THE PREDICTION OF HEAT TRANSFER COEFFICIENT IN CIRCULATING FLUIDIZED BED COMBUSTOR

by

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To My Parents, Brothers and Sisters,

With Love and Appreciation.

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NOMENCLATURE

A : constant in equation (3.2).

B : backscatter fraction.

Cp_c: specific heat of the cluster, J/kg.K.

Cp_g: specific heat of the gas, J/kg.K.

Cp_p: specific heat of the particles, J/kg.K.

d_p : diameter of the particles, m.

e_c : cluster emissivity.

e_{dis} : emissivity of the dispersed phase.

e_p : particle emissivity.

e_w : wall emissivity.

e_{wt} : wall material emissivity.

f : time fraction during which the wall surface is covered by the clusters.

g : acceleration due to gravity, 9.81 m / s^2.

h : height above the distributor plate, m.

H : height of the combustion chamber, m.

$\mathbf{h_c}$ **:** convective heat transfer coefficient, W/m^2.K.

$\mathbf{h_{cc}}$ **:** cluster convective heat transfer coefficient, W/m^2.K.

$\mathbf{h_{cd}}$ **:** dispersed phase convective heat transfer coefficient, W/m^2.K.

$\mathbf{h_{ov}}$ **:** overall heat transfer coefficient, W/m^2.K.

$\mathbf{h_r}$ **:** radiative heat transfer coefficient, W/m^2.K.

$\mathbf{h_{rc}}$ **:** cluster radiative heat transfer coefficient, W/m^2.K.

$\mathbf{h_{rd}}$ **:** dispersed phase radiative heat transfer coefficient, W/m^2.K.

k : constant in equation (3.2).

$\mathbf{k_c}$ **:** thermal conductivity of the cluster, W/m.K.

$\mathbf{k_g}$ **:** thermal conductivity of the gas, W/m.K.

$\mathbf{k_{gf}}$**:** thermal conductivity of the gas film between the bed and the wall, W/m.K .

$\mathbf{k_p}$ **:** thermal conductivity of the particles, W/m.K.

$\mathbf{L_c}$ **:** cluster length, m.

ΔP/ΔL: pressure gradient across the bed of the circulating fluidized bed, kPa / m.

R : radius or half - width of the furnace, m.

Re_p : Reynolds number based on the particle diameter,

$$Re_p = \rho_g \; U_g \; d_p / \mu_g .$$

t_c : cluster time, sec.

T_c : cluster temperature , K.

T_b : bed temperature , K.

T_w : wall temperature , K.

U_c : cluster velocity, m / s.

U_g : superficial gas velocity, m / s.

U_t : terminal velocity, m / s.

x : cluster distance from fin surface, m.

Y: solid concentration in dispersed phase.

Greek Symbols

ε_c : cluster voidage, % .

ε_w : wall voidage, % .

ε_{sus} : suspension voidage, % .

ρ_p : density of the particles , kg / m^3.

ρ_{sus} : suspension density, kg / m^3.

ρ_c : density of the cluster, kg / m^3 .

ρ_g : gas density, kg / m^3.

ρ_{dis} : density of the dispersed phase, kg / m^3 .

δ_g : thickness of gas film between the cluster and the wall, m.

δ_{rough} : peak value of surface roughness, m.

μ_g : viscosity of the gas , kg / m.s

σ : Stefan - Boltzmann's constant, $5.67*10^{-8}$, W/m^2.K^4 .

ABSTRACT

The prediction of heat transfer coefficient in circulating fluidized bed combustor

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In the present work, a theoretical study is performed to modify an existing model that is used to predict the heat transfer coefficient within a circulating fluidized bed combustor .

The modified model results are compared with both experimental and theoretical ones obtained previously. It is found that the modified model predictions are in good agreement with experimental results in most cases and reasonable in others.

CHAPTER ONE
INTRODUCTION

1.1 General :

Fluidized bed combustion is probably the most important practical development in combustion technology since the successful operation of large-scale fuel furnaces in the early 1920s. In recent years, circulating fluidized beds have been extensively used for solid fuel combustion. Interest in circulating fluidized bed boilers has been growing ever since this technology was successfully adopted for the efficient combustion of low grade fuels in an environmentally acceptable manner. Nevertheless, few topics of the fundamental properties of circulating beds remain only partially understood. Understanding of heat transfer, for example, is mostly empirical, although most circulating bed applications require an accurate knowledge of heat transfer.

For reliable design, modeling, and scale-up of circulating fluidized beds, it is important to know the underlying mechanisms involved in the heat transfer between gas-solid suspensions and immersed cooling surfaces or walls of the bed. The heat transfer coefficient in circulating fluidized bed comustors can be considered to consist of radiative heat transfer, particle and gas convective heat transfer. At high bed temperatures, the thermal radiation heat transfer contribution becomes significant.

Another thing should be mentioned here, is the importance of calculating the radiative heat transfer contribution since many of previous studies neglected this part, in which its importance appears when combustion occurs at high temperatures as in power plants.

The experimental work on circulating fluidized bed heat transfer has largely been concerned with attempts to develop an empirical correlation for the prediction of heat transfer and to explain the mechanisms involved.

1.2 Objectives Of The Present Work :

Heat transfer coefficient in circulating fluidized bed combustors is an important factor in determination the design requirements of circulating fluidized bed combustors. It is often determined experimentally or from expressions with considerable percentage of error. Therefore, the need to find an expression with reasonable results and good agreement with experimental results is an insisting one.

The aim of the present study is to determine a model to predict heat transfer coefficient in circulating fluidized bed combustors.

In the present work, a theoretical study is performed to modify an existing model that is used to predict the heat transfer coefficient within a circulating fluidized bed combustor.

Golriz *et. al.* (1994) have made an experimental investigation of thermal characteristics in a 12-MW_{th} circulating fluidized boiler where temperature distributions and local heat transfer coefficient were measured. They found that heat transfer coefficient increases with increasing bulk bed temperature, superficial gas velocity, and suspension density. They also deduced that the thermal boundary-layer thickness decreases with increasing gas velocity.

Golriz *et. al.* (1995) developed an empirical model to predict heat transfer coefficient in circulating fluidized bed combustors. They used an empirical relation for estimating cluster temperature and did not approximate it by bed temperature. They also compared their theoretical results of heat transfer coefficient with experimental ones .

In the present work, a modification will be performed on an existing model that is used to predict the heat transfer coefficient within a circulating fluidized bed combustor. Then the model is studied and certain parameters are modified by relaxing certain assumptions used in the model.

CHAPTER THREE
MATHEMATICAL MODEL

3.1 General :

In a fluidized bed, the particles tend to rearrange themselves to minimize drag forces where cavities called bubbles are formed. The circulating fluidized bed is the same as bubbling bed in which a circulating pattern of bed material is induced within the bed. Circulating bed is characterized by relatively high solids concentrations, aggregation of the particles in clusters which break apart and reform again. An illustration of the circulating bed is shown in Figure (3.1).

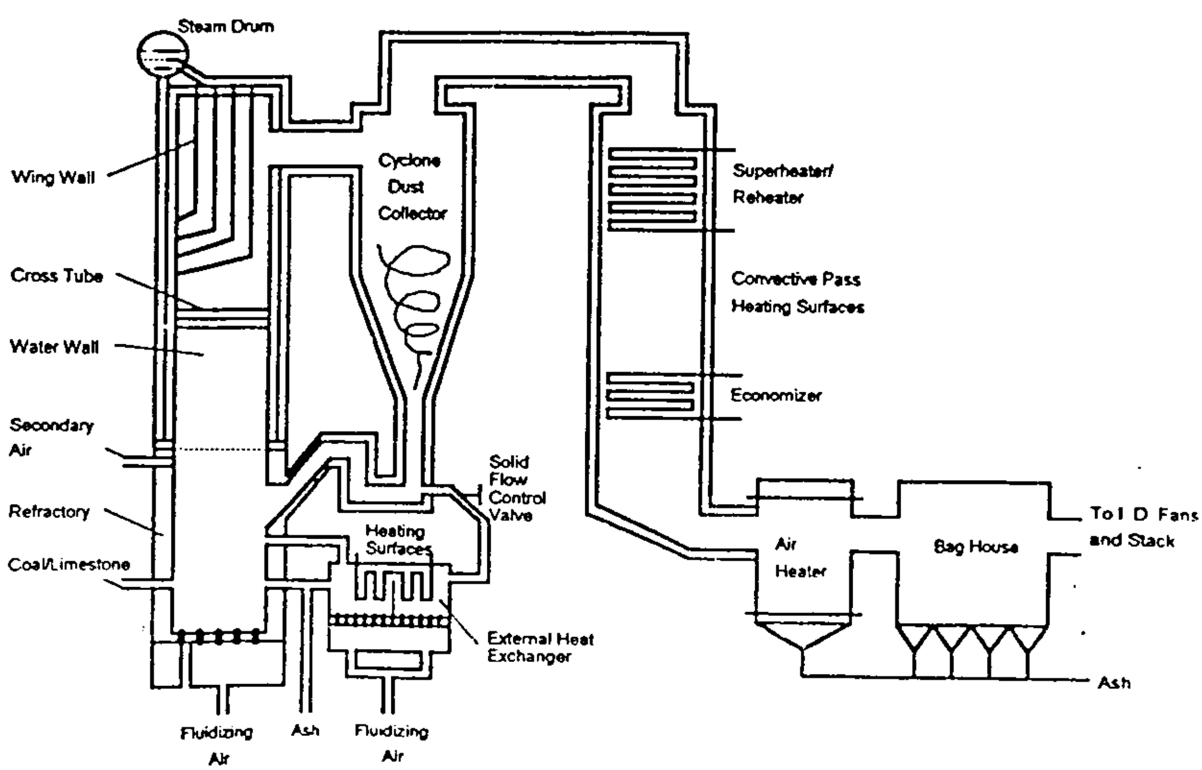

Figure (3.1) A Circulating fluidized bed

Heat transfer rate and its mechanism in the circulating fluidized bed combustor are largely governed by the hydrodynamic conditions prevailing in it.

The heat generated in the combustion chamber of a high temperature circulating fluidized bed combustor is transferred by the following means:

1- Particle convection and radiation through the cluster of particles.

2- Convection and radiation through the dispersed phase (gas with small fraction of solid material).

Figure (3.2) shows the important characteristics of the present model for the heat transfer inside a circulating fluidized bed combustors.

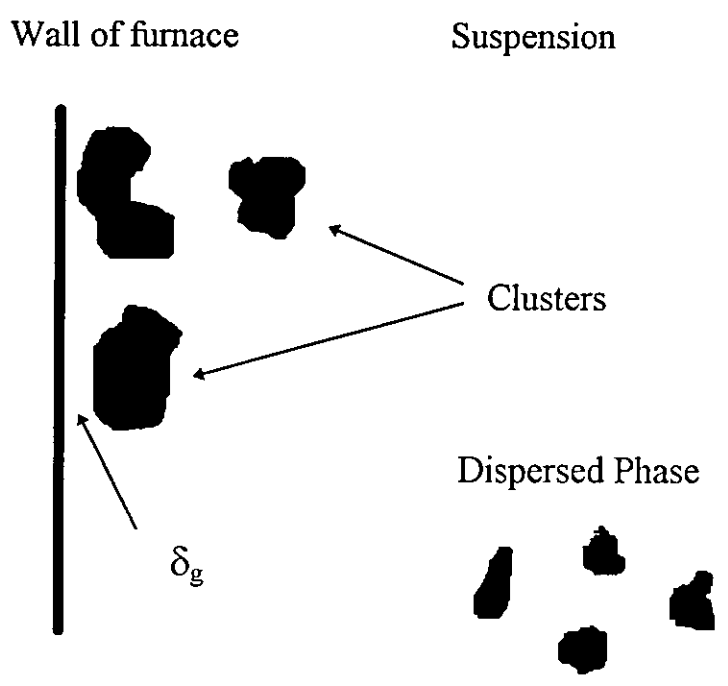

Figure (3.2) Conceptual view of cluster and gas close to a wall of a fluidized bed combustor.

3.2 The mathematical model :

The following is a description of the model intended to be modified :

The overall heat transfer coefficient, h_{ov}, in circulating fluidized bed combustors could be written as :

$$h_{ov} = f\ (h_{cc} + h_{rc}) + (1 - f)\ (h_{cd} + h_{rd}) \qquad (3.1)$$

which consists of :

1 - Convective heat transfer coefficient (h_c) which in turn consists of two parts :

I - Cluster convective heat transfer coefficient (h_{cc}).

II- Dispersed phase convective heat transfer coefficient(h_{cd}).

2 - Radiative heat transfer coefficient (h_r) which also consists of two parts:

I - Cluster radiative heat transfer coefficient (h_{rc}).

II - Dispersed phase radiative heat transfer coefficient (h_{rd}).

Now, a description of the individual heat transfer components is presented below. The time fraction, f, can be found from the following equation (Golriz *et. al.*, 1995) :

$$f = A \left[\frac{(1 - \varepsilon_w - Y)}{(1 - \varepsilon_c)} \right]^K \qquad (3.2)$$

where A and k are constants and their values are 0.5 and 0.5 respectively.

Wall voidage (ε_w) could be found from the investigations and analysis of Dou (1990) :

$$\varepsilon_w = 4\ \varepsilon_{sus} - 3.0 \qquad (3.3)$$

where (ε_{sus}) is the suspension voidage which may be determined as in Golriz *et. al.* (1995) :

$$\varepsilon_{sus} = 1 - \frac{\Delta P / \Delta L}{g\ \rho_p} \qquad (3.4)$$

Introducing the Suspension density (ρ_{sus}) correlated by Grace (1990) as :

$$\rho_{sus} = \frac{\Delta P / \Delta L}{g} \qquad (3.5)$$

substituting (3.5) in (3.4), ε_{sus} , becomes :

$$\varepsilon_{sus} = 1 - \frac{\rho_{sus}}{\rho_p} \qquad (3.6)$$

Moreover, substituting (3.6) in (3.3), ε_w becomes :

$$\varepsilon_w = 4\ [\ 1 - (\ \rho_{sus} / \ \rho_p\ )\ ]\ -\ 3.0 \qquad (3.7)$$

or

$$\varepsilon_w = 1 - 4\ [\ (\ \rho_{sus} / \ \rho_p\ )\ ] \qquad (3.8)$$

3.2.1 Cluster Convection :

The existence of a downward falling layer of single particles called clusters near the wall of a circulating fluidized bed combustor has been proven by previous work, (Basu *et. al.*, 1987). The clusters come in contact with the wall and after remaining there for a period of time they are either dissolved or moved to another location.

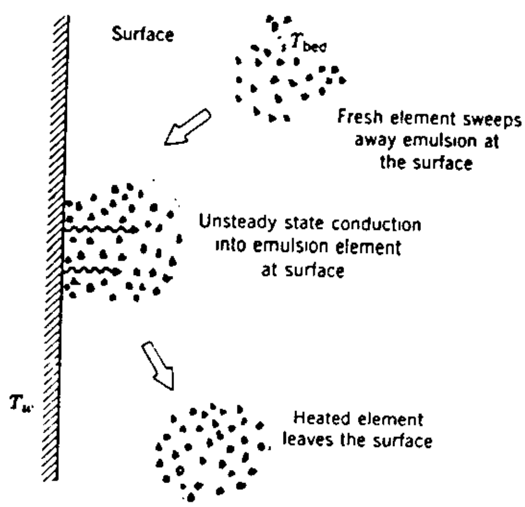

Figure (3.3) Cluster motion in a circulating fluidize bed.

Therefore, the heat transfer coefficient from the cluster in a circulating fluidized bed depends on the replacement frequency, the thermal properties of the clusters and the surface characteristics. On the other hand, gas film resistance between the cluster and the wall surface is considered in calculating cluster convective heat transfer coefficient.

Cluster convective heat transfer coefficient (h_{cc}) between the clusters and the wall is given by Golriz *et. al.* (1995) :

$$h_{cc} = \frac{1}{\dfrac{\delta_g}{K_{gf}} + \left(\dfrac{\pi\ t_c}{K_c\ \rho_c\ Cp_c}\right)^{0.5}} \qquad (3.9)$$

A survey revealed that the previous correlation is the most appropriate one for the present study. But, to calculate the cluster convection heat transfer, one needs to know the average residence time (t_c) of cluster on the wall. Therefore, there is a need to find a correlation for cluster residence time.

The thermal conductivity of the gas film (K_{gf}), was determined to be the thermal conductivity of the gas at the mean of bed and wall temperatures, T_b and T_w respectively.

The specific heat of the cluster (Cp_c) was found by Golriz *et. al.* (1995) as :

$$Cp_c = (1 - \varepsilon_c)\ Cp_p + \varepsilon_c\ Cp_g \qquad (3.10)$$

And the cluster density (ρ_c) is given by Golriz *et. al.* (1995) as:

$$\rho_c = (1 - \varepsilon_c)\ \rho_p + \varepsilon_c\ \rho_g \tag{3.11}$$

The effective thermal conductivity of the cluster , K_c , is determined as suggested by Gelperin and Einstein (1971) :

$$K_c = K_g \left[1 + \frac{(1 - \varepsilon_c)\ (1 - (K_g / K_p))}{(K_g/K_p) + 0.28\varepsilon_c^{\ (0.63((Kg/Kp) \wedge (0.18)))}}\right] \tag{3.12}$$

The thickness of the gas film between the cluster and wall surface (δ_g), is another important factor in determining the cluster convection contribution. In this work, the correlation used by Golriz *et. al.* (1995) was applied to calculate the gas film thickness. The correlation reads:

$$\delta_g = 0.0282\ d_p\ [(1 - \varepsilon_{sus})^{(-0.59)}] + \delta_{rough} \tag{3.13}$$

3.2.2 Cluster Radiation :

It has been well accepted that radiation plays an increasingly important role in fluidized bed heat transfer when temperature rises. The cluster and the gas radiation modes are independent from each other when calculating radiative components. Golriz *et. al.* (1995) suggested that a gray body expression may be used to predict radiative heat transfer coefficient between the cluster and the wall which is given by :

$$h_{rc} = \frac{\sigma \, [T_c^4 - T_w^4]}{[T_b - T_w] \; [(1 / e_c) + (1 / e_w) - 1]} \qquad (3.14)$$

In most previous works (Basu *et. al.*, 1987), cluster temperature (T_c) was approximated to be bed temperature (T_b) which produces a reasonable amount of error in evaluating the heat transfer coefficient in circulating fluidized bed combustors. In this work, cluster temperature (T_c) has been considered in the calculation so as to obtain more accurate results. In this work, cluster temperature (T_c) is determined from the correlation suggested by Golriz (1995) which is given by :

$$T_c = T_w + (T_b - T_w) \; \{1 - [-0.023 \; Re_p + 0.163 \; (T_b / T_w) + 0.294 \; (h / H)] \; \exp. (-0.0054 \, (x / d_p)\} \qquad (3.15)$$

Based on the results given by Grace (1982), the following expression may be used to evaluate the cluster emissivity (e_c) in circulating fluidized beds:

$$e_c = 0.5 \; (1 + e_p) \qquad (3.16)$$

Also the proper value of the wall emissivity (e_w) is hard to be found accurately, since the cluster particles hit the surface and affect the surface properties. In this work, an expression was formulated to find wall emissivity (e_w) through correlating the value taken from tables for the material with cluster time and particle diameter.

