HEAT-TRANSFER MODEL OF HEAT EXCHANGER TUBE IMMERSED IN PRESSURIZED FLUIDIZED BED BOILER

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ABSTRACT

By the data on heat-transfer of immersed tubes in fluidized bed boilers of two commercial plants of 250MWe PFBC and AFBC as well as several pilot plants such as 2MWth, 4MWth, 70MWe and 15MWth PFBCs, we propose a practical heat transfer model applying to the various PFBC with different tube arrangements and operating conditions. The proposed model is of the outer coefficient of immersed heat exchanger tube, which is consisted of particle convection, gas convection and gas radiation based on the Martin's model considering influence of pressure with mean free path of gas molecules between the tube-surface and fluidized bed materials. In this paper, the term of particle convection was modified by dimensionless superficial velocity. The calculated results of the external heat-transfer coefficients of immersed tubes were corresponding to the measured results well in 10% error range, including 250MWe PFBC and several PFBCs.

KEY WORDS: Pressurized Fluidized Bed Combustion, Heat-transfer coefficient, Immersed tube, Superficial velocity

INTRODUCTION

Pressurized Fluidized Bed Combustion Boiler (PFBC) has been developed as the latest coal fired power plant, which has several advantages such as wide flexibility for fuel, compact furnace, high combustion efficiency and lower environmental load of NOx, SOx etc.
The PFBC in Japan has achieved the high efficiency of 42%(net, HHV) on electrical terminal of the power station in the conditions of furnace pressure of 0.7 to 1.5 MPa and bed temperature of about 850°C by the combined cycle of gas turbine driven by pressurized flue gas and steam turbine.

Figure 1 shows the flow diagram of the Osaki Power Station of 250MWe PFBC of Chugoku Electronic Power Co., Inc. (Ref.1, 2). Since the heat-transfer characteristics of the tubes immersed in the fluidized bed, which have more than 90% of the total heating surfaces of the PFBC system, strongly influence the power plant design and the operating condition to provide the high power efficiency, the accurate estimation of the heat transfer by the in-bed tubes is considerably important. Although many estimation methods on the heat transfer coefficient of immersed tube surface were reported (Ref.3-7), there is no research on the estimation model to be applied the commercial plant of PFBC. Therefore, first of all, we analyzed many operating data of the 2MWth and 4MWth PFBC test facilities (Ref.8) and 15MWth PFBC pilot plant and obtained the external heat transfer coefficients of immersed heat exchanger tube.

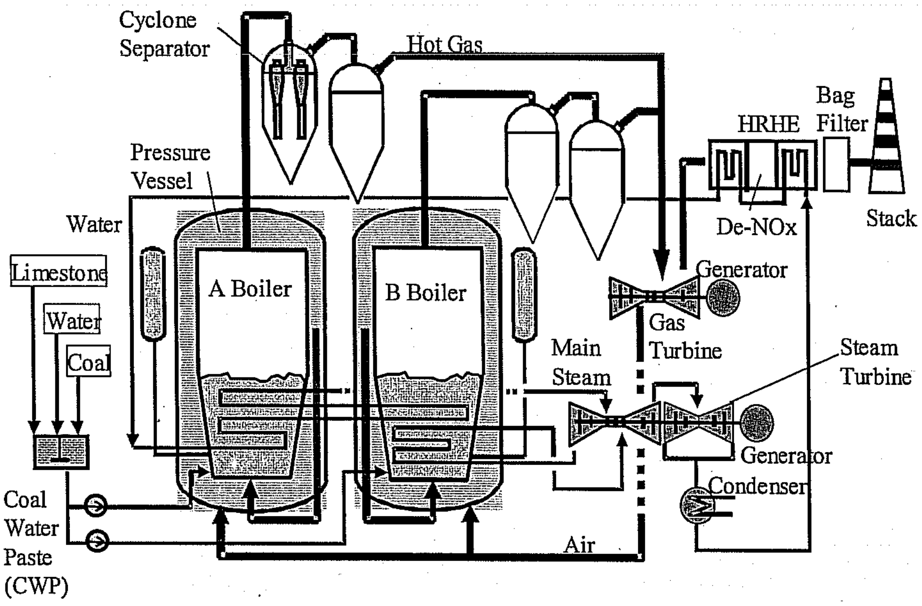

Figure 1: System diagram of Osaki PFBC plant

In this paper, we added the analysis results of the commercial plants of 250MWe PFBC and AFBC into the above results and proposed an estimation model of the external heat transfer coefficient of immersed tube that considered the design parameters such as tube diameter, tube arrangement and operating pressure.

