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THE UNIVERSITY OF MICHIGAN
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SUMMARY REPORT ON A PRELIMINARY STUDY OF THE FLOW OF PASTE

Seymour Calvert
Robert Miller
Henry Hartog

Project 2396

ATOMIC POWER DEVELOPMENT ASSOCIATES, INC.
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ABSTRACT

Experimental studies show that it is possible to cause the vertical flow of high-density (60 to 62% solids by volume) sediments by means of liquid flowing through the sediment. For upward flow, the pressure drop is somewhat greater than that equivalent to the weight of the sediment in the tube. For downward flow alone, the solids will flow under the influence of their weight. When downward and upward flow are combined, as in a vertical hairpin (bend at the bottom), the pressure drop in the downward leg is slightly higher than that in the upward leg. Flowing densities average around 61.1% solids by volume in the upward leg and 61.6% in the downward leg for the material studied.

OBJECT

The object of this preliminary study is to obtain order-of-magnitude data on the pressure drop required to cause the flow of high-density sediments through tubes.

INTRODUCTION

This report covers the findings of a preliminary study of the flow of paste which was conducted during the period from June 1 to August 1, 1955. The subject and object of the study were set forth in the contract covering this work and are quoted below.

"Subject.—The determination of the pressure-drop—flow-rate relationships for the flow of high-density pastes through tubes is required for the estimation of design requirements of a reactor. The system contemplated would have the following characteristics:

1. Paste is composed of uranium oxide or uranium powder suspended in molten sodium or sodium potassium.

   a. Density should be at least 40-50 volume-percent solids.
   b. Particle size may be varied to obtain optimum flow characteristics. A size range around 50-micron diameter is envisioned.

2. Tube diameter will be in the range of 1/4 to 1 in. Tube material will be stainless steel, probably 304.

3. Flow rate is anticipated to be in the range of 1/3 to 10 ft per day.

4. The orientation of the tube may range from horizontal to vertical.

"Object.—The object of this preliminary study is to obtain order-of-magnitude data on the pressure drop required to produce the desired flow rate and some insight into the mechanism of flow.

"For highly concentrated suspensions such as those of present interest, there are four general possibilities for the type of flow. If there is no appreciable attraction between the particles, there are two possibilities: the suspension will flow as a viscous fluid whose viscosity depends only on solids concentration and particle-size distribution, or the suspension may be so concentrated that it must increase in volume when sheared (i.e., it is dilatant). If there is attraction between particles, then the third possibility will occur and the behavior will be non-Newtonian and will exhibit a yield stress.

"The fourth possibility, which is dependent on the methods of feeding and withdrawal, is that the liquid could flow at a different linear velocity than the solid.

"Because of the range of possible modes of flow and the lack of generalized information which would enable the prediction of flow characteristics, it will be necessary to conduct an experimental study.

"The variables to be investigated as time permits are:

1. Flow rate
2. Paste density
3. Particle-size and size distribution
4. Tube material and wall finish
5. Tube geometry - turns and fittings
6. Vibration of the tube and/or pulsation of the pressure."

In view of the exploratory nature of this work, its course was discussed frequently in meetings with A.P.D.A. personnel, Dr. McDaniel, Mr. R. Thomas, and Mr. L. Kintner. These discussions made it possible to direct our efforts to the most significant points in the overall problem of determining the feasibility of the proposed system as the picture gradually took shape in the light of each new finding.

SUMMARY

The key fact disclosed by this study is that the mechanism of flow corresponds to the fourth possibility suggested above. The solids settle to a bed of about 61 to 62 volume-percent solids which will move under the influence of fluid passing through it. If, on the other hand, the motive force bears directly upon the solid particles, as when a piston is used for pushing, the bed cannot be moved if its length is more than about 2-1/2 tube diameters. Measurements of shear stress vs rate of shear with a concentric-cylinder viscometer are not directly applicable to flowing systems since the shear stress (or friction) depends on the bearing force exerted by the weight of the solids on the rotating cylinder. In fact, the rotating cylinder can be stopped by pressing with a finger on top of the sand surrounding the cylinder.

Once it was demonstrated that force was transmitted through the continuous sediment of particles as well as through the fluid, it became apparent that our previous knowledge of the flow of suspensions was not applicable. Our attention was then directed to the study of the flow of fluids through moving porous beds. Most of this work was done with water and silica flowing through glass tubes. Exploratory experiments with glass beads and copper metal powder indicated the same type of behavior as is exhibited by the silica. Flow through horizontal runs generally exhibits stratification with most of the water flowing in the upper 1/4 of the tube. Consequently, attention was

centered on vertical upward and downward flow.

The results of the experiments on vertical flow are summarized in the table below. It should be borne in mind that these are preliminary findings intended to provide order-of-magnitude quantities and are not to be used as reliable design data.

