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SIMULATION OF BED-TO-WALL HEAT TRANSFER IN CIRCULATING FLUIDIZED BEDS

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Abstract: In this study, the numerical simulation of bed-to-wall heat transfer in CFBs is presented which based on previously developed 2D CFB model which uses the particle-based approach and integrates and simultaneously predicts the hydrodynamics, combustion aspects. The study is also validated with published data. The comparisons of the model predictions and experimental data indicate that the model is flexible enough to operate under different operational conditions concerning superficial velocity, particle diameter and suspension density values. Additionally, the simulation matches the measured data quite faithfully for heat transfer coefficient as a function of the suspension density at different temperature values which is also an indicator that that the simulation is valid for both cold and hot CFB units.

Keywords: Heat transfer, Circulating fluidized bed, Modeling.

SİRKÜLASYONLU AKIŞKAN YATAKLARDA YATAKTAN DUVARA ISI GEÇİŞİNİN SİMULASYONU

Özet: Bu çalışmada, sirkülasyonlu akışkan yataklı yakıcılarda yataktan duvara ısı geçişinin nümerik simülasyonu yapılmıştır. Simülasyonda, daha önceden geliştirilmiş olan ve hidrodinamik ve yanmayı aynı anda tahmin edebilen ve tanecik yaklaşımını kullanan iki boyutlu sirkülasyonlu akışkan yatak modelinden yararlanılmıştır. Çalışma, aynı zamanda, literatürde yayınlanmış çalışmalarla da doğrulanmıştır. Simülasyon tahminlerinin deneysel verilerle karşılaştırılması; işletme hızı, tane çapı ve yatak yığın yoğunluğu gibi farklı işletme şartları için modelin esnekliğini göstermiştir. Ayrıca, simülasyon sonuçlarının; yatak yığın yoğunluğunun bir fonksiyonu olan ısı geçiş katsayısı için farklı sıcaklık değerlerinde deneysel verilerle göstermiş olduğu uyum, simülasyonun aynı zamanda hem soğuk, hem de sıcak akışkan yataklar için de geçerli olduğunun bir göstergesidir.

Anahtar Kelimler: Isı geçişi, Sirkülasyonlu akışkan yatak, Modelleme.

NOMENCLATURE

Ar	Archimedes number
C	gas concentration (kmol/m^3)
c	specific heat (kJ/kg K)
D	bed diameter (m)
d_p	particle diameter (m)
e	emissivity
G	suspension density (kg/m^3)
g	gravity (m/s^2)
h	overall bed to wall heat transfer coefficient (W/m^2 K)
h_c	convection heat transfer coefficient for clusters (W/m^2 K)
h_d	convection heat transfer coefficient for dispersed phase (W/m^2 K)
h_g	convection heat transfer coefficient for gas phase (W/m^2 K)
h_p	convection heat transfer coefficient for particle phase (W/m^2 K)
h_r	radiative heat transfer coefficient (W/m^2 K)
k_g	gas conduction heat transfer coefficient (W/m K)
Pr	Prandtl number
T	temperature (K)
U_{ter}	terminal velocity (m/s)

Subscripts

b	bed
c	cluster
d	dilute
g	gas
p	particle
wall	wall (heat transfer surface)

Greek letters

ε	void fraction
ρ	particle density (kg/m^3)
σ	Stefan-Boltzman coefficient (W/m^2K^4)

INTRODUCTION

The correct sizing of the heat transfer surfaces is important to ensure proper operation, load turndown, and optimization of circulating fluidized beds (CFBs).

Design or scale-up of heat transfer systems in CFBs require estimation of the effective heat transfer coefficient on heat transfer surfaces in contact with the fluidized medium. It is therefore essential to understand the mechanisms of heat transfer in CFBs, and to develop an appropriate model to predict the rate of heat transfer.

