DME-Fired Water-Tube Boiler - A R&D Study

DME-Fired Water-Tube Boiler—A R&D Study[*]

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Increasing attention has been given to the development of low-NOx combustion technology for DME (Dimethyl Ether). The present paper describes the R&D study for water-tube boiler carried out in Kansai University and Hirakawa Guidam Co., Ltd. under the support of DME project from METI. The major problem in DME use is the difficulty in the application of premixed flame due to its low ignition temperature and rather high burning velocity. However, the previously developed tube-nested combustor, i.e. water-tubes installed in the empty furnace, becomes effective means together with the flue-gas recirculation to overcome such difficulty in achieving low-NOx combustion. This paper begins with a brief review of the R&D study of the tube-nested combustor specifically designed for city gas. Then the further development for DME-fired water-tube boiler is described.

1. Introduction

Recent advances in small-capacity boilers are typically characterized by the small area for installation as well as achieving low-NOx combustion. The similarity law of boiler furnace, typically shown in Fig. 1[(1)], gives relevant relationship between specific furnace-heat-release rate and the equivalent steam-generation rate. The specific furnace-heat-release rate correlates with the furnace size, and this furnace size is limited by the residence time so as to complete the burning. Higher specific furnace-heat-release rate leads to very high temperature and very high thermal NOx generation. On the other hand, the water-walls in a conventional furnace should be operated within the safety range for burnout or critical heat flux in the water-tubes. Furthermore the specific furnace-heat-release rate depends on the heat absorption rate, i.e. steam generation rate, and on the furnace volume. On the other hand, the surface heat flux depends on the steam generation rate and the heat transfer area. Such relationships lead to the functional relationship, [specific furnace-heat-release rate] $\propto$ [steam generation rate]$^{-1/2}$ as can be clearly observed in Fig. 1. The relationship is consistent
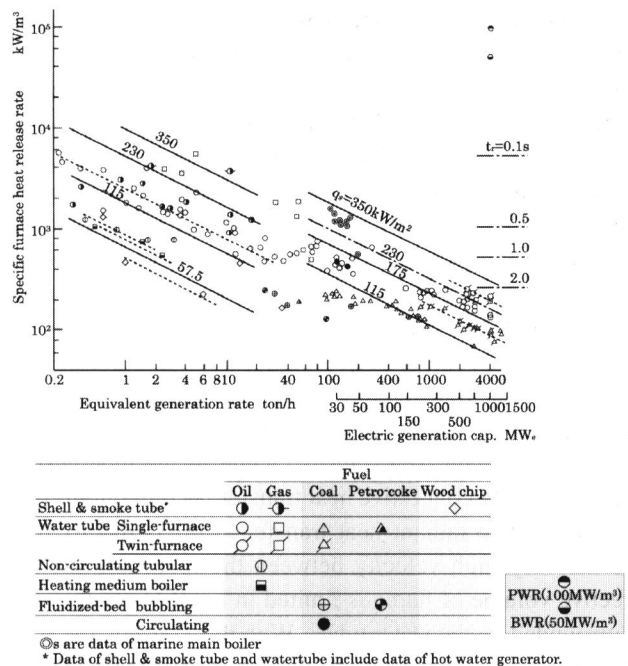

Fig. 1   Scaling law of conventional boiler furnace[(1)]

throughout each of small- and large-scale boilers, respectively. The plotted data have been obtained from the data of commercial boilers in the market, and thus it may be rather difficult to design far beyond this similarity law.

In terms of small-scale boiler, the highest specific heat-release rate reaches almost 6 MW/m^3. In order to achieve further reduction in size as well as low-NOx com-

bustion, alternative technology or concept is needed in the boiler construction and design. Ishigai et al. proposed a new concept, being referred to as tube-nested combustor, and developed compact water-tube boiler for commercial use[2],[3]. This tube-nested combustor has been well accepted in the market owing to the soundness in thermal flow design of combustor, and is widely applied in various aspects of combustion technologies. This concept is applicable to the present purpose for DME-fired boiler development as well. DME is characterized by lower ignition temperature, 623 K, and higher burning velocity, 50 cm/s, relative to methane, 923 K and 37 cm/s, and propane, 743 K and 43 cm/s. Such features cause difficulty in applying pre-mixed burner to low-NOx combustor. In a boiler, the problem of low ignition temperature may not be as severe as the gas turbine combustor[4], but the flash-back must be avoided. Thus the burner should be, in principle, diffusion-type, and tube-nested combustor is especially suitable for reducing NOx emission. In this paper, first, fundamental aspects of the tube-nested combustor are briefly reviewed and then R&D study for DME boiler is described.