TABLE I

Ottawa Sand Size	Tube Inside Diameter	Geometry	Paste Rate (ft/day)	Water Rate (ft/day)	Pressure Drop (psi)
(Mesh) 150/200	8 mm	Straight tube, 4 ft long, flow down	10	5.7	0.40
150/200	10 mm	Straight tube, 2 ft long plus 180° bend, flow down	10	34.8	1.92
150/200	10 mm	The above plus another 2-ft straight section to make a vertical hairpin	10	38.4	3.70
100/150	10 mm	"	10	63.2	2.37
100/150	10 mm	A vertical hairpin with 4-ft-long straight sections	10	92.0	7.25

Based on the experimental findings and our interpretation of them, estimates have been made for the flow of uranium and uranium oxide pastes through vertical hairpins at a paste rate of 10 ft/day. The estimated pressure drop for uranium paste is 10 psi/ft of hairpin and for uranium oxide paste it is 5.5 psi/ft. Thus, in a 10-ft hairpin (10 ft in each leg) the pressure drops would be 100 psi for uranium and 55 psi for uranium oxide.

PRELIMINARY EXPERIMENTS

It was found that a paste composed of sand and water or glass beads and water would flow in a vertical tube under the influence of the weight of the bed with no other driving force present. However, the flow would occur only if a layer of water was present on top of the bed. As the flow progressed, the water would flow through the bed until the point was reached when the layer of water on top of the bed had disappeared. At this point the flow of the bed would stop. The bed often would not stop as a single plug but the upper part would stop while the lower part would break away and continue to flow until the water had passed through. Thus, at the end of a run there would be several plugs in the tube with air spaces between them.

Other attempts to obtain flow were made using air pressure as the driving force. Here it was found that the water was driven from the bed and the bed would separate into individual plugs in much the same fashion as described above. A column of mercury was also found to be an unsatisfactory driving force. The mercury would gradually displace the water and the point was reached when the bed remained stationary while the mercury flowed through it. In this case it was also found that the bed had a tendency to separate into plugs.

When attempts were made to obtain flow in a horizontal tube, it was found that the sand would settle to the bottom of the tube, leaving a vacant space above. The fluid would then pass through this channel and the sand would remain stationary. It was decided to devise a system for applying pressure that would permit movement of the bed without the drying out of the sand.

EXPERIMENTS WITH THE PISTON-AND-CYLINDER APPARATUS

A piston-and-cylinder apparatus was designed to allow the paste to be compressed without drying out and is shown in Fig. 1. In this arrangement, the paste was first loaded through the pipe. The system was then inverted to allow removal of air through the two air vents. Once all the air was removed, the system could be oriented as desired for the particular type of flow.

In designing the above system, several assumptions were made. First, it was assumed that in the flow rates desired the paste would act as a Newtonian liquid and Poiseuille's equation would be valid:

