Polymer Drag Reduction in Hydraulic Capsule Pipeline

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A hydraulic capsule pipeline (HCP) transports solids as large cylindrical objects, or in cargo-carrying containers, by pipeline over long distances using water or another liquid as the carrier fluid. HCP was first proposed by Pyke during World War II (Lampe, 1959), and intensively studied from 1958 to 1978 at the Alberta Research Council—see Brown (1987) and Govier and Aziz (1972). More recent HCP research has been done at the University of Missouri by Liu and coworkers (Liu, 1981, 1992). Based on the HCP concept, Liu and Marrero (1990) invented the coal log pipeline (CLP), a technology for transporting compressed coal cylinders. Application of HCP and CLP for solids transport over long distances requires the minimization of energy consumption. The research reported in this note explores the possibility of using high molecular weight polymers for drag reduction in HCP and CLP in order to reduce energy consumption.

In HCP or CLP, a denser-than-fluid capsule becomes totally levitated or suspended by the flow when the fluid velocity reaches or exceeds a certain value called the liftoff velocity. By using dimensional analysis and experimental data, Liu (1982) deduced the following expression for the liftoff velocity:

$$V_L = 7.2\sqrt{|S-1|gak(1-k^2)D} \tag{1}$$

D is the pipe (inside) diameter. The absolute sign in Eq. 1 enclosing $S-1$ makes the same equation applicable to both denser-than-fluid capsules ($S>1$) and lighter-than-fluid capsules ($S<1$). At liftoff, the head loss (energy loss per unit weight of fluid) in the HCP is usually about 20% greater than without capsules at the same bulk fluid velocity. Richards (1992) found that the minimum energy loss and minimum abrasion (wear) to capsules and pipe occur at about V_L. At or above the liftoff velocity, contact friction between capsules and pipe diminishes, and friction is dominated by turbulent energy dissipation. Under such conditions, energy loss is expected to be reduced by adding fibers or long-chain polymers, which are drag-reducing agents.

Theoretically, drag reduction increases with increasing Reynolds number and increasing fluid velocity. However, in reality the long chain molecules break up under high shear and strong turbulence, causing drag reduction to decrease with time in turbulent flow.

Since the late 1940s, polymers have been studied for drag reduction in turbulent liquid flow. Generally, longer polymer chains are more effective than shorter ones, though the former is more susceptible to mechanical degradation. Depending on the type of polymer used, the effective polymer concentration range is usually from 1 to 500 parts per million by weight (ppm). (In this article, ppm is always based on weight.) Review articles on drag reduction have been published by Lumley (1969), Hoyt (1972), Virk (1975), and Sellin (1989). For HCP flow, the use of polymers for drag reduction has been reported by Huang (1994) and Vlasak (1995). The purpose of this article is to present experimental results obtained by Huang (1994) on the effectiveness of polyethylene oxide for drag reduction in HCP.

Experimental System and Test Method

The test facility shown in Figure 1 is a horizontal, recirculating closed-loop Plexiglas pipeline 54 mm inner diameter and 22 m long, having a 12 m straight test section. An open-top reservoir provides access for feeding and draining water, for inserting and removing capsules, for injecting polymer solution, and for maintaining a constant head. A special annular jet pump propels capsules through the pipeline without impeding capsule motion. A double pipe heat exchanger maintains constant water temperature at 20°C, approximately. Two groups of capsules were tested, all made of aluminum tubes with fillers, and their characteristics are given in Table 1. The capsules' metallic surface make it possible for detection by an Electromike, which is an inductance cell capable of detecting the distance to approaching metallic objects. The measurement system includes: two Electromikes to determine the capsule velocity and capsule location in the pipe, two pressure transducers to determine pressure drop across the straight test section, a magnetic flowmeter to determine the bulk fluid velocity, and an IBM-PC portable computer equipped with a Lab Master data acquisition board.

