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Experimental study of flow transitions in random packed beds with low tube to particle diameter ratios

Jian Yang [a,*], Shanshan Bu [a], Qingtai Dong [b], Jiangquan Wu [a], Qiuwang Wang [a]

[a] Key Laboratory of Thermo-Fluid Science and Engineering, Ministry of Education, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, PR China
[b] Shanghai Marine Diesel Engine Research Institute, Shanghai 201108, PR China

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ABSTRACT

In the present study, the electrochemical technique is used to test flow transitions in random packed beds with five low tube to particle diameter ratios ($N = d_t/d_p$), including $N = 2.6$, 5.3, 8.1, 9.9 and 12.5. The microelectrodes are placed at the tube wall and inner particle surfaces to test the local flow at the pore level, with particle Reynolds number (*Re*) ranging from 20 to 2200. The critical Reynolds numbers corresponding to the end of laminar flow and onset of turbulent flow are obtained according to Fluctuating Rate (*FR*) of current signals. The results of tube wall probes and inner probes are compared in detail to analyze the influences of the tube to particle diameter ratio *N* on flow transitions. It is found that, the critical Reynolds numbers corresponding to the end of laminar flow regime of packed beds with different tube to particle diameter ratios are at about 110 for packed beds with $N = 5.3$, 8.1, 9.9 and 12.5. Meanwhile, as the tube to particle diameter ratio *N* increases, the onset of turbulence would take place earlier for inner probes in different packed beds. Furthermore, the critical Reynolds numbers corresponding to both the end of laminar flow and onset of turbulent flow in the packed bed with $N = 9.9$ are quite close to those in the packed bed with $N = 12.5$, which would indicate that, when $N \geqslant 9.9$, the wall effects on flow transitions in the packed beds would be unremarkable.

1. Introduction

Due to the convenience of operation, random packed beds are widely used in chemical industries, such as chemical reactors, distillation process, and heat storage. [1–4]. According to various demands in industry, the tube to particle diameter ratio ($N = d_t/d_p$) of packed bed may vary from 1 to 1000. The packed beds with low aspect ratios ($N < 15$) are often used in highly exothermic processes such as ethylene epoxidation, or highly endothermic processes such as steam reforming [5], where the heat can be rapidly removed from or added to the packed beds.

Owing to the confinement of the tube wall, the porosity is about one at the tube wall and then declines in oscillations toward the center of packed beds. It would finally reach to a stable value in the bulk region at about five particle diameters away from the tube wall [6]. The oscillations of the porosity would lead to the flow maldistributions in the packed beds, which would further affect the pressure drop, heat or mass transfer inside. This phenomenon is usually called as the wall effect. The wall effect gets more serious as the tube to particle diameter ratio decreases. Therefore, the wall effect of the packed beds with low tube to particle diameter ratios ($N < 15$) often attracts more attentions. The pressure drop of packed beds can usually be calculated with Ergun's equation [7]. However, the Ergun's equation would not fit well for the pressure drop in the packed beds with low tube to particle diameter ratios. Other researchers [8–12] have obtained some useful empirical correlations of pressure drops in the packed beds with low tube to particle diameter ratios based on the Ergun's equation. The heat and mass transfer in the packed beds with low tube to particle diameter ratios are also widely investigated experimentally and numerically in recent literatures [13–16].

Flow transition is one of the most important issues in the transport of packed beds. Compared with the flow behavior in the straight and empty pipes, flow in the packed beds is characterized with multiscale phenomena [17]. On one hand, the macroscopic hydrodynamic performance in the packed beds is usually analyzed with pressure drop-flow rate characters. On the other hand, the local flow transition phenomena are also tested inside the pores of the packed beds. Jolls and Hanratty [18] investigated the flow in a packed bed with $N = 12$. The flow was observed to be turbulent through visualization when the particle Reynolds number *Re* was near 300. Four flow regimes were identified in two packed beds of spheres ($N = 7$) and rods by Dybbs and Edwards [19]. The

* Corresponding author. Tel./fax: +86 29 82663502.
E-mail address: yangjian81@mail.xjtu.edu.cn (J. Yang).

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Nomenclature

d_p	particle diameter (m)
d_t	tube diameter (m)
f	frequency (Hz)
FR	fluctuating rate
FR^T	average fluctuating rate at turbulence regime
i	fluctuating component of the current (μA)
I	instantaneous current (μA)
I_{limit}	instantaneous limiting current (μA)
L	length of packed cells (m)
m	total number of probes
N	tube to particle diameter ratio ($N = d_t/d_p$)
PSD	Power Spectrum Density
Re	particle Reynolds number ($Re = \rho U d_p/\mu$)
Re_i	interstitial Reynolds number ($Re = \rho U d_p/\varepsilon\mu$)
Re_p	pore Reynolds number ($Re = \rho U_{pore}\, d_{pore}\, /\mu$)
U	superficial velocity (m/s)
W_{ii}	Power Spectrum Density of current ($\mu A^2/s$)