2. Tube-Nested Combustor

In order to prevent thermal NOx generation, the flame temperature should be suppressed within a suitable range and the hot spot should be removed. Instead of removing large empty space of a furnace, water-tubes supplied with sufficient water or having such water supply system are installed in the burning space of a conventional furnace as shown in Fig. 2[2]. Then the flame is directly cooled down to the suitable level, so that the NOx generation is suppressed to a very low level. These water-tubes enhance mixing and thus relatively uniform temperature field is created in the combustor as well.

The heat transfer in the furnace, then, occurs in a different mode, i.e. conventional furnace is mainly dominated by radiant heat transfer, while in the tube-nested combustor the convective heat transfer becomes dominant relative to the radiant heat transfer. This is mainly due to the very high velocity between the tubes and the effective volume of flame is limited in a rather small space surrounded by the water tubes. With this concept, the specific furnace-heat-release rate rises to about 12 MW/m³, so that the installation space is reduced to 1/3 of the conventional water-tube boiler[2]. The soundness of the boiler is achieved by the sufficient cooling water passing through the heat transfer surface. The test boiler with city-gas fired tube-nested combustor in Thermal Engineering Laboratory, Kansai University, is shown in Fig. 3. This boiler produces 500 kg/h steam, i.e. 350 kW. The main parts consist of partially-premixed diffusion burner for city gas, the tube-nested combustor with bare water-tubes arranged in line, and the finned tubes in the convective heat transfer
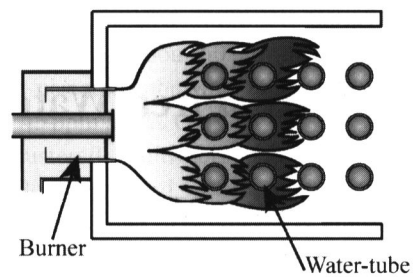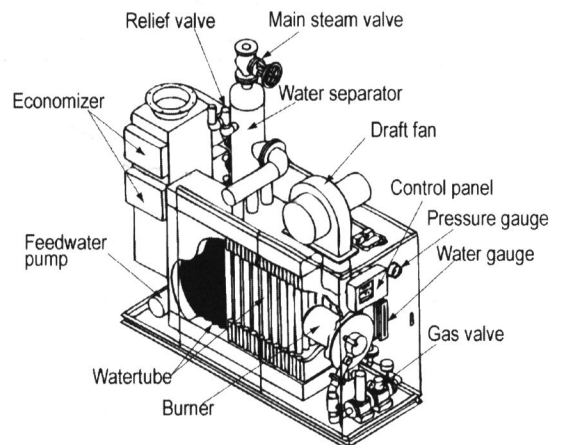

Fig. 2   Tube-nested combustor

Fig. 3   Test boiler (500 kg/h steam generation rate)

zone downstream the combustor. Both sides of finned-tube array are occupied by the insulation walls with which the velocity of gas flow is retained at a high level. In the case of higher steam generation rate, this insulation walls are removed and the finned tubes are arranged so that the heat absorption increases.

The design principles of this type of boiler are as follows:

(1)   Tube nest is installed so as to cool down the burner flame to a suitable temperature level to suppress NOx generation.

(2)   Tube nest gives sufficient turbulence or mixing effect on the gas flow to retain uniform temperature field, i.e. to prevent the appearance of hot-spot.

(3)   The flame stability is an essential factor for meeting the above-mentioned requirements. To achieve this, the tube arrangement and pressure drop in the gas flow imposed by the tube nest are of prime importance.

