PHOTOGRAPHIC OBSERVATION OF FLOW PATTERN IN VOIDS OF PACKED BED OF SPHERES

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Introduction

A knowledge of the flow pattern formed in the void of a packed bed of spheres is essential for investigation on heat and/or mass transfer and mixing characteristics in this type of apparatus. Mickley et al. measured the mean velocity and turbulence intensity in the void of a rhombohedral arrangement of spheres by means of a hot-wire anemometer. Hanratty et al. measured profiles of the pressure, velocity gradient, and local mass transfer rate on the surface of a sphere in a cubic arrangement.

Observations of the flow pattern in a single void of a packed bed of spheres were undertaken in order to clarify the actual behaviour which has not, as yet, been made clear.

1. Experimental Equipment

The packed bed used is shown in Fig. 1. The hollow spheres made of glass were about 0.5 mm in thickness and 50 mm in diameter. Working fluid through the bed was water (20 ± 1.0°C), and the same fluid was used to fill the hollow spheres so as to observe the streamline with less optical deformation. To reduce wall effect, hemispheres were attached to the wall. A flow channel was made of transparent polymethyl methacrylate sheet and a flow distributor was made up of a packed bed of 15 mm diameter glass beads. For more uniform distribution of flow, the test section of the packed bed was fitted with calming sections without packings in the vertical stream.

Nine injection needles of 1.6 mm diameter were set up, for which dye solution (Neutral Red of 0.05 weight percent water solution) was injected to the inlet of the test section. The effluent speed of the dye tracer was so regulated by a micro-feeder as to give the same velocity as the interstitial linear velocity through the packed bed. Each needle was connected to the buffer tank by a polyvinyl chloride tube of identical length. Streak lines from the needles were observed by naked eye and by photographs taken with a 35 mm camera (with power winder) and an 8 mm movie camera.

Figure 2 shows the photograph of a test pattern sheet on which a polar coordinate is drawn. In spite of a slight deformation of light path by the glass wall of spheres around the circumference of spheres, hollow glass spheres containing water would make it possible to visualize the flow pattern of water flowing through the three-dimensional packed bed.

2. Observation

The flow pattern was observed for three arrangements of spheres, i.e. (1) rhombohedral, (2) orthorhombic and (3) cubic arrangements, as shown in Table 1 and Fig. 3. On increasing the flow rate, three different flow patterns were observed for each arrangement.
arrangement. Similarly as Aratani et al.\textsuperscript{1)} defined for tube bundle arrays, three flow regions are simply defined, with respect to existence of vortices and turbulence. If there are no vortices and eddies, the region is laminar. Where large-scale whirling vortices are seen in a void, the flow region is a transition regime. If the void is full of eddies, the region is a turbulent one.

2.1 Laminar region

There are no vortices or eddies in this region. Red streak lines of the dye tracer are clearly seen without any intersection with each other. At a very low flow rate, these lines show creeping flow around the packed spheres, as shown for the cubic arrangement in Fig. 4. A flow pattern similar to that for the cubic arrangement is observed for the rhombohedral and orthorhombic arrangements.

The flow consists of two parts, i.e. the faster and slower flowing parts observed in the void of packed beads. The faster are shown by the streak lines in Fig. 5. (A), (B) and (C) are the flow patterns, respectively, for the rhombohedral, orthorhombic and cubic arrangements. Though the forms of faster flows vary according to the arrangement of packings, the fastest flow, as a rule, passes through the center of the flow channel in the void, while near the sphere surface extremely slow flow is observed.

2.2 Transition regime

The fluid in the void space is clearly distinguished as two parts in this regime. The fluid flows rapidly in one part, while it whirls slowly as vortices in the other part. The former is tentatively designated as the "Main Flow Part" and the latter as the "Side Flow Part".

The development of the vortices is shown in Fig. 6 by a series of photographs taken at a predetermined time interval (1/2 sec) for the cubic arrangement. These vortices exist in the each void, as shown in Fig. 7 (A). The vortices may be a cause for the res-
idence time curves showing a long tailing. On the other hand, rapid flow is observed at the center of the flow channel. This rapid flow may be a reason for the residence time curves showing a sudden starting up by short pass flow.

Figure 7 shows the flow patterns for the orthorhombic (B) and rhombohedral (C) arrangement. The scale of the vortices becomes smaller in the order of cubic, orthorhombic and rhombohedral arrangements. As for the rhombohedral arrangement, there are some voids without vortices.

With more increase in flow rate, the streak lines in the main flow part seem to be intercrossed with each other, as shown in Fig. 8. When the flow rate is raised closer to the turbulent region, the distinction between the main and side flow parts begins to fade out gradually.

Hanratty et al.4) defined the steady boundary layer flow and the unsteady boundary layer flow in their experimental study. Our vortices and rapid flow corresponds to their steady boundary layer flow, and the streak line flow seemingly intercrossed just agrees with the unsteady boundary layer flow. This transition flow regime was found to cover a flow rate range wider than that expected from fluid flow in a pipe.

2.3 Turbulent region

It is observed that the whole space in each void is full of eddies in this region. At the second or third void, intermittent streak lines are observed, but on and after the fourth void only fine streak lines with random motion are seen, as shown in Fig. 9.

Critical flow rates from laminar to transition and from transition to turbulent were measured with three arrangements of beds. The critical Reynolds number, $Re_{cr}$, is plotted against the void fraction, $\varepsilon$, as shown in Fig. 10. The figure shows a good linear correlation, from which critical flow rates for different void fraction of beds can be estimated.

Conclusion

By utilizing hollow spheres of thin glass filled with water as packing, photographic streak line observation of water flowing through a three-dimensional packed bed of spheres is found to be easily realized.

In laminar (or transition) regime, the fluid in a void consists of a slower flow (or vortices) part near the surface of the sphere, and a faster flow part at the center of the flow channel.

Critical Reynolds number can be correlated with the voidage.

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Fig. 8 Streak lines in voids of packed bed at a transition regime ($Re_{p} = 207$, Type 2)

Fig. 9 Streak lines in a turbulent region ($Re_{p} = 1219$, Type 2)

Fig. 10 Critical Reynolds number vs. voidage

**Nomenclature**

- $d_p$ = packing diameter [cm]
- $Re$ = $u_d/\nu$, Reynolds number [--]
- $u_0$ = superficial line velocity [cm/sec]
- $\varepsilon$ = voidage [--]
- $\mu$ = viscosity of fluid [g/cm·sec]
- $\rho$ = density of fluid [g/cm$^3$]

**Literature Cited**