2007 ECI Conference on The 12th International Conference on Fluidization - New Horizons in Fluidization Engineering
Vancouver, Canada
Editors: Franco Berruti, The University of Western Ontario, London, Canada
Xiaotao (Tony) Bi, The University of British Columbia, Vancouver, Canada
Todd Pugsley, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

Year 2007 *Paper* 30

Radiation Heat Transfer in Circulating Fluidized Beds

Leon R. Glicksman*

*Massachusetts Institute of Technology

Radiation Heat Transfer in Circulating Fluidized Beds

Abstract

Prediction of heat transfer between bed walls and adjacent clusters is a challenging problem especially for heat temperature applications. Radiation heat transfer is an important component. An accurate analysis must account for the radiation interactions between elements of the cluster at different distances from the wall. A new model that properly accounts for conduction and radiation within the cluster is compared to several mechanistic models from the literature. Substantial discrepancies are found, requiring a better understanding of the cluster physical behavior at the wall.

RADIATION HEAT TRANSFER IN CIRCULATING FLUIDIZED BEDS

Leon R. Glicksman
Massachusetts Institute of Technology, Cambridge, MA, U.S.A.

ABSTRACT

Prediction of heat transfer between bed walls and adjacent clusters is a challenging problem especially for heat temperature applications. An accurate analysis must account for the radiation interactions between elements of the cluster at different distances from the wall. A new model that properly accounts for conduction and radiation within the cluster is compared to several mechanistic models from the literature. Substantial discrepancies are found, requiring a better understanding of the cluster physical behavior at the wall.

INTRODUCTION

Circulating fluidized beds used for combustion include water cooled walls. Accurate estimation of the heat transfer coefficient at the walls is essential to proper bed design and operation. There are a very limited number of experimental results are available for high temperature commercial sized reactors, Glicksman, (1). Available prediction models range from empirical correlations to more mechanistically based approaches. While the former are useful when confined to the range of conditions fit by the existing data, their extrapolation to conditions outside this range is questionable. Mechanistic models appear to be more useful for this case. Such models need to be evaluated in terms of the physical structure and assumptions as well as the sensitivity of parameters used in the models.

Most mechanistic models consider separately heat transfer to wall surfaces covered by denser emulsion layers or clusters and surfaces free from the emulsion. This paper will focus on the heat transfer between clusters and wall. Although there are a proliferation of models that contain different structures and assumptions, most authors have managed to find reasonable agreement with experimental data. It is not the purpose of this work to establish the "best model". Rather, it is hoped that the distinguishing differences and the identification of the most controlling and sensitive parameters will provide fertile avenues for future researchers.

Heat Transfer Models

The overall bed to wall heat transfer coefficient is the sum of heat transfer to the wall fraction covered by clusters, f, and the wall fraction left uncovered, 1-f.

$$h_{overall} = fh_c + (1-f)(h_g + h_{r\_bare}) \quad (1)$$

where h_c is the heat transfer coefficient under the cluster and h_g and $h_{r\text{-}bare}$ represent gas convection and a linearized radiation term, respectively, for the bare surface area. There are two general mechanistic models that have been developed for the cluster to surface heat transfer. The first is based on the renewal model by Mickley (2). The walls are periodically covered by clusters or waves that move along the wall for a short time period, less than a second, and then depart, possibly due to aerodynamic forces. The cluster is assumed to be a uniform continuum with an effective conductivity and heat capacity. The cluster cools by transient heat transfer throughout the cluster. If the cluster thickness is greater than the depth of transient thermal penetration from the wall, the solution for a semi-infinite solid can be applied. Experiments by Lints (3) have shown that there is a thin gas layer that separates the cluster and wall setting up an additional resistance to heat transfer between the cluster and wall.

