Latent heat recovery from actual flue gas

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Latent heat recovery from exhaust flue gas is a key technology to improve a thermal efficiency of power plant, fuel cells and boilers. A prediction method has been proposed for the design of heat exchanger to recover the latent heat in the flue gas. For the condensation of steam on heat transfer tubes, the modified Sherwood number taking account of the mass absorption effect on the wall was used. The thermal hydraulic behavior was experimentally studied in several heat exchangers for the latent heat recovery from actual flue gas generated with the combustion of air-fuel or oxy-fuel. The steam mass concentration of the flue gas was approximately 10% in the air-fuel combustion and 30% in the oxy-fuel combustion. The countercurrent cross-flow heat exchangers consisted of bare tubes or spirally finned tubes of fin pitch 5 to 10mm. The total heat recovered in the experimental heat exchangers was 55 to 900 kW. Generally, the experimental results agreed well with the present one-dimensional prediction code. Finally, the prediction code was used on the parametric study of the heat exchanger design for the latent heat recovery. The thermal-hydraulic behavior was calculated for several kinds of heat exchangers using finned tubes or bare tubes. The calculation result indicated that the most compact heat exchanger was that using the bare tube of small diameter. So the compact countercurrent cross-flow heat exchanger using small bare tubes of SUS304 was designed and constructed to prove its high ability. The proposed compact heat exchanger was considered to be preferable for the latent heat recovery from the flue gas and the prediction code was useful for the design of the compact heat exchanger.

1. Introduction

The most part of energy losses in a boiler is due to the heat released by the exhaust flue gas to atmosphere. The released heat consists of sensible and latent one. Recently, for a biological and environmental safety, a clean fuel such as a natural gas is widely used in the boiler. As the clean fuel includes a lot of hydrogen instead of carbon, the exhaust flue gas includes a lot of steam accompanying with the latent heat. To reduce the toxic products of combustion and total amount of exhaust gas, it is preferable to use oxygen instead of air. As a next generation boiler, the oxy-fuel combustion boiler was planned and developed in Japan. The oxy-fuel combustion flue gas has the larger amount of steam concentration than that in the air-fuel combustion flue gas including nitrogen. So the latent heat recovery from the flue gas is very effective and important to compensate the additional energy to separate oxygen from air and improve the boiler efficiency.

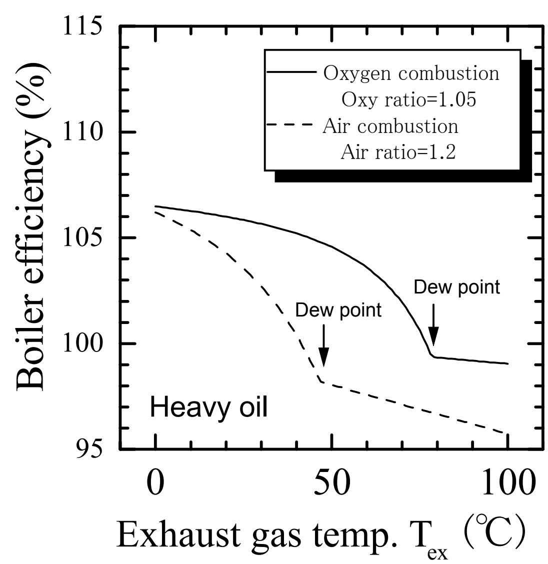

Fig. 1 Boiler efficiency in oxy-fuel and air-fuel combustion

Shown in Fig.1 is a relation between the boiler efficiency and the exhaust gas temperature in the oxygen and air combustion system. The efficiency is larger than 100% at the lower exhaust temperature as the boiler efficiency is defined with a lower heating value of heavy oil fuel. The efficiency in the oxygen combustion is much higher than that in the air combustion due to the lack of heat loss carried out with the nitrogen. The dew point of the oxy-fuel combustion flue gas including the larger amount of steam instead of nitrogen is higher than that in the air-fuel combustion flue gas. The steep increase of efficiency can be observed at the lower temperature region below the dew points. In this lower temperature region, the latent heat in the flue gas is recovered and the efficiency is increased. So the latent heat recovery from the flue gas is very important to improve the boiler efficiency in the oxygen combustion system.

