Drag Force Acting on a Sphere in Oblique Arrangement of Spheres

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(Received 8 January 2016; received in revised form 26 May 2016; accepted 5 June 2016)

Abstract: The aim of the study is to know characteristics of a drag force acting on a sphere in an oblique arrangement of spheres, which may be influenced by the interval and the geometrical arrangement of spheres. In the study, a passing water tank was used as an apparatus and the drag force on a sphere was measured by using a load cell in a uniform flow. The flow around the spheres was also obtained by PIV. The experiment results show the effect of the front sphere on the drag force of the rear sphere through the velocity field in an oblique arrangement. Furthermore, the drag force acting on a sphere in a triangle arrangement of three spheres was also shown.

Keywords: Drag Force, Sphere, Oblique Arrangement, Triangle arrangement, Velocity Field, Wake

1. Introduction

Dispersed two-phase flow is widely used in industrial fields, i.e. a solid-liquid two-phase flow in slurry transportation and a gas-liquid two-phase flow in chemical and power plants. In the dispersed two-phase flow, the pressure loss and the heat-transfer of the flow change with the flow pattern. Furthermore, clustering of the dispersed phase may cause flow instability. Therefore, in order to operate an industrial plant efficiently and safely, understanding the motion of the dispersed phase is important. In the study, the drag force acting on a particle in a group of particles is investigated because the drag force plays an important role to estimate the motion of a particle.

In the previous study, the drag force acting on a sphere in a flow was investigated in a system of two spheres [1, 2], where they were arranged in tandem or parallel. The study in the arrangement as a line of spheres was also done [3]. Furthermore, effects of the shape and the size of the front obstacle on the drag force acting on the rear body were investigated in a system of two bodies [4]. The tandem or line arrangement of particles has been mainly studied but other arrangements are also seen in the dispersed two-phase flow. In the study, the drag force acting on a single sphere in oblique and triangle arrangements of spheres is investigated experimentally.

2. Experimental Apparatus

2.1 Passing water tank

Figure 1 shows an experimental apparatus to investigate the drag force acting on a sphere, which is a passing water tank with a test section of a rectangular channel of 1100 mm in length, 300 mm in width, and 200 mm in height. The test section is made of transparent acrylic and an image processing such as PIV can be done. A uniform flow at the test section is obtained in the test section. The flow velocity can be controlled by changing the rotation number of a pump.

The flow velocity is changed as the particle Reynolds number to be 5000, 6000, 7000, 8000. Here, the diameter of the sphere, 20 mm, is used as the characteristics length when the particle Reynolds number, Re, was calculated. The range of the particle Reynolds number was chosen as the similar as the previous work but the arrangement of the spheres of the study was different from the previous one [2, 3].

2.2 Measurement of drag force

Figure 2 is an enlarged view of measurement part in the test section shown in Fig.1 and shows a measurement equipment of the drag force acting on a test sphere. The diameter of the test sphere, D, is 20 mm. The test sphere is supported by a rod made of stainless steel, which diameter is 2mm. Another end of the rod is connected with a load cell. The load cell of a strain gauge is used for the measurement of the drag force acting on the test sphere. Figure 5 shows the pattern C where the spheres were arranged as oblique or triangle and drag and lift forces may act on the spheres. In the study, however, the drag force acting on the sphere in the main flow direction was measured because a suitable sensor was not obtained in order to detect the small drag and lift forces simultaneously.

The drag force measured by the above method, however, is sum of drag force acting on the sphere and the rod. In order to obtain only the drag force acting on the sphere, the factor of the rod is subtracted from the total drag force. Furthermore, the influence of the channel on the drag force on the sphere can’t be ignored because the ratio of the sphere’s diameter to the width of the channel is more than...
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Abstract

The aim of the study is to know characteristics of a drag force acting on a sphere in an oblique arrangement of spheres, which may be influenced by the interval and the geometrical arrangement of spheres. In the study, a passing water tank is obtained in the test section. The flow velocity is changed as the particle Reynolds number, \( R_e \), is 20, 50, and 100. Note that the experimental results shown in the study include always the wall effect of the channel.

Other spheres except the test sphere are supported by a line of 0.2 mm in diameter in order to minimize the influence of a supporting item on flow. The sphere was fixed on the line and the both ends of the line was fixed on the upper and lower walls of the test section. By stretching the line, the sphere was fixed in the flow.

