The Effects of the Capsule Density Uniformity on the Behavior of Cylindrical Capsules Transported through a Pipeline

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ABSTRACT/This paper presents the results of a study conducted to improve the understanding of the characteristics of cylindrical capsule flow in a pipeline by taking into account of the effect of capsule density uniformity. The effect of capsule density variation in the axial direction was studied both experimentally and analytically. The experiments were conducted in a 190mm diameter straight pipe 17m long. The velocity, gap and tilt of capsules were measured under various conditions. In order to interpret the data on various capsule density conditions, the stability index given in the dimensionless number was introduced. The motion of capsules in pipelines is strongly affected by the stability of the capsules characterized by the stability index. The experiments conducted proved that the stability index is a valid criterion for explaining and correlating data on the capsule motion and the capsule density uniformity.

1. INTRODUCTION

Ever since the concept of capsule pipelining as a potential method of solid transport was initiated by Canada in 1958, much research in hydraulics of the technique has been reported in the literature. The progress made in the hydrodynamics and the hydraulics of capsule flow in a pipeline has been reviewed by Shook 1) and Liu 2),3)

In all the previous studies of cylindrical capsule flow in a pipeline, the capsule had uniform density in the axial direction or was assummed to be so. No attention was paid to the effect of the capsule density uniformity on the capsule behavior.

However, in commercial applications of capsule pipelining in the future, a certain degree of non-uniform density will be unavoidable. Therefore, it is important to understand the effect of the capsule density uniformity on the hydrodynamic behavior of capsules moving in a pipeline. The capsule density uniformity in the axial direction was determined by the location of the center of gravity. The

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capsules used in this study are assummed to be circular cylinders immersed in water and transported in a circular pipeline.

2. ANALYSIS

First, consider a heavier–than–water capsule resting on the bottom of a horizontal pipe as shown in Fig.1. Assume that the gravity center of the capsule in Fig.1 (point 1) is located at a horizontal distance x from the geometric center (i.e. the centroid, point 0). For a flow from right to left, the capsule is considered "rear–heavy" since the left end of the capsule is the front while the right is the rear. The opposite holds when the flow is from the left.

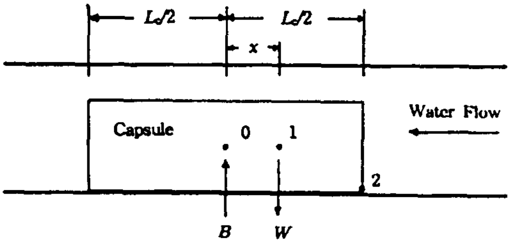


Fig.1 Forces and moments on a stationary capsule

Under static condition (i.e., when the capsule and the fluid are stationary), the capsule will remain in a horizontal position resting on the pipe bottom as shown in Fig.1. This will be so as long as the clockwise overturning moment generated by the buoyant force, B, about the rear–end point 2 is smaller than the counterclockwise stabilizing moment about point 2 generated by the weight of the capsule, W. Therefore, it seems reasonable to state that the stability of the capsule prevails when

$$B\frac{Lc}{2} < W\left(\frac{Lc}{2}-x\right)$$

or

$$\frac{2x}{Lc} < \left(1-\frac{B}{W}\right) \tag{1}$$

Similarly, the instability of the capsule prevails under static condition when

$$\frac{2x}{Lc} > \left(1-\frac{B}{W}\right) \tag{2}$$

For the judgement of density uniformity in the axial direction, we define the eccentricity, E:

$$E=\frac{2x}{Lc} \tag{3}$$

The density uniformity of a capsule in the axial direction can be characterized by the eccentricity, E. For a rear–heavy capsule, x is positive and the value of E is between 0 (for x is equal to 0, uniform density) and 1 (for a capsule with all its mass concentrated at the rear end). For a front–heavy capsule, x is negative and the value of E is between 0 and –1, with the latter being the value for a capsule with the entire mass concentrated at the front end. Thus, a negative value of E indicates a front–heavy capsule and vice versa.