In the previous basic studies (Osakabe et al., 1998, 1999a, 1999b, 2000a), condensation heat transfer on horizontal stainless steel bare or finned tubes has been investigated experimentally by using an actual flue gas from a natural gas boiler. The experiments were conducted using single and 2 stages of tubes at different air ratios and steam mass concentrations of the flue gas in a wide range of tube wall temperature. The condensation heat transfer was well predicted with the simple analogy correlation in the high wall temperature region. In the low wall temperature region less than 30°C or the high steam mass concentration presuming the oxy-fuel combustion, the total heat transfer was higher than that predicted by the simple analogy correlation. For the high steam mass concentration, the modified Sherwood number (Osakabe et al., 1999b) taking account of the mass absorption effect on the wall was proposed.

A prediction method has been proposed for the design of heat exchanger to recover the latent heat in the flue gas(Osakabe, 1999c, 2000b). In the prediction, the flue gas was treated as a mixture of CO_2, CO, SO_2, O_2, N_2 and H_2O, and its property was estimated with special combinations of each gas property proposed by the previous studies (Lindsay & Bromley, 1950)(C.R.Wilke, 1950). The mass diffusivity of steam in flue gas was estimated with the well-known mass diffusivity of steam in air (Fujii et al., 1977). The one-dimensional heat and mass balance calculation was conducted along the flow direction of flue gas in the heat exchanger. For the finned tubes, the fin efficiency at the condensing region was calculated with a semi-empirical correlation (Osakabe et al., 2000a). The heat and mass transfer on tubes was evaluated with the modified analogy correlation and the thermal resistance of the condensate film on tubes. In the calculation, it was possible that the gas temperature coincided with the dew point which was the saturation temperature corresponding to the partial pressure of steam in the flue gas. When the gas temperature decreased below the dew point, the condensation of steam in the flue gas took place and the latent heat increased the gas temperature until the gas temperature coincided with the dew point.

2. Verification of prediction code

2.1 Experimental apparatus and method

The thermal hydraulic behavior was experimentally studied in several heat exchangers for the latent heat recovery from flue gas generated with the combustion of air-fuel or oxy-fuel as summarized in Table 1. The steam mass concentration of the flue gas was approximately 10% in the air-fuel combustion and 30% in the oxy-fuel combustion. The countercurrent cross-flow heat exchangers consisted of bare tubes or spirally finned tubes of fin pitch 5 to 10mm. The horizontal heat transfer tubes were arranged in multi-stages and the neighboring stages were connected with headers. The water flow rate and temperature to each tube at a stage is maintained at the same values with the header. The flue gas and the generated condensate vertically crossed the horizontal tubes. The total heat recovered in the experimental heat exchangers was 55 to 900 kW. The parametric study varying the flue gas and feed water flow rate was conducted. The temperature distributions of cooling water and flue gas, the pressure loss and the amount of condensate were measured. The effect of condensate film on the tubes was considered to be negligibly small for the heat transfer and pressure loss calculation.

2.2 Typical results

Shown in Figs. 2 and 3 are the comparison of the experimental result and the prediction in the air-fuel combustion tests 1-3. In Fig. 2, the solid lines are the temperatures of gas and water in the bank. The a-dot-dashed line and the two-dots-dashed line are the inner and outer wall temperature of tubes, respectively. The dashed line is the saturation temperature (dew point) corresponding to the partial pressure of steam in the flue gas. When the outer wall temperature is smaller than the dew point, condensation on the wall takes place. The dew point decreases along the stages at the condensation region as the steam concentration decreases with the condensation. As the gas and water velocity changes stage-by-stage corresponding to the change of flow area in the present experimental apparatus, the wall temperatures shows zigzag polygonal line. The key O and Δ are the measured temperatures of gas and water, respectively. The prediction agrees well with the experimental result. Shown in Fig.3 is the comparison of experimental result and prediction for the amount of condensate throughout the heat exchanger in tests 1 to 3. The total amount of condensate generally agrees well with the one-dimensional mass and heat balance calculation.

