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Forced Convection Heat Transfer Characteristicsof Geometrically Ordered Packing of Steel Balls

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ABSTRACT

Heat transfer in packed bed gas-solid systems is an important operation in the chemical process industries. For example, packed beds are used in reactors, separators, dryers, filters, and heat exchangers. The heat transfer throughout a packed bed can have a significant effect on the performance of the equipment. Therefore, it is important to better understand the heat transfer through packed beds. Heat transfer in packed bed is profoundly affected by the effective thermal conductivity of the packing. Effective thermal conductivity ultimately depends on number of parameters such as arrangement of packed particles, porosity of packed bed, particle shape, particle size distribution, mechanical properties of particles, thermodynamic properties of fluid, etc. In the present work, forced convective heat transfer characteristics of geometrically ordered packings of steel balls have been experimentally investigated for body centered, face centered and random structure of particle packings. With body centered arrangement of solid particles in the packed bed,the pressure drop can be minimized and heat transfer performance can be improved.

Keywords— Packed bed gas-solid systems, pressure drop, Heat Transfer Performance.

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I. Introduction

In this experiment the macroscopic hydrodynamic and heat transfer characteristics in some novel structured packed beds (SC and BCC) will be studied, where the packing of ellipsoidal or non-uniform spherical particles will be investigate for the first time with experiments and some important results will be obtained. For present experiments, the interstitial heat transfer coefficient in the packed bed will be determined using an inverse method of transient single-blow technique. The effects of packing form and particle shape will be investigated. Firstly, it will be discover that, the computational method reported by Yang et al. (2010) [1] might be appropriate for heat transfer predictions in structured packing, while it might under estimate the friction factors, especially when the porosity is relatively low. Secondly, it is found that, the traditional Ergun's and Wakao's equations might over predict the friction factors and Nusselt numbers for the structured packings, respectively, and some experimental modified correlations will be obtained. Furthermore, it will be revealed that, both the effects of packing form and particle shape are significant to the macroscopic hydrodynamic and heat transfer characteristics in structured packed beds. With proper selection of packing form, such as Simple Cubic packing (SC), Body Centered Cubic packing (BCC), the pressure drops in the structured packed beds can be greatly reduced and the overall heat transfer performances will be improved. These experimental results would be reliable and useful for the optimum design in industry applications.

Types of Structure

There are three different structured packing are constructed, including SC (simple cubic packing with uniform spherical particles), BCC (body center cubic packing with uniform spherical particles) and random structure (packing with non uniform spherical particles) packing.

Simple Cubic (SC):

The unit cell is a primitive one, with one lattice point (atom) per unit cell.

If we assume the radius of the atom is “r” and the lattice constant is “a”, we have:

a = 2r (i.e., the adjacent atoms touch each other along the edge of the unit cell)

Vatom = 8 (1/8) $(4\pi r^3)/3 = (4\pi r^3)/3$

Vcell = $(2r)^3 = 8r^3$

The packing efficiency (or fraction of packing):

Vatom / Vcell = $(4\pi r^3/3) / (8\ r^3) = \pi/6 = 52.4\%$

The only example is polonium (Po). In this metal, 47% of the space is occupied by Po atoms, the rest (47.6%) are void spaces.

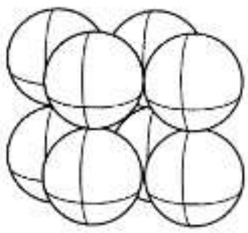

Fig 1 a: Simple Cubic structure (SC)

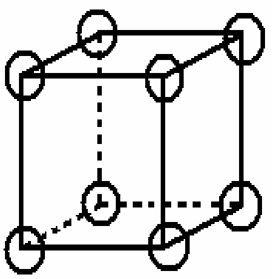

Fig 1 b: Simple Cubic structure (SC)

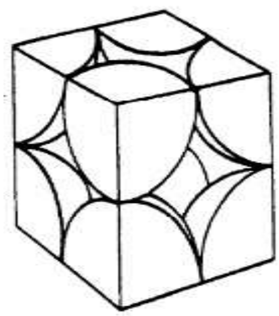

Fig 1 c: Unit cell (SC)

