The Impact of Bed Temperature on Heat Transfer Characteristic between Fluidized Bed and Vertical Rifled Tubes (Postprint)

Authors: Blaszczuk, A., Nowak, W.

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Abstract

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Full Text

The Impact of Bed Temperature on Heat Transfer Characteristics between Fluidized Bed and Vertical Rifled Tubes

Artur Blaszczuk[1]*, Wojciech Nowak[2]

[1]Czestochowa University of Technology, Institute of Advanced Energy Technologies, Dabrowskiego 73, 42-200 Czestochowa, Poland
[2]AGH University of Science and Technology, Faculty of Energy and Fuels, Czarnowiejska 30, 30-059 Cracow, Poland

In the present work, the heat transfer study focuses on assessment of the impact of bed temperature on the local heat transfer characteristics between a fluidized bed and vertical rifled tubes (38 mm O.D.) in a commercial circulating fluidized bed (CFB) boiler. Heat transfer behavior in a 1296 t/h supercritical CFB furnace has been analyzed for Geldart B particles with Sauter mean diameters of 0.219 and 0.246 mm. The heat transfer experiments were conducted for the active heat transfer surface in the form of membrane tubes with a longitudinal fin at the tube crest under normal operating conditions of a CFB boiler. A heat transfer analysis of a CFB boiler with detailed consideration of the bed-to-wall heat transfer coefficient and the contribution of heat transfer mechanisms inside the furnace chamber was investigated using a mechanistic heat transfer model based on the cluster renewal approach. The predicted values of heat transfer coefficient are compared with empirical correlations for CFB units at large scale.

Keywords: Cluster renewal approach, heat transfer coefficient, bed temperature, suspension density, circulating fluidized bed

Introduction

The heat transfer process between the fluidized bed and the boiler surface in the form of water membrane walls plays a critical role in circulating fluidized bed reactors used for heat recovery and the clean or high-efficiency combustion of fossil fuels. Particular attention has recently been drawn to the reduction of the energy intensity of the energy generation process while meeting the environmental protection requirements laid down by the IED Directive of the European Parliament and the Council [**?**]. Understanding the complex gas-solid flow pattern and heat transfer processes occurring during solid fuel combustion under circulating fluidized-bed conditions constitutes a factor decisive to the quality of the final product obtained. This applies to the method of receiving and supplying heat to the heat exchangers, while taking into account the location and geometry of the heatable surfaces. Understanding the mechanisms of heat flow, being in close correlation with the prevailing hydrodynamic conditions, will provide the necessary knowledge for process scaling and the design of heat exchange surfaces. The correct sizing of active heat transfer surfaces inside the CFB furnace ensures proper operation, load turndown, and also affects furnace temperature. The furnace temperature is of importance for the formation and reduction of harmful matter, which influences the economic indices of commercial CFB boilers.

The aims of the current work were to: (i) experimentally investigate bed temperature and suspension density profiles in a 1296 t/h supercritical CFB boiler; (ii) present overall heat transfer coefficient distributions; and (iii) depict the contribution of heat transfer mechanisms inside the furnace as a function of bed temperature.

In summary, this work addresses an existing gap in the literature data regarding the modeling of and experimentation on heat transfer to tubes in the furnace chamber [**?**], by providing experimental data from a CFB unit at large scale. The high labor intensity and cost of carrying out large commercial-scale tests are the cause of the lack of publications of the results of investigations of heat transfer processes on a large commercial scale [**?**]. In this situation, carrying out comprehensive studies would make it possible to establish the optimal heat transfer conditions in correlation with the bed hydrodynamics.

