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Effect of dilute and dense phase operating conditions on bed-to-wall heat transfer mechanism in a circulating fluidized bed combustor

G. Nirmal Vijay, B.V. Reddy *

Department of Mechanical Engineering, University of New Brunswick, Fredericton, NB, Canada E3B 5A3

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Abstract

In the present paper investigations are conducted on bed-to-wall heat transfer to water-wall surfaces in the upper region of the riser column of a circulating fluidized bed (CFB) combustor under dilute and dense phase conditions. The bed-to-wall heat transfer depends on the contributions of particle convection, gas convection and radiation heat transfer components. The percentage contribution of each of these components depends on the operating conditions i.e., dilute and dense phase bed conditions and bed temperature. The variation in contribution with operating conditions is estimated using the cluster renewal mechanistic model. The present results contribute some fundamental information on the contributions of particle convection, gas convection and radiation contributions in bed-to-wall heat transfer under dilute and dense phase conditions with bed temperature. This leads to better understanding of heat transfer mechanism to water-wall surfaces in the upper region of the riser column under varying load conditions i.e., when the combustor is operated under dilute and dense phase situations. The results will further contribute to understanding of heat transfer mechanism and will aid in the efficient design of heat transfer surfaces in the CFB unit.

Keywords: Heat transfer mechanism; CFB combustor; Particle convection; Radiation; Dilute phase; Dense phase; Suspension density; Bed temperature

1. Introduction

Circulating fluidized bed (CFB) combustors are becoming the core of "clean coal technology" for power production, owing to their efficient and clean burning of coal and other solid fuels including biomass and solid municipal waste, in an environment friendly manner with reduced pollutants. The major part of heat transfer from the combustion products in a CFB unit takes place above the secondary air injection in the riser column, where the water-wall and suspended surfaces are located. The bed hydrodynamic conditions influence the heat transfer to the water-wall surfaces. The bed-to-wall heat transfer depends on the contributions of particle convection, gas convection and radiation heat transfer components. Wu et al. [1], Basu and Nag [2], Glicksman [3,4], Grace [5] and Leckner [6] reported heat transfer measurements/investigations in CFB units. Wu et al. [1] proposed a mechanistic model to estimate the

* Corresponding author. Tel.: +1 506 458 7515; fax: +1 506 453 5825.
E-mail address: reddybv@unb.ca (B.V. Reddy).

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Nomenclature

c	specific heat, J/kg K
c_{sf}	cluster solid fraction
d_p	mean bed particle size, μm
e	emissivity
f	fraction of the wall covered by clusters
g	acceleration due to gravity, m/s^2
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_r	radiation heat transfer coefficient, W/m^2 K
k_c	thermal conductivity of the cluster, W/m K
L_c	cluster characteristic travel length, m
n	cross-sectional average solids volume concentration
Pr	Prandtl number
t_c	cluster residence time, s
T	temperature, K
U_c	cluster descent velocity, m/s
U_t	terminal velocity of bed solid particles, m/s
Y	fraction of particles in the dispersed phase

Greek symbols

α_g	thermal diffusivity of the gas, m^2/s
ε	volumetric void fraction or voidage
ε_{avg}	cross-sectional average voidage at the considered location
δ	non-dimensional gas layer thickness between the wall and cluster
μ_g	dynamic viscosity of the gas, N s/m^2
ρ	density, kg/m^3
ρ_b	bed density, kg/m^3

Subscripts

b	bed
c	cluster
d	dispersed
g	gas
p	particle
w	wall

bed-to-wall heat transfer coefficient in the riser column in a CFB unit. Basu and Nag [2] reviewed the published literature on heat transfer in CFB units and have summarized the mechanistic models as the single-particle, cluster renewal and continuous film models. Noymer and Glicksman [7] reported the experimental investigations on cluster motion and particle convection in a CFB unit. Noymer and Glicksman [8] proposed empirical models to estimate cluster descent velocities in CFB units. He et al. [9] employed fluid dynamic numerical approach to simulate the bed-to-wall heat transfer in a CFB unit along the riser height and has provided some results on the contribution of the particle, gas and radiation in bed-to-wall heat transfer along the riser height in the CFB unit. Reddy [10] has described the fundamental bed-to-wall heat transfer mechanism in a CFB combustor, and presented some results on the effect of operating conditions.