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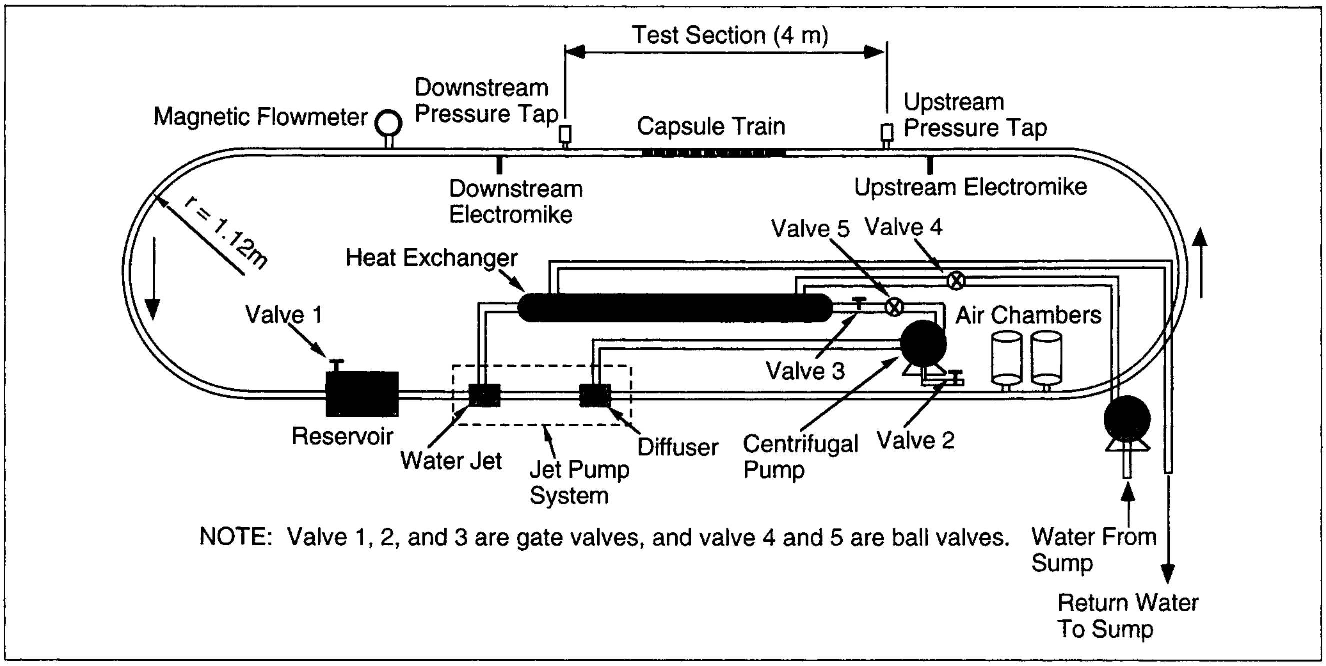

Figure 1. HCP system for studying polymer drag reduction.

Details of the experimental procedures are described by Huang (1994).

The polymer used for drag reduction tests was polyethylene oxide (trade named Polyox, from WSR Coagulant, Union Carbide) that has an approximate molecular weight of five million. Polyox powder was first weighed and then mixed slowly in a predetermined amount of water in a bucket to form a concentrated Polyox solution of 500 ppm, approximately. Then, the concentrated solution was poured into the open-top reservoir which enabled rapid dilution and entry into the pipe. Within about 40 s, the solution was uniformly diluted in the recirculating pipe system. The Polyox concentration in the pipe was then calculated by dividing the weight of the Polyox powder used by the total weight of the water in the recirculating pipeline system.

The experiments consisted of four types of pipeline flow: (i) water, (ii) water with polymer, (iii) water with capsules, and (iv) water with both capsules and polymer. In all the tests, the pressure gradient was determined as a function of bulk velocity from 0.6 to 2.2 m/s. The relatively narrow velocity range is due to interest in testing drag reduction near the liftoff velocity. In the second set of tests (water with polymer), the drag reduction for water flow with a Polyox concentration range of 5–40 ppm was determined. The third set of tests included measurements of the pressure gradient and the capsule velocity as a function of the bulk fluid velocity in polymer-free water. Finally, tests were conducted on the effects of polymer concentration on capsule flow behavior including drag reduction and capsule velocity.

Test Results

Water flow

Experimental results for water-only flow (that is, flow without capsules or polymer) were converted to friction factor f vs. the Reynolds number Re over the Reynolds number range of 30,000 to 120,000. By plotting f vs. Re on the well-known Moody diagram, the relative roughness of the pipe was found to be 0.0003, approximately.