3. Fundamental Study for Tube-Nested Combustor

At the beginning of the R&D study, flow visualization was conducted with a cold model. Figure 4 represents one of the typical examples of simulated burner jet and induced recirculation flow visualized by smoke[5],[6]. As far as burner jet stability is concerned, formation of symmetric stable recirculation flow is essential, and is closely related to the tube arrangement, i.e. a certain confined space formed by the tube nest and the imposed pressure drop are
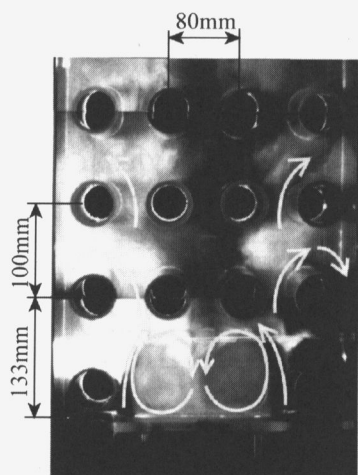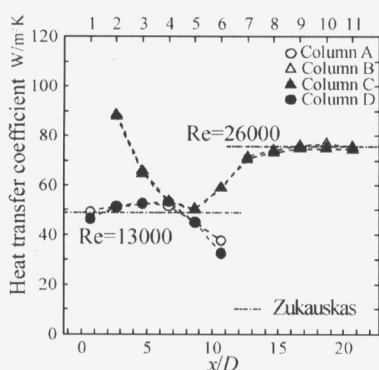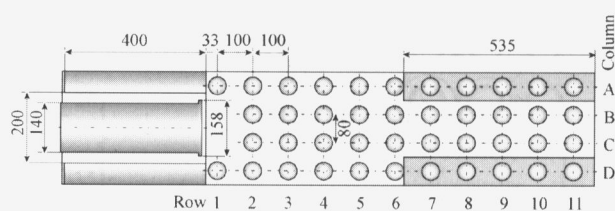
Fig. 4   Recirculation flow induced by burner jet

Fig. 5   Average heat transfer coefficient (cold model test)

Fig. 6   Boiler tube

$Nu=0.357Re^{0.587}Pr^{1/3}$

$Nu=0.0459Re^{0.766}Pr^{1/3}$

Fig. 7   Finned tube heat transfer

Fig. 8   Cross-sectional view of test boiler

essential as mentioned above.

The heat transfer characteristics were then measured with the cold model having the same dimension as the test boiler. Typical example is shown in Fig. 5[7]. The heat transfer coefficient at the column A and D close to the side wall is almost equal to the Zukauskas' correlation[8], while in the middle columns B and C is significantly influenced by the burner jet. This effect of burner jet damps along the flow direction, and again the heat transfer coefficient increases to a higher level in the convective heat transfer zone due to an increase in the gas velocity. The plotted data in the convective zone was, however, obtained with bare tubes. The photos of the boiler tubes are shown in Fig. 6; the one on the left is a bare tube in the combustion zone, and on the right is the finned tube in the convective zone. The finned tube has an extended surface area, while the heat transfer coefficient becomes lower as shown in
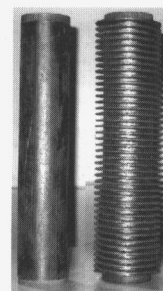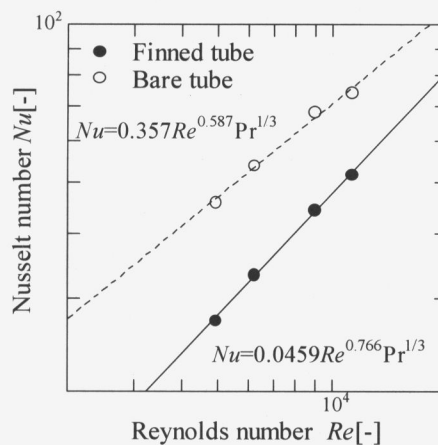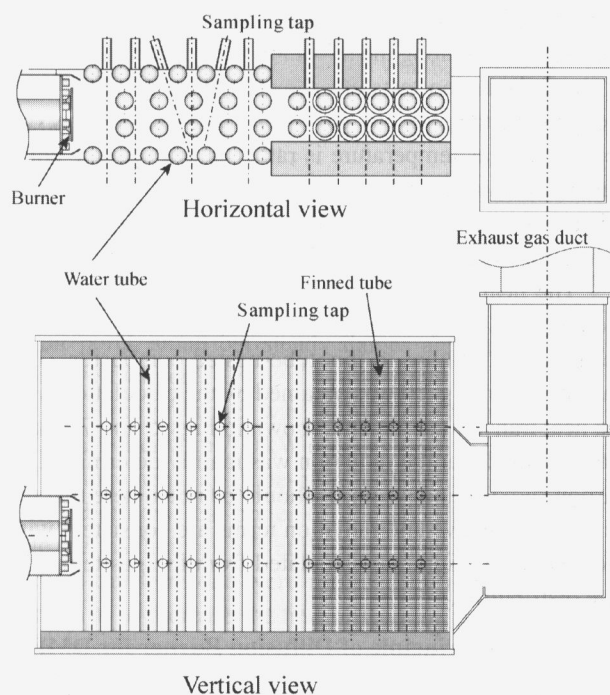
Fig. 7. These heat transfer coefficients obtained in the cold model test were applied to the heat balance calculation of the test boiler.