Body-Centered Cubic (BCC):

Just like the simple cubic lattices, the body-centered cubic (BCC) lattice (Fig.2.3) has four 3-fold axes, 3 4-fold axes, with mirror planes perpendicular to the 4-fold axes, and therefore belongs to the Oh point group. The body centered cubic structure only has a coordination number of 8. Nevertheless some metals form into a BCC lattice (Ba V Nb, Ta W M, in addition Cr and Fe have bcc phases.) Bonding of p-orbitals is The lattice is not a primitive one since there are 2 lattice points (atoms) per unit cell, one at the vertices (one eighth at each vertex) and other at the center of the cubic cell. Ideal in a BCC lattice is simply composed of two interpenetrating cubic lattices. This structure allows the next-nearest neighbor p orbital to overlap more significantly than structure would. This increases the effective coordination number by including the next nearest neighbor shell in the bonding.

If we assume the radius of the atom is “r” and the lattice constant is “a”, we have:

$\sqrt{3}$ a = 4 r (i.e., at maximum packing when the adjacent atoms touch each other along

the body diagonal of the cubic cell)

Vatom = $2\ (4\pi r^3)/3 = 8\pi r^3/3$

Vcell = $(a)^3 = (4r/\sqrt{3})^3$

The maximum packing density (or fraction of packing):

Vatom / Vcell = $(8\pi r^3/3) / (4r/\sqrt{3})^3 = \sqrt{3}\pi/8 = 68.0\%$

A typical example is iron (Fe), which is a magnetic material.

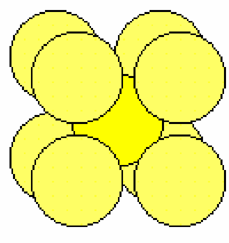

Fig 2a: Body Simple Cubic structure (BCC)

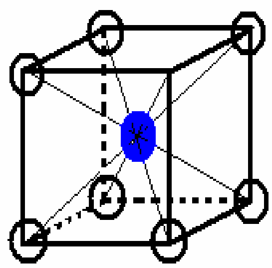

Fig 2 b: Simple Cubic structure (BCC)

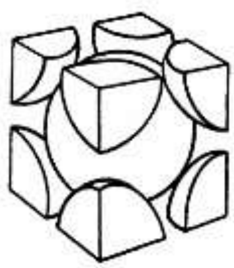

Fig 2 c: Unit cell (BCC)

II. LITERATURE REVIEW

Tsotsas (2010a) [2] has well summarized the axial heat dispersion characteristics in the packed tubes. It is demonstrated that, axial dispersion of heat in packed tubes with fluid flow is not due to the effective thermal conductivity alone, but to a combination of heat transport in the direction of flow, heat transfer between particle surface and fluid, and heat conduction inside particles. For low Peclet number, axial dispersion of heat is mainly due to the effective thermal conductivity; for middle Peclet number, the effect of fluid-to-particle heat transfer should be dominate; and for high Peclet number, the heat conduction in the particles prevails.

Tsotsas (2010b) [3] has also well summarized the effective thermal conductivity models for the packed beds. It shows that, the effective thermal conductivity of packed beds is related to a variety of factors, including thermal conductivities of particles and fluid, porosity of packed bed, particle shape, particle size distribution, mechanical properties of particles, thermodynamic properties of fluid, etc.

A.P. Collier et. al. [4] studied that the heat transfer coefficient has been measured for a heated phosphor-bronze sphere (diam. 2.0, 3.0 or 5.56 mm) added to a bed of larger particles, through which air at room temperature was passed. The bronze heat transfer sphere was attached to a very thin, flexible thermocouple and was heated in a flame to 140 ◦C before being immersed in the bed. The conclusion of this study is that for the commoner situation of ds/db, h rises to a maximum, when U slightly exceeds Umf . This is because a hot (relatively large) particle then loses heat by being in contact with very many of the smaller fluidized particles. When (ds/db) changes from being less than unity to well above unity, there is thus a change of mechanism from heat transfer to the gas flowing through the bed to heat transfer to the other particles. Some factors affecting this change of mechanism must include:

1) When (ds/db) is decreased below unity, the number of contacts between the heat transfer sphere and the other fluidized particles becomes smaller.
2) When (ds>db), it is possible that a smaller heat transfer sphere is fluidized, when the other particles in the bed are not. Consequently, a progressively smaller (and consequently more mobile) heat transfer sphere contacts the fluidized particles for shorter times, making heat transfer to the other particles less likely.
3) The magnitude of the Reynolds number for the gas flowing over the bronze heat transfer sphere is important, in that heat transfer to the gas is favored by a large Re, as in this work.

