An Experimental Study of Aerodynamics of Capsules Moving through Long Tube

An Experimental Study of Aerodynamics of Capsules Moving through Long Tube

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This paper describes experimental studies to clarify the motion of capsules moving through a tube.

The effect of the following parameters on capsule velocity is investigated both in moving tests and in wind tunnel tests: the capsule shape, length, weight, air flow velocity and blockage ratio.

The qualitative results of this study provide an information on design of the capsule moving in a tube.

The empirical equation to estimate the capsule velocity is obtained, although the region generally applicable is restricted.

1. Introduction

Transportation systems which make use of vehicles travelling through tubes have recently attracted the attention of many researchers. Since the support is provided from all sides, the tube vehicle is free from tilt when negotiating a curved tube.

The closed guideway also offers the protection from many environmental hazards. While at present, in some factories and offices, a few types of them have been already put into practical use. Light weight goods such as small parts and cards, for example, have been carried by using capsules through tubes.

There are several methods for propelling capsules, and in this experiment passive capsules rather than capsules with powerplants are used, that is, capsules are propelled through tube by air flow supplied from a turbo-blower.

For proper capsule design, an understanding of the aerodynamic interaction between a tube and a capsule is very important, since stability and terminal velocity of the capsule are directly related to the capsule aerodynamics.

The terminal velocities of capsules are a function of capsule shape, lenght, weight, tube inside air flow velocity and blockage ratio (the ratio of capsule cross-sectional area to tube cross-sectional area).

The purpose of this paper is to present the results of an experimental investigation of capsule velocities as a function of bolckage ratio and the other factors. In addition to moving through tests, wind tunnel tests have been done to obtain the drag coefficient of capsules.

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Symbols

x distance along tube axis (m)
t time (sec)
ν kinetic viscosity coefficient of air (m^2/sec)
ρ density of air (kg・sec^2/m^4)
g acceleration of gravity (m/sec^2)
v capsule velocity (m/sec)
d capsule diameter (mm), (m)
l capsule length (mm)
w capsule weight (g), (kg)
U air flow velocity (m/sec)
D tube diameter (mm), (m)
$S_c = \pi d^2/4$, capsule cross-sectional area (m^2)
$S_t = \pi D^2/4$, tube cross-sectional area (m^2)
$\beta = S_c/S_t$, blockage ratio
$C_D = \text{drag force} \Big/ \left[\frac{1}{2}\rho(U-v)^2 \cdot S_c\right]$, drag coefficient
$\lambda = \text{contact frictional force} \Big/ \left[\frac{1}{2D}\frac{w}{g}v^2\right]$, contact coefficient
$R_e = (U-v)d/\nu$, Reynolds number

2. Experimental Program

Moving through a tube tests and wind tunnel tests were performed and capsule velocity and its drag force were measured in this program.

2.1 Moving Through A Tube Tests

(a) Capsule

Two types of capsule used in this experiment are illustrated in Fig. 1. Simple cylindrical type was mainly used to investigate the effect of various parameters on the capsule velocity, and the other was compared with it. Balsa (specific gravity 0.1) was adopted as material of a mainpart of the capsule due to the merits of light weight and easy forming.

Geometrically similar models of the ratios of capsule length to tube diameter of 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 were used in this program.

In order to clarify the effect of blockage ratio and Reynolds' number, ten capsule diameters for each ratio of capsule length to tube diameter were also tested, so that the effect of the blockage ratio could be studied. All the capsule dimensions are shown (both in dimensional form and in nondimensional form) in Table 1.

Capsule weight was adjusted covering the range of

{empty weight of capsule} + {loading weight (0 g~300 g)}

by adding iron weights and spongy fragments to the hollow along the capsule axis.

