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Experimental study of transition flow in packed beds of spheres with different particle sizes based on electrochemical microelectrodes measurement

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HIGHLIGHTS

- Transition flow in packed beds is investigated with electrochemical method.
- Laminar flow in the packed beds would end at $Re \approx 100$.
- Turbulent flow in the packed beds would start at $230 < Re < 400$.
- Transition flow region in the packed beds would be from $Re \approx 100$ to $230 < Re < 400$.

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ABSTRACT

In the present study, the transition flow in the packed beds of spheres with different particle sizes is experimentally investigated by using electrochemical method. The microelectrodes are inserted into the beds to test the local flow at the pore level with particle Reynolds number (*Re*) ranging from 20 to 1100. Both the variations of Power Spectrum Density (PSD) and Fluctuating Rate (*FR*) are carefully analyzed to obtain different flow regions in the packed beds, including laminar, transition and turbulent flow regions. Firstly, it is revealed that, as Reynolds number increases, the high frequency ratios of the current signal increases, and the slope of the PSD curve decreases and tends to reach at $-5/3$. When the slope of the PSD curve decreases to $-5/3$, it would become turbulent flow in the packed beds. Secondly, it is found that, the laminar flow in the packed beds would end at $Re \approx 100$, while the turbulent flow would start at $230 < Re < 400$. Therefore, the transition flow region in the packed beds of present study would be from $Re \approx 100$ to $230 < Re < 400$.

1. Introduction

In recent years, momentum and heat transfer in packed beds have received considerable attention due to the increasing interest in engineering applications, such as catalytic reactors, packed bed regenerators and high temperature gas-cooled nuclear reactors, etc. [1–5].

An understanding of flow dynamics in the packed beds is quite important for scientific research and practical applications. Compared with the flow behavior in the straight and empty pipes, flow in the packed beds is characterized with multiscale phenomena. On one hand, the macroscopic dynamic performance in the packed beds is usually analyzed with pressure drop-flow rate characteristics. On the other hand, techniques such as direct visualization, laser Doppler anemometry, particle image velocimetry, magnetic resonance imaging, hot wire, as well as electrochemical microelectrodes, have been employed to test the local flow transition phenomena inside the pores of the packed beds. More information about both macroscopic and microscopic hydrodynamic performances in the fixed beds were also carefully reported by Hlushkou and Tallarek [6].

It is noted that, until recently, the Reynolds number ranges for different flow regions in the packed beds, such as laminar, transition and turbulent flow regions, are still quite uncertain. For example, Jolls and Hanratty [7] discovered that, a transition from laminar flow to turbulent flow in a packed bed of spheres occurred over the particle Reynolds number ranging from 110 to 150 with electrochemical microelectrodes and direct visualization. The flow

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Nomenclature

A_e	electrode area (m^2)
d_p	particle diameter (m)
d_{tube}	tube diameter (m)
D	diffusion coefficient (m^2/s)
f	frequency (Hz)
F	Faraday's constant (96,500 (C))
FR	fluctuating rate
i	fluctuating component of the current (μA)
I	instantaneous current intensity (μA)
I_{limit}	instantaneous limiting current intensity (μA)
$\bar{I}$	time-averaged current (μA)
n	number of particles
n_e	number of electrons
Re	particle Reynolds number ($Re = \rho U d_p/\mu$)
Re_L	laminar ending Reynolds number
Re_T	turbulence starting Reynolds number
U	superficial velocity (m/s)
W_{ii}	power spectrum density of current ($\mu A^2/s$)
Greek symbols	
ε	porosity
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
τ	time (s)
Subscripts	
e	electrode
L	ending of laminar flow
p	particle
T	starting of turbulent flow
Abbreviation	
PSD	power spectrum density