Opaque Cluster Renewal Model

Assuming that the cluster is opaque so that radiation only plays a role at its surface, the cluster renewal model can be expressed as a transient heat transfer problem,

$$\frac{\partial T(x,t)}{\partial t} = \alpha \frac{\partial^2 T(x,t)}{\partial x^2} \quad with \quad T(x,0) = Tbed; \quad (2)$$

$$at\ x = 0 \quad \frac{\partial T(0,t)}{\partial x} = \frac{h_{wall} + h_{r\_wall}}{k_e}\left[T(0,t) - Twall\right] \quad at\ x \to \infty \quad \frac{\partial T(x,t)}{\partial x} = 0$$

where $\alpha = \dfrac{k_e}{\rho_p \varepsilon_c c_p}$ with ε_c the solid fraction in the cluster and k_e the effective conductivity of the solid -gas combination in the cluster. The latter can be closely represented by the relationship given by Gelperin and Einstein (4),

$$\frac{k_e}{k_g} = 1 + \frac{\varepsilon_c(1 - k_g / k_p)}{k_g / k_p + 0.28(1-\varepsilon_c)^{0.63(k_p/k_g)^{0.18}}} \qquad (3)$$

The wall heat transfer coefficients are given by,

$$h_{wall} = \frac{k_g}{\delta d_p} \quad and \quad h_{r-wall} = 4\sigma\left[\frac{T_{wall} + T_{bed}}{2}\right]^3 \qquad (4)$$

In this case the wall has been assumed to be a black body as has the cluster surface. The gas layer thickness has been found by Lints based on a limited number of experiments as,

$$\delta = 0.0282c^{-0.590} \qquad (5)$$

and Lints fitted the cluster solid volume fraction to the cross-section average solids volume fraction,c, as

$$\varepsilon_c = 1.23c^{0.54} \qquad (6)$$

This model has been applied to the upper portion of the risers of circulating beds by Subbarao (4), Glicksman (1), and Basu (5) among others.

Gloski (6) has shown that the solution to equation 2 can be closely approximated for very low as well as longer contact times by two resistances in series, the resistance of the wall layer plus the effective resistance to transient conduction through the emulsion. The resultant expression for h_c is,

$$h_c = \left[\frac{1}{h_H} + \frac{1}{h_{wall} + h_{r\_wall}} \right] \tag{5}$$

where the effective emulsion resistance comes from the solution for the average conduction from a semi-infinite body with a mean cluster residence time τ ,

$$h_H = 2\sqrt{\frac{k_e \rho_p c_p \varepsilon_c}{\pi \tau}} \tag{6}$$

Opaque Continuous Particle Exchange

Golriz (7) has presented a newer mechanistic model for the portion of the wall covered by clusters. The heat transfer is composed of the wall resistance, similar to the term in equation 5, in series with two resistances that represent the radiation from the core of the riser to the outer surface of the cluster and a term for the continuous flux of solids from the core to the cluster. The latter term is $1/Gc_p$ where G represents the solids flux per unit area from the core to the cluster surface. Resistance due to conduction through the emulsion and any transient effects are omitted in the Golriz model. This implies that the cluster is narrow enough to negate this resistance or that the continuous incoming flux is rapidly mixed with the cluster material to reach a uniform emulsion temperature. Xie (8) proposed a model including elements of both of the above. Particle and gas temperatures are allowed to vary across the cluster width and along the flow direction as they moved along the wall. The variation in the flow direction is directly analogous to a transient analysis in the emulsion renewal. The particles throughout the wall layer are assumed to exchange mass continuously with the core. This model of the fluid dynamics seems most appropriate for very dilute wall regions where particles can move laterally through the wall layer with little hindrance.

Semi-transparent Cluster

Observations suggest that the cluster are composed of particles that spaced apart so that radiation can be transmitted through several layers of particles beforebeing fully absorbed. Xie used the 2-flux model to account for radiation. This contains the restrictive assumption that the intensity of radiation is uniform for the radiation in the two hemispheres: streaming toward and away from the wall, respectively. We will consider the more accurate solution assuming only that the cluster is a medium that is uniform and continuous, scattering is neglected, with an one dimensional temperature gradient within the cluster normal to the wall. For simplicity the wall and the particles within the bed interior will be assumed to be black bodies.