$$\Delta P_f = \frac{32 L \, v \, \mu}{g_c \, D^2} , \tag{1}$$

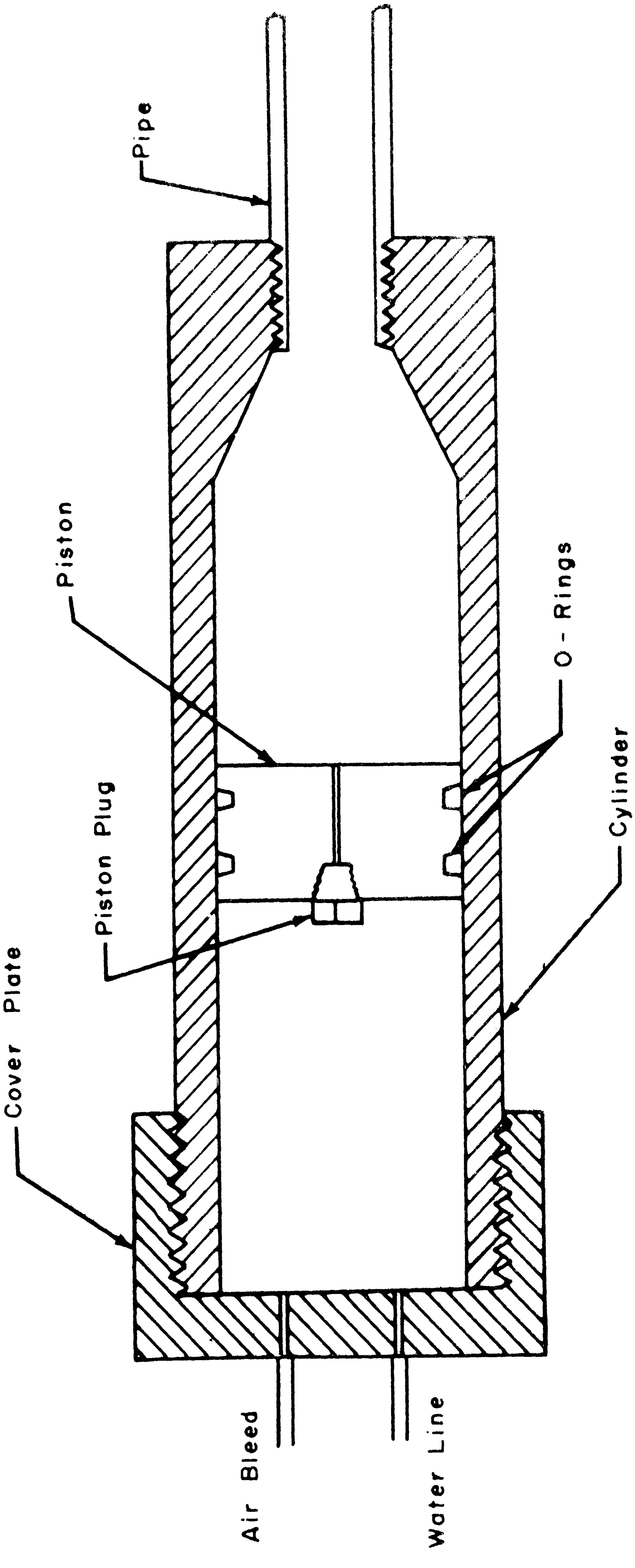


Fig. 1. Piston and cylinder

where

ΔP_f = loss in pressure due to friction,
L = length of tubing,
v = bulk velocity,
μ = viscosity of paste,
g_c = 32.17 ft/sec^2,
and D = pipe diameter.

Second, it was assumed that the bulk velocity of the paste and water would not differ appreciably from that of the paste alone. Third, no viscosity data could be found for the volume concentrations desired (about 60%). Data presented in the U.S. Bureau of Mines Report Inv. 3469-R(1939) were extrapolated from 46 volume-percent solids to 60% solids. These calculations showed that the pressure drop through a two-foot length for a flow rate of 10 ft/day of 60 volume-percent sand would be 0.3 psi for a one-inch-diameter tube, and 7.5 psi for a 1/4-inch-diameter tube. Since the pressure drop is greatly affected by a small change in density, the system was designed to withstand a pressure of 500 psi.

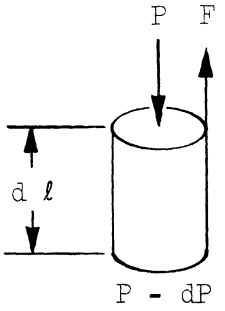
With the piston and cylinder it was found that if vertical upward flow were attempted, water would flow for a short time, after which no further flow would occur. At no time would the paste flow. Apparently the piston was forcing the excess water out of the bed. Similarly, no paste flow could be obtained when the apparatus was mounted horizontally.

If the apparatus was mounted for vertical downward flow, it was found that flow could be obtained if there was excess water between the piston and the bed of paste. The pressure measured was equal to the pressure required to move the piston. Runs were made using water pressure alone, that is, by removing the piston plug, and it was found that the pressure-gauge reading in this case was zero. If the cylinder was vented to the atmosphere, the paste would flow due to its own weight.

During one run, the piston was allowed to force out all the excess water while the apparatus was mounted for vertical upward flow. The apparatus was then inverted and it was found that no flow could be obtained. Thus, in all runs in which flow was obtained, excess water was present.

The volume-percent sand in the discharge stream was measured in the runs in which flow was obtained and ranged from 58.5 to 61.5%. The volume-percent sand obtained by vibrating some paste in a graduated cylinder until a constant volume was obtained was 67.5%.

The apparent reason for the failure of the paste to flow in this type of system is that the bed transmits all the axial force applied by the piston to the walls in a short distance. The following derivation illustrates the nature of this effect. Consider a paste plug of length "$d\ell$" in a tube of radius "r."



Let F = frictional force = $C_f F_n$,
C_f = coefficient of friction,
F_n = normal force = $2P\pi r d\ell$
and F_z = axial force = $\pi r^2 \, dP$.

a force balance must exist whether there is flow or not, so

$$-F_z = F, \tag{2}$$
$$-\pi r^2 dP = 2P\pi r C_f d\ell, \tag{3}$$

and

$$-\frac{dP}{P} = \frac{2C_f}{r} d\ell. \tag{4}$$

Integration of (4) gives

$$\ell n\left(\frac{P_1}{P_2}\right) = 2C_f\left(\frac{\Delta \ell}{r}\right) . \tag{5}$$

Perry's Chemical Engineers' Handbook (3rd ed, p. 1347) lists the coefficient of friction of wet sand against steel plate as 1.0. Thus, Equation 5 indicates that there is an extremely rapid dissipation of driving force as friction as tube length is increased. For example, a pressure ratio of 1000 would occur for a tube length of 3.5 radii.