Nomenclature

Variables and Parameters - a, b, c: coefficients in Eq. (2), - - Ar: Archimedes number, - - B: coefficient, - - c_g: specific heat of gas, kJ/(kg • K) - c_p: specific heat of bed particle, kJ/(kg • K) - d_h: hydraulic diameter, m - d_p: mean bed particle size, mm - d_{32}: Sauter mean particle diameter, mm - e: emissivity, - - f: fractional of wall covered by clusters, - - G_s: lateral solid circulation flux, kg/(m^{2}s) - g: acceleration due to gravity, m/s^2 - H: furnace height, m - h: bed-to-wall heat transfer coefficient, W/(m^{2}K) - h_c: cluster heat transfer coefficient, W/(m^{2}K) - h_g: gas convection heat transfer coefficient, W/(m^{2}K) - h_p: particle convection heat transfer coefficient, W/(m^{2}K) - h_w: wall contact heat transfer coefficient, W/(m^{2}K) - k: thermal conductivity, W/(m • K) - L_c: cluster characteristic travel length, m - MCR: maximum continuous rating, - - p: pressure, kPa - Δp: pressure drop, kPa - Pr: Prandtl number, - - T: temperature, K - t_c: cluster residence time, s - U_c: cluster descent velocity, m/s - U_0: superficial gas velocity, m/s - U_{mf}: minimum fluidization velocity, m/s - U_t: terminal velocity of bed particles, m/s - X: fraction of particles in the dispersed phase, - - Y: volumetric concentration of bed particles in the dispersed phase, - - z: height above air distributor, m - Δz: distance between pressure taps, m - δ: wall layer thickness, m - δ_f: fin depth, mm - δ_g: gas gap thickness, m - ε: cross-sectional bed average voidage, - - ε_{mf}: voidage at minimum fluidization velocity, - - μ: viscosity, kg/(m • s) - ρ: density, kg/m^3 - ρ_b: suspension density, kg/m^3 - σ: Stefan-Boltzmann' s constant, W/(m^{2}K)

Greek Letters - α, β, γ: coefficients

Superscripts - ad: air dried basis - ar: as received

Subscripts - b: bed - c: cluster phase - d: dispersed phase - g: gas - max: maximum value - p: particle - r: radiation - rc: radiation from cluster phase - rd: radiation from dispersed phase - w: wall

Heat Transfer Process in CFB Furnace

Heat transfer between the fluidized bed and containing walls involves three modes: (i) convection by particles, (ii) convection by gas, and (iii) radiation from clusters, as well as (iv) radiation from the dispersed phase. The contribution of individual heat transfer mechanisms is considered separately due to the complexity of the bed hydrodynamics.

Mechanistic models based on the cluster renewal approach commonly assume that the walls are not covered by a continuous stream of solids. In the case of CFB boilers, each portion of the active heat transfer surface (i.e., water membrane wall) is intermittently washed by down-flowing clusters of bed particles and dispersed medium. Thus, one part of the heat transfer surface is in contact with clusters while the rest is in contact with the gas or dispersed phase. This fact is due to a major feature of the core-annulus flow structure inside the CFB furnace as indicated by Fig. 1 [Figure 1: see original paper].

Consequently, the bed-to-wall heat transfer coefficient can be stated in the following equation (1) as the sum of heat transfer mechanism contributions [?]:

$$h = f \cdot h_p + (1 - f) \cdot h_g + f \cdot h_{rc} + (1 - f) \cdot h_{rd} \quad (1)$$

where the subscripts p, g, rc, and rd denote particle convection, gas convection, radiation from clusters, and radiation from the dispersed phase, respectively. In equation (1), the parameter f represents the fractional wall coverage by clusters and is estimated using the hydraulic diameter and height of the CFB furnace in a non-dimensional form:

$$f = a \cdot \left(\frac{d_h}{H}\right)^b \cdot \left(\frac{z}{H}\right)^c \quad (2)$$

To derive values of the coefficients a, b, c in equation (2), heat transfer data from four large-scale CFB boilers with different equivalent diameters–1.6 m (12 MWth), 5.2 m (20 MWe), 6.2 m (145 MWth), and 10.6 m (170 MWe)–and also at different elevations above the secondary air supply (11.5 m, 25.0 m, 26.0 m, and 30 m) were analyzed, and then the coefficients were estimated using multiple regression analysis [?].

Fig. 1 Single cluster formation and gas gap in the vicinity of the water membrane wall inside CFB furnace [?].

