The Visualization of Flow Patterns on a Sphere in a Packed Bed

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Abstract

An experiment was made to visualize the surface flow pattern of spheres in a packed bed. Spheres, the surface of which were coated with benzoic acid, were set within a packed bed and exposed to water flow for a certain period of time. The flow patterns on the surface were observed by the patterns of dissolution of benzoic acid. The patterns were compared with the results of visualizations by other workers using a different method. It was found that the present results are in good agreement with those results in terms of the location of separation lines and singular points on the surface.

1. Introduction

A packed bed is often used as an effective way of dust collection in a gas at high temperatures. When the basic mechanisms of dust capture are analysed in such a bed, the fluid motion within the bed should be taken into consideration. Also, in considering mass transfer in the packed bed, the flow around each particle is an important factor. However, there have been very few investigations of fluid motion within the bed, and a series of works by the Hanratty group (Jolls and Hanratty1), Wegner et al.2), Karabelas et al.3)) are the only ones which dealt with visualization of the flow around an individual particle in a bed. Since particles are in contact with each other in the bed, flow structure becomes very complicated even for spherical particles.

Wegner et al.2) made a test model of the packed bed consisting of transparent glass spheres. The fluid that they used in the experiment was a liquid which had the same refractive index as that of the glass. To visualize the flow, a small amount of dye was injected into the flow through a nozzle installed in the sphere. They related the flow pattern on the surface to the problem of singularity caused by three dimensional separation on the boundary layer. This kind of problem has been dealt with by Lighthill4). Wegner et al.2) pointed out that the contact point between spheres becomes what is called the “saddle point” on the skin friction line. They also clarified the locations of the nodal and focal points.

The flow field in the present experiment was almost the same as that of Wegner et al.2), but it was visualized in a way which was different from theirs. The method presented in this paper was based on the dissolution of solid chemicals in a liquid. That is, the sphere was coated with benzoic acid. The degree of dissolution of benzoic acid depends on the surface shear stress. As a result, the surface flow pattern was recorded in the form of streak lines. This method is easier to use than the dye injection method, particularly for a complicated flow field in a packed bed as in the present example.

In this paper, a technique of visualization using benzoic acid is described first, and then the results of the sphere in the packed bed are presented.

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† This report was originally printed in J. Soc. Powder Technology, Japan, 22, 599-605 (1985) in Japanese, before being translated into English with the permission of the editorial committee of the Soc. Powder Technology, Japan.
2. Arrangement of the experiment

2.1 Water tunnel

A water tunnel was specially designed, in which a uniform stream flowed vertically in the upward direction. The outline of the tunnel is shown in Fig. 1. The tunnel has a square test section of 15 x 15 cm, and the length of the test section is 25 cm. Most parts of this tunnel are made of acrylic plates. The flow velocity can be adjusted arbitrarily by changing the height of the over-flow tank ②. Figure 1 shows a single sphere hung from a string in the test section. In the packed bed experiment, many steel balls are regularly packed in a wooden box, the bottom of which is made of a mesh screen. This box is hung from strings as shown in Fig. 2 and set up in the test section of the tunnel.

2.2 Visualization technique

The present visualization technique was based on the phenomena of mass transfer from the surface of a body. As described above, the test sphere was coated with benzoic acid, and exposed to the flow for a certain period of time. The dissolution of benzoic acid is remarkable where the velocity gradient on the surface is steep. Therefore, the surface flow patterns could be observed at leisure after taking up and drying the test sphere.

The actual process of this kind of visualization is described next. The benzoic acid, which is a white powder at ordinary temperatures, was made molten by heating (its melting point is 122.4°C). Three kinds of yet to be hardened steel bearing balls were used as the test spheres, the diameters of which were \( d = 10, 15 \) and 19.5 mm. A metal string used as a support was attached to the sphere. First, the surface of the spheres was coloured white using spray lacquer, while benzoic acid was coloured differently from the sphere with ink. Coating with the benzoic acid was done by dipping the sphere in to the molten benzoic acid and taking it up quickly. The film of benzoic acid could be made thinner by pre-heating the sphere. In this experiment, the thickness of the film was about 0.5 mm. The metal string was cut and removed when the test sphere was set in the packed bed.

If the fluid velocity was high, the benzoic acid dissolved quickly even in pure water. However, the present velocity was so low that a means for promoting dissolution was necessary. Thus, methyl alcohol was added to the water at 40% in weight. The rate of dissolution was influenced by temperature, too. Therefore, a heater was set in the tank ① to keep the pipe-
line at a constant temperature by covering it with glass wool. When the temperature of the liquid was 23 to 26°C, about 10 to 15 minutes were needed for the flow patterns to be seen clearly on the spheres.

3. Results

3.1 Single sphere

The visualization method presented here was checked by using it for a certain well-known flow before it was applied to the packed bed. Such confirmation is particularly important at low fluid velocities. The fluid velocities in this work were adjusted to be so low that similarity in flow based on the Reynolds number could be obtained between the present packed bed and actual ones. That is, the particle size was 10 to 20 mm in the present flow, while it is much smaller in ordinary packed beds. The superficial fluid velocities were in the order of several cm/sec in this experiment. If the density of the coated material (benzoic acid) is different from that of the fluid, true flow patterns cannot be obtained at low velocities due to the effect of gravity. Therefore, a preliminary experiment was done in which the flow around a single sphere was visualized in a uniform stream by using the method presented here.