The emulsion is characterized by an absorption coefficient,

$$K = \frac{3\varepsilon_c}{2d_p} \tag{7}$$

and one mean free path y_{free} corresponds to Ky_{free} of unity. For typical cluster densities, y_{free} is of the order of the cluster width W.

The transient heat transfer within the cluster can written as,

$$\frac{\partial T(x,t)}{\partial t} = \alpha \frac{\partial^2 T(x,t)}{\partial x^2} - \frac{dq_r}{dx} \qquad (8)$$

$$Initial \quad condition: \; T(x,0) = Tbed$$

$$at \;\; x=0 \;\; \frac{\partial T(0,t)}{\partial x} = \frac{h_{wall}}{k_e}\left[T(0,t) - Twall\right] \; and \; at \;\; x = W \;\; \frac{\partial T(x,t)}{\partial x} = 0$$

The radiation emitted by the wall is not absorbed at the boundary; rather it is absorbed within the emulsion. The solution must include that for the radiant flux q_r which varies through the cluster and is a function of the emulsion temperature. dq_r/dx is the difference between emitted and absorbed radiation at a point within the emulsion. It is determined as,

$$\frac{dq_r(x,t)}{dx} = K\left[4\sigma T(x,t)^4 - G(x,t)\right] \qquad (9)$$

where G(x,t) represent the incoming radiation from all directions arriving at a point. It is given as,

$$\begin{aligned} G(x,t) &= 2\left[\sigma T_{wall}{}^4 E_2(Kx) + \sigma T_{Bed}{}^4 E_2(K(W-x)\right] + \\ &+ 2K\left[\int_0^x \sigma T(x')^4 E_1(K(x-x')dx' + \int_x^W \sigma T(x')^4 E_1(K(x'-x)dx'\right] \end{aligned} \qquad (10)$$

The exponential integrals, $E_n(x) = \int_1^\infty e^{-xt}\frac{dt}{t^n}$, arise from consideration of radiation incoming from all hemispherical directions. The solution of equation 8 combined with equations 9 and 10 for the radiation contribution is formidable. In the past, some investigators assumed a temperature distribution through the emulsion thickness, Hua (9). However, the temperature distribution is not know and in general varies over time. In the present work, the temperature distribution and radiative flux are found by a method of successive iterations. The temperature solution of the emulsion is used to determine $dq_r(x,t)/dx$ at given interval of x and t. These values are then used in equation 8 to determine the temperature distribution for the next iteration. The process converges rapidly.
The net radiation exchange with the wall is determined from

$$q_{wall} = -\sigma T_{wall}{}^4 + 2\sigma T_{Bed}{}^4 E_3(KW) + 2K\int_0^W \sigma T(x')^4 E_2(Kx')dx' \qquad (11)$$

RESULTS

The three major models will be compared, the simplified cluster renewal, equation 5, the Golritz continuous particle exchange model and the semi transparent cluster model, equation 8. To compare the models with equivalent average solids flux to the wall, when the fraction of the wall area covered by clusters, f, remains the same, G, the mass flow to the wall, can be related to τ, the residence time, and W, the cluster thickness, as,

$$G = \varepsilon_c \rho \frac{W}{\tau} \qquad (12)$$

For all three models the Lints relationship for δ and ε_c as a function of cross section averaged solids concentration, C, will be used along with equation 4 for the wall heat transfer coefficients. Initial values of the parameters are typical of those for a large combustor riser. Tbed is taken as 1100K,Twall is 800K, the cross-sectional average, solids conc.is 0.002, dp is 150 μm, the solids density is 2500 kg/m^{3,} the cluster thickness, W is 2mm, δ is 1.1dp and ε_c is 0.043.