Numerous experimental and theoretical investigations to describe the heat transfer to the walls of fluidized beds have been studied since 1949 with the work of Mickley and Fairbanks (1955). Since then much experimental and modeling work has been done in both laboratory and industrial scale units. Many authors approximate the overall heat transfer coefficient as the result of adding the heat transfer coefficients for particle convection, gas convection and thermal radiation. A number of mechanistic models have been suggested to explain each of these components. The models to describe the particle convective heat transfer component can be classified broadly as single-particle models, cluster renewal models and continuous film models and have been summarized by Basu and Nag (1996). Leckner et al. (1991) identified two kind of heat transfer processes in a CFB, thermal radiation and convection heat transfer between the particles-gas and the wall. The convection provides larger proportion of the total heat transfer Gloriz (1995). Since the particle convection coefficient is much greater than the gas convection coefficient for the range of particle sizes used in almost all CFB applications, most models pay little or no attention to the dilute phase heat transfer coefficient. Radiation is a major contributor to heat transfer in CFB boilers and other high temperature CFB reactors, especially for the low suspension densities found under turndown conditions. The relative contribution of radiation depends primarily on the wall and furnace temperatures. Basu and Nag (1996) and Glicksman (1997) presented comprehensive reviews of CFB heat transfer. Recently, Xie et al. (2003a) was proposed a 2D model which coupled radiation, conduction and convection from the hot core on the furnace side to conduction and convection into the coolant on the wall side. In a further study authors also developed an advanced model to accommodate the 3D membrane wall geometry Xie et al. (2003a). Gupta and Reddy (2005) were proposed a mechanistic model to predict the bed-to-wall heat transfer coefficient in the top region of a CFB riser column for different riser exit configurations. Chen et al. (2005) were suggested that mechanistic models based on the surface renewal concept hold promise for design and scale-up of heat transfer systems for both bubbling dense beds and fast CFBs.

As mentioned above, although many works have been done in modeling bed-to-wall heat transfer, the understanding of the process of the heat transfer in a CFB is still in a developing stage. From this point of view, in this study, the numerical simulation of bed-to-wall heat transfer in CFBs is presented which based on previously developed 2D CFB model which uses the particle-based approach and integrates and simultaneously predicts the hydrodynamics, combustion aspects. The study is also validated with published data (Furchi et al., 1988, Han et al., 1996, Pagliuso et al., 2000, Wu et al., 1989).

BED-TO-WALL HEAT TRANSFER

From a heat transfer point of view, mathematical modeling is an attractive solution which allows developing an appropriate model to predict bed-to-wall heat transfer characteristics for better understanding heat transfer mechanism to enhance combustion performance in a much shorter time period and at lower costs.

Because of CFB bed-to-wall heat transfer is strongly influenced by the system hydrodynamics, especially the particle and gas motion in the vicinity of the wall (Basu and Nag, 1996, Glicksman, 1997), it is essential to understand the hydrodynamic flow structure in the riser column of a CFB. Numerous hydrodynamic parameters such as the solids volume fraction, suspension density, the circulated solids mass flux, the superficial velocity, particle diameter and the size distribution of particles play roles in bed-to-wall heat transfer process:

- Shi et al. (1998) reported that, the bed-to-wall heat transfer coefficients increase as the solids volume fraction at the wall increases. This study also presents that the smaller particles result higher heat transfer coefficients than larger ones for the same solids volume fraction values.
- A higher suspension density results in a thicker wall layer having a higher concentration of particles. Also, there is a greater rate of particle exchange between the core and the wall layer which augments the transfer of heat from the bulk to the wall. On the other hand, a thicker wall layer and higher particle concentration increases the radiation resistance between the bulk and wall, thereby decreasing the radiation contribution. This phenomenon is confirmed by Pagliuso et al. (2000).
- The heat transfer coefficient and the circulated solids mass flux is less sensitive to particle diameter than suspension density; probably because the mass flux itself is a function of particle diameter (Pagliuso et al., 2000, Tian and Peng, 2004). This can be explained by the fact that circulated flux is also directly proportional to the average density suspension in the riser and inversely proportional to the particles diameter. Feugier et al. (1987) also observed a linear relationship between the solid mass flux and the average heat transfer coefficient.
- At constant suspension density, the superficial velocity does not have a significant influence on the heat transfer coefficient (Wu et al., 1987, Xie et al., 2003c). However, for a given suspension density, the heat transfer coefficient is hardly influenced by

the superficial velocity as observed in other studies (Xie et al., 2003a, 2003b).

