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An Experimental Study on the Effects of Air Distributions in the High Intensity Combustion Chamber*

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An experiment was made to study the relations of the air distributions to the combustion chamber performances and the combustion processes in a high intensity combustion chamber. The box-type combustion chamber used in the experiment can supply the primary-, the secondary- and the tertiary-air flow separately with desired rate. The combustion efficiencies, the flow patterns, the lean blow-off limits, the pressure losses and the temperature distributions in the combustion chamber were measured for various air distributions and liner-swirler combinations, and it was found that these factors depended on each air distribution and liner-swirler combination.

According to the main result of the experiment, if the informations on the primary combustion zone, for example, the air-fuel ratio in it and the length of the recirculation zone, are obtained, it is possible to explain the combustion chamber performances and the combustion processes in the combustion chamber reasonably.

1. Introduction

When one is going to develop a new combustion chamber, one is obliged to perform many troublesome combustion experiments using various types of combustion chambers by trial and error method^{(1)~(3)}. However, if one analyses the complex combustion processes, especially the processes in the primary combustion zone and knows how the combustion processes take place, it seems that one may design a new combustion chamber more easily. Further, there have been a few reports about the combustion processes practically taking place in the combustion chamber.

From the above mentioned point of view, we performed a series of experiments to study the effects of several parameters on the combustion chamber performances and the combustion processes using a simple box-type model combustion chamber⁽⁴⁾. Among these parameters, the air distributions were found to have a great influence on the combustion chamber performances. Therefore, the present study was performed to find out the relations of the air distributions to the combustion chamber performances and the combustion processes in the combustion chamber. The experiment was made using five combinations of the liner and the swirler configurations. Concerning these problems, Andre constructed a two-

dimensional combustion chamber into which the air flowed through a set of 48 rectangular air admission ducts and investigated the effects of the air distributions operated with gaseous fuels^{(5) (6)}. Also, Tamaoki estimated the air flow from the flow factors for the air holes of the liners and discussed the effects of the air distributions⁽⁷⁾, and Otsuka and others measured the air flow to the swirler by the pitot tube⁽³⁾. However, these problems are not fully solved yet.

The box-type combustion chamber used in the present work has a practical geometry and is equipped with a swirler and two rows of air holes. The combustion chamber was designed to divide the total air flow into the primary-, the secondary- and the tertiary-air flow with desired rate, therefore it was possible to study the effects of the air distributions with accurate quantity of each air flow.

2. Experimental apparatus

2.1 Air and fuel supply system⁽⁸⁾

Figure 1 shows a schematic diagram of the air and fuel supply system. The air was supplied from the spherical air reservoir (diam, 10 m). The pressure in the settling tank (2 kg/cm²g) and the total air flow rate (0.48 kg/sec) were controlled automatically by the valves V_1 and V_2 , respectively. At the downstream of V_2 , the total air flow was divided into three flows. Namely, they were the primary air flow which was introduced into the combustion chamber through the swirler, the secondary air flow

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which was introduced through the first row of the liner air holes and the tertiary air flow which was introduced through the second row of the liner air holes. The flow rates of the total air flow and the three divided air flows were measured by the orifices O_1 , O_2 , O_3 and O_4 .

The fuel used was JP-4 and was supplied from the fuel tank by the gear-pump (max. pressure, 30 kg/cm²g). The fuel flow rate and pressure were controlled by the bypass valve V_6 , and the fuel flow rate was measured by the burette. The range of the fuel flow rates in the present experiment was about 0.1~1.2 l/min.

2.2 Combustion chamber

The combustion chamber, shown in Fig. 2, is box-type and equipped with a simplex swirl atomizer ②. The combustion chamber has special structures in order to introduce the primary-, the secondary- and the tertiary-air flow separately.