Note that in the foregoing equations, the ratio B/W is the same as $1/S$ where S is the specific gravity of the capsule. Introducing the value of S, and substituting eqn.(3) into eqns.(1) and (2) yield the following results for rear–heavy capsules:

$$E < 1 - \frac{1}{S} \quad \text{(stable capsule)} \tag{4}$$

and

$$E > 1 - \frac{1}{S} \quad \text{(unstable capsule)} \tag{5}$$

A similar derivation for front–heavy capsules yields the condition for static stability as follows:

$$E > \frac{1}{S} - 1 \quad \text{(stable capsule)} \tag{6}$$

and

$$E < \frac{1}{S} - 1 \quad \text{(unstable capsule)} \tag{7}$$

Next, the same derivation for heavier–than–water capsules is applied to lighter–than–water capsules which, under stable condition, rests against the top of the pipe rather than the bottom. The results is

$$E < \frac{1}{S} - 1 \quad \text{(stable capsule)} \tag{8}$$

and

$$E > \frac{1}{S} - 1 \quad \text{(unstable capsule)} \tag{9}$$

for rear–heavy capsules ($E > 0$), and

$$E > 1 - \frac{1}{S} \quad \text{(stable capsule)} \tag{10}$$

and

$$E < 1 - \frac{1}{S} \text{ (unstable capsule)} \tag{11}$$

for front-heavy capsules (E < 0).

All the eight stability criteria given in eqns. (4) to (11) for various types of capsules can be combined into two criteria by using absolute values as follows:

$$I = \frac{|E|}{|1 - \frac{1}{S}|} < 1 \text{ (for all stable capsules)} \tag{12}$$

$$I = \frac{|E|}{|1 - \frac{1}{S}|} > 1 \text{ (for all stable capsules)} \tag{13}$$

The quantity I may be termed the "static stability index" or in short the "stability index" of capsules. From the foregoing derivation, it can be seen that a capsule is stable when I is smaller than one and unstable when I is greater than one. The greater the value of I, the more unstable a capsule becomes.

The foregoing analysis is valid only under static condition, i.e. for stationary capsules in a stationary fluid. When the water and the capsule in a pipe are moving, in addition to the weight of the capsule, W, and the buoyancy, B, the hydrodynamic forces such as lift force and drag force are generated. They all play a role in the stability of capsules and in the determination of the equilibrium position of capsules in pipe. However, it is not possible at present to predict the stability, orientation and position of any moving capsule since the hydrodynamic surface stresses on a capsule moving in a pipe vary in a complex and unknown manner. Therefore, in this study to determine the effect of capsule density uniformity, only the static stability criteria described before will be used. However, as will be seen from the test data, the static stability index works very well to explain not only stationary but also moving capsules, at least in the range tested in this study.

3. EXPERIMENTAL SETUP AND PROCEDURE

The experiments were carried out in the Hydraulic Laboratory of the University of Missouri-Columbia. The experimental setup was built in a pilot pipeline scale. Fig.2 shows the general layout of experimental pipeline system. The experimental pipeline system consists of a 190mm I.D. straight acryl pipe 17m long, an intake tank and an outlet tank connected to the two ends of the pipe, a constant-head tank to supply water to the pipe, two valves and one flowmeter.

Referring to Fig. 2, at the beginning of each test, a capsule was placed manually into the pipe inlet before inlet was sealed. The capsule was held near the inlet by a capsule stopper, and water was released from a 9m constant-head tank into the pipe via a branch upstream of the capsule. After a

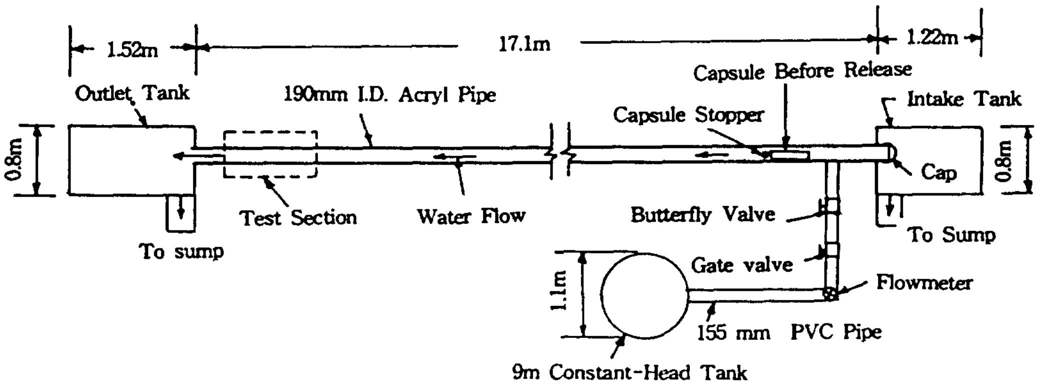


Fig. 2 General layout of experimental pipeline system.