In the cluster renewal model of heat transfer for CFB boilers, the particle convection heat transfer coefficient comprises unsteady heat conduction into clusters h_c and the conduction across the thin gas layer between the cluster and the heat transfer surface h_w. Finally, the particle convection heat transfer coefficient h_p is given by:

$$h_p = \frac{1}{\frac{1}{h_c} + \frac{1}{h_w}} \quad (3)$$

Formulas needed to estimate the physical and thermal properties for the clusters and gas have been detailed by Blaszczuk et al. [?] and will not be repeated in this work.

When the vertical heat transfer surfaces (i.e., membrane walls) are exposed to a fluidized bed at large Archimedes number or dilute lean phase, the gas convection component in the overall heat transfer coefficient may be expressed as follows [?]:

$$h_g = \frac{k_g}{d_p} \cdot \left(\frac{U_t \cdot d_p \cdot \rho_g}{\mu_g}\right)^{0.5} \cdot Pr_g^{0.33} \cdot \left(\frac{c_p}{c_g}\right)^{0.5} \cdot \left(\frac{\rho_p}{\rho_d}\right)^{0.25} \cdot \left(\frac{g \cdot d_p}{U_t^2}\right)^{0.25} \quad (4)$$

where k_g denotes thermal conductivity of the gas, d_p represents mean bed particle size, U_t means terminal velocity of the bed particles, c_g and c_p are specific heat of gas phase and particle, respectively. In equation (4), g is acceleration due to gravity, ρ_p represents particle density, and ρ_d denotes dispersed phase density.

In the current heat transfer study, dispersed phase density is found by the following equation:

$$\rho_d = \rho_g \cdot (1 - Y) + \rho_p \cdot Y \quad (5)$$

In this correlation, Y is the volumetric concentration of bed particles in the dispersed phase, and the value of this parameter is recommended as 0.001% [?]. In the heat transfer model, the dispersed phase contains a small concentration of bed particles (i.e., dilute gas-particle mixture) and gas.

The radiation heat transfer from the cluster to the water membrane wall is similar to that between two infinite parallel plates with a view factor of 1. Thus, the cluster radiation component of the bed-to-wall heat transfer coefficient is calculated from the expression:

$$h_{rc} = \frac{\sigma \cdot (T_c^4 - T_w^4)}{T_b - T_w} \cdot \frac{1}{\frac{1}{e_c} + \frac{1}{e_w} - 1} \quad (6)$$

where σ is the Stefan-Boltzmann constant, T_w represents active heat transfer surface temperature, T_c means cluster temperature which is estimated from the empirical correlation for radial temperature distribution proposed by Golriz [?]. In equation (6), e_c and e_w are the emissivities of the cluster and wall, respectively. The membrane wall emissivity e_w is assumed to have a constant value of 0.8, as for oxidized steel. For analysis of heat transfer in commercial CFB combustors, the cluster emissivity can be derived by equation (7) which takes account of bed particle radiation:

$$e_c = 1 - \frac{1 - e_p}{Y} \cdot \ln\left(\frac{1}{1 - Y}\right) \quad (7)$$

Here e_p denotes particle emissivity and is equal to 0.7 as suggested by Basu [?]. Thus, the cluster emissivity is larger than particle emissivity.

At high furnace temperature (>973 K) and also in regions with low suspension density (<5 kg/m^3) inside the furnace chamber of CFB boilers [?], the dispersed radiation component of the overall heat transfer coefficient becomes important and is estimated using the following equation:

$$h_{rd} = \frac{\sigma \cdot (T_b^4 - T_w^4)}{T_b - T_w} \cdot \frac{1}{\frac{1}{e_d} + \frac{1}{e_w} - 1} \quad (8)$$

where T_b denotes bed temperature, e_d is the emissivity of the dispersed phase which may be calculated by Brewster' s relationship for isotropic scattering [?]. The expression for e_d is given as:

$$e_d = \frac{e_p}{1 + B \cdot (1 - e_p)} \quad (9)$$

For isotropic scattering, B can be taken to equal about 0.5. Other denotations in equation (8) are explained in equation (6).

