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Heat Transfer in Semifluidized Beds

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This paper predicts heat transfer coefficient in semi-fluidized beds as a function of properties of solid, gas and operating conditions. It includes collected data on heat transfer coefficient using glass beads, coal particles, porcelain beads and sugar crystals as bed material and air as the fluidizing medium. A copper column of 5.08 cm internal diameter with a cooling jacket was used as the semi-fluidizer. With the help of dimensional analysis an equation has been formulated to predict Nusselt number in terms of different system variables. The equation has been verified by carrying out additional independent experiments and it has been found that the equation holds good for all the data within ± 16%.

NOTATIONS

A = area of heat transfer, m^2

C_g = specific heat of gas (air), k cal/kg °C

C_p = specific heat of the particles, k cal/kg °C

D_p = particle diameter, m

G_{sf} = superficial semifluidization mass velocity, kg/h m²

G_{msf} = superficial maximum semifluidization mass velocity, kg/h m²

h_s = static bed height, m

h = heat transfer coefficient, kcal/h m² °C

h_{pa} = height of packed section in a semifluidized bed, m

k_g = thermal conductivity of air, kcal/m °C h

k_p = thermal conductivity of the particles, kcal/m °C h

m = flow rate of air, kg/h

Nu = $\dfrac{h D_p}{k_g}$ = Nusselt number

R = bed expansion ratio in semifluidization

β = constant

ρ_g = density of fluid, kg/m³

ρ_p = particle density, kg/m³

μ_g = viscosity of gas, kg/m h

INTRODUCTION

A semi-fluidized bed is a combination of packed and fluidized beds in which the drawbacks of both have been partially rectified. A bed of this nature is obtained by incorporating a movable restraint to the top of a conventional fluidized bed. The application of the technique of semi-fluidization has become a major achievement in the last decade. While several papers have been published on momentum transfer aspects of this but only meagre information on heat and mass transfer aspects is available. Literature reveals that much work has been reported by Fan, *et al*[1,2], Poddar & Dutt[3], Kurian & Raja Rao[1], Roy & Sarma[5], Roy & Sengupta[6] and others in the field of momentum transfer whereas information available on heat and mass transfer is scanty.

Rao and Kaparthi[7] were the first to report their studies on wall-to-bed heat transfer coefficients in semifluidization in a 2.5 cm copper column using glass beads, quartz and aluminium particles with air as the fluidizing medium. Verma, *et al*[8] studied the heat transfer characteristics of liquid-solid systems. Their correlations in terms of Nusselt number do not take into account the particle properties, except the size.

DEVELOPMENT OF THE EQUATION

The heat transfer coefficient is dependent on physical and thermal properties of gas, solid particles, bed expansion ratio and flow rate of gas. Thus the heat transfer coefficient (h) can be expressed as

$$h = f\,(D_p,\ \rho_p,\ k_p,\ C_p,\ k_g,\ \rho_g,\ C_g,\ \mu_g,\ D_t,\ G_{sf},\ R) \qquad (1)$$

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Since $\frac{D_t}{D_p}$ is sufficiently high for all the runs carried out, the wall effect is negligible[9]. Hence in dimensional analysis the variable $\frac{D_t}{D_p}$ is eliminated. The effect of $\frac{k_g}{k_p}$ can also be neglected since thermal equilibrium between gas and solid particles is reached instantaneously[9]. Since the experiments are carried out below 600°C, heat losses to surroundings by radiation can be neglected[9].

Thus eliminating the dimensionless variables $\frac{k_g}{k_p}$ and $\frac{D_t}{Dp}$ and substituting $\frac{G_{sf}}{G_{msf}}$ for Reynolds number $\frac{D_p\, G_{sf}}{\mu_g}$, the dimensional analysis gives

$$Nu = \frac{hD_p}{K_g} = f\left(\frac{G_{sf}}{G_{msf}}, \frac{\rho_p}{\rho_g}, \frac{C_p}{C_g}, R\right) \quad (2)$$