3.2.3 Dispersed Phase Convection :

From available earlier observations it is evident that in the furnace of a circulating fluidized bed, the wall surface is in contact with either a dispersed phase or clusters. Previous works (Basu *et. al.*, 1987), suggest that in between contacts with two successive clusters, the wall is in contact with an up-flowing dispersed phase with a continually developing boundary layer on the wall. In the absence of any appropriate correlation for this kind of situation, the correlation used by Golriz *et. al.* (1995) for evaluating heat transfer coefficient in the dilute phase could be used, which is given by :

$$h_{cd} = \left(\frac{\mu_g\ C_{pp}}{d_p}\right) \left(\frac{\rho_{dis}}{\rho_p}\right)^{0.3} \left(\frac{U_t^2}{g\ d_p}\right)^{0.21} \qquad (3.17)$$

The density of the dispersed phase (ρ_{dis}), is determined as in Golriz *et. al.* (1995) which is given by:

$$\rho_{dis} = Y\,\rho_p + (1 - Y)\,\rho_g \qquad (3.18)$$

Also terminal velocity (U_t) has been always determined through measurements, so in this work an expression for it will be found in order to reduce the error sources resulting from measurements.

3.2.4 Dispersed Phase Radiation :

Radiation is a major component of heat transfer coefficient in circulating fluidized bed combustors especially when the temperatures are high. For the calculation of radiative properties, the bed and the wall may be viewed as two very large parallel planes where gray body expression may be used. Therefore, the radiative heat transfer coefficient for dispersed phase can be written as in Golriz *et. al.* (1995):

$$h_{rd} = \frac{\sigma\,[\,T_b^4 - T_w^4\,]}{[\,T_b - T_w\,]\,[(1/e_w) + (1/e_{dis}) - 1]} \qquad (3.19)$$

Brewster (1986) showed that for an isothermal bed the effective emissivity is only a function of particle emissivity (e_p) and backscatter fraction (B). It can be calculated from :

$$e_{dis} = \left(\frac{e_p}{(1-e_p)\,B}\left(\frac{e_p}{(1-e_p)\,B} + 2\right)\right)^{1/2} - \frac{e_p}{(1-e_p)\,B} \qquad (3.20)$$

where a value for (B) of 0.5 was used.

3.3 Objectives of this work:

Although a tremendous work has been done through the passing years to estimate the total heat transfer coefficient in circulating fluidized bed combustors, some weakness points have arised in these works. Therefore, in order to achieve the target which is the most appropriate model for predicting heat transfer coefficient in circulating fluidized bed combustors, these weakness points should be cured through finding expressions for certain parameters that are usually determined experimentally producing an amount of error or try to improve on the existing expressions. Now, a description of these weakness points is presented:

- **Cluster residence time (t_c) :**

To calculate the cluster convection heat transfer, one needs to know the cluster time (t_c). However, investigations, (Basu *et. al.*, 1987) showed some parameters that affect the determination of cluster residence time.

Therefore, an expression for cluster time should be composed of the affecting parameters on it.

- **Cluster length (L_c) :**

Models were proposed to predict the cluster length (L_c) but did not account for the effect of many parameters such as : superficial gas velocity (U_g), terminal velocity (U_t), suspension voidage (ε_{sus}) and particle diameter (d_p). Therefore, it is necessary to correlate these parameters together with finding an expression for cluster length (L_c) taking into consideration their effects on the model.

- **Cluster velocity (U_c) :**

Cluster velocity (U_c) is also an important factor in determining cluster time (t_c) and consequently affect the determination of heat transfer coefficient in circulating fluidized bed. Most of the investigations used measured cluster velocity (U_c) and did not use a correlation or expression relating to the prevailing parameters.

- **Cluster voidage (ε_c) :**

Cluster voidage was always determined experimentally (Golriz *et. al.*,1995). Then there is a need to find an expression for cluster voidage

(ε_c) to minimize error occurring in calculating total heat transfer coefficient showing the effect of each parameter according to the relationship with cluster voidage.

- **Terminal velocity (U_t) :**

In most previous works (Grace, 1986), (Golriz *et. al.*, 1995), terminal velocity (U_t) was determined experimentally. Therefore, a correlation must be found in order to reduce the deviations of predicted results with experimental ones.

- **Wall emissivity (e_w) :**

It is likely that cluster particles hit the surface and affect the surface properties. However, there is no simple way of determining the emissivity of the wall. Therefore, a proper value for evaluating wall emissivity is hard to be accurately determined.

- **Time fraction (f):**

Time fraction (f) is an important factor in determining the heat transfer coefficient in circulating fluidized beds. It needs some work in order to improve the constants related to it so as to achieve more reasonable results concerning the heat transfer coefficient.

The above factors are the weakness points that will be cured in this work aiming to obtain more accurate results and getting closer to the experimental ones with focusing on the accuracy of the results for these expressions so as to reduce the sources of error as much as possible.

3.4 Modifications on the mathematical model :

- **Time fraction (f)** :

The expression used for time fraction (f) appearing in equation (3.1), was taken from Golriz *et. al.*(1995). They used the values of 0.5 for both A and k, where A and k are constants. But, in this work, a modification on the values of these constants will be done in order to obtain more accurate results.

- **Cluster voidage (ε_c) :**

Cluster voidage (ε_c) appearing in equation (3.2) is always determined experimentally (Golriz *et. al.*, 1995), as the minimum fluidization voidage in fluidized bed combustors. Therefore, there is a need to find a reasonable correlation for evaluating it according to the influencing factors affecting its value.

- **Cluster time (t_c) :**

An expression for cluster time (t_c) appearing in equation (3.9) should be composed of the affecting parameters on the existing relationship between the parameters from one side and cluster time (t_c) on the other side. The cluster time (t_c) which depends on cluster velocity and cluster length, could be written as in Subbarao. *et. al.* (1986) in the following form:

$$t_c = \frac{L_c}{U_c} \qquad (3.21)$$

Till now, most of the previous works used experimental values to determine the cluster time (t_c) (Glicksman, 1988). An expression relating the influencing parameters is correlated in this work, aiming to reduce the error resulting from experimental values through considering some parameters not taken into account before.

- **Cluster length (L_c) :**

Cluster length (L_c) appearing in equation (3.21) has been determined experimentally (Basu, 1990). Then there is a need to correlate all affecting parameters which determine cluster length (L_c) taking into consideration their effects on the model.

• Cluster Velocity (U_c) :

Cluster velocity (U_c) appearing in equation (3.21) is also an important factor in determining cluster time and consequently affect determination of heat transfer coefficient in circulating fluidized bed.

It has been always determined experimentally (Basu, 1990). Therefore, one of the modifications in this work, is to investigate the effects of governing parameters on cluster velocity (U_c) and to find an expression giving reasonable values.

• Terminal Velocity (U_t) :

Terminal velocity (U_t) appearing in equation (3.17) has been always determined through measurements (Grace, 1986), in which once again the error makes a contribution and deviates results from real values. But in this work, a correlation for evaluating it will be found after studying the affecting parameters.

• Wall Emissivity (e_w) :

Unfortunately, the proper value of the wall emissivity (e_w) appearing in equation (3.14) is hard to find accurately, since the cluster particles hit the surface and affect the surface properties. Therefore, the real value of wall emissivity is not used because only the value taken from tables for the selected material is considered. However, in this work, an expression was formulated to find wall emissivity (e_w) through correlating the affecting parameters together with the value of the wall emissivity taken from tables (e_{wt}).

CHAPTER FOUR
RESULTS

4.1 General :

This chapter presents the results obtained from the modified model for determining heat transfer coefficient in circulating fluidized bed combustors at various operating conditions to show the effect of such parameters or conditions on the heat transfer coefficient. The formulas used in this work are implemented into a computer program from which the results are obtained.

First of all, modifications on the existing model are presented, in addition to explanation about each modification and how is it developed through studying the affecting parameters.

4.2 The modifications on the model :

- **Time fraction (f) :**

The time fraction (f) appearing in equation (3.1), is an important factor in determining overall heat transfer coefficient (h_{ov}) in circulating fluidized bed combustors. Both constants A and k were set to be 0.5 as suggested by Golriz *et. al.* (1995). But, after trying values for these constants and noticing the effect on the predicted results, it was found that when A and k are set to be 0.35 and 0.65 respectively, more accurate and closer results to the experimental results were obtained. The correlation after modifications reads :

$$f = 0.35 \left[\frac{(1 - \varepsilon_w - Y)}{(1 - \varepsilon_c)}\right]^{0.65} \tag{4.1}$$

- **Cluster voidage (ε_c) :**

Cluster voidage (ε_c) appearing in equation (3.2) has been always determined as the minimum fluidization voidage in fluidized bed combustors. It was found that cluster voidage (ε_c) depends on the suspension voidage (ε_{sus}) and also on the distance between the particles and the surface of the combustor (Basu ,1990). In this work, cluster voidage was correlated by the following correlation :

$$\varepsilon_c = 0.5 \ \varepsilon_{sus}^{(2.074\ (x/R))} \tag{4.2}$$

The results obtained from the previous expression for cluster voidage were compared with others and, the agreement was excellent .

- **Cluster residence Time (t_c) :**

It is necessary to find an expression for cluster time (t_c) appearing in equation (3.9). When obtaining this expression, it was assumed that small clusters detach themselves from the wall after traversing a length equivalent to the length of the cluster (Basu, 1990). Cluster time (t_c) could be written as in equation (3.19).

Now, a full description of cluster length (L_c) and cluster velocity (U_c) will be presented :

- **Cluster Length (L_c) :**

The cluster length, (L_c), is very important in determining the cluster time (t_c). Therefore, there is a need to find an expression for cluster length (L_c) through correlating different parameters such as: superficial gas velocity (U_g), terminal velocity (U_t), suspension voidage (ε_{sus}) and particle diameter (d_p) which affect determining cluster length (L_c) taking into consideration their effects on the results of the modified model.

After studying the effect of the previous governing parameters, an expression is found in this work to determine cluster length (L_c) which could be written as :

$$L_c = 0.005894 \left[\frac{U_g^{2/3} \, U_t^{\,2} \, (1 - \varepsilon_{sus})^{2/3}}{g \, d_p^{2/3} \, \varepsilon_c^{4/3}} \right] \qquad (4.3)$$

Results obtained from the previous correlation showed a reasonable degree of agreement with other results.

- **Cluster Velocity (U_c) :**

When determining cluster time (t_c), cluster velocity (U_c) is considered as an important factor and consequently affect determination of heat transfer coefficient in circulating fluidized bed. After investigating the effects of governing parameters, cluster velocity (U_c) in this work is correlated to be in the following form :

$$U_c = 0.1158 \left[\frac{U_g}{\varepsilon_c \, (\rho_p \; d_p)^{2/3}} \right] \qquad (4.4)$$

Results obtained from previous correlation were also compared with others from previous works, such as those of Golriz *et. al.* (1995), and agreement was very good. Dividing (4.3) by (4.4), cluster time t_c, could be obtained as :

$$t_c = 0.0509 \left[\frac{[\rho_p \, (1- \varepsilon_{sus})\,]^{2/3} \; U_t^2}{g \; [\, U_g \; \varepsilon_c \,]^{1/3}} \right] \qquad (4.5)$$

When comparing the results of cluster time (t_c) correlation with experimental ones, the agreement is good.

- **Terminal Velocity (U_t) :**

The terminal velocity (U_t) which has been always determined experimentally, is considered as an important factor in determining heat transfer coefficient in circulating fluidized bed combustors. In this work, the following correlation for evaluating it has been set after studying the affecting parameters. The correlation for terminal velocity (U_t) in circulating fluidized beds reads :

$$Ut = 1.2\ d_p \left(\frac{\rho_p^2}{\mu_g} \right)^{1/3} \qquad (4.6)$$

The previous correlation gave very good results compared with the experimental ones taken from the work of (Basu *et. al.*, 1987).

- **Wall Emissivity (e_w) :**

Wall emissivity (e_w) appearing in equation (3.14), has been always determined as the wall emissivity value of the material of the combustion chamber taken from tables without considering any effect for the cluster particles and the effect of their collision with the surface of the combustion chamber. In this work, an expression is formulated to find wall emissivity through correlating the value taken from tables for the material of the combustion chamber with cluster time (t_c) and particle diameter (d_p). The expression of wall emissivity is found to be :

$$e_w = 0.75\ e_{wt}^{tc\ dp} \qquad (4.7)$$

Those were the modifications applied to the existing model so as to obtain more accurate results and to minimize the deviation and error of predicted heat transfer coefficient results in circulating fluidized bed combustors from the experimental ones.

CHAPTER FIVE
DISCUSSION OF RESULTS

5.1 General :

In the circulating fluidized bed combustors heat transfer literature, most of the heat transfer data are reported using the suspension density as the main variable, this is also applied in this work. Heat transfer coefficient was computed for different operating conditions, the effect of which on heat transfer coefficient in circulating fluidized bed is discussed below :

5.1.1 Effect of suspension density :

Figures (5.4) through (5.12) present results on the effect of suspension density on the overall, convective and radiative heat transfer coefficient. As expected, both the overall and the convective coefficients increase with increasing suspension density, the overall heat transfer coefficient increases to a maximum value of 172 $W/m^2.K$ corresponding to $\rho_{sus} = 90.0\ kg/m^3$. This is due to the fact that the thermal capacity of solids is much higher than that of the gas, hence heat transfer between solid particles and the wall of combustor is much higher than that between the wall and the gas. Radiative component is almost independent of suspension density, since the effect of suspension density on the determination of radiative component is negligible.

5.1.2 Effect of particle diameter :

The effect of particle size on heat transfer coefficient is shown in figures (5.13) through (5.15). As shown in figure (5.13) and (5.14), smaller diameter particles yield higher value for both overall and convective heat transfer coefficients than larger ones. This is due to the fact that smaller particles have lower thermal resistance (as shown in equation 3.9). However, this equation indicates that the term that contains wall resistance becomes less significant as cluster time increases, leading to a less influence of particle size on heat transfer coefficient. The radiative component seems to be unaffected significantly by particle diameter, as shown in figure (5.15) and this is due to the fact that particle diameter does not affect the determination of radiative heat transfer coefficient.

5.1.3 Effect of bed temperature :

As shown in figure (5.16), the overall heat transfer coefficient increases with the bed temperature to a maximum value of 169.0 $W/m^2.K$ for a specific value of suspension density of 50.0 kg/m^3. Similarly, figure (5.17) shows that the convective component increases by increasing bed temperature and this is due to the increased thermal conductivity of gas film at the elevated temperatures as indicated in equation (3.9). Further the radiative component increases with increasing bed temperature leading to an increase in radiative exchange between clusters and wall surface(figure5.18).

5.1.4 Effect of superficial gas velocity :

The superficial gas velocity does not have significant influence on the heat transfer coefficient as indicated in figures (5.19) through (5.21), This is due to the relatively low contribution of the gas convective component in determining overall heat transfer coefficient. The radiative component, as shown in figure (5.21) is unaffected by superficial gas velocity due to the fact that superficial gas velocity is not a determining parameter of radiative heat transfer coefficient.

5.1.5 Effect of cluster time :

Figure (5.22) shows the effect of residence time on heat transfer coefficient. Both overall and convective heat transfer coefficients decreases with increasing cluster time to a minimum values of 157.93 $W/m^2.K$ and 68.75 $W/m^2.K$ respectively corresponding to a value of $t_c = 1.5$ sec, beyond this value, it reaches constant values. This is obvious from equation (3.9), since increasing cluster time will decrease convective component leading to a decrease in overall heat transfer coefficient. The radiative component is unaffected since cluster time does not affect the determination of the radiative heat transfer coefficient as indicated in equations (3.14) and (3.19).

5.1.6 Effect of cluster length :

As presented in figure (5.23), both the overall and the convective heat transfer coefficients decrease with increasing the cluster length. This behavior can be explained by the fact that as the particles fall down along the wall they are cooled by the wall of lower temperature, leading to a decrease in the heat transfer coefficient. In the same figure it can be seen that cluster length does not affect at all the determination of radiative heat transfer coefficient.

5.1.7 Effect of terminal velocity :

As shown in figure (5.24), terminal velocity does not have any influence on the overall, convective and radiative heat transfer coefficients. This is due to the fact that terminal velocity has a minor effect on the determination of the dispersed phase convective heat transfer coefficient as shown in equation (3.17), where the radiative component is not affected hence the terminal velocity parameter does not exist in its determining equations.

5.2 Comparison between theoretically predicted and experimental data:

In this work, comparison of the predicted heat transfer coefficient in circulating fluidized bed combustors is made against two theoretically predicted values obtained from previously published models. Further it was also compared against previously published experimental data. It was found that the present model successfully predicts all the above effects of physical variables on heat transfer coefficient in circulating fluidized bed combustors.

Figure (5.1) compares the present predicted results against an experimental and theoretical results obtained by Wu. et. al. (1989). The results show excellent agreement between the present predicted heat transfer coefficient data and experimental heat transfer coefficient from their work.