(1) Casing and liner: The combustion chamber has no outer casing (Fig. 2). The perforated liners ⑦ with the secondary and the tertiary-air admission ducts ④ ⑤ are inserted in the grooves of the upper and the lower parts of the casing ⑥, in which the quartz side walls ⑧ are fitted. The primary air passes through the admission pipe ① and flows into

Fig. 1 Air and fuel supply system

Fig. 2 Combustion chamber

the combustion chamber through the swirler ③. The secondary- and the tertiary-air pass through each air admission duct and flow into the combustion chamber through two air holes having the thimble 3 mm in height. Two types of liners, called S-type and M-type, were used (Fig. 3). The secondary air holes of M-type are located 15 mm upstream as compared with those of S-type.

(2) Swirler: Four types of swirlers are all axial flow type and have sixteen vanes with vane angles of 45° (Fig. 4). The differences among these four types originate from variations in the diameters

Type	S	M
1	50	35

Fig. 3 Liner

Type	70φ/10°	70φ/5°	52φ/15°	70φ/10° R*
d_1	40φ	40φ	22φ	40φ
d_2	70φ	70φ	52φ	70φ
θ	10°	5°	15°	10°

* Primary air and fuel spray turn round in reverse direction

Fig. 4 Swirler

of openings (inner diam, d_1 , outer diam, d_2), the angles of openings (θ) and the direction of swirl. The types were expressed in the form of $[d_2/\theta(R)]$ as listed in Fig. 4. When the symbol R is attached last, it means that the primary air and the fuel spray turn round in the reverse direction. Each type of the swirlers is explained in the following.

$70\phi/10^\circ$: it is considered to be the standard type here.

$70\phi/5^\circ$: its opening area is reduced to half of $70\phi/10^\circ$.

$52\phi/15^\circ$: its opening diameter is reduced but its opening area is the same as that of $70\phi/10^\circ$.

$70\phi/10^\circ R$: it has the reverse direction of swirl.

(3) Fuel atomizer: The fuel atomizer is simplex swirl type. In order to obtain good spray characteristics, a nozzle tip having an appropriate exit orifice diameter was chosen from among five prepared tips and used according to the fuel flow rate of the experiment. The spray angle is about 90° and the calculated droplet mean diameters range from 54μ to 120μ for five nozzle tips at the fuel pressure of $20 \text{ kg/cm}^2 \text{g}^{(9)}$.

2.3 Measuring instruments

At the inlet of the primary air, the air temperature and the total pressure were measured by the alcohol thermometer and the total pressure tube, respectively. At fifteen points across the exit plane of the combustion chamber, the combustion gas temperatures and the total pressures were measured by chromel/alumel thermocouples (wire diam, 0.64 mm) and stainless steel total pressure tubes, respectively. The temperatures in the combustion chamber were measured by Pt/Pt-Rh thermocouple (wire diam, 0.5 mm).

Since the cold flow patterns in the combustion chamber are thought to be substantially similar to the hot flow patterns⁽¹⁰⁾ and the cold flow experiment can be made more easily, in most cases the flow pattern studies have been made by means of scale models without combustion using pressure probes, streamers or suitable tracers. In the present experiment, a cotton streamer was used in the cold flow experiment to see the flow patterns in the combustion chamber with the same rate of the air flow as in the combustion experiment.

3. Procedure

3.1 Experimental conditions

The combustion experiment was performed at the atmospheric pressure, and the inlet air was not preheated. The total air flow rate was about 0.48 kg/sec , which was equivalent to the mean cold flow velocity in the liners of about 25 m/sec , and it was

maintained constant throughout the experiment. Then the main parameters were the air-fuel ratio λ (and so the fuel flow rate), the air distributions and the liner-swirler combinations. The air distributions were expressed as $W_1-W_2-W_3$, in order of the primary-, the secondary- and the tertiary-air flow, by the percentage of each air flow rate to the total air flow rate, (e.g. $10-20-70$ expresses that W_1 is 10 %, W_2 20 % and W_3 70 %). In the experiment, W_3 was chosen as 60 %, 70 %, 80 % and 90 %, and the remainder of the air flow was divided into W_1 and W_2 in such manner that both might be greater than 5 % and at intervals of 5 % (see Table 1).