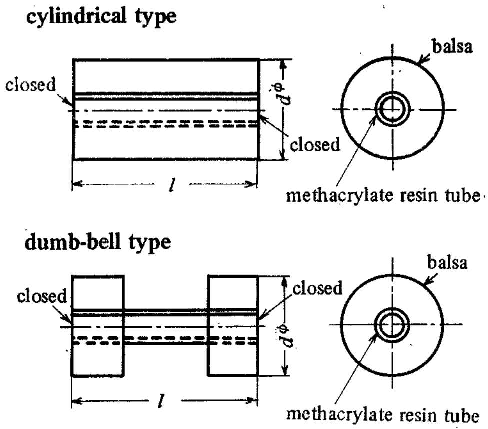


Fig. 1. Two types of capsule.

Table 1. Tested capsnle dimensions.

d (mm)	58	62	66	70	74	78	82	86	90	92
β	0.365	0.418	0.474	0.531	0.595	0.662	0.726	0.803	0.880	0.918

ℓ (mm)	48	96	144	192	240	288
ℓ/D	0.5	1.0	1.5	2.0	2.5	3.0

(b) Measurement of Capsule Velocity

The experimental apparatus for moving through tests is schematically shown in Fig. 2. A transparent methacrylate resin tube, 96 mm inside diameter and 20 m long, was used in this experiment. Air flow was supplied by a turbo-blower driven by an electric motor of 15 HP, and flow velocity in the tube was measured by pitot tube.

For the capsule velocity measurement, ten C_dS cells and light bulbs were equipped along the tube for intervals of about 2 meters. And these C_dS cells voltage outputs were connected in series to a galvanometer of a oscillograph. When each light beam

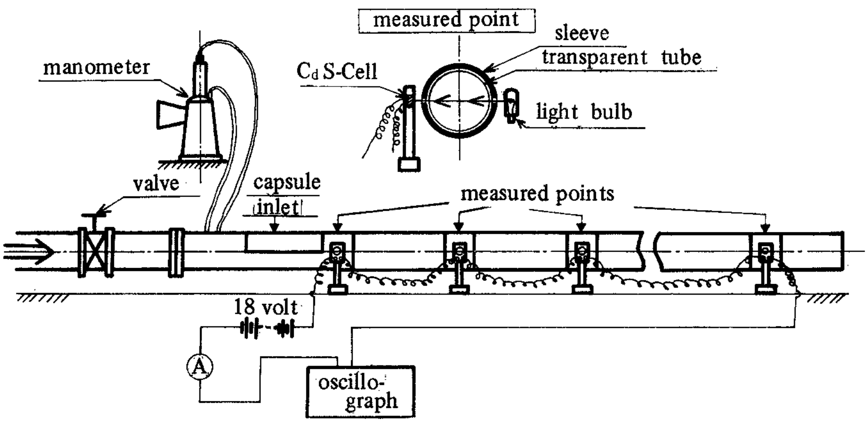


Fig. 2. Experimental apparatus for capsule velocity measurement.

was intercepted by the capsule passing through the tube, a steep current decrease was recorded on the oscillograph paper. A typical oscillograph record is given in Fig. 3. Thus the capsule position histories along the tube could be established.

To improve the accuracy of experimental results, relationships between capsule position and time were obtained by using the method of least squares from observed values, and were differentiated numerically to yield capsule velocity with the aid of electronic computer. A typical result is shown in Fig. 4.

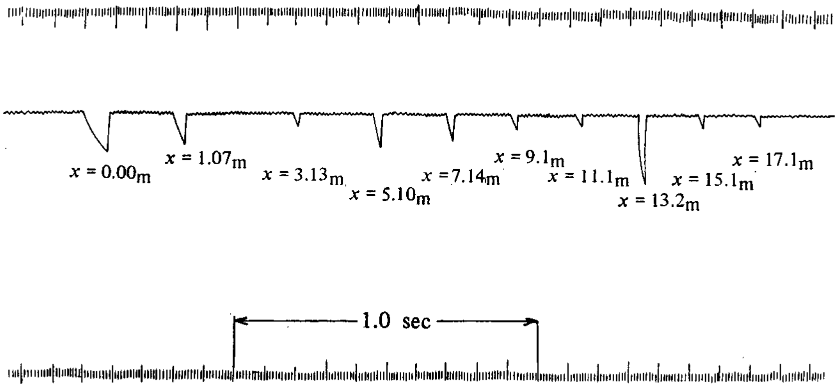


Fig. 3. Typical oscillograph recording.