Based on such data, tube arrangement was determined and resultant combustor design is shown in Fig. 8,
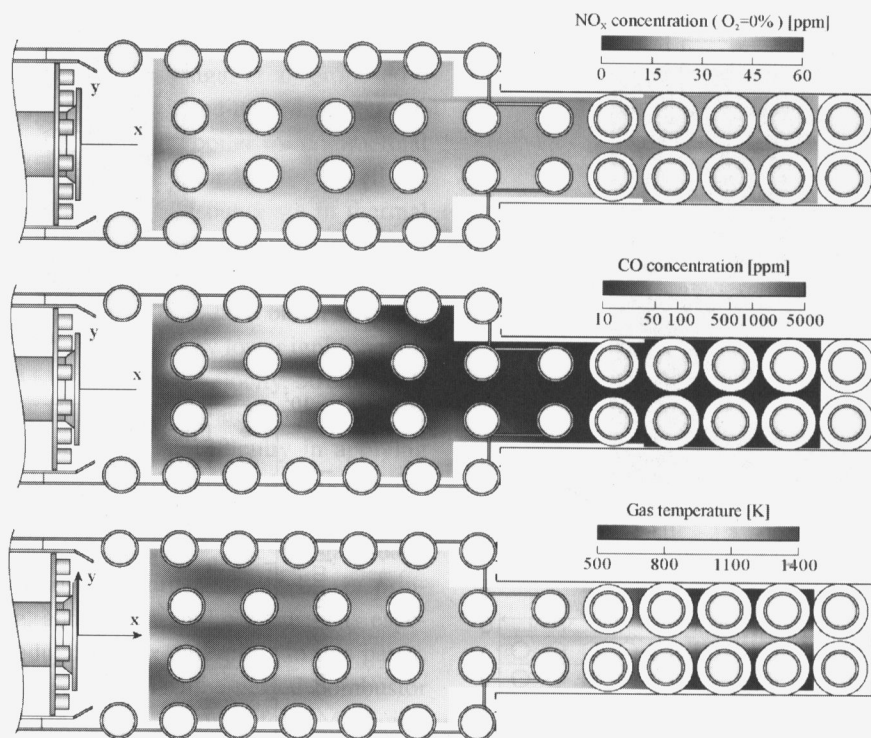
Fig. 9   NOx, CO and temperature distribution in the test boiler (city gas)

where many sampling holes for measuring gas and temperature are installed on the side walls of the combustor. In addition, water-tube metal temperatures were measured at about 50 points along the flow direction. Typical examples of the combustion tests are shown in Fig. 9. These tests were conducted with city gas as the fuel. As is clearly observed, the gas temperature is rather uniform in the combustor and thus the NOx generation is suppressed at a sufficiently low level to meet the flue gas regulation. The CO concentration is, of course, very low[7].

The heat transfer in the combustor is dominated by the convective heat transfer as indicated in Fig. 10, being an important feature in this tube-nested combustor. The data shown in Fig. 10 was obtained by the calculation with the heat transfer coefficients shown in Figs. 5 and 7, and it was assumed that the radiation was mainly determined by carbon-dioxide and steam. It should be noted here that the sum of convective and radiation terms are consistent with the heat absorption rate calculated from the gas temperature distribution.

