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Studies on Luminous and Non-luminous Flames

with Spray Combustor*

(2nd Report: Case of Swirl Combustor)

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Swirl type combustor for study of spray combustion has been designed. Using this combustor luminous flame and non-luminous flame can be produced by shifting the spray nozzle position without changing the operating conditions. From the experimental studies the following results were obtained.

(1) Supplying combustion air from tangential port, swirl number of $S=0.99$ was obtained. The circulation length was nearly equal to the combustion tube diameter.

(2) Flame appearances were controlled by diffusion process of fuel spray and combustion air. If fuel spray was injected into a reverse flow in toroidal vortex, combustion process was so fast that non-luminous flame was obtained.

(3) Paying attention to the primary combustion, combustion efficiency of swirl-type combustion was found better in the case of luminous flame, and it was shown combustion performances were controlled by the flow pattern and the spray directions.

Key words: Combustion, Swirl, Spray Combustion, Luminous Flame
Non-luminous Flame, Emission Gas

1. Introduction

There have been many reports published on combustor design and/or combustor system developments directed at solving the problems of fuel choice, low level emission firing, decreasing combustion noise and the establishment of a reasonable combustor system design.⁽¹⁾

Flames are classified into two groups: luminous and non-luminous flames. Their colours are, in the practical combustor, yellowish and bluish respectively. If these different kinds of flames could be produced under the same operating conditions, it would be very easy and useful to estimate the validity of different numerical simulation or prediction methods for combustion phenomena.

Nakayama⁽²⁾ has reported on a spray-type combustor which can provide both the luminous and non-luminous flames in the same system, by changing only the combustion air supply hole position. The following parameters were set constant in this combustor; fuel flow rate W_f g/s, atomizing air flow rate W_{a1} g/s, combustion air flow rate W_{a2} g/s, total air-fuel ratio $(W_{a1}+W_{a2})/W_f$ and S.M.D of fuel droplet X_{32} μm . In this system, however, the air blast atomizing system used was a small-size modified type, so it was too difficult to

evaluate the emission characteristics.⁽³⁾ A new type combustor system was, therefore, designed to solve these problems.

To obtain stable and high intensity combustion, swirl vane type combustors are used in the industrial field: in boilers, gas turbines and so on. Many aerodynamical studies on swirl flow have been carried out. L.M.Beér and N.A.Chigier⁽⁴⁾ presented the relation between swirl number S and swirling jet flow pattern generated from various swirl vanes. A large amount of information on swirl combustion has come from a series of systematic trials in the Ijmuiden tunnel furnaces, and also from experimental and theoretical research carried out at the research establishment working in co-operation with the International Flame Research Foundation.⁽⁵⁾ This research has shown important influences on flame stability, combustion intensity and NO_x formation.⁽⁶⁾ These results, however, show only the effects of the swirl jet flow on flame stability, combustion intensity and NO_x formation rate. The relation between the fuel and the combustion process and air mixing process in which they control the combustion characteristics of diffusion flames, has not been investigated.

In this experimental study, a swirl type combustor with axial and tangential air inlet ports was developed. Using this combustor, various swirl intensities were obtained by selecting the air flow rate or the air port. By supplying kerosene to this combustor, both the luminous and non-luminous flames were produced at the swirl number of $S=0.99$, without any change in operating conditions. We tried to induce the appearance of luminous flame or non-luminous flame as in the previous study,

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without change of atomizing characteristics or operating conditions. Only the nozzle position was varied for this purpose. The luminous flames were obtained by injecting the fuel into the recirculation zone detected in the torroidal vortex region, and the non-luminous flames were produced by injecting fuel into a strong shear flow region observed.

This report presents the results about the effects on flame appearance of the relative position of the main spray flow and the swirling air flow, and compares the combustion characteristics of luminous flame and non-luminous flame obtained with the same spray characteristics and the same operating conditions.