Performance Tests and Experimental Conditions

The heat transfer experiments were performed in a 1296 t/h supercritical CFB boiler located at Tauron Generation S.A. Lagisza Power Plant, Poland. More information about the CFB facility can be found in the works [?, ?, ?, ?], in which construction data, cross-sectional area, arrangement of measuring points, and data acquisition system are particularly presented.

The planning of large commercial-scale experiments required a series of preliminary tests to be performed, which involved observations of the variability of process parameter change rates. Based on these observations, the frequency of process data archiving in accordance with the Shannon-Kotelnikov theorem [?] and the duration of an individual test were selected.

To assess the impact of bed temperature on the local heat transfer characteristics between a fluidized bed and vertical rifled tubes, experiments were conducted during a four-day period. Each test lasted eight hours at four different boiler loads (i.e., 40% MCR, 60% MCR, 80% MCR, and 100% MCR). The eight hours for each test were needed in order to establish the repeatability of experimental results.

The measurement of furnace data (i.e., static pressure and bed/wall temperature) was carried out under stable operating conditions. During performance tests on the supercritical CFB boiler with capacity 966 MWth, the mass flow of feeding materials supplied into the furnace chamber (i.e., coal and limestone) was kept at a constant level.

Air-fuel firing conditions of the performance tests are summarized in Table 1 .

For the performance tests described in this paper, bed temperatures between 1063 K and 1183 K were achieved by burning Polish bituminous coal (Ziemowit coal mine, Poland) with approximately 20% excess air. The characteristics of the fossil fuel used in the performance tests are given in Table 2 .

Determination of proximate parameters of the bituminous coal was made in accordance with applicable standards for fossil fuel in Poland. Meanwhile, the ultimate analysis data were obtained by means of the LECO TrueSpec™ analyzer. All analytical data for fossil fuel are averages from five repetitions for each fuel constituent.

Table 1 Operation parameters of performance tests

Parameter	Overall range
Boiler loads, Q	40 100% MCR
Superficial gas velocity, U_0	3.89 5.11 m/s
Minimum fluidization velocity, U_{mf}	0.0164 0.0243 m/s
Voidage at minimum fluidization velocity, ε_{mf}	0.40 0.41
Solids circulation rate, G_s	21.4 25.5 kg/(m²s)
Sauter mean particle diameter, d_{32}	0.219 0.246 mm
Suspension density, ρ_b	1.55 6.14 kg/m³
Bed temperature, T_b	1063 1183 K
Wall temperature, T_w	636 735 K
Pressure drop, Δp	6.86 8.25 kPa

Table 2 Properties of bituminous coal used in the tests

Parameter	Overall range
Ultimate analysis (air dried basis)	
C_{ad}, carbon	52.32 56.50%
H_{ad}, hydrogen	4.02 4.74%
O_{ad}, oxygen	5.35 6.98%
N_{ad}, nitrogen	0.73 0.84%
S_{ad}, sulphur	0.87 1.21%
Proximate analysis (as-received)	
Q_{ar}, Caloric value	20.11 22.79 MJ/kg
V_{ar}, Volatile matter	25.61 30.37%
A_{ar}, Ash	9.10 20.11%
M_{ar}, moisture	11.81 19.13%

In the supercritical CFB boiler above the secondary air injection level (transport zone) are located the active heat transfer surfaces, i.e., membrane wall, wing wall evaporators, and also radiant superheater. In the current study, heat transfer at the membrane wall inside the furnace chamber is considered. The membrane wall is the main absorbing heat transfer surface from products of the solid fuel combustion process. The membrane walls are constructed in the form of membrane rifled tubes with a longitudinal fin at the tube crest. The vertical rifled tubes have a 38 mm outside diameter with spacing of 63 mm. More detailed information on the geometry of membrane walls can be found in the following publications [**?**, **?**].

Results and Discussion

Experimental data used in this heat transfer study are given in dimensionless scale by reason of confidential information about industrial CFB boilers at large scale. Besides, suspension density was normalized by the maximum value obtained during all tests.

