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Review on Forced Convective Heat Transfer in Structured Packed Beds

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ABSTRACT

The literature on heat transfer in packed beds subject to flowing gases has been critically reviewed with the emphasis on experimental techniques. It is observed that the two major modes of heat transfer, namely, conduction between the particles in the bed and convection between the flowing gas and the particles, interact with each other. This is believed to be the major reason for the difficulty in obtaining a single generalized experimental correlation or theoretical Vs experimental models to evaluate the total heat transfer rates in packed bed gas-solid systems.

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I. INTRODUCTION

Packed beds, due to their high surface area-to-volume ratio, are widely used in a variety of industries, such as catalytic reactors, absorption towers, packed bed regenerators, high temperature gas-cooled nuclear reactors and heat accumulators, etc. Heat transfer in packed bed gas-solid systems is an important operation in the chemical process industries. It is obvious that an extensive knowledge and thorough understanding of the heat transfer phenomena in the bed is essential for the successful design of such systems. The phrase, "packed bed heat transfer," is currently used to describe a variety of phenomena, namely:

(1) The convective heat transfer from the walls of the packed bed to the fluid;
(2) The convective heat transfer from the particles to the fluid flowing through the bed, sometimes referred to as the fluid-particle mode;
(3) The conduction heat transfer from the walls of the bed to the particles constituting the bed;
(4) The conduction heat transfer between the individual particles in the bed; this is sometimes referred to as the particle-particle mode;
(5) Radiant heat transfer; and
(6) Heat transfer by mixing of the fluid.

These modes are illustrated schematically in Figure 1.1, the fourth mode, namely the conduction between the particles, can be further subdivided into the axial and radial directions. Moreover, at elevated temperatures heat transfer by radiation will also be an important mode. In many industrial applications, it is found that two or more of the modes cited above take place simultaneously. Moreover, the modes may interact with one another. For example, the conduction between the particles may be affected by the convection heat transfer between the particles and the fluid. This interaction among the different modes is one of the main reasons for the difficulty in correlating the total heat transfer and analyzing the experimental data in this field. In the next two sections some of the highlights of the experimental and theoretical research studies in the different aspects of heat transfer in gas-solid packed bed systems are presented.

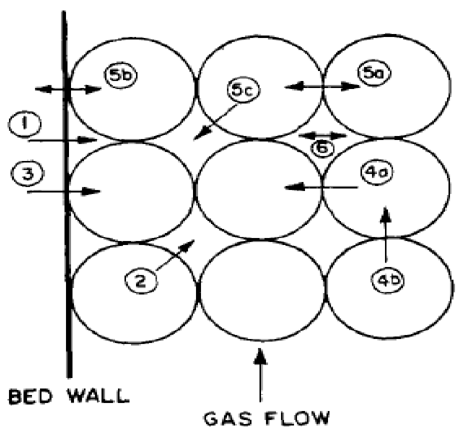

Figure 1.1 Modes of heat transfer in packed beds

Moreover, the modes may interact with one another. For example, the conduction between the particles may be affected by the connection between the particles and the fluid. This interaction among the different modes is one of the main reasons for the difficulty in correlating the total heat transfer and analyzing the experimental data in this field. In the next two sections some of the highlights of the experimental and theoretical research studies in the different aspects of heat transfer in gas-solid packed bed systems are presented.

II. LITRATURE SURVEY

Jian Yang et. al.(2010) [1] packed bed reactors are widely used in chemical process industries, because of their low cost and ease of use compared to other packing methods. However, the pressured rops in such packed beds are usually much higher than those in other packed beds, and the overall heat transfer performances may be greatly lowered. In order to reduce the pressure drops and improve the overall heat transfer performances of packed beds, structured packed beds are considered to be promising choices. In this paper, the flow and heat transfer inside small pores of some novel structured packed beds are numerically studied, where the packed beds with ellipsoidal or non-uniform spherical particles are investigated for the first time and some new transport phenomena are obtained. Three-dimensional Navier–Stokes equations and RNG k–e turbulence model with scalable wall function are adopted for present computations. The effects of packing form and particle shape are studied in detail and the flow and heat transfer performances in uniform and non-uniform packed beds are also compared with each other. Firstly, it is found that, with proper selection of packing form and particle shape, the pressure drops in structured packed beds can be greatly reduced and the overall heat transfer performances will be improved. The traditional correlations off low and heat transfer extracted from randomly packings are found too verpredict the pressured ropes and Nusselt number for all these structured packings, and new correlations of flow and heat transfer are obtained. Secondly, it is also revealed that, both the effects of packing form and particle shape are significant on the flow and heat transfer in structured packed beds. With the same particle shape (sphere), the overall heat transfer efficiency of simple cubic (SC) packing is the highest. With the same packing form, such as face center cubic (FCC) packing, the overall heat transfer performance of long ellipsoidal particle model is the best. Furthermore, with the same particle shape and packing form, such as body center cubic (BCC) packing with spheres, the overall heat transfer performance of uniform packing model is higher than that of non-uniform packing model. The models and results presented in this paper would be useful for the optimum design of packed bed reactors.

Tsotsaset. al. (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.

Tsotsaset. al. (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 favoured by a large Re, as in this work.

Dong sheng Wenet. al. [5] reports an experimental study of both the transient and steady-state heat transfer behaviour 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 behaviour of the effective heat transfer parameters and non-uniform flow behaviour are proposed to be responsible. He concluded that both the transient and steady-state heat transfer behaviour 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 behaviour 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-extrudates particles are employed to study air–water down flow in a packed bed of 14 cm i.e. 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.

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.

Nijemeisland et al. (2004) and Reddy and Joshi (2010) [8] reported some other recent studies for random packing. 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 et al. (1967) [9] 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) [10] have numerically studied the flow in a three-dimensional spatially periodic array of cubic 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) [11], but the inertia coefficient was much lower.

All these studies demonstrate that not only local behaviour, 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. CONCLUSION

The following summarizes the conclusions that may be drawn from this review.

(1) The majority of the experimental studies were directed toward correlating the total heat transfer rates (generally in dimensionless form) with Reynolds number.

(2) The total heat transfer consisted, in most cases, of both the conduction mode and the convective mode. Since the conduction mode depends on the physical and transport properties of the bed materials, these correlations although often reliable are applicable to the particular bed materials for which they were developed only. One exception is the correlation for the convective heat transfer alone proposed by Pei and co workers.

(3) A number of analytical and empirical models to predict the conductive mode have also been discussed. However, many of these models, particularly the earlier ones, are highly empirical in nature and need considerable refinement before they can be used with confidence for design purposes

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