The liner-swirler combinations were expressed in the form of [the type of the liner · the type of the swirler] and were called simply A-combination, B-combination, C-combination, D-combination and E-combination, as shown in Fig. 5. In the former expressions, the underlined parts represented those which were different from those of $S\cdot70\phi/10^\circ$.

Since the combustion chamber was provided with no ignition equipments, the flame was ignited by the pilot flame inserted into the combustion chamber at the beginning of the experiment.

There seemed to be two problems arising from the special geometry of the air admission method. The first was the problem of the equality of the air flows through each of four secondary- and four tertiary-air holes. Concerning this problem, the discharge velocities from each air hole were measured, and no noticeable inequality of air flow was found except for the effect of the swirl motion of the primary air. The second was the problem of the discharge angles of the air flow through the air holes into the combustion chamber. As the secondary- and the tertiary-air flow were introduced through the admission ducts which were normal to

Fig. 5 Liner-swirler combination

the liner walls, it was considered that the discharge angles of this admission method were different from those of ordinary method. However, only the effects of the discharge air flow rates were taken into consideration and the effects of the discharge angles were not taken into consideration in the present work.

3.2 Combustion efficiency

The combustion efficiency η is represented by

$$\eta = \frac{(\lambda + 1)i'' - \lambda i'}{H} \times 100(\%)$$

where H : calorific value of JP-4 = 10 250 kcal/kg
 i' : enthalpy of inlet air estimated by the inlet air temperature
 i'' : enthalpy of exit combustion gas estimated by the mean exit combustion gas temperature⁽¹⁾.

3.3 Heat release rate

The heat release rate per unit volume of the combustion chamber Q is represented by

$$Q = \frac{HW_f}{V_c P^2} \times \frac{\eta}{100} \times 3600 (\text{kcal/m}^3 \text{hr atm}^2)$$

where W_f : fuel flow rate
 V_c : liner volume = 0.004 62 m³
 P : pressure = 1 atm.

3.4 Blow-off limit

Under a certain experimental condition, by reducing the fuel flow rate slowly, a blow-off of flames occurred, and thus the lean blow-off air-fuel ratios $\lambda_{B.O}$ were determined. In the present work only the lean blow-off limit was obtained.

3.5 Pressure loss

A modified total pressure loss factor ϕ is defined as

$$\phi = \frac{P_t' - P_t''}{1/2 \cdot \rho U_o^2}$$

where P_t' : total pressure of the inlet primary air
 P_t'' : total pressure of the exit combustion gas
 ρ : air density

U_o : mean flow velocity

A "modified" total pressure loss factor means that P_t' is not taken as the total pressure of the inlet total air but of the inlet primary air.

3.6 Coordinates in combustion chamber

Coordinates in the combustion chamber were defined as shown in Fig. 2, their origin being located at the center of the fuel atomizer.

4. Experimental results and discussion

4.1 Combustion efficiency

In this section, the effects of the air distributions in a representative combination (A-combination) will be discussed rather in detail first, then the effects of the liner-swirler combinations and the relations between the combustion efficiency and the heat release rate will be discussed briefly.

The combustion efficiency with respect to λ for A-combination (S-70 ϕ /10 $^\circ$) is presented in Fig. 6. Figure 6 (a) shows η when W_1 is equal to W_2 . For 5-5-90, η increases with an increase of λ asymptotically to the maximum value and η has not a distinct maximum point. Also for 5-5-90, the combustion zone was occupied with yellow luminous flames and a stable burning was maintained. As W_1 and W_2 increase, η decreases in the range of large values of λ and finally η becomes to have a maximum point in the figure. For 20-20-60, the combustion zone was occupied with blue flames.

Figure 6 (b) shows an example of η when W_3 is constant. As W_1 increases (hence W_2 decreases) and exceeds 20%, η decreases considerably in the range of large values of λ and η becomes to have a distinct maximum point.

