Experimental Thermal and Fluid Science 60 (2015) 106–114

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Experimental study of flow transitions in structured packed beds of spheres with electrochemical technique

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ARTICLE INFO

Article history:
Received 28 June 2014
Received in revised form 1 September 2014
Accepted 2 September 2014
Available online 16 September 2014

Keywords:
Structured packed bed
Transition flow
Electrochemical technique
Turbulence
Experimental study

ABSTRACT

In the past years, structured packed beds have been attracting more attention due to their special performances and potential applications. In this paper, the flow transitions are experimentally tested with electrochemical techniques in three different structured packed beds, including simple cubic (SC), body center cubic (BCC) and face center cubic (FCC) packing forms, which would be investigated for the first time and some interesting results are obtained. The microelectrodes are placed at the tube wall and inner particle surfaces to test the local flow fluctuations at the pore level, with particle Reynolds number (*Re*) ranging from 20 to 1100. According to the analysis of fluctuating rate (*FR*), three different flow regimes in the packed beds, including laminar, transition and turbulent flow regimes are identified. It is found that, the flow transition in SC packed bed is later and that in FCC packed bed is earlier, considering both the end of laminar flow and onset of turbulent flow when compared with those obtained in random packed beds. For SC packed bed, the transition flow regime occurs at Reynolds number ranging from 260 to 430 for most electrodes. For BCC packed bed, the end of laminar flow occurs at about $Re \approx 130$, the onset of turbulent flow of inner probes occurs at about $Re \approx 350$ and that of tube wall probes at about $Re \approx 580$. For FCC packed bed, the transition regime covers a range of $70 < Re < 250$ for most electrodes.

1. Introduction

Packed beds are widely used in lots of industries, such as chemical reactors, distillation process and heat storage systems. Understanding of detail flow information in the packed bed is quite important for practical applications.

Generally, more attentions are focused on random packed beds due to their convenience in construction and operation. A considerable number of investigations on the flow, heat and mass transfer in random packed beds are well presented in literatures [1–5]. On the other hand, structured packed beds have also been concerned in the past years, due to their special performances and potential applications. For example, the flow within a periodic array of cubic blocks was numerically studied by Nakayama et al. [6]. It was found that the inertial coefficient in the friction factor correlation was much lower than that in the Ergun's equation [7]. Calis et al. [8] and Romkes et al. [9] have investigated the flow and heat transfer characteristics in a variety of composite structured packed beds of spheres. It was revealed that, with composite structured packings, the pressure drop would be lowered and the traditional correlations [7,10] were questionable for structured packings. Furthermore, Yang et al. [11,12] recently have also numerically and experimentally studied the flow and heat transfer in some novel structured packed beds. It was found that, with proper selection of packing form and particle shape, the pressure drops in the structured packed beds could be greatly reduced and the overall heat transfer performances would be improved. All these studies may indicate that, the hydrodynamic and heat transfer performances in random and structured packed beds would be quite different. The tortuosity and pressure drop in structured packed bed are usually much lower and the overall heat transfer performances would be better.

Flow transition is one of the most important issues in the transport of packed beds. The flow transition in random packed beds has been widely investigated. Jolls and Hanratty [13] investigated the flow in a packed bed of spheres by visualization and electrochemical technique. The flow was observed to be turbulent when the Reynolds number was near 300. Four flow regimes were identified in two packed beds of spheres and rods by Dybbs and Edwards [14]. The unsteady laminar flow regime was in the range of Reynolds number 150-300. With the electrochemical techniques, Latifi et al. [15] found that the transition corresponding to an unsteady-

Abbreviations: SC, simple cubic; BCC, body center cubic; FCC, face center cubic.

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http://dx.doi.org/10.1016/j.expthermflusci.2014.09.001
0894-1777/

Nomenclature

d_p	particle diameter (m)
f	frequency (Hz)
FR	fluctuating rate
FR^T	average fluctuating rate at turbulence regime
H	height of packed cells (mm)
i	fluctuating component of the current (μA)
I	instantaneous current (μA)
I_{limit}	instantaneous limiting current (μA)
L	length of packed cells (mm)
Re	particle Reynolds number ($Re = \rho U d_p/\mu$)
Re_i^{local}	local interstitial Reynolds number $\left(Re_i^{local} = \rho U d_p / \mu \varepsilon_{local}\right)$
U	superficial velocity (m/s)
W	width of packed cells (mm)
W_{ii}	power spectrum density of current ($\mu A^2/s$)
ε	bulk porosity
ε_{local}	local porosity, the fraction of void area to total area of a typical cross section at the tube wall
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
τ	time (s)