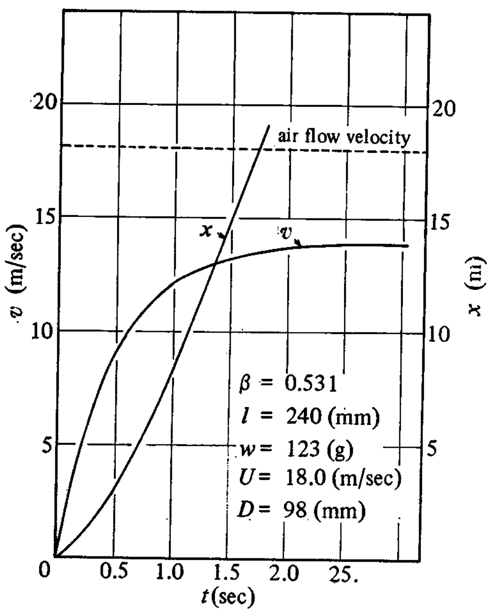


Fig. 4. Typical trajectory curve.

Five time runs were carried out for each capsule after the reliability of the results had been confirmed by more than ten time runs for several capsules. Due to shortness of the tube length in this experiment, the desired terminal velocity had to be extrapolated.

2.2 Wind Tunnel Tests

Both the same guideway tube and models as those in moving through tests were used in wind tunnel tests. The experimental apparatus used in wind tunnel tests is schematically shown in Fig. 5. In this case capsule was mounted on the tube axis at a distance of 1.5 meter downstream from a stream strainer. Air flow velocities in the tube were measured by the same way as in moving through tests. Capsule drag force, which was led to a cantilever beam with a tension wire of a nylon string, was measured by an electric strain gauge.

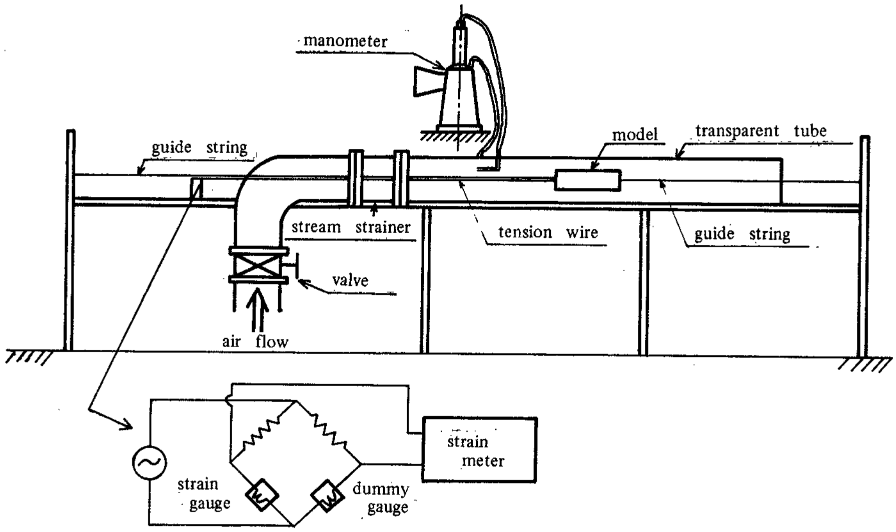


Fig. 5. Experimental apparatus for wind tunnel tests.