In this heat transfer study, the concept of a mechanistic heat transfer model is used to investigate the heat transfer mechanism behavior near the vertical rifled tubes, according to the cluster renewal approach. The bed-to-wall heat transfer coefficient and contribution of heat transfer components along the furnace chamber are generated based on the experimental conditions given in Table 1.

The bed-to-wall heat transfer coefficient distribution along furnace height at different bed temperatures for a 1296 t/h supercritical CFB boiler is depicted in Fig. 2 [Figure 2: see original paper]. With increase in bed temperature, the heat transfer coefficient increases for the same non-dimensional distance Z/H from the air distributor level. The bed-to-wall heat transfer coefficient increases with bed temperature for higher fractional wall coverage by clusters. This fact is due to the combined effect of increased cluster heat transfer and reduced gas gap resistance due to higher gas thermal conductivity. Another reason for the higher bed-to-wall heat transfer coefficient arises from suspension density variations along the furnace height of the CFB boiler.

Fig. 2 Bed-to-wall heat transfer coefficient variation with furnace height of CFB boiler at different bed temperature.

Figure 3 [Figure 3: see original paper] illustrates a strong influence of suspension density on the bed-to-wall heat transfer coefficient. In our heat transfer study, solid suspension density was calculated by the following empirical correlation:

$$\rho_b = \frac{\Delta p}{\Delta z} \quad (10)$$

where Δp represents pressure drop and Δz denotes distance between pressure taps. Attrition and gas-particle acceleration effects were neglected in equation (10).

The bed temperature has an essential effect on the heat transfer data at high relative suspension density. In the case of low normalized suspension density, the bed temperature has negligible impact on the overall heat transfer coefficient. In addition, it can be seen from Fig. 3 that the influence of solid suspension density diminishes with bed temperature. In Fig. 3, the heat transfer data obtained using the cluster renewal approach were correlated by a non-linear function using regression analysis. The heat transfer grey curves in Fig. 3 have a steeper slope in the experimental data region. In addition, it can be seen from Fig. 3 that there is not much difference between the experimental data points for the cluster renewal approach and the published experimental data for Chalmers and Dalhousie boilers [**?**, **?**] at suspension densities varying in the range of 2 4 kg/m³. In the case of suspension density covering the range of 5.44 6.14 kg/m³, a significant difference was observed.

Fig. 3 Bed-to-wall heat transfer coefficient distribution as a function of the bed temperature and the normalized suspension density.

Figures 4 7 illustrate the contribution of heat transfer mechanisms at different bed temperatures inside the CFB furnace. The contribution of heat transfer mechanisms is drawn as individual color and line type for each heat transfer mode. In this heat transfer study, the gas convection contribution was not significant in the bed-to-wall heat transfer coefficient, as demonstrated by Figs. 4 7.

Fig. 4 Contribution of heat transfer mechanisms as a function of bed temperature at $Z/H = 0.25$.

At a non-dimensional height coordinate Z/H of 0.25 (lower region of transport zone), high bed particle concentration and more clusters were recognized in comparison with other elevations above the fluidization grid (i.e., $0.5 < Z/H < 0.87$). Due to high suspension density in the vicinity of the vertical rifled tubes, the particle convection component in heat transfer mechanisms prevails in the overall heat transfer coefficient. The high particle convection heat transfer results from the thermal conductivity of the cluster. The cluster thermal conductivity increases with bed temperature due to higher gas thermal conductivity. The resistance due to gas gap thickness between cluster and rifled tubes was reduced due to increased gas thermal conductivity. The value of h_{rc}/h increases with the increase of bed temperature. The experimental tests show that radiation from the cluster phase does not depend upon furnace temperature directly above the slope section of the furnace chamber.

Fig. 5 Contribution of heat transfer mechanisms as a function of bed temperature at $Z/H = 0.5$.