4.   Design Principle of Diffusion Burner for DME

Low-NOx combustion of DME is realized by the stable burner jet and direct cooling of flame by means of water tubes installed in the combustion zone[9]. The burner plate geometry or burner configuration has a dominant influence on the stability of burner jet, i.e. flame holding. The fuel gas and air are preferably well-mixed at the burner plate, especially for the diffusion burner, so that the combustion state becomes similar to a pre-mixed combustion. Then the flame should be small in size but uniformly distributed to prevent hot spots leading to thermal NOx generation. To meet such requirements, various types of burner plates were examined in the laboratory test[10]. The newly-developed burner plate, consisting of fuel injection port in the center and small air injection ports surrounding the fuel port, realized short and clearly distinguished flames aligned on a circumference, so that an annular flame with uniform height is formed. This burner was installed into the test combustor with water-tube nest, and exhaust gas concentration was measured at the rated input of 11.6 kW. The NOx emission obtained with previously developed burner plate[9] (air is injected through the annular gap around the plate) is around 50 ppm, while the newly developed burner plates, e.g. with a fuel injection port of 6 mm diameter and twelve air-injection port of 4 mm diameter, gave around 20 ppm. This indicates that the proposed design principles for the burner plate are substantial for low-NOx combustion and may be applicable to the commercial-scale burner design. The detailed description can be found elsewhere[10]. In what follows, the 700 kW-class (steam output 1 ton/h) and 7 MW-class (10 ton/h) boilers are described.

5.   700 kW- and 7 MW-Class Water-Tube Boiler for DME

The burner for commercial-base 700 kW-class DME-boiler was designed on the basis of above-mentioned principles. One of the preliminary tests in the open air is shown in Fig. 11, when partially-premixed multi-port dif-
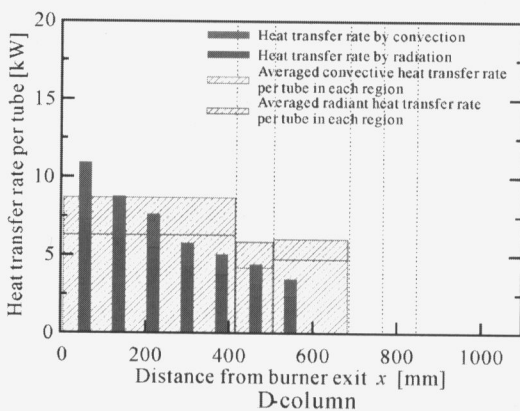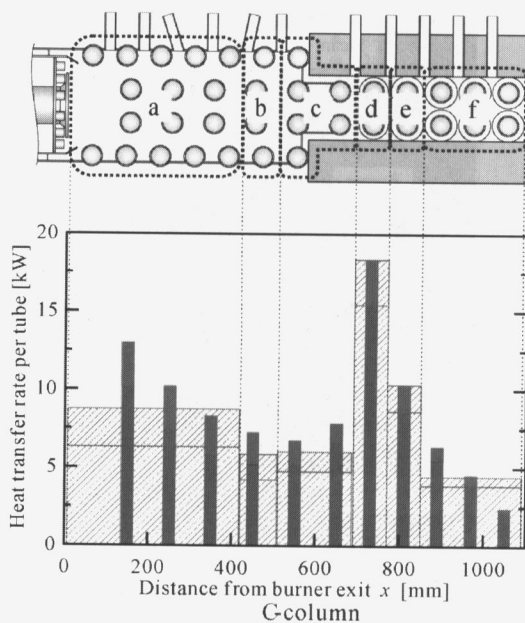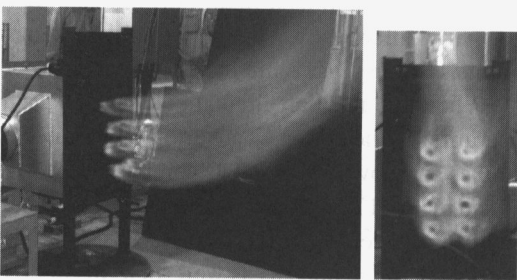
Fig. 10 Distribution of heat absorption rate

Fig. 12 Multi-port diffusion burner for 700 kW boiler
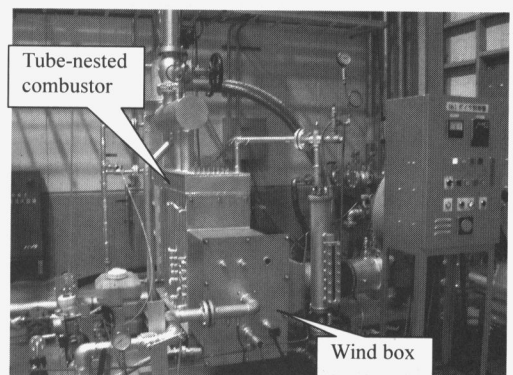
Fig. 13 700 kW-class test boiler developed by Hirakawa Guidam Co., Ltd.