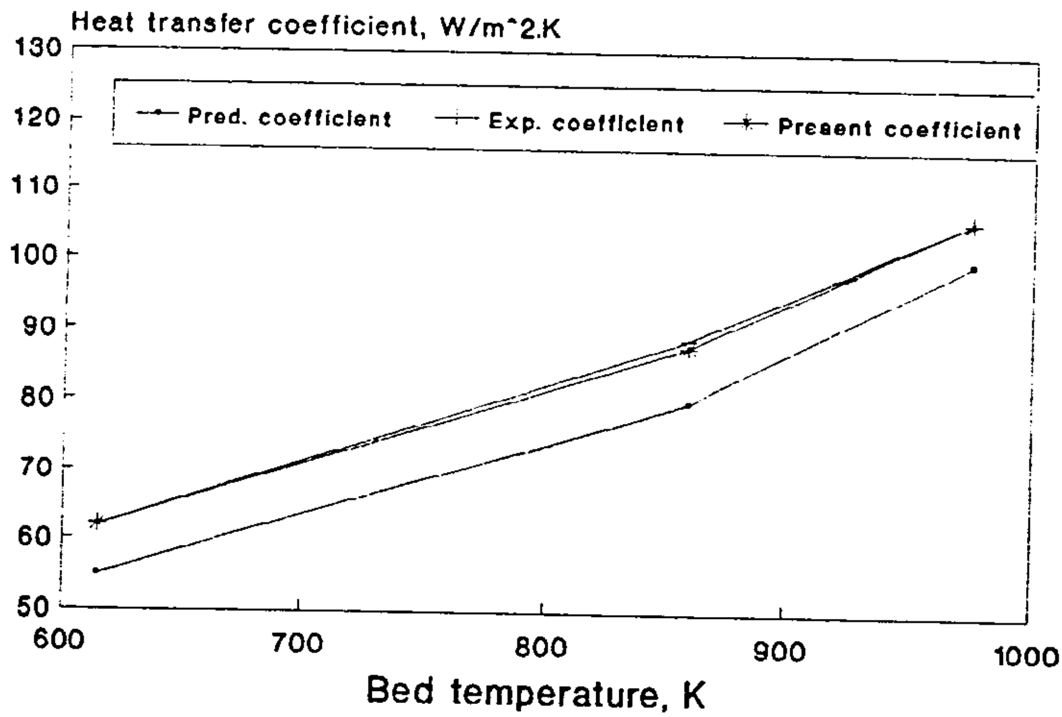

Figure 5.1 Comparison between present results and those of Wu. et. al. (1989). ($\rho_{sus} = 15$ kg/m^3, $d_p = 241$ μm)

Figures (5.2) and (5.3) compares the present predicted results of heat transfer coefficient against both experimental and theoretical results obtained by Golriz. et. al. (1995) at the same operating conditions. It seems that the agreement between the present predicted results and experimental ones from their work is fair.

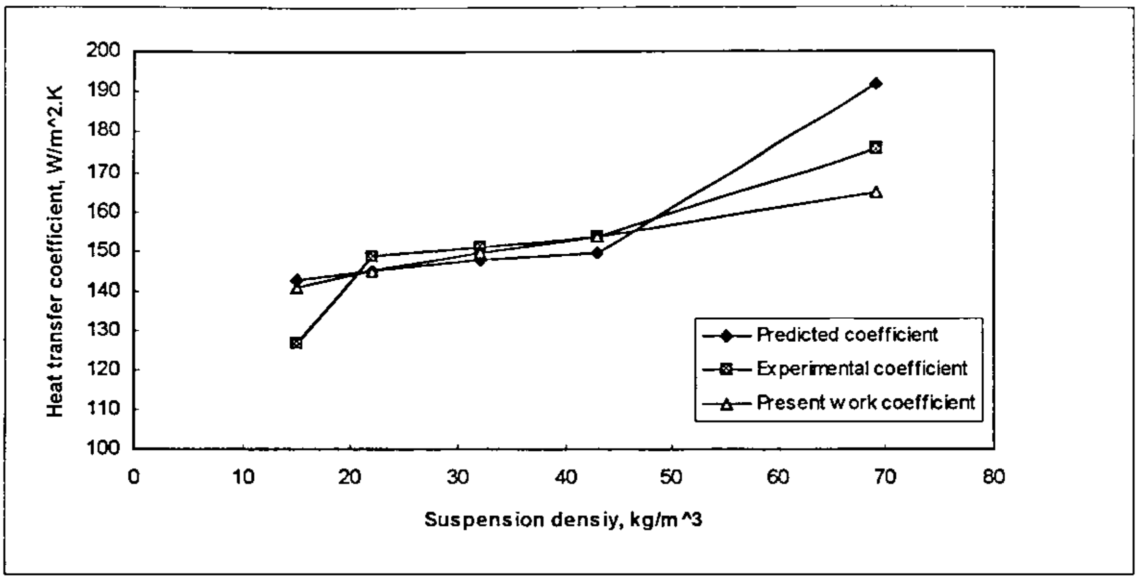

Figure 5.2. Comparison between present results and those of Golriz et. al. (1995). ($T_b = 1123$ K, $U_g = 6$ m/sec, $d_p = 270\mu m$)

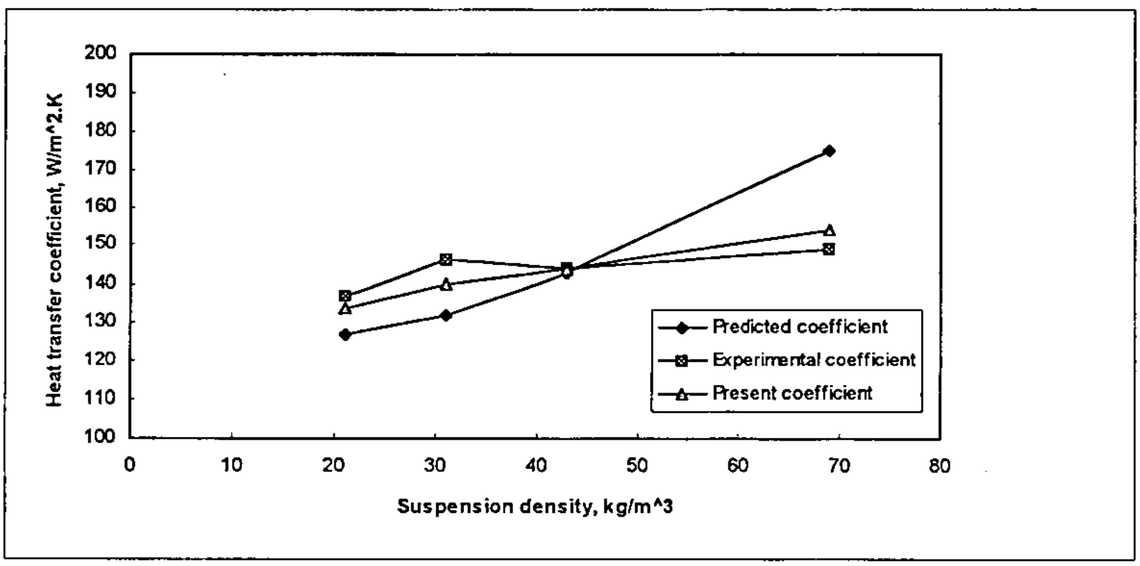

Figure 5.3. Comparison between present results and those of Golriz et. al. (1995). ($T_b = 1073$ K, $U_g = 6$ m/sec, $d_p = 270\mu m$)

5.3 Figures :

In the next section, figures will be presented.

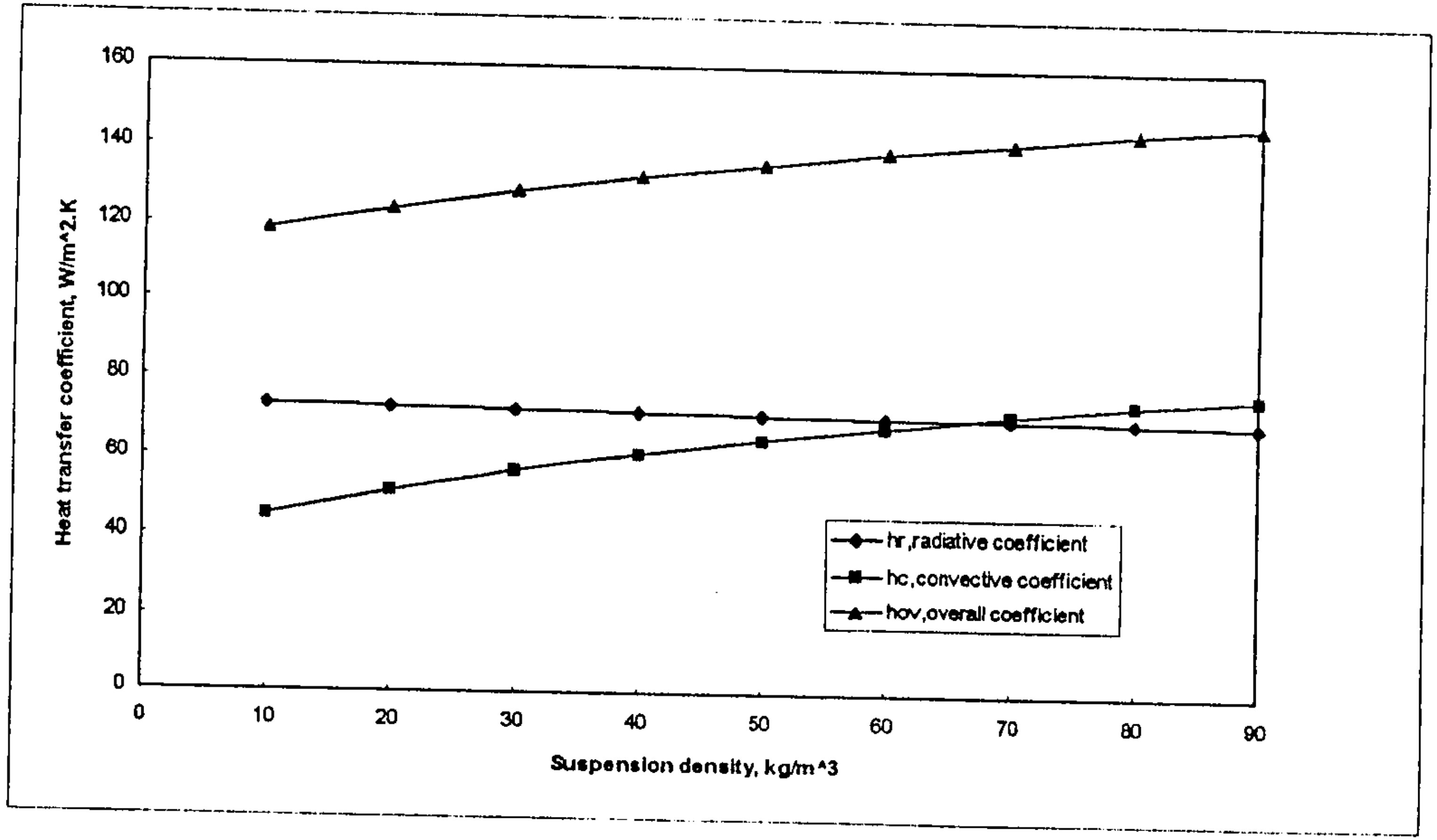

Figure 5.4 Predicted heat transfer coefficient vs suspension density.
(T_b = 1023 K, U_g = 4 m/sec, d_p = 270 μm)

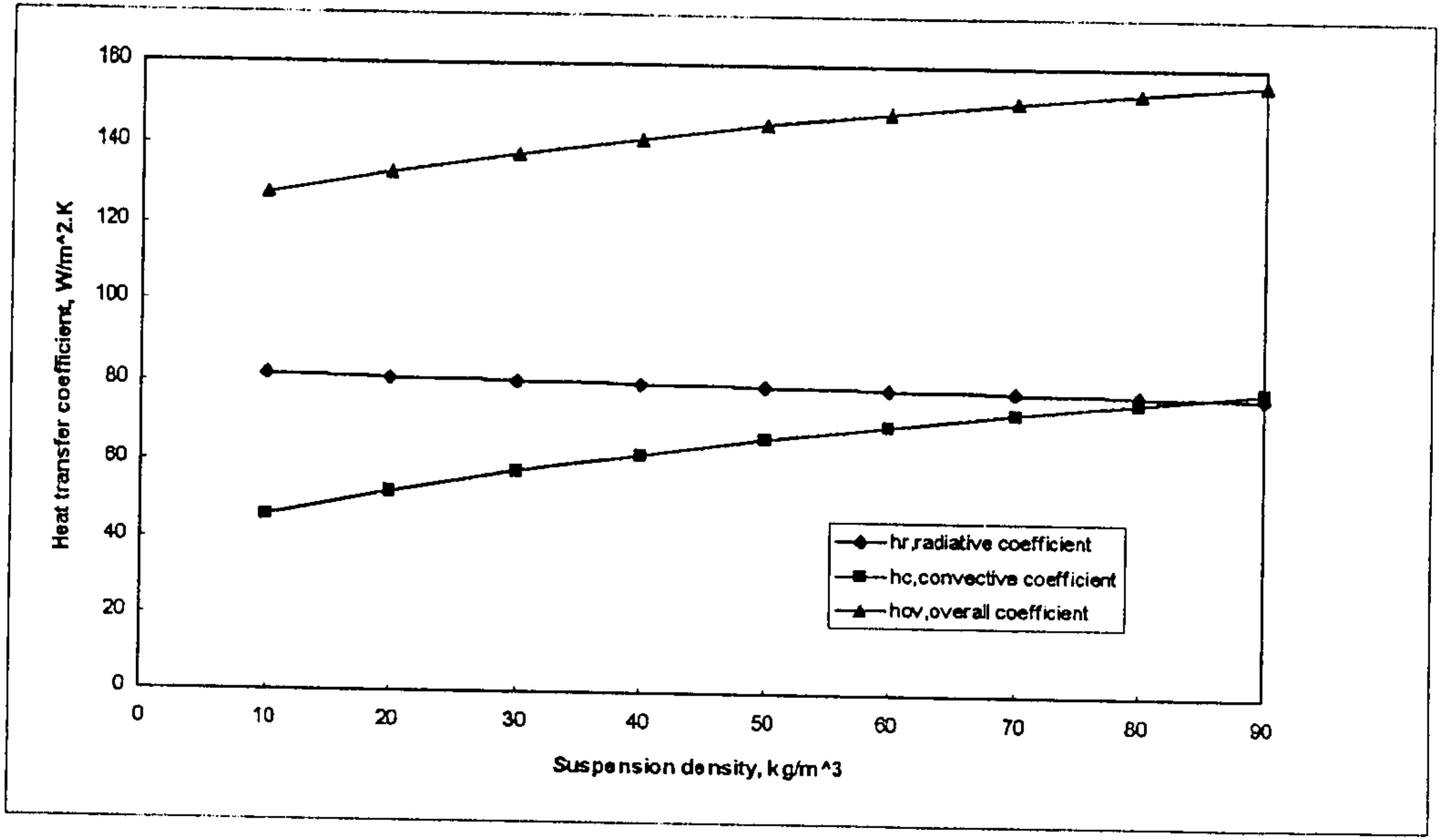

Figure 5.5 Predicted heat transfer coefficient vs suspension density.
(T_b = 1073 K, U_g = 4 m/sec, d_p = 270 μm)

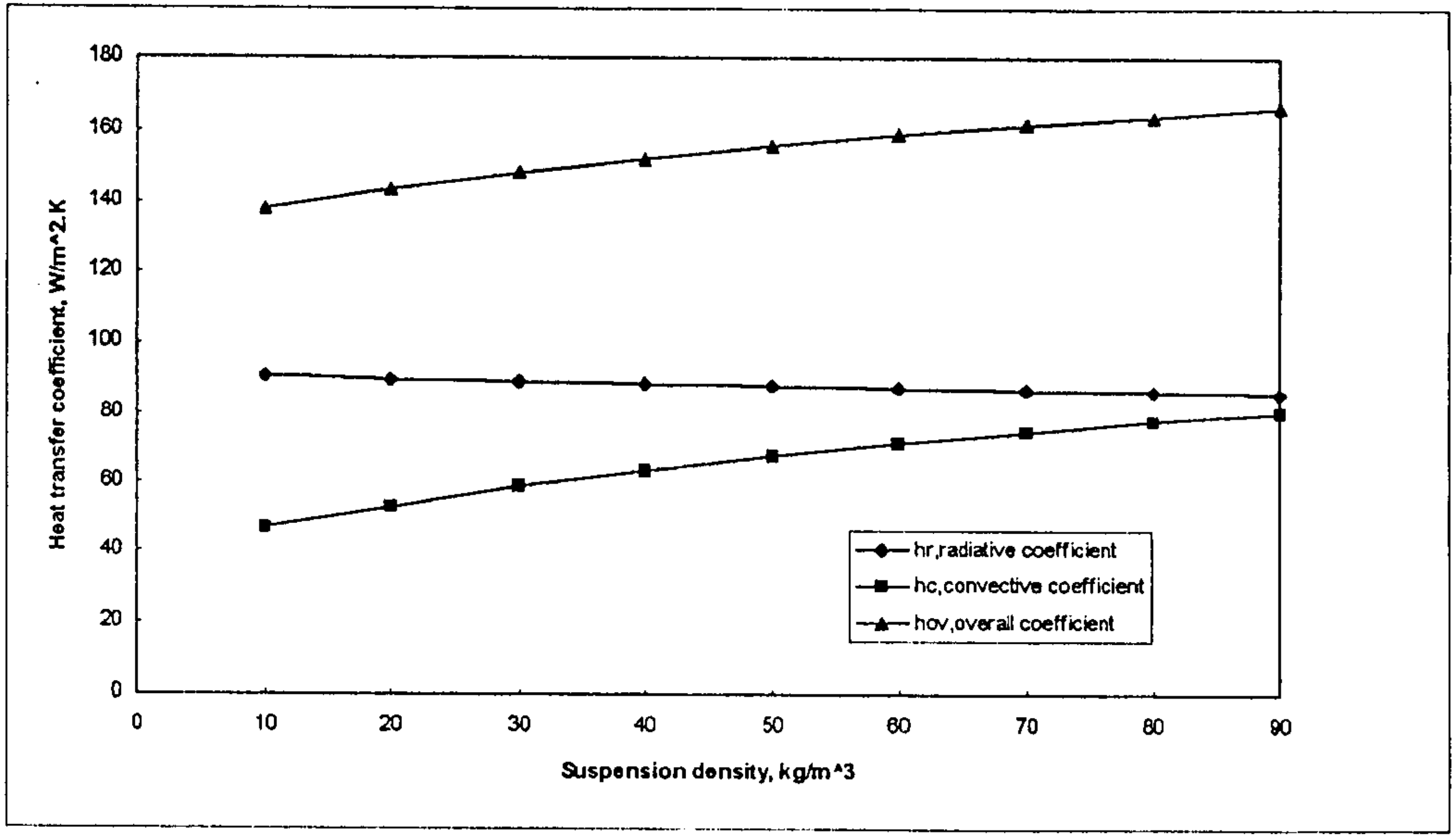

Figure 5.6 Predicted heat transfer coefficient vs suspension density.
(T_b = 1123 K, U_g = 4 m/sec, d_p = 270 μm)