Shown in Figs.4 and 5 are the comparison of the experimental result and the prediction in the oxy-fuel combustion test 6. As the outer wall temperature is always smaller than the dew point in Fig.4, the condensation takes place on the entire tube wall. The dew point decreases with increasing stages as the steam concentration decreases. The prediction for the water and gas temperature agrees well with the experimental result. This result also indicates the precise calculation for the white fuming condition when the saturation and gas temperature merge. Shown in Fig.5 is the comparison of experimental result and prediction for the amount of condensate throughout the heat exchanger. The total amount of condensate generally agrees well with the one-dimensional mass and heat balance calculation

Table1 Heat exchanger tests for verification of prediction code

No	Tube type	Fin length (mm)	Fin pitch (mm)	Outer diameter (mm)	Tube no.	Fuel/Combustion	Heat transfer area (m^2)	Recovered heat	
								Total (kW)	Latent (kW)
1	Bare	-	-	27.2	226	Propane /Air	9.27	55	20
2	Fin	12	10	58	86	Propane /Air	18.9	46	14
3	Fin	12	5	58	50	Propane /Air	18.9	40	9.6
4	Bare	-	-	25.4	198	Heavy oil/Oxy	15.8	141	125
5	Fin	12	10	45.7	216	Heavy oil/Oxy	35.2	147	132
6	Fin	8	8.5	41.4	936	Heavy oil/Oxy	372	898	734

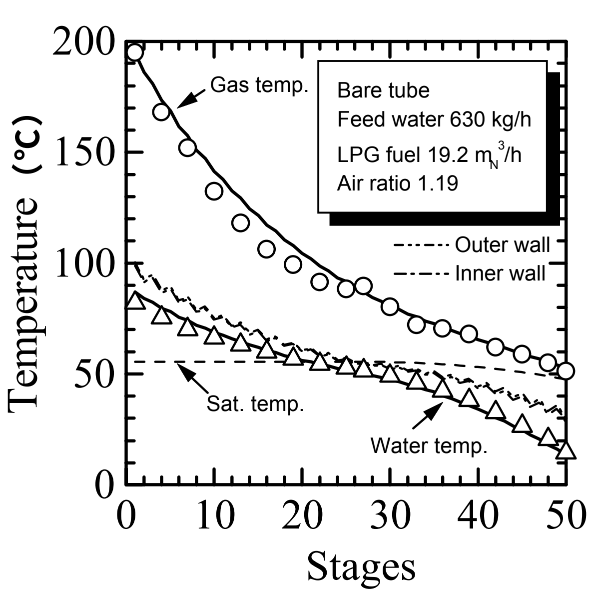

Fig. 2 Temperature distribution along heat exchanger in air-combustion tests 1

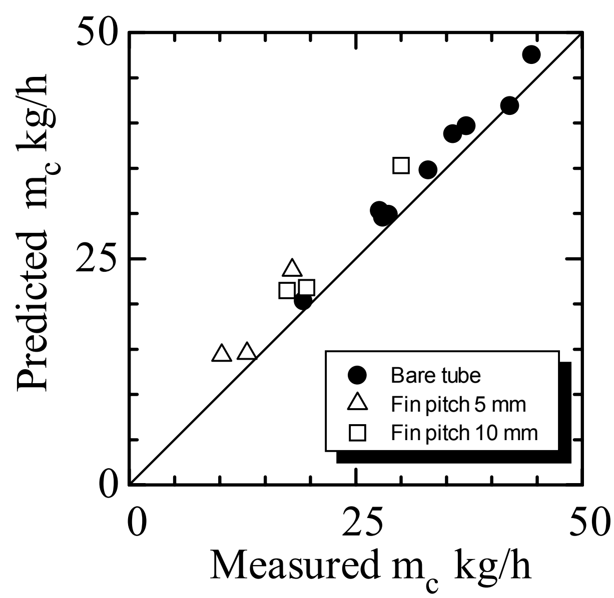

Fig. 3 Comparison of measured and predicted amount of condensate in air-combustion tests 1-3

