# A MODEL OF HEAT TRANSFER IN A CIRCULATING FLUIDIZED BED COMBUSTOR

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*Abstract: the developed model is based on simplified cluster renewal concept and recent developments in hydrodynamics studies. The research work has been focused to develop the suspension-to-wall heat transfer model. In order to measure accuracy with real systems, the model was tested through experimental investigations in a specially designed fluidized bed combustor. The obtained results were compared with the model. The model predictions showed a good agreement with the present experimental data. Empirical correlations were also developed for axial as well as redial heat transfer coefficient.*

## 1. INTRODUCTION

Technical knowledge about design and operation of CFB (circulating fluidized bed) combustor is widely available but little has been done in the field of mathematical modeling of heat transfer in CFBC's. In order to explain heat transfer in circulating fluidized beds and predict heat transfer coefficient, several models have been proposed. However, In order to improve the optimization and control of CFB combustor and to predict heat transfer coefficient precisely, accurate real time model is required to describe it clearly [17].

Several mechanistic models have been proposed to explain this heat transfer in CFBC. [4] and [8] have presented complete reviews on heat transfer studies. A simple and reliable prediction of heat transfer to the wall of a CFBC, based on dimensional analysis has also been looked by many other researchers [14,18,15].

[13] has presented a model for suspension to wall heat transfer coefficient based on simplified cluster renewal concept and recent developments in hydrodynamics studies, including the effects of radiative heat transfer. Therefore, this model has been modified and tested for the present research to increase the accuracy of the model by the development of empirical correlations.

## 2. GENERAL ASSUMPTIONS OF THE MODEL

The following assumptions were made during the development of suspension–to–wall heat transfer in a CFB .

1. Riser of CFB consists of clusters and disperse phase.
2. Heat transfer from suspension-to-wall takes place by renewed contact of clusters and the dispersed phase on the wall;
3. Particles flow downward along the riser wall for a distance 'L' which has been named as thermal contact length of clusters at the wall;
4. The velocity of a cluster is constant;
5. Temperature gradient in the axial direction is negligible.
6. Temperature varies in the radial direction.

## 3. MODEL FORMULATION

As per assumption of the model, mathematically it can be presented as follows:

$$\left(\begin{array}{l} h_t = h_{conv} + h_{radiative} \\ h_t = (h_{solid} + h_{gas}) + h_r \\ h_t = h_{(solid + gas)} + h_r \\ h = fhp + (1-f)\, hg + hr \end{array}\right) \qquad (1)$$

Above equations are similar to the expressions of [4].

In the present model, particle convective and radiative heat transfer coefficient consisted of the clusters and dispersed phase so the above equation can be written as:

$$h = fh_{wc} + (1-f)\, h_d + f\,(h_{wcr} + (1-f)\, h_{dr} \qquad (2)$$

In the above co relations, "f" is the fraction of the wall covered by the clusters in contact with heat transfer surface and (1-f) be that of dispersed phase contacting with heat transfer surface.

In order to estimate "f" the following correlation [12] was used:

$$f = 3.5\, c^{0.37} \qquad (3)$$

Where "c" is the average volume fraction of the solid.

[2] has shown that radiative heat transfer due to clusters and the dispersed phase are the same i.e. $h_{wcr} = h_{dr} = h_r$.

Hence,

$$h = fh_{wc} + (1 - f)\, h_d + h_r \qquad (4)$$

A description of the individual heat transfer components in equation (4) is given below:

### a. CONVECTIVE HEAT TRANSFER COEFFICIENT OF PARTICLE CLUSTERS

A number of models have been proposed to describe the particles convective heat transfer coefficient in details. These models can be classified as: (1) the single particle model (2) the gas solid homogenous model (3) cluster renewable model.

[1] considered a gas resistance between the wall and clusters in calculating the convective heat transfer coefficient:

$$h_{wc} = \frac{1}{R_w + \frac{1}{h_w}} \qquad (5)$$

Where “$h_w$” is the effective heat transfer coefficient for unsteady state heat transfer in the homogenous semi-infinite medium. “$R_w$” is the resistance offered by the gas.