At half the CFB furnace height ($Z/H = 0.5$), radiative heat transfer plays a dominant role in heat transfer mechanisms when bed temperature exceeds 1125 K. This fact indicates the significant role of suspension density and also furnace temperature (i.e., wall and bed temperature) on the contribution of heat transfer modes between the fluidized bed and the active heat transfer surface inside the CFB furnace. The slope of the particle convection curve is directly proportional to bed particle concentration and bed temperature. The same trend was also confirmed by [?]. The radiation from clusters slowly decreases with the increase of radiation from the dispersed phase.

Fig. 6 Contribution of heat transfer mechanisms as a function of bed temperature at $Z/H = 0.65$.

Fig. 7 Contribution of heat transfer mechanisms as a function of bed temperature at $Z/H = 0.87$.

The variations of heat transfer mechanism contributions in the exit region of the furnace chamber occupied by membrane wall and radiant superheater SH II (transport zone at $0.65 < Z/H < 0.87$) are presented in Figs. 6 7. The shape of profiles for h_p/h, h_{rc}/h, and also h_{rd}/h contribution is almost the same for both $Z/H = 0.65$ and $Z/H = 0.87$. The upper part of the furnace chamber was operated in a dilute phase ($\rho_b < 1.55$ kg/m^3) whereas the middle and lower regions of the transport zone were a dense phase ($\rho_b > 6$ kg/m^3).

As can be seen in Figs. 6 7, dilute phase radiation heat transfer h_{rd} increases with bed temperature and is characterized by a linear function for non-dimensional distance $0.65 < Z/H < 0.87$. Nevertheless, the radiation from the dispersed phase at $0.25 < Z/H < 0.5$ is characterized by an exponential function. This conclusion is consistent with the results presented in Figs. 4 5. Moreover, a similar trend of the heat transfer components variation was observed by Basu [?] when the CFB unit was operated at 70% load condition. Due to sufficiently low suspension density (dilute phase) and high bed temperature in the exit region of the furnace chamber, radiation from the dispersed phase has a dominant role in heat transfer mechanisms from the core region to the vertical rifled tubes.

The performance tests show that there is interplay between bed particle concentration and clusters in the contributions of particle convection and radiation from clusters. Under dilute phase conditions, the active heat transfer surface was covered by fewer clusters (ca. $f = 13\%$) than in a dense region of the transport zone (ca. $f = 68\%$).

Conclusions

In this heat transfer study, the mechanistic heat transfer model that integrates bed hydrodynamics in the CFB furnace was used to assess the effect of bed temperature on heat transfer behavior in a CFB coal combustor. A heat transfer analysis was carried out between the fluidized bed and vertical rifled tubes based on the cluster renewal approach. Heat transfer data were compared with published literature data for CFB units at large scale. The experimental data agree quite well with the results for CFB boilers at large scale. The experimental measurements of furnace data (bed temperature and suspension density) show that the bed-to-wall heat transfer coefficient was strongly correlated with furnace height. The bed temperature and suspension density affected the overall heat transfer coefficient. This conclusion was also confirmed by authors [?, ?, ?].

Obtained heat transfer data prove the effect of the fraction of wall exposed to clusters on the particle heat transfer coefficient, especially at non-dimensional distances of 0.25 and 0.5 from the fluidization grid. Low particle concentration (suspension density) and low value of the parameter f contribute to a decrease in convection heat transfer mechanism. Meanwhile, the radiation from the dispersed phase proportion increased with increase in bed temperature. In the upper part of the combustion chamber occupied by superheater SH, the contribution of the radiative heat transfer coefficient was dominant in the bed-to-wall heat transfer. This is due to sufficiently high bed temperature and also low suspension density. The contribution of radiation from clusters does not exceed 20% and 12% for $0.25 < Z/H < 0.5$ and $Z/H > 0.65$, respectively. The gas convection heat transfer mechanism was negligible during all performance tests.

The heat transfer data will be useful in the design and scale-up of heat exchangers operated in circulating fluidized bed conditions. Very important and useful for the development of computational methods and the design of commercial CFB boilers is the comprehensive study of the impact of bed temperature on the heat transfer mechanisms behavior. The observed variation of heat transfer mode will provide fundamental design basis for fluidized bed systems.

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Note: Figure translations are in progress. See original paper for figures.