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Studies of a Diffusion Flame Matrix Burner in a Combustion Chamber with Heat Exchanger*

By Yukio SAKAI** and Hiroshi TSUJI***

Experimental studies were carried out to make clear the combustion characteristics of a diffusion flame matrix burner in a combustion chamber with heat exchanger. The shape and the stability limits of the matrix burner flame were examined, and the concentrations of stable species and NO_x in the exhaust gases were measured for methane flame, the burner surface/heat exchanger separation being the parameter. The minimum separation to maintain a stable flame with low emissions of pollutants was investigated.

It has been found that this burner can be operated with good combustion and emission characteristics at a separation of only 10 mm, similarly to the matrix burner operated in the open atmosphere.

Key Words: Combustion, Matrix Burner, Combustion Chamber.

1. Introduction

Experimental studies were made by the present authors to make clear the flame stability limits, the flame structure, and the pollutant emission characteristics of a diffusion flame matrix burner^{(1)~(3)}. This burner produced a very short connected mat of laminar flame at a few millimeters above the surface of burner matrix. For appropriate flow rates of air and fuel, the burner operated silently and with low pollutant emission. The thermal output of the stable combustion for this matrix burner was found to be several times larger than that of the Schwank burner, which is known as a typical short flame burner of premixed flame⁽¹⁾⁽²⁾. It has become clear that this diffusion flame matrix burner is a useful burner from the standpoint of the combustion characteristics and exhaust emissions.

Since the special emphasis was laid on the basic combustion characteristics of the diffusion flame matrix burner, all measurements were made with burners in the open atmosphere. However, in order to make a practical application of this matrix burner, the burner is usually used in conjunction with a heat exchanger in a combustion chamber. Therefore, the combustion chamber volume may have an effect on the combustion characteristics of this burner. The present experimental studies were made to investigate the combustion characteristics of a diffusion flame ma-

trix burner used in combination with a combustion chamber and a heat exchanger. The special emphasis was laid on the studies of a minimum burner surface/heat exchanger separation to preserve the good combustion and exhaust emission characteristics, because a small combustion chamber volume has a potential for making combustion appliances more compact. There are several studies which are concerned with the combustion chamber volume^{(4)~(7)}. In the fuel-jet type diffusion flame matrix burner^{(6)~(9)}, the burner could be operated at a burner surface/heat exchanger separation of only 25 mm⁽⁷⁾. However, there is no study of the combustion chamber volume for the air-jet type burner⁽¹⁰⁾ which is similar to the diffusion flame matrix burner used in the present experiment.

Fig. 1 Cross-sectional view of combustor.

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** Lecturer, Department of Mechanical Engineering, Saitama Institute of Technology, Okabe, Saitama.

*** Professor, Institute of Interdisciplinary Research, Faculty of Engineering, The University of Tokyo, Komaba, Meguro-ku, Tokyo.

2. Experimental apparatus

2.1 Burner

Figure 1 shows a cross-sectional view of the combustor. The combustor was composed of a matrix burner, a duct (glass tube), and a heat exchanger which was used to vary the combustion chamber volume. In the present experiment, the type-C burner matrix^{(1)~(3)} was used, in which the most favorable combustion characteristics were obtained among the burner matrices used in the previous experiments. The type-C burner matrix consisted of an upper porous plate, a bottom brass plate, and fifty-five thin stainless steel tubes of outer diameter of 6 mm which were arranged in a regular matrix to form an equilateral triangle as a unit (the pitch of tubes was 8.1 mm). However, some air tubes could not be arranged around the periphery of the burner matrix, so that the regular arrangement of air tubes was not preserved around the periphery of the burner matrix. Therefore, the ejection area ratio of fuel and air around the periphery of the burner surface became larger than that in the central part of the burner surface, and the fuel/air ratio around the peripheral region of the burner became larger than that in the burner central part. Then, in the present experiments, in order to increase the air ejection area around the burner periphery and also to reduce the interference between the duct wall and the flame around the burner periphery, we arranged six small air tubes (outer diameter : 3.5 mm) on the periphery of the burner where the fuel ejection area was large, and at the same time, an annular air exit was provided around the burner circumference. From this annular air exit, an auxiliary air was ejected through a foam metal plate (Selmet #5).

2.2 Duct and heat exchanger

The duct was made of a Pyrex glass tube which had an inner diameter of 80 mm and a length of 180 mm, and it was situated vertically on the burner surface.

The heat exchanger was made of copper, and its diameter was 79 mm. Eighty-five draught tubes which had outer diameter of 4 mm ran through the upper and bottom plates of the heat exchanger. In the present experiments, two heat exchangers, 20 mm and 100 mm in height, were prepared. The heat exchanger was mounted on a slide compound provided with micrometer screws that permitted traversing normal to the burner surface in the duct. The burner surface/heat exchanger separation L was varied to adjust the combustion chamber volume. The draught tubes of the heat exchanger were arranged to form an equilateral triangle as a unit (the pitch of the draught tubes was 8.1 mm).

