FLOW CHARACTERIZATION WITHIN A SPHERE-PACKED BED USING PIV MEASUREMENT

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ABSTRACT

Flows in porous media widely exist in various engineering application such as heat exchange, filtration systems, as well as the 4th generation nuclear reactor for example the pebble bed reactor, coolant pass through a randomly stacked channel formed between fuel pebbles. Hence, an investigation of flow field is crucial to the basic reactor design. The paper is to identify the flow characteristics in a randomly sphere-packed bed by application of particle image velocimetry (PIV). It is filled with 30 mm diameter PMMA spheres, and sodium iodide solution used as the working fluid to match the refractive-index of fluid and channel. Several typical pore structures are distinguished and their distinct flow properties are described. The flow through pore media is determined by a pore Reynolds number, $Re_{pore} = \frac{\rho U D_B}{\mu(1-\varepsilon)}$, in the range of $Re_{pore} = 6$ and 300 to analyze the pore scale flow characteristics.

KEYWORDS
Randomly, Sphere-Stacked Bed, PIV, Refractive-Index Match

1. INTRODUCTION

Flow through porous media is of considerable value in a number of engineering application, such as advance heat exchanger, filter system, chemical reactor as well as the pebble bed reactor. Pebble bed reactor (PBR) is one of selected prototype designs for Generation IV nuclear system. Reactor core consisted of the tens or hundreds of thousands of fuel pebbles, while gas or liquid molten coolant flow around randomly stacked sphere to take the fission heat out. Therefore, identifying and understanding relevant flow is crucial for accurate design verification and analysis of the PBR system.

At present, the relative flow characteristics in a random packed sphere bed have been studied numerically (Hassan 2008[1]; Pavlidis et al 2013[2]; Fin 2013[3]) and experimentally (Hassan et al 2008[4]; Patil et al 2013[5]; Arthur 2013[6]). Due to the complexity of solid-fluid interface, the physics of pore scale flow are not generally well understood. Simulation techniques confront the challenges, and it is important to continue developing accurate and efficient CFD code capable of predicting the pore scale flow behaviors. A better understanding of pore scale flow properties could help to develop better models applicable to the complex flow through a packed bed. In order to increase the understanding of this problem, we performed flow visualization experiment for packed bed, and PIV method provides full field temporal data measurement. The present research is to characterize flow through a packed bed for Reynolds number ranging from 6 to 300 based on PIV and refractive index match technology.

2. EXPERIMENT

2.1. EXPERIMENTAL SETUP

As was Figure1 indicated, the test facility was made up of the test model, a centrifugal pump, a turbine flow meter, a 0.5 m^3 tank, interconnecting hoses, tubing connection accessories and valves. A centrifugal pump of 750 W was used to pump the liquid from the tank, and the required flow rate through the model was adjusted by the valve using both the model inlet and the bypass. A turbine flow meter measured the liquid flux through the model during the experiment.

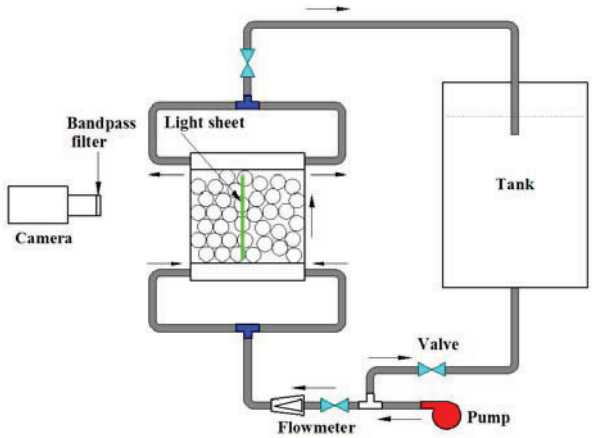


Figure 1. Schematic view of flow experimental loop

The test model was scaled down the reactor core, which was fabricated into a quasi-octahedron with transparent PMMA plate (distances of parallel planes: 240 mm and 228 mm). As shown in Figure.2, the model consisted of the lower inlet plenum (40 mm high), active area (175.64 mm high) and upper exit plenum (56.96 mm high). To provide uniform liquid flow through the model, the perforated support plate was placed in the position of 40 mm from the bottom, with bottom support plate containing 37 spherical pits of 28.4 mm and 76 holes of 10 mm diameters. Similarly, the upper plate having same 76 holes of 10 mm diameter to assure a relatively uniform outlet flow. Active area lying between two plates, could contain 9 layers with 30 mm spheres. The spheres were packed randomly but distributed regularly 2 layers at the bottom. Two inlet pipes connected with the lower plenum, were arranged at a 180 angle to each other, and two outlet pipes were asymmetrically distributed outside the upper plenum.