pattern was observed to be turbulent at particle Reynolds number near 300 through direct visualization. Wegner et al. [8] did some studies of the motion of dye streak lines on the surface of a sphere in a packed bed. The transition to unsteady flow was found to be in the range of Reynolds numbers of 90–120. Dybbs and Edwards [9] identified four flow regimes in two packed beds of spheres and rods by laser anemometry and direct visualization. The end of steady laminar flow regimes occurred at a pore Reynolds number of 150. A highly unsteady and chaotic flow regime resembling turbulence was at a pore Reynolds number greater than 300. Latifi et al. [10] used electrochemical microelectrodes to determine flow regimes in packed beds of spheres. The transition corresponding to an unsteady-state laminar flow was located in the range of Reynolds numbers of 110–370. Using similar experimental apparatus, Rode et al. [11] found that, the onset of unsteady flow was in the particle Reynolds number range of 110–150 with electrochemical microelectrodes. With the same technique, Seguin et al. [12,13] implemented local instantaneous measurements to determine flow regimes in various media, such as beds packed with spheres, stratified media and reticulated media. It was founded that, the stable laminar regime ended at a pore Reynolds number near 180 and a value of pore Reynolds number near 900 corresponded to a turbulent flow regime. Magnetic Resonance Imaging (MRI) velocity measurement techniques were used by Johns et al. [14] to study flow in the pore of a packed bed. Transition from creeping to inertial flow was at a local pore Reynolds number of 30. Using flow visualization, hot wire and Particle Image Velocimetry (PIV), Masuoka et al. [15] studied the chaotic behavior in the transition to turbulence of flow through porous media consisting of a bank of tubes. By means of variations of Lyapunov exponent with Reynolds numbers based on the hydraulic diameter and the Darcy velocity, the weak chaos governed by the laminar flow was induced for $60 < Re < 100$, and the transition to turbulent flow in porous media occurred at $Re > 300$. Takatsu and Masuoka [16] performed the PIV and Laser Induced Fluorescence (LIF) techniques to examine the microscopic flow field in porous media. 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. Lesage et al. [17] carried out local hydrodynamic measurements at the pore level of a fixed-bed reactor. A transient regime from laminar to turbulence was observed for Reynolds numbers between 110 and 280 with the electrochemical technique. Horton and Pokrajac [18] used the ultrasonic velocity profiler and particle image velocimetry to study turbulent flows through a regular porous matrix of spheres packed in a cubic arrangement. Three different regimes were observed, including unsteady laminar, transition and turbulent flow. The results showed that, a Reynolds number of 370 was found just before the onset of turbulence based on the PIV test. Although it is not easy to identify flow regimes using numerical methods, some researchers still do some efforts to study flow patterns of packed beds with numerical simulations. Hellström et al. [19] performed the simulations of flow through arrays of packed cylinders with a laminar flow setup as well as with a two-equation turbulence model. After compared to each other and results from the literature, it was found that turbulent flow needs to be considered when interstitial Reynolds number was above 300. Hill et al. [20–22] studied flow ranging from small Reynolds numbers to moderate Reynolds numbers in some arrays of spheres using lattice-Boltzmann methods. It was found the transition from steady to unsteady flow occurred at a Reynolds number of approximately 30, accompanied by a breaking of rotational symmetry in a FCC packed array.

All these studies demonstrate that, the Reynolds number ranges for different flow regions in the packed beds, such as laminar, transition and turbulent flow regions, are quite different. And it is still unclear which Reynolds number range would be more reliable and accurate for the corresponding flow regions. This would be far from sufficient for scientific and practical applications. Therefore, a systematic study of transition flow in the packed beds would be quite necessary. On account of above reasons, in the present paper, the transition flow in the packed beds of spheres with different particle sizes are systematically investigated with electrochemical method. The microelectrodes are inserted into the beds to test the local flow fluctuations at the pore level with Re ranging from 20 to 1100. And the variations of power spectrum density (PSD) and Fluctuating Rate (FR) are analyzed to determine different flow regions in the packed beds, including laminar, transition and turbulent flow regions.

2. Experimental system and procedure

2.1. Electrochemical technique

The microelectrode 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 microelectrode. According to the work