PARTICLE MIXING IN LIQUID FLUIDISED BEDS

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Abstract

Rapid particle mixing in fluidised beds is one of the major advantages in their application. Much work has been done on the measurement and correlation of heat transfer coefficients with the basic physical properties of the system; however, their dependence on the fluid and solids flow patterns is not fully understood.

In this investigation a mathematical model was employed to predict the unsteady thermal behaviour of the liquid fluidised systems. The bed was considered as being divided into a series of cells, each containing a homogenised mixture of liquid and particles. Hence, the level of mixing decreased with increasing number of cells. The predicted thermal responses in the liquid stream emerging from the surface of the bed were compared with those measured in the experiments. Thus, the degree of particle mixing inside fluidised beds can be determined.

Introduction

In this investigation, the liquid to particle heat transfer coefficients were measured under unsteady state conditions by introducing a step change in the temperature of the inflowing liquid to beds of aluminium and alumina particles fluidised by water or three glycerol-water mixtures.

A mathematical model has been developed to predict the unsteady state behaviour of fluidised beds in response to the introduction to the bed of a step change in the temperature of the incoming liquid. For the purpose of the model the bed was considered to be divided into a series of cells with perfect mixing of both particles and liquid within each cell.

Theory

For a bed divided into a series of cells with an equal height, l, and containing a flow of liquid with a net linear velocity, v_z, the time delay between the entries of liquid into two consecutive cells may be considered to occur in the following manner: It is assumed that no time delay exists inside the boundaries of the cells and that the delay equal to l/v_z takes place between the time the liquid leaves the first cell and enters into the second. Time is measured relative to the entry of the liquid into a particular cell, the relationship between the time coordinate at the entry in the n^{th} cell and the time of entry in the first cell is

$$t_n = t_1 - \frac{nl}{v_z} \qquad (1)$$

Assuming that there are no heat losses in the system , the following thermal energy balance holds for the n^{th} cell.

$$G\frac{l}{L}C_P\frac{dT^P_n}{dt_n} = m_L C_L(T^L_{n,1} - T^L_{n,2}) \qquad (2)$$

With the initial condition at $t_n \leq 0$, $T^P_n = T_o$ (3)
where

l = Length of a cell	(m)	
L = Height of the bed	(m)	
G = Total mass of the particles in the bed	(kg)	
C_P= Specific heat capacity of the particles	($J\ kg^{-1}\ K^{-1}$)	
C_L = Specific heat capacity of the particles	($J\ kg^{-1}\ K^{-1}$)	
m_L = Mass flowrate of the liquid	($kg\ s^{-1}$)	
T = Temperature	(K)	
t = Time	(s)	

the subscripts n = n^{th} cell
1 = entry to cell
2 = exit from cell
the superscript L = liquid
P = particle

Under the condition of complete liquid and particle mixing inside the cell, the particle temperature (T^P_n) is uniform and the temperature of the liquid is equal to that of the out-going liquid ($T^L_{n,2}$). The rate equation may then be expressed as

$$G\frac{l}{L}C_P\frac{dT^P_{LP}}{dt_n} = h_{LP}A_P\frac{l}{L}(T^L_{n,2} - T^P_n) \qquad (4)$$

where

h_{LP} = Liquid to particle heat transfer coefficient ($W\ m^{-1}\ K^{-1}$)
A_P = Total surface area of the particles (m^2)