3. Results

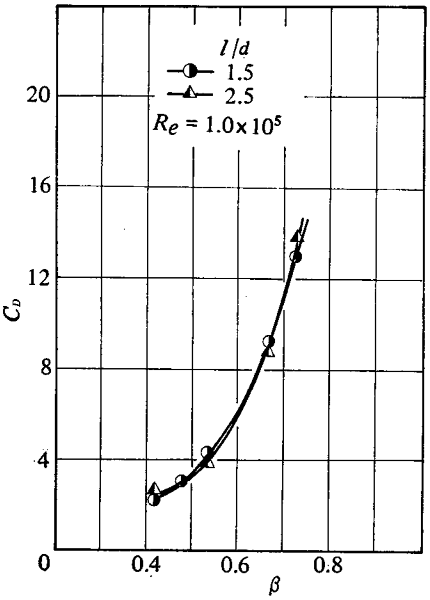
3.1 The effect of Blockage Ratio

The effect of blockage ratio upon drag coefficient and capsule velocity is shown in Fig. 6 and Fig. 7, in which the capsule velocity and the drag coefficient indicate a monotonic increasse with the increase of blockage ratio for $\beta > 0.8$, and blockage ratio is clearly more dominant than the ratio of capsule length to tube diameter. In some experiments, the sudden increase of the friction between capsule and tube wall was observed for $\beta > 0.8$ because of the capsule oscillation. The capsule velocity with ordinary run, for $\beta > 0.8$, shows no increase in spite of the increase of blockage ratio. As far as blockage ratio is concerned, it can be concluded that optimum blockage ratio is about 0.8 for getting the highest speed.

However, it should be noted that only the case of one capsule in the tube is studied in this experiment. So in the case of many capsules in the tube this experimental data is not sufficient and more extensive experiments will be necessary.

In Fig. 7 the capsule velocity for $\beta > 0.803$ is greater than the air flow velocity. This phenomenon can be explained by a pressure rise of the air flow supplied, that is, when the capsule is set in the tube on the capsule supporter at $x=0$, the pressure of the air flow behind the capsule increases, so that the cpasule is pushed ahead like an air-gun in the initial part of the capsule traveling. The capsule velocity may be smaller than the air flow velocity after sufficient long travel.

Before leaving the discussion of blockage ratio, it should be pointed out that this experiment was made for the range of Reynold' number from 2×10^4 to 2×10^5. In this range of Reynolds' number, drag coefficient is almost constant for each blockage ratio as shown in Fig. 8.



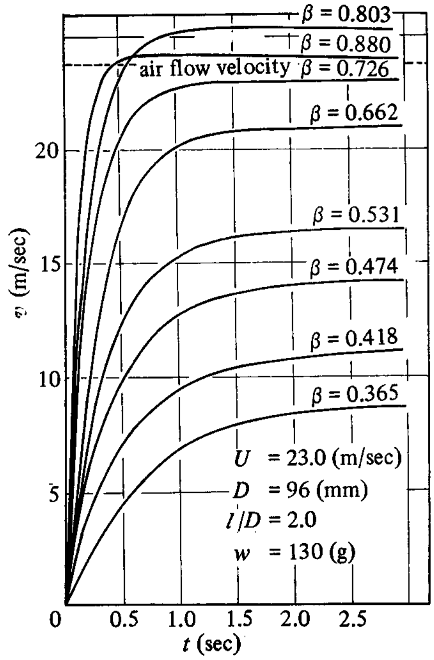


Fig. 6 Fig. 7

Fig. 6. Drag coefficient vs. blockage ratio (wind tunnel test).

Fig. 7. The effect of blockage ratio on capsule velocity.