From the available CFB literature, it is observed that good amount of experimental work and modeling has been done on bed-to-wall heat transfer in CFB units. The experimental works have reported the behavior of the phenomena occurring inside the CFBC units from the measured values of heat transfer coefficients. Several mechanistic models have been proposed based on correlations and statistical analysis of the experimental results. These have contributed to the understanding of the heat transfer mechanism in CFB units. Not much information is reported in the published literature (except [9]) on the role of dilute and dense phase operating conditions including bed temperature on the contributions of particle convection, gas convection and radiation contributions in bed to wall heat transfer to water walls in the CFB unit. The heat is transferred to the water-wall tubes to produce steam. Also, not enough information is reported in the literature on the contributions of individual components under dilute and dense phase operating conditions with bed temperature.

The heat transfer mechanism in a CFB combustor depends on the operating conditions namely bed/suspension density and bed temperature. Depending on the operating conditions, the water -wall surfaces located above the secondary air injection in the riser column are exposed to dilute and dense phase conditions. This influences the heat transfer to water-wall surfaces from the combustion products inside the CFB unit. In the present work, the heat transfer mechanism i.e., the contributions of particle convection, gas convection and radiation in bed-to-wall heat transfer and their dependence on dilute and dense phase conditions and on bed temperature are investigated using cluster renewal model. The contributions have been analyzed for dilute and dense phase conditions to get a good perspective of the heat transfer mechanism in the CFB unit under varying load conditions. This also helps to understand particle, gas and radiation heat transfer behavior and contributions in dilute and dense phase conditions. This enhances the understanding of the heat transfer phenomena in the CFB unit. The fundamental understanding of heat transfer in a CFB unit leads to better design of heat transferring surfaces.

2. Heat transfer mechanism

The heat transfer mechanism in a circulating fluidized bed combustor is a complex phenomenon. In the riser column, above the secondary air injection level, the gas–solid flow is typically of core-annulus structure. Near the wall, particles in the form of clusters/agglomerates travel downwards and the gas with few particles will flow upwards in the center of the riser column. The clusters travel downwards near the wall for a certain distance and then disintegrate and again reforming occurs as shown in Fig. 1. The cluster formation, traveling length and residence time depends on bed hydrodynamic conditions. The clusters contribute significantly to the bed-to-wall heat transfer in a CFB unit. Apart from this the dispersed phase, and radiation contribute in bed-to-wall heat transfer. The bed-to-wall heat transfer comprises of heat transfer contributions from clusters, dilute phase and radiation. The time averaged cluster heat transfer coefficient (h_c), is given by Mickley and Fairbanks [11],

$$h_c = \left(\frac{4k_c\rho_c c_c}{\pi t_c}\right)^{0.5} \tag{1}$$

The thermal conductivity of the cluster (k_c) can be estimated from the expression given by Gelperin and Einstein [12]

$$k_c = k_g\left(1 + \frac{(1-\varepsilon_c)(1-k_g/k_p)}{k_g/k_p + 0.28\varepsilon_c^{0.63(k_p/k_g)^{0.18}}}\right) \tag{2}$$

Eq. (2) is valid for $d_p < 0.5$ mm and $k_p/k_g < 5000$.

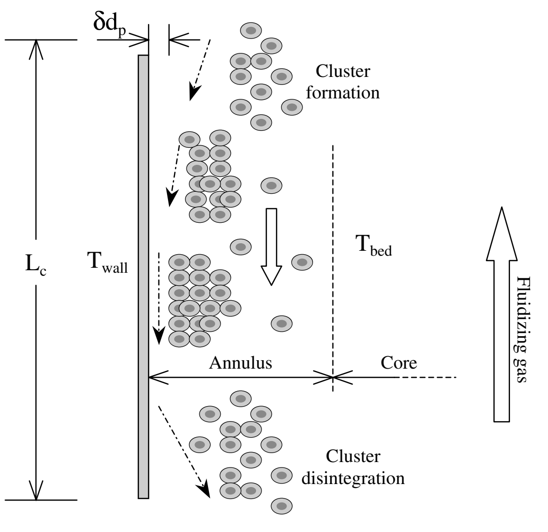

Fig. 1. Schematic of the cluster renewal model.