Since the tertiary air flow acts mainly as a dilution air, it seems to have little influence on the

(a) $W_1 = W_2$

(b) $W_3 = 70\%$

(c) W_1 or $W_2 = 10\%$

Fig. 6 Combustion efficiency for A-combination (λ - η)

combustion processes in the primary combustion zone. Then, to see the effects of the primary- and the secondary-air flow separately, Fig. 6 (c) shows η when W_1 or W_2 is constant ($=10\%$). As W_1 increases from 10% to 20%, and further to 30%, W_2 being constant, η decreases considerably in the range of large values of λ and η becomes to have a distinct maximum point. On the other hand, however, as W_2 increases, W_1 being constant, the forms of the curves change little. Hence, it was considered that W_1 had a greater influence on the combustion processes than W_2 , and hereafter η is plotted against the primary air-fuel ratio λ_1 which is defined as $\lambda_1 = \lambda \times W_1/100$.

Figure 7 shows λ_1 - η curves for A-combination ($S.70/\phi 10^\circ$). When W_1 is equal to W_2 [Fig. 7 (a)], four curves show similar forms and they

Fig. 7 Combustion efficiency for A-combination (λ_1 - η)

don't intersect with each other, in contrast to the curves in Fig. 6 (a). As W_1 and W_2 increase, it is thought that the residence time of the mixture in the primary combustion zone decreases and therefore η decreases. Figure 7 (b) shows when W_1 or W_2 is extremely large, viz. $W_1/W_2 \geq 3$ or $W_1/W_2 \leq 1/3$. The curves show similar forms for two cases respectively. In the former case ($W_1/W_2 \geq 3$), the combustion processes in the primary combustion zone are considered to be mainly governed by W_1 , and η has a maximum point at a certain value of λ_1 close to the stoichiometric air-fuel ratio of JP-4 ($=15.1^{(11)}$). On the other hand in the latter case ($W_1/W_2 \leq 1/3$), the combustion processes are considered to be governed by W_2 as well as W_1 , and the curves shift towards the rich side. Figure 7 (c) shows when W_1 is nearly equal to W_2 ($2 \geq W_1/W_2 \geq 1/2$), and the curves show similar forms for $W_3 = 60\%$ and $W_3 = 70\%$, respectively.

Two air-fuel ratios at which η attains its maximum value, $\lambda_{\eta \max}$ and $\lambda_{1\eta \max}$, are obtained from the λ - η curves and λ_1 - η curves for A-combination and are listed in Table 1. The values of $\lambda_{1\eta \max}$ scatter within a narrower range than $\lambda_{\eta \max}$ and they lie within the range from 11 to 15 except for $W_1/W_2 \leq 1/3$, which are close to the stoichiometric air-fuel ratio of JP-4. As mentioned above, if the air distributions are classified according to the value of W_1/W_2 and η is plotted against λ_1 , λ_1 - η curves belonging to a certain group show similar forms and the values of $\lambda_{1\eta \max}$ lie close to the stoichiometric air-fuel ratio of JP-4 except for $W_1/W_2 \leq 1/3$. Hence, although it is reasonable to consider that the sum of W_1 and

Table 1 $\lambda_{\eta \max}$ and $\lambda_{1\eta \max}$

	$\lambda_{\eta \max}$	$\lambda_{1\eta \max}$
30-10-60*	45	14
25-15-60*	45	12
25-5-70	50	13
20-20-60	60	12
20-10-70	55	11
15-25-60*	80	12
15-15-70	100	15
15-5-80	80	12
10-30-60*	70	7
10-20-70	110	11
10-10-80	115	12
5-25-70	—	—
5-15-80*	—	—
5-5-90	—	—

* These air distributions were used only for A-Combination.

a part of W_2 flow into the primary combustion zone and give an important influence on the combustion processes, W_1 has the greatest influence except for $W_1/W_2 \leq 1/3$. Therefore, since the air distributions

can be varied little with the fuel flow rate in the conventional combustion chamber, it is difficult to maintain high combustion efficiency over a wide range of air-fuel ratios with a fixed combustion chamber configuration.

Figure 8 shows η for five liner-swirler combinations with respect to λ_1 . In the following, the differences of λ_1 - η curves between above mentioned combination, A-combination [Fig. 7 and 8 (a)], and other combinations will be discussed.