Figure 1 shows the results of the predicted temperature distribution across the cluster thickness for two different times 0.1 and 0.5 seconds after the cluster contacts the surface. The continuous exchange model, which is a steady state model, shows no variation either temporally or spatially. Figure 2 compares the time averaged heat transfer coefficients between the bed and the wall for combined conduction and radiation. In this case, varying cluster residence times and, by virtue of equation 12, different solids exchange rates are examined. Longer residence times yield lower average heat transfer. All of the models show the same general behavior. The simple emulsion model substantially underpredicts the results compared to a more realistic radiation model. The continuous exchange model agrees more closely with the semi-transparent model but the two models still disagree by 30 percent for a residence time of 0.5s. These results already illustrate the sensitivity of the prediction to the residence time, or in analogous fashion, the solids exchange rate.

One additional prediction is shown on figure 2, In the modified emulsion model, the conduction to the wall is found in the absence of radiation. The radiation heat transfer to the wall is then added to the wall conduction assuming, as an upper limit, that the radiation is emitted at the core bed temperature.

$$h_c = \left[\frac{1}{h_H} + \frac{1}{h_{wall}} \right]^{-1} + h_{r\_wall} \qquad (13)$$

where the terms in equation 13 are given by equations 4 and 6.

When the temperatures are close to ambient, the simple emulsion approximation gives close agreement to the more exact calculation while the continuous exchange model is still in disagreement, figure 3.

Figure 4 shows the resulting heat transfer at combustor temperatures when the cluster thickness is doubled to 4 mm. The continuous exchange model now disagrees with the semi-transparent results by 57 percent at a 0.5 s contact time.
Similar behavior is observed when the cross section averaged solids concentration is increased to 0.005 with a decrease of the dimensionless gas layer at the wall, δ, to 0.64 and an increase of the cluster solids fraction to 0.07, fig. 5. The semi transparent model exhibits a modest increase in heat transfer of 12 percent at a residence time of 0.5s while the continuous model exhibits a 40 percent increase. In this case, the two models differ substantially. When the particle diameter is increased to 450 μm and all the other parameters remain the same, the semi transparent heat transfer results change by only 13 percent, fig. 6. In this one case, the continuous

and semi transparent assumptions give remarkably close agreement.

CONCLUSIONS

There are two general mechanistic model types in the literature for the emulsion or cluster portion of the bed to wall heat transfer for a circulating fluidized bed riser.. The more traditional model assumes that a cluster arrives at the wall and its geometry remains rigid until it leaves. At typical combustor operating conditions, radiation is an important component of the total heat transfer from the cluster to the wall. The cluster is not opaque; rather, there is radiation heat transfer between internal volumes of the cluster at different distances from the wall as well as between the internal volumes and the wall and the internal portion of the riser. An exact solution of this model must include the internal radiation heat transfer in the temperature prediction. The simple resistance in series approximation for the opaque cluster renewal model yields good agreement at ambient conditions but is not accurate at elevated temperatures because it underpredicts the radiation contribution from the cluster to the wall. A new approximate model has been proposed that yields better agreement with the exact solution.

The second general model type ignores any temperature gradients across the cluster, assumes the cluster is opaque and that there is a continuous exchange of particles between the cluster and the riser interior. This model would be appropriate if the cluster or wall layer experiences substantial lateral mixing while it is at the wall. Comparisons of the two general types shows the same general trends as the key parameters are varied. They exhibit different sensitivity to changes in the particle diameter and the bed density. A determination of which model is a more appropriate characterization of the process awaits better understanding of the cluster behavior at the wall.

NOTATION

C	Cross section average solids concentration
c_p	Specific heat of solids
d_p	Particle diameter
E	Exponential integral
f	Fraction of wall covered by clusters
G	Incoming radiation flux from all directions
h	Heat transfer coefficient
k	Thermal conductivity
q	Heat transfer rate per unit area
T	Temperature
t	Time
W	Cluster width
x	Distance form the cluster wall

Subscripts

c	Cluster
e	Emulsion
g	Gas
H	Effective value for emulsion
p	Particle
r	Radiation

Greek

α	Thermal diffusivity
δ	Dimensionless gas gap
ε	Solids volume fraction
ρ	Density
σ	Stefan Boltzmann constant
τ	Cluster residence time

REFERENCES

1) Glicksman, L.R. Heat transfer in Circulating Fluidized Bed in *Circulating Fluidized Beds*. 1997 Chapman and Hall.