Test Facilities

PFBC pilot facilities

2MWth PFBC was the first test facility to study the heat transfer rate and environmental potentials prior to the design of the large scaled 250MWePFBC plant. Following the 2MWth PFBC, 4MWth PFBC test facility, shown in Fig.2, was assembled, which had two combustion furnaces (beds) to obtain the scale-up data of 250MWe PFBC plant system.

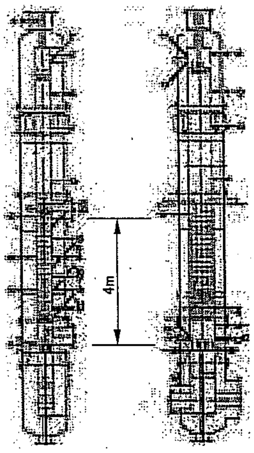

Figure 2: 4MWth PFBC test furnace

The design specification of the 4MWth PFBC test facility is shown in Table 1. The furnace size is 0.46 m x 0.64 m and fluidized bed height is 4.0 m or less. The operating conditions such as furnace pressure, temperature and fluidizing velocity were almost the same to the conditions of 250MWe PFBC plant except the steam pressure of7MPa instead of 16.7MPa for the 250MWe PFBC. 15MWthPFBC pilot facility.

Table 1: 4MWth PFBC design specifications

Thermal Input	4 MWth
Steam Conditions	
Superheater steam temperature and pressure	571 deg C, 6.96 MPa
Reheater steam temperature and pressure	596 deg C, 1.57 MPa
Combustion Conditions	
Bed temperature	865 deg C
Pressure	0.9 MPa
Fluidizing velocity	0.9 m/s
Excess air	20 %
Coal Feed Rate (Coal Water Paste)	645 kg/h
Furnace Dimensions	
Wide x Depth	457 mm x 336 mm
Bed height	Max. 4 m

250MWe PFBC boiler

The side view of the 250MWe PFBC boiler with two fluidized bed furnaces as mentioned is shown in Fig.3. Plane sectional area of the furnace is $49m^2$ (8.5m x 5.8m) and the furnace height is 10m. In-bed tubes are located horizontally between the height of 0.7m and 4.0m from the distributor level. The combustion air was supplied from the wind box through the many air nozzles on the distributor panel. Coal combustion flue gas was exhausted from the furnace upper section through the freeboard area in the furnace.

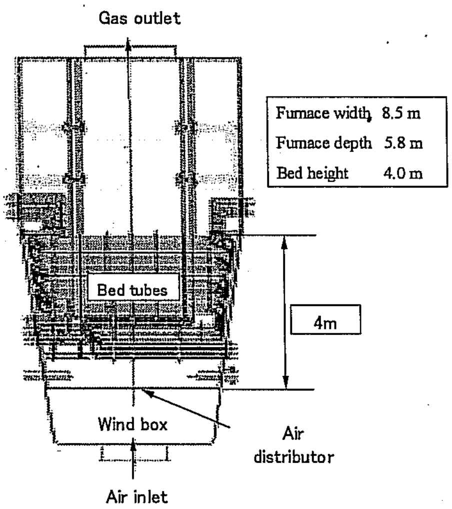

Figure 3: Side view of 250MW PFBC furnace

Operation Data of 250MWe PFBC Boiler (Ref.9)

Gas pressure in the furnace

Figure 4 shows the effect of the operation load of the boiler on the furnace gas pressure. The x-axis is the ratio of the electric power output to 100 % load of 250 MWe, which is a total load with steam turbine and gas turbine. In the PFBC operation, since the flow rate of the flue gas is a critical velocity at the inlet of the gas turbine, it would be changed with the pressure drop through the gas turbine. As shown in Fig. 4, the furnace pressure is almost proportionate to the gas flow rate with operation control.