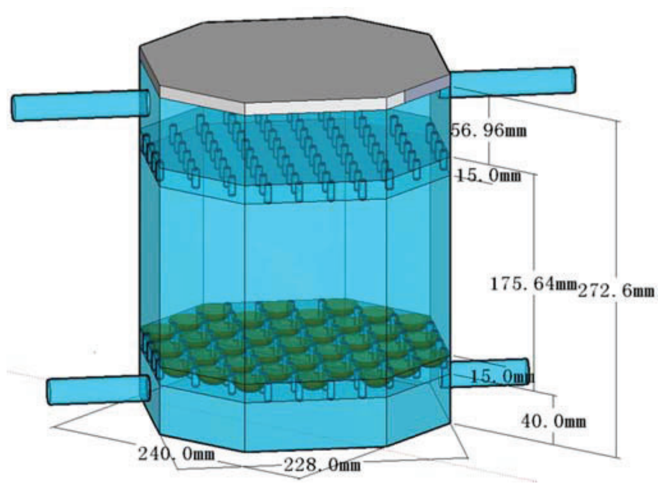


Figure 2. 3D view of the octahedral test section

2.2 VISUALIZATION OF SPHERE-PACKED BED

NaI solution was selected as the working fluid, and the refractive index measured by an Abbe refractometer. The refractive indices between the work fluid and sphere were matched with an index of 1.49. To void trapping air bubbles, acrylic spheres were firstly packed into the model in the experiment, and then making the fluid flow through the bypass to exclude the air bubble there, finally making the whole model full of the liquids expel the adsorbed bubbles from the spherical surface, and thus the system may run normally.

To provide the best flow state in pore with sphere-packed bed, the observed area was more than 4 layers spheres away from the upper and below plate in the center of bed. For this test, 10 micron silver coated glass beads were used as tracer, and a Nd: YAG laser (λ=532 nm) was used as light source generating 400 mJ/pulse energy at 15 Hz. The laser beam was then illuminating the center of sphere-packed bed. Maximum resolution of the camera was 2448 × 2050 pixels. The interrogation window was 64× 64 pixels, using 50% overlap, resulting in a velocity vector spacing ranging from 64 to 76 vectors. The visualization of flow field was conducted in pore Reynolds numbers range from 6 to 300, where U and D_B stand for the superficial velocity and sphere diameter in the bed.

3 Result and Discussion

In the section, the flow behavior was described through porous media at various Reynolds numbers. Based on the analysis of flow structures to visualize in different pore geometry, three flow characteristics were identified which include tortuous channel flow, recirculating flow and jet flow for pore Reynolds numbers ranging from $Re_{pore} = 6$ to $Re_{pore} = 300$. According to the classification shown in Figure3 (IIa): tortuous channel flow (red curve zone), recirculating flow (red elliptic zone), jet flow (red rectangular zone) .This study experimentally investigated these flow on the basis of the porous Reynolds numbers $Re_{pore} = \frac{\rho U_{pore} D_H}{\mu}$, where Re_{pore} is shown by the porous bed hydraulic diameter, $D_H = \varepsilon D_B / (1-\varepsilon)$ and average pore velocity, $U_{pore} = U / \varepsilon$,were $U = Q / A_{bed}$, with Q being the volumetric flow rate and A_{bed} the bed cross section normal to flow (Patil 2013[7]). Flow types through these regions are not isolated and associated with the magnitude of Re_{pore}.