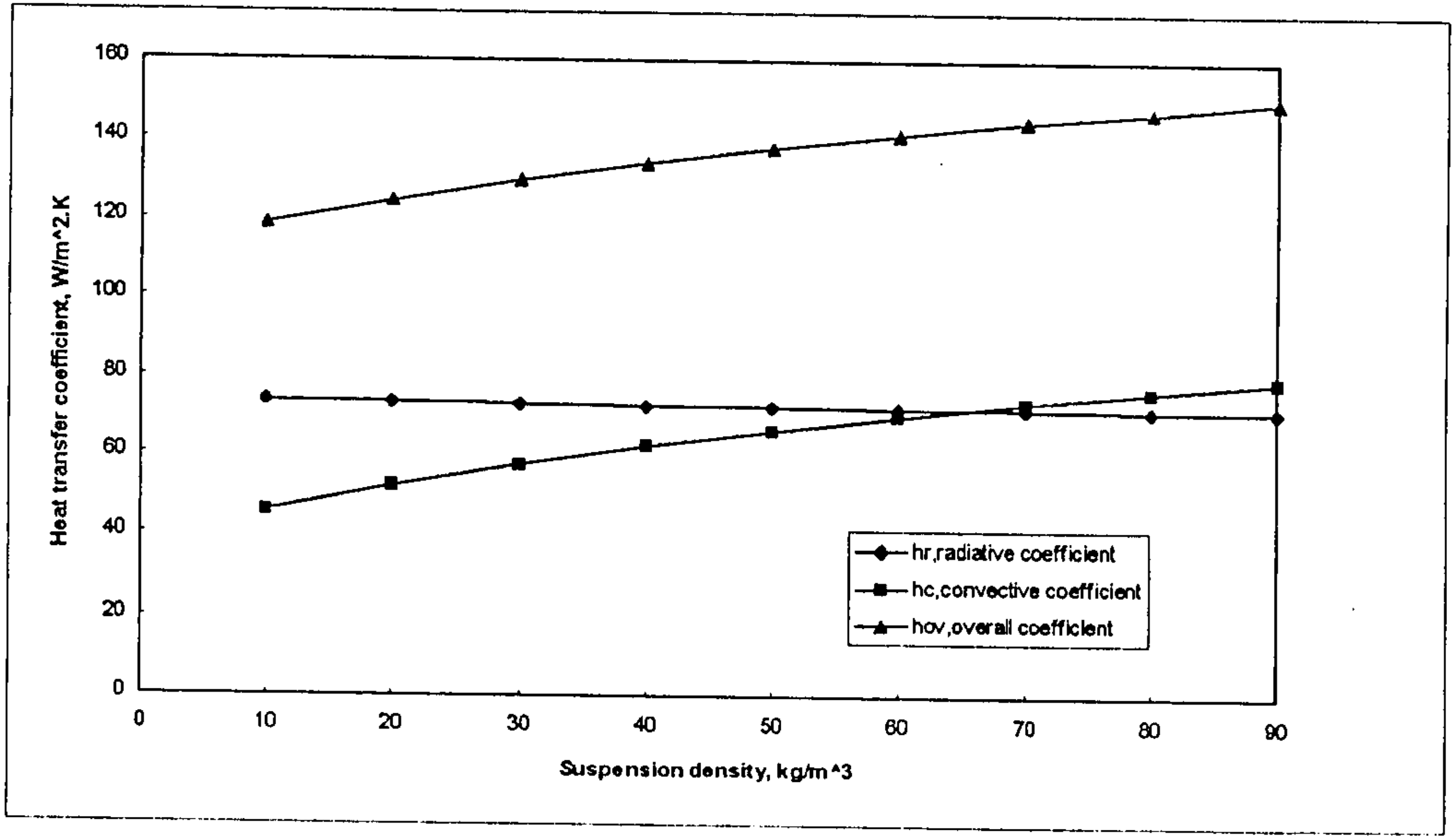

Figure 5.7 Predicted heat transfer coefficient vs suspension density.
(T_b = 1023 K, U_g = 6 m/sec, d_p = 270 μm)

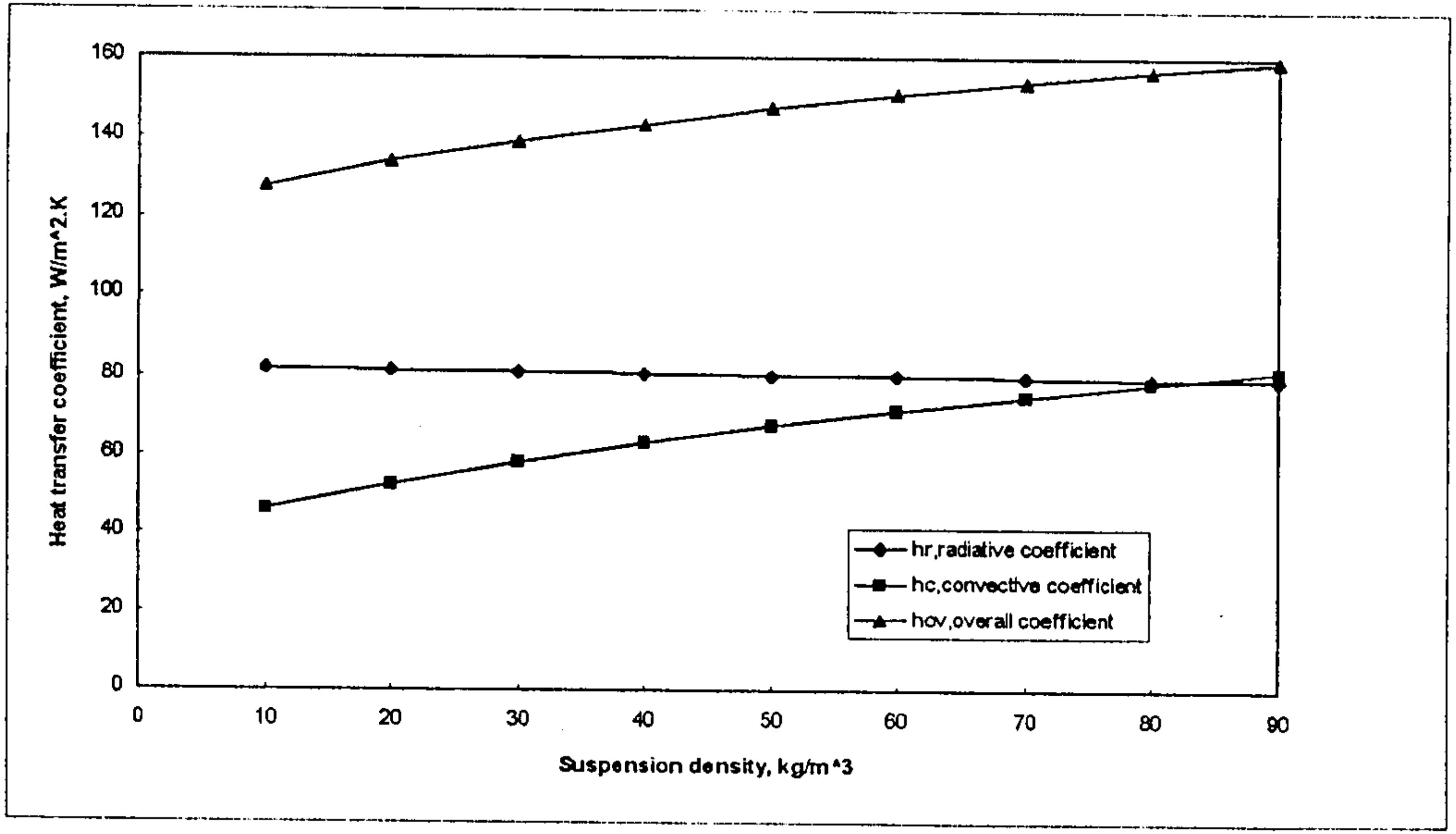

Figure 5.8 Predicted heat transfer coefficient vs suspension density.
(T_b = 1073 K, U_g = 6 m/sec, d_p = 270 μm)

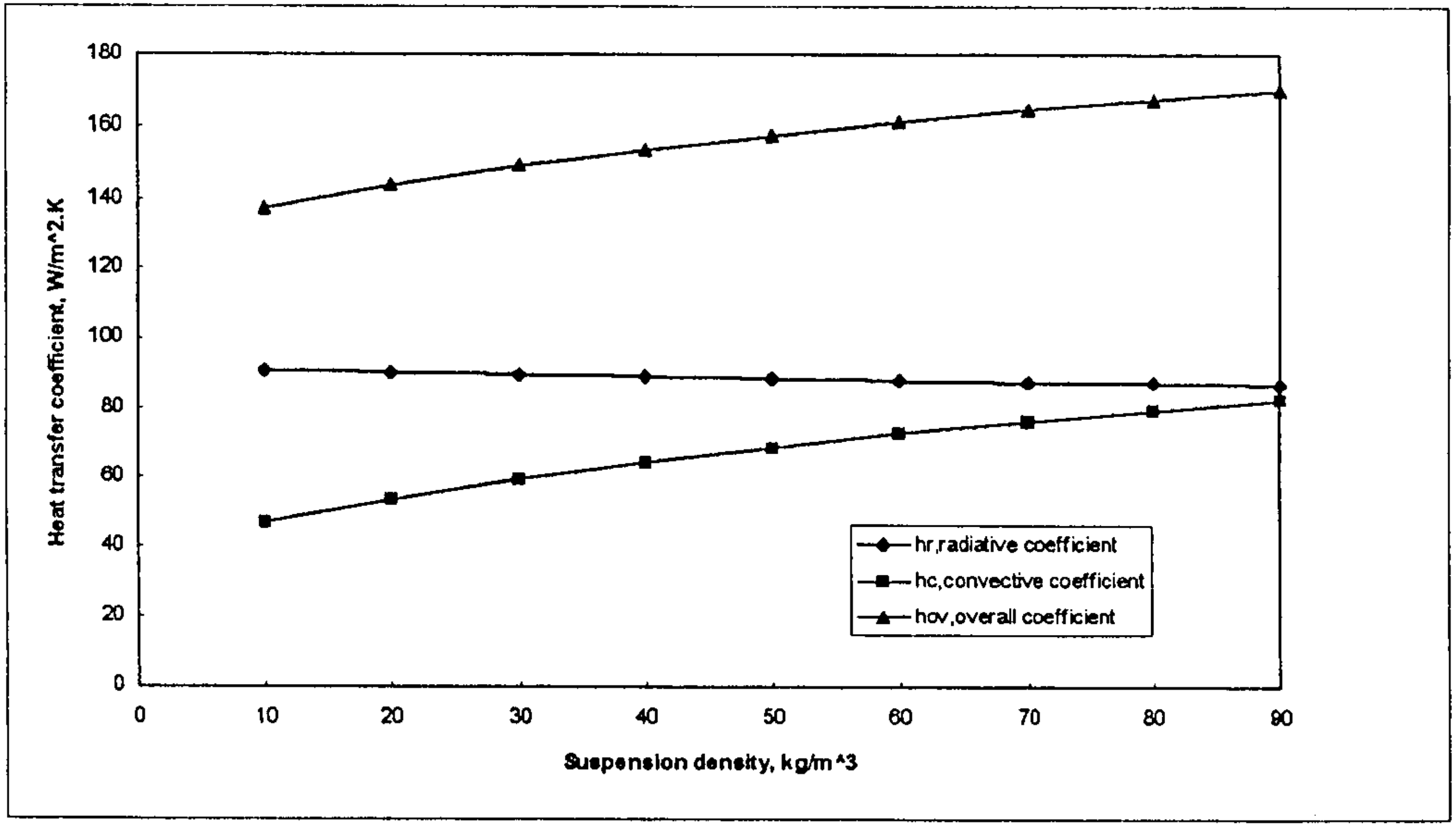

Figure 5.9 Predicted heat transfer coefficient vs suspension density.
(T_b = 1123 K, U_g = 6 m/sec, d_p = 270 μm)

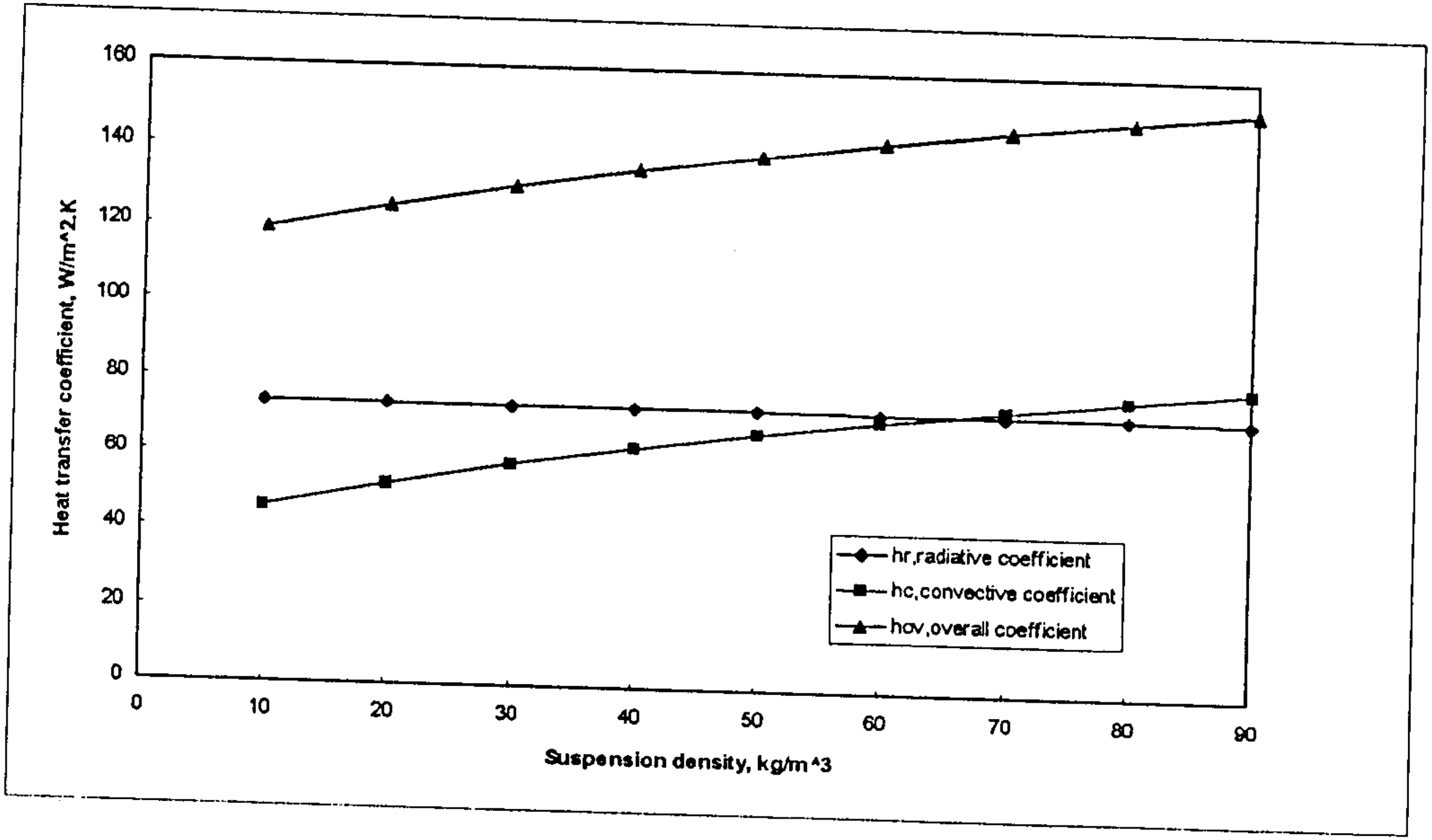

Figure 5.10 Predicted heat transfer coefficient vs suspension density.
(T_b = 1023 K, U_g = 8 m/sec, d_p = 270 μm)

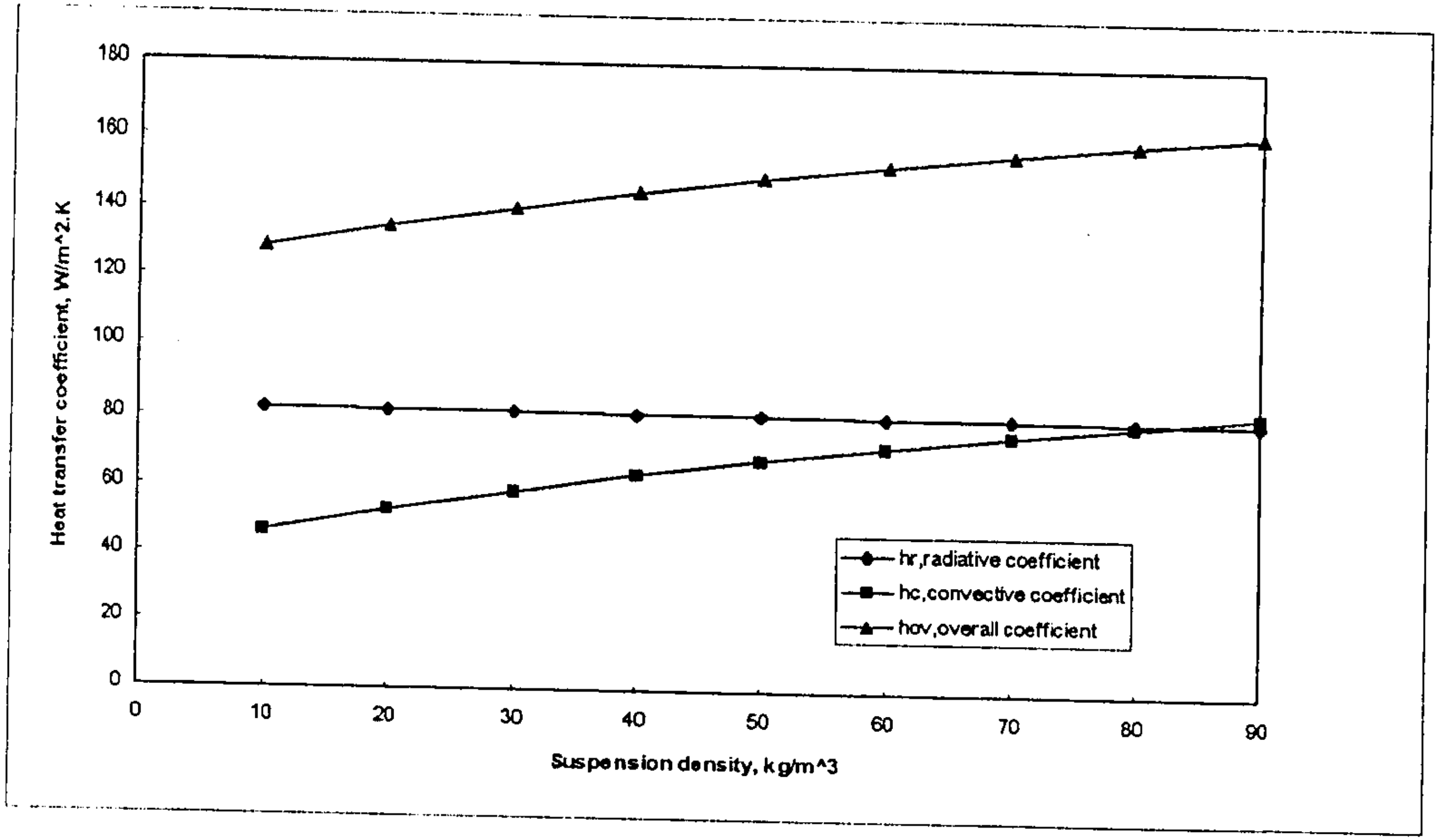

Figure 5.11 Predicted heat transfer coefficient vs suspension density.
(T_b = 1073 K, U_g = 8 m/sec, d_p = 270 μm)