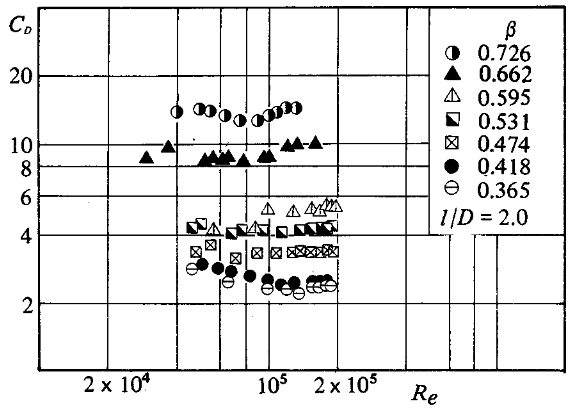


Fig. 8. Drag coefficient vs. Reynold' number (wind tunnel test).

3.2 The Effect of the Ratio of Capsule Length to Tube Diameter

Drag coefficients and terminal velocities versus the ratios of capsule length to tube diameter are shown in Fig. 9 and Fig. 10. For $\beta \leqslant 0.531$, the drag coefficient is almost constant throughout the ratio of capsule length to tube diameter.

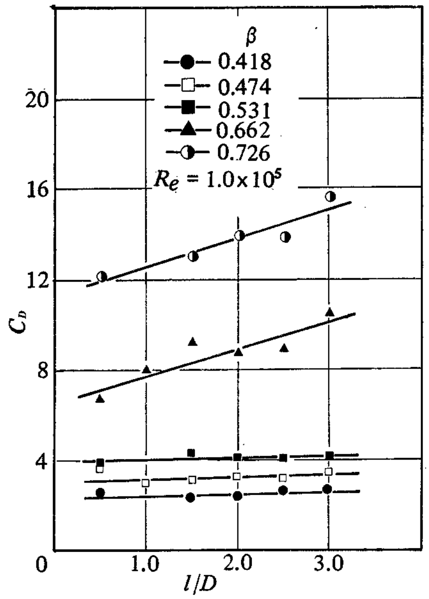


Fig. 9

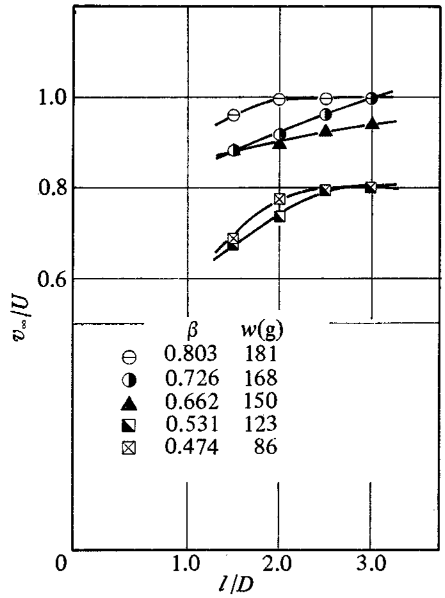


Fig. 10

Fig. 9. Drag coefficient vs. the ratio of capsule length to tube diameter.
Fig. 10. Terminal velocity vs. the ratio of capsule length to tube diameter.

Terminal velocity obtained in moving tests increases with the increase of l/D when l/D is smaller than 2.5, and terminal velocity does not increase for l/D of greater than 2.5. It becomes clear from the observation of these moving tests that capsules run stably through the tube in the case of l/D of greater than 2.5.

On the other hand, for $\beta > 0.531$, the drag coefficient obtained from wind tunnel tests increases with increasing l/D. It should be considered that this tendency is due to the increase of pressure force rather than the increase of skin frictional drag. The increase of pressure force is cancelled by the increase of frictional force between capsule and tube wall in moving through tests. In these tests, when the capsule length to tube diameter ratio is equal to 1.0, an abnormal unstable running of the capsule (i.e., unstable spinning inside the tube wall) was observed for almost all blockage ratios.

3.3 The Effect of Capsule Weight

The effect of capsule weight upon the dapsule velocity is shown in Fig. 11. The capsule velocity increases with the decrease of capsule weight as is expected.

3.4 The Effect of Capsule Shape

In this experiment, in order to find a more useful capsule shape for high speed tube transportation system, some dumb-bell type capsules were also investigated.