- It is a well known the fact that particle diameter is also an important parameter for heat transfer in CFBs. The smaller particles show higher coefficients than larger ones for the same suspension density. The effect of particle size on the heat transfer coefficient is more significant for smaller particles and larger suspension densities (Pagliuso et al., 2000).
- The shape of the size distribution is a significant parameter concerning heat transfer, as was observed by Pagliuso et al. (2000). Heat transfer coefficients of widely size-distributed solids fractions are slightly higher than those of narrowly size-distributed solids fractions. Hence, the width of the particle size distribution seems to have only a minor influence on the heat transfer coefficient if all particles are well fluidized and no axial segregation of particles occurs in the riser (Shi et al., 1998).

Bed hydrodynamics is modeled taking into account previous work (Gungor and Eskin, 2007). In the modeling, the CFB riser is analyzed in two regions: The bottom zone in turbulent fluidization regime is modeled in detail as two-phase flow which is subdivided into a solid-free bubble phase and a solid-laden emulsion phase. In the upper zone core-annulus solids flow structure is established. As previous study verifies (Gungor and Eskin, 2007), in the present study a particle-based approach is applied with adequate choice of calculation domain in the core and annulus regions of the riser.

The gas and solid concentrations at the riser wall along the bottom zone can be estimated with sufficient accuracy using the developed hydrodynamic model and as a function of the local bed density, the bed-to-wall heat transfer coefficient is calculated as the expression given by Basu and Nag (1996) which was validated previously (Park and Basu, 1997);

$$h = 40\left(\rho_b\right)^{1/2} \qquad (1)$$

where ρ_b is the local bed density; $\rho_b = \rho\left(1-\varepsilon\right) + C\varepsilon$.

The bed-to-wall heat transfer coefficient in the upper zone of CFB consists of the contributions of four components i.e., conduction and radiation components of particle phase and convective and radiation components of gas phase. As illustrated schematically in Fig.1, any part of the heat transfer surface comes in contact with the solid phase and the gas phase with respect to the rates of their voidage at the region in vicinity of the heat transfer surface. This assumption is based on the ability of developed hydrodynamic model to make the calculations for any given time step (Gungor and Eskin, 2007).

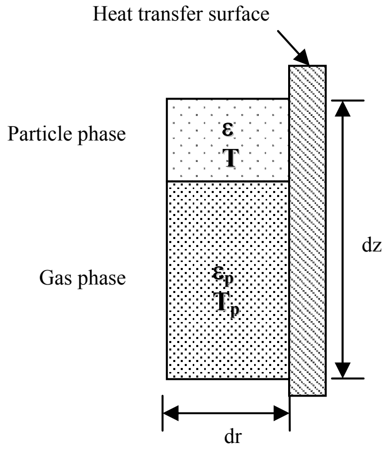

Figure 1. Schematic view of heat transfer model.

The local solids volume fraction (ε_p) and gas concentration (ε) at the riser wall along the upper zone can be estimated with sufficient accuracy using the developed hydrodynamic model, the bed-to-wall heat transfer coefficient, h, is calculated as the sum of the particle conductive, gas convective and particle and gas radiative heat transfer coefficients in the model as follows:

$$h = \varepsilon_p \cdot h_p + \varepsilon \cdot h_g + \varepsilon_p \cdot h_{r,p} + \varepsilon \cdot h_{r,g} \qquad (2)$$

where h_p is the conductive heat transfer coefficient for solids phase and h_g is the convective heat transfer coefficient for the gas phase.