Subscripts

IN	inner electrodes
W	tube wall electrodes

Superscript

L	ending of laminar flow
T	starting of turbulent flow

state laminar flow in packed beds of spheres was located in the range of Reynolds numbers of 110-370. Seguin et al. [16,17] implemented local instantaneous measurements to determine flow regimes in various media, such as beds packed with spheres, stratified media and reticulated media with electrochemical techniques. It was founded that, the stable laminar regime ended at a pore Reynolds number near 180 and a turbulent flow regime occurred at a value of a pore Reynolds number near 900. Furthermore, the transition flow in the packed beds of spheres with different particle sizes was investigated by Bu et al. [18] with electrochemical method. It was found that, the laminar flow in the packed beds would end at $Re \approx 100$, while the turbulent flow would start at $230 < Re < 400$. Some other relevant studies were also reported in literatures [19–21].

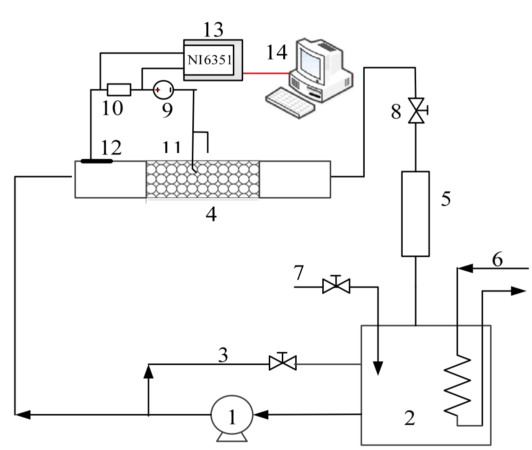
However, flow transition in structured beds has been rarely investigated. Masuoka and Takatsu [22] performed the particle image velocimetry and Laser Induced Fluorescence techniques to examine the microscopic flow field in porous media consisting of a bank of tubes. The transition regime from laminar to turbulent flow was in the range of $Re = 80–511$ when porosity was 0.386, and $Re = 193–731$ for porosity at 0.525, respectively. The ultrasonic velocity profiler and particle image velocimetry were used by Horton and Pokrajac [23] to study turbulent flows through a regular porous matrix of spheres packed in a cubic arrangement. The results showed that the onset of turbulence based on the particle image velocimetry test was at a Reynolds number of 370. The above studies demonstrate that, the investigations of flow regimes in structured packed beds are far from sufficient for scientific and practical applications. Meanwhile, it is believed that flow transitions in structured packed beds would present some special behaviors. In our previous numerical study [24], the flow was identified to be turbulent when the pore Reynolds number was above 300. However, it was found that the maximum error between some numerical results and experimental results [12] existed in the moderate Reynolds numbers flow region ($Re = 500–1000$). The reason may be that the critical Reynolds number of turbulence ($Re = 300$) was not so appropriate for structured packing forms. Therefore, a systematic study of flow transitions in structured packed beds would be quite necessary.

On account of above reasons, the electrochemical techniques are used to test flow transitions in three kinds of structured beds including simple cubic (SC), body centered cubic (BCC) and face centered cubic (FCC) packing forms. In order to achieve an accurate control, 3D printing technique is used to construct our packed cells. The electrodes are placed at the both tube wall surfaces and inner particles surfaces. The values of Reynolds number based on particle diameter and superficial velocity varies from 20 to 1100. The critical Reynolds numbers corresponding to the end of laminar flow and the onset of turbulence are obtained according to the analysis of fluctuating rate (FR) of current signals. The obtained results are also compared with those in the random packed beds.

2. Experimental system and procedure

2.1. Electrochemical technique and experimental system

The electrochemical technique is based on the measurement of the current produced by chemical reactions at the anodes and cathodes, which is working probes, made of 0.5 mm nickel wire in our present work. At the operation condition, the test electrodes are polarized and the corresponding current at this stage is called limiting current. The limiting current is mainly controlled by the diffusion of reacting specie across the mass transfer boundary layer and related to the variations of velocity gradient at the cathodes. Therefore, the limit current would be fluctuating simultaneously with flow velocity in the vicinity of related surface [16]. Based on the work of Seguin et al. [16], the electrolyte is an aqueous solution



1 centrifugal pump, 2 solution tank, 3 bypass, 4 test tube, 5 flow meter, 6 cooling equipment, 7 nitrogen input, 8 valve, 9 constant voltage power source, 10 resistance, 11 cathode, 12 anode, 13 data acquisition card, 14 computer.

Fig. 1. Experimental system.