ISSN 2395-1621

Experimental evaluation of forced convective heat transfer in structured packed beds

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ABSTRACT

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. Conclusions from studied experiment are as follows.
When heat is transferring from air to bed, the heat transfer coefficient of structured packed bed (both SC and BCC) increases with increase in source temperature. When heat is transferring from air to bed, the friction factor of structured packed bed (both SC and BCC) increases with increase in source temperature. When heat is transferring from air to bed, the performance of BCC structured bed is better than SC structured bed. When heat is transferring from bed to air, the heat transfer coefficient of structured packed bed (both SC and BCC) decreases with increase in source temperature. When heat is transferring from bed to air, the friction factor of structured packed bed (both SC and BCC) decreases with increase in source temperature. When heat is transferring from bed to air, the performance of BCC structured bed is better than SC structured bed.
Keywords— Structured Bed, SC, BCC, Random Structure, Heat Transfer.

ARTICLE INFO

Article History

Received :23h May, 2015

Received in revised form :

25th May, 2015

Accepted :28th May, 2015

Published online :

1st june 2015

I. INTRODUCTION

In this chapter, the most common models of structured packed bed reactors are presented, which were also used in the present investigation. The currently applied models for this investigation are Simple Cubic (SC), Body Centered Cubic (BCC) and random structured and contain effective transport parameters in which heat transport processes at different scales.

All metals, a major fraction of ceramics, and certain polymers acquire crystalline form when solidify, i.e. in solid state atoms self-organize to form crystals. Crystals possess a long-range order of atomic arrangement through repeated periodicity at regular intervals in three dimensions of space. When the solid is not crystalline, it is called amorphous. Examples of crystalline solids are metals, diamond and other precious stones, ice, graphite. Examples of amorphous solids are glass, amorphous carbon (a-C), amorphous Si, most plastics.

There is very large number of different crystal structures all having long-range atomic order; these vary from relatively simple structures for metals to exceedingly complex structures for ceramics and some polymers. To discuss crystalline structures it is useful to consider atoms as being hard spheres, with well-defined radii. In this scheme, the shortest distance between two like atoms is one diameter. In this context, use of terms lattice and unit cell will be handy. Lattice is used to represent a three-dimensional periodic array of points coinciding with atom positions. Unit cell is smallest repeatable entity that can be used to completely represent a crystal structure. Thus it can be considered that a unit cell is the building block of the crystal structure and defines the crystal structure by virtue of its geometry and the atom positions within.

In all structured bed models, axial symmetry is assumed, which will avoid the variation of the porosity in angular direction. The packed bed is mostly divided into a core zone and a wall zone. As is illustrated in Fig. 1 for the case of an exothermic reaction, the temperature profiles in these zones are very different. A typical temperature profile in the core zone of the packing is parabolically shaped. In the wall zone, the temperature shows a sharp decrease. In the models, the heat flux at the wall is proportional to the difference between the wall temperature and the fluid temperature inside the bed close to the wall. Since wall is impermeable, the radial mass flux is zero at the wall.

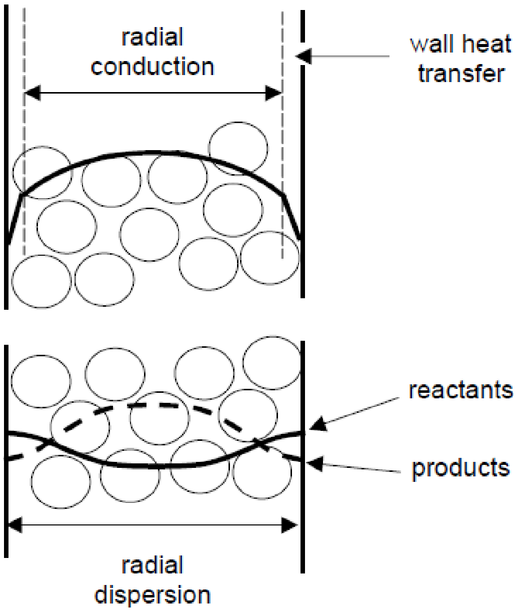

Fig. 1 Typical radial temperature and concentration profiles

In packed beds, dispersion of heat and mass are mainly caused by fluid convection and mixing.