2. Experimental Apparatus and Experimental Methods

Fig.1 shows a schematic view of the experimental setup. The kerosene oil is supplied from fuel tank 1 through oil filter 3 and fuel feed pump 4, and injected at fuel nozzle 25. The flow rate is regulated by control valve 6 and pressure gauge 9, and measured by fuel flow meter 10. The combustion air is supplied from blower 11 and its flow rates are controlled by control valves 15, 18 and 21, and measured by orifice-type flow meters 13, 16 and 19, and manometers.

Fig.2 shows a cross-section of the swirl type combustor. The fuel is supplied from port A, and injected into combustor tube 8 through a swirl-type fuel nozzle. The combustor is equipped with two combustion air ports: B and C. Combustion air from port B flows axially into swirl generator tube 7 through perforated plate 5 and the air from port C is introduced tangentially into a tube 7 through eighteen tubes (see Section X-X). These air flow rates are controlled independently to produce various swirl intensities. Nozzle

Fig.1 Schematic of the experimental apparatus

holder 1 is movable within a range of 60 mm, and the nozzle can be set at any position. The standard position (N.P=0) is at L=490mm from the left end, and its positive direction is defined by the down-stream direction from the nozzle. The flow pattern inside the chamber was measured in detail in a cold state using transparent models and cotton fiber streamers. Flow velocity distributions were measured using a pitot tube.

Pt-PtRh13% (0.3mm dia.) thermocouples coated with silica were used for temperature measurements. No error correction was carried out. For gas sampling, a water-cooled stainless probe was used, and gas compositions were measured for species of CO, CO₂, O₂, and NO_x. Their dry based volumetric concentration values were shown in the following. Measurement was performed in the horizontal plane.

3. Swirl Intensity and Flow Pattern in a Cold State

In this study, the authors expected to obtain the luminous flame and/or non-luminous flame by changing only the position of fuel injection nozzle.

The spatial distributions of swirl velocities are shown in Fig.3. Swirl velocity profiles are of a Rankin vortex type with maximum values at r=30mm.

Dimensionless number S is well known as a similarity parameter of swirl intensity, and S is defined as follows:

$$S = G_{\phi} / G_x R \quad \dots\dots (1)$$

$$G_x = 2\pi \rho \int_0^R U^2 r dr + 2\pi \int_0^R p r dr \quad \dots\dots (2)$$

$$G_{\phi} = 2\pi \rho \int_0^R U V r^2 dr \quad \dots\dots (3)$$

G_x and G_{ϕ} are, respectively, the constant axial flux of axial momentum and the con-

①: Nozzle holder	⑥: Outer case II
②: Fixed nut	⑦: Swirl generator tube
③: End flange	⑧: Fuel injection nozzle
④: Outer case I	⑨: Combustor tube
⑤: Holder	

Fig.2 Design of swirl combustor

stant axial flux of angular momentum in swirl jet flow. P is the static pressure. The calculated S was about 0.99, and this value coincides with that of IFRF's furnace experiment.

Some examples of the flow patterns are illustrated in Figs.4-6. Two arrows plotted at one point indicate the extent of the change in flow directions and the small circles indicate circulation of the flow at the point. These figures show the effects of nozzle position and mean air flow velocity on flow patterns. S.A in the figures stands for spray angle. Although the nozzle position was shifted from $N.P.=+20\text{mm}$ to -20mm and the mean flow velocity was altered from 2 m/s to 8 m/s, the flow patterns were almost the same. Because of centrifugal force, the swirling jet flow was expanded rapidly at the end of the swirl generator tube, and stable recirculation and reverse flow regions were formed in the combustion tube. The length of the recirculation zone was nearly equal to the combustor tube diameter D , and the eye of the torroidal vortex is detected at a position of around $0.3 D$ downstream from the nozzle. At $1 D-2 D$ positions, a large scale turbulent zone was detected. Further downstream, the turbulent region was expanded into a cone-like shape.

Comparing Fig.4 and 5, the effect of the nozzle position on the flow pattern is observed only near the nozzle. From Figs.5 and 6, the turbulent area is seen to expand with an increase in flow velocity.