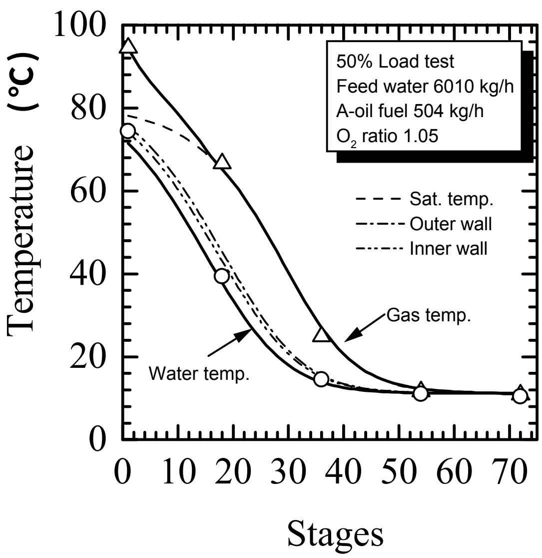

Fig. 4 Temperature distribution along heat exchanger in oxy-combustion test 6

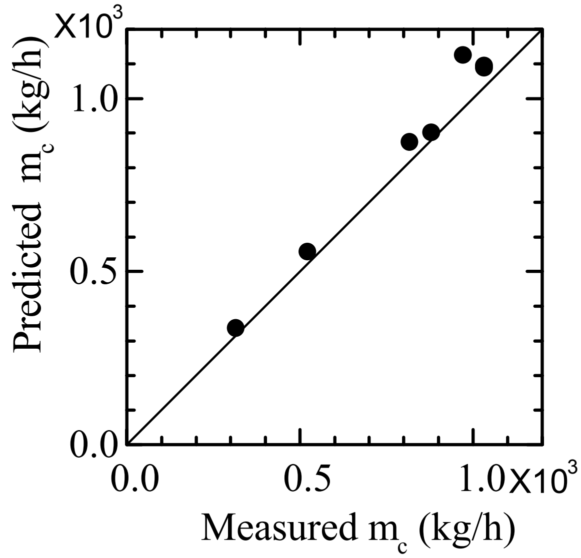

Fig. 5 Comparison of measured and predicted amount of condensate in oxy-combustion test 6

3. Compact heat exchanger for latent heat recovery

Finally, the prediction code was used on the parametric study of the heat exchanger design for the latent heat recovery. The thermal-hydraulic behavior was calculated for several kinds of heat exchangers using finned tubes or bare tubes.

3.1 Parametric study

Heat transfer tubes were installed in the rectangular duct of 205×205mm to recover the latent heat in flue gas as shown in Fig.6. This duct size is approximately the same as the flue gas duct of test boiler used in this experiment. The outlet temperature of flue gas from the boiler was 280℃. The flue gas was generated with natural gas 13A at the flow rate of 15 m_N^3/h and the air ratio of 1.2. The flow rate and inlet temperature of feed water was 600kg/h and 20℃, respectively. The temperature of the feed water was increased from 20℃ to 60℃ with the heat recovery.

The various kinds of heat transfer tubes are installed in the duct as the parametric design study as shown in Table 2. Bare tubes of 21.7 and 10.5 in outer diameter, spirally finned tubes were selected in the study. The plate fins were welded on the base tubes of 21.7 mm in diameter and the fin heights were 12, 8 and 3mm. The pitch of tube arrangement is larger than the tube outer diameter by 10mm considering the fabrication ability of holes at the tube sheets. The maximum number of tubes was 333 using the tube of 10.5 mm in outer diameter. The minimum number was 102 using the finned tube of 12mm in height, which is often used in conventional economizer for the sensible heat recovery. The most