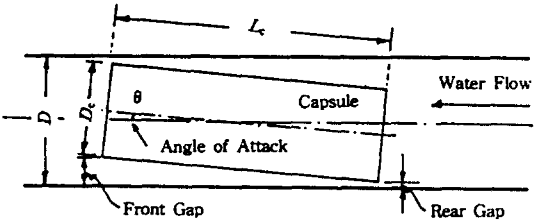


Fig. 3 Gap and angle of attack measured for the capsule which moves in a pipeline.

steady flow had been established with the water flowing around the stationary capsule, the capsule stopper was triggered to free the capsule. The released capsule accelerated to reach a constant velocity before it exited from the pipe. The test section, instrumented with electromike to detect the passage of capsule, was near the pipe exit where the capsule reached terminal (constant) velocity. The electromikes are induction cells that sense the presence of metallic capsules in the vincinity of the cells. They were used to detect the passage of capsules and to measure the gap (i.e. the small spacing between capsule surface and the pipe wall). The discharge of the flow was measured with an elbow flowmeter. All data were recorded automatically on a personal computer capable of analog-to-digital conversion. The computer also analyzed the data and printed or plotted the results.

The capsules were made of 3.2mm thick steel pipe of two different outer diameter: 165 and 177mm, corresponding to diameter ratios ($k=Dc/D$) of 0.867 and 0.933, respectively. Twelve capsules were used in the test. Their physical properties are listed in Table 1. As can be seem from the Table 1, the capsules had two aspect ratios ($a=Lc/Dc$) of 2.0 and 4.0, two diameter ratios ($k=Dc/D$) of 0.867 and 0.933, and four specific gravity values of 1.030, 1.056, 1.077 and 1.165. Only heavier-than-water capsules were tested in this study. The eccentricity was between -0.039 (front heavy) and +0.039 (rear heavy), and stability index was from 0 to 1.3. Except for the last two capsules (11 and 12), the stability index was smaller than one which means stable capsule.

Each of the twelve capsules was tested at approximately 20 different mean flow velocities, ranging from 0.2 to 2.8 m/s. For each velocity, the gap ,h, between the capsule bottom and the pipe bottom was measured both at the capsule front (front gap) and at the capsule rear (rear gap). Also measured for each run are angle of attack, θ, and capsule velocity. The Fig. 3 shows the front gap, rear gap and angle of attack measured for a capsule moving in a pipeline. The maximum possible gap and angle of attack for each capsule tested in this study are given in Table 1 for references.

Table 1. Physical properties of capsules in a pipeline

Capsule no.	Aspect ratio a	Diameter ratio k	Specific Gravity S	Eccentricity E	Stability index I	Max. Angle (degree) θ^{*}_{max}	Max. Gap (mm) h_{max}
1	2	0.867	1.077	0.0	0.0	4.4	25
2				+0.024	0.34		
3				−0.024	0.34		
4	2	0.933	1.165	0.0	0.0	2.0	12
5				+0.009	0.064		
6				−0.009	0.064		
7	4	0.867	1.056	0.0	0.0	2.2	25
8				+0.019	0.36		
9				−0.019	0.36		
10	4	0.993	1.030	0.0	0.0	1.0	12
11				+0.039	1.3		
12				−0.039	1.3		

4. TEST RESULTS

For each of the capsule tested, the front gap, rear gap, angle of attack and capsule velocity were measured. The dimensionless numbers were calculated from the gap and the angle of attack. The gaps are devided by the maximum possible gap for the given condition of capsule and result in relative gaps (h/h_{max}). The angles of attack are also devided by the maximum possible angle of attack for a given condition and result in inclinations (θ/θ_{max}).

