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EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER IN A PACKED BED OF IRON ORE PARTICLES

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ABSTRACT

Packed bed studies have been carried out to estimate effective thermal conductivity and wall-to-bed interfacial heat transfer coefficient using comparative method. Heat transfer in packed bed has contributions from conduction, convection from gas phase and inter-particle radiation. To separate the effect of convection, experiments have been carried out in air as well as in vacuum. The convective contribution to the effective thermal conductivity has been found to vary little with average bed temperature. The variation of convective heat transfer coefficient with effective temperature difference between the wall and the particle at the vicinity of the wall found to follow a power law relation.

INTRODUCTION

Packed beds are extensively used in metallurgical and chemical process industries as reactors, heat treatment units, heat exchangers, dryers etc. In these processes, heat transfer is one of the important phenomena, wherein, transfer of heat between the wall and the packed bed, and that within the bed itself is important. Heat transfer within the bed involves particle–to–particle conductive and radiative transfer and fluid–to–particle heat transfer. At the wall too, all three modes of heat transfer are important. Large amount of work has been carried out in determining the effective thermal conductivity of the packed bed. Even though numerous studies on heat transfer in packed at low temperatures have been reported, studies at relatively higher temperatures are less [1-8]. In the present work, heat transfer studies in a packed of iron ore particles have been carried out at relatively high temperatures wherein radiative contributions are significant. These are of great importance to many metallurgical reactors.

Heat transfer within the bed can be characterized by estimating an effective bed thermal conductivity. Wall–to–bed heat transfer, on the other hand, is usually characterized by defining an interfacial heat transfer coefficient. Various studies have been carried out to study the effect of particle size, fluid velocity and the temperature on the heat transfer coefficient [9-21]. At high temperatures, the contribution from radiation plays a significant role in determining the wall-to-bed heat transfer as well as effective thermal conductivity. It has been reported that radiation becomes important for 1 mm particles above 400 ^{0}C and for 0.1 mm particles above 1500^{0}C [20-21].

Tsotsas and Martin [22] have classified methods to estimate the thermal conductivity of packed beds. The method adopted in the present work is the comparative method, where heat is transferred in one direction (1-D) at the same rate through two materials, the thermal conductivities of one of the materials being known. Iron ore particles constitute the packed bed, a stainless steel disk, heated from below forms the other conducting material.

In a heat transfer process, where all the three modes of heat transfer make significant contributions, separating the effect of each of them to understand the underlying mechanisms is difficult. If the gas phase involved is non-participative, however, the effect of gas–phase heat transfer can be eliminated by conducting the experiments in vacuum.

NOMENCLATURE

d_p Diameter of particle (m)

h Wall to bed interfacial heat transfer coefficient (W/m^2 k)

h_{conv} Convective contribution to heat transfer coefficient (W/m^2 k)

k_{ss} Thermal conductivity of stainless steel disk (W/m K)

k_{bed} Thermal conductivity of packed bed (W/m K)

$\dot{q}''$ Steady state heat flux (W/m^2)

ΔT_{conv} Temperature difference between the steel disk at the interface and the particle in the vicinity of the interface (driving force for convection) (K)

T_{w-} Measured temperature on the face of the stainless steel disk (K)

T_{w+} Bed temperature at the interface obtained by extrapolation (K)