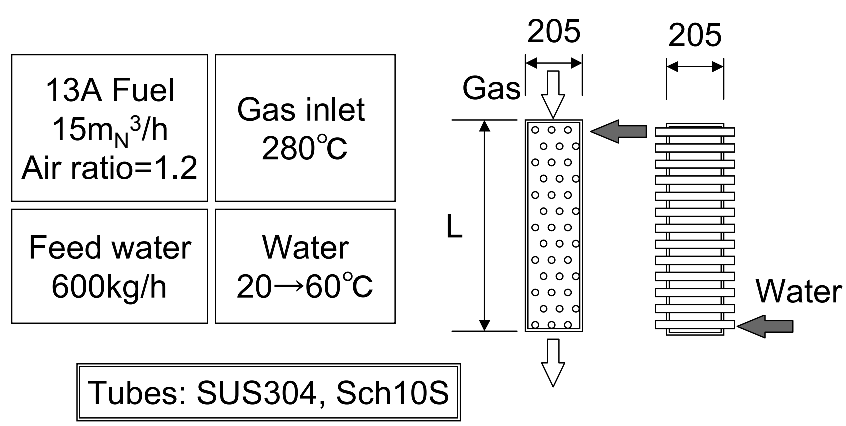

Fig. 6 Boundary conditions for parametric study

compact economizer was that using small bare tubes of 10.5mm in diameter. The height and the total tube weight of the economizer using small bare tubes were 718mm and 18.9kg, respectively. The pressure loss in the waterside was slightly higher than the others but could be allowable. On the other hand, the total weight of that using the finned tubes of 12mm in height was 62.6kg. The bare tube of small diameter is preferable for the compact design of economizer for the latent heat recovery. As the fin efficiency is relatively low due to the high heat transfer coefficient of condensation, the bare tube is preferable in the latent heat recover region.

Table2 Comparison of bare and finned tubes heat exchanger

Tube type	Bare1	Bare2	Fin1	Fin2	Fin3
Pipe diameter (mm)	10.5	21.7	21.7	21.7	21.7
Pitch (mm)	20.5	34.2	51.0	41.0	34.2
Stage	35	40	29	25	27
Pipe no.	333	220	102	113	149
Fin pitch	-	-	5	5	5
Fin height	-	-	12	8	3
Length L (mm)	718	1370	1480	1030	923
Heat transfer area (m^2)	2.25	3.07	12.4	8.73	5.04
Tube weight (kg)	18.9	46.1	62.6	51.1	42.5
Gas pressure loss (mmAq)	11.5	21.6	19.8	22.1	22.4
Water pressure loss (mmAq)	515.0	65.3	117.0	60.5	43.9

3.2 Compact heat exchanger experiment

The calculation result indicated that the most compact heat exchanger was that using the bare tube of small diameter. So the compact countercurrent cross-flow heat exchanger using bare tubes of SUS304 was designed and constructed to prove its high ability. Shown in Fig.7 is a schematic of experimental apparatus. The experiment was conducted by using flue gas generated with the combustion of air and natural gas fuel. The flue gas from a natural gas boiler was led to the inlet plenum of the test heat exchanger. The flue gas was released to atmosphere from the outlet plenum. The countercurrent cross-flow heat exchanger consisted of bare tubes of 10.5 and 8.1mm in outer and inner diameter, respectively. The horizontal bare tubes of small diameter were arranged as a bank of 10-9 rows and 40 stages and the neighboring stages were connected with the rectangular header. The effective heating length of the tubes was 200mm. The temperature distributions of water and flue gas in the heat exchanger were measured with sheath T-type thermocouples of 0.5mm in diameter. The thermocouple signals were transferred to a data logger and analyzed.