MEASUREMENTS WITH A CONCENTRIC-TUBE VISCOMETER

At the same time that the piston apparatus was being used, measurement of paste "viscosity" was being attempted with a Brookfield viscometer. This instrument is of the concentric-cylinder type with the inner cylinder rotating at one of four constant speeds while the outer cylinder is held stationary. The shear stress is indicated by the deflection of a helical spring as it is subjected to the driving torque. Both smooth- and rough-finished rotating cylinders were used.

The data obtained on sedimented sand in water were quite erratic and were sensitive to previous treatment of the sand bed. The fact that shear stress depended on the normal force exerted by the sand grains could be demonstrated by pressing a finger on top of the sand. If sufficient pressure was exerted, the rotation of the cylinder could be stopped and the torque pickup forced off scale. When the experiments on flow had progressed to the point where it became clear that the flow of sediments had little in common with the flow of suspensions, the utility of viscometer measurements became very doubtful. Consequently, the work with this apparatus was discontinued.

PASTE FLOW WITH WATER DRIVE

In all the previous experiments, paste flow occurred only when a layer of water was present on top of the bed. This pointed to the use of water pressure as the driving force. Qualitative experiments showed that flow of sand could be obtained at pressure drops below 10 psi for a 4-ft length of 3/8-in. copper tubing bent in the shape of a double hairpin. Using this water-drive method, flow can be obtained in a vertically oriented hairpin-shaped tube or a helix, but uniform horizontal flow is very difficult, if not impossible, to obtain. At the low flow rates used, the sand settles to the bottom of the tube and most of the water flow is along the top. A very definite velocity gradient of sand flow can be seen and it is possible that the sand in the bottom of the tube either does not flow at all or else flows with a very small velocity. In using the helix, it was found that the angle of inclination should be at least 45° in order to keep the tubing completely full of sand. This is only an approximate value and also may depend upon the tube diameter, flow rate, particle density, and particle diameter.

DETERMINATION OF PRESSURE DROP FOR VERTICAL PASTE FLOW

Several runs were made to determine the relationship between pressure drop and flow rate for pastes of Ottawa (rounded-grain) sand. These were carried out in glass tubing so that the flow could be observed. The paste was forced from a reservoir (about 1-in. diameter) through a conical contraction into the flow tubing (10-mm ID in most runs). Since the water flows at a faster rate than the paste, the outlet sample collected during the run consists of paste and excess water. This excess water is the amount of water that flows through the bed. The samples collected in a measured time interval were vibrated until the paste reached a constant volume. The total volume, paste volume, and excess-water volume were then measured and from them flow rates could be computed.

For comparative purposes, runs were made holding the bed of paste fixed by means of a screen at the tube end. It was found that the flow rate was directly proportional to the pressure. This is what was expected from Darcy's relationship for fluid flow through a porous media:

$$v = k\frac{-\Delta P_f}{L\mu} , \qquad (6)$$

where v = superficial velocity based on empty cross section of tube,
$-\Delta P_f$ = pressure drop due to friction,
L = length of tube,
μ = viscosity of fluid,
and k = permeability (a function of the porosity of the bed).

It was found that the excess-water flow rate for a given pressure drop in the moving bed was slightly larger than for the same pressure drop in a fixed bed. (See Figs. 2 and 3.) This indicates that in order to move the bed must expand, slightly increasing the porosity and, subsequently, decreasing the resistance to the flow of water through the bed.

Measurements of the density of the paste were made for various flow configurations. The results are as follows for 200-mesh sand:

	Volume-Percent Solids
Vertical leg - downward flow	61.6
Vertical leg - upward flow	61.1
90° bend	60.7
180° bend	59.7
Overall average	60.6
Vibrated settled density	66.3

Variations from the above values were less than ± 2%. The sampling technique consisted of cutting a section of tubing out of the flow system, drying the contained sand, and then, from the tube volume and the sand weight, computing the bulk density. From this and the true density of silica, one can compute the volume-percent solids, The above data show that for a flowing bed there is about a 6% decrease from the vibrated settling density.

The flow of 150/200-mesh Ottawa sand and water was studied in three configurations and the results are shown in Figs. 2, 3, and 4. These graphs show that as the pressure was increased the flow rate increased gradually at first and more rapidly at high pressures. With the systems used, pressure was controlled by a needle valve that throttled water from 20-psi pressure. The system was very critical and a small change in needle-valve setting would result in a large pressure change. Much better results were obtained by controlling the water pressure by a regulator on the airline to the water tank and using the needle valve for fine adjustments in pressure. This decreased the pressure drop through the needle valve and the pressure was much easier to regulate.