Fig.4 gives the results for capsule No.1 which was a heavier-than-water capsule. The density of this capsule was uniform ($E=0$) and hence the capsule was stable ($I=0$). Parts (a), (b) of Fig.4 give respectively the variations of gaps and the angle of attack in dimensionless number with the mean flow velocity. From (a), it seems that the capsule gaps, especially the front gap, increased rapidly when the flow velocity exceeded 1.7 m/s, approximately. This sudden increment of a front gap indicates that the capsule is lifted off the bottom of the pipline. The mean flow velocity at which the capsule is lifted off the bottom of the pipe is called the lift-off velocity. The lift-off velocity of the capsule No.1 is near the velocity of 1.7 m/s. Therefore, it can be said that to prevent the capsule from touching the pipe wall, the mean flow velocity should stay above the lift-off velocity of 1.7 m/s.

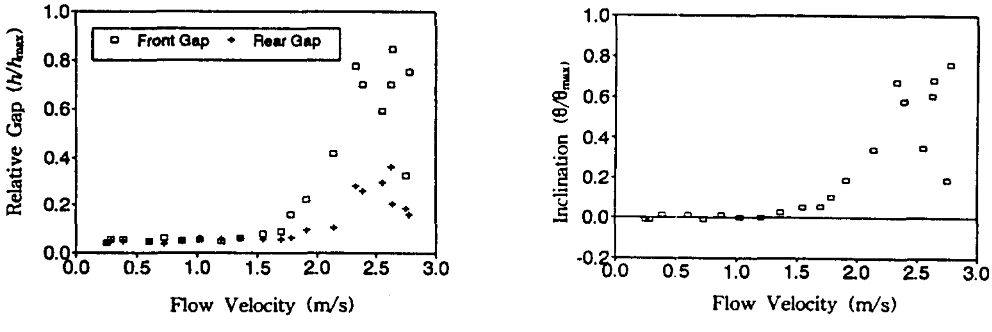
Fig. 5 gives the same graphs for capsule 2 which is identical to capsule 1 except that the capsule is rear-heavy with $E=0.024$ and $I=0.34$. A comparison of the two graphs in Fig. 5 with those in

Fig. 4 shows that the former (i.e., the rear–heavy capsule) had a lift–off velocity approximately equal to 1.4 m/s which is smaller than that of the latter (i.e., the uniform density capsule).

The capsule in Fig. 6 is the same as those capsules in Figs. 4 and 5 except that the front is heavy. The lift–off velociy of front–heavy capsule was 2.1 m/s which was higher than those for both the rear–heavy and uniform–density capsules. The hydraulic capsule pipeline should be operated at a velocity slightly higher than the lift–off velocity in order to minimize head loss and abrasion. The result suggests that it may be more advantageous to use a rear–heavy capsule than a uniform–density capsule in the operation of capsule pipeline.

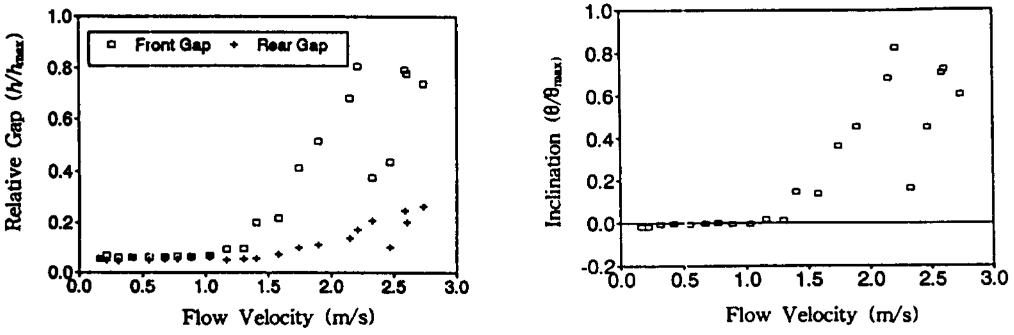
All the capsules discussed so far are statically stable ($I<1.0$). The next capsules to be discussed are unstable ($I>1.0$). Fig. 7 is for capsule No.11 which is a rear–heavy unstable capsule with $I=1.3$, approximately. The maximum possible angle of the capsule was about 1°. As can be seen from Fig. 7(b), the capsule maintained an angle of attack equal to or near the maximum possible angle of attack for a given condition at all the velocities tested except at high speeds where the angle of attack was slightly reduced. The same can be seen from(a) in which the front gap remained large(at the physical maximum of 12mm) whereas the rear gap remained almost zero. This shows the orientation of the capsule moving through pipe was the same as expected for an unstable static capsule. Fig. 8 is for capsule No.12 which is the same as No.11 except that the front and rear were switched. Therefore, capsule No.12 is a front–heavy unstable capsule with I=1.3. The test result shows that over the range of the velocities tested, the front gap was always smaller than the rear gap, indicating the capsule had a downward tilt when moving through the pipe–the same as predicted from static stability considerations.