Fig. 11 Combustion test of newly developed burner in open air (DME combustion at 43.1 Nm^3/h, 712 kW, Hirakawa Guidam Co., Ltd.)

fusion burner is applied. The flame from each burner port is clearly distinguished and is uniform in length. Not only this type of burner but also other various burner types were examined. The successfully designed burner is shown in Fig. 12. The DME gas is introduced through the pipe located at the center connected to the rectangular manifold. The DME gas is injected in the normal direction through the small ports of 5 mm in diameter at the both sides of the manifold, and then m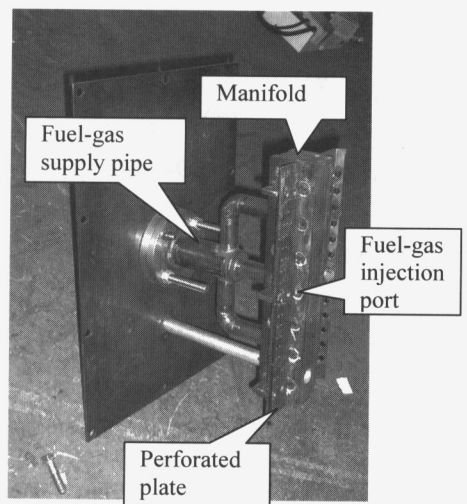ixed with the air supplied through the perforated plates. The hole size of the perforated plate is relatively small near the manifold, while large near the another edge of the plate. With such an arrangement of fuel and air ports, small but steady flames are formed at the respective fuel port.

This type of burner was installed in the wind box of the DME-boiler with 700 kW output shown in Fig. 13. The tube arrangement, i.e. tube-nest configuration, is similar to the laboratory test boiler of 350 kW shown in Fig. 3, while the insulation walls at the both sides of the convective heat transfer zone were replaced by the finned tube banks so as to increase the heat absorption there. A series of combustion test was conducted and the typical example of the test results is shown in Fig. 14. The NOx emission decreases with an increase in the O_2 concentration in the flue gas, while the CO concentration first decreases drastically and then turns to increase. Such a feature is not unique, but is a general trend in combustion. At around 8%-O_2 in the flue gas, the NOx emission becomes 45 ppm at 0%-O_2, while the CO emission has a minimum 5 ppm. Further increase in the O_2 percentage results in a further decrease in the NOx, e.g. 27.6 ppm, the CO concentration
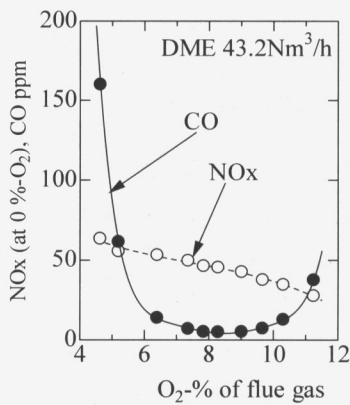
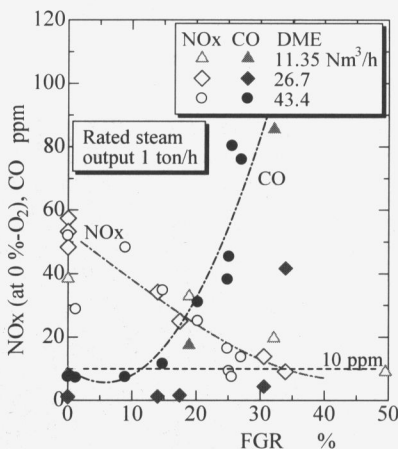Fig. 14 NOx and CO concentration of flue gas (1 ton/h-boiler)

Fig. 15 Effect of flue-gas recirculation on NOx concentration (1 ton/h-boiler)

Fig. 16 7 MW-class natural circulation boiler developed by Hirakawa Guidam Co., Ltd.

increases up to 38 ppm. Such a level of NOx emission is similar to that achieved by the test facility for 13 A city gas shown in Fig. 3. In other words, the NOx reduction by means of the direct flame cooling by the water-tube nest reaches a limiting level, retaining the CO emission level within an acceptable range. This is because the tube-nest concept is based on the balance between the flame cooling to reduce the temperature and the CO generation by the flame cooling. An additional means, typically the flue-gas recirculation (FGR), is needed to achieve super-low NOx combustion far below this level of NOx emission.