Water flow with polymer

Drag reduction is defined by the change of pressure gradient along the pipe before and after polymer is used, namely,

$$R_1 = \frac{\left(\frac{\Delta P}{L}\right)_w - \left(\frac{\Delta P}{L}\right)_p}{\left(\frac{\Delta P}{L}\right)_w} \quad \text{(at constant velocity)} \qquad (2)$$

where R_1 is the drag reduction without capsules, $\Delta P/L$ is the pressure gradient, and the subscripts w and p denote water

Table 1. Capsule Characteristics*

Capsule Group	Aspect Ratio, a	Dia. Ratio, k	Specific Gravity, S	Liftoff Vel. V_L (m/s)	No. of Capsules in Train, N	Train Length, L_t (m)
1	3.23	0.77	1.14	1.95	12	1.6
2	1.6	0.89	1.33	1.64	12	0.91

*All capsules were made of aluminum tubes with filled interior.

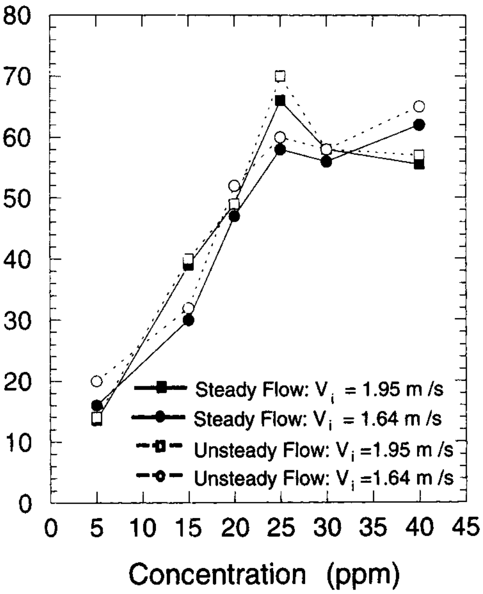

Figure 2. Polymer drag reduction in water without capsules: steady vs. unsteady analyses.

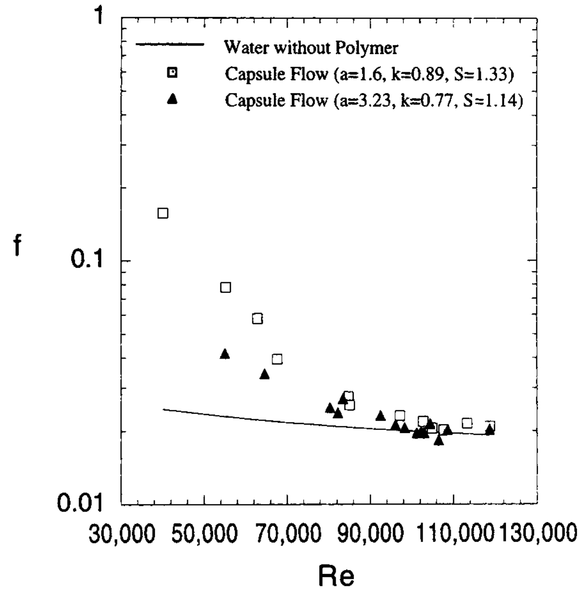

Figure 3. Variation of friction factor *f* with Reynolds number *Re* for capsule-water flow without polymer.

only and polymer in water, respectively. L is the length of the pipe test section. Note that Eq. 2 holds only when $(\Delta P/L)_w$ and $(\Delta P/L)_p$ are measured at the same velocity V. Otherwise, the measured value of $(\Delta P/L)_w$ must be adjusted to that of the same velocity of $(\Delta P/L)_p$.

In ordinary drag reduction tests that use a once-through pipe flow system driven by a constant-head tank and by injecting polymer into the pipe at a constant rate (continuous injection), the flow is steady. The present study used a recirculating flow system (Figure 1) and polymer was injected as a single slug and not continuously. Each polymer injection causes an increase in flow velocity, but after about one minute, due to polymer degradation the flow gradually decelerates until it reaches an asymptotic value in about 5 min. Strictly speaking, unsteady-flow drag reduction should be determined from the reduction of head loss (energy loss) rather than reduction of pressure drop or pressure gradient. However, Huang (1994) showed that for the system in Figure 1, drag reduction treated as unsteady flow is only slightly higher than for steady flow. Therefore, for simplicity pressure gradients were used in this study to determine drag reduction. This is illustrated in Figure 2 for two different flows having different initial velocities V_i. (Initial velocity is defined as the mean velocity of fluid in a pipe before the polymer was injected.) From Figure 2, the optimum polymer concentration is about 25 ppm corresponding to a maximum drag reduction of approximately 70%.