Where

$$h_w = \sqrt{\frac{4\rho_e k_e c_{pe}}{\pi t_r}} \tag{6}$$

And

$$C_{pe} = C_{pp}\,(1 - \varepsilon_{ww}) + C_{pg}\,\varepsilon_{ww} \tag{7}$$

“$C_{pp}$” and “$C_{pg}$” are the heat capacities of the particles and the fluidizing gas respectively.

$$\rho_e = \rho_p\,(1 - \varepsilon_{ww}) + \rho_g \varepsilon_{ww} \tag{8}$$

Where “$\varepsilon_{ww}$” is voidage near the wall, and can be estimated from [16]:

$$\varepsilon_{ww} = \varepsilon_{av}^{3.81} \tag{9}$$

“$\varepsilon_{av}$” is the average cross- sectional voidage estimated from the measured pressure drop along CFB column [14].

$$\varepsilon_{av} = 1 - \frac{1}{g\rho_p}\left(\frac{\Delta P}{\Delta L}\right) \tag{10}$$

Where “$\Delta P$” is the differential pressure and “$\Delta L$” is the distance between the pressure tappings.

The effective thermal conductivity of the clusters $k_e$ was estimated by [7]:

$$k_e = \left[k_g\left\{1 + \frac{(1-\varepsilon_{ww})\left[1-(k_g/k_p)\right]}{(k_g/k_p) + 0.28\varepsilon_{ww}^{0.63(k_p/k_g)^{0.1x}}}\right\}\right] \tag{11}$$

Where “kg” and “kp” are thermal conductivity of gas and particles.

The contact time or residence time of cluster ($t_r$) on the wall can be calculated by the following relation:

$$t_r = \frac{L}{U_s} \tag{12}$$

However, this expression does not clearly predict characteristics length. A good approximate value of ‘‘L” has been taken by the researchers. [20] found a good correlation of measured values with the predicted ones when the value of L was 10 times then calculated from the above equation.

It is assumed that clusters move downward on the wall for a distance ‘‘L” before leaving the heat transfer surface. [19] correlated their results using two instantaneous heat transfer probes in a smooth wall column and suggested there existed a characteristic residence length at the wall for clusters. They estimated that at room temperature, in a smoothed wall column (0.152m i.d), the characteristic length was proportional to cross sectional average suspension density.

The clusters after traveling a certain distance dissolve or detached from the wall of the heat transfer surface. Then they are replaced by new ones. So, detailed measurements of cluster velocities, their voidage and characteristics length of travel “L” are necessary. [19], by using two heat transfer probes showed that this “L” may be correlated with the cross sectional average suspension density $\rho_s$ in a 0.152 m ID CFB combustor as follows.

$$L = .0178\,\rho_s^{0.596} \tag{13}$$

The contact resistance between the cluster and the riser wall “$R_w$“can also be expressed as a resistance offered by a gas gap of thickness $d_p/n$ as

$$R_w = \frac{d_p/n}{K_g} \tag{14}$$

Hence the particle convective component in equation 5 becomes:

$$h_{wc} = \left[\frac{1}{\dfrac{d_p/n}{K_g} + \sqrt{\dfrac{\pi\left(C d_p \rho_{susp}^{0.596}\right)}{4\rho_e K_e C_{pe} U_s}}}\right] \tag{15}$$

## b. CONVECTIVE HEAT TRANSFER COEFFICIENT OF THE DISPERSED PHASE

From earlier observations, it is clear that in the furnace of CFB the wall surface is in contact with either a dispersed phase or clusters. So, in these observations the correlation of [10] can be used for estimating heat transfer coefficient in the dilute phase as follows.

$$hd = \left(\frac{\mu_g C_{pp}}{d_p}\right)\left(\frac{\rho_{dis}}{\rho_p}\right)^{0.3}\left(\frac{Ut^2}{g_{dp}}\right)^{0.21} \tag{16}$$

