A Fundamental Investigation of the Capsule Transport

(3rd Report, Friction of Capsule Wheels and Transport Experiment of a Single Capsule)

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First, the frictional force between a capsule wheel and the wall was measured by applying an equipment in which the load and revolutions of the wheel were changeable. Based on the measured values, an empirical expression of the friction term which is included in the equation of capsule motion was obtained. Second, combining a micro-computer for automatic data processing, a measuring system was developed on the transport pipeline, which was built by authors. The effects of various factors such as the diameter and mass of the capsule on the capsule motion were experimentally clarified in the transport pipeline. It has been found that the fluid drag coefficient of a moving capsule is larger than that of the corresponding stationary capsule by 20%.

Key Words: Fluid Machine, Capsule Transport, Friction, Micro-computer, Drag

1. Introduction

In the 1st report*, fluid drag acting on a stationary capsule in a pipe flow and distributions of pressures and velocities were described. In the 2nd report**, turbulent structure of the wake of the stationary capsule and the effects of the interaction between two capsules on the drag were investigated in detail. However, the problem as to whether the data obtained for the stationary capsule are applicable to the practical transport system or not is further to be solved, because of the presence of relative velocity between pipe wall and capsule in the practical pipeline. Also frictional resistance between the pipe wall and capsule wheels should be considered on the condition of a moving capsule. Particularly, the fluid drag plays an essential role in the motion of capsule and therefore it is necessary to make clear quantitatively the difference between stationary and moving capsules with respect to the drag. The equation governing the capsule motion consists generally of three terms, i.e., acceleration, fluid drag and frictional resistance terms. Although the transport experiments of capsules have been reported*, there have been few that dealt with each term of the equation of motion.

In this paper, the method and results of measurements of the friction between a wheel and the wall are described at first. Furthermore, a transport pipeline and a measuring system using a micro-computer are explained and the results of transport experiment are presented. The drag coefficient of the moving capsule is obtained experimentally by use of the equation of motion together with measured results. Comparison is made between moving and stationary capsules in connection with the drag coefficient.

Nomenclature

- A: Cross-sectional area of capsule end-plate
- C: Capsule drag coefficient
- c: Capsule velocity
- s: Capsule velocity at the inlet of the stopper region
- D: Inner diameter of the pipe
- d: Diameter of capsule end-plate
- g: Gravitational acceleration
- h: Diameter ratio (=d/D)
- l: Length of the stopper region
- M: Mass of the capsule
- m: Mass of the model shown in Fig. 1
- N: Normal force
- p: Pressure (gauge)
- R: Frictional force of a single wheel
- R: Frictional force of a capsule
- t: Time taken for a capsule to pass between the i-th rubber magnet and the (i+1)th one
- u: Time
- v: Air velocity
- \(v_{max}\): Maximum air velocity
- \(v\): Capsule velocity calculated from the revolutions of wheels
- \(r\): Friction coefficient of wheel defined by Eq. (4)

2. Frictional Force of Wheels

2.1 Apparatus and experimental procedure

In most of the previous works, the frictional force between a capsule wheel and the wall was obtained by measuring the force of a rope by which the capsule was taken in tow. The capsule velocity under such condition is usually smaller than the practical velocity. To improve this kind of experiment, the wheel was removed from the capsule and the frictional force was...
measured at arbitrary rotating velocities and loads by use of a model shown in Fig. 1. The surface of wheels is coated with polyurethane rubber. The apparatus for experiment is schematically shown in Fig. 2. The rotation given by a motor was controlled by a variable speed transmission and transmitted to a pulley. The periphery of the pulley was covered with FRP (fiberglass reinforced plastic) pipe which is of the same material as the transport pipe. A wheel shown in Fig. 1 rotates on the periphery. Appropriate tension exerted by strings keeps the model in balance. The rotating velocity of a wheel, which corresponds to the capsule velocity, is calculated from the revolutions of a pulley on the assumption that no slip exists between the wheel and the pulley.