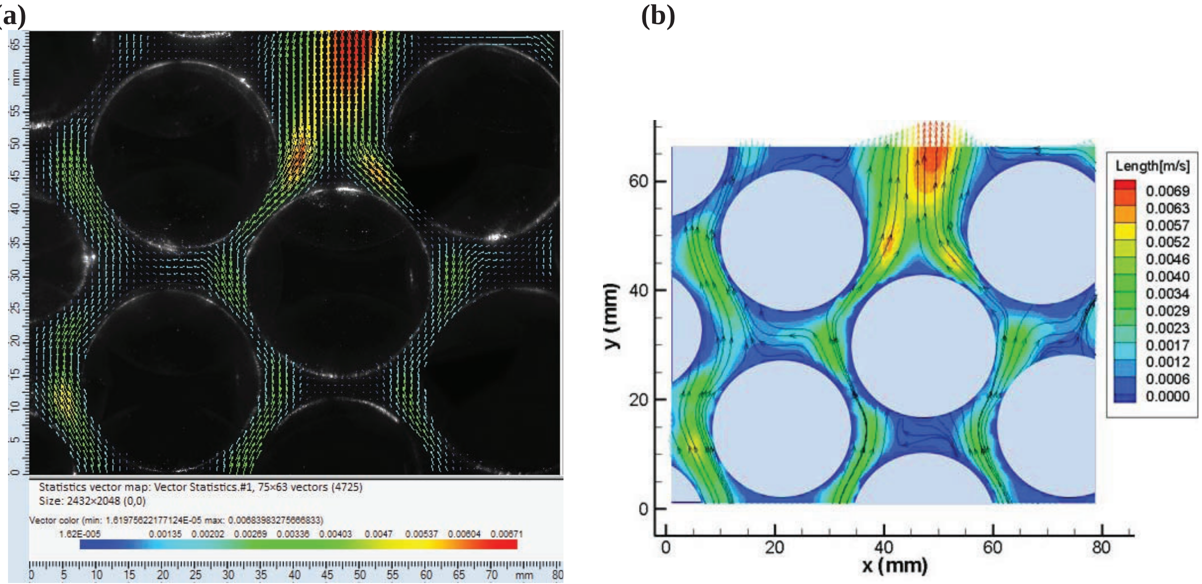
As showed in Figures 3 (I) - 3(VII), two dimensional velocity fields have been obtained within pores for randomly packed sphere bed.

(i) For very Low Re_{pore} of 6, the streamlines follow the sphere surface as seen in Figure 3(I), and the flow around the sphere is very symmetrical. The vector maps show no discernible recirculating flow behaviors, and other interstitial velocity nearly uniformly distributed for tortuous channel flow and jet flow.

(ii) Figures3 (II) - 3(VII) show flow structure evolution corresponding to Re_{pore} range from 26 to 300. It can be seen from Figures3 (II) that the counter-rotating eddies begin to form between adjacent longitudinal spheres, and the whole zone contains three recirculation zone. As is shown in Figures3 (II) - 3(VII), the pore scale flow trend between the second row and fourth row shows symmetrical distribution, and then we observe that the eddies evolution is similar in two recirculation zones, and that two eddies formation and cyclic behavior be stronger with increasing Re_{pore}. For $Re_{pore} > 26$, stable eddies are formed in the second and fourth row of Figures3 (II) - 3(VII), and maybe origin from flow separation adjoining downstream jet flow region. However, unstable eddy occur in the third row of Figures3 (II) - 3(VII), and may only intersperse among tortuous channel flow.

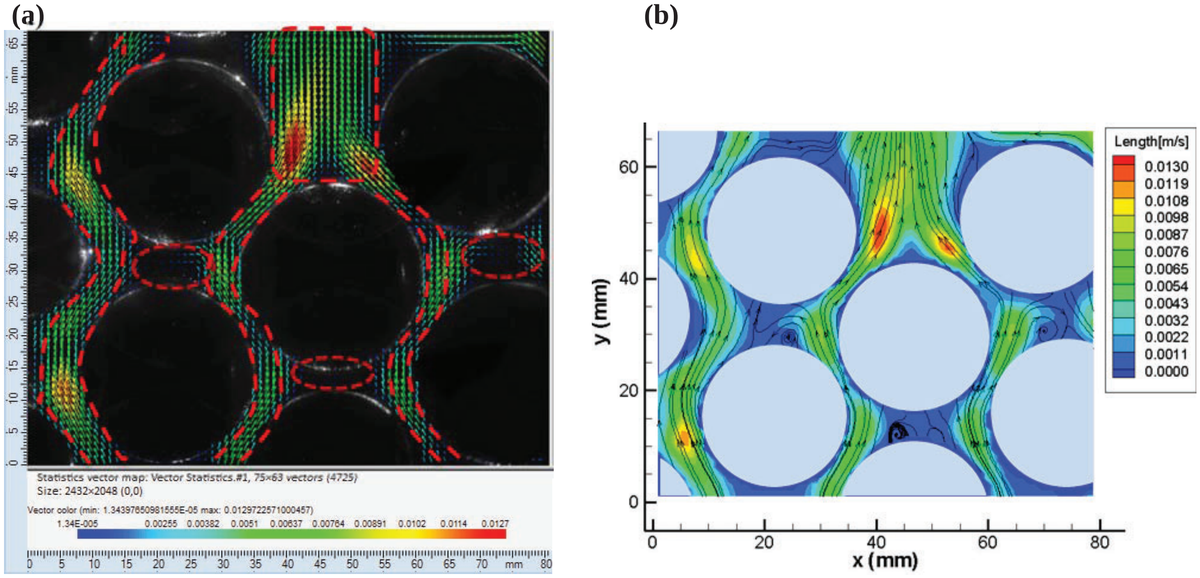
(iii) Another two flow types, the tortuous channel flow as well as jet flow, are essentially uniform within the pore of all flow zones, and Figures3 (II) - 3(VII) indicate flow in mean streamlines through the bed.