Combining equations (2) and (4) produces

$$T^L_{n,2} = \frac{MT^L_{n,1}}{M+1} + \frac{1}{M+1}T^P_n \qquad (5)$$

where the constant M is given by

$$M = \frac{m_L C_L L}{A_{LP}h_{LP}l} \qquad (6)$$

Substituting equation (5) into equation (2) gives

$$\frac{dT^P_n}{dt_n} = N(T^L_{n,1} - T^P_n) \qquad (7)$$

where the constant N is given by

$$N = \frac{m_L C_L L}{GC_P l}\frac{1}{(M+1)} \qquad (8)$$

The following dimensionless temperatures are introduced;
for the liquid

$$\theta_{n,m} = \frac{T^L_{1,1} - T^L_{n,m}}{T^L_{1,1} - T_o} \qquad (9)$$

where m = 1,2

and for the particle

$$\theta_n = \frac{T^L_{1,1} - T^L_n}{T^L_{1,1} - T_o} \qquad (10)$$

Hence, the initial condition (3) becomes that at $t_n \le 0$,

$$\theta = 1 \qquad (11)$$

and it also holds that at the inlet to the bed

$$\theta_{1,1} = 0 \qquad (12)$$

Substituting equations (9) and (10) into equation (8) yields the following relationships:
For the liquid emerging from the cell

$$\theta_{n,2} = \frac{M\theta_{n,1}}{M+1} + \frac{1\ \theta_n}{M+1} \qquad (13)$$

and the differential equation for the particle temperature becomes

$$\frac{d\theta_n}{dt_n} = N(\theta_{n,1} - \theta_n) \qquad (14)$$

Integrating equation (14) and introducing the initial and inlet conditions (11) and (12), respectively, yields the following expression for the particle temperature.

$$\theta_n = [N \int_0^{t_n} \theta_{n,1}\, e^{Nt_n} dt_n + 1]e^{-Nt_n} \qquad (15)$$

From successive applications of equations (15) and (13), expressions may be derived that enable the liquid and particle temperatures to be evaluated for any number of cells. For $\theta_{2,1} = 0$ and from equation (15), the particle temperature in the first cell can be obtained as Further, by substituting equation (16) into equation (13) the temperature of the liquid leaving the first cell is found to be

$$\theta_{1,2} = \frac{1e^{-Nt_1}}{M+1} \qquad (16)$$

and so the temperature of the liquid entering the second cell will be given by

$$\theta_{2,1} = \frac{1e^{-Nt_2}}{M+1} \qquad (17)$$

$\theta_{2,1}$ is substituted into equation (15) to obtain the particle temperature in the second cell, θ_2, and then equation (13) is employed again to provide an expression for the temperature of the liquid leaving the second cell. The alternate use of equations (15) and (13) henceforth establishes the following general expression for the liquid temperature at the exit from an arbitrary cell.

$$\theta_{n+1,2} = e^{-Nt_{n+1}} \sum_{i=0}^{n} \left[\frac{N^i t^i_{n+1}}{(M+1)^{i+1}} \frac{1}{i!} \sum_{j=0}^{n-1} \beta_{i,j} \left(\frac{M}{M+1} \right)^j \right] \qquad (18)$$

where

$$\beta_{o,j} = 1 \qquad (19)$$

and for i = 0

$$\beta_{o,j} = \Sigma\beta_{i-1,k} \qquad (20)$$

Results and Discussion

The response to the introduction of a step signal in the inflowing liquid temperaaure was recorded in the liquid stream above the surface of the bed. The degree of particle mixing was investigated by comparing the measured response curves with those predicted by means of the theory stated previously. For a specified set of experimental conditions, the shape of the response curve predicted from the analysis of the heat transfer equations is dependent on the chosen number of perfectly mixed cells, with both the liquid and the particles in a cell being fully homogenised. A bed consisting of one cell exhibits a high degree of mixing. As the number of cells is increased, the intensity of mixing is reduced. For a particular bed the effect of varying the number of mixed cells on the response curve is illustrated in Fig. 1. Here, equation (19)_ has been employed to demonstrate the different responses of a bed containing 1.4 kg of alumina spheres fluidised by water to a voidage of 0.56 and operated under adiabatic conditions for a number of cells equal to 1,2,3,4,5, and 20.

The following text contains numerous references to figures in which the bed response curves obtained by means of the mathematical models of the theory are compared with response data measured from the experiments. In each instance the experimental temperature data are plotted in terms of the dimensionless parameters used earlier in equation (19). Also, the time coordinate is such that, at a particular point, t = 0 coincides with the arrival of the signal. Hence, at the surface of the bed the time coordinate is given by

$$t_s = t_1 - \frac{L}{v_z} \qquad (21)$$

where

t_1 = Time measured at the entry to the bed from the moment of the introduction of the signal (s)
L = Total height of the bed (m)
v_z = Linear liquid velocity ($m\ s^{-1}$)

Hence, both the experimental data and the theoretical response curves were plotted in the same coordinates.