Heat transfer by particle conduction hp refers to the energy transfer due to continuous particle motion between heat transfer surface and inner region of the CFB and it is closely related with suspension density in the riser and is calculated in the model as follows (Ryabov et al., 1999);

$$h_p = \frac{k_g}{d_p} \cdot 0.009 \times \mathrm{Pr}^{0.33}\,\mathrm{Ar}^{0.5} \qquad (3)$$

Heat transfer by gas convection hg becomes significant in fluidized beds at large Archimedes-numbers or low solids concentrations (Martin, 1984). The convection heat transfer from the gas phase to the wall is estimated by the modified equation of Wen and Miller (1961), which was given by Basu et al. (1996) as:

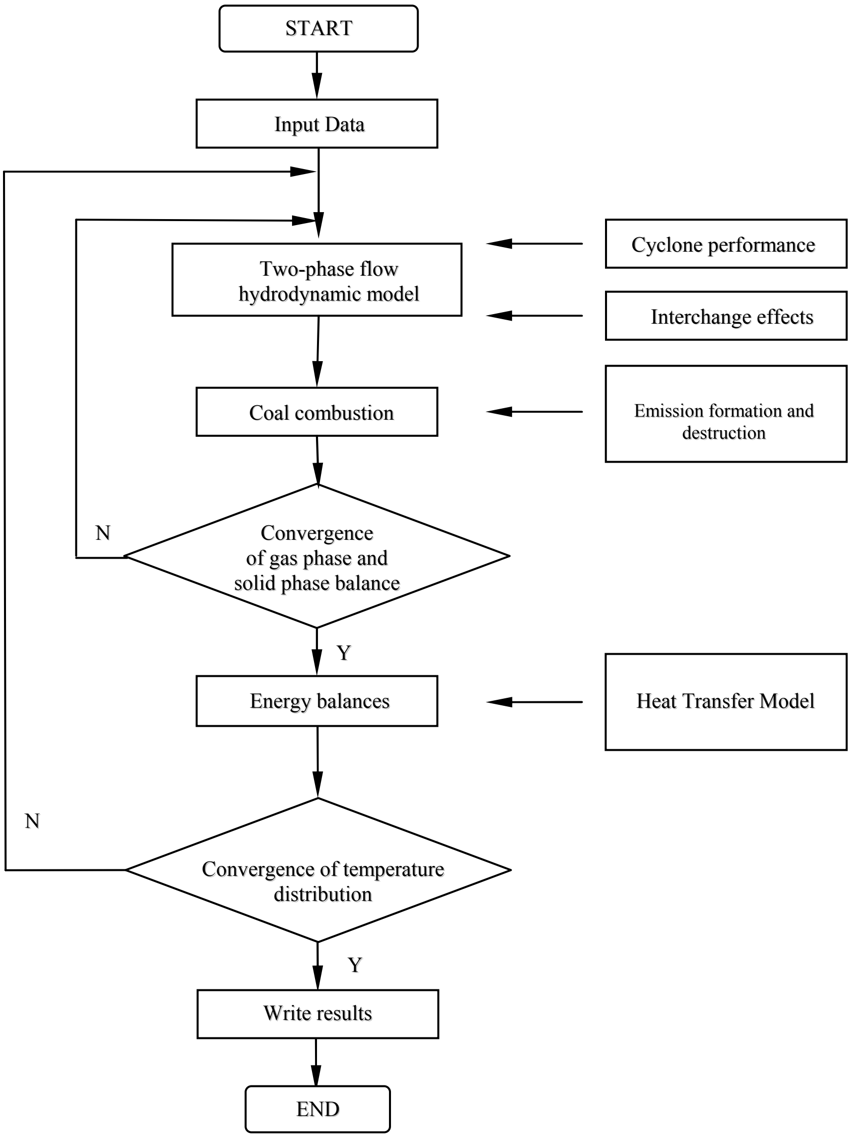

Figure 2. Flow chart of the numerical solution of the CFB model.

$$h_g = \left(\frac{k_g}{d_p}\right)\cdot\left(\frac{c_p}{c_g}\right)\cdot\left(\frac{C}{\rho}\right)^{0.3}\cdot\left(\frac{U_{ter}}{gd_p}\right)^{0.21}\cdot \Pr \qquad (4)$$