Dong sheng Wen, et. al. [5] reports an experimental study of both the transient and steady-state heat transfer behavior of a gas flowing through a packed bed under the constant wall temperature conditions. Effective thermal conductivities and convective heat transfer coefficient are derived based on the steady-state measurements and the two-dimensional axial dispersion plug flow (2DADPF) model. The results reveal a large temperature drop at the wall region and the temperature drop depends on the axial distance from the inlet. The 2DADPF model predicts the axial temperature distribution fairly well, but the prediction is poor for the radial temperature distribution. Length-dependent behavior of the effective heat transfer parameters and non-uniform flow behavior are proposed to be responsible. He concluded that Both the transient and steady-state heat transfer behavior of a gas flowing through a packed bed has been investigated experimentally. Both radial and axial direction temperature distributions have been measured under the constant wall temperature conditions. Effective thermal conductivities and convective heat transfer coefficient have been derived based on the steady-state measurements and the two-dimensional axial dispersion plug flow (2DADPF) model. The results reveal a large temperature drop at the wall region and the temperature drop depends on the distance from the entrance of the column. The 2DADPF model predicts the axial temperature distribution fairly well, but the prediction of radial temperature distribution is less satisfactory, particularly in the region close to the inlet, indicating the length-dependent behavior of the effective heat transfer parameters. A comparison of the effective parameters with published correlations shows reasonable agreement. It is found to predict the effective radial thermal conductivity well, while the wall–fluid heat transfer coefficient is better represented by the Li–Finlayson correlation. Discussion of the results suggests that coupling the influence of flow field to the heat transfer model be a key to unravel the fundamental reasons for the observed disagreement.

Trivizadakis et al. (2010) [6] studied Uniform-spherical and cylindrical-extrudate particles are employed to study air–water down flow in a packed bed of 14 cm i.d. The effect of particle shape, neglected in the literature so far, is shown to be very significant. A packed bed of extrudates displays significantly greater global dynamic liquid holdup hd and pressure drop, as well as a trickling-to-pulsing transition boundary at higher gas flow rates, compared to beds of spheres of comparable size. Moreover, packed extrudates exhibit a significant increase of holdup, hd , in the axial flow direction, a trend reported for the first time as there are no similar data available in the literature; on the contrary beds of spherical particles are characterized by practically constant hd in the axial direction. Although an explanation for this hd axial variation is not obvious, one might attribute it to the anisotropy and non-uniformity of interstitial voids of packed cylindrical particles. For beds of uniform spheres, in the diameter range examined (3–6 mm), the effect of size on both dynamic holdup and pressure drop, although quite pronounced, is not as significant as the effect of particle shape. An extensive survey of literature data, obtained with similar spherical particles, suggests that small bed diameters have an appreciable influence on trickling-to-pulsing transition boundary. Comparisons are reported with literature methods for predicting the measured parameters; discrepancies between data and predictions may be partly due to the inadequacy of a single “equivalent” diameter to represent both shape and size of non-spherical particles; predictive methods performing best are also identified. He concluded that The trickling-to-pulsing transition observed at higher gas flow rates, in beds of extrudates, implies that flow stability extends to somewhat higher flow rates. A similar trend of higher transition velocities is identified (in several literature studies for spheres) with small bed diameters (40–60 mm). This trend, which has not been noted in the literature, might be also attributed to packing non-uniformities, probably due to the relatively small bed-to-particle diameter ratio. Although it is not within the scope of this investigation, the effect of bed diameter on flow characteristics evidently should be of concern to design engineers, especially for large size industrial TBR for which there is practically no information in the literature.