Where “Ut” is the terminal velocity

## c. RADIATIVE HEAT TRANSFER COEFFICIENT

The radiative heat transfer coefficient can be calculated by the following general expression.

$$h_r = \frac{\sigma\left(T_b^{-4} - T_w^{-4}\right)}{\left(1/\varepsilon_{susp} + 1/\varepsilon_w - 1\right)\left(\bar{T}_b - \bar{T}_w\right)} \tag{17}$$

Where σ =Stefan–Boltzmann constant,

5.667 × $10^{-8}$ W/$m^2$ $K^4$

$\bar{T}_b$ = Temperature of the gas – particle suspension, K

$\bar{T}_w$ = Riser wall temperature of the wall, K $\varepsilon_{susp}$ = Emissivity of gas-particle suspension

$\varepsilon_w$ = Emissivity of riser wall surface, the value was assumed to equal to 0.73

[11] has approximated the emissivity of the gas-particle by the following correlations by using multiple reflection of particle.

$$\varepsilon_{susp} = 0.5(1+\varepsilon_p) \tag{18}$$

Where “$\varepsilon_p$” is the emissivity of particles.

This method of heat transfer was also proposed by [3] with different methods of estimating the suspension and surface wall emissivity.

## 4. MODEL COMPARISON WITH THE PRESENT EXPERIMENTAL DATA

The model formulated has been tested with present findings at different operating conditions and for 0.61 m heat transfer surface length and is shown in the figures (1-8) respectively. Model predictions and experimental results of the variation of heat transfer coefficient with suspension density at temperature of 600°C and 750°C. It can be noticed that in both cases, the predicted and measured heat transfer coefficients increased with suspension density. Agreement between model prediction and experimental results is very encouraging. Results shown in figures (3) and (4) give the comparison of model prediction and experimental results of the variation in heat transfer coefficient with high bed temperature. It is obvious from the results that there is a direct relationship between model prediction and measurement of heat transfer coefficients.

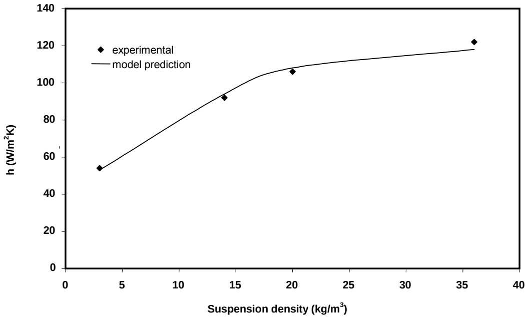
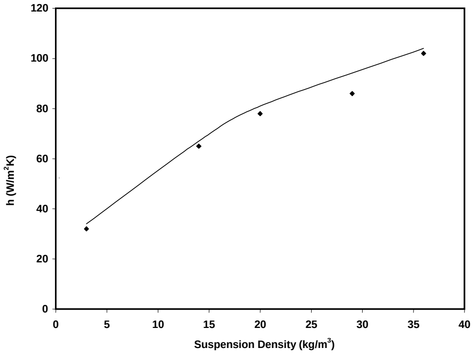


Fig (1):Comparison of model prediction and experimental results
(Tb =750 $^{o}$C, U =5 m/s)



Fig(2): Comparison of model prediction and experimental results(Tb=700$^0$C,U=5 m/s)

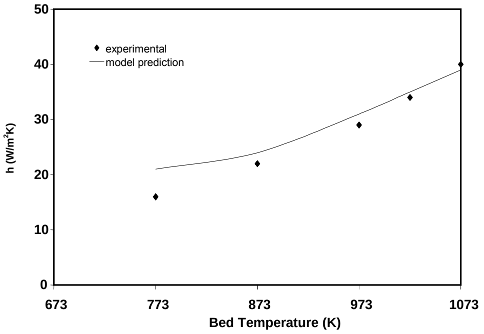


Fig.(3):Comparison of moel prediction and experimental results
(suspension density=20kg/m$^3$, U=5 m/s)