Nozzle Type	Capacity ($P=0.49-3.92\text{MPa}$)	Spray Angle
Nozzle A-1	2.90-8.00 g/s	90°
Nozzle B-1	2.10-5.95 g/s	90°
Nozzle C-1	1.05-2.55 g/s	90°
Nozzle B-2	1.92-6.15 g/s	60°

Table 1 Specification of fuel nozzle

Fig.3 Velocity distribution

Fig.4 Flow pattern

Fig.5 Flow pattern

Fig.6 Flow pattern

Fig.7 Characteristic droplet diameter vs. atomizing pressure

Fig.8 Dispersion rate (water injection)

4. Spray Characteristics

Commercial simplex pressure atomizers (Delavan Co.'s Hollow cone type) were used, and their specifications are shown in Table 1. Fuel flow rates are shown on the abscissas of Fig.9(A)-(D) and their characteristic droplet diameters were measured with a particle sizer using the Fraunhofer diffraction theory.⁽⁷⁾ The result is shown in Fig.7. Characteristic diameter X_u and index number N are given by Rosin-Ramler distribution function(4).

$$R = \exp\{-(X/X_R)^N\} \dots\dots\dots (4)$$

where R : cumulative weight percentage(%)

X_R : characteristic diameter calculated from $R=1/e=0.368$ (μm)

N : index of Rosin-Ramler function ($N \approx 2$ for $P_f=0.69-5.0\text{MPa}$)

It is important to know the spatial distribution of sprayed fuel when discussing the relative position of the recirculating flow and main spray sheath in the primary combustion zone. Fig.8 shows the dispersion rate of nozzle B-1 measured at $H=50\text{mm}$ from the nozzle. The maximum dispersion rate position is detected at $r=50\text{mm}$ from the center axis. The spray angle agreed well with its specifications.

It seems that a cloud of spray droplets flies along S.A line in Figs.4-6, because of strong penetration capability near the nozzle tip.

5. Combustion Characteristics

Combustion characteristics of the swirl combustor tested are shown in Fig.9 (A)-(D) for each fuel nozzle used. The effects of the nozzle position are shown. A solid line indicates that the characteristics of the operating condition are such that $N.P.=+20\text{mm}$ and the dotted line indicates the condition of $N.P.=-20\text{mm}$ (see Fig. 4). Keeping the fuel flow rate W_f constant with the air flow rate low, the main flame appears outside the flame tube. (see curve

(1) and (1')) With an increase of air flow rate, different flame appearances are observed.

When $N.P.=+20\text{mm}$, a column-like flame was observed on the center axis of the combustion tube, and the flame front stretched to the outside of combustion tube. The flame luminosity was much higher than that of the diffusion type flame observed outside the combustor tube. With a further increase in air flow rate, the end of the column-like flame coincides with the exit of the combustor tube (on (2')). The flame luminosity of the center axis part was intense and that of the wall side part was a faint, bluish, non-luminous flame. With a further increase in air flow, the column-like flame was shortened (on (3')), and the flame color of peripheral part turned deep blue. With a still further increase in air flow rate, the flame front came to stay in the recirculating flow region (on (4')) and its flame color turned bluish and non-luminous. In the center part of the combustor, a yellowish, highly luminous, cup-like flame was observed. When the air flow rate W_a was increased further, the column-like flame was observed near the center. No weak flame blow out phenomenon was detected.

[A] nozzle A-1

[B] nozzle B-1

[C] nozzle C-1

[D] nozzle B-2

Fig.9 Combustion characteristic curve

When $N.P. = -20\text{mm}$, with an increasing air flow rate, a column-like yellowish flame was observed as in the previous case, but in this case a bluish non-luminous flame was observed at the initial part of the combustion flame and a blue and yellow mixed colour flame appeared at the combustor exit. With a further increase in air flow rate, the column-like flame expanded toward the exit, and a large percentage of the flame volume was bluish. A cup-like yellowish flame appeared and the column-like flame became shorter (on(4)). When the air flow rate was increased still further, a large part of the flame volume changed to a bluish non-luminous flame except in the center axis part. When the air flow rate W_a was increased again, a weak blow out was observed at $\star$ point.