Greek letters

ε	porosity of packed bed
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
σ	standard deviation of Re^T $\left(\sigma = \frac{1}{m}\sum_{k=1}^{m}\left(Re_k^T - \overline{Re^T}\right)^2\right)$
τ	time (s)

Subscripts

IN	inner electrodes
W	tube wall electrodes

Superscript

L	ending of laminar flow
T	starting of turbulent flow

unsteady laminar flow regime was in the range of interstitial Reynolds number Re_i of 150–300. With the electrochemical technique, Latifi et al. [20] found that, the transition corresponding to an unsteady-state laminar flow in packed beds of spheres ($N = 12$) was located in the range of particle Reynolds numbers of 110–370. Seguin et al. [21,22] implemented local instantaneous measurements to determine flow regimes in various media, such as beds packed with spheres ($N = 12$ and $N = 7.5$), stratified media and reticulated media with the electrochemical technique. It was found that, the stable laminar regime ended at a pore Reynolds number (Re_p) near 180 and a turbulent flow regime occurred at a value of a pore Reynolds number near 900. Lesage et al. [23] carried out local hydrodynamic measurements at the pore level of a fixed-bed reactor ($N = 11$). A transient regime from laminar to turbulence was observed for particle Reynolds numbers between 110 and 280 with electrochemical technique. The ultrasonic velocity profiler and particle image velocimetry were used by Horton and Pokrajac [24] to study turbulent flows through a regular porous matrix of spheres packed in a cubic arrangement ($N = 9$). The results showed that, the onset of turbulence based on the PIV test was at a pore Reynolds number (Re_p) of 370. The transition flow in the packed beds of spheres with different particle sizes ($N = 10$) was also investigated by Bu et al. [25] with electrochemical method. It was found that, the laminar flow in the packed beds would end at particle Reynolds number $Re \approx 100$, while the turbulent flow would start at $230 < Re < 400$. Meanwhile, Bu et al. [26] have also studied flow transitions in some structured packed beds, and found that flow transitions were greatly dependent on the packing structures. Some other relevant studies were also reported by Wegner et al. [27], Rode et al. [28] and Masuoka et al. [29].

All these studies may demonstrate that, the wall effect related to the tube to particle diameter ratio, would be remarkable on hydrodynamic, heat and mass transfer performances in the packed bed. Due to the wall effect, the flow transitions near the tube wall and bulk regions of the packed bed may present some different behaviors, which would finally affect the hydrodynamic, heat and mass transfer performances inside. However, until recently, the wall effect related to the tube to particle diameter ratio on the flow transitions in the packed bed is still unclear and it was rarely discussed in the open literatures. Therefore, in the present study, the electrochemical technique is used to test flow transitions in random packed beds with five low tube to particle diameter ratios, including $N = 2.6$, 5.3, 8.1, 9.9 and 12.5. The working probes are placed at the tube wall and inner particles surfaces. The values of Reynolds number based on particle diameter and superficial velocity varies from 20 to 2200. The critical Reynolds numbers corresponding to the end of laminar flow and the onset of turbulence are obtained according to Fluctuating Rate (*FR*) of current signals. The results of tube wall and inner probes are compared in detail to analyze the effects of the tube to particle diameter ratio on flow transitions.

2. Experimental system and procedure

2.1. Electrochemical technique

The electrochemical technique is based on the measurement of the current produced by chemical reactions at the anodes and cathodes. The working cathodes used in the experiment is one part of an electrochemical cell, as is shown in Fig. 1. A voltage is applied to the cell to drive a reaction at the electrodes. The reduction of ferricyanide occurs at the cathode and the reverse reaction occurs at the anode.

$$\text{Cathode}: \ [Fe(CN)_6]^{3-} + e = [Fe(CN)_6]^{4-}$$
$$\text{Anode}: \ [Fe(CN)_6]^{4-} - e = [Fe(CN)_6]^{3-}$$

At the operation condition, where the test electrodes are polarized, the current is mainly controlled by the diffusion of reacting specie across the mass transfer boundary layer and related to the

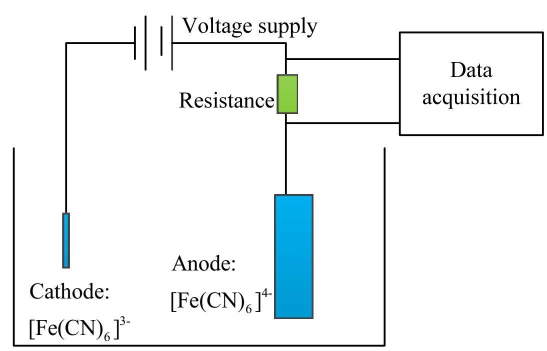

Fig. 1. Electrochemical reaction system.