(Ergun c, 1952; Wakao and Kaguei, 1982) [7] were unavailable for structured packings.All these studies demonstrate that not only local behavior, but also macroscopic characteristics of flow and heat transfer are significantly affected by the internal structural properties of packed beds. The hydrodynamic and heat transfer performances in random and structured packings are quite different. The tortuosity and pressure drop in randomly packed bed are usually much higher and the overall heat transfer performance may not be optimal. While in structured packings, the pressure drops are usually much lower and the overall heat transfer performances may be better.

III.EXPERIMENTAL SETUP LAYOUT

The experimental system for investigation of heat transfer performances in the structured packed beds is shown in Fig. 3. It consists of an air flow circuit, a test section and several instruments. In the present study, air will be induced to the wind tunnel by a centrifugal suction blower and the inlet temperature is read by a thermometer. Before entering the test packed bed, the air flow will be heated by passing through a removable electric heater and then transverses the test packed bed, where the particles inside will be heated by the hot air. When the packed bed temperature will be stabilized, the cold air will be passed into the channel and the packed bed is cooled down until its temperature decreases to the ambient temperature. During the cooling process, the experimental data will be measured and recorded simultaneously. The volumetric flow rate through the test section will be measured by a parallel flow meter system, which will be situated at the downstream of the test section. This flow meter system is composed with rotameter. The static pressure difference across the test section will be displayed by a micro-differential meter combined with a U-tube water column manometer. The air flow and particle temperatures will be measured by PT100 thermocouples.

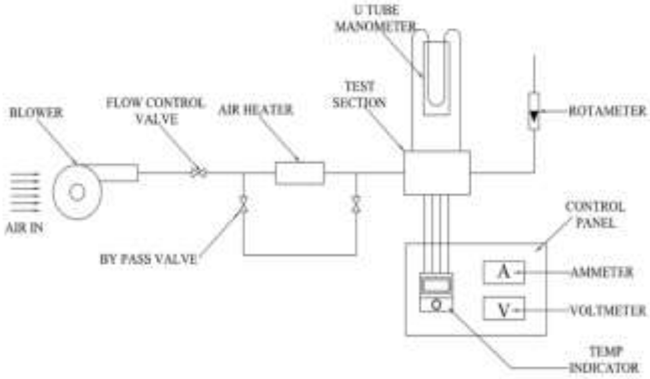

Figure 4.1 Schematic layout of proposed experimental system

1. Blower, 2. Flow Control Valve, 3. By-pass valve, 4.Removable electric heater, 5.Test Section, 6.U tube manometer, 7.Rotameter, 8. Control Panel

Test Section

The test channel is made of Acrylic Sheet plates (thickness of 10mm) and the particles are orderly stacked inside. In present study, the test packed bed is composed of 08(x) X 5(y) X 5(z) packed cells, which would guarantee the fully developed flow and heat transfer inside.), three different structured packings are constructed, including SC (simple cubic packing with uniform spherical particles), BCC (bodycantered cubic packing with uniform spherical particles) and Random Structure (Packing of particle with random structure) packings.

The non-uniform packing (BCC-1) is composed of eight big spherical particles (dp¼12 mm) at eight corners and one small spherical particle (dp¼9 mm) at body center, where the small particle is closely contacted with all big particles.

Meanwhile, in order to reduce the wall effect as possible, the air flow and particle temperatures in the packed bed are only measured for the central packed channel, where the average inlet and outlet air flow temperatures are gauged by using two thermocouple racks and the particle temperatures are monitored with the thermocouples embedded in the selected particles (each particle with one bed inside).

Formulae Used

$$f = \frac{c_1}{R_e} + c_2$$

$$N_u = a_1 + a_2 P_r^{1/3} R_e^n (\frac{d_p}{d_h} \emptyset)^n$$

Where C1, C2 are the friction factor constants, with C1and C2 in Ergun's equation; a1, a2 and n are the heat transfer model constants, with a1, a2 and n in Wakao's equation.