If operating conditions are set as follows: $W_f = 4.11\text{g/s}$ ($P_f = 1.0\text{MPa}$), $W_a = 144.0\text{g/s}$, that is, $W_a/W_f = 35$ (see X point in Fig.9(A)), and the nozzle position is continuously moved from $N.P. = -20\text{mm}$ to $+20\text{mm}$, then by setting the nozzle at $N.P. = -20\text{mm}$, a nonluminous flame is observed, and by moving the nozzle position to downstream, luminous flame volume percentage increases. When the nozzle is set at $N.P. = +20\text{mm}$ the combustor tube is filled with a luminous flame.

Based on these results, we shall be able to observe different types of flames under the same spray characteristics and operating conditions. In these characteristic figures, both luminous flame and non-luminous flame are obtained in the hatching zone near the center. No weak flame blow out phenomenon was detected.

If the same spray angle nozzle is used for this combustor and a larger capacity nozzle is set, a wider combustion range is obtained. If the same capacity nozzle is used and a wider spray angle nozzle is set (for example; $60\text{deg} \rightarrow 90\text{deg}$), a wider combustion range is obtained.

6. Flame Temperature Distribution

The flame or gas temperature was measured in detail to explain the differences in flame appearances.

Fig.10 shows the isotherms for three nozzle setting positions. The maximum flame temperature is detected with the nozzle position at $N.P. = +20\text{mm}$. At that time, the flame appearance is luminous and its high temperature zone exists on the downstream side. But with the nozzle at $N.P. = -20\text{mm}$, its flame temperature is lower, while its high temperature zone is detected in the toroidal vortex region. Compared with the cold flow pattern, the flow direction pattern is similar to the isotherm map at downstream from 1D position. In the case of the non-luminous flame, both of the spatial distributions coincide. In the column-like flame or contracted flame zone, turbulent intensity is very high, and differences in flame temperature are slight. From these experimental results, it is supposed that the mixing rates of combustion air and fuel spray are slow in luminous flame burning

and fast in non-luminous flame.

7. Gas Concentration

A CO concentration contour map is shown in Fig.11. The maximum concentration region is located in the recirculation zone. In the case of non-luminous flame and mixed colour flame, it is detected in the central part of the toroidal vortex. The magnitude of CO concentration decreases in the order of luminous flame, mixed flame and non-luminous flame. The highest concentration was detected in luminous flame.

Fig.12 is a contour map of CO_2 concentration. The maximum CO_2 concentration region in non-luminous flame or mixed colour flame exists in the recirculation zone, but in the case of luminous flame combustion it is located further downstream. The maximum concentration area of CO_2 was found further downstream than that of CO concentration. It is seen that the combustion rate is slowest with luminous flame, and fastest with non-luminous flame.

A O_2 contour map is shown in Fig.13. The O_2 concentration region is located in recirculation zone. With luminous flame the contour of low level value extends downstream.

With a shift of the nozzle position, the profiles of the CO , CO_2 and O_2 contour maps differ in their recirculation zones ($<1\text{D}$). Further downstream, although their

Fig.10 Isotherms of tested combustor

Fig.11 CO contours map

gas concentration levels are different, their profiles on the contour maps resemble one another.

Fig.14 shows NO concentration. The measured value and corrected value CNO_x (at residual O₂ vol%=4%) are given. Further downstream, a higher level NO concentration appears. In the column-like flame, very high concentration values were registered. When N.P.=+20 mm and 0 mm, the maximum concentration zone appears in the torroidal vortex region, and for N.P.=0 its concentration gradient was especially steep. The NO concentration at the combustor exit was the lowest in the case of N.P.=-20 mm because of a slow combustion rate, followed by the case of N.P.=0, +20 mm. The order of concentration values agrees with that of the maximum flame temperature values.