2.3 Air and fuel supply system and measuring equipment

The air was supplied from a compressor to the air tubes of the burner matrix

and to the annular air slit around the burner circumference. The fuel (methane) from a compressed gas cylinder was fed to the burner through a metering orifice.

In order to investigate the combustion characteristics of this burner used in combination with a combustion chamber and a heat exchanger, various species concentrations and temperatures were measured. The concentrations of various stable species were determined by using a gas chromatograph (Hitachi Model 163), and the NO_x concentrations were measured by using a chemiluminescent NO_x analyzer (Yanagimoto Model ECL-30). The gas samples were withdrawn through a quartz microprobe, 40 μm orifice diameter. In order to prevent water condensation of the sample gases, the sampling lines were all heated to about 120°C. In the case of measurements of NO_x concentrations, we corrected the experimental data for the quenching effect of H_2O and CO_2 in the chemiluminescence detector⁽³⁾. The temperature was measured with a silica-coated Pt/Pt-13%Rh thermocouple (wire diam. 0.1 mm).

3. Experimental procedure

At first, the experiment was carried out without a heat exchanger. After we confirmed that the stable flame became almost flat as a whole by ejecting the auxiliary air from the annular air exit, the flame stability limits, the concentrations of various species and the temperature profiles in the duct were determined. Then, an experimental study was made with

(a) Oblique view of flame

(b) Side view of flame

Fig. 2 Direct photographs of stable flame ($V_a = 2.0$ m/sec, $V_g = 2.0$ cm/sec, $V_c = 1.0$ m/sec).

a heat exchanger. The effect of the burner surface/heat exchanger separation on the flame appearance and on the exhaust concentrations of unburned species and nitrogen oxides was examined, the fuel and air velocities being kept constant. And the effect of the fuel and air velocities on the exhaust emissions was examined, the burner surface/heat exchanger separation being kept constant. In these experiments, the heat exchanger with the height of 20 mm was used, and the water flow rate was maintained at 15 cc/sec. Water was preheated to $30^{\circ}\text{C} \sim 40^{\circ}\text{C}$ at the inlet of the heat exchanger to prevent water condensation in the combustion gases. At last, the heat transfer performance was investigated by using the heat exchangers with the heights of 20 mm and 100 mm.

4. Experimental results and discussion

4.1 Combustion characteristics without heat exchanger

In this burner, there is no need for the secondary air, because the air necessary for combustion is sufficiently supplied. As described in Chap. 2.1, however, the fuel/air ratio around the periphery of the burner became larger than that in the burner central part. So that if the glass duct was put on the burner surface and the flame was shielded from room air current, and if the annular air ejection was not made, the flame length around the periphery of the burner became long. However, the flame length around the burner periphery could be controlled by changing the annular air velocity (the auxiliary air velocity from the annular exit V_c). When the annular air velocity was 1.0 m/sec, it was found that the stable flame became almost flat as a whole.

Fig. 3 Stability diagram of flame; ●, with a duct; ○, in the open atmosphere.

Figure 2 shows a typical short flame stabilized for the air ejection velocity V_a of 2.0 m/sec, the fuel gas ejection velocity V_g of 2.0 cm/sec, and the annular air velocity V_c of 1.0 m/sec. It is clear that the flame zone exists only above the porous plate of fuel exit, and appears to be almost flat as a whole. Therefore, hereafter the experiments were carried out, V_c being kept constant at 1.0 m/sec.

Figure 3 shows a flame stability diagram of the burner mounted within a duct and a stability diagram of the burner in the open atmosphere obtained previously⁽¹⁾ (2). In both cases, two transitional regions adjacent to the stable flame region were observed. One was a partial flame blow-off region in which the flame on the burner was partly extinguished, and the other was a partial flame oscillating region in which the flame around the burner periphery oscillated⁽¹⁾ (2). In this diagram, however, these two regions are included in the flame blow-off region and in the flame oscillating region, respectively. When the burner was installed within the duct, the partial blow-off and oscillation of the flame around the periphery of the burner were suppressed, therefore, the stable flame region became a little wider in comparison with the flame in the open atmosphere.

Figure 4 shows the radial temperature profiles at a height of 70 mm above the burner surface ($Z = 70$ mm) for $V_a = 2.0$ m/sec, V_g being the parameter. Corresponding to the high temperature region behind the flame zone above the porous burner surface and the low temperature region above the air tube, the temperature shows regular profiles over the wide region of the burner surface. It was found that a very regular temperature profile

Fig. 4 Radial temperature profiles ($V_a = 2.0$ m/sec, $V_c = 1.0$ m/sec, $Z = 70$ mm).

as a whole was observed between $V_g = 1.0$ cm/sec and 2.0 cm/sec.