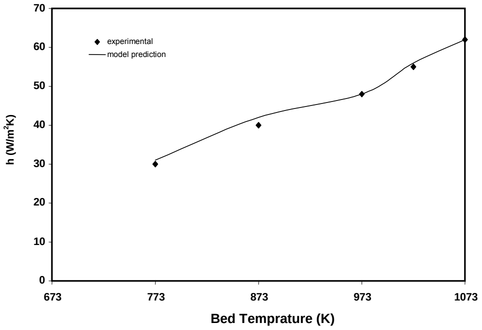


Fig.(4):Comparision of model prediction and experimental results
(suspension density =10 kg/m$^3$ U=4.6m/s)

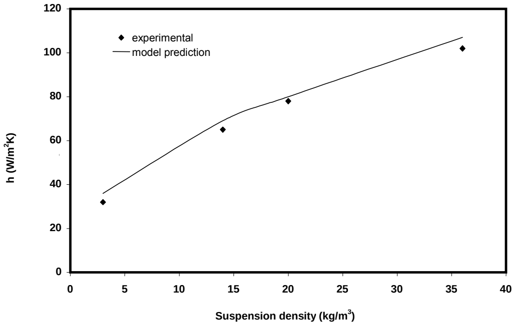


Fig.(5):Comparison of model prediction and experimental results

(Tb=700$^{o}$ C, U =5 m/s, heat transfer surfeace length =0.61 m)

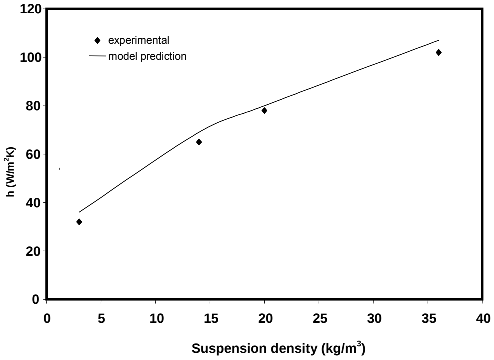


Fig.(6):Comparison of model prediction and experimental results
(Tb=700$^0$C, U =5 m/s, heat transfer surfeace length =0.61 m)

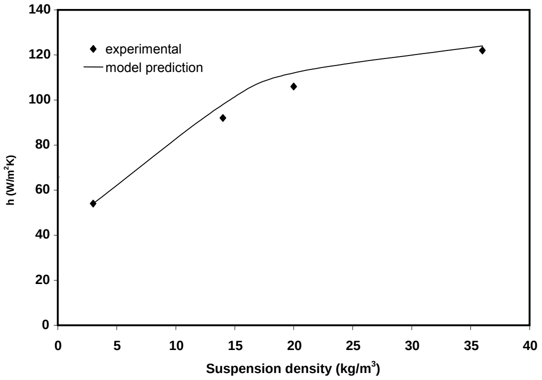


Fig.(7):Comparison of model prediction and experimental results
(Tb=750$^0$C, U=5 m/s, heat transfer surface length=0.61 $\overset{o}{m}$)

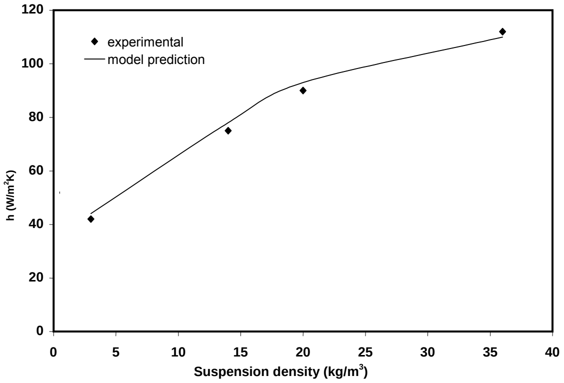


Fig.(8):Comparison of model prediction and experimental results
(Tb =600° C ,U =4.6 m/s,heat transfer surface length=0.61 m)