For B-combination ($M \cdot 70\phi/10^\circ$), the effects of the secondary air on λ_1 - η curves are observed [Fig. 8 (b)]. In almost all the cases, when W_2 is larger than 15%, η decreases in the range of large values of λ_1 but increases in the range of small values of λ_1 as compared with A-combination. As the secondary air holes locate upstream in B-combination, these differences are considered to be due to the increase of the rate of the secondary air flow into the primary combustion zone.

For C-combination ($S \cdot 70\phi/5^\circ$), η increases almost all over the range of λ_1 except for $W_1=5\%$, as compared with others [Fig. 8 (c)]. This increase in η is considered to be due to the improvement of the mixing between the air and the fuel droplets.

For D-combination ($S \cdot 52\phi/15^\circ$), η decreases abruptly as λ_1 increases except for 25-5-70, and λ_1 - η curves show dissimilar forms as compared with others [Fig. 8 (d)]. This decrease in η is considered to be due to the distortion of the fuel spray induced by the primary air which is introduced near the root of the fuel spray. When λ is large, the upstream region of the primary combustion zone is occupied with unstable blue flames for D-combination but with stable yellow flames for others. Thus a distinct difference occurs in D-combination.

For E-combination ($S \cdot 70\phi/10^\circ R$), η decreases in the range of large values of λ_1 as compared with A-combination [Fig. 8 (e)]. As the primary air and the fuel spray turn round in the reverse direction, this decrease in η is considered to be due to the distortion of the fuel spray, which is not so great as that in D-combination.

As described above, for D-combination and E-combination, it was found from λ_1 - η curves and the observations of the flames that the primary air disturbed the fuel spray. Especially in D-combination, this effect was remarkable and dominant, so, after this, the discussion will often be made except for D-combination.

When $\lambda_{1, \max}$ was obtained from λ_1 - η curves for five liner-swirler combinations except for $W_1=5\%$, they ranged from 11 to 15 for afore-mentioned A-combination, from 9 to 13 for B-combination, from 10 to 16 for C-combination, from 7 to 13 for D-combination and from 11 to 14 for E-combination. Most values of $\lambda_{1, \max}$ were close to the stoichiometric air-fuel ratio of JP-4 except for D-combination, and for 25-5-70, $\lambda_{1, \max}$ for all cases ranged from 13 to 16 which was much closer to the stoichiometric air-fuel ratio of JP-4.

When the variations of η due to the liner-swirler combinations were compared with those due to the air distributions except for D-combination, the results described below were obtained. In the range of small values of λ , if one air distribution is chosen (in the present experiment, 20-20-60 or 15-15-70), η can be varied considerably according to the change of the liner-swirler combinations. In the range of large values of λ , however, η can be varied greatly according to the change of the air distributions by only 5%.

The relations between the heat release rate per unit volume of the combustion chamber Q and η were

examined except for D-combination. Two examples of Q - η curves for A-combination and B-combination are shown in Fig. 9. When Q - η curves are examined with respect to the air distributions, η increases as W_1 is reduced in the range of small values of Q , but, as a whole, η increases as W_1 increases in the

(a) A-combination ($S \cdot 70\phi/10^\circ$)
(b) B-combination ($M \cdot 70\phi/10^\circ$)
● 5-5-90, ▲ 10-10-80, × 15-15-70, ▽ 20-20-60,
▼ 5-25-70, ■ 10-20-70, △ 20-10-70, ○ 25-5-70
Fig. 9 Heat release rate and combustion efficiency

range of large values of Q . The boundary between these two ranges exists within $Q=4-6 \times 10^7$ kcal/m³hratm². Such nature of Q - η curves with respect to the air distributions and the liner-swirler combinations can be predicted from λ - η curves.