A comparison of the data for the complete hairpin and the straight run plus 180° bend is shown in Fig. 5, which is replotted from Figs. 2 and 4. It can be seen that the additional length in the hairpin does not quite add

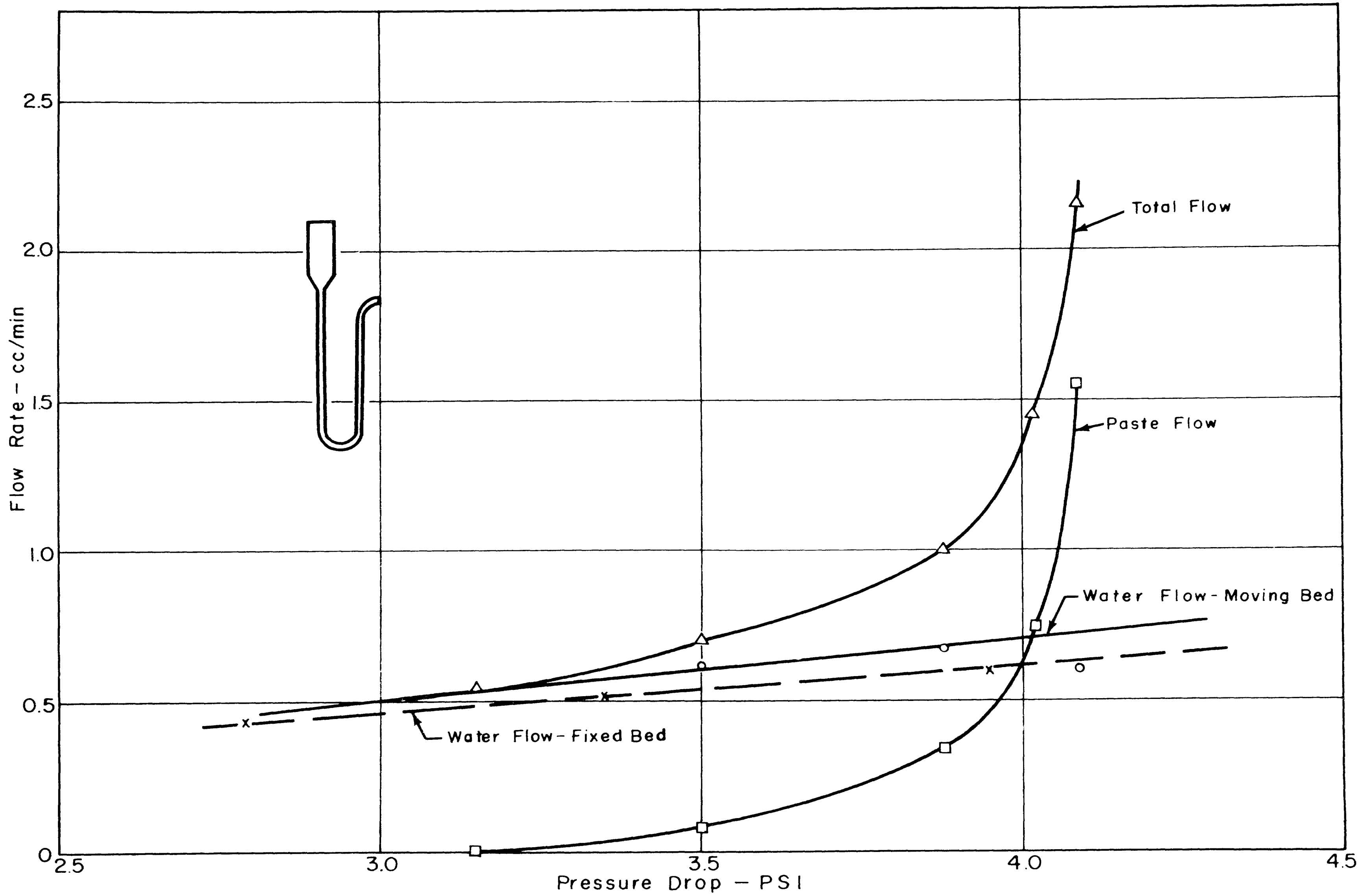


Fig. 2. Pressure drop vs flow rate for 200-mesh Ottawa silica sand flowing in a 2-ft-long hairpin of 10-mm-ID glass tubing