The specific heat of the cluster (c_c) is given by

$$c_c = (1-\varepsilon_c)c_p + \varepsilon_c c_g \tag{3}$$

The volumetric void fraction of the cluster (ε_c) is estimated from the expression given by Lints and Glicksman [13],

$$\varepsilon_c = 1 - c_{sf} \tag{4}$$

The cluster solid fraction (c_{sf}) is a function of cross-sectional bed average voidage (ε_{avg}) is given as

$$c_{sf} = 1.23n^{0.54} = 1.23(1-\varepsilon_{avg})^{0.54} \tag{5}$$

where n is the cross-sectional average solids volume concentration ($n = 1 - \varepsilon_{avg}$). The cross-sectional bed average voidage (ε_{avg}) is calculated as given below

$$\varepsilon_{avg} = (\rho_b - \rho_p)/(\rho_g - \rho_p) \tag{6}$$

The cluster solid fraction and the number of clusters formed depend on the operating conditions, i.e., dilute and dense phase bed conditions and temperature. The density of the cluster (ρ_c) is estimated using the following relation:

$$\rho_c = (1-\varepsilon_c)\rho_p + \varepsilon_c\rho_g \tag{7}$$

The residence time of the cluster (t_c) in a CFB riser is given as

$$t_c = \frac{L_c}{U_c} \tag{8}$$

Here the cluster descent velocity (U_c) is taken from Glicksman [4] and an average value of 1.26 m/s is used in the model predictions. The characteristic travel length (L_c), (descent) of the cluster in a CFB unit is given by Wu et al. [1],

$$L_c = 0.0178\rho_b^{0.596} \tag{9}$$

A thin gas layer residing between the cluster and wall introduces another resistance. Gloski et al. [14] have shown that the resistances due to cluster and gas gap can be assumed to be in series with each other. The heat transfer coefficient due to conduction through the thin gas layer (between cluster and wall) near the wall of the circulating fluidized bed riser is given by the relation

$$h_w = \frac{k_g}{d_p\delta} \tag{10}$$

where δd_p is the non-dimensional thickness of the gas layer between the wall and the cluster. The expression for δ as given by Lints and Glicksman [13] is used

$$\delta = 0.0282n^{-0.590} = 0.0282(1-\varepsilon_{avg})^{-0.590} \tag{11}$$

The particle convection heat transfer coefficient is calculated as

$$h_p = \frac{1}{\left(\frac{\pi t_c}{4k_c\rho_c c_c}\right)^{0.5} + \frac{d_p\delta}{k_g}} \quad (12)$$

The gas convection heat transfer coefficient to water-wall surfaces is estimated from the Wen and Miller [15] correlation proposed for the dust-laden gas

$$h_g = \frac{k_g c_p}{d_p c_g}\left(\frac{\rho_d}{\rho_p}\right)^{0.3}\left(\frac{U_t^2}{g d_p}\right)^{0.21} Pr \quad (13)$$

where the dispersed phase density (ρ_d) is given by

$$\rho_d = \rho_p Y + \rho_g(1 - Y) \quad (14)$$

The solids fraction in the dispersed phase (Y) is taken a value of 0.001% as suggested by Basu [16].

