K, "The hysteresis phenomenon in flame lift-off on a bluff-body burner under air flow dominant conditions", *Combustion and Flame*, accepted
- [9] Nishimura T., Kawahara H., and Hataoka H.. "Flame stability by the air style in a bluff body type burner" *Journal of the Japan Institution of Marine Engineering*, Vol.44, No.5 (2009) pp.793-800
- [10] Huang R.F, and Tsai F.C., "Flow field characteristics of swirling double concentric jets", *Experimental Thermal and Fluid Science* 25 (2001), pp.151-161
- [11] Huang R.F., and Chun C. Yen, "Aerodynamic characteristics and thermal structure of non-premixed reacting swirling wakes at low Reynolds numbers", *Combustion and flame* 155 (2008), pp.539-556
- [12] Yasir M.AI-Abdeli and Assaad R. Masri, "Recirculation and flowfield regime of unconfined non-reacting swirling flows", *Experimental Thermal and Fluid Science* 27 (2003), pp.655-665
- [13] Yasir M.AI-Abdeli and Assaad R. Masri, "Stability characteristics and flowfield of turbulent non-premixed swirling flames", *Combust. Theory Modelling* 7 (2003), pp.731-766
- [14] University of Sydney, Swirl flame web database, <http://sydney.edu.au/engineering/aeromech/thermofluids/swirl.htm>