Figure 3 shows a photograph of the pattern on the sphere. The horizontal line observed on the sphere near the equator corresponds to the separation line of the flow. The measured results of the separation angle $\theta$, which is defined in Fig. 4, are shown in Fig. 5. The empirical curve given by Taneda is also presented in the figure for comparison. A group of white symbols nearly agrees with Taneda’s curve, while the black symbols show a considerable disagreement. Experimental points of black

Fig. 3 Separation line on a single sphere

Fig. 4 Separation angle $\theta$

Fig. 5 Measured results of separation angle,

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symbols were obtained at a velocity $u$ less than 1.5 cm/s. The disagreement observed at low velocities came from the effect of gravity, as has been mentioned. The specific weight of benzoic acid is larger than 1 (1.2659 at 15°C). Therefore, when the flow approaches the sphere upwards at very low velocities, the dissolved material tends to fall down along the surface of the sphere, indicated by the large values of $\theta$. This phenomenon was observed by the naked eye as well. Based on the above result, visualization at velocities less than 2 cm/s was avoided in the present experiment.

3. 2 Packed bed

Generally, particles in an actual bed have a variety of sizes and shapes. Also, the geometrical position of particles with respect to each other is irregular. However, the present study dealt with only three cases where spheres of a constant diameter were packed regularly, as shown in Fig. 6. Cases (1) and (2) have the same packing structure, called tetrahedral or rhombohedral packing, but these are treated separately in this work because flow fields in them differ depending on the relative direction of the uniform flow to the bed. Case (3) is called cubic packing. The number of contacts of the sphere is 12 in cases (1) and (2), and it is 6 in case (3).

The present bed consisted of 4 or 5 layers, and the test sphere were set in the third layer from the front facing the uniform flow. The coordinate system used in this paper is shown in Fig. 7, where $\Theta$, $\Phi$ and $R$ are the components of the spherical coordinate, and $Z$ is the vertical axis with the downward direction which is
positive. The direction perpendicular to the paper is chosen as the X-axis.

Figure 8 shows the results of case (1). Wegner et al. also presented the results of this case. Figs. 8 (1) and (2) are side-views observed from the position $\phi = 0$ and $45^\circ$, while Fig. 8 (3) is a picture seen from the top $\theta = 180^\circ$. For convenience of explanation, a sketch is given for each photograph. The dark parts correspond to the places of much benzoic acid. It is found from these pictures that a characteristic flow field which is closely related to three-dimen-
The surface shear stress becomes zero at two apices and along the separation line, as shown in Figs. 3 and 4. The sphere in the packed bed has several points of zero shear stress besides the two apices. These are identified as singular points in the theory of three-dimensional separation.

Let us consider points and lines where the surface shear stress becomes zero. For a single sphere, the shear stress is zero at two apices and along the separation line, as shown in Figs. 3 and 4. The sphere in the packed bed has several points of zero shear stress besides the two apices. These are identified as singular points in the theory of three-dimensional separation.

Such singular points are classified into some groups by analyzing the trajectories of a fluid particle on the limiting stream line. The sphere in the bed has the singular points shown in Fig. 9. This figure schematically presents the trajectories of the fluid particle near the singular points. Lighthill defined the line running from a saddle point to a nodal point as the line of separation of the three-dimensional flows. The saddle, nodal and focal points.
indicated by Wegner et al.\(^2\) are shown in the sketches of Fig. 8. The present flow pattern is almost the same as Wegner's results except that the focal point cannot be observed in this work. What is noted here is that the benzoic acid remained in the form of curved streaks connecting separation zones. This means that the shear stress is so small along these streaks that a separation of the three dimensional boundary layer occurs there. The visualization for case (1) was made at a Reynolds number of from 210 to 380, in which the patterns obtained were the same as those in Fig. 8.

The results for case (2) in Fig. 6 are shown in Fig. 10. The patterns are quite different from those in Fig. 8. Neither the focal point nor the nodal point can be observed clearly in the pictures. Experiments on this packing were made at the Reynolds number \(R_e = 70 \sim 460\), but the results were almost the same within this range. However, at a high Reynolds number, several streaks were observed near the apex, as shown in Fig. 11. It is not clear at this stage in the present work whether these streaks are characteristic of such high Reynolds numbers or of the sort of packing.

Figure 12 shows the results of cubic packing. A curve catenary-like is observed around the central part. A line similar to this was sketched by Karabelas et al.\(^3\). Figure 12 shows that longitudinal streaks appear alternatively from the bottom to the central part. These streaks were not observed in Karabelas' experiment where the cubic bed consisted of only one layer.

**Nomenclature**

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\begin{align*}
d & : \text{diameter of sphere} \\
R_e & : \text{Reynolds number } ud/v \\
u & : \text{fluid velocity} \\
\theta & : \text{separation angle} \\
\Theta, \Phi, R & : \text{spherical coordinates [degree, degree, mm]}
\end{align*}
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