4.2 Effect of the burner surface/heat exchanger separation on the flame appearance

In the present diffusion flame matrix burner, the air ejection velocity is much greater than the fuel ejection velocity, so that the burner surface/heat exchanger separation has a great effect on the flow pattern near the burner surface. Thus, the burner surface/heat exchanger separation may affect the combustion characteristics. At first, we examined the effect of the combustion chamber volume on the flame appearance.

Figure 5 shows photographs of flame in the case where the burner surface/heat exchanger separation is varied ($V_a = 2.0$ m/sec, $V_g = 2.0$ cm/sec). When the heat exchanger was attached at 50 mm height above the burner surface, the flame approached the burner surface a little. However, even if the heat exchanger was moved gradually toward the burner surface, the flame location scarcely changed. When L was decreased to about 15 mm, the flame of an almost flat shape began to approach the burner surface gradually. If L was decreased to about 5 mm, a part of the flame zone was extinguished. At L of 3 mm the flame was extinguished completely. In other experimental conditions, it was found that the flame was partly extinguished when L became 5 mm $\sim$ 8 mm and the

flame was completely extinguished when L became 3 mm $\sim$ 4 mm. Therefore, the burner surface/heat exchanger separation can be made as small as 8 mm.

4.3 Effect of the burner surface/heat exchanger separation on the exhaust emissions

As it was found that L could be made as small as 8 mm, the exhaust concentrations of various species were measured when the burner surface/heat exchanger separation was decreased. The measurements of various species concentrations were made at 80 mm height above the burner surface. The average value of concentrations obtained at the radial 6 $\sim$ 9 points was regarded as the exhaust concentrations of these species. The relation between the burner surface/heat exchanger separation and exhaust concentrations of various species is shown in Fig. 6 (a) for $V_a = 1.0$ m/sec and in Fig. 6 (b) for $V_a = 3.0$ m/sec, respectively.

In these figures the exhaust concentrations of various species obtained in the burner without a heat exchanger are also shown. The exhaust concentrations of various species obtained in the burner without a heat exchanger are almost the same as those in the open atmosphere⁽³⁾. In Fig. 6 (a), the exhaust concentrations of various species for $L = 50$ mm are nearly equal to those of the burner without a heat exchanger, so that the heat exchanger attached at $L = 50$ mm has no effect on the

Fig. 5 Photographs of flame in the case where the burner surface/heat exchanger separation is varied ($V_a = 2.0$ m/sec, $V_g = 2.0$ cm/sec, $V_c = 1.0$ m/sec).

exhaust concentrations of these species. When the heat exchanger is moved gradually toward the burner surface, the N_2 concentration does not change. The concentrations of O_2 , H_2O , and CO_2 are almost constant for $L > 8$ mm, but when L is decreased below 8 mm, the O_2 concentration increases gradually, and the concentrations of H_2O and CO_2 decrease rapidly. CO and H_2 , which are intermediate products, and CH_4 are not observed when L is large. However, if L becomes smaller than about 10 mm, and if the concentrations of H_2O and CO_2 begin to decrease, the concentrations of unburned species (CH_4 , CO , H_2) increase rapidly. It is found that if L is larger than 10 mm, the combustion process is, essentially, complete.

The NO_x concentration for $L = 50$ mm coincides with that of the burner without a heat exchanger. If L is decreased, the NO_x concentration decreases rapidly. The difference between the NO_x concentration and the NO concentration increases gradually as L is decreased, and it shows a maximum at L of about 7 mm, and then it decreases rapidly. Therefore, it is confirmed that, in the case where $V_a = 1.0$ m/sec, if the burner surface/heat exchanger separation is larger than 10 mm, an almost complete combustion is attained, similarly to the burner without a heat exchanger, and the exhaust concentration of NO_x becomes lower than that of the burner without a heat exchanger.

In Fig. 6 (b), the exhaust concentrations of various species for $L = 50$ mm do not coincide with those of the burner without a heat exchanger, and the heat exchanger has an effect on the exhaust concentrations of these species. The unburned species appear in the whole range of L that has been examined. When L be-

comes smaller than 7 mm, the concentrations of these unburned species become larger than those obtained in the burner without a heat exchanger. When L becomes smaller than 10 mm, the exhaust concentration of NO_x becomes smaller than that obtained in the burner without a heat exchanger.

Similar measurements were also made for various value of V_g . It is found that, if L is larger than 10 mm, the exhaust concentrations of unburned species are almost the same as those of the burner without a heat exchanger. This 10 mm separation is one fifteenth that of the conventional boilers fitted with an aerated jetted burner(7). The potential for making the combustion chamber volume more compact, through the application of this matrix burner, is therefore considerable.