2.3 Arrangement of spheres

In the experiment, spheres were arranged in four patterns. Figure 3 shows the pattern A where two spheres are arranged obliquely in the main flow direction. The distance between two spheres in the flow direction, \( L_x \), is fixed as 30 mm or \( L_x/D = 1.5 \) but the distance between two spheres in the perpendicular direction to the main flow, \( L_y \), is changed at every 5 mm in the range of 0 to 25 mm. The drag force acting on each sphere is measured, i.e. one of two is the test sphere. Hereafter, the sphere measured its drag force acting on is called as the test sphere. In Fig.3, the test sphere is shown as a solid circle.

In the pattern B shown in Fig. 4, one of two spheres is fixed at the center of a dotted half circle (it is called as a fixed sphere and shown as a solid circle) and the other sphere shown as the open circle is arranged on the circumference of the dotted half circle. The distance between two spheres, \( L \), is fixed at 30 mm or \( L/D=1.5 \) but the angle \( \theta \) between the line connecting two spheres and the flow direction is changed. The definition of the angle \( \theta \) is shown in Fig. 4 and is changed at every 15° from zero to 180°. The drag force acting on the fixed sphere is measured, i.e. the fixed sphere is the test sphere.

In the pattern C and D, three spheres are arranged at the vertexes of a triangle. Figure 5 shows the pattern C where a sphere is at the front and the others in the rear. The distance between the rear two spheres is fixed as \( L_y/D = 3 \) but the distance the front and the rear spheres along the flow direction, \( L_x \), is changed at every 30 mm from 30 mm to 120 mm. The drag forces on the front and the rear spheres shown as solid circles were also measured.

In the pattern D shown in Fig. 6, two spheres are at the front and the other is at the rear. In the pattern D, also, the distance between the front two spheres is fixed as \( L_y/D = 3 \)

but the distance the rear and the front spheres along the flow direction, \( L_x \), is changed at every 30 mm from 30 mm to 120 mm. The drag forces on the front and the rear spheres shown as solid circles were also measured.

3. Result and Discussion

3.1 Measurement of a drag force

3.1.1 Arrangement of two spheres

Figures 7 and 8 show the drag forces acting on the front and the rear spheres in the pattern A, respectively, under the different particle Reynolds number conditions. The axis of ordinate is the ratio of the drag force acting on the
The test sphere to the drag force acting on a single sphere under
the same particle Reynolds number, \( C_D/C_D0 \), hereafter
called as the drag force ratio. \( C_D \) and \( C_D0 \) denote the drag
coefficients of a test sphere and a single sphere, respectively. Under the same condition of the sphere size
and the velocity of the uniform flow, the ratio of the drag
force acting on the test sphere to that acting on a single
sphere is the ratio of the drag coefficients, \( C_D/C_D0 \).

The axis of abscissa is \( L_Y/D \) which is the ratio of the
distance between two spheres, \( L_Y \), to the diameter of a
sphere, \( D \). The drag force ratio of the front sphere was
larger than 1 under all flow conditions shown in Fig.7,
especially it was large in cases of \( L_Y/D = 0.25, 0.5 \). On the
other hand, the drag force ratio of the rear sphere was
larger than 1 in \( L_Y/D = 0.25, 0.5 \), and smaller than 1 in
\( L_Y/D = 0, 0.75, 1, 1.25 \) (as shown in Fig.8). Strong
dependence of the experimental results on the particle
Reynolds number was not observed in these figures.

Figure 9 shows the drag force ratio of the fixed sphere
shown in Fig. 4. The axis of abscissa is the angle \( \theta \)
between the line connecting two spheres and the main flow
direction as shown in Fig. 4. The drag force ratio was very
sensitive to the angle \( \theta \) in the range from \( 0^\circ \) to \( 75^\circ \).
Especially, the drag force ratio at the angle of \( 45^\circ \)
depended on the particle Reynolds number and was large
at the particle Reynolds number of 5000. In the range
from \( 0^\circ \) to \( 75^\circ \), the test sphere located in the rear of the
other sphere. Therefore, the wake of the front sphere
influenced on the drag force on the test sphere very much.
In case of the angle larger than \( 105^\circ \) where the test sphere
was in front of the other sphere, the drag force ratio took
more than 1. It was similar to the drag force ratio of the
front sphere of the pattern A, as shown in Fig. 7.