## 5. DEVELOPMENT OF EMPIRICAL CORRELATION

Suspension density is established as the most important factor influencing the heat transfer coefficient in CFBC. Particle size, bed temperature and varying heat transfer surface length are other important parameters to be considered in the heat transfer studies. Suspension density is again related to other key-parameters like superficial gas velocity, solid circulation rate, particle density, particle size distribution, gas density and viscosity. Therefore, many investigators [8,2,6,13] have taken suspension density as the most important parameters in their studies and in there correlations.

In present study, the same approach has been employed to develop an empirical correlation by correlating the parameters h, $\rho_{susp}$ , and $k_g$ in a fundamental relationship as follows.

$$h = \alpha \rho_{susp}^{a} k_{g}^{b} \tag{19}$$

Where h = heat transfer coefficient, W/m$^2$ K

$\rho_{susp}$ = Suspension density, kg/m$^3$

kg = Thermal conductivity of fluidizing gas, W/m k

$\alpha$, a and b are constants.

For radial heat transfer coefficient the correlation can be written as same as that of [13]:

$$h = 73.83\ \rho_{susp}^{0.4} k_{g}^{0.155} \tag{20}$$

However, the deviation is about 4 – 7% in the present model. Using the present experimental data of heat transfer coefficient variation with suspension density and temperature, the average value of slopes ‘a’ and ‘b’ were computed to be 0.5 of 0.163 respectively. The value of $\alpha$ was found to be 93.52 and for axial heat transfer coefficient the modified relation can be written as:

$$h = 93.52\ \rho_{susp}^{0.5} k_{g}^{0.163} \tag{21}$$

The predicted results from equations (20-21) were compared with the experimental results and were found to be in good agreement. The applicable range of this correlation was found to be: T = 600 -750$^0$C, U = 4.6 – 5.2 m/s and particle diameter of 125 µm. The results are shown in figures (9-14).

## 6. CONCLUSION

The modified model was based on the cluster renewal concept. It was consisted of contribution of convective and radiative heat transfer by clusters as well as dispersed phase. The present experimental results were tested in this modified model. Model predictions were found to be in good agreement with the heat transfer coefficient measurements in CFB system for various ranges of suspension density, bed temperature, particle size at the heat transfer surface length of 0.61m.