As shown in Fig.8, the experimental results for the temperature distributions of water and flue gas in the heat exchanger agreed well with the prediction. The proposed compact heat exchanger using small bare tubes was considered to be preferable for the latent heat recovery from the flue gas and the prediction code was

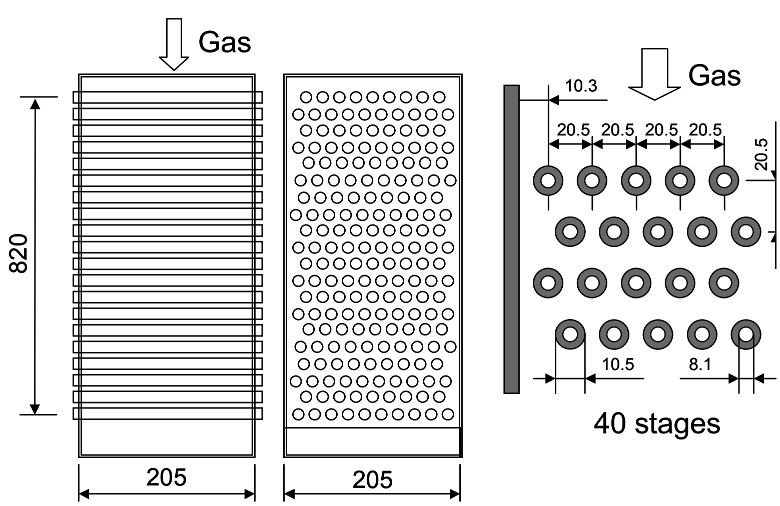

Fig. 7 Experimental apparatus

useful for the design of the compact heat exchanger.

4. CONCLUSION

1. The thermal hydraulic behavior was experimentally studied in several heat exchangers for the latent heat recovery from actual flue gas generated with the combustion of air-fuel or oxy-fuel. The steam mass concentration of the flue gas was approximately 10% in the air-fuel combustion and 30% in the oxy-fuel combustion. The countercurrent cross-flow heat exchangers consisted of bare tubes or spirally finned tubes of fin pitch 5 to 10mm. The total heat recovered in the experimental heat exchangers was 55 to 900 kW. Generally, the experimental results agreed well with the one-dimensional prediction code in this study.
2. The prediction code was used on the parametric study of the heat exchanger design for the latent heat recovery. The thermal-hydraulic behavior was calculated for several kinds of heat exchangers using finned tubes or bare tubes. The calculation result indicated that the most compact heat exchanger was that using the bare tube of small diameter.
3. The compact countercurrent cross-flow heat exchanger using bare tubes of SUS304 was designed and constructed to prove its high ability. The outer and inner diameters of the bare tube were 10.5 and 8.1mm, respectively. The bare tubes were arranged in a staggered bank of 10-9 rows and 40 stages. The experimental study varying the air ratio of flue gas, feed water temperature and flow rate was conducted. The experimental results for the temperature distributions of water and flue gas in the heat exchanger with bare tubes of small diameter agreed well with the prediction. The proposed compact heat exchanger using small tubes was considered to be preferable for the latent heat recovery from the flue gas.

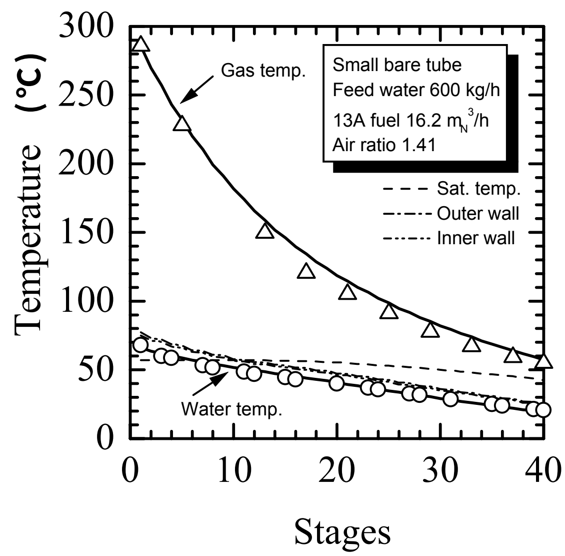

Fig. 8 Temperature distribution in compact heat exchanger

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