IV. RESULTS AND DISCUSSION

Experimentation is carried out to investigate the heat transfer coefficient and friction factor at various heat input and mass flow rate of hot and cold air streams on the structured packed bed. On the basis of the observations recorded the heat transfer coefficient for particular heat input and mass flow rate of hot and cold air streams were calculated. The variation of heat transfer coefficient of structured packed bed with heat input i.e. source temperature and mass flow rate of air streams are represented graphically. The effect of mass flow rate, temperature rise, pressure drop for SC structure and BCC structure also represented graphically. Thermal behavior of SC structure and BCC structure is compared.

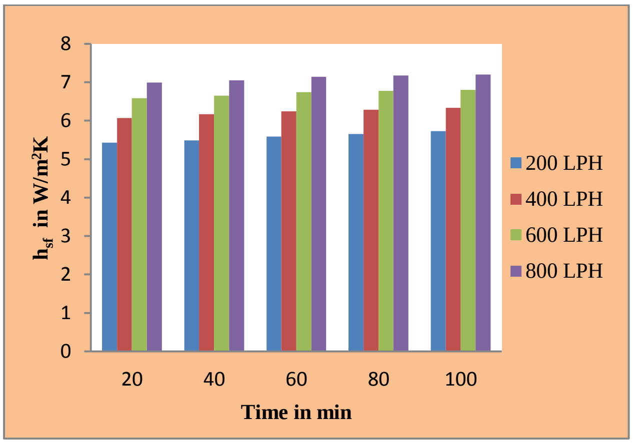

Fig. 4.1 Variation in heat transfer coefficient of SC structured packed bed with volume flow rate

Fig. 4 shows the variation in heat transfer coefficient of SC structured packed bed with volume flow rate. It is observed that the heat transfer coefficient of SC structured packed bed increases with increase in volume flow rate.

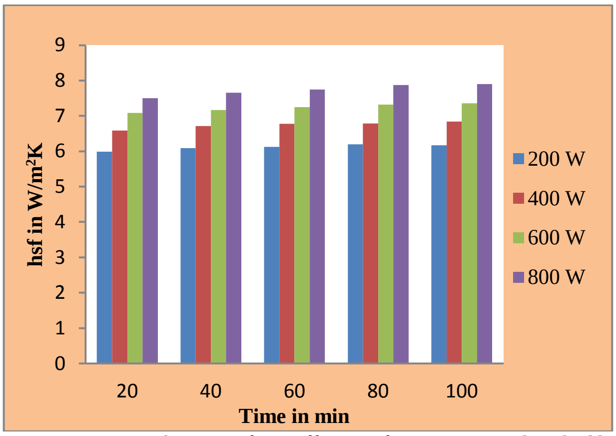

Fig. 4.2 Variation in heat transfer coefficient of BCC structured packed bed with volume flow rate

Fig. 4.2 shows the variation in heat transfer coefficient of BCC structured packed bed with volume flow rate. It is observed that the heat transfer coefficient of BCC structured packed bed increases with increase in volume flow rate.

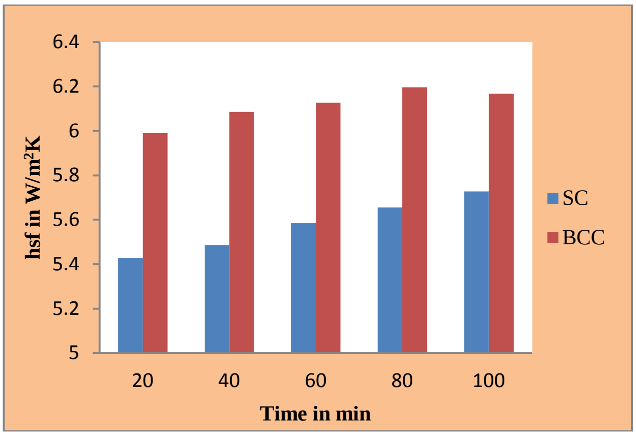

Fig. 4.3 Comparison between heat transfer coefficient of SC and BCC Packed bed.