$$Nu = f\,(x_1,\ x_2,\ x_3,\ x_4) \quad (3)$$

$$x_1 = \frac{G_{sf}}{G_{msf}} \quad ; \quad X_1 = \frac{x_1 - 0.575}{0.175}$$

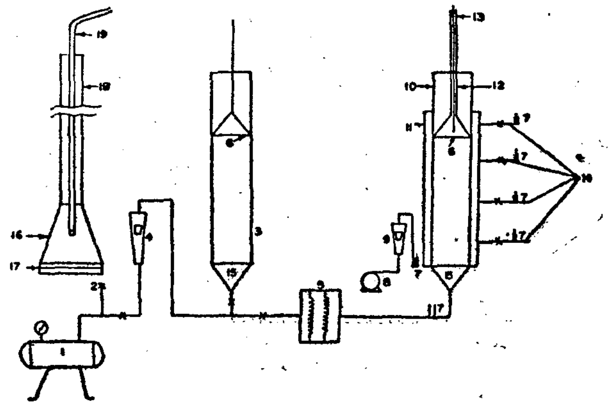
$$x_2 = \frac{\rho_p}{\rho_g} \quad ; \quad X_2 = \frac{x_2 - 2.725\times 10^3}{0.275\times 10^3}$$

$$x_3 = \frac{C_p}{C_g} \quad ; \quad X_3 = \frac{x_3 - 0.87}{0.207}$$

$$x_4 = R \quad ; \quad X_4 = \frac{x_4 - 2.75}{0.75}$$

EXPERIMENTAL SET-UP

A schematic diagram of the apparatus is shown in Fig 1. The main unit consists of a copper column of 5.08 cm internal diameter (id) and is surrounded by a cooling jacket. The jacket is provided with outlets at different heights to adjust the water level to the required height. Cocurrent flow is used in view of low temperature difference and operational convenience. The jacket is lagged with asbestos rope and covered by refractory cement layer to minimise heat losses. The copper column is preceded by a heating box which is used to heat the air to the required temperature. A fractional hp pump is used to pump water through the cooling jacket. The flow rates of air and water are measured by rotameters. The restraint used to arrest the motion of particles is made up of a 60 mesh stainless steel wiremesh fixed in between two mild steel rings. This restraint is screwed to a movable tube. For signalling and recording convenience the inlet and outlet temperatures of air are measured by iron-constantan thermocouples. A perspex column of same diameter as that of copper column is connected in the line to determine maximum semi-fluidization velocity and the amount of material to be charged in the copper column for required height.



Schematic diagram of experimental set up

EXPERIMENTAL PROCEDURE

The required amount of a material to obtain the desired height is found by charging the material to the perspex column. The maximum serti-fluidization velocity of each material is obtained from the packed bed height-flow rate plot by extrapolation. The same amount of materia] is then charged to a 5.08 cm id copper column and the restraint position is adjusted to a desired bed expansion ratio. Measured amount of air is heated to required temperature and kept flowing through the column. Water is pumped through the cooling jacket. Air temperature is controlled by means of a variac and observations are noted for steady state conditions.

The properties of the materials and experimental conditions are given in Table **1**.

TABLE 1 PROPERTIES OF THE MATERIALS AND EXPERIMENTAL CONDITIONS

Material	Sp Gravity	$D_p\times10^6$ (m)	Sp Heat (kcal/ kg °C)	$G_{msf}\times10^4$ (kg/h m²)	Temperature °C
Glass beads	2.6	328.0	0.160	1.336	45.0
Glass beads	2.6	486.0	0.160	1.521	35.0
Glass beads	2.6	918.0	0.160	2.227	43.5
Porcelain	2.4	599.5	0.260	1.600	49.5
Sugar	1.6	1 103.5	0.301	1.455	44.0
Coal	1.5	928.0	0.215	1.173	47.5

The water temperature is found to remain almost constant with a maximum variation of 1.5°C. Hence it is assumed that the wall is maintained at constant temperature and the individual heat transfer coefficient from bed-to-wall is calculated from the heat balance equation

$$h\,A\,(\Delta T)_{lm} = m\,c_g\,(\Delta T)_{air} \quad (4)$$

where $(\Delta T)_{lm}$ is the log mean temperature difference.

EXPERIMENTAL DESIGN

Factorial design of experiments is used to formulate an equation which requires less observations. It is assumed that the response Y can be expressed as a linear function of the main effects and interactions of the independent variables X_1 X_z, X_s and X That is, the equation could be expressed in the form

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \dots + \beta_{12} X_{12} + \beta_{13} X_{13} + \beta_{14} X_{14} \quad (5)$$

where β_0, β_1, β_2 etc are the constants to be determined from experimental design.