The radiation heat transfer coefficient is a combination of radiation from the clusters and from the dilute phase. For the clusters, it is given as ([16]),

$$h_{rc} = \frac{\sigma(T_b^4 - T_w^4)}{(1/e_c + 1/e_w - 1)(T_b - T_w)} \quad (15)$$

The radiative heat transfer coefficient for the dispersed phase is given as

$$h_{rd} = \frac{\sigma(T_b^4 - T_w^4)}{(1/e_d + 1/e_w - 1)(T_b - T_w)} \quad (16)$$

The emissivity of the cluster is estimated using the relation given by Grace [17],

$$e_c = 0.5(1 + e_p) \quad (17)$$

The emissivity of the dispersed phase is calculated from the relation given by Brewster [18],

$$e_d = \sqrt{\frac{e_p}{(1-e_p)B}\left(\frac{e_p}{(1-e_p)B} + 2\right)} - \frac{e_p}{(1-e_p)B} \quad (18)$$

$B = 0.5$ for isotropic scattering. The radiative heat transfer coefficient is given by

$$h_r = f h_{rc} + (1 - f)h_{rd} \quad (19)$$

The fractional wall coverage (f) by clusters is given by Lints and Glicksman [13] as

$$f = 3.5n^{0.37} \quad (20)$$

The fractional wall coverage depends on dilute and dense phase operating conditions. Under dilute conditions the wall is covered by few clusters and is exposed mostly to dispersed phase (gas), while under dense phase conditions the wall is covered by more clusters and the value of f in Eq. (20) will be high.

The bed-to-wall heat transfer coefficient in the circulating fluidized bed riser is given by

$$h = h_{conv} + h_{rad} = (f h_p + (1 - f)h_g) + h_r \quad (21)$$

3. Results and discussion

From the described cluster renewal mechanistic model the contributions of particle convection, gas convection and radiation contributions in bed-to-wall heat transfer coefficient in the upper region of the riser column of a circulating fluidized bed combustor are estimated under dilute and dense phase conditions. The results are generated for the operating conditions listed in Table 1. Depending on the solids circulation rate and superficial air velocity (operating conditions), the upper region will be under dilute phase conditions (less particle and more gas) and dense phase conditions (more particles and clusters with less gas). Thus the presence of dilute phase (<10 kg/m^3) and dense phase (20–40 kg/m^3), influences the contributions of particle, gas and radiation contributions in bed-to-wall heat transfer to surfaces located in the CFB unit. At present not much is reported on this in the published literature.

3.1. Convection heat transfer (particle convection and gas convection)

Particle convection depends on the cluster heat transfer contribution and resistance across the gas-gap layer resistance between the clusters and wall (as described

Table 1
Values of operating parameters used in the present model predictions

Bed temperature, T_b (K)	575–1200
Wall temperature, T_w (K)	300–800
Suspension density, ρ_b (kg/m^3)	2–50
Cluster descent velocity, U_c (m/s)	1.26
Bed solid particle (sand) size, d_p (μm)	250
Superficial gas velocity, U (m/s)	6
Emissivity of wall	0.7
Properties of sand	ρ = 2300(kg/m^3), k_p = 0.27 W/m K
	c_p = 800 (J/kg K), e_p = 0.85
	Values taken from property tables [19]

in Eqs. (10) and (12)). The formation of clusters, solids fraction within the cluster, cluster density, gas-gap thickness between cluster and wall depends on bed suspension densities i.e., dilute and dense phase conditions. Apart from this for the same bed (gas–solid suspension) density, the cluster heat transfer and gas-gap resistance depends on gas thermal conductivity, which in turn depends on bed temperature.

Fig. 2 shows the particle convection heat transfer coefficient to bed-to-wall heat transfer coefficient ratio variation with bed suspension density. For the given bed temperature the ratio increases with suspension density due to increased particle convection heat transfer in bed-to-wall heat transfer. This is due to the following reasons: The increase in bed suspension density results in higher cluster concentration near the wall, higher solids fraction within the cluster, resulting in higher cluster heat transfer coefficient values. Also, due to higher bed suspension density, the gas-gap thickness decreases, due to higher clusters concentration near the wall and higher solids fraction within the cluster resulting in reduced gas-gap resistance. More details on this are reported by Reddy [10]. With increase in bed temperature the convection and radiation heat transfer contributions in bed-to-wall heat transfer coefficient increases. Though the particle heat transfer coefficient increases with suspension density and bed temperature, the radiation heat transfer increases at a faster rate, and the ratio of particle convection coefficient to bed-to-wall heat transfer coefficient (fh_p/h) decreases with temperature, due to higher contribution of radiation in bed-to-wall heat transfer coefficient compared to particle convection as demonstrated by Figs. 2 and 3 respectively.