Combustion efficiency is shown in Fig.15. The sampling position was 25 mm upstream from the combustor exit and the sampling probe was moved in the radial direction. Gerrish et al.'s equation⁽⁸⁾ was used for calculation.

$$\eta = 0.870 \left(\frac{20.74 - O_2 + 1.079 CO_2}{21.11 - O_2 - 0.491 CO_2} \right) \quad \text{----(5)}$$

η : local combustion efficiency (%)

O₂ : O₂ concentration (vol%)

CO₂ : CO₂ concentration (vol%)

Judging from the distribution of local combustion efficiencies, the highest combustion efficiency is obtained on the

Fig.12 CO₂ contours map

Fig.13 O₂ contours map

center axis, except in the operating condition of n=25 and 35 for N.P.= +20 mm, and the combustion efficiencies decrease toward the side wall.

As already shown in Figs.4-6, the turbulent cone region extends from the center axis to 2r/D=0.5 and the local combustion efficiency levels are nearly constant in these areas.

Compared with the combustion efficiency as calculated from the conventional enthalpy method,⁽²⁾ its absolute value is low, but its relative value in luminous flame is higher than in non-luminous flame.

Nozzle: B-1

Fig.14 NO contours map

Fig.15 Local combustion efficiency calculated from gas concentration

8. Discussion

It seems that combustion phenomena in a swirl combustor are controlled by the process of mixing combustion air and fuel droplets in the recirculation zone, and that these factors influence the combustion performance.

When the nozzle position is shifted into the combustion tube (+ direction) and fuel is injected into the torroidal vortex, luminous flame can be expected to occur, because a large amount of the fuel droplets is injected into the torroidal vortex area in which velocity is relatively slow, and fine droplets having weak penetration burn in fuel-rich conditions. Large droplets having strong penetration disturb the torroidal vortex flow and penetrate into the vortex flow, and are entrained into a high speed swirl flow. These entrained fuel droplets are superheated from circumferential flame, so column-like flames appear. The diffusion process of the combustion air and fuel spray is slow and its condition is fuel-rich. Consequently, soot formation is accelerated in the reaction zone. From these processes, the flame appearance turns yellowish and luminous.

The flame is kept stable during combustion, and a weak blow out is not detected. A high CO_2 concentration region is detected considerably downstream of a high level CO concentration and low level CO_2 region, and the reaction time of spray combustion is sufficiently long for high combustion efficiency to be expected.

When the nozzle position is shifted to upstream, fuel droplets are injected into the high-speed swirl flow. The flame appearance becomes bluish and non-luminous. Fuels injected into the steep velocity gradient field are rapidly mixed with combustion air, and homogeneously mixed gases are formed. This flammable mixture gas flows into the torroidal vortex zone and burns. Some large droplets having strong penetration strike the combustion tube wall, and evaporating-type combustion is observed. The other droplets are entrained into the swirling flow and burnt as a column-like flame. Unburnt fuels were sometimes detected at the outlet. In these observations, the spray combustion in the recirculation zone is similar to premixed combustion, so the flame is expected to become bluish non-luminous. The area of high concentration of emission gases and the area of high gas temperature or flame are close to each other. Flame stability is poor. As shown in Fig.15, the combustion efficiency is reduced in this combustion, the reasons being that unburnt gases flow out, that chemical reactions are suppressed by rapid cooling and that excess air has a cooling effect.

9. Conclusions

A swirl-type combustor for study and research of spray combustion has been designed. Luminous and non-luminous flames are obtained by shifting the nozzle posi-

tion. The spray characteristics and operating conditions are not changed. The major conclusions of the study are as follows:

(1) When supplying the combustion air from the tangential port, a swirl number of $S=0.99$ is obtained. The length of the recirculation zone is nearly equal to the combustion tube diameter.

(2) Flame appearances are controlled by the diffusion process of fuel spray and combustion air. If the fuel spray is injected into the recirculation zone, the combustion process is slow and luminous flames are formed. If fuel spray is injected into the shear flow region, the combustion process is fast and non-luminous flame is formed.

(3) The stability of luminous flame is better than that of non-luminous flame. Combustion efficiency is better in luminous flame.

(4) The correlation between flow pattern and spray direction affects the combustion performance.

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