A complete combustion with a reduced volume can be attained in this matrix burner because a very short flame is stabilized and a very unique flow pattern is established in this matrix burner(1)(2). Near the burner surface the flow is recirculating, so that even when the heat exchanger is installed downstream of the flame, the flow pattern near the burner surface is not affected very much provided the heat exchanger is not located near the burner surface. Therefore, the flame itself is not affected by the heat exchanger attached downstream of the flame.

4.4 Emission characteristics of unburned species and nitrogen oxides

The combustion characteristics of this burner was seriously affected by the air ejection velocity(1)(3). Then, the exhaust concentrations of unburned species

(a) $V_a = 1.0$ m/sec

(b) $V_a = 3.0$ m/sec

Fig. 6 Effect of the burner surface/heat exchanger separation on the exhaust concentrations of various species ($V_g = 3.0$ cm/sec, $V_c = 1.0$ m/sec).

Fig. 7 Exhaust emissions ($V_g = 3.0$ cm/sec, $V_c = 1.0$ m/sec); $\square$, $\circ$, with a duct; $\blacksquare$, $\bullet$, $L = 10$ mm.

and nitrogen oxides were measured by varying the air ejection velocity. The concentrations of unburned species and nitrogen oxides obtained in the burner without a heat exchanger were compared with those of the burner with a heat exchanger ($L = 10$ mm) for $V_g = 3.0$ cm/sec (Fig. 7). The unburned species concentration was shown as the sum of the concentrations of CH_4 , CO , and H_2 . The exhaust concentrations of unburned species and nitrogen oxides obtained in the burner without a heat exchanger coincided with those obtained previously in the open atmosphere⁽³⁾. In the case where the burner is installed in the duct and without a heat exchanger, the exhaust concentrations of unburned species and nitrogen oxides become lower than 50 ppm and 20 ppm, respectively, in the range of V_a of 0.9 m/sec $\sim$ 1.6 m/sec. It has been found that the exhaust emissions can be made very small. In the case where the burner is used in conjunction with a heat exchanger in a combustion chamber, the appropriate range of the air ejection velocities in which both unburned species emissions and nitrogen oxides emission are small shifts to the smaller air ejection velocity.

In this figure, a CO/CO_2 ratio at the burner surface/heat exchanger separation of 10 mm is also presented. There is a criterion set for the small gas appliances

Fig. 8 Efficiency of the heat exchanger ($V_a = 1.0$ m/sec, $V_g = 3.0$ cm/sec, $V_c = 1.0$ m/sec, $L = 10$ mm).

which require that the carbon monoxide to carbon dioxide ratio in the combustion products does not exceed $0.02(6)(8)^{(10)}$. This burner comes up to the above criterion in the whole range of conditions that have been examined.

4.5 Heat-transfer performance

The ratio between the heat transferred from the hot burned gases to cold water and the higher heat of combustion of the fuel was defined as the efficiency of the heat exchanger η (%).

Figure 8 shows the relation between the water flow rate q and η , H being the parameter, for $V_a = 1.0$ m/sec, $V_g = 3.0$ cm/sec, and $L = 10$ mm. For the heat exchanger of $H = 20$ mm, η is almost constant, and it is about 45 %. For the heat exchanger of $H = 100$ mm, however, η increases with q , and η reaches 79 % at $q = 35$ cc/sec. If the water flow rate is decreased, the water outlet temperature from the heat exchanger of $H = 100$ mm increases to 85°C.

5. Conclusions

Experimental studies were carried out to make clear the combustion characteristics of a diffusion flame matrix burner in a combustion chamber with a heat exchanger. The main results may be summarized as follows:

(1) In the case where the burner was used in conjunction with a duct and the auxiliary air was ejected through the annular exit around the burner circumference, it was found that the stable flame became almost flat as a whole, and the radial temperature showed regular profiles over a wide area of the burner surface, and at the same time, the stable flame region in the flame stability diagram became a little wider, and the exhaust concentrations of various species and exhaust emissions were almost the same as those of the burner in the open atmosphere.

(2) If the burner surface/heat exchanger separation was larger than 8 mm, the shape of the luminous flame zone was almost the same as that of the burner without a heat exchanger.

(3) If the burner surface/heat exchanger separation was larger than 10 mm, an almost complete combustion was attained, similarly to the burner without a heat exchanger, and the exhaust concentration of NO_x became lower than that of the burner without a heat exchanger.

(4) For the heat exchanger with the height of 100 mm, the efficiency of the heat exchanger increased to 80 %, and the water outlet temperature from the heat exchanger increased to 85°C.

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