In addition to the flow velocity, the capsule velocity was measured with electromikes installed on the test section of the pipe. The capsule velocity was compared with the mean flow velocity. The capsule velocity is slower than the mean flow velocity when the capsule starts to move. However, the capsule velocity becomes faster than the mean flow velocity as the capsule velocity increases. When the capsule velocity is equal to the mean flow velocity, the mean flow velocity is called as equal velocity. The equal velocity and the lift–off velocity were experimentally determind herein.



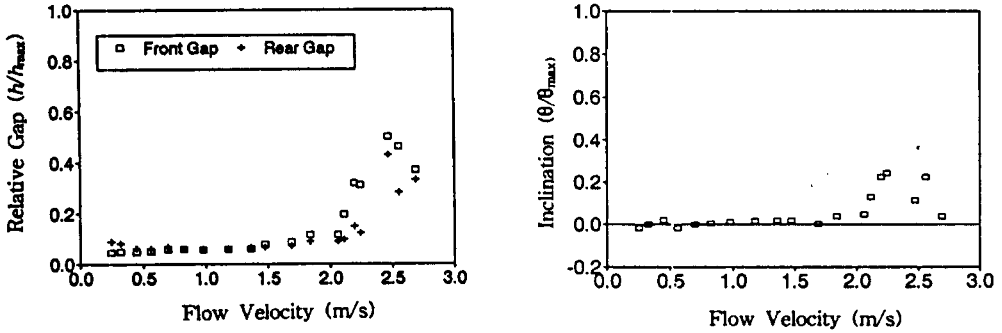
(a) (b)

Fig. 4 Test data for capsule no. 1 ($a=2$; $k=0.867$; $S=1.077$; $E=0.0$; $I=0,0$).



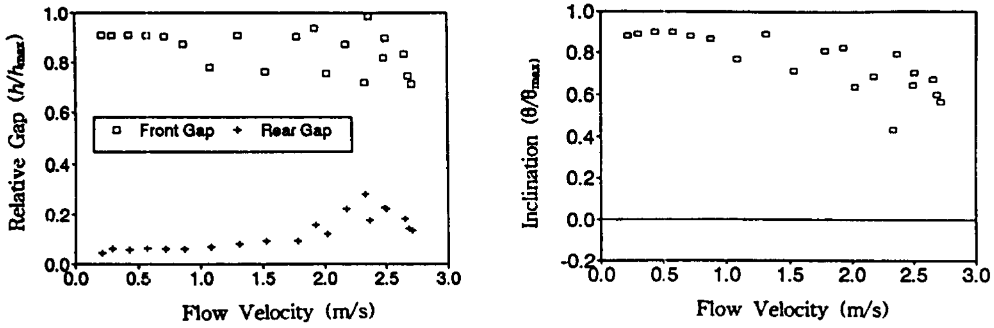
(a) (b)

Fig. 5 Test data for capsule no. 2 ($a=2$; $k=0.867$; $S=1.077$; $E=+0.024$; $I=0.34$)