2) Mickley, H.S. and Fairbanks, D.F. Mechanisms of heat transfer to fluidized beds in *AIChE Journal*, 1, 1955, 374-384.
3) Lints, M. and Glicksman, L.R. The structure of particle clusters near the well of a circulating fluidized bed in *AIChE Symposium Series*, 89, No. 296, 1993, 35-47.
4) Subbarrao, D. and Basu, P. A model for heat transfer in circulating fluidized beds in *Int. J. Heat Mass Transfer,* No. 27, 1986, 487-489.
5) Basu, P. and Nag, P.K. An investigation into heat transfer in circulating fluidized beds in *Int. J. Heat Mass Transfer,* No. 30, 1987, 2399-2409.
6) Gloski, D., Glicksman, L.R. and Decker, N. Thermal resistance at a surface in contact with fluidized bed particles in *Int. J. Heat and Mass Transfer,* No. 27, 1984, 599-610.
7) Golriz, M.R. Grace, J.R. in: Grace, J.R. Zhu, J. deLasa, H. Circulating Fluidized Bed Technology VII, CSChE, Ottawa, 2002, 121-128.
8) Xie, D. Bowen, B.D. Grace. J.R. Lim, C.J. Two-dimensional model of heat transfer in circulating fluidized beds. Part I: Model development and validation in *International Journal of Heat and Mass Transfer.* No. 46, 2003, 2179-2191.
9) Hua, Y. Flamant, G. Lu, J. Gautyhier, D. Li, H. 3D Modelling of Radiative Heat Transfer in a Circulating Fluidized Bed Combustor in *Fluidization XI: Present and Future for Fluidization Engineering,* 2004 Engineering Conferences International.

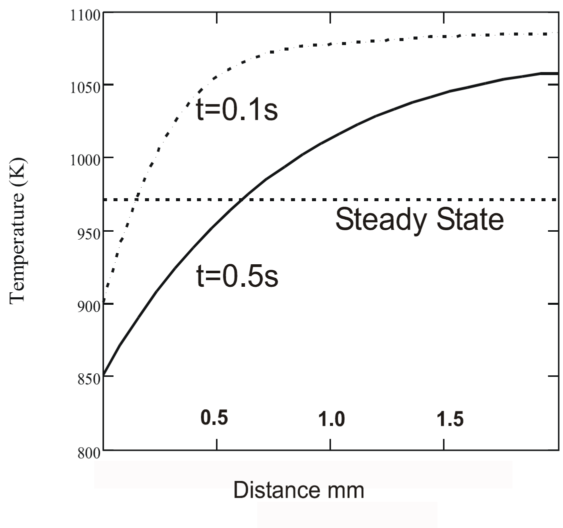

Figure 1. Temperature distributions from semi transparent and continuous models, Conditions of table 1.

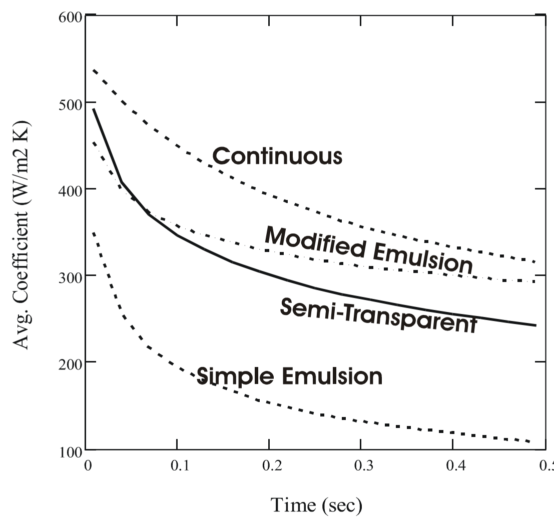

Figure 2 Predicted time averaged heat transfer for different models, all with conditions of table 1.