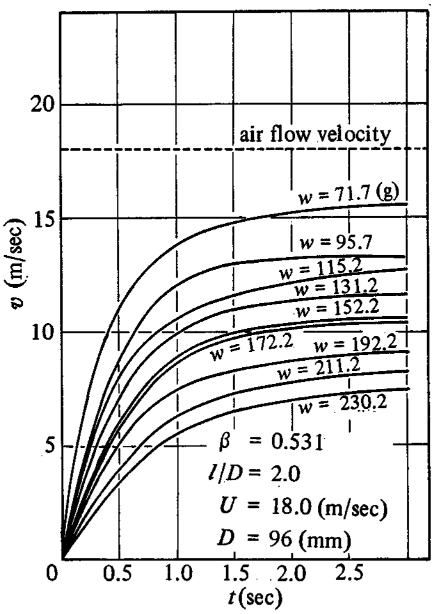


Fig. 11. The effect of capsule weight on capsule velocity.

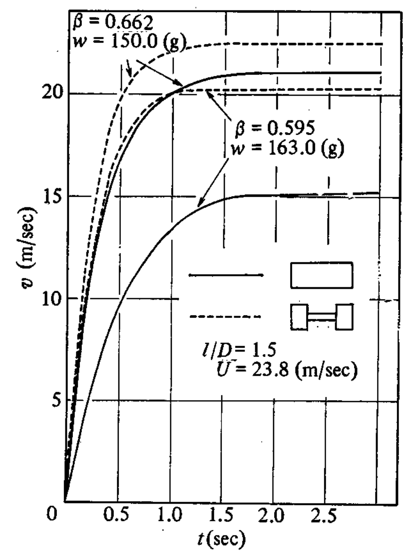


Fig. 12

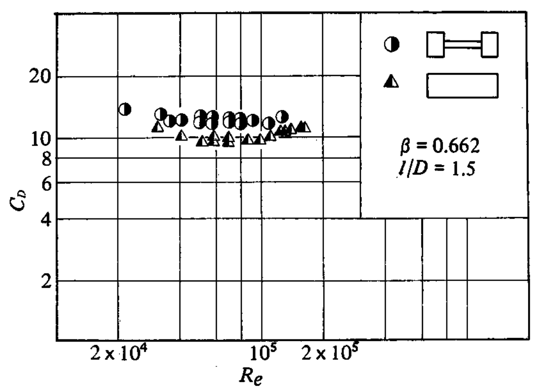
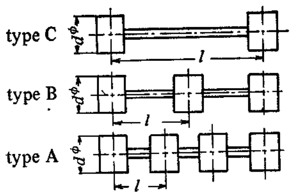


Fig. 13

Fig. 12. Comparision of dumb-bell type with simple cylindrical type in capsule velocity.
Fig. 13. Drag coefficient of dumb-bell type and simple cylindrical type capsules.

The velocity of dumb-bell type capsule compared with that of simple cylindrical type is shown in Fig. 12. Dumb-bell type capsule has higher velocity than simple cylindrical type capsule. To make clear this fact, wind tunnel tests were also carried out and the drag coefficients of two types were measured. The drag coefficient of dumb-bell type is greater than that of simple cylindrical type as shown in Fig. 13. This agrees with the result of moving tests. Furthermore, it is observed that the running condition of dumb-bell type capsules is more stable owing to a pressure balance around the body center.

Next, three various dumb-bell type capsules, which are shown in Fig. 14, were tested. These results are shown in Fig. 15 and Fig. 16. The terminal velocity and the drag coefficient increase according to the order of type A, B and C. These results show an reverse tendency to that of labyrinth seal. It seems that the annular clearance between capsule and tube wall is so wide for air flow to pass through it that the labyrinth seal effect cannot be appeared.