There were many studies on tandem two spheres [1-3],
[6]; the cases of \( \theta=0^\circ \) and \( 180^\circ \) in pattern B. The drag
force ratio was about 0.9 at \( \theta=0^\circ \), corresponding to the case
of the rear sphere in tandem two spheres, while in the
previous work, it was 0.32 in case of the particle Reynolds
number, \( Re=10000 \) [2] and 0.57 in case of \( Re=130 \) [1]. In
the same way, the drag force ratio was about 1.04 at
\( \theta=180^\circ \) corresponding to the case of a front sphere in
tandem. It was 1.15 in case of \( Re=10000 \) [2] and 1.09 in
case of \( Re=130 \) [1]. The drag force ratio was influenced
by the particle Reynolds number. In the study it was large
in case of the rear sphere and small in case of the front
sphere, comparing with the other results.

3.1.2 Arrangement of three spheres

Figures 10 and 11 show the drag force ratio of the front
sphere and the rear spheres in the pattern C, respectively.
The axis of abscissa is \( L_Y/D \) corresponding to the distance
between the front and the rear spheres in the main flow
direction. The experiments were done under the different
particle Reynolds numbers but their results show the
similar tendency as follows. Figure 10 shows that the drag
force ratio of the front sphere was larger than 1 but
decreased with the distance between the spheres and took
the smallest at \( L_Y/D=3 \). After that, it turned to increase and
approach to 1 with the distance between the spheres.
The drag force ratio of the rear sphere took almost constant of more than 1 as shown in Fig. 11. In the previous study, increase of the drag force due to the presence of a side sphere was shown [1]. The reason why the drag force ratio of the rear sphere was more than 1 in Fig. 11 is also considered as the presence of the side sphere in the pattern C.

Figures 12 and 13 show the drag force ratio of the front and the rear spheres in the pattern D, respectively. Figure 12 shows that the drag force ratio of the front sphere took almost constant of more than 1, similar to the rear sphere in the pattern C. It was also thought that the drag force on the front sphere was influenced by the side sphere. The tendency of the drag force ratio of more than 1 appears clearly in cases of small particle Reynolds numbers.

Figure 13 shows that the drag force ratio of the rear sphere increased with the distance between the spheres, \( \frac{L_Y}{D} \) in the pattern D. The velocity of the water flowing between the two front spheres was accelerated from the uniform flow and the accelerated flow impinged on the rear sphere. As a result, the drag force ratio of the rear sphere took more than 1. The drag force ratio also took the maximum at \( \frac{L_Y}{D}=4.5 \). Because the area of the high velocity flow was near the front spheres, the drag force ratio might decrease in the region of \( \frac{L_Y}{D}>4.5 \). The tendency of the results is almost same under the different particle Reynolds numbers.

### 3.2 Flow velocity field around two spheres

In order to know the mechanism of change in the drag force on the sphere, the time averaged velocity field around spheres was obtained by PIV in the pattern A under the particle Reynolds number of 6000. The instantaneous velocity field was measured at every 12.5 ms and the time averaged velocity field was obtained based on the instantaneous data for 2 s. Figure 14 (a) and (b) show the velocity fields in cases of \( \frac{L_Y}{D}=0.25 \) and 1.0, respectively. Figure 14 (a) shows the velocity filed in case of \( \frac{L_Y}{D}=0.25 \), where the separated flow from the front sphere impinged on the rear sphere. On the other hand, in case of \( \frac{L_Y}{D}=1.0 \)
The axis of abscissa is the location velocity was obtained based on the velocity measurement. The velocity was almost constant in the core region and the uniform flow at the test section without the spheres. The velocity was rear sphere was more than 1 in case of weak (Fig. 14 (b)). Therefore, the drag force ratio of the front sphere and the flow in front of the rear sphere became as shown in Fig. 14 (b), the wake was formed behind the rear sphere in the pattern A and the origin of the coordinate system is taken at the center of the rear sphere. The velocity distribution was obtained. Figure 15 shows a coordinate system to discuss the velocity distribution. The circle is diameter of the sphere, \( D \), \( X \)-axis, \( Y \)-axis, to the uniform flow normalized by the diameter of the sphere, \( D \), on the \( Y \)-axis.