(a) (b)



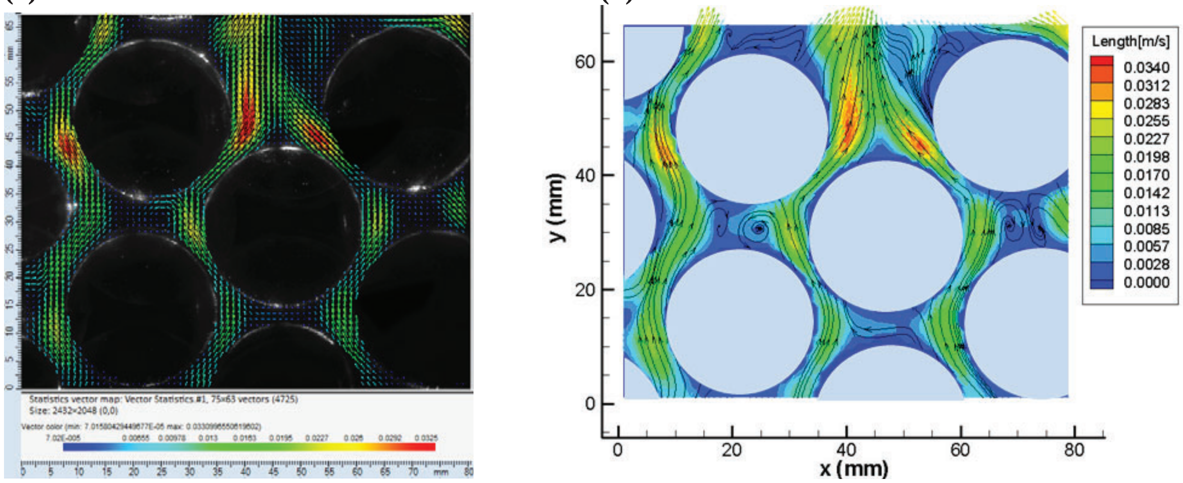
(I) $\boldsymbol{Re}_{\mathbf{pore}}$**=6**

(a) (b)



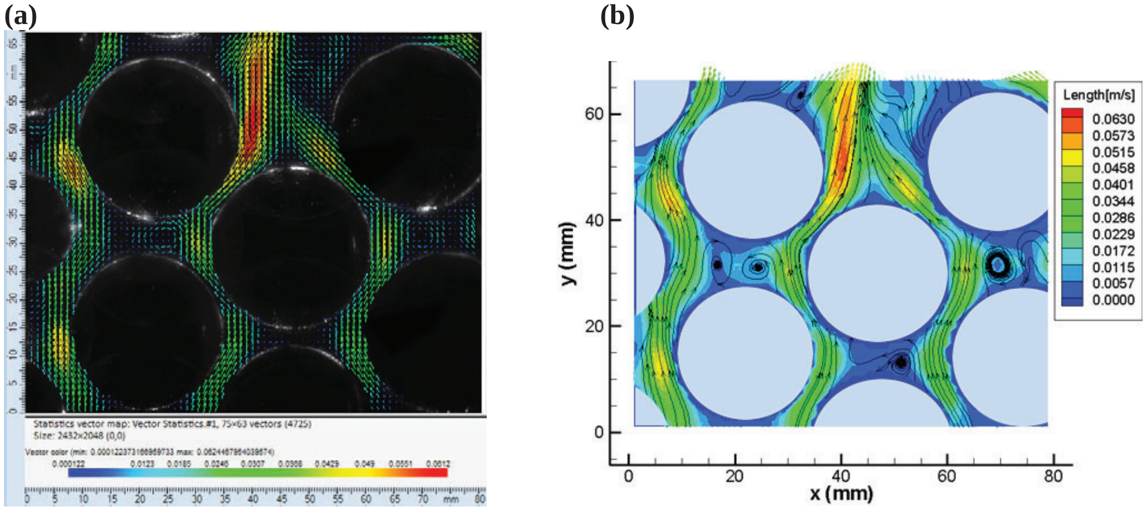
(II) $\boldsymbol{Re}_{\mathbf{pore}}$**=26**