Independent of fluid velocity:

1. Conduction/diffusion through the solid
2. Conduction through the solid-solid contact points
3. Heat transfer by radiation between the surfaces of particles
4. Diffusion and conduction within the fluid

Depending on fluid velocity:

1. Convection by the fluid in axial direction
2. Axial and transverse mixing of the fluid
3. Fluid-solid heat- and mass transfer
4. Diffusion and conduction through the fluid film near the solid-solid contact point

Variation of the fluid density over the bed may lead to free convection, which causes additional dispersion of heat and mass in axial and radial direction. Transport of heat and mass occurs in both phases both in parallel and in series. The bulk of the fluid flows axially and causes convective transport in this direction

Inside the packing, fluid elements chaotically move between the particles (see Fig. 2), which causes additional heat and mass transport in radial and axial direction. Mixing of the fluid elements occurs due to turbulence and molecular diffusion and conduction. At high fluid flow rates, which are typical for industrial packed bed reactors, this transport additional to the overall convective transport is referred to as ‘dispersion’ of heat.

If the temperature and/or concentration at the surface of the particle differ from its value in the fluid phase, mass and/or heat exchange between the fluid and the particles will occur in fig.1.2.

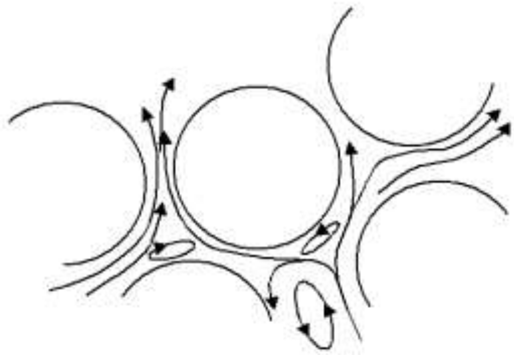

Fig. 2 Mixing of fluid elements between particles

Due to variation of the temperature over the surface of the pellets and the occurrence of chemical reaction inside the solid, temperature and concentration profiles will exist within the particles, as is shown schematically in Fig. 3. Inside the particle, the temperature will increase towards the center of the particle if the reaction is exothermic. At the same time reactants are consumed and products are formed, which leads to concentration gradients. Since it would require a large computational effort to perform these calculations for the entire structured bed.

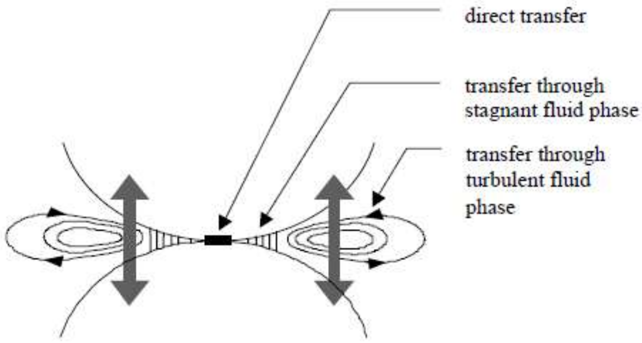

Fig. 3 Heat transfer near a solid-solid contact

II. LITERATURE REVIEW

In the past decades, the flow and heat transfer in the packed beds, including random and structured packings, were extensively investigated by lots of researches.

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. The solid-particle heat transfer in the packed beds was also well summarized by Gnielinski (2010) [4], where the definitions, determination methods and the model validities of the solid-particle heat transfer coefficients in the packed beds were carefully presented and discussed. Further-more, Carpinlioglu and Ozahi (2008) [5] have experimentally studied the pressure drop characteristics of a variety of randomly packed beds in turbulent flow of air. The measured pressure drops were compared with the well-known Ergun’s equation (Ergun a, 1952) [6] and the deviations were within an acceptable error margin. A simplified correlation for the measured pressure drop was obtained and it was observed to be correlated in terms of particle sphericity, porosity and Reynolds number. Lanfrey et al. (2010) [7] recently have developed a theoretical model for the tortuosity of fixed bed randomly packed with identical particles. They found that, the tortuosity was proportional to a packing structure factor, which could well capture the balancing effect between porosity and particles phericity. As porosity or particles phericity decreased, the tortuosity increased and it did not depend on the particle size. A comparison between the performance in flow and heat transfer estimation of different turbulence models in a randomly packed bed were also performed by Guardo et al. (2005) [8]. Some other recent studies for random packing were also reported by Nijemeisland and Dixon (2004) and Reddy and Joshi (2010) [9]. On the other hand, the investigations for structured packing were also popular, and the flow and heat transfer characteristics were found to be quite different. Susskind and Becker (1967) [10] have experimentally measured the pressure drops of water in an ordered packed bed of stainless steel ball bearings. It was found that, as the relative horizontal spacing of balls increased, the pressure drop in the packed bed would be greatly decreased. Nakayama et al. (1995) [11] have numerically studied the flow in a three-dimensional spatially periodic array of cubicb locks. It was discovered that, the macroscopic hydrodynamic correlation obtained by their model could fit well with that of Ergun’s equation (Ergun b, 1952) [12], but the inertia coefficient was much lower. Calis et al. (2001) and Romkes et al. (2003) [13] have investigated the flow and heat transfer characteristics in a variety of composite structured packed beds of spheres. It was revealed that, the flow and heat transfer performances in the composite structured packed beds were significantly affected by the packing form. With composite structured packings, the pressure drop could be greatly lowered and the traditional correlations (Ergun c, 1952; Wakao and Kaguei, 1982) [14] 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. DESIGN AND DEVELOPMENT