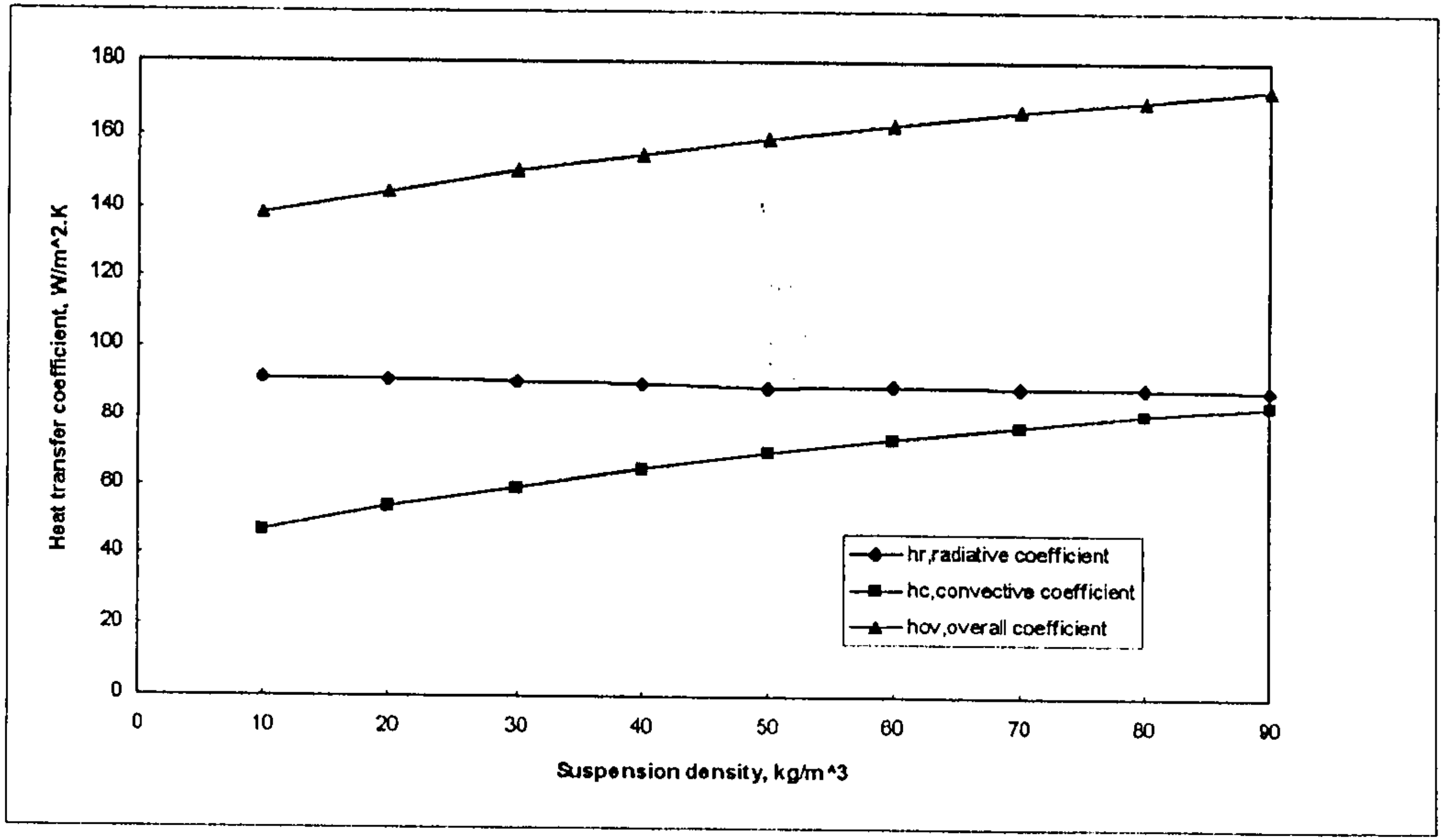

Figure 5.12 Predicted heat transfer coefficient vs suspension density.
(T_b = 1123 K, U_g = 8 m/sec, d_p = 270 μm)

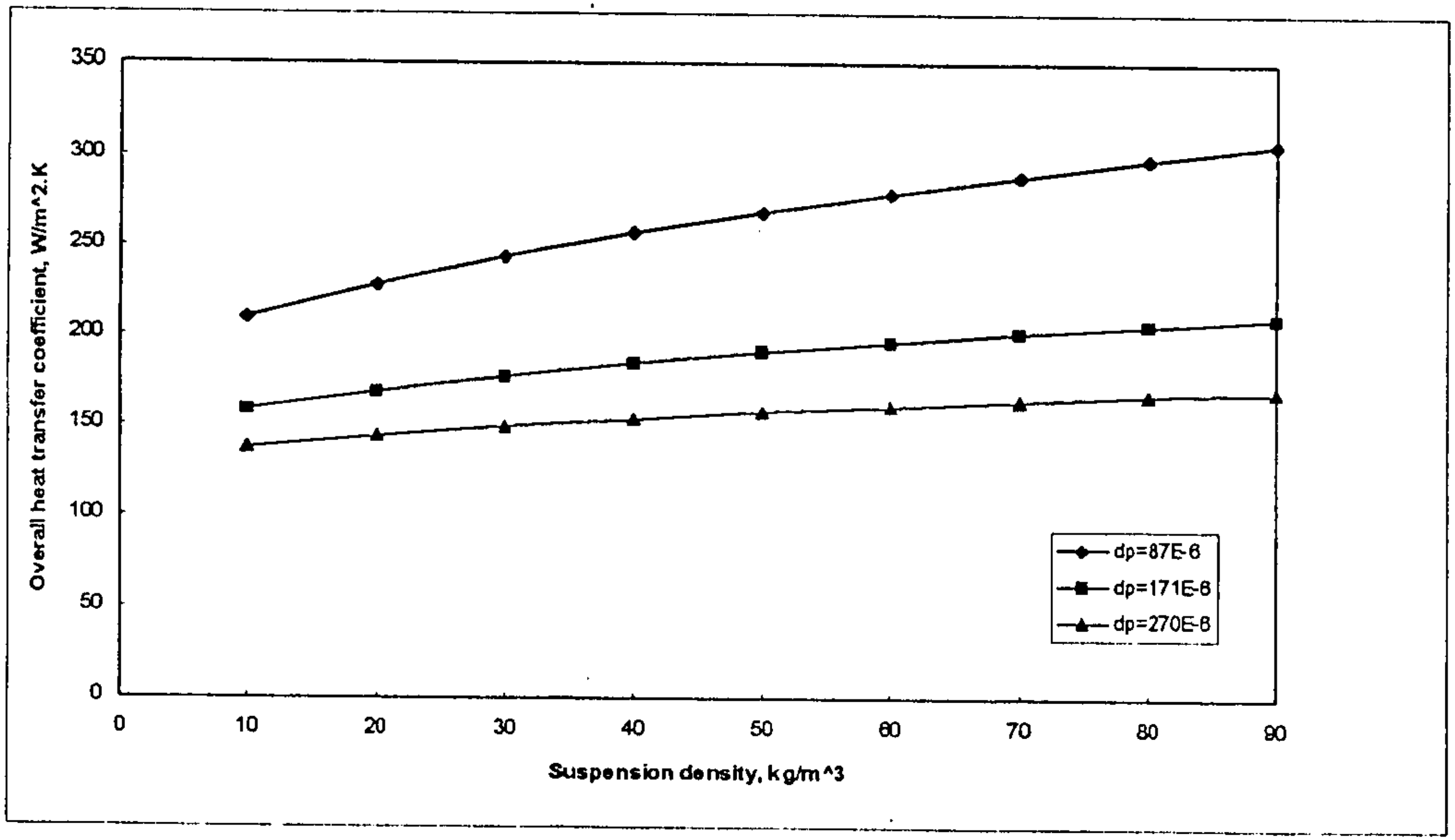

Figure 5.13 Predicted overall heat transfer coefficient vs suspension density.
(T_b = 1123 K, U_g = 6 m/sec)

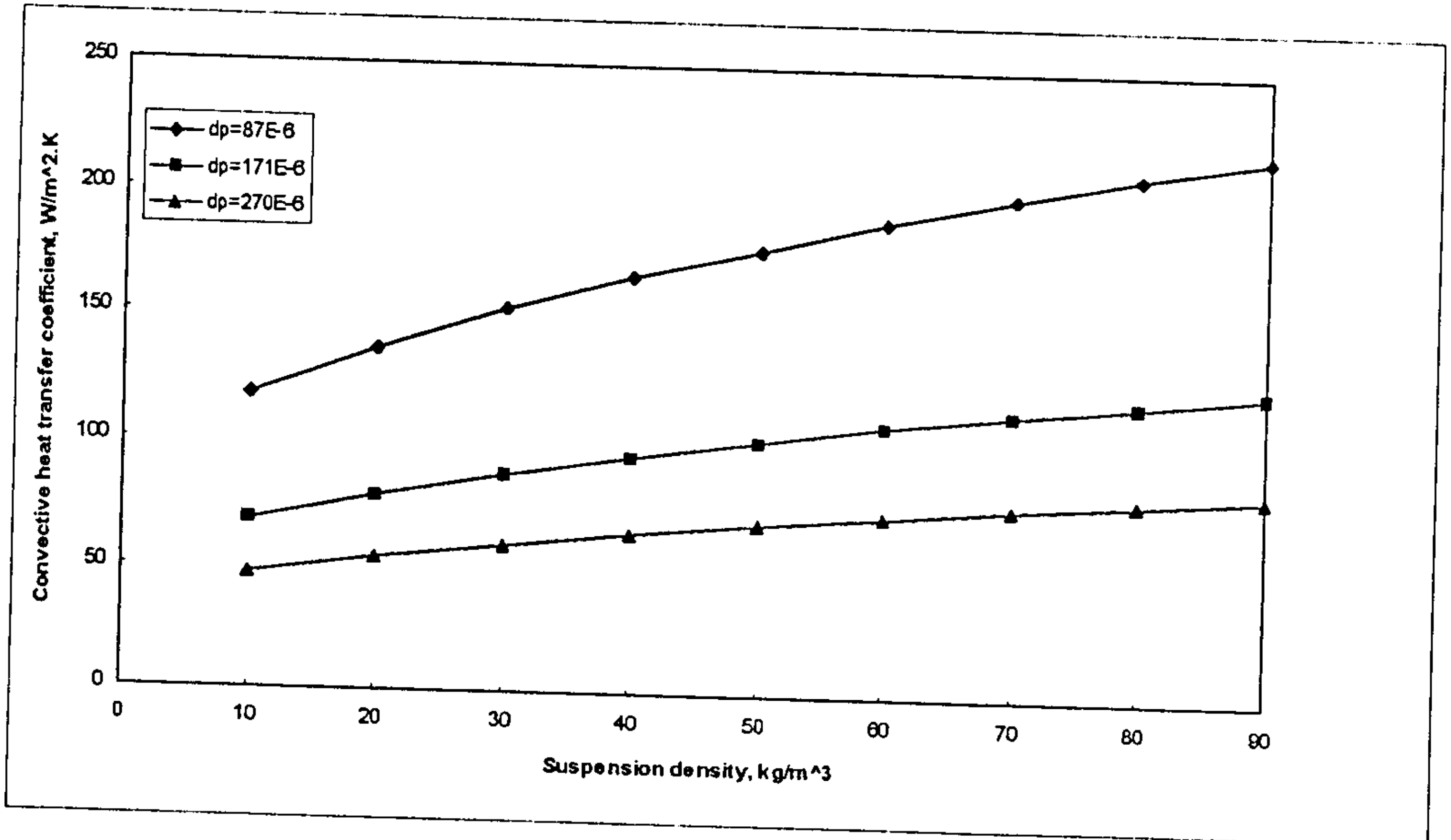

Figure 5.14 Predicted convective heat transfer coefficient vs suspension density.
(T_b = 1123 K, U_g = 6 m/sec)

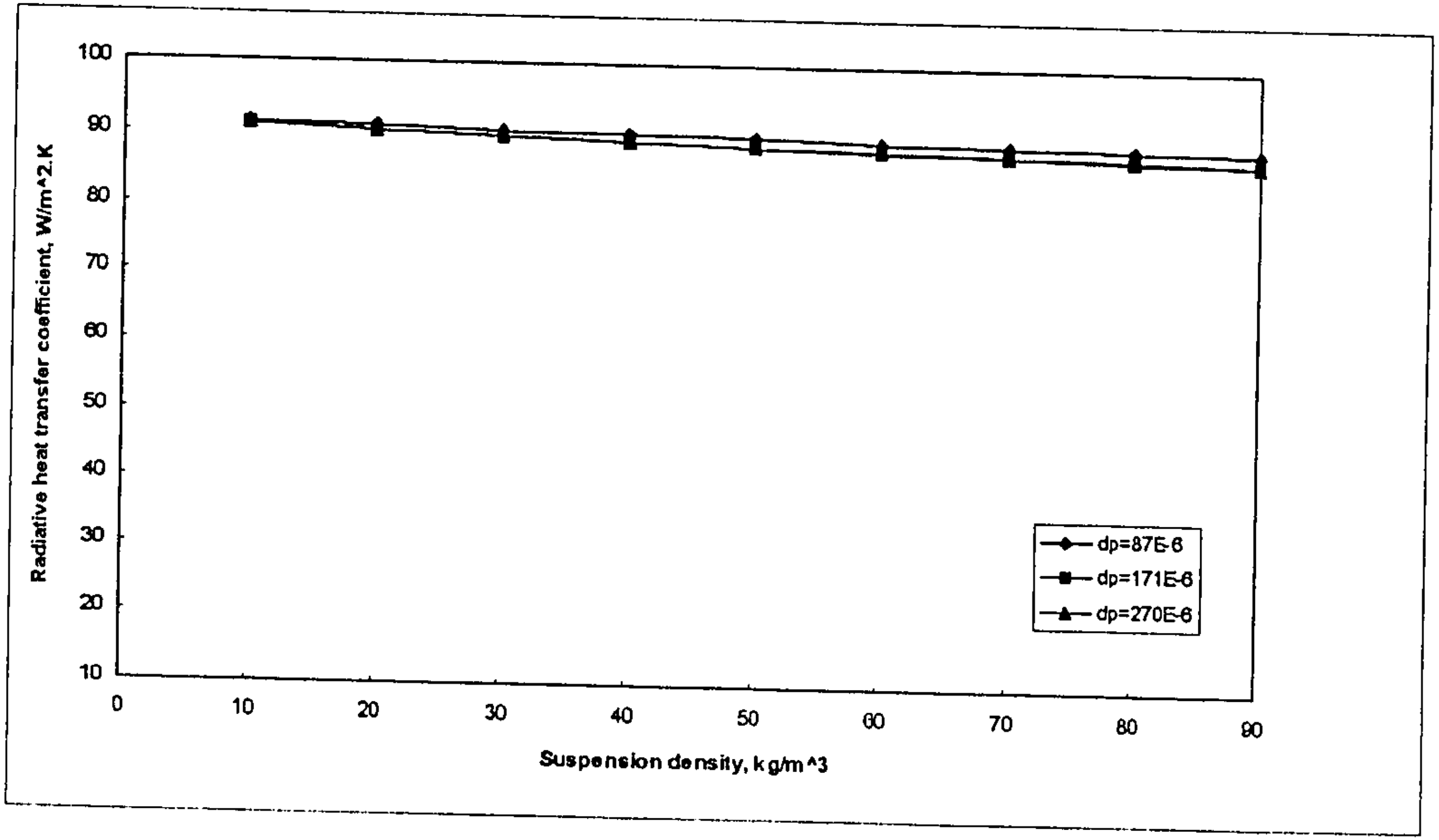

Figure 5.15 Predicted radiative heat transfer coefficient vs suspension density.
(T_b = 1123 K, U_g = 6 m/sec)