(a) (b)



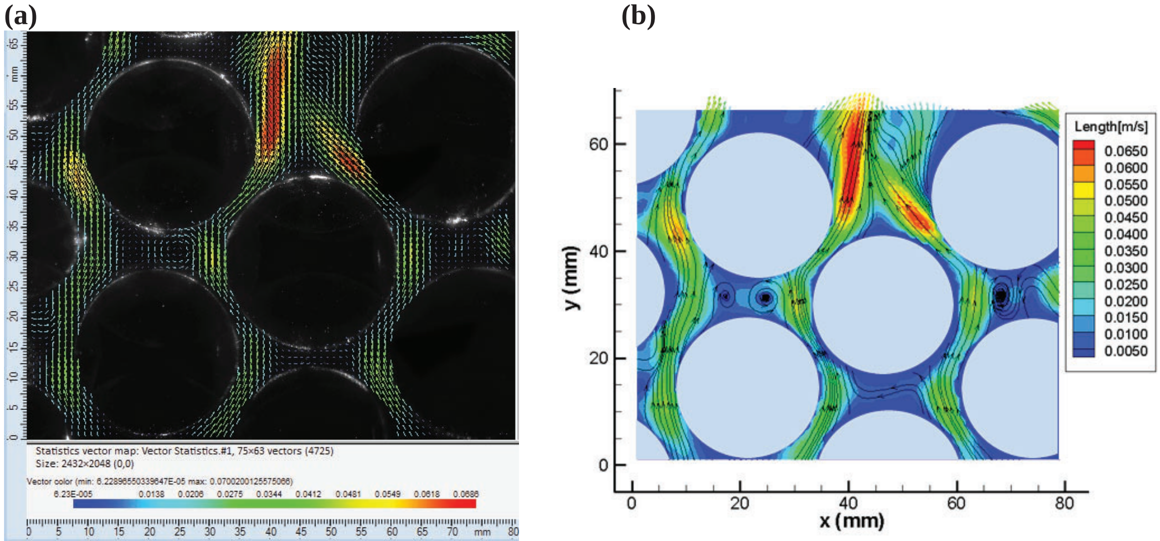
(III) Re_{pore}=82

(a) (b)