The experimental layout shown in Fig.2 is designed and constructed to investigate the effect of structured packed bed on the heat transfer.

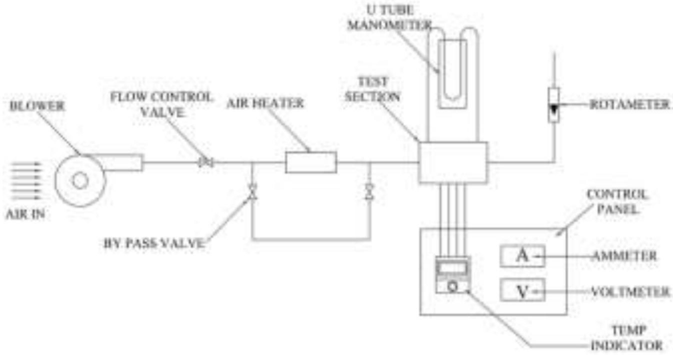

Fig.No.2:-Schematic layout of proposed experimental system

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

The experimental system for investigation of macroscopic hydrodynamic and heat transfer performances in the structured packed beds is shown in Fig. 2. 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. After the packed bed temperature increases, the electric heater is turned off and moves away. When the packed bed temperature is stabilized, the cold air is sucked 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 is measured and recorded simultaneously. The volumetric flow rate through the test section is measured by a parallel flow meter system, which is situated at the downstream of the test section. This flow meter system is composed with rotameter. The static pressure difference across the test section is displayed by a micro-differential meter combined with a U-tube water column manometer. The air flow and particle temperatures are measured by copper constant thermocouples.

IV. NUMERICAL APPROACH

i. Calculation of Porocity (Ø)

$$\emptyset = \frac{V_{pore}}{V_{bulk}} = \frac{V_{bulk} - V_{matrix}}{V_{bulk}}$$

ii. Calculation of Pore scale Hydraulic Diameter (dh)

$$d_h = 4\ X\ \frac{\emptyset}{1-\emptyset}\left(\frac{V_p}{A_p}\right)$$

iii. Calculation of Pore scale Hydraulic Diameter (dh)

$$d_p = 2\ X\left(\frac{3V_p}{4\pi}\right)^{1/3}$$

Table 4.1: Geometric parameters for the test packed beds

Packing Mode	dp	dh	a	b	c	Lp	Wp	Hp	∅
SC	12.49	7.600	12.5	12.50	12.50	100	50	50	0.47
BCC	12.49	6.759	12.5	12.50	12.50	100	50	48	0.41

Table 4.2: Particle properties for the test packed beds

Particle Shape	Material	Material Density (ρ) in kg/m3	Material Specific Heat (Cp) in J/kg.K	Thermal Conductivity W/mk
Spherical particle	Bearing steel	7810	553.0	40.1

According to the previous studies of Ergun (1952), Wakao and Kaguei (1982), Calis et al.(2001), Romkes et al.(2003) and Yang et al.(2010), the friction factor (f) and Nusselt number(Nusf) in the packed beds can also be formulated with following correlations

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

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

where c1, c2 are the friction factor constants, with c1=133 and c2=2.33 in Ergun’s equation (Ergun, 1952); a1, a2 and n are the heat transfer model constants, with a1=2.0, a2=1.1 and n=0.6 in Wakao’s equation(Wakao and Kaguei, 1982).