Owing to the low ignition temperature and high burning velocity, the FGR is successfully applied so that the NOx emission is drastically reduced to a very low level. The effect of this FGR on the NOx emission is plotted as a function of the percentage of FGR in Fig. 15. The curves in the figure represent general trends of NOx at 0%-O_2 and CO, respectively. In addition, the horizontal dashed line indicating 10 ppm is drawn for reference. The plotted data includes data of 26%-load, 62%-load and 100%-load. Throughout these data, the NOx concentration in the flue gas decreases successively with an increase in the FGR, and reaches a very low level, i.e. less than 10 ppm at FRG
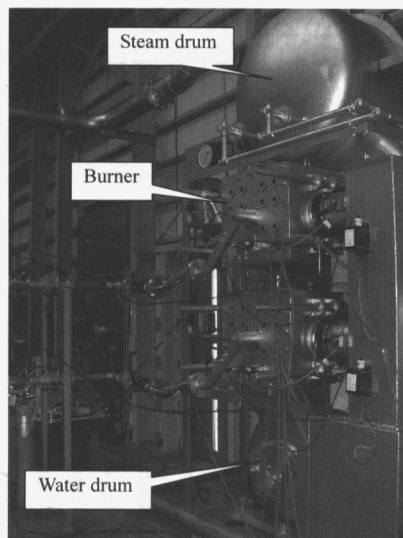
= 25 – 35%. On the other hand, the CO concentration in the flue gas is rather low at low FGR, while increases to about 40 – 90 ppm, being within an acceptable range. This figure demonstrates a very high potential of NOx reduction by FGR, and is also achieved rather wide turn-down ratio of the newly developed DME boiler. It should be noted that such a high percentage of FRG is successfully applied for the low-NOx combustion of the DME.

In addition to this 700 kW-class boiler, 7 MW-class boiler was developed as well. The over-view of 7 MW-class boiler is shown in Fig. 16. This boiler has two burner sections, upper and lower, aiming at rather wide turn-down ratio. The above-mentioned multi-port diffusion burners, being slightly different from but principally the same configuration as that in Fig. 12, are installed in this burner section. This boiler is a natural circulation type, and the upper steam drum and the lower water drum are connected by water tubes and downcomers. The combustion test results are plotted in Fig. 17 as a function of FGR percentage. The curves in Fig. 17 represent the trend of the NOx and CO concentrations in the flue gas as well. In terms of NOx reduction, the concentration at FGR = 0% shows relatively wide scatter, while the dispersion becomes small with an increase in the FGR. The minimum NOx emission reaches a level less than 10 ppm, while the CO emission becomes high, e.g. 60 – 80 ppm. Typically, the NOx emission at the lowest load becomes less than 10 ppm, while the CO concentration becomes rather high, i.e. 800 ppm, far beyond the graph scale. Thus for low-load operation, i.e. 86.6 Nm³/h: 20%-load, the improvement in the furnace and burner designs may be needed. On the other hand at relatively high load, beyond 60% in the present case, the NOx reduction is very effective, and the NOx emission from the boiler furnace reduces successively with an in-
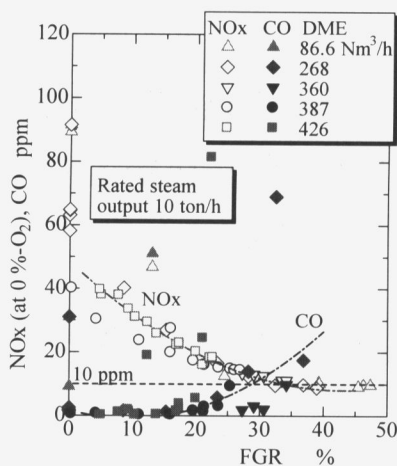
Fig. 17 Effect of flue-gas recirculation on NOx concentration (10 ton/h-boiler)

crease in the FGR, retaining the CO emission within the acceptable range. The minimum value of NOx reaches less than 10 ppm, similarly to 1 ton/h boiler mentioned above. The boiler efficiency of the present 10 ton/h boiler is rather high, 88.1% at 20%-load and 94.4% at 100%-load.

6. Conclusion

R&D study was conducted aiming at super-low-NOx boiler for DME. Previously established concept of tube-nested combustor and flue-gas recirculation were successfully applied to the DME-combustor design. In addition, the burner-design principles for low-NOx combustion were established. The newly developed boiler demonstrated around 10 ppm of NOx emission with the boiler efficiency of about 94%.

Acknowledgment

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