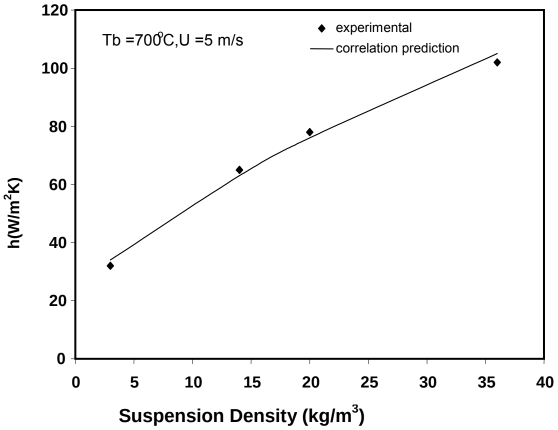


Fig.(9): Comparison of experimental and predicted results

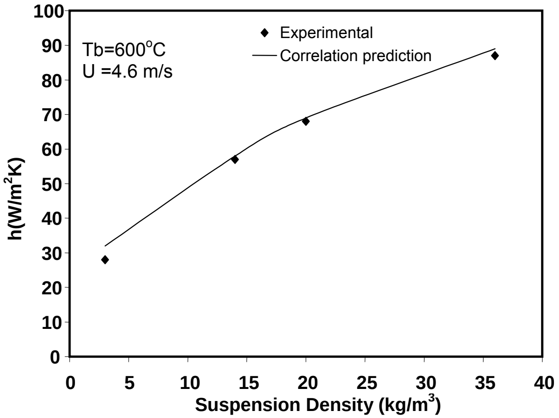


Fig.(10): Comparison of experimental and predicted results

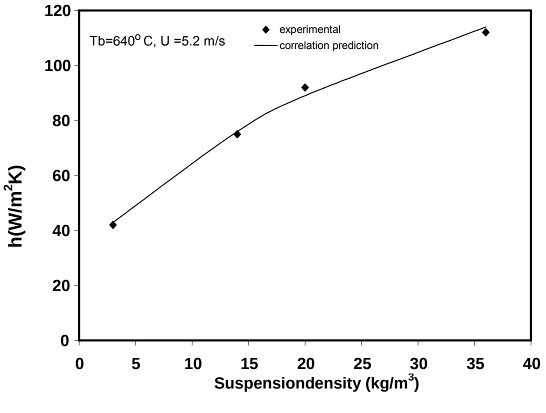


Fig.(11) Comparison of experimental and predicted results

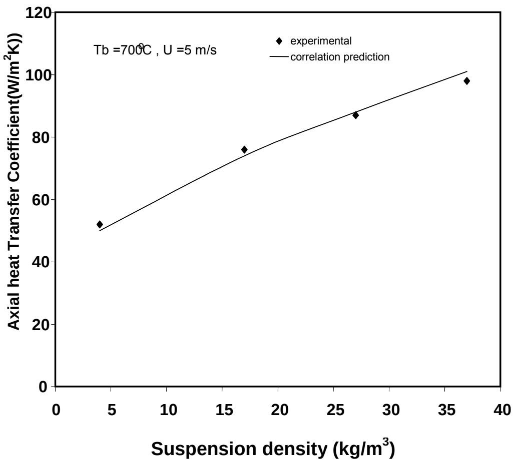


**Fig.(13):Comparison of experimental and predicted results**

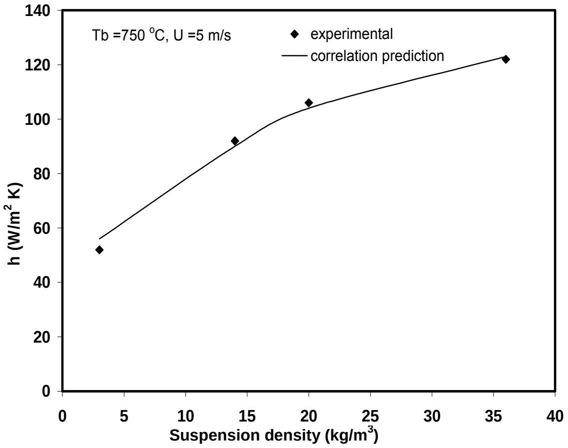


**Fig.(12) Comparison of experimental and predicted results**

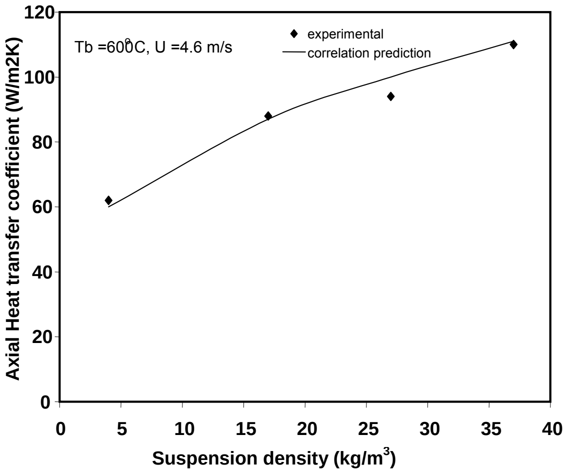


**Fig.(14):Comparison of experimental and predicted results**

## REFERENCES

1. Baskakov, A. P, Berg, B. V, Vit, O. K, Filipovsky, N. F, Kirakosyan, V. A, Goldobin, J. M. and Maskaev, V. K. (1973) “Heat Transfer to Objects Immersed in Fluidized Beds” Powder Technology, 8, 273 - 282.
2. Basu, P and Nag P. K. (1987) “An Investigation into Heat Transfer in Circulating Fluidized Beds” Int. J. Heat Mass Transfer 30 (11) 2399 - 2409. s
3. Basu, P. and Kounche F. (1988), “Radiative Heat Transfer from a Fast Fluidized Bed” Circulating Fluidized Bed Technology II, P. Basu and J. F. Large (Eds.), Pergamon Press, 245 - 253.
4. Basu, P. and Nag, P. K. (1996) “Heat Transfer to the Walls of a Circulating Fluidized Bed Furnace A Review” Chern. Eng. Science 51 (1) 1 - 26.
5. Basu. P. (1999) “Combustion of Coal in Circulating Fluidized Bed Boilers A Review”. Chemical Engineering Science 54, 5547-5557
6. Ebert T. A., Glicksman L. R and Lints M. (1993) “Determination of Particle and Gas Convective Heat Transfer Components in a Circulating Fluidized Bed, Chern. Eng. Science, 48 (12) 2179 - 2188.
7. Gelperin N. I. and Einstein V. G. (1997) “Heat transfer in fluidized beds”. In Fluidization eds J. F. Davidson and D. Harrison Academic Press .London p. 471.
8. Glicksman L. R. (1988) “Circulating Fluidized Bed Heat Transfer” In Circulating Fluidized Bed Technology II P. Basu and J. F. Large (Eds.) Pergamon Press Oxford 13 - 29.