At bed temperatures higher than 800°C, the available information suggests that the effect of radiation becomes significant (Basu and Nag, 1996, Glicksman, 1997). Within the operating temperature ranges of CFBs, the radiative heat transfer coefficients lie between 60 and 120 W/m^{2}K. In a typical gas fired combustor, the major heat transfer mechanism between bed and heat transfer surfaces is the gas convective heat transfer, and the gas convective heat transfer coefficients lie between 50 and 100 W/m2K (Holman, 1990). Therefore, compared with the gas fired combustors, the CFB combustors have the advantage of higher heat transfer coefficient due to suspension radiation as well as gas convection. According to Werner (2001), solids concentration and temperature, about 1/3 of total heat flux to the furnace walls is transmitted by radiation. The radiation heat exchange is calculated similar to parallel planes approach in radiation (Basu and Nag, 1996). The particle radiation component of the heat transfer coefficient is estimated using the following equation:

$$h_{r,p} = \frac{\sigma\left(T_p^4 - T_{wall}^4\right)}{\left\{\left(e_p^{-1} - e_{wall}^{-1}\right) - 1\right\}\left(T_p - T_{wall}\right)} \qquad (5)$$

where e_p is the emissivity of the particle and ewall is the emissivity of the heat transfer surfaces which is the property of the surface (Basu et al., 1996). The gas phase radiation heat transfer coefficient from bed to wall is estimated using the following equation (Basu et al., 1996):

$$h_{r,g} = \frac{\sigma\left(T^4 - T_{wall}^4\right)}{\left\{\left(e_g^{-1} - e_{wall}^{-1}\right) - 1\right\}\left(T - T_{wall}\right)} \qquad (6)$$

Basu and Nag (1996) reported that the emissivity of cluster or the dispersed phase is between 0.85 and 0.95, and Wirth (1995) also used the emissivity of 0.91 for the analysis of commercial CFB coal combustors. The particles are assumed to constitute a continuous absorbing, emitting and scattering medium in the model. The wall emissivity of 0.85 and the particle emissivity of 0.90 are used in the simulations.

The model allows dividing the calculation domain into $m \times n$ control volumes, in the radial and the axial directions and in the core and the annulus regions respectively. In this study the calculation domain is divided into 20×50 control volumes in the radial and the axial directions and in the core and the annulus regions respectively. In the model, the last control volume in the annulus region which is in vicinity of the wall is considered as the basis of heat transfer coefficient calculations. The gas phase and solid phase properties (temperature, void fraction, etc.) are considered in the control volume which is in the mentioned region. The set of differential equations governing mass, momentum and energy for the gas and solid phases are solved using an IBM-PC-AMD processor (CPU speed is 2800 MHz) with a computer code developed by the author in FORTRAN language where the time step is 10^{-6} seconds. The Gauss-Seidel iteration which contains successful relaxation method and combined Relaxation Newton-Raphson methods are used for solving procedure. Flow chart of the numerical solution of the model is shown in Fig.2. Details about solving procedure are given in previous study (Gungor, 2006).

RESULTS AND DISCUSSION

In the present study, to verify the accuracy of the model bed-to-wall heat transfer coefficient predictions along the bed height, simulation results are compared with Furchi et al. (1988), Han et al. (1996), Pagliuso et al. (2000) and Wu et al. (1989)'s experimental results. In these comparisons, the same input variables are used in the tests as the simulation program input. The measurement conditions of experimental data used for the comparison of the model is summarized in Table 1.

Furchi et al. (1988) reported experimental local bed-to-wall heat transfer coefficients for temperatures up to 250°C at which radiation is unimportant. The riser was 72.5 mm in internal diameter, 6.0 m high, with six double-pipes, annular, water-cooled heat exchangers, each 0.93 m high, located one above the other. The particles were glass spheres of average diameters ranging from 109-269 μm. The superficial gas velocity ranged from 5.8-12.8 m/s, and the particle circulation flux from 0-80 kg/m^{2}s. Fig.3. shows the comparison of model bed-to-wall heat transfer coefficient values with Furchi et al. (1988)'s experimental data. From the extensive hydrodynamic study of CFBs, it was found that the axial suspension density distribution shows the typical S-shape profile along the bed height. Therefore, it is expected that the bed-to-wall heat transfer coefficient decreases with bed height.