Fig. 4 represents how the cluster descent velocity can influence particle convection in a CFB unit. The particle convection depends on cluster heat transfer and this depends on the velocity at which the cluster descends. The faster the cluster falls, the cluster will be at high temperature (less cooling), higher heat transfer due to particle convection, before the cluster disintegrates. The effect of cluster descent velocity on particle heat transfer coefficient is shown in Fig. 4.

Fig. 5 represents the gas convection to bed-to-wall heat transfer coefficient ratio variation with suspension density. The gas convection component is affected

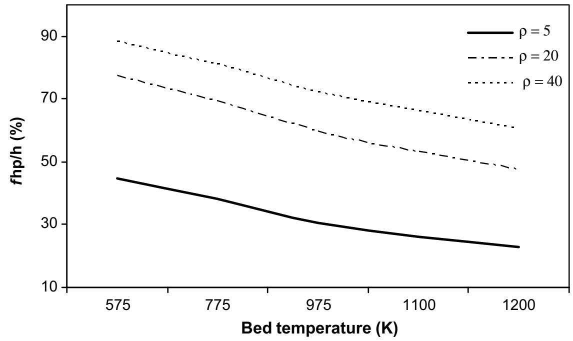

Fig. 3. Particle convection to bed-to-wall heat transfer coefficient ratio vs bed temperature.

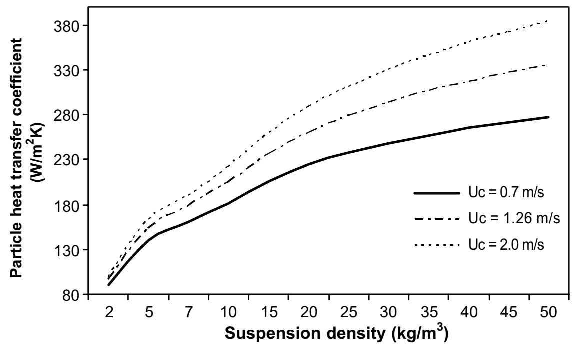

Fig. 4. Effect of suspension density on particle convection heat transfer coefficient for different cluster descent velocities, T_b = 1100 K.

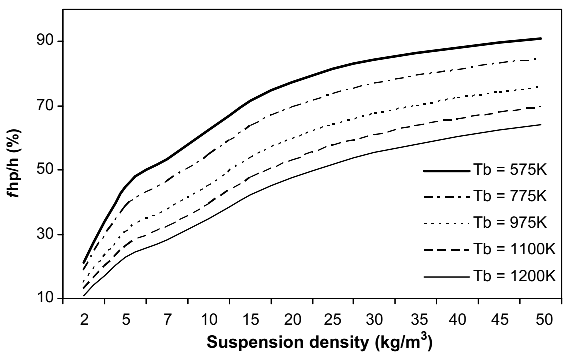

Fig. 2. Particle convection to bed-to-wall heat transfer coefficient ratio variation with suspension density.

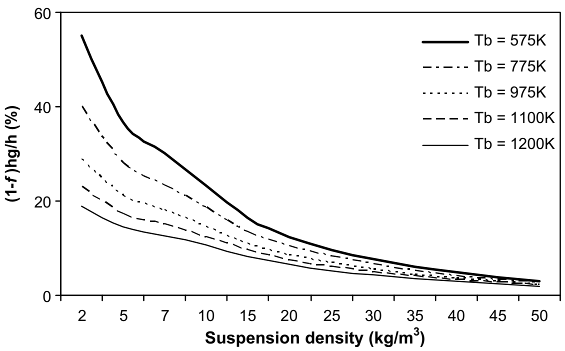

Fig. 5. Gas convection coefficient to bed-to-wall heat transfer coefficient ratio variation with suspension density.