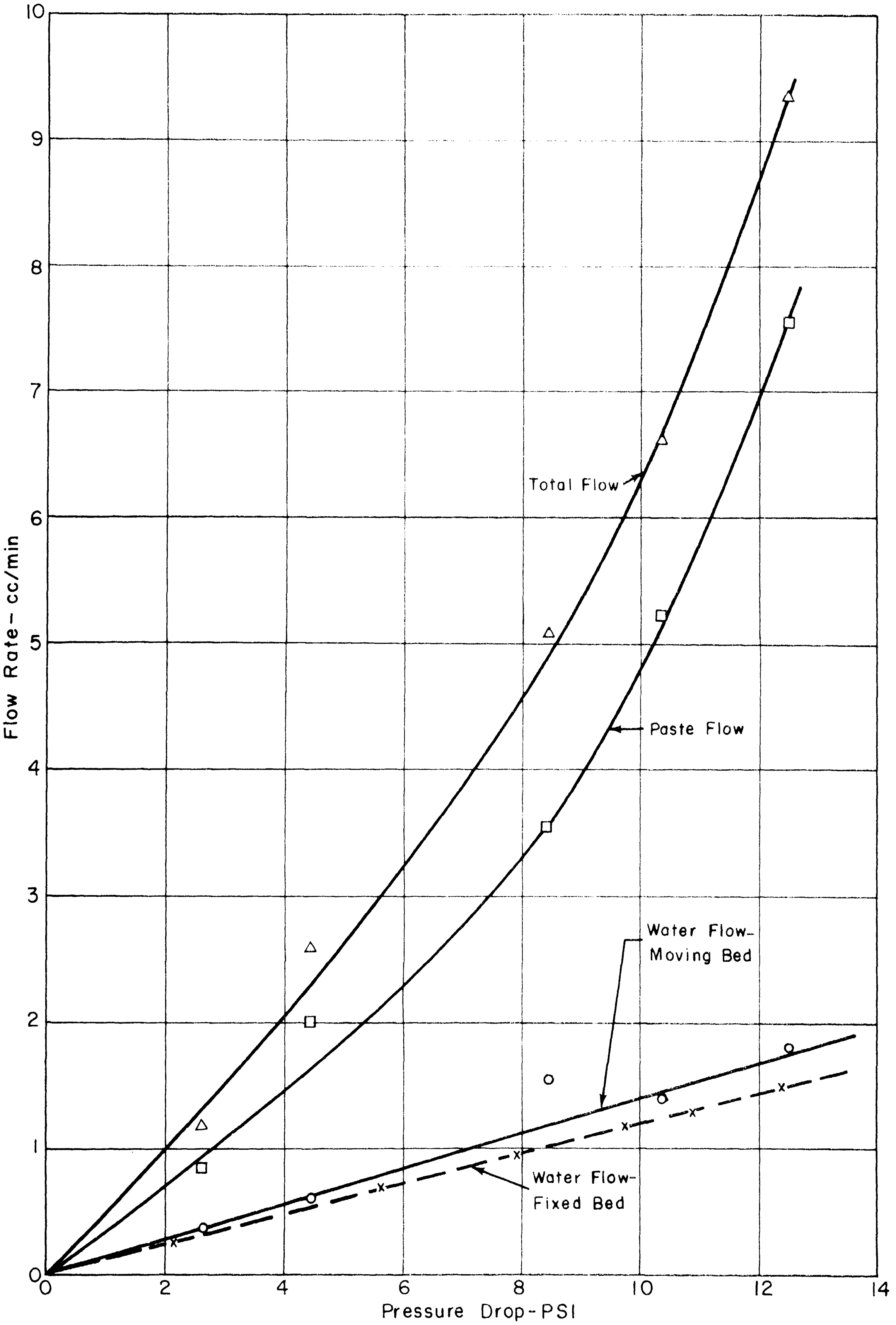


Fig. 3. Pressure drop vs flow rate for 200-mesh Ottawa silica sand flowing in a 4-ft-long vertical glass tube of 8-mm ID