Water flow with capsules

The pressure gradient of quasi-steady capsule flow can be determined from

$$\left(\frac{\Delta P}{L}\right)_c = \frac{\Delta P_t - (L_t - NL_c)\left(\frac{\Delta P}{L}\right)_w}{NL_c} \qquad (3)$$

N is the number of capsules in the test section, and t is time. Using pressure gradient data and measured velocity V, the Darcy-Weisbach friction factor of capsule flow is plotted as a function of Reynolds number Re as shown in Figure 3 for two sets of aluminum capsules having different aspect ratio a, diameter ratio k, and density ratio (capsule density divided by fluid density) S. The results show that at low velocities (corresponding to relatively low Reynolds number), capsule pressure gradient (corresponding to f) are much higher than that of the water-only flow. This is especially true for the heavy capsules ($S = 1.33$). At or above the liftoff velocity (corresponding to Re equals 95,000), the pressure gradient (or friction factor f) of the heavy capsule flow ($S = 1.33$) is about 10% to 20% higher than that of the water-only flow, whereas for the light capsules ($s = 1.14$) the pressure gradient and f are about the same as those of water-only flow.

The relationship between capsule velocity and bulk fluid velocity is shown in Figure 4 in dimensionless form. Near the liftoff velocity ($V/V_L \simeq 1$), the capsule velocity is approximately 10% greater than the bulk fluid velocity ($V_c/V \simeq 1.10$) for both sets of capsules. The capsule velocity at any bulk fluid velocity appears independent of the polymer concentration or drag reduction.

Water flow with capsules and polymer

Polymer drag reduction in HCP is given by the following equation:

$$R_2 = \frac{\left(\frac{\Delta P}{L}\right)_w - \left(\frac{\Delta P}{L}\right)_{cp}}{\left(\frac{\Delta P}{L}\right)_w} \quad \text{(at constant velocity)} \qquad (4)$$

For capsule flow, polymer injection greatly increased bulk

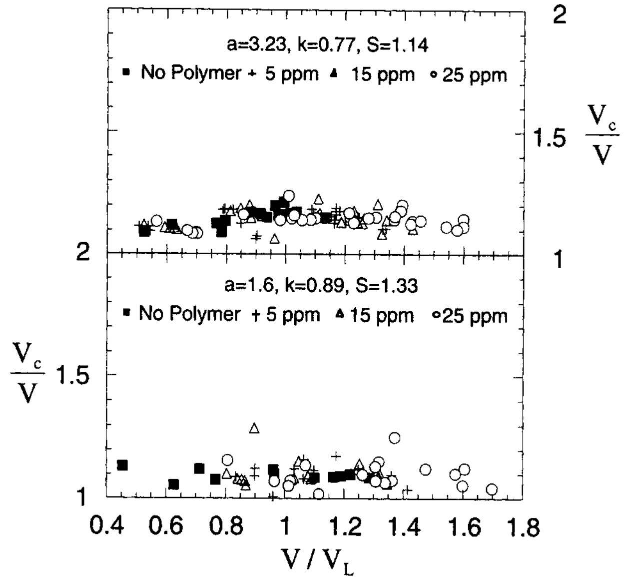

Figure 4. Variation of capsule velocity with bulk fluid velocity.

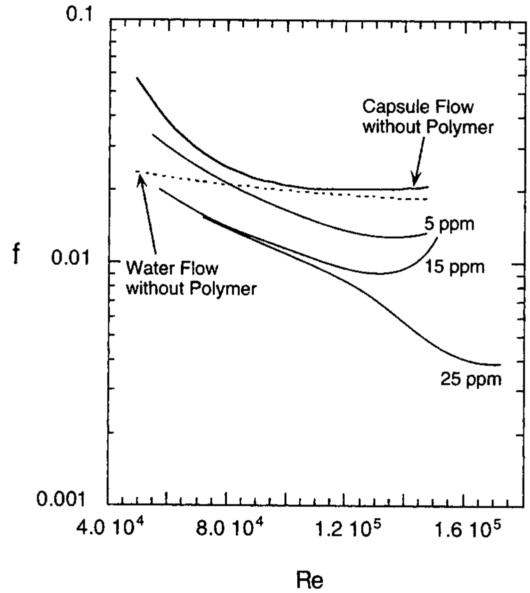

Figure 6. Variation of friction factor *f* with Reynolds number *Re* for capsule-water flow with polymer ($a = 3.23$; $k = 0.77$; $S = 1.14$).