As is known from the force balance in Fig. 1, the frictional force $R$ is given by

$$R = \frac{(T_0 - gm) r}{r} \quad (1)$$

in which $m$ is mass of the model and $T_0$ the tension measured by the load cell in Fig. 2. The position of the center of gravity $r$ is obtained from the relation

$$r = T/r \quad (2)$$

in which $r$ is the coefficient of wheel friction. The values of $r$ and $N$ for each wheel are given in Table 1, which were obtained using the method of least squares. $N$ differs largely with each wheel, while $r$ shows a similar value. Therefore, the difference in the resultant frictional force is caused mainly by the difference in $N$, $N$ is considered an inherent property of a wheel bearing. That is, Eq. (4) means that the friction $R$ is the sum of rolling friction between the wheel and wall and friction inherent of the bearing.
used. When the normal force $N_r$ on the wheel is sufficiently large, the frictional force is approximately expressed as

$$R = EN_r$$

which can be applied to the case of a large capsule. However, when a capsule is small the term $R$ is dominant. This is the case when a bearing is used as a wheel under a light load compared with an allowable load of bearing. Though Eq. (5) is often used as an expression of the friction in equation of capsule motion, such an expression can not always be used for a model experiment. The fact mentioned above is related to scatter of data shown in Fig. 4 and Table 1. It is suggested that as the friction is measured under a very small load, a slight difference of each bearing appears remarkably. The relation between the rotating velocity and the friction is shown in Fig. 5. This figure indicates that there is no significant effect of the velocity on the friction within the present measurements. For the capsule model used in this transport experiment, four wheels are set up at both ends of the capsule body as shown in Fig. 6. The wheels shown by hatched lines in the figure were tested before the transport experiment. When the wheels make an angle with the wall as shown in Fig. 6, the normal force $N_r$ acting on the single wheel becomes

Table 1 Values of $\xi$ and $E_r$ of each wheel

<table>
<thead>
<tr>
<th>Wheel No.</th>
<th>$\xi \times 10^4$</th>
<th>$R_r \times 10^2$ N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.25</td>
<td>2.00</td>
</tr>
<tr>
<td>2</td>
<td>4.49</td>
<td>3.45</td>
</tr>
<tr>
<td>3</td>
<td>4.12</td>
<td>2.84</td>
</tr>
</tbody>
</table>

![Fig. 5 Relation between the rotating velocity $V$ and the frictional force $R$](image)

where $M$ is mass of capsule. Substituting Eq. (6) into Eq. (4) and using the values in Table 1, the friction of wheels acting on a capsule $R_r$ can be given by

$$R_r = 1.25 \times 10^{-4} \cdot M + 1.36 \cdot (N)$$

3. Transport Experiment

3.1 Apparatus and experimental procedure

The pipeline used for the transport experiment is shown in Fig. 7. The transport pipe was straight and set horizontally. Transparent acrylic pipes and polyvinyl chloride pipes were used at the flow rate measuring section and controlling section, respectively. The transport pipe is made of FRP pipe, inner diameter of which is $D=125.6 \pm 0.2$ mm. The distance between the starting point and the pipe end was 30 m. In order to stop the capsule, the capsule was introduced into an end-closed pipe, where the capsule motion was suppressed by the compressibility of air. There were several air-exhaust holes, positions of which were 5, 7.5 and 10 m from the pipe end, so that the length of the stopper region was changeable. Injection of a capsule into the pipeline, as well as ejection of it was easily done by adopting the V-band joint. In the experiment, first, the capsule was stopped by a metal rod intruding into the pipe during operation of the blower. The capsule was started by pulling up the metal rod which was driven by an electromagnetic solenoid. The capsule remaining in the stopper region can be sent back to the starting point by operating the valves 2, 3, and 6. Most previous investigators estimated the capsule velocity from the time required for the capsule to pass the positions of sensors (phototube etc.) which were set outside the pipe. In such a case many sensors are necessary to get high precision and moreover preparation of many sensors is generally expensive. Therefore, the number of measuring points in the works adopting such a method has been comparatively limited. In the present