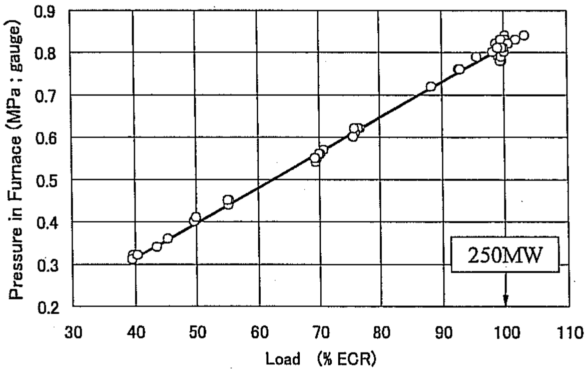

Figure 4: Furnace operating pressure of 250MW PFBC

Fluidized bed height

The load of the PFBC is controlled by changing the bed height or the heat transfer vertical area, that is, by supplying the bed materials (BM) into the furnace and withdrawing from the furnace to the BM tank. Figure 5 shows the relationship between the bed height and the load control. During 100 % load operation, the bed height of the furnace "A" and "B" was respectively 4.0 m and 3.8 m which were the bed heights when designed. The bed heights were the calculated average values based on the pressure differences through the bed measured in level points (Ref.10).

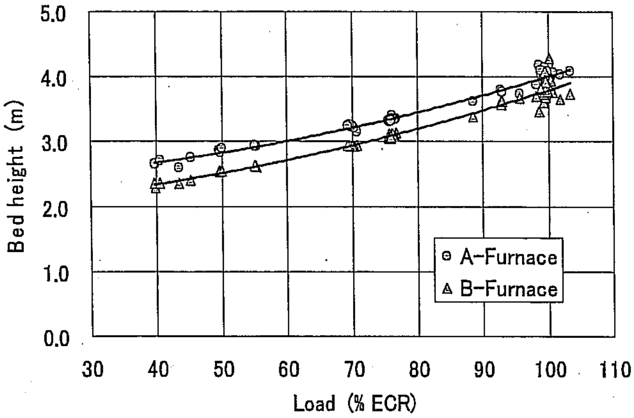

Figure 5: Characteristics of furnace bed height

Bed temperature distributions

Figure 6 shows an example of bed temperature profiles above the distributor plate. The bed temperature profiles when obtaining heat transfer data were uniform as shown in Fig.6, which means that the fluidizing and heat transferring conditions were well.

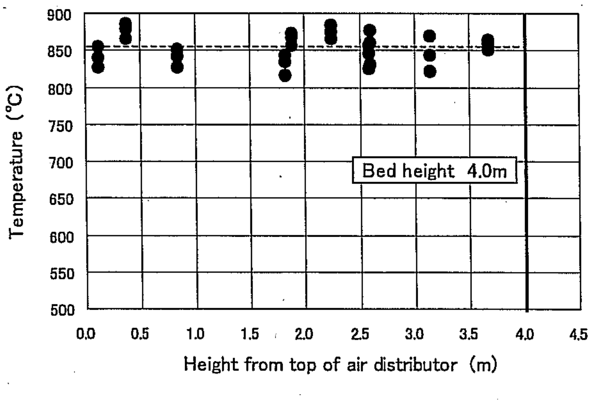

Figure 6: Temperature profiles in A-furnace

Analysis Results of Heat Transfer Coefficient

Analysis method

General analysis method was applied to each in-bed tube bundles in several PFBC test facilities and large commercial plant. The heat flux absorbed by the tube bundles were calculated by the difference of enthalpy based on the input and output steam temperature and pressure and the steam flow rate measured at the inlet of the boiler. The bed temperature used in this analysis was a average of the several measured temperatures in the bed.

Analysis results

Figure 7 shows the estimated external heat transfer coefficient of immersed tube in the fluidized bed of all test facilities, the commercial plants of the PFBC and the AFBC. It gradually becomes a saturation tendency though the external heat transfer coefficient increases along with a pressure increase in furnace.