V. RESULT 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, BCC structure and Random structure also represented graphically. Thermal behavior of SC structure, BCC structure and random structure is compared.

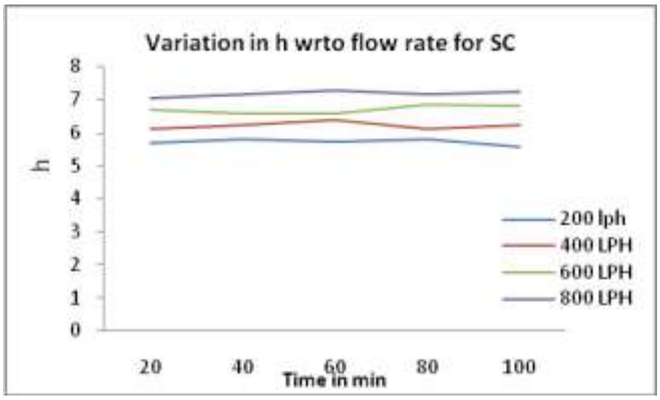

Figure 6.1 Variation in heat transfer coefficient of SC structured packed bed with volume flow rate

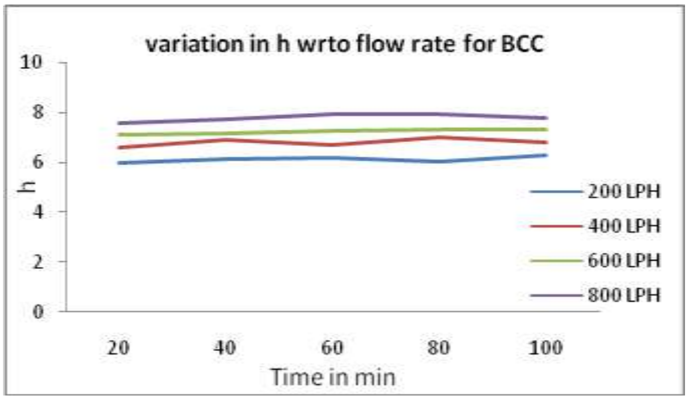

Figure 6.2 Variation in heat transfer coefficient of BCC structured packed bed with volume flow rate

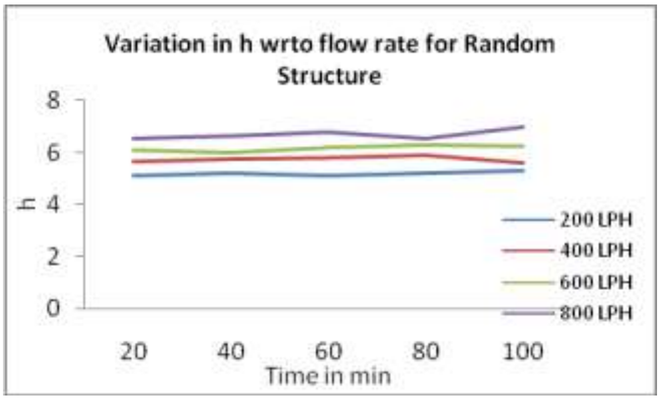

Figure 6.3 Variation in heat transfer coefficient of Random structured packed bed with volume flow rate

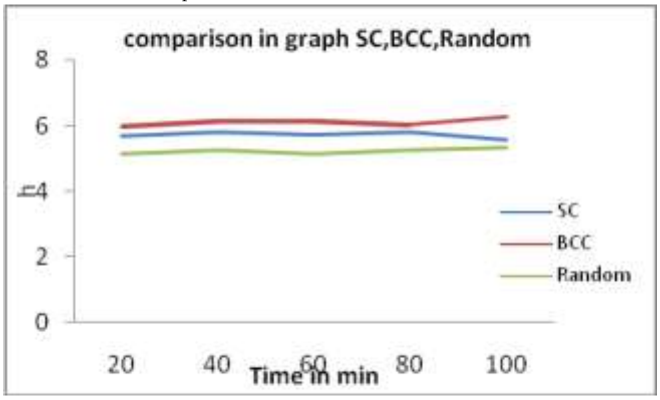

Figure 6.4 Comparison between heat transfer coefficient of SC, BCC and Random structured packed bed