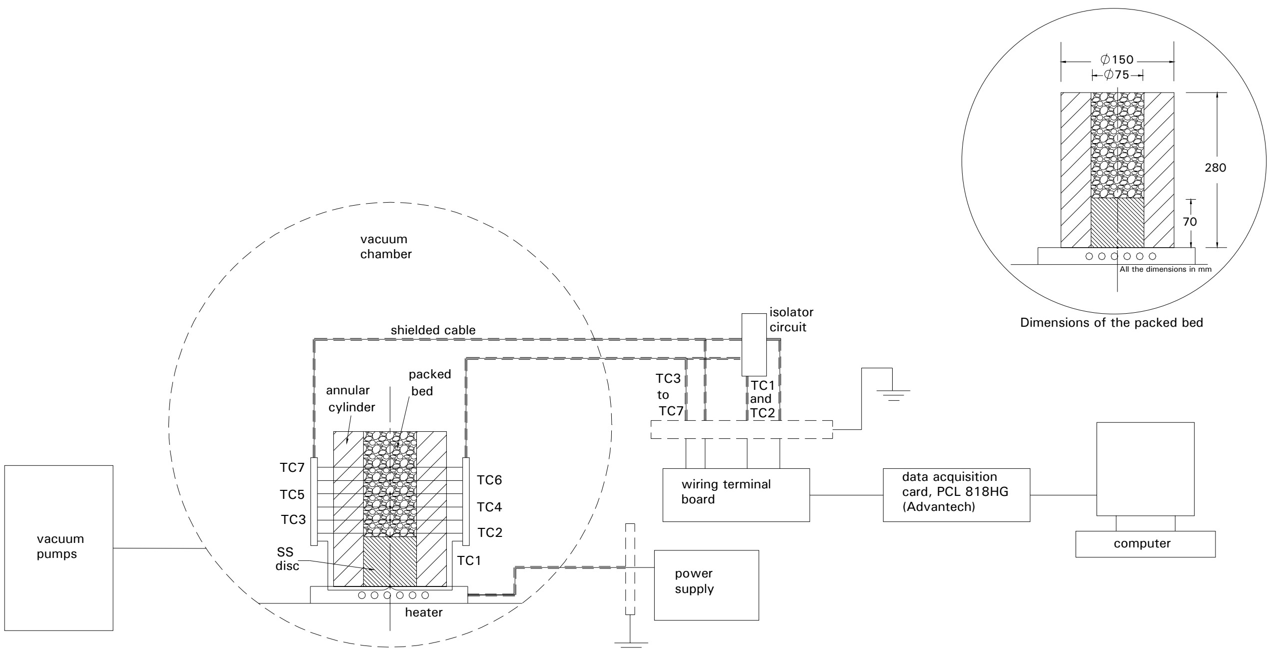

Figure 1 Schematic diagram of experimental set-up

EXPERIMENTAL WORK

Experimental set up

Experimental set up, designed to determine the effective thermal conductivity and wall-to-bed heat transfer coefficient in a packed bed iron ore particles, is shown in Figure 1. The set up consists of a cylindrical insulating container made up of highly foamed cement concrete, one end of which is enclosed with a 316L stainless steel disk (ϕ 75.0 mm, length 70.0 mm). The estimated thermal conductivity of the foamed cement concrete is 1-2 orders of magnitude lower than that of the bed. Rest in the space above the disk is filled with iron ore particles to form a packed bed. The disk is heated from the bottom by an electric heater.

Heat flow primarily along the axial direction (1-D) in the packed bed is ensured by the foam refractory whose thermal conductivity is significantly lower than that of the bed. In addition, preliminary experiments were carried out to check the validity of the 1D axial heat flow by placing thermocouples along the axial and radial directions, in the bed as well as in the stainless steel disk. These experiments showed little variation in temperatures measured along radial direction at several axial distances, confirming that the 1D heat transfer assumption through the stainless steel disk and the packed bed is valid.

In order to measure the particle temperature separately, some thermocouple junctions were carefully embedded within the particles. It was observed that under the present experimental conditions, there were no significant difference between the temperatures measured by thermocouples with bare beads and those whose beads were embedded within particles. Henceforth, the temperatures measured in the packed bed will be referred as bed temperature irrespective of whether it is the particle temperature or the temperature measured in void between particles.

Instrumentation

The experimental set–up and the data acquisition systems are shown schematically in Figure 1.Data from thermocouples are recorded continuously using a high gain data acquisition card (PCL 818HG, Advantech, USA) and a PC.

The hot junction of thermocouples TC1 and TC2 were embedded at each face of the stainless steel disk to determine the respective temperatures, from which heat flux is calculated. Since the two hot junctions are at the same potential, the output signals were connected to the data acquisition system card through isolation modules (ADAM, 3011, Advantech, USA).Thermocouples TC3 to TC7 measure the bed temperatures along the axial direction.