In cases of \( L_Y/D = 0.25 \), \( 0.5 \) in the pattern A, the velocity \( u/U_0 \) takes almost zero in the region of \( 0 < Y < 0.5 \). Based on such velocity distributions, it was estimated that the separated flow from the front sphere impinged on the upper part of the rear sphere and turned to upward. Therefore, the rear sphere was pushed downstream. On the other hand, the velocity \( u/U_0 \) is almost 0.5 in cases of \( L_Y/D = 0.75, 1.0, 1.25 \). It shows that the flow direction was not changed so much as the cases of \( L_Y/D = 0.25, 0.5 \). As a result, the drag force on the rear sphere was smaller than that in cases of \( L_Y/D = 0.25, 0.5 \). These velocity distributions correspond to the drag force change on the rear sphere in the pattern A, in which the drag force ratio took more than 1 in cases of \( L_Y/D = 0.25, 0.5 \) and less than 1 in cases of \( L_Y/D = 0.75, 1.0, 1.25 \) as shown in Fig. 8.

In pattern B, the velocity fields also obtained because the drag force ratio varied at \( \theta = 45^\circ \) depending on the particle Reynolds number while it took almost the same value at the other angles among different Reynolds numbers, as shown in Fig. 9. Figure 17 (a) and (b) show the velocity fields around the fixed sphere in cases of the particle Reynolds numbers of 5000 and 8000, respectively. In case of \( Re = 5000 \), two vortexes were observed in the wake of the sphere. On the other hand, the upper vortex was large and it was difficult to find the lower vortex on the velocity field in Fig. 17 (b). Such flow structure change may be induced by the change of the intensity of
The axis of abscissa is the location almost constant in the core region and the uniform flow at the test section without the spheres. The velocity was rear sphere was more than 1 in case of weak (Fig. 14 (b)). Therefore, the drag force ratio of the front sphere and the flow in front of the rear sphere became than 1 in case of $u/U_0$ velocity, main flow velocity along the PIV. In Fig. 16, the axis of ordinate shows the ratio of the which was extracted from the velocity field measured by sphere along the flow direction. The velocity distribution was obtained on the red line in the rear sphere in the pattern A and the origin of the system to discuss the velocity distribution. The circle is distribution was obtained. Figure 15 shows a coordinate $\frac{D}{2}$ at $\frac{Y}{D}=0.25, 0.5$ in the pattern A, the velocity $\frac{Y}{D}=0.25, 0.5$, and less than 1 at $\theta=45^\circ$ depending on the $\frac{Y}{D}=0.25$ is almost 0.5 in cases of $\frac{Y}{D}=0.25$ and less than 1 $\frac{D}{2}$, on the $\frac{Y}{D}=0.25$, $\frac{D}{2}$ is a time averaged velocity distribution on it, $\frac{Y}{D}=0.25, 0.5$. It shows that the flow direction was $\frac{Y}{D}=0.25, 0.5$. As a result, the drag force acting on the rear sphere was smaller than that on the single sphere. This tendency came from that the drag force on the sphere was affected by the side sphere strongly. The drag force on the front sphere in the pattern D showed the similar tendency.

4. Conclusions

In the study, the drag force acting on a sphere in the oblique and the triangle arrangements of spheres was investigated experimentally. The findings were as follows;

1. In case of the oblique arrangement of two spheres (the patterns A), the drag force acting on the rear sphere depended on the distance between two spheres because the flow pattern around two spheres was changed. When the separated flow from the front sphere impinged on the rear sphere, the drag force acting on the rear sphere increased. On the other hand, when the separated flow flowed into the space between two spheres, the drag force acting on the rear sphere was smaller than that on the single sphere.

2. In case of the pattern B (i.e. the oblique arrangement with different angle between the line connecting two spheres and the flow direction but constant distance between the spheres), the characteristics of the drag force on the sphere were similar to those in case of oblique arrangement as the pattern A. The drag force, however, was sensitive to the angle in the oblique arrangement.

3. The drag force acting on the rear sphere in the triangle arrangement of three spheres as the pattern C did not change with the distance between the front and the rear spheres but it was larger than that on the single sphere. This tendency came from that the drag force on the sphere was affected by the side sphere strongly. The drag force on the front sphere in the pattern D showed the similar tendency.

4. The drag force of the rear sphere in the pattern D increased in cases of $L_y/D = 1.5$ to 4.5 due to the acceleration of the flow between the front two spheres.

Acknowledgement

The study is supported by a grant of Casio Science Promotion Foundation.

References