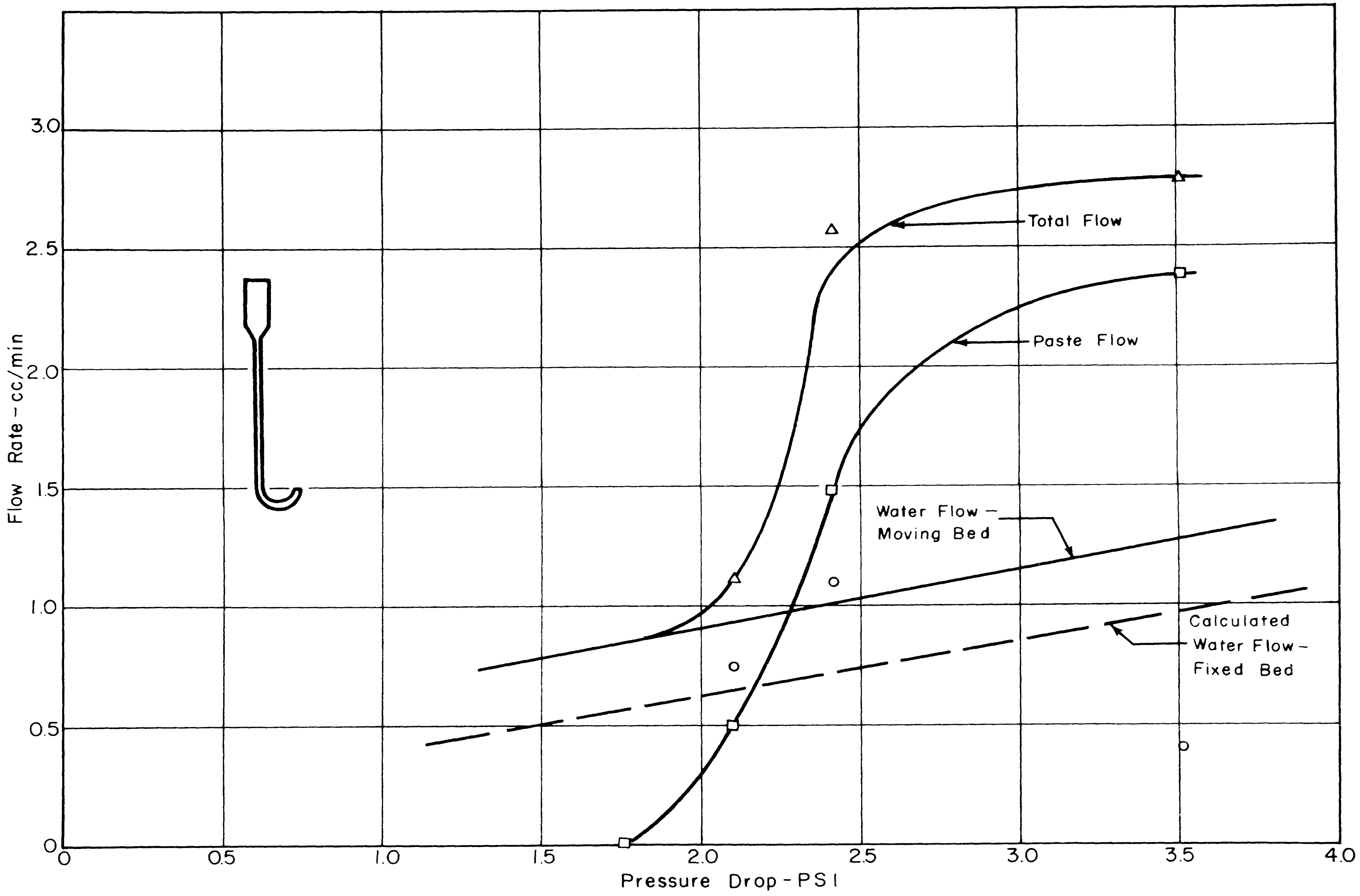


Fig. 4. Pressure drop vs flow rate for 200-mesh Ottawa silica sand flowing in a 2-ft-long vertical tube plus a return bend of 10-mm-ID glass tubing