In order to study the heat transfer under vacuum, experiments were also carried out in vacuum by placing the entire experimental set-up inside a vacuum chamber of 800mm diameter and 1200 mm length. The power cables and the thermocouple wires are taken out through sealed connections. The vacuum is achieved using double stage rotary pump equipped with 5 HP, 3 Ph induction motor. Typical vacuum level achieved was 0.0533 – 0.0933 millibar (5.33×10^{-3} to 9.33×10^{-3} kPa).

PROCEDURE

Once the experimental set up is ready, the annular foam refractory cylinder is filled carefully with iron ore particles of average size 4.3mm. This gives the ratio of the bed diameter to particle diameter to be more than 15. Special care was taken to ensure that packing is as uniform as possible in the bed as well as near the thermocouple junctions. The heater at the bottom is switched on by applying a constant voltage across the heater coil maintaining a constant heat input to the system. The experiment is allowed to run for few hours to obtain the steady state data. In order to investigate the heat transfer at various bed temperatures, the experiments were conducted for several heat inputs.

RESULTS AND DISCUSSION

Figure 2 gives a typical steady state temperature profile in the bed. Comparing slope of the temperature profile in the stainless steel disk and the packed bed, one can write

$$\dot{q}'' = -k_{ss}\ slope\ of\ line 1 = -k_{bed}\ slope\ of\ line 2$$

Knowing the thermal conductivity of the stainless steel, one can calculate the effective bed thermal conductivity of the bed.

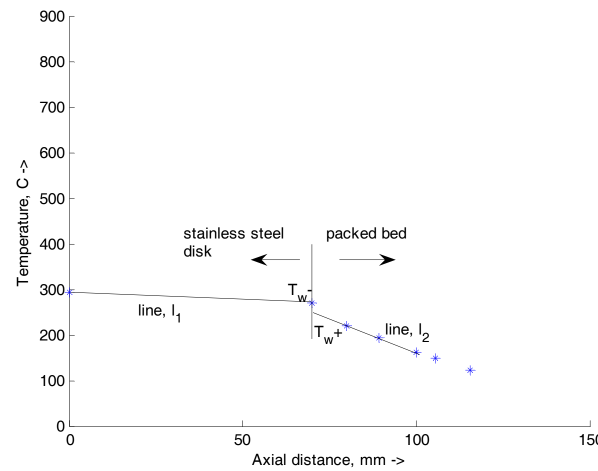

Figure 2 Typical steady state temperature profile as a function of axial distance

In order to determine the wall–to-bed interfacial heat transfer coefficient, one needs to measure the temperatures on either sides of the interface. In the case of packed beds, however, the bed side temperature is determined by extrapolating the bed temperature profile (line 2) up to the interface [23]. The wall to bed heat transfer coefficient (h) can be defined then as

$$\dot{q}'' = -k_{ss}\ slope\ of\ line 1 = h(T_{w-} - T_{w+})$$

Where T_{w-} is the measured temperature on the face of the stainless steel disk, T_{w+} is the bed temperature at the interface obtained by extrapolation and k_{ss} is the thermal conductivity of stainless steel disk .

The effective thermal conductivity has contributions from inter-particle radiation, convective transfer between particles through the gaseous medium, and conduction through the solid and at points of contact. In the present work, an attempt has been made to separate the effect of convective transfer from the other modes transfer by conducting experiments at atmospheric conditions and under vacuum.

The estimated effective bed thermal conductivity is plotted against the average bed temperature at atmospheric condition as well as under vacuum in Figure 3. The conductivity shows a linear trend with temperature. The conductivity in vacuum consists of radiative and conductive components whereas that in air includes convective in addition to the above. Hence, the difference between conductivities that measured at atmospheric condition and that under vacuum gives the convective contribution and is equal to 1.46 W/m K. It is interesting to note that this contribution is independent of bed temperature.