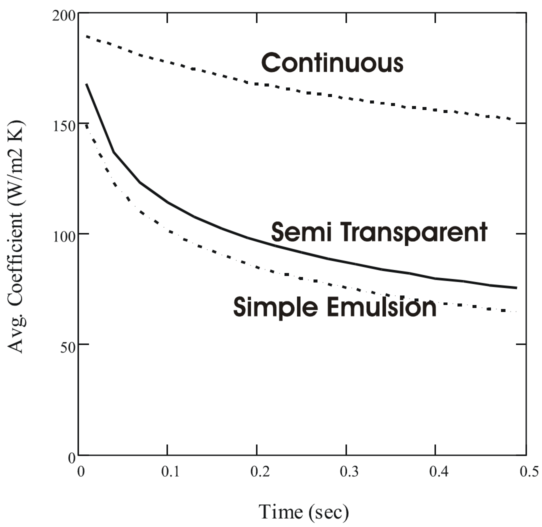

Figure 3 Heat transfer when bed and wall are near ambient temperature.

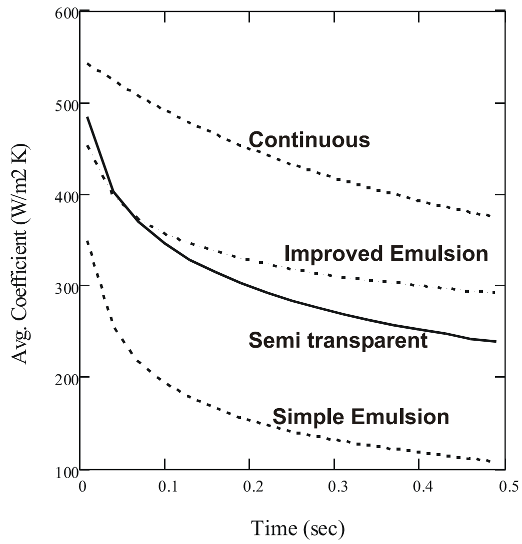

Figure 4 Heat transfer when cluster thickness, 4 mm, is twice table 1 conditions.

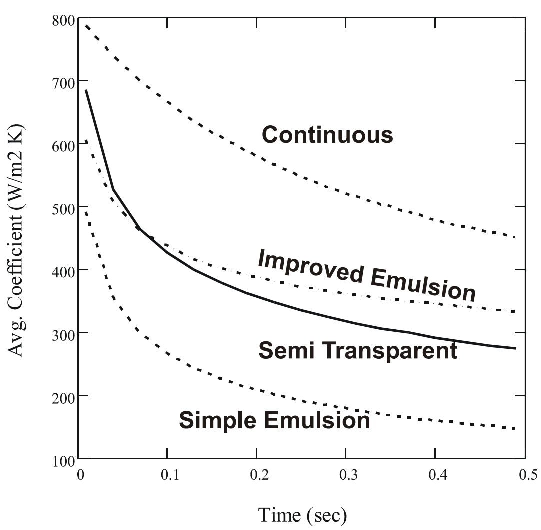

Figure 5 Heat transfer when cross section averaged solids concentration is 0.005.

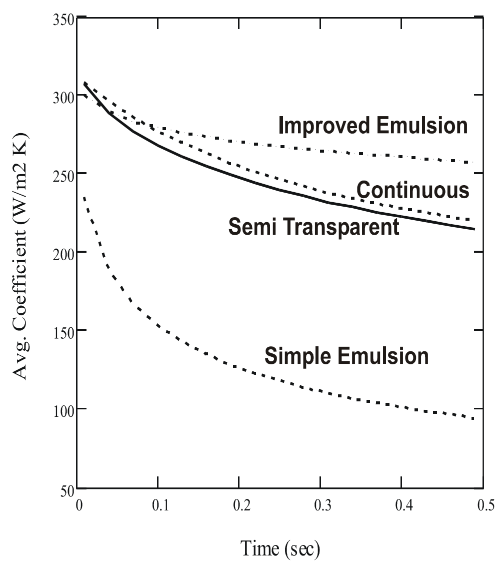

Figure 6 heat transfer when particle diameter is 450 μ m.