![Fig. 6 State of wheels set](image)

![Fig. 7 Pipeline for transport experiment](image)
work, the sensor (magnetic proximity switch) was installed in the capsule and many rubber magnets, 13 mm in width, were set outside the pipe. This method makes it possible to increase the number of measuring points of time difference economically, because the rubber magnets are much cheaper than sensors. Moreover, as the alteration of the position of rubber magnets is easy, various experimental conditions can be produced with flexibility. The experimental procedure is explained in detail in 3.2. The intervals of rubber magnets were 20-30 cm in the accelerating and stopper regions where the capsule velocity rapidly changed. The intervals were 1 m in the other parts of the line. Air velocity was measured by a hot wire anemometer. A pressure transducer of strain gauge type was used to measure the exhaust pressure of the blower.

In general, the larger the diameter ratio $k$, the more efficiently the capsule is transported. However, some allowance for the clearance is necessary to avoid direct contact of the capsule body with pipe wall, particularly in the part of pipe bends. Therefore, end-plates, which have diameters larger than the capsule body, are installed in the capsule. The diameter ratio of the capsule body is usually from 0.8 to 0.9. In this work, a capsule having such end-plates was used. Fig. 8 shows the test capsule. This model was made of a transparent acrylic pipe and plate. The eight wheels in total are attached to the capsule. The diameter ratio $k$ can be varied by the exchange of end-plates. The unit contains a magnetic proximity switch, an FM transmitter and a few cells. The magnetic proximity switch detected the magnetic field emanated from rubber magnets. The output signal from the magnetic proximity switch was transmitted to the FM receiver in a data control room by the FM transmitter. The transmitting frequency was 76 MHz. The capsule mass can be changed by putting a piece of lead in the space of the capsule.

Since the transport pipe was not long enough, a capsule entered the stopper region before the capsule velocity reached a constant value. The air velocity, which increased with an increase of the capsule velocity, reached a maximum value after a capsule entered the stopper region. In this work, this maximum air velocity $U_{max}$ is adopted as the representative velocity for showing data. The measurements were conducted in the following conditions. Diameter ratio $k = 0.85, 0.90, 0.93$ and 0.96. Maximum air velocity $U_{max} = 4, 8$ and 12 m/s. Capsule mass $M = 2.78, 3.77$ and 4.77 kg (specific gravity $= 1.02, 1.38$ and 1.75, respectively).

3.2 Signal processing procedure

Figure 9 shows a block diagram of the signal process based on a micro-computer. The analogue data taken from a hot wire anemometer and a pressure transducer pass through a low pass filter and a DC amplifier. These data are put into the data channels of the A/D converter. This A/D converter had an 8 bit resolution and the data put into two data channels were sampled simultaneously. Both the air velocity and exhaust pressure of the blower changed corresponding to the capsule motion, but changes in these quantities were not so fast. Thus the data sampling was made only at moments when the capsule passed the position of the rubber magnets. Figure 10 shows a timing chart of the signals. The signal $A$, which shows that a capsule has passed the positions of rubber magnets, is a direct output from the FM receiver. This signal is converted to a signal $B$ by using an S/N sample and hold amplifier having 1 ms hold time. The signal $C$ is a switching signal obtained at the moment when an electromagnetic solenoid is operated and therefore it gives the starting time of a capsule. As seen in Fig. 10, the signal $C$ contains a chattering. To remove this

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**Fig. 9** Block diagram of the signal process

**Fig. 8** Test capsule

**Fig. 10** Timing chart of the signals
chattering it is made to pass through two S/H amplifiers having 20 and 1 ms hold times, and the signal C is converted to a signal E. The logical sum of the signals B and E is a signal F, which is put into the external trigger terminal of the A/D converter.