For the sake of clarity and for comparison purposes, the response curves measured from the experiments using four different fluidising liquids were limited to a confined bed voidage range of 0.54 to 0.56. Moreover , at higher voidages the error of the predicted response curves was rather high.

In the experiments involving aluminium cylinders, temperature data were recorded at intervals of 0.1 seconds, but, to avoid overloading the graphs only a proportion of the measured data was plotted. Figure 2 illustrates the favourable comparison between the response curves obtained from the model and the experimental data. With water and 20% glycerol-water mixture , the beds appear to be represented by one mixed cell as shown in Figure 3 and 4 respectively. The results in Table 1 indicate that as the fluidising liquid becomes more viscous, the number of perfectly mixed cells increases.

Table 1 : Particle mixing study in beds of aluminium cylinders

Fig.	Fluidising liquid	Voidage	Approx. no. of cells
3	water	0.55	1
4	20% glycerol	0.56	1
5	40% glycerol	0.54	4
6	50% glycerol	0.56	5

For beds of alumina spheres, the response curves obtained from the experimental data were compared with the predicted response curves as shown in figures 7 to 10. The results in Table 5.4 indicate a similar trend to that observed in beds of aluminium cylinders, though the number of cells for alumina spheres fluidised by the 50% glycerol-water mixture increased dramatically to 20.

Table 2 : Particle mixing study in beds of alumina spheres

Fig.	Fluidising liquid	Voidage	Approx. no. of cells
7	water	0.56	1
8	20% glycerol	0.55	3
9	40% glycerol	0.56	5
10	50% glycerol	0.56	20

Figures 3 to 10 and tables 1 and 2 indicate that, as the fluidising liquids become more viscous, the degree of particle mixing decreases. This is attributed to the increased restriction to the movement of the particles in a more viscous liquid. Hence the decreased mobility leads to a reduction in the degree of particle mixing.

For a given set of experimental conditions, the response curves were calculated for between 1 and 20 perfectly mixed cells. The curve which most closely fitted the experimental data was identified by minimising the sum of the squares of differences between the measured temperatures and those calculated from equation (19). A computer program was employed for the purpose of comparing the response curves obtained from the experiments with those calculated using the mathematical model.

The comparison between the experimental data and the calculated response curves were not undertaken for consecutive numbers of perfectly mixed cells when the number of cells needed for the fit was greater than five, since, as the number of cells was increased, the differences between the calculated response curves became extremely small. Therefore, when the number of cells representing the mixing process was more than five, comparisons were only drawn between the experimental data and the response curves calculated for 10 and 20 perfectly mixed cells. The goodness of the fit was expressed as the square root mean difference between the experimental and calculated temperatures as given by the following equation.

The temperatures recorded from the experiments were first normalised using equation (9) before being compared with the normalised temperatures obtained from the mathematical model. Typically, one unit of normalised temperature is equivalent to approximately 40°C. As an example, a value of $\Delta\theta_{av}$ is equal to 2×10^{-3} represents an average temperature difference between the calculated and experimental data of ±0.08°C. From Table 3 the values of $\Delta\theta_{av}$ for the best fitting curves are between 3.86 x 10^{-3} and 1.61 x 10^{-3}. This indicates that the success achieved in predicting the experimental response curves using the theory is quite good.

Table 3: Results of the comparison between the experimental data and the response curves predicted by equation (19).