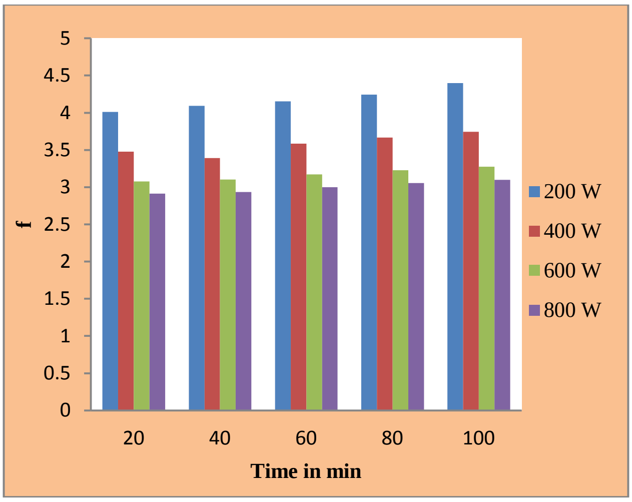

Fig 4.4 Variation in friction factor of SC structured packed bed with volume flow rate

Fig. 4.4 shows the variation in friction factor of SC structured packed bed with volume flow rate. It is observed that the friction factor of SC structured packed bed increases with increase in volume flow rate.

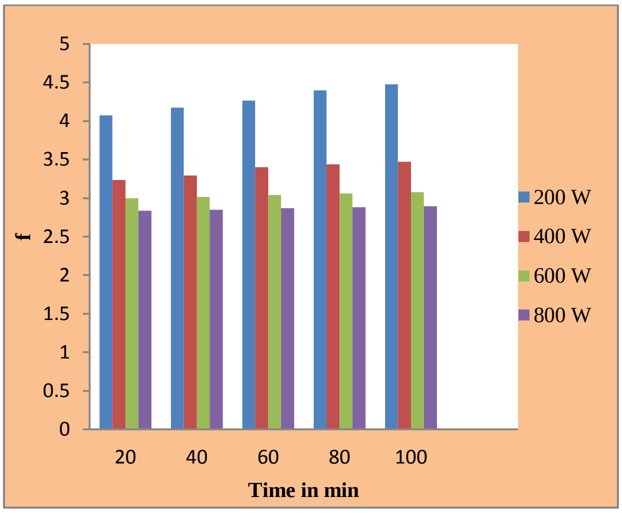

Figure 4.5 Variation in friction factor of SC structured packed bed with volume flow rate

Fig. 4.5 shows the variation in friction factor of BCC structured packed bed with volume flow rate. It is observed that the friction factor of BCC structured packed bed increases with increase in volume flow rate.

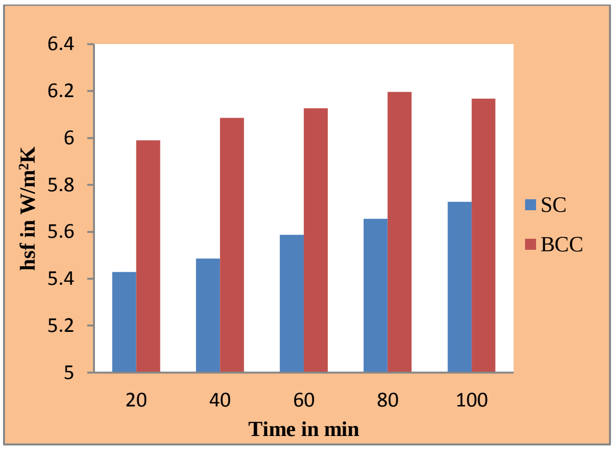

Fig 4.6 Comparison between friction factor of SC and BCC Packed bed

V.Conclusion

The experimental investigation was carried out on two types of SC and BCC structured packed bed. The effect of source temperature and mass flow rate of hot and cold air streams on heat transfer coefficient and frictional factor of SC and BCC structured packed bed is experimentally investigated. The heat input to band air heater was varied from 200 W to 800 W and hot and cold air stream flow rate varied from 200 LPH to 800 LPH. The effect of variation in source temperature and mass flow rate of hot and cold air streams on heat transfer coefficient and friction factor of packed bed is experimentally studied. The structured bed in experimentation is specially designed for heat transfer application. It is conclude that heat transfer coefficient of structured packed bed (both SC and BCC) increases with increase in source temperature.Friction factor of structured packed bed (both SC and BCC) increases with increase in source temperature.

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