4.2 Flow patterns in combustion chamber

Figure 10 shows an example of the flow patterns in x - z plane for A-combination ($W_3=70\%$, at $y=25$ mm, 0 and -25 mm). It is clearly found from Fig. 10, especially from the patterns at $y=0$, that the region in which the reverse flow is present (viz. the recirculation zone) extends gradually towards downstream as W_1 increases and W_2 decreases. This is due to the increase in the degree of swirl induced by the primary air flow. The length of the recirculation zone L which is defined as the length between the fuel atomizer and the downstream end of the recirculation zone is also presented in Fig. 10. The flow patterns at $y=25$ mm and -25 mm show that the penetration of the secondary air varies with the air distributions, and further some parts of the secondary air flow make a reverse flow into the primary combustion zone. However, it is impossible to estimate the flow rate of this reverse flow from the flow patterns.

Figure 11 shows L for all cases. L ranges from

Fig. 10 Flow patterns in combustion chamber (A-combination, $W_3=70\%$)

Fig. 11 Length of recirculation zone

60 mm to 130 mm and it increases as W_1 increases for $W_1=W_2$ and $W_3=70\%$ except for 10-10-80 of D-combination. The recirculation zone mentioned here is considered to be identical with the primary combustion zone, so the length of the primary combustion zone is mainly governed by W_1 . Though it is reasonable to consider that L varies with respect to the liner-swirler combinations, the definite nature of L with respect to them has not been found as a whole. Then, it follows that the length of the recirculation zone is strongly affected by the air distributions alone in the present experiment.

4.3 Blow-off limit

The lean blow-off air-fuel ratio $\lambda_{B.O}$ is shown in Fig. 12. With respect to the air distributions, $\lambda_{B.O}$ is reduced and so the extinction of flames is apt to occur on the lean side as W_1 increases. With respect to the liner-swirler combinations, the values of $\lambda_{B.O}$ for A-combination and B-combination are nearly equal to each other and larger than those for other three combinations. Then the values of $\lambda_{B.O}$ are reduced for E-combination and C-combination successively, and those for D-combination turn out the smallest as predicted from an abrupt decrease of η when λ increases. Further, it is found that $\lambda_{B.O}$ is affected by the liner-swirler combinations

when W_1 is small ($W_1 \leq 15\%$). The reason is thought that the gas velocity in the primary combustion zone decreases as W_1 is reduced, so the flames in the upstream region near the fuel atomizer may be affected by a slight change of the flow patterns due to a change of the liner- and the swirler-configuration.

Longwell and others showed that the combustion processes in the recirculation zone behind a bluff-body appeared to proceed homogeneously with high mixing intensity and the blow-off occurred at certain values of the air-loading parameter W_a/VP^2 (W_a : air mass flow rate, V :

Fig. 12 Lean blow-off air-fuel ratio

volume of recirculation zone, P : pressure) for a fixed air-fuel ratio⁽¹²⁾. Furthermore, they applied this concept to the simple can-type combustion chamber⁽¹³⁾. Although the combustion chamber used in the present work has a practical configuration, the blow-off limit has been tried to evaluate with above mentioned concept for four liner-swirler combinations except for D-combination and for $W_1=5\%$. The value of W_a/VP^2 was calculated putting W_a as the primary air flow rate, V as the volume of the liner from $x=0$ to $x=L$ and P as 1 atm.

In Fig. 13 W_a/VP^2 is plotted against the blow-off equivalence ratio for the primary air flow $\phi_{1B.O.}$. In spite of the complexity of the processes in the combustion chamber, ordinary stability curves could be obtained except for some 10-20-70 and 20-20-60. The reason for the deviations of the points for 10-20-70 and 20-20-60 will be discussed in section

Fig. 13 Blow-off limit

Fig. 14 Pressure loss factor (A-combination)

4.5. Hence, it is concluded that the blow-off limit can be explained from the concept that the combustion processes in the primary combustion zone proceed homogeneously with high mixing intensity. As L , which is used to calculate V , varies little with respect to the liner-swirler combinations, the lean blow-off curves in Fig. 13 show a similar nature to $\lambda_{B.O.}$ in Fig. 12.