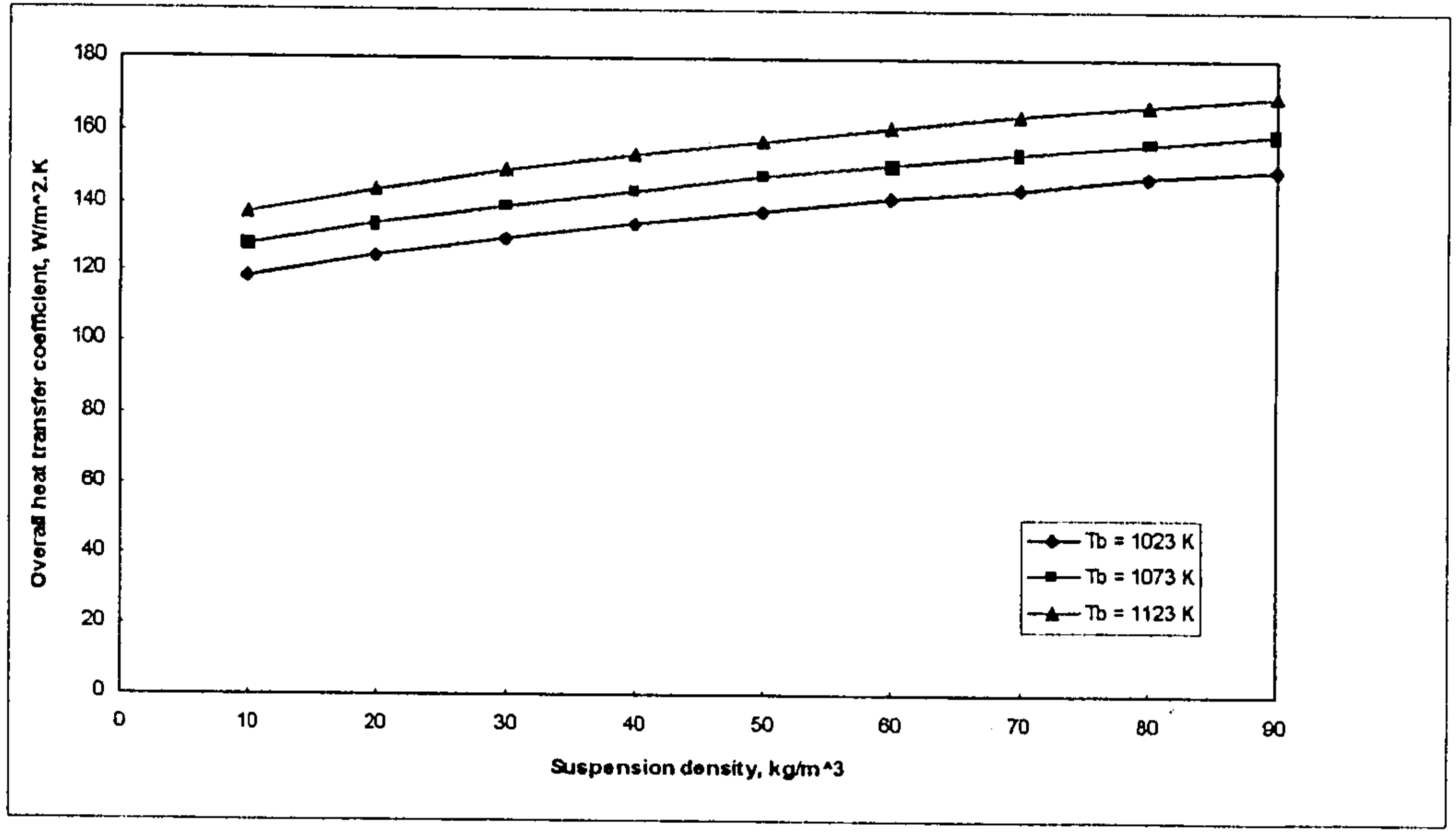

Figure 5.16 Predicted overall heat transfer coefficient vs suspension density.
(U_g = 6 m/sec, d_p = 270 μm)

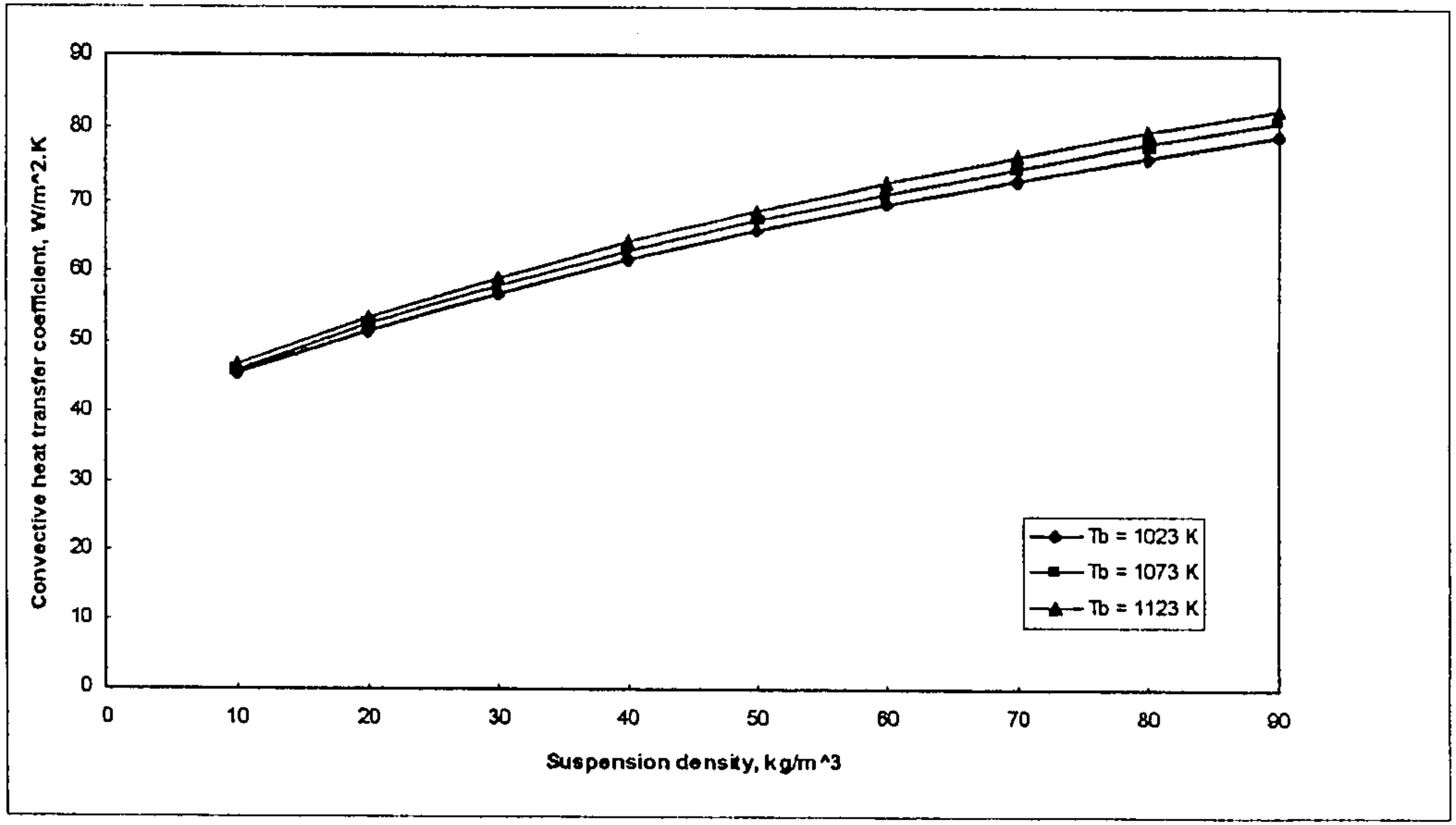

Figure 5.17 Predicted convective heat transfer coefficient vs suspension density.
(U_g = 6 m/sec, d_p = 270 μm)

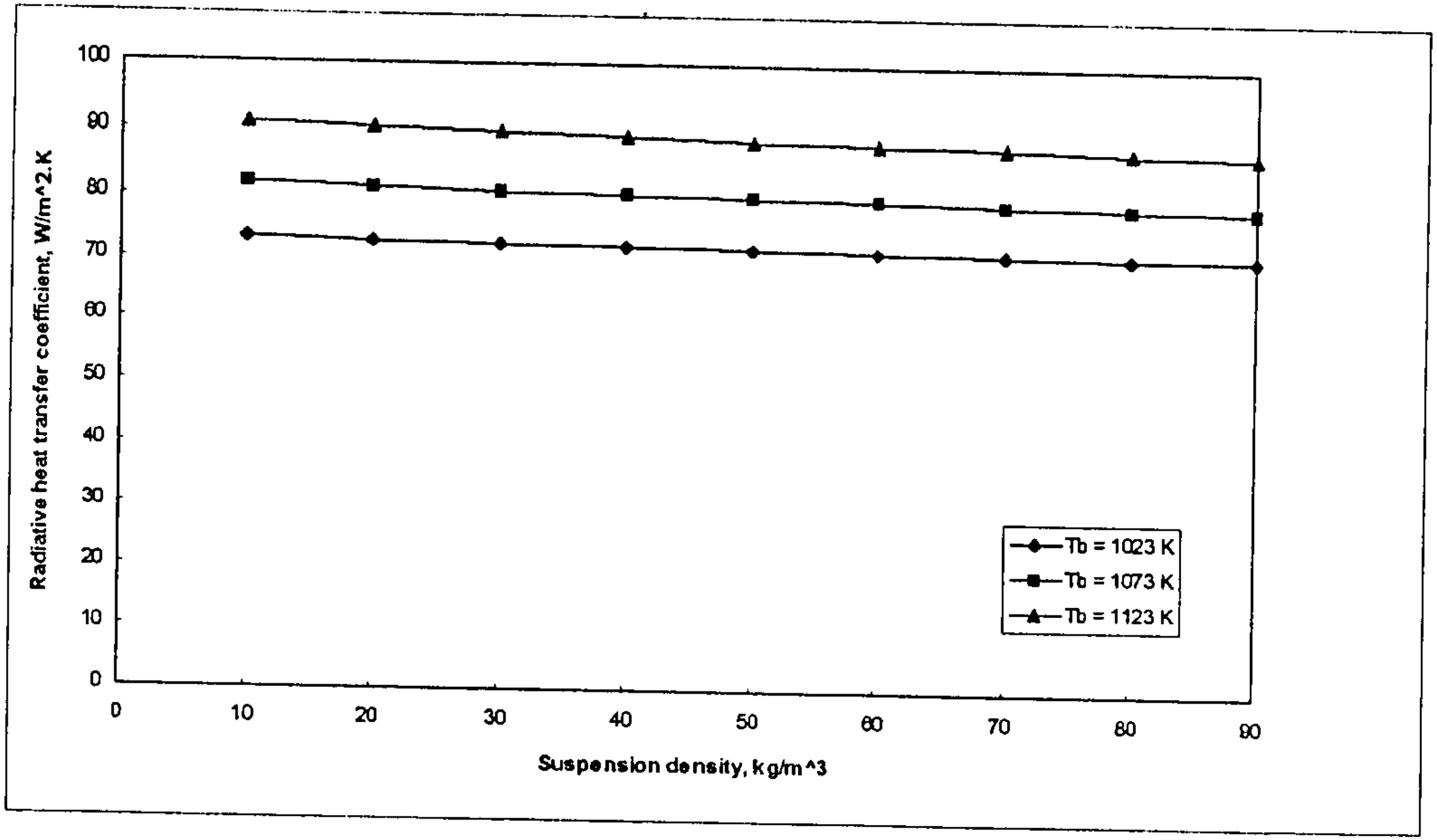

Figure 5.18 Predicted radiative heat transfer coefficient vs suspension density.
(U_g = 6 m/sec, d_p = 270 μm)

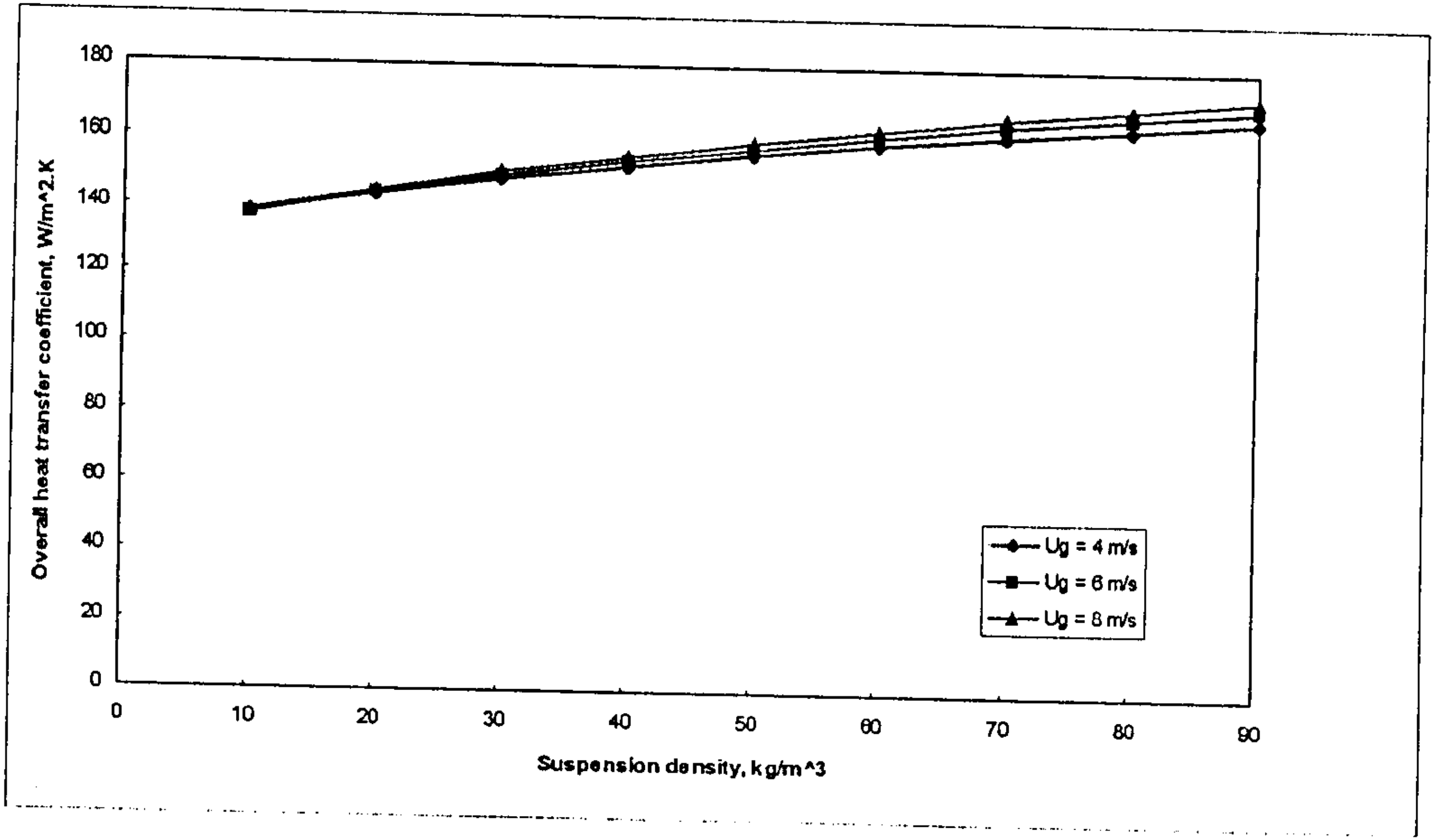

Figure 5.19 Predicted overall heat transfer coefficient vs suspension density.
(T_b = 1123 K, d_p = 270 μm)

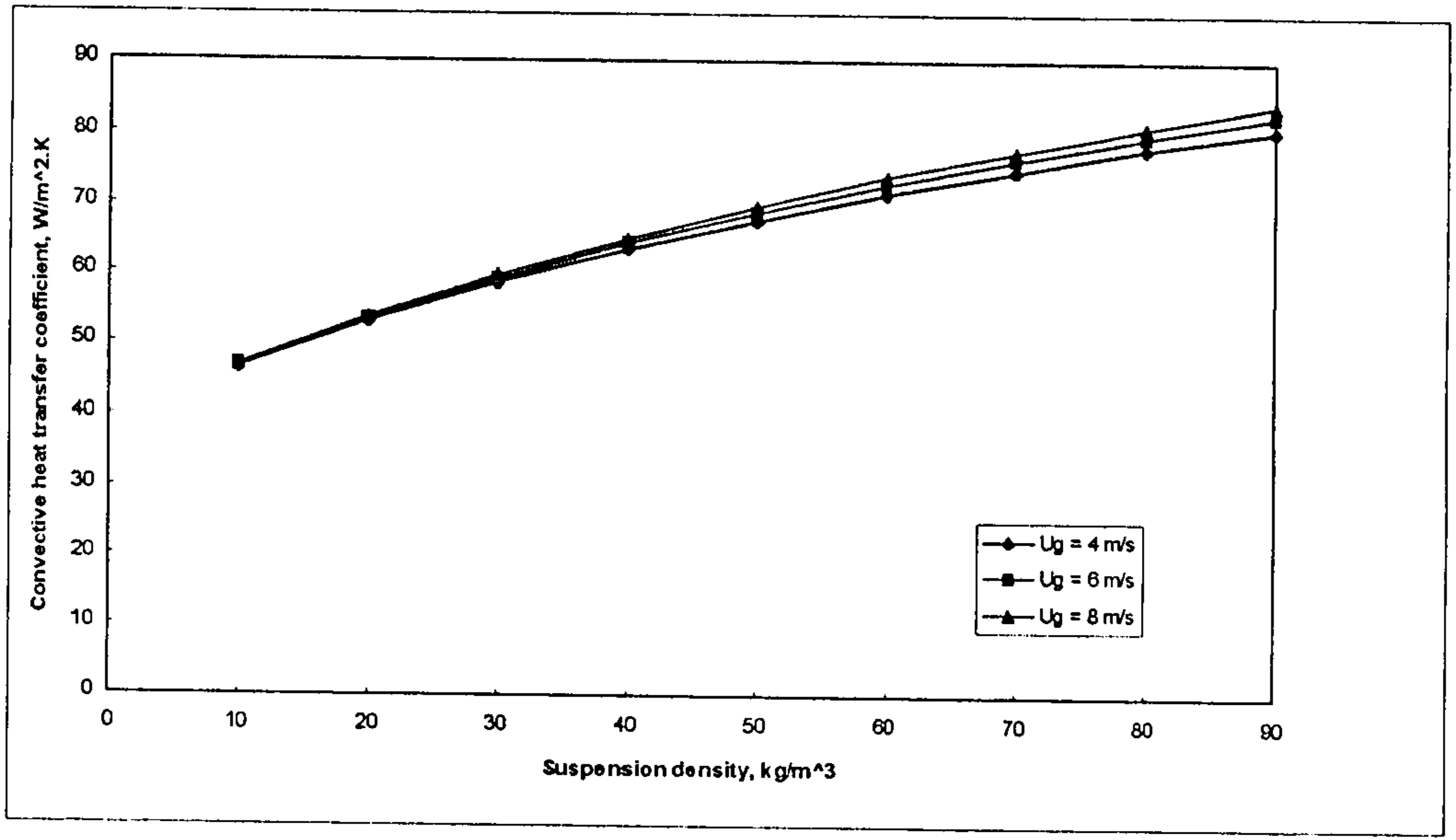

Figure 5.20 Predicted convective heat transfer coefficient vs suspension density.
(T_b = 1123 K, d_p = 270 μm)