The capsule velocity can be calculated from the time interval \( T \) of pulses in the signal F. In this work, this \( T \) was obtained by means of devising a software. To be more specific, the data converted into digital form were stored in a memory at the moments the \( n \)-th pulse was put into the external trigger terminal of the A/D converter. At the same time, simple calculations, CPU time of which was known, were repeated in the micro-computer. These calculations were repeated until the \( i \)-th pulse came in. The time \( T \) was obtained by counting the number of repetitions of calculations which was proportional to \( T \). In this experiment, when \( T \) became more than 3.3 s, a capsule was judged to have stopped and the data sampling was terminated. The rubber magnets are arranged at intervals of 20-30 cm in the stopper region as mentioned before. Therefore the value of 3.3 s corresponds to a capsule velocity of about 0-3 cm/s, which is sufficiently small. The calculation time of a micro-computer after the transport experiment was less than about 15 s.

![Graph](image)

**Fig. 11** An example of experimental results

![Graph](image)

(a) Effect of the diameter ratio \( d \)

![Graph](image)

(b) Effect of the mass \( M \)

**Fig. 12** Capsule velocity in the accelerating region

3.3 Experimental results

The capsule velocity \( v \), the air velocity \( U \) and the exhaust pressure of a blower \( \phi \) are plotted against the time \( t \) in Fig. 11. This figure indicates that the capsule is accelerated smoothly until \( t = 2.7 \) s and that the air velocity increases with the motion of the capsule while the exhaust pressure of a blower decreases. The capsule enters the stopper region at \( t = 2.7 \) s and is decelerated quickly for less than 1 s and almost stops after 7 s from a start. A close observation of Fig. 11 also indicates that a little increase in the air velocity occurs at the moment the capsule enters the stopper region.

Figures 12(a) and (b) show the effects of the diameter ratio \( d \) and the mass \( M \) on the capsule velocity in the accelerating region. As is expected, the larger the diameter ratio and the less the mass, the larger the rate of acceleration.

Figures 13(a) to (d) show the effects of \( d \), \( M \), \( \phi \) and \( L \) on the capsule velocity in the stopper region. \( L \) is the length of the stopper region and \( \phi \) is the capsule velocity at the inlet of the stopper region. The ordinate indicates the velocity ratio \( C_{0} \), to see the rate of deceleration of a capsule. The data break for the case of \( k=0.85 \) and 0.96 in Fig. 13(a). In the case of \( k=0.85 \), the capsule is considered to collide with the pipe end as the capsule decelerates slowly. In the case of \( k=0.96 \), the rate of deceleration of the capsule is very fast. With respect to the effects of \( d \) and \( M \), the results shown in Figs. 13(a) and (b) are such as expected. It could be found in the experiment of the accelerating section that the larger the value of \( d \), the larger the fluid drag on a capsule. Also the result that the less the value of \( M \), the larger the resulting change in the capsule velocity. The same
tendency as in those results is shown in Figs. 13(a) and (b). Figure 13(c) shows that it takes 4 s for a capsule to stop in all cases, i.e., the effect of is little. This result means that in the case of large a capsule is quickly decelerated and in the case of small a, the deceleration is gradual. Figure 13(d) indicates that has no effect on the capsule velocity.

The theoretical analysis of the above results will be explained in detail in the next report.