4.4 Pressure loss

The magnitude of the modified pressure loss factors ϕ varied considerably according to the amount of the primary air, because the total pressure of the inlet primary air was employed to calculate ϕ . For example, in the cold flow experiment for A-combination, the average value of ϕ was 5.2 for $W_1=5\%$, 19.0 for $W_1=10\%$ and 38.5 for $W_1=15\%$. Therefore it was meaningless to compare between the magnitudes of ϕ . ϕ was plotted against T''/T' (T' : absolute temperature of the inlet air, T'' : absolute temperature of the exit combustion gas) and an example is shown in Fig. 14 for A-combination. All the points fit well with the straight lines except when W_1 is large ($W_1=20\%$, 25%) and their gradients have nearly constant values. The average values of them are 2.0 for A-combination, 2.1 for B-combination, 2.3 for C-combination and 2.2 for D-combination and E-combination.

4.5 Temperature distributions in combustion chamber

The temperature in the combustion chamber T was measured at two air-fuel ratios, $\lambda \approx 130$ and $\lambda \approx 60$.

Figure 15 shows an example of the vertical

Fig. 15 Vertical temperature distribution for A-combination

temperature distributions in the upstream region of the primary combustion zone (at $\lambda \approx 60$, $x=30$ mm, $y=0$) for A-combination. For all the air distributions, it is found that the temperature increases abruptly near the inside of the conical fuel spray and has nearly constant values in the central region. Thus in the upstream region, the shape of the temperature distributions agrees closely with that in the recirculation zone behind a bluffbody stabilizer⁽¹⁴⁾. In the downstream region, this shape of the temperature distributions, being affected by the cold air flow from the air holes of the liners and the flames along the liner walls, breaks down. For example, at $x=105$ mm, three temperature peaks, near the upper- and lower-wall and in the central region, appear. Being strongly affected by the cold air flow from the air holes, the vertical temperature distributions at $y \neq 0$ and the horizontal temperature distributions become more complex.

Although the temperature distributions in the combustion chamber appear to be rather complex, it seems that the temperature distributions on the chamber axis ($y=0$, $z=0$), which are not directly affected by the cold air flow and walls, represent the nature in the combustion chamber. Hereafter, discussions about the temperature distribution on the

chamber axis will be made. The temperature was measured at intervals of 5 mm, and the temperature distributions were shown for $x \geq 15$ mm because the fuel droplets collided with the thermocouple considerably near the fuel atomizer.

With respect to the air distributions, Fig. 16 shows examples of the temperature distributions for A-combination at $\lambda \approx 60$. There are always fuel rich mixtures in the upstream region near the fuel atomizer, accordingly the temperature in this region rises as W_1 increases. In Fig. 16 (a) ($W_1=W_2$), the high temperature region exists in the downstream region when W_1 and W_2 are small. In Fig. 16(b) ($W_3=70\%$), when W_1 is small, the temperature rises again due to the secondary combustion, and when W_1 is large, the temperature does not fall to further downstream region due to the extended recirculation zone.

At $\lambda \approx 130$, as compared with the temperature distributions at $\lambda \approx 60$, the high temperature region exists in the upstream region, and the maximum temperature rises when W_1 is small but falls when W_1 is large due to the change of the air-fuel ratio in the combustion zone.

With respect to the liner-swirler combinations, the temperature are plotted against the nondimensional distance x/L , as shown in Fig. 17 ($W_1=70\%$, $\lambda \approx 60$). The temperature distributions for A-combination [Fig. 17 (a)] and B-combination [Fig. 17(b)] show similar shapes, though the temperature falls more quickly in the recirculation zone for [A-combination]. For C-combination [Fig. 17 (c)], since the penetration of the secondary air is reduced due to the increase of the velocity of the primary air, the secondary temperature rise is reduced. This nature is also seen for D-combination and E-combination, but the reason has not been found yet. For D-combination [Fig. 17 (d)], the temperature falls quickly for $W_1 \leq 15\%$ and two temperature peaks occur for $W_1 \geq 20\%$, due to the distortion of the fuel spray induced by the primary air. For E-combination [Fig. 17 (e)], the high temperature region exists in the downstream region of the recirculation zone, and this is supposed to be due to the reduction of the air flow recirculated towards upstream.