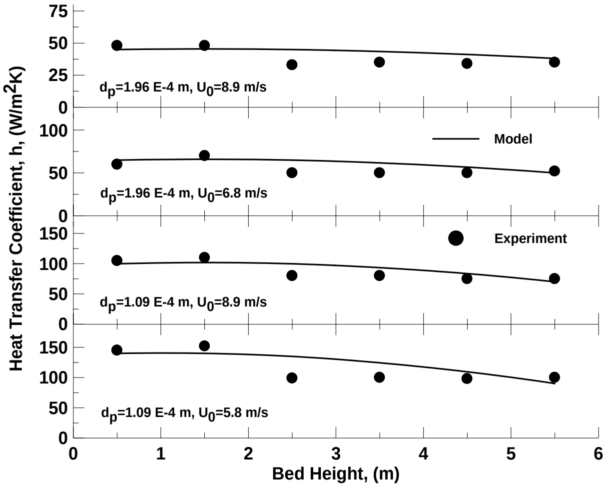

Figure 3. Comparison of model bed-to-wall heat transfer coefficient values with Furchi et al. (1988)'s experimental data.

The model gives very good predictions with experimental data. Many studies report that at constant suspension density, the superficial velocity does not have a significant influence on the heat transfer coefficient (Xie et al., 2003c) as Fig.3 clearly shows. This comparison also proves that the model is flexible enough to operate under different operational conditions concerning superficial velocity and particle diameter values.

Pagliuso et al. (2000) reported experimental local bed-to-wall heat transfer coefficients for temperatures at which radiation is unimportant. The riser was 72.5 mm in internal diameter, 6.0 m high, with six double-pipes, annular, water-cooled heat exchangers, each 0.93 m high, located one above the other. Five narrow size fractions of quartz sand particles–d_p=179, 230, 385, 460 and 545 μm–were tested. The suspension temperature

Table 1. Measurement conditions of the experimental data referred to in this study.

Author(s)	Bed Temp. T(°C)	Bed Diameter D(m)	Bed Height H(m)	Superficial Velocity U_0(m/s)	Particle Diameter d_p(μm)
Furchi et al. (1988)	250	0.072	6.00	5.8-12.8	196
Pagliuso et al. (2000)	150	0.159	2.44	2.5-3.3	179-545
Wu et al. (1989)	410-870	0.152	7.30	4-6-7.5	188-241
Han et al. (1996)	650-850	0.200	6.00	1.5-13	157

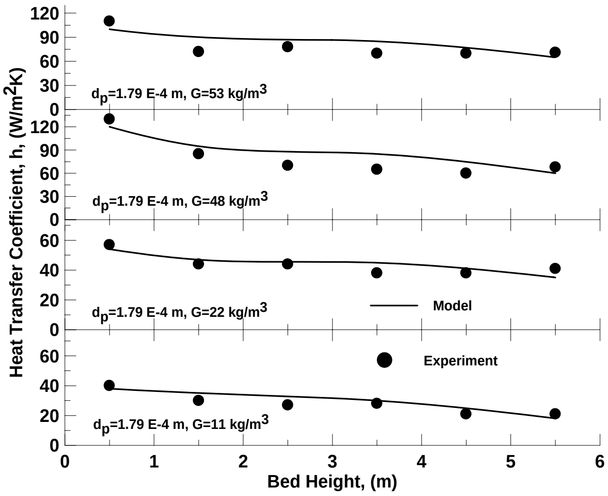

Figure 4. Comparison of model bed-to-wall heat transfer coefficient values with Pagliuso et al. (2000)'s experimental data.

was kept approximately constant at 423 K while the superficial gas velocity was 10.5 m/s. Water and gas–solid suspension temperatures were measured at the inlet and outlet of each jacketed section. Pressure drops were also recorded to determine the suspension density. Fig.4 shows experimental and predicted local bed-to-wall heat transfer coefficients for different suspension density conditions for 179 µm particles. As it is seen from the figure, the model calculates hydrodynamic behavior of CFB with sufficient accuracy so that the model predictions show a good agreement with experimental data concerning different suspension densities.

