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Heat transfer of gas flow through a packed bed

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Abstract

This paper 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. A comparison with previously published correlations and data in the literature shows that the relationships proposed by Bunnell et al. and Demirel et al. agree well with the measured effective radial thermal conductivity, whereas the wall–fluid heat transfer coefficient is better represented by the Li–Finlayson correlation.

Keywords: Heat transfer; Packed bed; Effective thermal conductivity; Effective wall heat transfer coefficient; Transient temperature distribution

1. Introduction

Packed beds are extensively used in the chemical and process industries as reactors, separators, dryers, filters and heat exchangers. Heat transfer can play a crucial role in determining the performance of such devices and has therefore been a subject of numerous investigations over the past few decades. These studies addressed fluid-packed particle heat transfer, transient response of packed beds, and various effective parameters under the steady-state including effective axial and radial thermal conductivities, wall to fluid heat transfer coefficient and overall heat transfer coefficient (Kunii and Suzuki, 1967; Gunn and De Souza, 1974; Wakao et al., 1979; Shent et al., 1981; Beasley and Clark, 1984; Ferreira et al., 2002; Collier et al., 2004). These effective parameters are obtained by solving the inverse problems using various macroscopic models. The simplest macroscopic model is one-dimensional and contains an overall heat transfer coefficient (U) based on the difference between the radial average temperature of particle bed and the corresponding wall temperature (Wakao and Kaguei, 1982). A more complicated approach is the use of two-dimensional models with either a plug flow or an axially dispersed plug flow assumption. The former is often referred to as the 2DPF model and uses the effective radial thermal conductivity (k_{er}) and the apparent wall heat transfer coefficient (h_w), whereas the latter is referred to as the 2DADPF model and utilises the axial dispersion term (k_{eax}) (Wakao and Kaguei, 1982). Depending on the temperature difference between packed particles and flowing fluid, these models can be classified into one-phase homogeneous models and two-phase heterogeneous models (De Wasch and Froment, 1971, 1972). If the temperature difference between the bulk fluid phase and the solids phase is small, the one-phase homogenous models can be used. The two-phase heterogeneous models are more appropriate if the temperature difference is considerable. The criterion for the selection of an appropriate model can be based on the so-called Biot number defined as the ratio of the thermal resistance within the packed particles to that between the fluid and packed particles. If the Biot number is smaller than ~ 0.05 than the one-phase models could be used.

The two-dimensional homogeneous models have been shown by some researchers to be able to predict well the temperature profile in packed beds if the effective radial thermal

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conductivity and the wall–fluid heat transfer coefficient are used as the adjustable parameters (Dixon, 1985; Dixon and van Dongeren, 1998; Demirel et al., 2000; Nijemeisland and Dixon, 2001). These models, however, fail to represent quantitatively experimental results in many cases if independently determined heat transfer parameters are used (Paterson and Carberry, 1983; Eigenberger and Ruppel, 1986; Daszkowski and Eigenberger, 1992; Bey and Eigenberger, 2001). One reason for the quantitative disagreement is insufficient experimental information of the flow field and temperature distributions in the interior of packed beds used for deriving the effective parameters. Indeed, many published studies have measured radial distribution of temperature at the inlet and outlet regions of packed beds, see for examples Schertz and Bischoff (1969), Marivoet et al. (1974), Lerou and Froment (1977), Dixon (1985), Freiwald and Paterson (1992), Ziòlkowska and Ziòlkowski (1993), Dixon and van Dongeren (1998) and Nijemeisland and Dixon (2001). It is also noted that lots of studies used two-dimensional homogenous models but did not measure temperature difference between the gas phase and the solids phase, which makes it difficult to justify the homogenous model assumption.