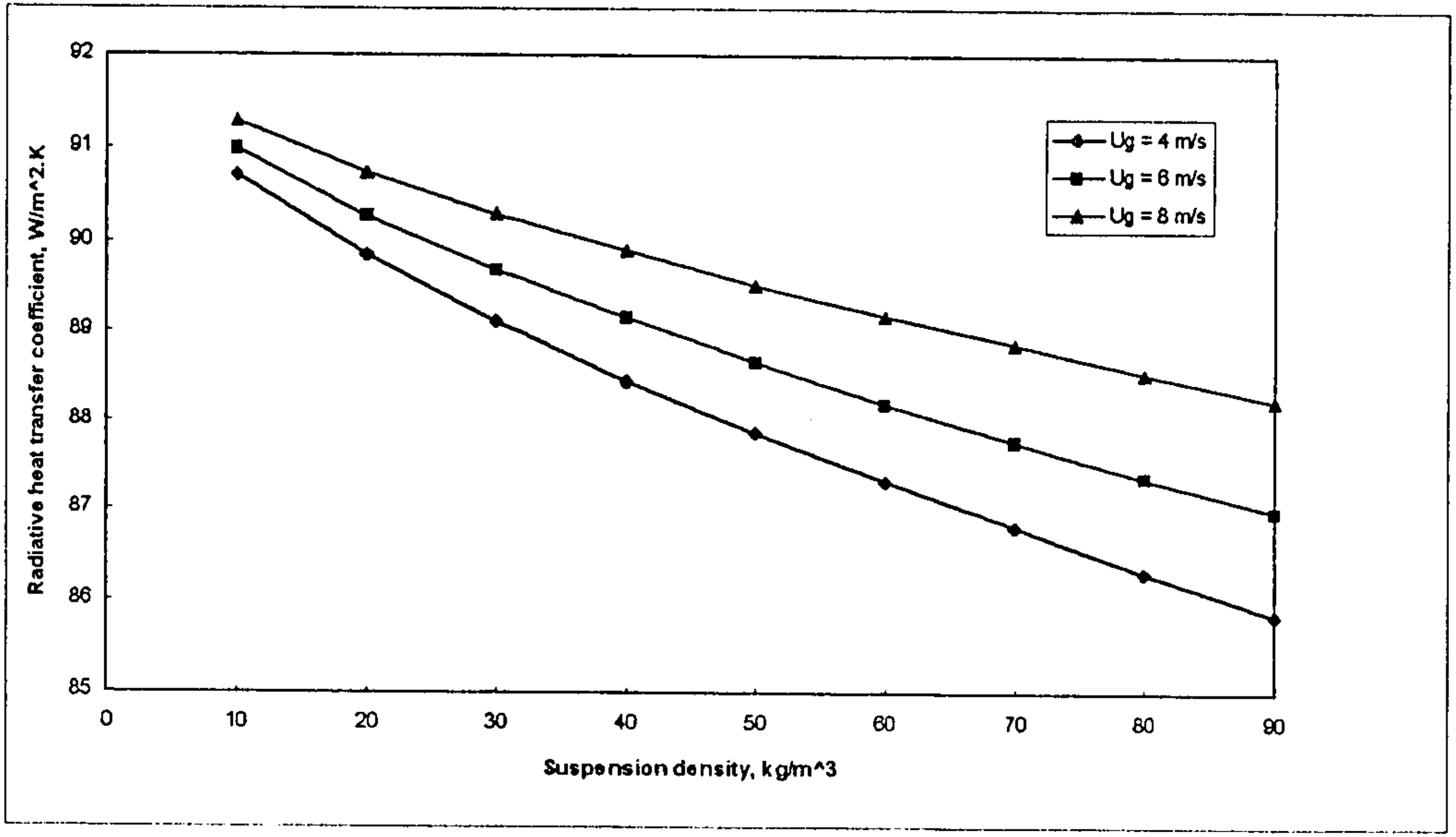

Figure 5.21 Predicted radiative heat transfer coefficient vs suspension density.
(T_b = 1123 K, d_p = 270 μm)

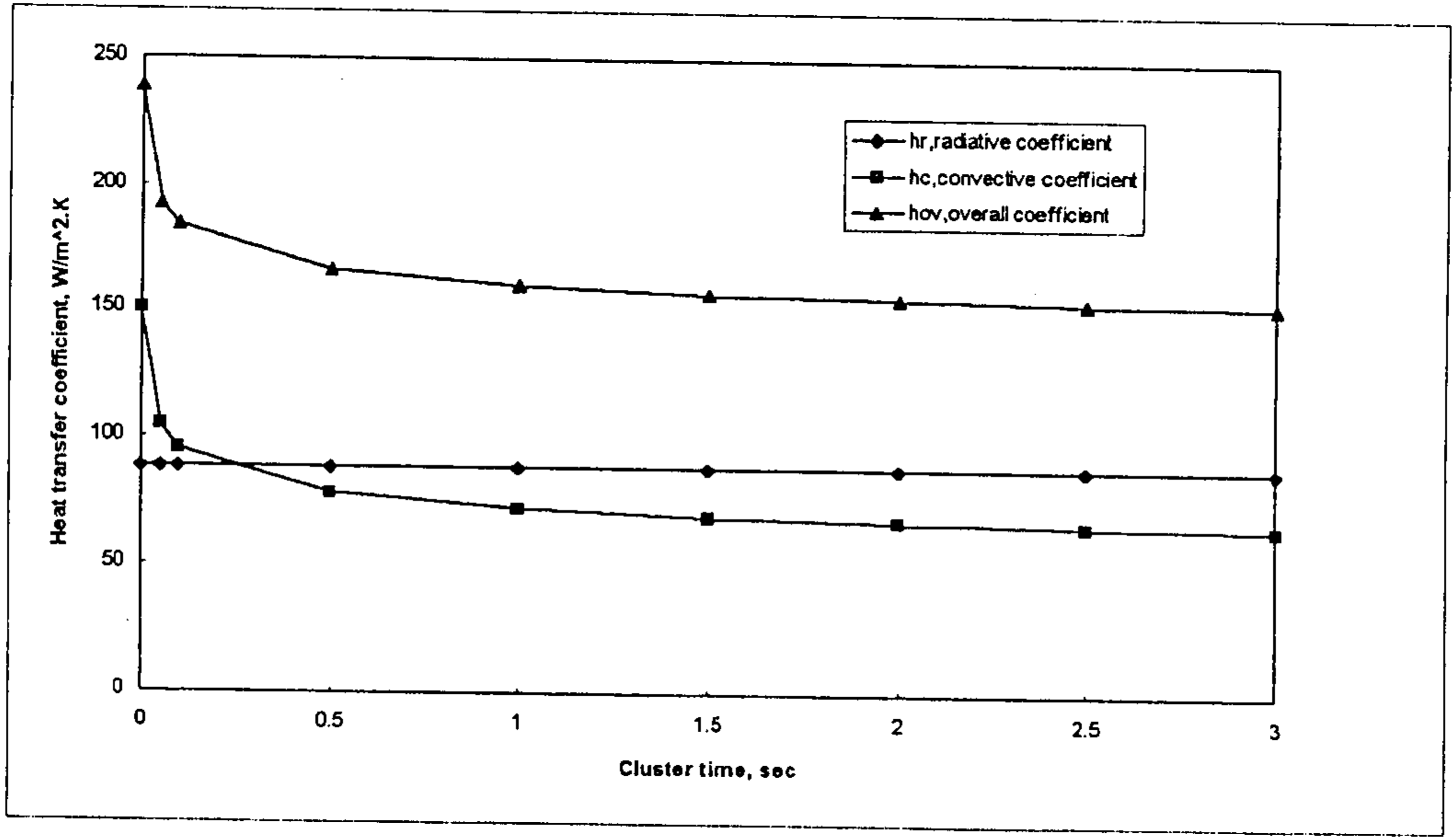

Figure 5.22 Predicted heat transfer coefficient vs cluster time.
(T_b = 1123 K, U_g = 6 m/sec, d_p = 270 μm, ρ_{sus} = 50 kg/m^3)

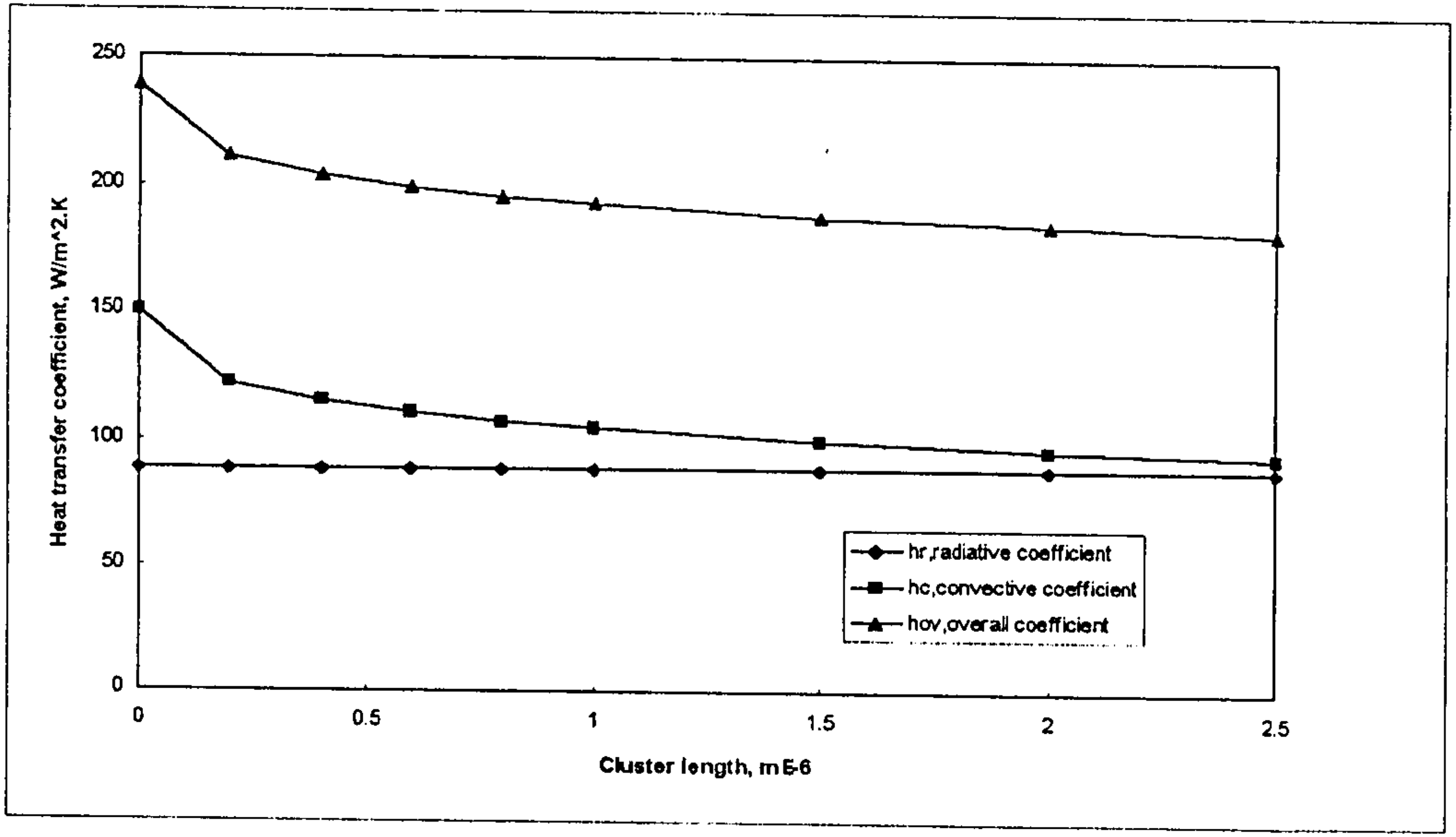

Figure 5.23 Predicted heat transfer coefficient vs cluster length.
(T_b = 1123 K, U_g = 6 m/sec, d_p = 270 μm, ρ_{sus} = 50 kg/m^3)

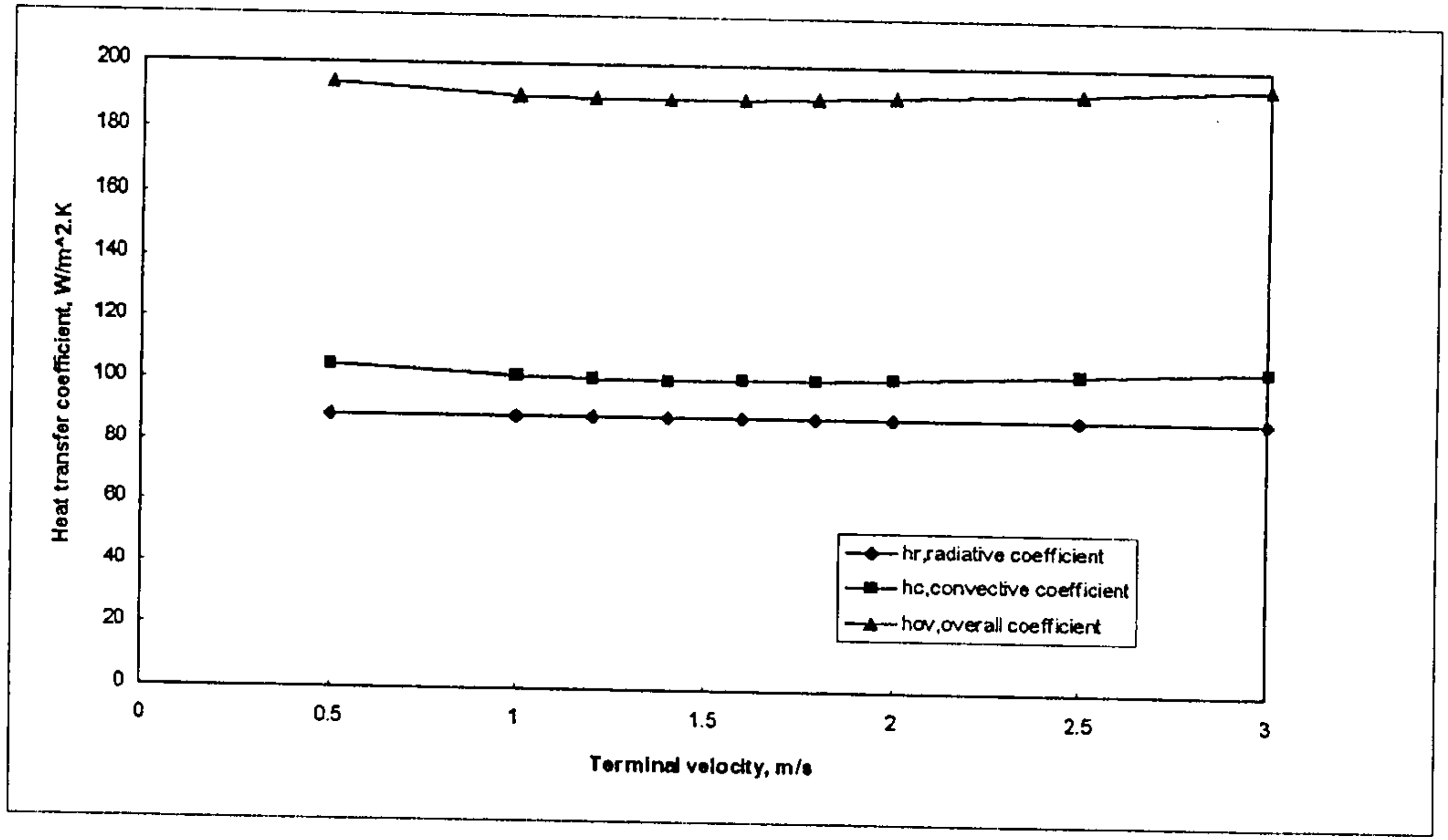

Figure 5.24 Predicted heat transfer coefficient vs terminal velocity.
(T_b = 1123 K, U_g = 6 m/sec, d_p = 270 μm, ρ_{sus} = 50 kg/m^3)

CHAPTER SIX
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions :

From this work, the following may be concluded :

- Suspension density is the most significant factor influencing the heat transfer in a circulating fluidized bed combustor, followed by bed temperature, particle diameter, cluster time and consequently cluster length, and superficial gas velocity, while the least effective parameter is terminal velocity.
- As particle size decreases, the heat transfer coefficient increases for a given suspension density.
- The cluster length is found to affect the determination of convective and total heat transfer coefficient. As the cluster length increases, the total and convective heat transfer coefficients decrease.
- Finer particles play a much stronger role in the determination of heat transfer coefficient than larger particles. This fact appears clearly when the cluster length is short.

6.2 Recommendations :

Although numerous work has been done in the recent years, further work needs to be done to understand and predict the heat transfer performance in circulating fluidized bed boilers. Additional studies are recommended in several areas including :

- It is expected that the shape of heat transfer surface area has a profound influence on the heat transfer exchange. Additional work is especially needed to study local flow patterns and heat transfer coefficient within membrane wall assemblies.
- In almost all work done so far, furnace side convection, furnace - side radiation and conduction within the steel walls themselves have been treated as entirely separate phenomena. Future work is recommended to study coupled heat transfer mechanisms.
- Erosion has proved to be a serious problem in many operating circulating fluidized beds. Work is recommended to investigate the influence of counter erosion devices on heat transfer characteristics.
- Many investigations reported data for small scale circulating fluidized beds. There is a need for data on large scale units for comparison and for verification of models.

- While there is a very large group of potential variables which affect heat transfer in fluidized bed, it is clear that the number which determines the heat transfer is more limited. Work should be done to develop hydrodynamic laws appropriate to circulating fluidized bed heat transfer. The geometric configuration of the heat transfer surface is clearly important. The effect of the interior geometry on the flow pattern of particles must be taken into account for non - smooth surfaces like membrane walls to give improved agreement with experimental results.