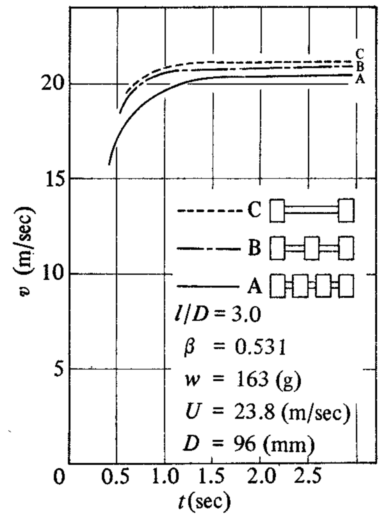


Fig. 14 Fig. 15

Fig. 14. Dumb-bell type capsules: Type A, B and C.
Fig. 15. Velocity of dumb-bell type capsules.

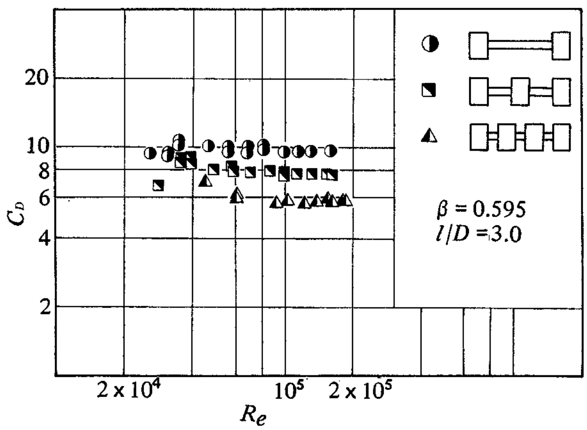


Fig. 16. Drag coefficient of dumb-bell type capsules.

4. Empirical Equation

The equation of motion for the passive capsule in a tube is derived from the assumption that the aerodynamic darg force (i.e., thrust of a capsule) is equal to the sum of the capsule inertia force and the jumping contact frictional force between capsule and tube wall, as follows,

$$\frac{w}{g}\frac{d^2x}{dt^2} = C_D S_C \frac{\rho}{2}\left(U - \frac{dx}{dt}\right)^2 - \lambda\frac{1}{2D}\frac{w}{g}\left(\frac{dx}{dt}\right)^2, \tag{1}$$

where λ is a nondimensional contact coefficient. Integrating the above equation with the initial condition; $x=0$, $dx/dt=0$ for $t=0$, we have

$$\frac{dx}{dt} = \frac{\sqrt{A}\,(He^{2\sqrt{A}at}+1)}{He^{2\sqrt{A}at}-1} - \frac{b}{2a} \tag{2}$$

$$x = \left(\sqrt{A} - \frac{b}{2a}\right)t + \frac{1}{a}\log\left(\frac{H-e^{-2\sqrt{A}a_t}}{H-1}\right) \tag{3}$$

where

$$a = \frac{\lambda}{2D} - \frac{C_D S_C \rho}{2w/g}, \quad b = \frac{C_D S_C \rho U}{w/g},$$

$$c = -\frac{C_D S_C \rho U^2}{2w/g}, \quad A = \frac{b^2}{4a^2} - \frac{c}{a},$$

$$H = \frac{(b/2a)+\sqrt{A}}{(b/2a)-\sqrt{A}}.$$

Substituting the practical values of a, b, c, A and H into equations (2) and (3), in which λ and C_D can be obtained from Fig. 17 and Fig. 6, respectively, it is possible to estimate the capsule motion at arbitrary time. In Fig. 18, the typical velocity-time curves calculated from equation (2) agree very well with the experimental velocity-time ddeta.

But this agreement is no longer appeared for blockage ratio of greater than 0.6. The value of C_D in the above empirical equation may be used the values of that obtained in wind tunnel tests. Although stationary model in a wind tunnel does not simulate the exact boundary conditions of a capsule moving through a tube, stationary wind tunnel walls can produce reasonable results for the capsule moving in the tube with moderate values of the ratio of capsule length to tube diameter and with small blockage ratio.