directly by the superficial gas velocity and is also affected by the bed temperature (the gas property changes, Eq. (14)). The contribution of gas convection heat transfer coefficient in bed-to-wall heat transfer coefficient is high under dilute phase conditions as demonstrated by Fig. 5. Under dilute phase conditions the bed-to-wall heat transfer mainly consists of radiation and dilute phase convection with the contribution of particle convection being minimum. The solids fraction in the dispersed phase (Y) is taken a value of 0.001% as suggested by Basu [16] in the model predictions. Fig. 6 shows how the change in the value of Y can affect the gas convective heat transfer in a CFB unit.

The convection heat transfer in the CFB unit depends on the contributions of particle and dilute phase convection components. Under dilute phase operating conditions, the particle concentration is less, the particle convection contribution is less and the gas convection contributes significantly in the bed-to-wall heat transfer as demonstrated by Fig. 7. With increase in bed density, the particle concentration, cluster concentration near the wall increases which enhances particle convection. The gas convection contribution decreases with increase in suspension density and at one point its contribution is going to be negligible. This is due to the fact that near the wall the cluster and particle concentration is so high, the bed-to-wall heat transfer coefficient mainly consists of particle convection and radiation heat transfer contributions. This trend can be used as an approximation in circulating fluidized bed heat transfer models to consider the convection component as pure particle convection for higher bed suspension densities. This information is not reported in the published literature so far.

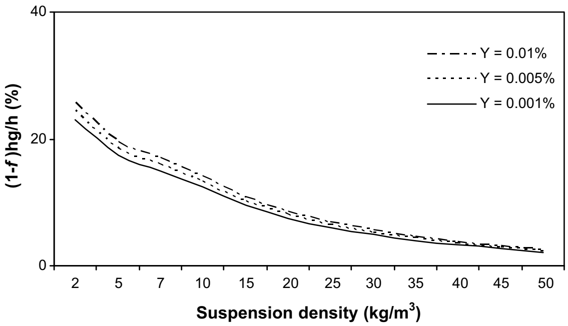

Fig. 6. Effect of solids concentration in the dilute phase on gas convective heat transfer to bed-to-wall heat transfer coefficient ratio, $T_b = 1100$ K.

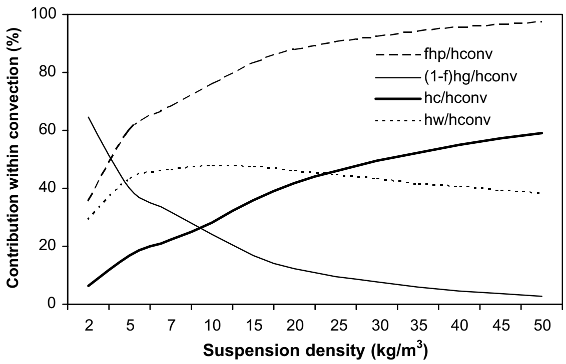

Fig. 7. Contribution of particle and gas convective components in convection heat transfer coefficient, $T_b = 1100$ K.

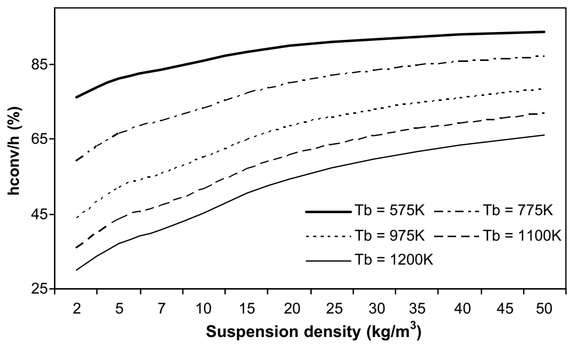

Fig. 8. Convection heat transfer coefficient to bed-to-wall heat transfer coefficient ratio variation with suspension density.