9. Glicksman LR & Hyre MR (1994) “Scaling of Bed-to-Wall heat transfer in Circulating Fluidized Bed” In AIChE Conference San Francisco, 334-347.
10. Golriz MR and Sunden B (1995) “An analytical empirical model to predict heat transfer coefficient in Circulating Fluidized Bed Combustors” Journal of Heat and Mass Transfer 30(7), 377-383.
11. Grace J. R. (1982) “Fluidized Bed Heat Transfer” In Handbook of multiphase Flow Hestroni G. (Eds.) Mcgraw-Hill Hemishere, Wasington DC 9 - 70.
12. Lints M. C. and Glicksman L. F. (1994) “Parameters governing particle-to-wall heat transfer in a circulating fluidized bed” In Circulating Fluidized Bed Technology IV (Edited by A. Avidan) pp. 297-304. AIChE New York.
13. Munir A. (1996) “Heat Transfer Studies in a Circulating Fluidized Bed” A Ph.D. Thesis University of Leeds U.K.
14. Nag P. K. and AIi M. S. (1992) “Effect of Operating Parameters on Bed-to-wall heat transfer in a high temperature circulating fluidized bed” lnt. J. of Energy Research 16 61 -73.
15. Nag P.K. and Moral M. N. A. (1991) “Prediction of Heat Transfer in Circulating Fluidized Bed”. In Circulating Fluidized Bed Technology III, P. Basu, M. Haria and M. Hasatani (Eds.) Pergamon Press Oxford 253 - 261.
16. Tung, Y.Li, J and Kwauk, M. (1988) “Radial Voidage Profile in Fast Fluidized Beds” In Fluidization 88, M. Kwauk and Kunii (Eds.), Science Press, Beijing, 139-145
17. Turton R, Huang Y & Perviz F (2006) “Dynamic model of the riser in circulating fluidized bed” Powder Technology 163 ,23-31

18. Wirth K. E. (1995) “Heat Transfer in Circulating Fluidized Beds” Chem. Eng. Science 50 (13), 2137 - 2151.
19. Wu R. L, Grace J.R and Lim C.J. (1990) “A model for heat transfer in circulating fluidized bed” Chem. Eng. Science 45 (12) 3389-3398.
20. Wu, R. L., Grace, J.R and Lim, C.J., (1990b) “A model for heat transfer circulating fluidized beds” Chemical Energy Science 45, 3389-3398.