On the other hand, in the case of larger blockage ratio, the effect of the difference of the velocity profile around a body between stationaly models and moving models in a tube can not be neglected. The value of C_D obtained in wind tunnel tests can not be substituted in empirical equation for the blockage ratio of greater than 0.6.

Empirical equation obtained in this study is useful within the following range;

blockage ratio β,	$0.531 > \beta$
capsule length to tube diameter l/D,	$2.5 < l/D$
capsule weight w,	$0.05\ \text{kg} < w < 0.2\ \text{kg}$
air flow velocity U,	$20\ \text{m/sec} < U < 50\ \text{m/sec}$

In this range, the capsule motion is well estimated from equations (2) and (3).

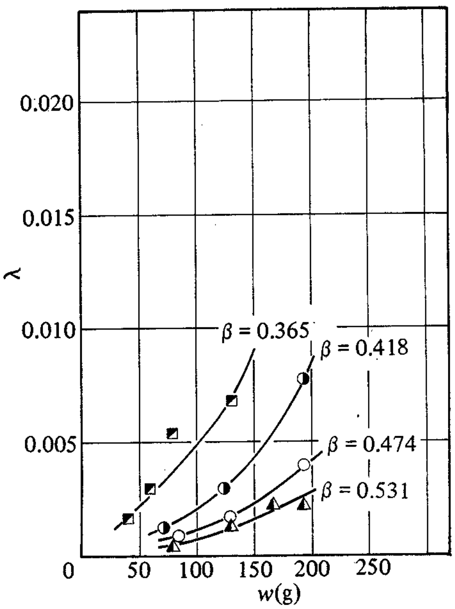


Fig. 17

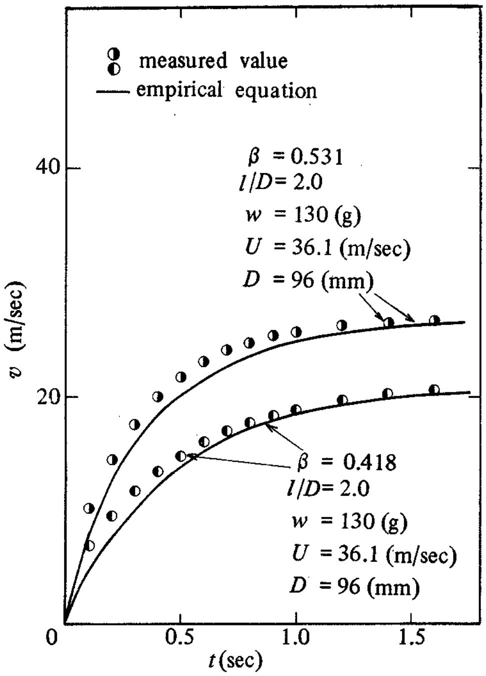


Fig. 18

Fig. 17. Values of contact coefficient λ.
Fig. 18. Velocity-time curves: Measured and calculated.

5. Conclusions

The following conclusions have been derived from the experiments described above.

(1) It is most effective to set blockage ratio β to about 0.8 for getting high speed, provided that only one capsule moves through the tube.

(2) It was found that, when the ratio of capsule length to tube diameter is more than 2.5 and blockage ratio β is smaller than 0.5, the capsule velocity is independent of the capsule length.

(3) The empirical equation was obtained for the capsule velocities over the range as described above. As the drag coefficient C_D in this empirical equation, the values of that is obtained from wind tunnel tests may be used.

Thus, we can estimate the capsule velocity.

(4) Dumb-bell type capsule is more effective than simple cylindrical type capsule for the purpose of minimizing the velocity differences between capsule and air flow.

Concerning the problem of the capsules moving through the tube, we confirmed in this study that it is important to obtain the information on the jumping contact friction between capsule and tube wall.

In order to make more clear this point, we will deal with it as a two-dimensional oscillation problem in the next step of investigation.

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