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Suspension density, kg/m^3	hr (W/m^2.K)	hc (W/m^2.K)	hov (W/m^2.K)
10	73.07	45.17	118.25
20	72.48	51.18	123.67
30	72.00	56.36	128.35
40	71.56	60.84	132.40
50	71.17	64.76	135.93
60	70.80	68.25	139.05
70	70.45	71.39	141.83
80	70.12	74.23	144.35
90	69.80	76.83	146.63

Table A.1. Results of predicted heat transfer coefficients vs suspension density (U_g = 4.0 m/sec, T_b = 1023 K, d_p = 270 μm).

Suspension density, kg/m^3	hr (W/m^2.K)	hc (W/m^2.K)	hov (W/m^2.K)
10	81.55	45.91	127.47
20	80.83	52.11	132.94
30	80.23	57.45	137.68
40	79.70	62.08	141.78
50	79.21	66.14	145.35
60	78.75	69.75	148.50
70	78.32	73.00	151.32
80	77.92	75.94	153.86
90	77.53	78.63	156.16

Table A.2. Results of predicted heat transfer coefficients vs suspension density (U_g = 4.0 m/sec, T_b = 1073 K, d_p = 270 μm).

Suspension density, kg/m^3	hr ($W/m^2.K$)	hc ($W/m^2.K$)	hov ($W/m^2.K$)
10	90.72	46.63	137.35
20	89.84	53.02	142.86
30	89.11	58.53	147.65
40	88.45	63.31	151.78
50	87.88	67.50	155.38
60	87.33	71.23	158.56
70	86.81	74.58	161.39
80	86.32	77.63	163.94
90	85.85	80.41	166.26

Table A.3. Results of predicted heat transfer coefficients vs suspension density ($U_g = 4.0$ m/sec, $T_b = 1123$ K, $d_p = 270$ μm).

Suspension density, kg/m^3	hr ($W/m^2.K$)	hc ($W/m^2.K$)	hov ($W/m^2.K$)
10	73.34	45.28	118.62
20	72.90	51.50	124.40
30	72.54	56.92	129.46
40	72.22	61.65	133.87
50	71.92	65.82	137.75
60	71.65	69.55	141.20
70	71.39	72.90	144.30
80	71.14	75.96	147.10
90	70.91	78.76	149.67

Table A.4. Results of predicted heat transfer coefficients vs suspension density ($U_g = 6.0$ m/sec, $T_b = 1023$ K, $d_p = 270$ μm).

Suspension density, kg/m^3	hr (W/m^2.K)	hc (W/m^2.K)	hov (W/m^2.K)
10	81.82	46.02	127.84
20	81.25	52.43	133.69
30	80.78	58.03	138.81
40	80.36	62.92	143.28
50	79.98	67.23	147.21
60	79.62	71.08	150.70
70	79.28	74.55	153.83
80	78.96	77.72	156.68
90	78.65	80.62	159.27

Table A.5. Results of predicted heat transfer coefficients vs suspension density($U_g = 6.0$ m/sec, $T_b = 1073$ K, $d_p = 270$ μm).

Suspension density, kg/m^3	hr (W/m^2.K)	hc (W/m^2.K)	hov (W/m^2.K)
10	90.99	46.73	137.00
20	90.27	53.35	143.62
30	89.67	59.12	148.80
40	89.14	64.17	153.31
50	88.65	68.62	157.27
60	88.20	72.60	160.80
70	87.78	76.18	163.96
80	87.37	79.45	166.82
90	86.98	82.45	169.43

Table A.6. Results of predicted heat transfer coefficients vs suspension density ($U_g = 6.0$ m/sec, $T_b = 1123.0$ K, $d_p = 270$ μm).

Suspension density, kg/m³	hr (W/m².K)	hc (W/m².K)	hov (W/m².K)
10	73.64	45.35	118.99
20	73.37	51.72	125.09
30	73.14	57.32	130.46
40	72.91	62.23	135.17
50	72.76	66.58	139.34
60	72.63	70.47	143.07
70	72.43	74.00	146.43
80	72.28	77.20	149.50
90	72.14	80.15	152.29

Table A.7. Results of predicted heat transfer coefficients vs suspension density (U_g = 8.0 m/sec, T_b = 1023 K, d_p = 270 μm).

Suspension density, kg/m³	hr (W/m².K)	hc (W/m².K)	hov (W/m².K)
10	82.13	46.09	128.21
20	81.72	52.66	134.38
30	81.39	58.44	139.83
40	81.09	63.51	144.61
50	80.82	68.00	148.83
60	80.57	72.03	152.60
70	80.34	75.67	156.00
80	80.11	79.00	159.11
90	79.90	82.05	161.94

Table A.8. Results of predicted heat transfer coefficients vs suspension density(U_g = 8.0 m/sec, T_b = 1073 K, d_p = 270 μm).

Suspension density, kg/m³	hr (W/m².K)	hc (W/m².K)	hov (W/m².K)
10	91.29	46.82	138.11
20	90.74	53.58	144.32
30	90.29	59.54	149.83
40	89.88	64.77	154.65
50	89.51	69.41	158.92
60	89.17	73.57	162.74
70	88.84	77.33	166.17
80	88.53	80.76	169.30
90	88.24	83.92	172.16

Table A.9. Results of predicted heat transfer coefficients vs suspension density ($U_g = 8.0$ m/sec, $T_b = 1123$ K, $d_p = 270$ μm).

Suspension density, kg/m³	hr (W/m².K)	hc (W/m².K)	hov (W/m².K)
10	91.39	117.68	209.07
20	90.91	136.25	227.16
30	90.50	152.30	242.80
40	90.14	166.30	256.43
50	89.81	187.67	268.50
60	89.50	189.77	279.28
70	89.21	199.84	289.05
80	88.94	209.06	298.00
90	88.67	217.55	306.23

Table A.10. Results of predicted heat transfer coefficients vs suspension density ($U_g = 6.0$m/sec, $T_b = 1123$ K, $d_p = 87$ μm).

Suspension density, kg/m^3	hr (W/m^2.K)	hc (W/m^2.K)	hov (W/m^2.K)
10	90.98	67.91	158.89
20	90.25	78.10	168.34
30	89.65	86.95	176.60
40	89.11	94.69	183.80
50	88.62	101.52	190.15
60	88.17	107.63	195.80
70	87.74	113.16	200.90
80	87.33	118.20	205.53
90	86.94	122.83	209.77

Table A.11. Results of predicted heat transfer coefficients vs suspension density (U_g = 6.0m/sec, T_b = 1123 K, d_p = 171 μm).

Cluster time, sec	hr (W/m^2.K)	hc (W/m^2.K)	hov (W/m^2.K)
0.0	88.62	150.25	238.87
0.02	88.62	114.82	203.44
0.04	88.62	106.66	195.28
0.06	88.62	101.17	190.33
0.08	88.62	98.18	186.80
0.10	88.62	95.46	184.09
0.50	88.62	77.76	166.38
1.00	88.62	71.75	160.37
1.5	88.62	68.75	157.38
2.00	88.62	66.86	155.48
2.50	88.62	65.51	154.13
3.00	88.62	64.49	153.11

Table A.12. Results of predicted heat transfer coefficients vs cluster time (U_g = 6.0m/sec, T_b = 1123 K, ρ_{sus} = 50.0 kg/m^3, d_p = 270 μm).

Cluster length, μm	hr (W/m².K)	hc (W/m².K)	hov (W/m².K)
0.0	88.62	150.25	238.87
0.20	88.62	122.70	211.40
0.40	88.62	115.43	204.06
0.60	88.62	110.75	199.38
0.80	88.62	107.32	195.94
1.00	88.62	104.61	193.23
1.50	88.62	99.64	188.26
2.00	88.62	96.12	184.75
2.50	88.62	93.43	182.06
3.00	88.62	91.27	179.90

Table A.13. Results of predicted heat transfer coefficients vs cluster length (U_g = 6.0m/sec, T_b = 1123 K, ρ_{sus} = 50.0 kg/m³, d_p = 270 μm).

Terminal velocity, m/sec	hr (W/m².K)	hc (W/m².K)	hov (W/m².K)
0.5	88.62	105.27	193.89
1.00	88.62	101.87	190.50
1.20	88.62	101.35	189.98
1.40	88.62	101.18	189.80
1.60	88.62	101.27	189.89
1.80	88.62	101.57	190.20
2.00	88.62	102.03	190.66
2.50	88.62	103.68	192.31
3.00	88.62	105.80	194.42

Table A.14. Results of predicted heat transfer coefficients vs terminal velocity (U_g = 6.0m/sec, T_b = 1123 K, ρ_{sus} = 50.0 kg/m³, d_p = 270 μm).

APPENDIX B

Algorithm used to calculate overall heat transfer coefficient in circulating fluidized bed combustor :

1) Calculating time fraction (f) [equation 3.2] :

a) Compute wall voidage (ε_w) from equation (3.8) by inserting desired value of suspension density (ρ_{sus}).

b) Compute cluster voidage (ε_c) from equation (4.2) where the values of x and R are set to be (0.025m) and (0.7m) respectively as in Golriz. et. al. (1995).

c) The value of Y is set to be (0.001 %) as in Golriz et. al. (1995).

d) In this work, A and k are set to be 0.35 and 0.65 respectively.

2) Calculating cluster convective heat transfer coefficient (h_{cc}) [equation 3.9] :

a) Compute specific heat of the cluster (Cp_c) from equation (3.10).

b) Compute cluster density (ρ_c) from equation (3.11).

c) Compute cluster thermal conductivity (k_c) from equation (3.12).

d) Compute gas film thickness (δ_g) from equation (3.13) where suspension voidage (ε_{sus}) is calculated from equation (3.6) after inserting the desired value of suspension density (ρ_{sus}) and particle density (ρ_p), also (δ_{roug}) is considered to be (10 μm) as in Golriz et. al. (1995).

e) Compute thermal conductivity of the gas film (k_{gf}) as thermal conductivity of the gas at $T = (T_b + T_w) / 2.0$.

f) Compute cluster time (t_c) from equation (4.5) where ρ_p, ε_{sus}, ε_c, U_g, and g are known or calculated before. Terminal velocity (U_t) appearing in the equation is determined from equation (4.6).

3) Calculating cluster radiative heat transfer coefficient (h_{rc}) [equation 3.14]:

a) Compute cluster temperature (T_c) from equation (3.15) where the following assumptions are used as in Golriz et. al. (1995) :

$h / H = 0.5$

$x = 0.025$ m

b) Compute cluster emissivity (e_c) from equation (3.16) where emissivity of particles (e_p) is set to be (0.6).

c) Compute wall emissivity (e_w) from equation (4.7) where t_c and d_p are known but wall material emissivity (e_{wt}) is taken from tables and a value of (0.81) is used in this work.

4) Calculating dispersed phase convective heat transfer coefficient (h_{cd}) [eqaution 3.17] :

a) Compute density of the dispersed phase (ρ_{dis}) from equation (3.18) .

b) All the other parameters are either known or calculated before.

5) Calculating Dispersed phase radiative heat transfer coefficient (h_{rd}) [equation 3.19] :

a) Compute the emissivity of the dispersed phase (e_{dis}) from equation (3.20) where B was set to be 0.5 .

b) All other parameters are known.

6) Calculate overall heat transfer coefficient (h_{ov}) from equation (3.1) where all the components are known besides time fraction.

APPENDIX C

Sample Calculation :

Cluster voidage (ε_c) :

1) In previous works, it was found that cluster voidage (ε_c) depends on the suspension voidage (ε_{sus}) and the distance between the cluster and the wall (x) where also the size of the fluidized bed must be taken into consideration (R).

$$\varepsilon_c = f(\varepsilon_{sus}, x, R)$$

2)Therefore, the expression for the cluster voidage must consist of these affecting parameters. Then, the best form of relation between the affecting parameters is chosen.

$$\varepsilon_c = Z\, \varepsilon_{sus}^{N(x/R)}$$

3) The results of the obtained expression are compared with those of experimental works. Then, the constants (Z and N) are changed till the best agreement is achieved between the obtained results from the expression and the experimental ones.

$$\varepsilon_c = 0.5\ \varepsilon_{sus}^{(2.074\ (x/R))}$$

APPENDIX D

```
C        *****************************************************
C       ****  THIS  PROGRAM IS TO DETERMINE THE HEAT  ******
C       ****  TRANSFER COEFFICIENT IN CIRCULATING    *******
C       ****        FLUIDIZED BED COMBUSTORS          *******
C       ****   DONE BY : ABD AL-RAHMAN AL-QAQ         *******
C        *****************************************************

      CALL A3(HCD,UT2)
      CALL A4(HCC,UT1,TCC1)
      CALL A1(HRC,TC22)
      CALL A2(HRD)

      Y = 0.00001

      WRITE(*,44)
44    FORMAT(5X,"INPUT ROSUS",/)

      READ(*,33)RO1SUS
33    FORMAT(F15.8)

      ROP = 2600.
      EPSSUS = 1 - (RO1SUS/ROP)
      EPSW = (4.* EPSSUS) - 3.

      X = 0.025
      R = 0.7

      EPSC = 0.5 * EPSSUS**(2.074*(X/R))
      F = 0.35*((1-EPSW-Y)/(1-EPSC))**(0.65)
      HRT = F*HRC+(1-F)*HRD
      HCT = F*HCC+(1-F)*HCD
      HTOT = HRT + HCT

      WRITE(*,20)HRT,HCT,HTOT
20    FORMAT(7X,"HRT",20X,"HCT",20X,"HTOT",/,5X,F8.4,15X,
```

```
     + F8.4,15X,F8.4)

      STOP
      END

      SUBROUTINE A1(HRC,TC2)

      WRITE(*,1)
1     FORMAT(3X,/,5X,"DETERMINE Hrc")

      WRITE(*,21)
21    FORMAT(2X,/,5X,"INPUT UG,TB,DP",/)

      READ(*,2)UG,TB,DP
2     FORMAT(F15.8)

      TW = 485.0
      EP = 0.6
      EW = 0.81
      H1 = 0.5
      HTOT1 = 1.0
      ROG = 351. /TB
      XMUG = (TB**(2./3.))*(0.42E-6)
      X = 0.025

C     *****   WALL  EMMISSIVITY ********

      EW1 = 0.75*EW**(TCC1*DP)

      EC1 = (1.+EP)/2.
      RE1 = ROG*UG*DP/XMUG

C     ****  DETERMINING CLUSTER TEMPERATURE  *************

      TC11 = 1-((-0.023*RE1+0.163*(TB/TW)+0.294*(H1/HTOT1))
     + *EXP(-0.0054*(X/DP)))
      TC2 = TC11*(TB-TW) + TW
      HRC = (5.67E-8 * (TC2**4. - TW**4.))/(((1/EC1)+(1/EW1)-1.)*
     + (TB-TW))

      RETURN
      END
```

```
      SUBROUTINE A2(HRD)
      B = 0.5
      WRITE(*,4)
4     FORMAT(3X,/,5X,"DETERMINE Hrd")

      WRITE(*,24)
24    FORMAT(2X,/,5X,"INPUT TB",/)
      READ(*,2)TB
2     FORMAT(F15.8)

      TW = 485.0
      EP = 0.6
      EW = 0.81

C      *****   WALL EMMISSIVITY ********

      EW1 = 0.75*EW**(TCC1*DP)
      XX1 = EP/(1.-EP)
      EDIS1 = (((XX1/B)*((XX1/B)+2.))**(0.5)) - (XX1/B)

      HRD = (5.67E-8 * (TB**4. - TW**4.))/(((1/EDIS1)+(1/EW1)-1.)*
     +  (TB-TW))

      RETURN
      END

      SUBROUTINE A3(HCD,UT1)

      G = 9.81
      Y = 0.00001

      WRITE(*,7)
7     FORMAT(3X,/,5X,"DETERMINE Hcd")

       WRITE(*,27)
27     FORMAT(2X,/,5X,"INPUT TB,UG,DP",/)

      READ(*,2)TB,UG,DP
2      FORMAT(F15.8)
```

```
      ROP = 2600.
      CPP = 800.0
      ROG = 351. /TB
      XMUG = (TB**(2./3.))*(0.42E-6)

      RODIS1 = Y*ROP + (1-Y)*ROG
      CC = (ROP-ROG)**(2.01)
      UT1 = ((CC/XMUG)**(1./3.))*DP*1.2


       HCD=(XMUG*CPP/DP)*((RODIS1/ROP)**(0.3))*
            (UT1**(2.0)/(G*DP))**(0.21)

      RETURN
      END

      SUBROUTINE A4(HCC,UT,TCC)
      G = 9.81
      C1 = 0.0509

      WRITE(*,10)
10     FORMAT(3X," DETERMINE hcc,/" )

      WRITE(*,30)
30     FORMAT(3x,/,5X,"Input ROSUS,UG,TB,DP",/)


      READ(*,11)RO1SUS,UG,TB,DP
11     FORMAT(F15.8)


      TW = 485.0
      ROP = 2600.
      X = 0.025
      R = 0.7
      TF = (TB + TW)/2.0
      XKGF = (5.66E-5)*TF + 1.1E-2
      CPP = 800.0
      ROG = 351./TB
      XMUG = (TB**(2./3))*(0.42E-6)
      CPG = 1000*(0.99+((1.22E-4)*TB)-(5.68*(TB**(-2.))))
      XKG = (5.66E-5)*TB + 1.1E-2
```

```
XKP = 1.87

EPSSUS = 1 - (RO1SUS/ROP)
BB = (ROP-ROG) **(2.01)
UT = 1.2*DP*((BB/XMUG)**(1./3.))
DG = (0.0282*(1-EPSSUS)**(-0.59))*DP +0.00001
EPSC = 0.5 * EPSSUS**(2.074*(X/R))
CPC = (1-EPSC)*CPP + EPSC*CPG
ROC = (1-EPSC)*ROP + EPSC*ROG
XXX = XKG /XKP

        1+(((1EPSC)*((XXX))(XXX+(0.28*EPSC)**
        (0.63*(XXX**(0.18))))))

ROSUS = ROP * (1- EPSSUS)

UC = 0.1158 * (UG/((EPSC*(ROP*DP)**2./3)))

TCC = C1*((ROSUS)**(2./3)*UT**(2.))/(G*(UG*EPSC)**(1./3))

HCC = 1/(((DG/XKGF)+(3.142*TCC/(XKC*ROC*CPC))**(0.5)))

RETURN
END
```