This paper aims principally to obtain more comprehensive experimental information of temperature field in the interior of a packed bed including both radial and axial temperature distributions, temperature difference between packed particle surface and surrounding fluid and the effect of flow on the temperature distribution. The measured information is then used to derive the effective parameters to compare with and assess the reported correlations for the effective heat transfer parameters. The motivation also arises from an on-going study on adsorption enhanced chemical reaction processes for hydrogen production through steam-methane reforming (Wang et al., 2004; Ding et al., 2005), where adequate supply and control of heat to the packed bed and heat transfer in the interior of the bed are crucial due to highly endothermic reaction on the packed catalyst particle surface and exothermic adsorption on the adsorbent surface.

2. Experimental

The experimental set-up used in this work was part of a catalytic reacting system for non-periodic adsorption enhanced chemical reaction process for low-temperature hydrogen production (Ding et al., 2005). Fig. 1 illustrates the experimental packed bed and thermocouple arrangements. The column was 1100 mm long made of stainless steel and had an internal diameter of 41 mm and an external diameter of 48 mm. Glass balls of 5 mm in diameter were packed into the column in a random manner and compressed air was passed through the bed to simulate the flow condition of the actual reaction process. Two thermocouple assemblies (TC Direct, UK), each having 12 Type J thermocouples were used to measure the temperature field in the interior of the packed bed. A 1 mm stainless-steel rod with two radial supporting arms (1 mm) was inserted in the central part of the column to accurately position the thermocouples. The thermocouples were carefully wired along the rod with thermocouple tips protruding into the bed side to ensure that they were bathed in the surrounding flowing gas. Particular attention was also paid to connecting the thermocouple wires to the data-logger through the supporting rod to minimise disturbance to the flow and temperature fields. Axial temperature profile was measured in the column centre by seven thermocouples located at seven axial positions of 30, 188, 379, 579, 764, 964 and 1062 mm from the inlet. Radial temperature profiles in two axial positions of 579 and 764 mm from the inlet were obtained by five thermocouples in each of the axial position, where the thermocouples were located and supported by the two tiny supporting arms. The external surface temperature of the packed bed was measured by seven thermocouples located in different axial and tangential positions to monitor the wall temperature uniformity. A thermocouple was carefully mounted onto the surface of a particle located approximately half-way between the centre and the column wall, where another one was positioned nearby to measure the fluid temperature passing across the particle so that the temperature difference between the fluid and packed particles could be investigated. All temperature signals were collected by a data acquisition system (NI PCI-6052E) inside a PC. A SCXI-1102 32-channel thermocouple amplifier was used to achieve high accuracy of temperature measurements. A software package, Labview, was used for system configuration and data logging. The heating was provided by a three-zone ceramic heater controlled by an independent temperature control unit (Watlow, UK). The inlet gas flow was measured and controlled by a massflow controller. A piezo-resistance pressure transducer (RS, UK) was used to measure the gas pressure, and the pressure drop across the packed bed was obtained with a DM2L micro-manometer logged to a PC through an RS232 interface. Experiments were performed in both the transient and steady states under constant wall temperature conditions. The wall temperature was maintained at $\sim 100\,^{\circ}\mathrm{C}$ and the temperature control was within $2\,^{\circ}\mathrm{C}$ for a given experiment.It normally took about two hours (depending on the gas flowrate) from the cold to reach the steady state when the temperature profile in the packed bed did not change with time.

All thermocouples were calibrated before use and were found to have an accuracy of 0.2 K. Heat conduction through the stainless-steel supporting rod and arms was found to be very small due to small diameter. As the temperature is low, the radiation effect can be neglected. The uncertainties of gas flowrate and pressure drop measurements under the conditions of this work were estimated to be 5% and 7%, respectively.

3. Experimental results

3.1. Pressure drop of gas flows through the packed bed

Fig. 2 shows the pressure drop across the packed bed as a function of the superficial gas velocity. Comparison with predictions by the one-dimensional Ergun equation (Ergun, 1952) is also included with the gas properties based on the average gas temperature and the average voidage ε_b calculated from the Jeshar equation $\varepsilon_b = 0.375 + 0.34 d_p/d_t$, where d_p and d_t are, respectively, the diameters of the packed particles and the