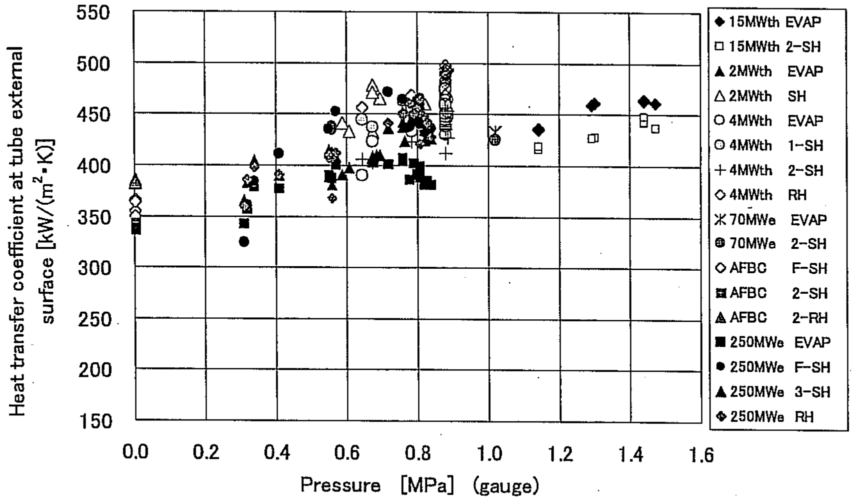

Figure 7: Heat transfer coefficient of PFBC and AFBC plants

Prediction of Heat Transfer Coefficient of External Surface of Immersed Tube

Basic mechanism

Though there are a lot of researches on heat transfer mechanism between the fluidized bed and the heat exchanger tube, the research including the pressure factor is limited (7). Martin proposed a model of heat transfer coefficient of external surface of immersed tube (α) consisted of particle convection (α_p), gas convection (α_G) and gas radiation (α_R) as shown Eq.1.

$$\alpha = \alpha_p + \alpha_G + \alpha_R \qquad (1)$$

The particle convection (α_p) in Eq.1 is derived from Eq.2 and Eq.3 as below.

$$\alpha_p = \frac{Nu_p \lambda_g}{d} \qquad (2)$$

$$Nu_p = F(\Lambda) \qquad (3)$$

Equation 3 indicates that Nusselt number Nu_P is a function of Λ, which is the mean free path of gas molecules relating to heat transfer between fluidized particle and heating surface. It is inverse proportion to the gas pressure.

Figure 8 shows the heat transfer coefficient of immersed tubes calculated by Eq.1 and each contribution of particle convection, gas convection and radiation. In Fig.8, the particle and the gas convections seem to be influenced by the pressure but the radiation factor is not so. The contribution of the particle convection is about 50 %, the gas convection is about 25% and the heat radiation is about 50% at the pressure of 1 MPa.

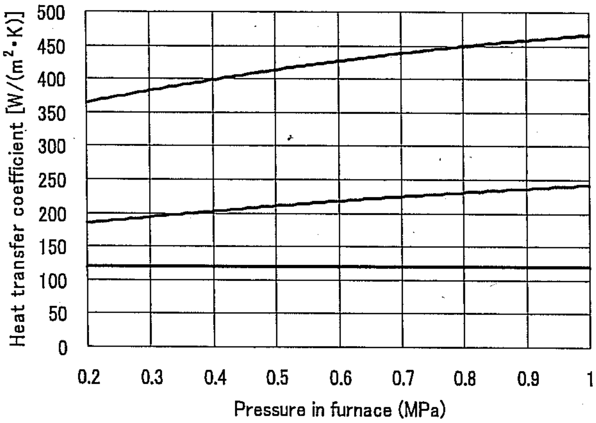

Figure 8: A sample of calculation result according to Eq.1

Modification by Superficial Velocity

In comparison of the heat transfer coefficients between calculated by Eq.1 in Fig.8 and measured in Fig.7, the trend as the whole with the gas pressure is similar but the individual value is not similar except for AFBC's data. The coefficient group of the 15 MWth PFBC was considerably different from other PFBC's data. The tendency is classified into the following three categories.

i) Measurements of the AFBC is well estimated by the predicted equation.

ii) Measurements of the 15MWth PFBC is over estimated about 20 to 25 % by the predicted equation.