fluid velocity while the pressure gradient only slightly decreased. On the other hand, if velocity were held constant the pressure gradient would have decreased by a relatively large amount. The capsule flow was visually observed to be more stable with polymer in the water than without polymer even though the bulk fluid velocity was increased due to use of polymer.

Figure 5 presents drag reduction as a function of Reynolds number for Polyox of different concentrations. The HCP drag reduction increases with increasing Polyox concentration and Reynolds number. For the long capsules ($a = 3.23$) at liftoff velocity and Polyox concentration of 25 ppm, the drag reduction R_2 was as high as 76%. This means that the HCP pressure gradient containing 25 ppm Polyox was only 24% of that

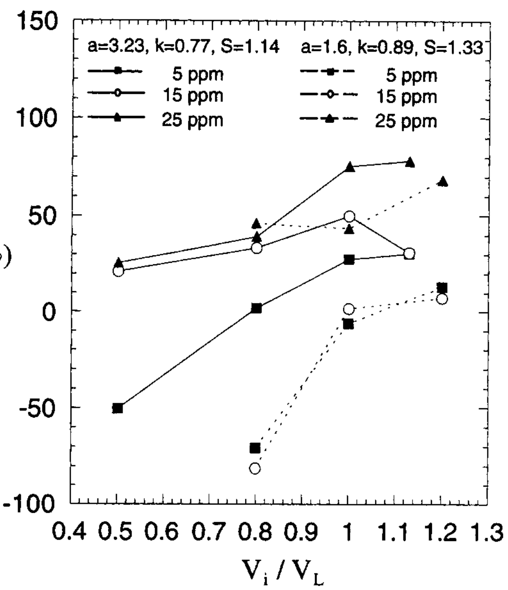

Figure 5. Drag reduction in capsule flow with polymer.

due to water flow without polymer and without capsules at the same bulk fluid velocity. For the short capsules ($a = 1.6$), at an initial bulk fluid velocity of 1.2 V_L and a Polyox concentration of 25 ppm, the drag reduction R_2 was approximately 69%.

Comparison of hydrodynamics of HCP with and without polymer

The friction factor vs. Reynolds number of HCP with and without polymer is given in Figure 6 for Polyox concentrations of 0, 5, 15 and 25 ppm. The result shows that the friction factor decreases with increasing Reynolds number, and it decreases with increasing Polyox concentration up to 25 ppm. Even with only 5 ppm of Polyox, the f values at high Reynolds numbers are significantly below those of water flow through pipe without Polyox. This shows the effectiveness of drag reduction in HCP flow using Polyox.

Conclusions

Polyethylene oxide at 25 ppm in the test HCP exhibits a maximum drag reduction of the order of 75%. Drag reduction in HCP depends on polymer concentration, initial bulk velocity, and capsule characteristics, including the aspect ratio, diameter ratio, and density ratio. Increases in drag reduction occur with increases in initial bulk fluid velocity up to the capsule liftoff velocity. Capsule velocity to bulk fluid velocity ratio appears to be independent of the presence of Polyox and its concentrations.

Although the above results (75% drag reduction in HCP flow at 25 ppm of Polyox) are promising, the tests were conducted in a small (54 mm dia.) recirculating pipe. Rapid degradation of polymer occurred due to the pumping system used to circulate the capsules. Each time polymer circulates around the pipe (equivalent to 22m), it must pass through a centrifugal pump and a jet pump. Both create large shear stresses that readily break up the polymer chains. In long-distance liquid pipelines, polymers are sometimes injected after each booster pump to prevent degradation of polymer by pumps and to produce drag reduction over a long time and distance. The same strategy can be used for HCP.

Acknowledgments

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Notation

g = gravitational acceleration
h = head loss

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