As observed from dimensional analysis the response Y (= Nu) is dependent on four dimensionless variables, $\frac{G_{sf}}{G_{msf}}$, $\frac{\rho_p}{\rho_g}$, $\frac{C_p}{C_g}$ and R. Experiments are carried out keeping, these variables at two levels. The levels of these variables are shown in Table 2 and the number of experiments required for the four factors keeping each at two levels are 16. The two levels for X_2 are maintained by keeping the inlet temperature of air equal to 70°C for lower level and 170°C for higher level for glass beads. After carrying out experiments, the data have been tested by Yates technique[10] for the importance of the main effects and interactions of the variables.

TABLE 2 LEVELS OF THE VARIABLES

DIMENSIONLESS VARIABLE	HIGHER LEVEL (+ 1) LEVEL	LOWER LEVEL (− 1) LEVEL
$\frac{G_{sf}}{G_{msf}}$ (X_1)	0.75	0.40
$\frac{\rho_p}{\rho_g}$ (X_2)	3×10^3	2.45×10^3
$\frac{C_p}{C_g}$ (X_3)	1.074	0.661
R (X_4)	4.00	2.75

From the analysis of variance of data, it is noted that the variables, X_1, X_2, X_3, X_4 and $X_1 X_4$ are statistically significant at 5 percent level.

The following equation was thus obtained :

$$Y = 0.975 - 0.067 X_1 - 0.052 X_2 + 0.093 X_3 - 0.043 X_4 + 0.07 X_1 X_4 \quad (6)$$

RESULTS AND DISCUSSION

The final equation obtained above has been tested for various conditions of the independent variables and the heat transfer coefficients have been compared as shown in Table 3. The mean and standard deviations are 15.8 and 17.9 respectively.

It is found that the heat transfer coefficient decreases with density, particle size, bed expansion ratio and air mass velocity but increases "with specific heat of the material. Though the heat transfer coefficients decrease with $\frac{G_{sf}}{G_{msf}}$ and R, their interaction causes an increase in the value of the coefficient. The conclusions reached agree with those of Rao and Kaparthi[7] as far as density and particle size are concerned. The equation predicts the heat transfer coefficients as expected, except at low values of $\frac{G_{sf}}{G_{msf}}$ where h is decreasing with increase of R. The reason is that at low values of $\frac{G_{sf}}{G_{msf}}$ with increase of R, there is not much packed bed variation.

CONCLUSIONS

The equation predicted gives a reasonable estimate of the heat transfer coefficient in semifluidized beds. The equation shows the interaction of the main variables which might not have been observed during a conventional single factor experiment. The experimental observations justify the assumption that response Y can be expressed as a linear function of the effects.

TABLE 3 OBSERVATION FOR CHECKING THE EQUATION

EXPT No	MATERIAL	$D_p \times 10^6$ (m)	$\frac{G_{sf}}{G_{msf}}$	R	INLET TEMP (°C)	h, CALCULATED [(kcal/h-°C m²)	h, EXPTL (kcal/m²-h-°C)]	PERCENT ERROR
1	Glass beads	328	0.300	2.91	75	95.40	83.20	+14.6
2	Glass beads	328	0.581	2.91	75	86.40	75.60	+14.2
3	Glass beads	328	0.814	2.91	75	63.00	60.84	+ 3.5
4	Glass beads	486	0.575	3.25	124	49.68	58.70	−15.3
5	Glass beads	486	0.575	3.25	74	48.10	55.44	−13.2
6	Glass beads	486	0.638	4.00	74	46.30	54.00	−14.2
7	Glass beads	928	0.336	2.00	80	34.56	45.00	−23.2
8	Glass beads	928	0.336	4.00	75	24.12	36.00	−33.0
9	Glass beads	928	0.574	4.00	75	25.20	30.24	−16.6
10	Coal	928	0.395	3.39	75	34.34	33.36	+ 3.6
11	Coal	928	0.658	3.39	75	32.40	27.00	+19.2
12	Coal	928	0.395	2.12	75	40.00	45.40	−11.8
13	Coal	928	0.658	2.12	75	32.90	34.16	+ 8.6
14	Sugar	1 103.5	0.727	2.50	75	29.60	24.12	+23.9
15	Sugar	1 103.5	0.385	2.50	77	36.00	41.40	−13.0
16	Sugar	1 103.5	0.385	4.00	78	34.20	46.00	−26.0

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