4. Comparison of Drag Coefficient

4.1 Drag coefficient of a stationary capsule

The drag coefficient of a capsule is defined by the equation

$$ F = C_d A \frac{1}{2} \rho V^2 $$

where $F$ is the fluid drag on a capsule and $A$ the area of end-plate. In the previous paper, the pressure distributions around a cylindrical capsule which has fixed in a circular pipe were measured and the fluid drag on a capsule was obtained by making use of the pressure distribution in the longitudinal direction. On the basis of the results of the pressure distributions, an equation of the drag coefficient is also obtained, which agrees well with that for a capsule suspended stationarily in a vertical pipe flow. The capsule used in this work consists of a body and two end-plates whose diameter is larger than that of the body, and furthermore it possesses wheels. Consequently, the drag coefficient for a cylindrical capsule obtained in previous work can not be applied to this work. As was confirmed in the previous report, the fluid drag on a capsule is related to the static pressure distribution in the longitudinal direction. Thus, an attempt was made to get the drag coefficient of the capsule with end-plates from the pressure distribution. Figure 14 shows the measurements of pressure distribution in the case of $t=0.96$. The pressure divided by the dynamic pressure is plotted against the non-dimensional distance from the front plate of the capsule. This figure indicates that the static pressure drops sharply at both front and rear end-plates. The static pressure on the front plate is equal to the upstream total pressure and the static pressure on the rear plate is equal to the pressure in the dead water region behind the capsule. The fluid drag acting on the capsule generally consists of a pressure drag which is due to the static pressure difference between the front and rear plates and a frictional drag which acts on the side wall of the capsule. Because a capsule which had a comparatively large clearance between the body and pipe wall was used in this experiment, the frictional drag mentioned above could be neglected. The static pressure on the front plate is equal to the sum of the upstream static pressure at pipe wall and the dynamic pressure. Consequently, using the pressure difference at pipe wall between the front and rear plates $dp$ and the area of the plate $A$, the fluid drag $F$ is presented as

$$ F = \frac{dp + \frac{1}{2} \rho V^4}{A} $$

Substituting Eq. (9) into Eq. (8), the drag coefficient $C_d$ is obtained as

$$ C_d = \frac{dp}{\frac{1}{2} \rho V^4} + 1 $$

4.2 Comparison of the drag coefficient

The drag coefficient of a moving capsule is indirectly obtained from the equation of motion

$$ M \frac{dV}{dt} = C_d A \frac{1}{2} \rho (U - c)^2 - R $$

$0 1 2 3 4 5$

$-400 -300 -200 -100 0 2$

Fig. 14 Static pressure distribution in the longitudinal direction of a stationary capsule
where all the terms except for $C_s$ are experimentally obtained. If the transport pipeline is sufficiently long, a capsule moves at a constant velocity and the fluid drag is balanced with the friction of wheels. As the pipeline in this experiment was not long enough, the left hand side in Eq. (11), i.e., the acceleration term was estimated from the experimental data. Figure 15 shows an example of drag coefficient of the moving capsule. The data are scattered widely in the figure, for which the reason is considered to lie in the fact that instantaneous fluctuating velocities sampled by the present data acquisition system were used to calculate the coefficient. In this work, an arithmetic mean of these data was taken. The drag coefficients of the stationary and moving capsules are compared in Fig. 16. It is found from this figure that the drag coefficient of a moving capsule is larger than that of the corresponding stationary capsule by 20% for all diameter ratios. The above difference can be called small considering the practical transport of capsules, because a slight change in the diameter ratio causes a large difference in the value of the drag coefficient.

5. Conclusions

(1) As a fundamental research for transport experiment and analysis of capsules, the frictional force between a capsule wheel and wall was measured. A bearing was used as a wheel in this experiment. It is found that the frictional force must be expressed by Eq. (4) when the load is comparatively small. The rotating velocity has little effect on the frictional force.

(2) An experimental apparatus for capsule transport was built and a measuring system using a micro-computer was developed, by which the capsule, air velocity, etc. were obtained. Making use of this apparatus for capsule transport, the effects of various factors on the capsule motion were experimentally investigated.

(3) The drag coefficient of a moving capsule was experimentally obtained from the equation of capsule motion. It is made clear from comparison of the drag coefficients of the stationary and moving capsules that the drag coefficient of the moving capsule is larger by 20%.

Acknowledgements

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