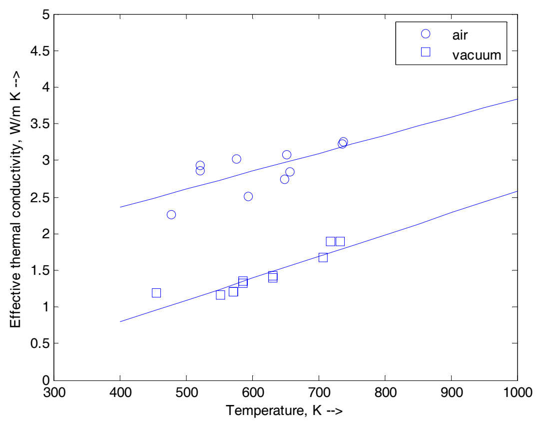

Figure 3 Effective thermal conductivity of the bed in air and in vacuum

Figure 4 shows the variation of wall–to– bed interfacial heat transfer coefficient with temperature at the face of the stainless steel disk (T_{w-}). Two trends are clearly visible. The heat transfer coefficient in air increases with temperature. The heat transfer coefficient determined under vacuum also shows a similar trend, the rate of increase is increasing with temperature. This phenomenon is probably related to the contribution from radiation, which increases as T^3.

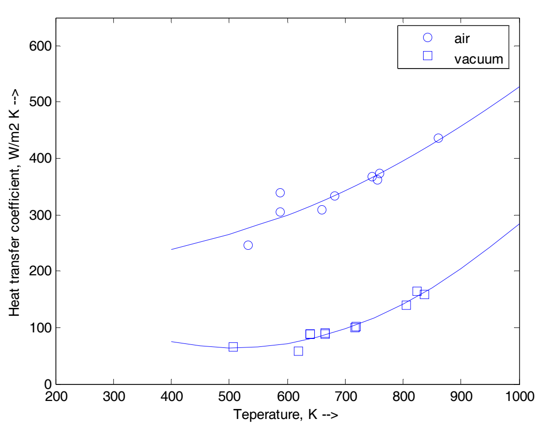

Figure 4 Wall - to - bed heat transfer coefficient as a function of temperature in air and vacuum

The difference between heat transfer coefficient values is measured in air and in vacuum, corresponds to the effect of convection and is plotted in Figure 5 in a log–log scale. Since the convection is driven by the temperature gradients in the cavities near the wall, the abscissa in the graph is the temperature difference defined as

$$\Delta T_{conv} = (T_{w-} - T_{w+}) + \left(\frac{dT}{dx}\right)_{bed} \frac{d_p}{2}$$

Where dp refers to the size of the particle.

It is interesting to see that heat transfer coefficient increases with $\triangle T_{conv}$ with the slope of approximately 0.27 (in the log–log plot). In natural convection, heat transfer coefficient varies as $(\triangle T_{conv})^n$, where n is typically between 0.25 and 0.33[24]. Further work is in progress to investigate the effect of particle size, material of the particle on the packed bed heat transfer.

CONCLUSIONS

1) The convective contribution to heat transfer in a packed bed of iron ore particles has been separated by conducting heat transfer experiments at atmospheric condition and under vacuum.
2) The convective contribution to the effective thermal conductivity has been found to be 1.46 W/m K and it varies little with bed temperature under present experimental conditions.
3) The variation of convective contribution to the wall-to-bed interfacial heat transfer coefficient with effective temperature difference between the wall and the particle at the vicinity of the wall (ΔT_{conv}) found be follow a power law relation with an exponent of 0.27.

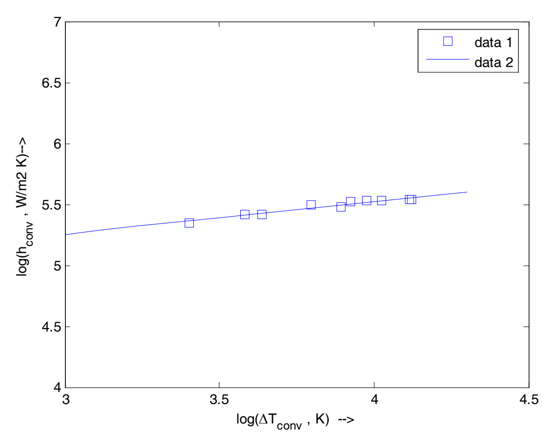

Figure 5 Variation of h_{conv} with ΔT_{conv} (log-log scale)

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