Measurements of other PFBCs except for 15MWth is over estimated about 10 to 20 % by the predicted equation.

The reason of the discrepancy could be due to the difference of the superficial velocities among the above three groups. The superficial velocity of each group is about 2 m/s of AFBC, 0.9 - 1.0 m/s of 15MWthPFBC and 0.7 - 0.8 m/s of other PFBCs in order, which is not considered in Eq.1. Therefore, we applied the correction by the superficial velocity into the term of particle convection. Also in many papers (Ref.11,12,13), effect of the superficial velocity (Uf) on the outer heat transfer coefficient is reported, which suggests that it would be increased with the superficial velocity. Here, the following dimensionless superficial velocity, which is divided by minimum fluidization velocity and defined as $\sqrt{Uf/Umf}$, was introduced into Eq.1. A correction factor was decided by fitting the measurement values. Consequently, we obtained the following Eq.4.

$$\alpha = C\sqrt{\frac{Uf}{Umf}}\alpha_p + \alpha_G + \alpha_R \qquad (4)$$

Figure 9 shows the comparison results between the predicted values and the measurement values. From this figure, it can be seen that the predictability by Eq.4 is within ±10%.

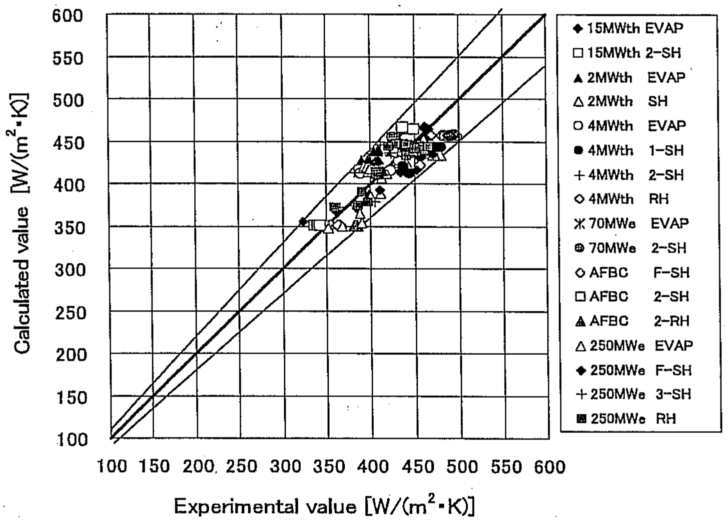

Figure 9: Comparison between field data and prediction evaluating by Eq.4

CONCLUSIONS

To predict the heat transfer on heat exchanger tube immersed in the fluidized bed boiler of commercial scaled PFBC, we first analyzed heat transfer data from several pilot plants of PFBC with various tube arrangements and different operating conditions as well as the commercial scaled PFBC and AFBC and obtained the heat transfer coefficient of the external surface of the immersed tube. The measured coefficients were compared with the calculated values by Martin's model, resulting in that it could not describe the pressure effects and the heat transfer coefficients of different scale plants. And confirmed that the equation can predict the heat transfer coefficients of different scale PFBCs as well as AFBC with ± 10% accuracy.

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NOMENCLATURE

C	correction factor in the term of particle convection
d	particle diameter (m)
Nu_P	Nusselt number for particle convective heat transfer coefficient
Uf	superficial velocity (m/s)
Umf	minimum fluidization velocity (m/s)
α	heat transfer coefficient (W/(m^2 · K))
α_G	gas convective heat transfer coefficient (W/(m^2 · K))
α_P	particle convective heat transfer coefficient (W/(m^2 · K))
α_R	radiative heat transfer coefficient (W/(m^2 · K))
λ_g	gas thermal conductivity (W/(m · K))
Λ	mean free path of gas molecules (m)

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