The convection coefficient to bed-to-wall heat transfer coefficient ratio variation with suspension density is demonstrated in Fig. 8. The contribution of convection heat transfer increases with suspension density for the same bed temperature. This is due to increased particle convection with increased suspension density. However, for the same suspension density, with increase in bed temperature, the ratio decreases. This is due the fact that, though particle heat transfer coefficient increases with bed temperature, the radiation heat transfer contribution increases at a faster rate resulting in higher bed-to-wall heat transfer coefficients. At low suspension densities (dilute phase conditions) and at higher bed temperatures (1100–1200 K) the contribution of convection heat transfer is less compared to radiation heat transfer. For the same bed temperature, at higher suspension densities the convection heat transfer coefficient increases due to higher particle convection heat transfer contributions in bed-to-wall heat transfer coefficient.

3.2. Radiation heat transfer

Radiation is another important heat transfer phenomena in a CFB combustor, which influences the bed-to-wall heat transfer coefficient. Radiation depends on furnace walls and the bed temperatures. The emissivities of the wall, clusters, and the dispersed phase (phase in the circulating fluidized bed riser which does not

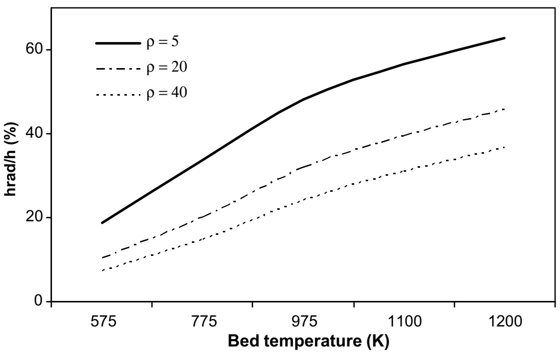

Fig. 9. Radiation heat transfer coefficient to bed-to-wall heat transfer coefficient ratio vs bed temperature.

include the clusters), do affect the radiation heat transfer significantly. Fig. 9 demonstrates the radiation heat transfer coefficient to bed-to-wall heat transfer coefficient ratio variation with bed temperature. As mentioned in the cluster renewal model earlier, isotropic scattering was used to estimate the emissivity of the bed in Eq. (18). The radiation heat transfer coefficient depends on the cluster radiation heat transfer and dispersed phase radiation heat transfer contributions. The radiation heat transfer coefficient contribution in bed-to-wall heat transfer coefficient is dominant at higher bed temperatures and at low suspension densities (dilute phase, <10 kg/m^3). With increase in suspension density, the particle concentration increases, which enhances particle convection heat transfer coefficient in bed-to-wall heat transfer coefficient. Thus at higher suspension densities, the contribution of radiation heat transfer decreases due to the above mentioned reasons, but still contributes significantly. Under dilute phase conditions radiation dominates, contributing (Fig. 9) almost 50–60% in total bed-to-wall heat transfer coefficient.

3.3. Bed-to-wall heat transfer

For a particular solids circulation rate and superficial air velocity (operating conditions), the suspension density is more, above the distributor plate and decreases along the riser height in CFB unit. For the same solids circulation rate, with increase in air velocity more solids are transported along the riser height resulting in higher suspension densities in the upper region of the riser column. Under dilute phase conditions radiation heat transfer dominates in bed-to-wall heat transfer, when compared with particle convection and gas convection components. With increase in suspension density, the contribution of particle convection increases. The gas convection contribution is comparatively low both in dilute and dense phase conditions. He et al. [9] have observed higher particle convection heat transfer to bed-to-wall heat transfer ratios in the bottom region due to higher bed density and the ratio decreases along the height due to reduced suspension density. The radiation heat transfer ratio is low in the bottom region due to higher particle convection, and it increases along the height due to dilute nature of the bed and radiation contribution is maximum in the upper region. He et al. [9] did calculations from the data obtained from a coal-fired circulating fluidized bed boiler, with bed temperatures ranging from 1123 to 1223 K, superficial gas velocity from 5 to 6.5 m/s, and for two different bed particle sizes. He et al. [9] represented the results along the riser height of the CFB unit, where the bottom of the unit has higher bed density and the bed density decreases along the riser height. The present model predictions on percentage variation of particle, gas and radiation heat transfer contributions in bed-to-wall heat transfer coefficient with suspension density are shown in Fig. 10. The present results also show similar trends as reported by He et al. [9]. Under dilute conditions (low densities), the contribution of radiation is dominant and at higher bed densities the contribution of particle convection is significant. The gas convection variation is pretty much same in both the cases, owing to its dependency on temperature and gas velocity as described by Eq. (13).