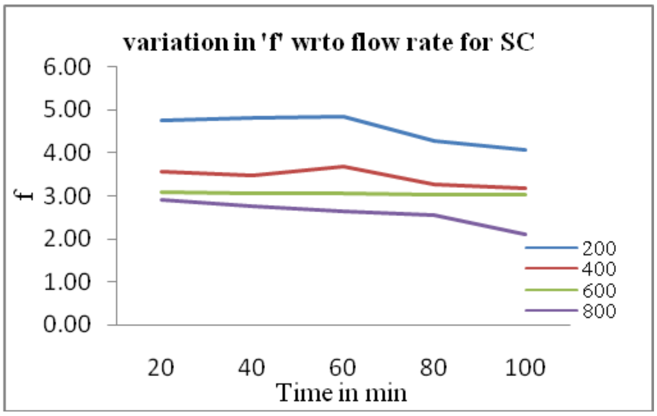

Figure 6.5 Variation in friction factor of SC structured packed bed with volume flow rate

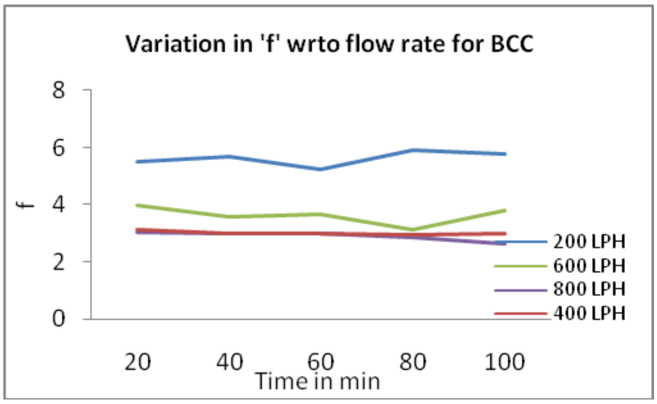

Figure 6.6 Variation in friction factor of BCC structured packed bed with volume flow rate

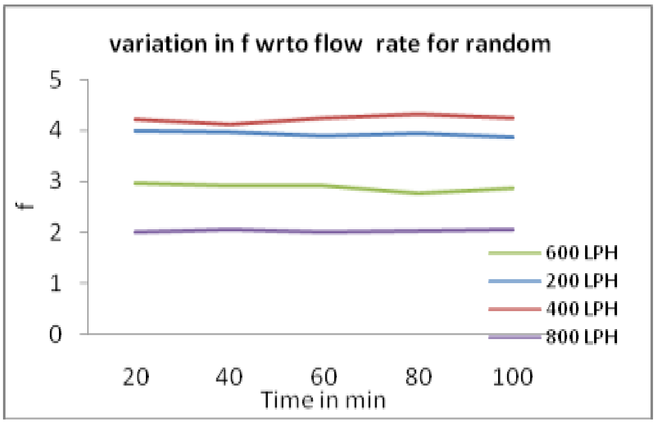

Figure 6.7 Variation in friction factor of Random structured packed bed with volume flow rate

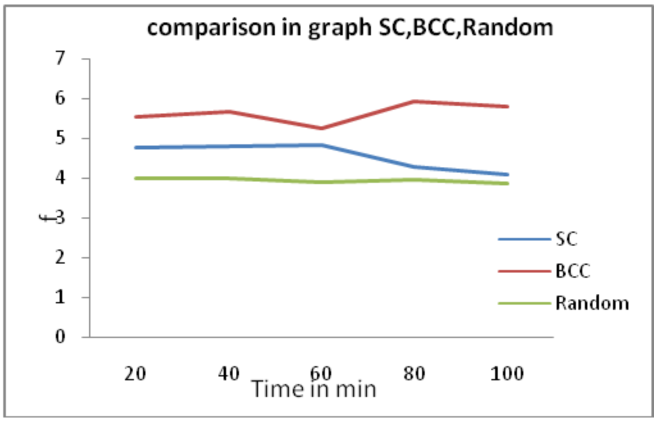

Figure 6.8 Comparison between friction factor of SC, BCC and Random Structured Packed bed

VII. CONCLUSION

The experimental investigation was carried out on two types of SC, BCC and Random 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, BCC, Random 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. Conclusions from studied experiment are as follows,

a) The heat transfer coefficient of structured packed bed (SC, BCC and Random) increases with increase in source temperature.
b) The friction factor of structured packed bed (SC, BCC and Random) increases with increase in source temperature.
c) The performance of BCC structured bed is better than SC and Random structured bed.

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