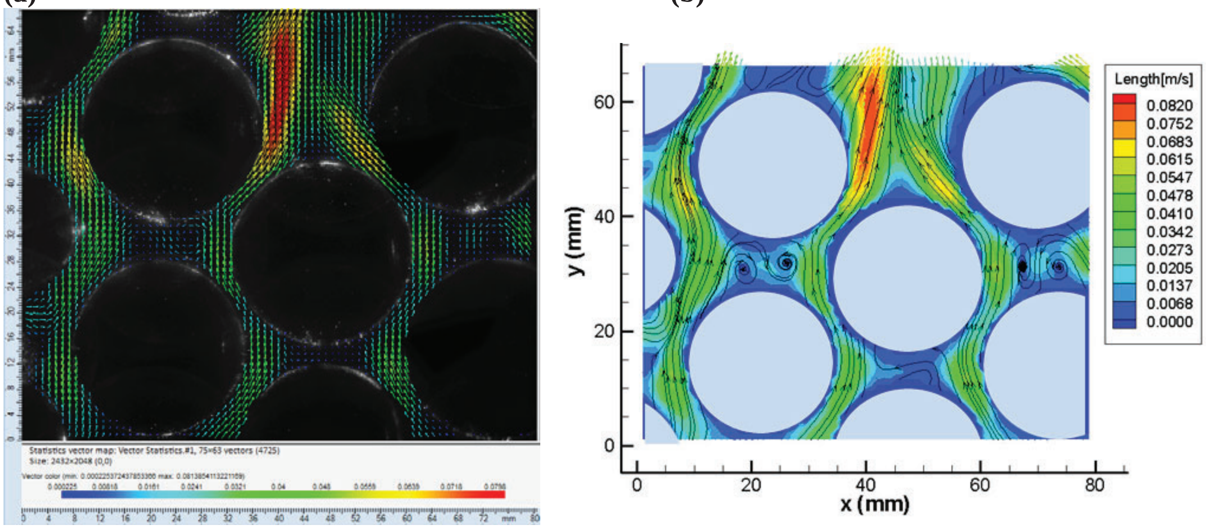
(IV) Re_{pore}=144

(a) (b)



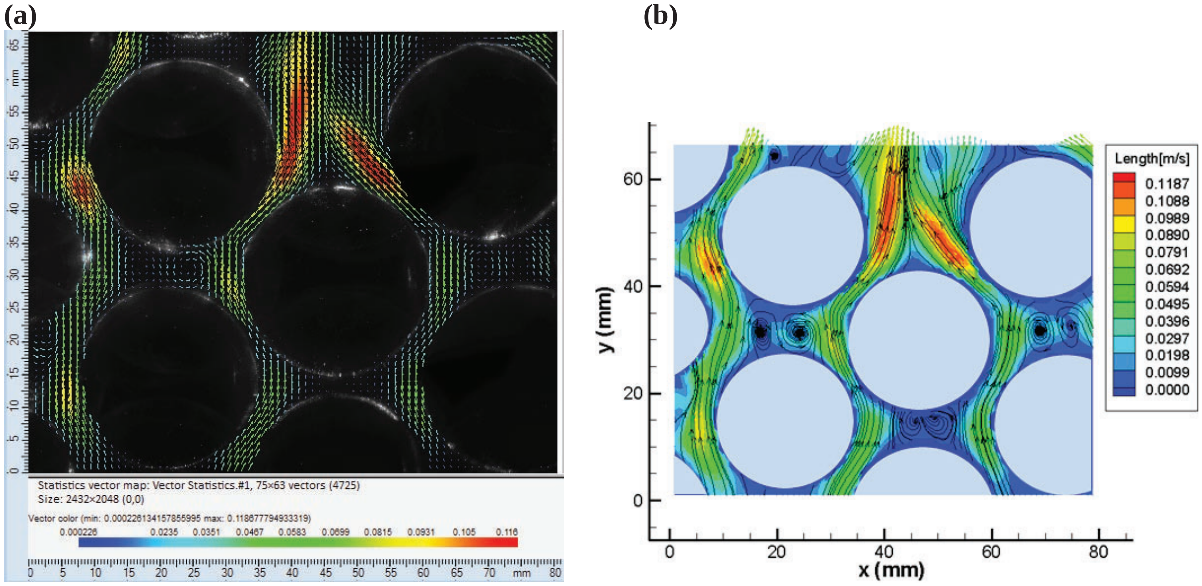
(V) Re_{pore}=179

(a) (b)



(VI) Re_{pore}=238

(a) (b)



(VII) Re_{pore}=300

Figure 3. Velocity vector field at center plane for random stacked-sphere bed with (I) Re_{pore}=6 (II) Re_{pore}=26 (III) Re_{pore}=82 (IV) Re_{pore}=144 (V) Re_{pore}=179 (VI) Re_{pore}=238 (VII) Re_{pore}=300 ((a) Measured velocity field (b) Vector field map overlaid by mean velocity contours)

4 CONCLUSIONS

An experimental research was conducted to study the pore scale flow through randomly packed bed. Velocity distributions were obtained using PIV and refractive index matching technology for pore Reynolds number range from 6 to 300. Flow behaviors are relevant to the Reynolds number and the pore geometry, and include tortuous channel flow, recirculating flow and jet flow. For low $Re_{pore} = 6$, recirculating flow did not exist in the measure zone, other tortuous channel flow and jet flow were observed. With the increasing of Re_{pore} , recirculating flow occurred between the adjacent longitudinal spheres, and swirl strength increased with Re_{pore} increasing.

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