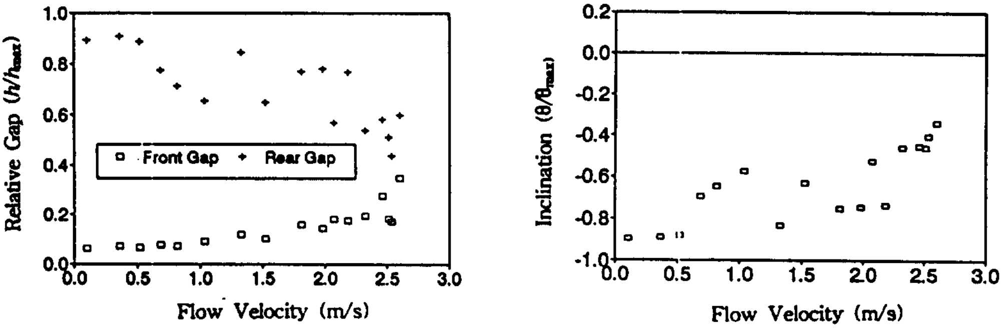
(a) (b)

Fig. 6 Test data for capsule no. 3($a=2$; $k=0.867$; $S=1.077$; $E=-0.024$; $I=0.34$).



(a) (b)

Fig. 7 Test data for capsule no. 11 ($a=4$; $k=0.993$; $S=1.030$; $E=+0.039$; $I=1.3$).



(a) (b)

Fig. 8 Test data for capsule no. 12 ($a=4$; $k=0.933$; $S=1.030$; $E=-0.039$; $I=1.3$).

Table 2. Lift–off velocity and equal velocity of capsules in a pipeline

Capsule	Density distribution	Eccentricity E	Lift–off velocity (m/s)	Equal velocity (m/s)
1	Uniform	0.0	1.7	0.5
2	Rear–heavy	+0.024	1.4	0.5
3	Front–heavy	−0.024	2.1	0.5
4	Uniform	0.0	2.1	0.7
5	Rear–heavy	+0.009	2.0	0.3
6	Front–heavy	−0.009	2.1	0.5
7	Uniform	0.0	1.9	0.7
8	Rear–heavy	+0.019	1.1	0.7
9	Front–heavy	−0.019	2.1	0.6
10	Uniform	0.0	1.0	0.4
11	Rear–heavy	+0.039	–	0
12	Front–heavy	−0.039	–	0

They are listed in Table 2. Table 2 shows that the lift–off velocity for a given capsule is the lowest when the capsule is rear–heavy, medium when the capsule has a uniform density and highest when the capsule is front–heavy. The differences among the three are the least when eccentricity is small, as for capsules 4, 5 and 6. Table 2 shows that the lift–off velocity of the capsules tested was 2 to 6 times greater than the equal velocity. It was observed that the magnitudes of the capsule velocity and the fluid velocity are generally within 10% of each other.

5. CONCLUSION

The motion of capsules in pipelines is strongly affected by the static stability of the capsules characterized by the stability index, I. The experiments conducted proved that the stability index is a valid criterion for explaining and correlating data on capsules of which density is non–uniform in the axial direction.

When the value of I of a capsule is greater than unity ($I>1.0$), the capsule is unstable, and it tilts to its physical limit with one end touching the pipe top and the other end touching the pipe bottom. Only at high velocity will this maximum inclination be reduced somewhat. The large inclination for unstable capsules at low velocty generates high lift which in turn reduces the contact friction between the capsule and the pipe. Consequently, capsules move as fast as or faster than the fluid even at low velocity. Although this appears to be a desirable feature, there is the danger that unstable capsules, due to their large tilts, may jam in the pipe when a capsule front encounters a large roughness element, such as that normally exists at pipe joints or welds. Therefore, it is not recommended that unstable capsules be used in hydraulic capsule pipeline, at least not without having first conducted extensive studies.

When the I value of a capsule is smaller than unity ($I<1.0$), the capsule is stable and it slides along the pipe at zero angle of attack when speed is low. The capsule becomes lifted off the pipe wall when the mean–flow velocity has exceeded the lift–off velocity. The lift–off is often accompanied by a sudden increase in the angle of attack. The lift–off velocity is the lowest for rear heavy capsules, medium for uniform–density capsules and the highest for front–heavy capsules. Thus, it may be more desirable to use rear heavy capsules than uniform capsules in the hydraulc capsule pipeline. The use of front–heavy capsules should be discouraged.

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