At $\lambda \approx 130$, the temperature distributions vary little with respect to the liner-swirler combinations as compared with those at $\lambda \approx 60$.

Considering from the temperature distributions, the concept that the combustion processes in the primary combustion zone proceed homogeneously with high mixing intensity can be applied for the case when the temperature has nearly constant values in the recirculation zone and decreases abruptly after

Fig. 16 Temperature distributions in combustion chamber for A-combination

(a) A-combination
($S \cdot 70 \phi / 10^\circ$) (b) B-combination
($M \cdot 70 \phi / 10^\circ$) (c) C-combination
($S \cdot 70 \phi / 5^\circ$) (d) D-combination
($S \cdot 52 \phi / 15^\circ$) (e) E-combination
($S \cdot 70 \phi / 10^\circ R$)Fig. 17 Temperature distributions in combustion chamber ($W_3 = 70\%$, $\lambda \approx 50$)

the recirculation zone. In Table 2, the average values and the standard deviations of the temperature, $\bar{T}$ and s , are listed except for D-combination. From Fig. 17 and Table 2, the cases which well satisfy the above mentioned conditions are found to be 25-5-70, 20-10-70 and 10-10-80, and the case which roughly satisfies is 15-15-70 of A-combination, B-combination and C-combination. Also, it is found from Table 2 that the average values of the temperatures for these cases are large. Furthermore, it is found from Fig. 13 that the blow-off points for these cases come close to the straight lines, but that the points for 10-20-70 and 20-20-60, whose temperatures reduce quickly still in the recirculation zone, deviate considerably. Although the temperature at large air-fuel ratio near blow-off reduces in the recirculation zone, the temperature distributions at small air-fuel ratio, such as shown in Fig. 17, provide a criterion by which it is possible to know

whether or not the combustion processes in the primary combustion zone proceed homogeneously with high mixing intensity.

5. Conclusions

A combustion experiment was made to study the effects of the air distributions on the combustion chamber performances and the combustion processes, using a box-type model combustion chamber which could supply the primary-, the secondary- and the tertiary-air flow separately with desired rate. The main results obtained are summarized in the following.

(1) The combustion efficiency is strongly affected by the air-fuel ratio in the primary combustion zone except when the primary air flow is too little and when the distortion of the fuel spray occurs. Therefore it is difficult to maintain high combustion efficiency over a wide range of air-fuel ratios with a fixed air distribution.

(2) The length of the recirculation zone increases as the primary air flow increases.

(3) The ordinary lean stability curves can be obtained by the concept that the combustion processes in the primary combustion zone proceed homogeneously with high mixing intensity for some cases.

(4) The gradients of the pressure loss factor curves have nearly constant values for all cases.

(5) In the upstream region of the primary combustion zone, the temperature has a nearly

constant value in the central region inside the fuel spray. The temperature distributions on the chamber axis at small air-fuel ratio provide a criterion by which it is possible to know whether or not the combustion processes in the primary combustion zone proceed homogeneously with high mixing intensity.

Although the combustion processes in the combustion chamber are complex, according to the above mentioned results, when the experiment to study the effects of the air distributions is carried out and the informations on the primary combustion zone, for example the air-fuel ratio in the primary combustion zone and the length of the recirculation zone, are obtained, it is possible to explain the combustion chamber performances and the combustion processes in the combustion chamber reasonably.

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Table 2 Average value and standard deviation of temperature in recirculation zone

	A-combination		B-combination		C-combination		E-combination	
	$\bar{T}$ °C	s °C	$\bar{T}$ °C	s °C	$\bar{T}$ °C	s °C	$\bar{T}$ °C	s °C
10-10-80	1249	24	1446	66	1244	100	1016	243
10-20-70	1158	218	1228	156	1044	109	1048	188
15-15-70	1239	192	1405	81	1142	71	1085	286
20-10-70	1353	107	1505	51	1314	58	1152	331
20-20-60	855	383	1222	195	1026	162	1067	246
25-5-70	1479	50	1530	28	1334	80	1120	409