Wu et al. (1989) reported experimental average and local heat transfer coefficients obtained with the CFB facility which The riser was 7.3 m in height and its cross-section was 0:152 m × 0:152 m and membrane surface under higher suspension temperature conditions. The bed material was silica sand with a density of 2610 kg/m3 with a mean diameter of 286 µm. Fig.5 compares the predicted local heat transfer coefficients with the experimental results of Wu et al. (1987). As it is clearly seen from the figure, the model matches the measured data quite faithfully for heat transfer coefficient as a function of the suspension density at different temperature values which is also an indicator that that the model is valid for both cold and hot CFB units.

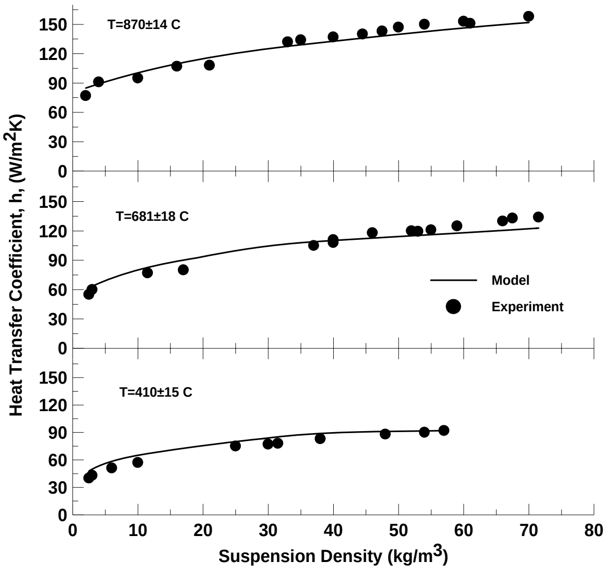

Figure 5. Comparison of model bed-to-wall heat transfer coefficient values with Wu et al. (1989)'s experimental data.

Han et al. (1996) determined the thermal performance of a CFB heat exchanger operating with vertical up-flow of a hot gas loaded with solid particles. Their facility consisted of a combustion chamber, a cylindrical heat transfer test section, and a solids recycle and feeding system. In the experiments, the suspension temperatures varied from 100-600°C, while the inlet gas superficial velocity ranged from 1.5-13 m/s. Particulate material was sand with a mean diameter of 157 µm. The combustion fuel used in these experiments was anthracite coal, premixed with limestone in the model comparisons. Fig.6 presents the bed-to-wall heat transfer coefficient as a function of the suspension density along the riser. The heat transfer coefficient increase with suspension density. This predicted influence of suspension density is consistent with experimental results.

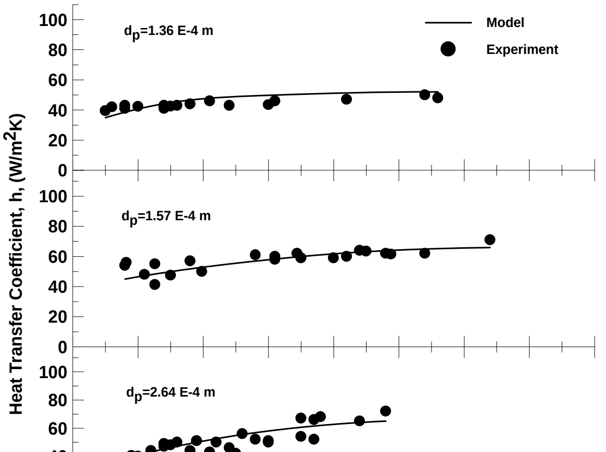

Figure 6. Comparison of model bed-to-wall heat transfer coefficient values with Han et al. (1996)'s experimental data.

CONCLUSIONS

In this study, the numerical simulation of bed-to-wall heat transfer in CFBs is presented which based on previously developed 2D CFB model which uses the particle-based approach and integrates and simultaneously predicts the hydrodynamics, combustion aspects. The study is also validated with published data (Furchi et al., 1988, Han et al., 1996, Pagliuso et al., 2000, Wu et al., 1989). The comparisons of the model predictions and experimental data indicate that the model is flexible enough to operate under different operational conditions concerning superficial velocity, particle diameter and suspension density values. Additionally, the model matches the measured data quite faithfully for heat transfer coefficient as a function of the suspension density at different temperature values which is also an indicator that that the model is valid for both cold and hot CFB units.

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