No. of cells / Fig.	1	2	3	4	5	10	20
	$\Delta\theta_{av}$ x 10^3			(equation (22))			
3	1.61	1.70	1.79	-	-	-	-
4	1.93	2.08	2.11	-	-	-	-
5	11.21	6.37	3.32	2.45	2.59	2.77	-
6	9.74	6.52	3.99	2.96	2.62	2.80	2.89
7	2.31	2.47	2.51	-	-	-	-
8	6.17	3.33	2.95	3.18	3.22	-	-
9	13.04	7.66	5.25	4.40	3.86	3.97	4.01
10	10.09	8.12	6.73	4.71	3.53	2.88	2.13

The best fitting curve is underlined.

Conclusions

The results show a close match between the predicted and the measured thermal response curves in both both types of beds. As the liquid becomes more viscous, the degree of particle mixing was found to decrease from a high mixing intensity corresponding to 1 cell to a low level of mixing of 20 cells.

Acknowledgements

The author is grateful to Pn. Noorhalieza Ali and Encik Luqman Onn for typing the manuscript. The author would also like to acknowledge Encik Muhammad Onn for his support and encouragement.

Figure 1 : Predicted thermal responses for a bed containing 1.4 kg of alumina spheres fluidised by water to a voidage of 0.56

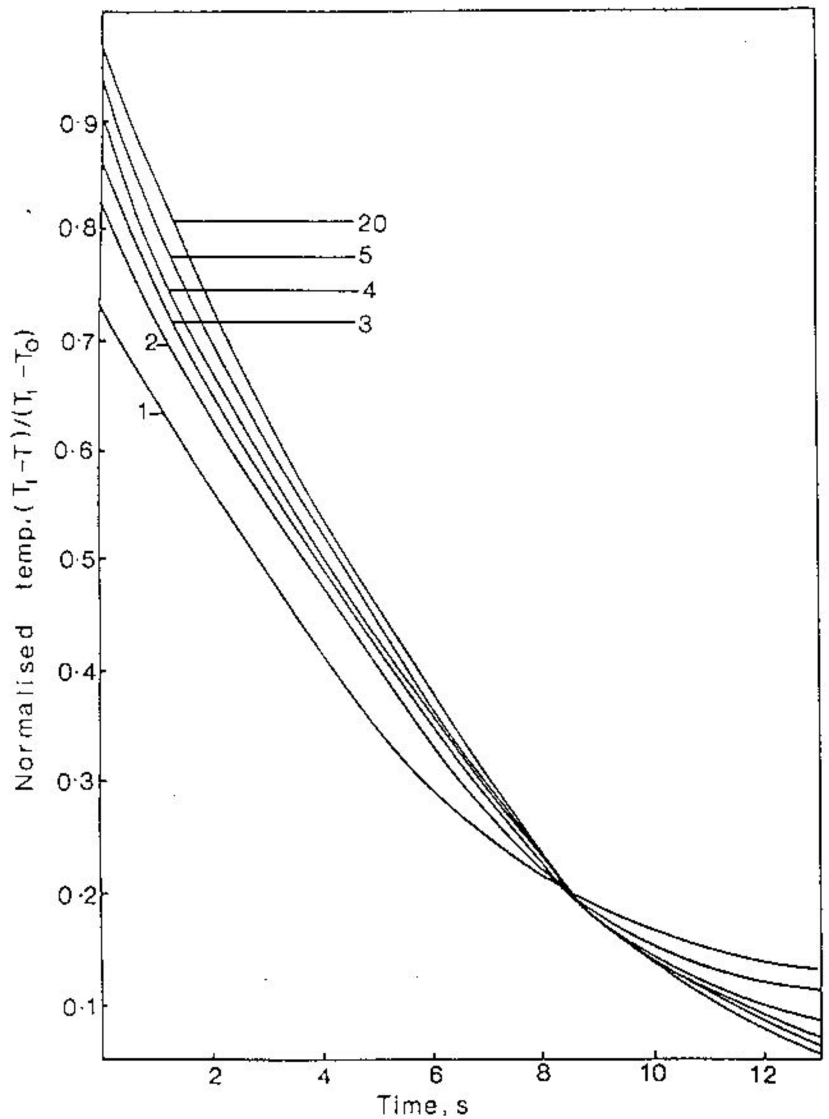

Figure 2: Typical experimental and predicted responses curves