The load variation in a CFB unit determines the range of suspension densities in the upper region of the riser column. At low operating air velocities the upper region of the riser column will operate in dilute phase and the contribution of radiation and gas convection is higher in bed-to-wall heat transfer. Under dense phase conditions the particle convection and radiation contribution is significant with bed temperature as shown in Fig. 11. The percentage contribution of different heat transfer components for two bed suspension density cases (5 and 20 kg/m^3) are represented in Fig. 11. This gives a better picture of the heat transfer mechanism under varying load conditions (dilute and dense phase conditions) in the upper region of the CFB riser column.

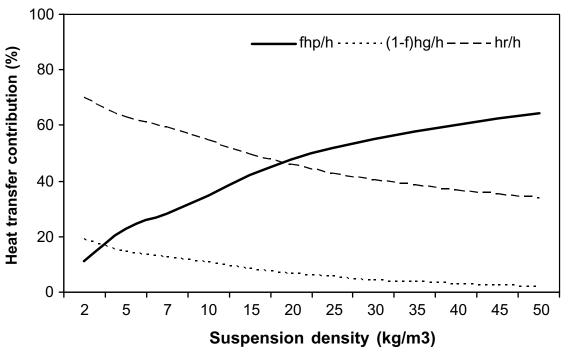

Fig. 10. Particle, gas and radiation heat transfer contribution in bed-to-wall heat transfer with suspension density; model predictions from the present work, $T_b = 1100$ K.

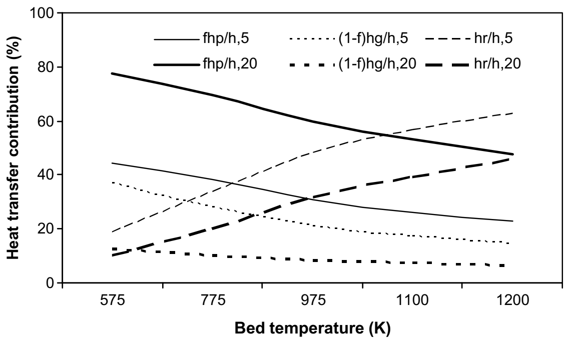

Fig. 11. Heat transfer contributions (ratios) with bed temperature under varying load conditions in the upper region of the CFB combustor.

4. Conclusion

In a CFB combustor the bed-to-wall heat transfer coefficient depends on particle convection, gas convection and radiation heat transfer contributions. They in turn depend on the operating conditions i.e., dilute and dense phase and bed temperature. The clusters contribute more in particle convection in the dense phase conditions and their contribution in the dilute phase is low because of less number of clusters formation and reduced cluster solids fraction. The gas convection contributes in dilute phase conditions than in the dense phase conditions. The radiation contribution is dominant in the dilute phase conditions and at higher bed temperatures. The relative contributions of particle convection, gas convection and radiation heat transfer are different along the combustor height due to variation in suspension density in the CFB unit. Under dilute phase conditions in the upper region of the riser, radiation heat transfer dominates than particle convection and gas convection in bed-to-wall heat transfer coefficient. Gas convection contribution in bed-to-wall heat transfer coefficient is also significant. In the upper region under dense phase conditions, the particle convection contributes significantly in bed-to-wall heat transfer coefficient apart from radiation. The present work provides some fundamental details to understand the heat transfer mechanism under dilute/dense phase conditions in the upper region, which occurs due to load change (control) situations in the riser column of a CFB combustor.

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