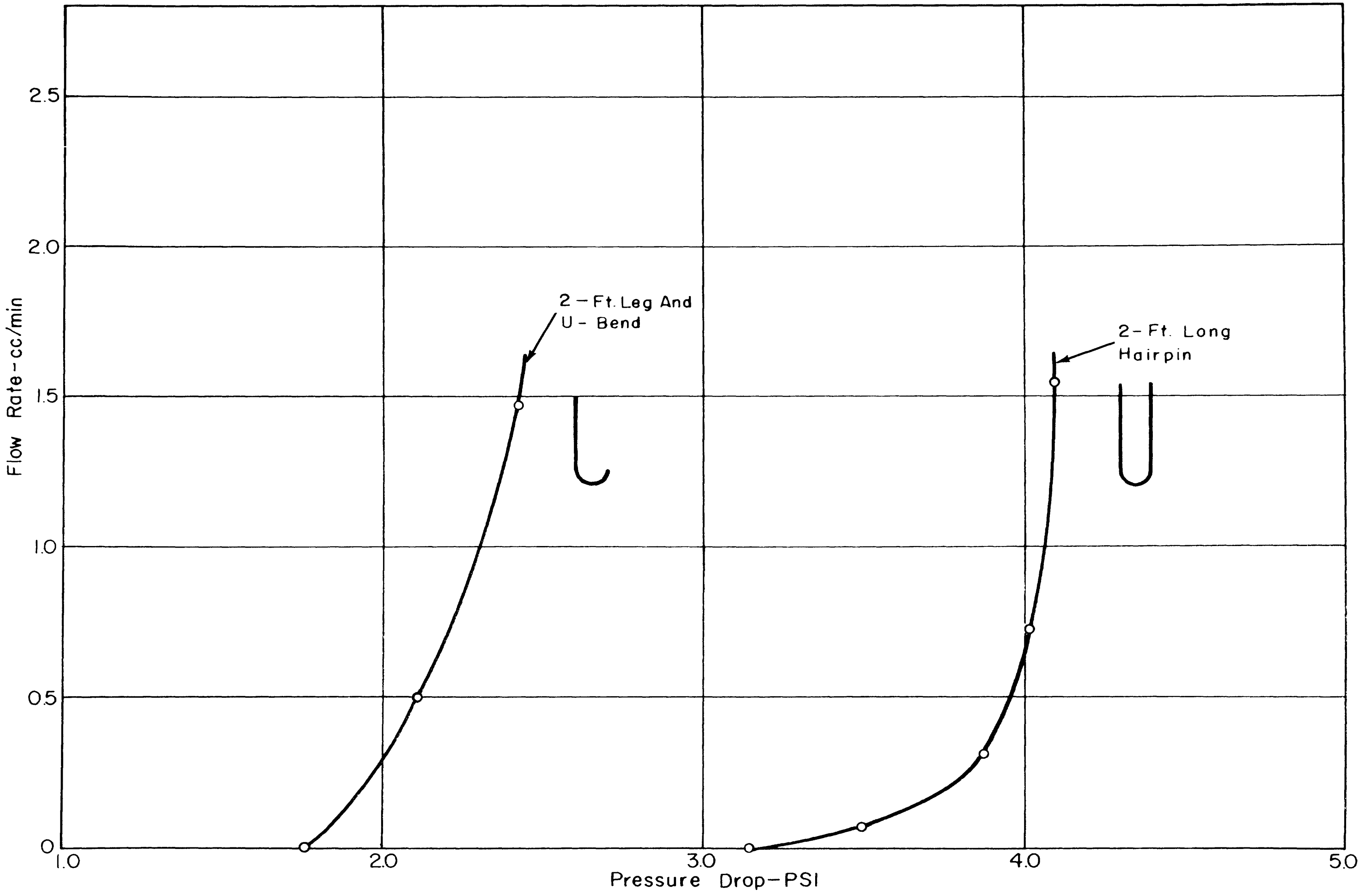


Fig. 5. Pressure drop vs flow rate for 200-mesh Ottawa silica-sand paste flowing in 10-mm-ID glass tubing

a proportionate amount to the pressure drop for a given flow rate. While these particular data do not point it out conclusively, other runs also show that the pressure drop in the downward leg is higher than that in the upward leg.

The effect of particle size is illustrated in Figs. 6 and 7, which show flow rate vs pressure drop for 100/150-mesh Ottawa sand in a 2-ft hairpin (Fig. 6) and a comparison of this data with that for 150/200-mesh sand (Fig. 7) in the same size of hairpin. The data in Fig. 6 are typical for the 100/150-mesh sand in being very erratic. This is in noticeable contrast to the 150/200-mesh sand, which flows in a much more constant fashion. The comparison in Fig. 7 shows that frictional effects are appreciably lower with the larger particles.

The effect of tube length is shown in Figs. 8 and 9, which are plots of flow rate vs pressure drop for 100/150-mesh sand in a 4-ft hairpin (Fig. 8) and a comparison of this with the data for the same sand in a 2-ft hairpin. The comparisons shown in Fig. 9 are quite interesting in that they point out that pressure drop per unit length increases with length. This confirms the evidence which is described in the following section. It is also apparent from the water-flow curves that the average porosity decreases as length is added.

DETERMINATION OF MINIMUM PRESSURE DROP FOR UPWARD FLOW

A brief experiment was conducted to determine the magnitude of the minimum pressure drop required to produce upward flow of a bed of sand. A 10-mm-ID Lucite tube was fitted with a screen across its bottom end and means for introducing water and measuring pressure at the bottom. The tube was filled to a measured height with 150/200-mesh Ottawa sand which setted to 63 volume-percent solids when the tube was tapped for a few minutes. The water-flow rate was slowly increased until the bed first expanded and the pressure drop at that point was recorded. This procedure was repeated for several bed heights.

The results of this experiment are shown in Fig. 10, a plot of "fraction overweight" vs bed length. "Fraction overweight" is the ratio of pressure drop required just to expand the bed to pressure drop equivalent to the bed weight (taking buoyancy into account). If the fraction overweight is 1.0, the bed weight is just balanced by the pressure drop exerted by the water. Any value of the fraction overweight greater than 1.0 indicates the force required to overcome friction and it can be seen that this increases with tube length. The peculiar thing is that the data show an increase in pressure drop per unit length as length is increased.

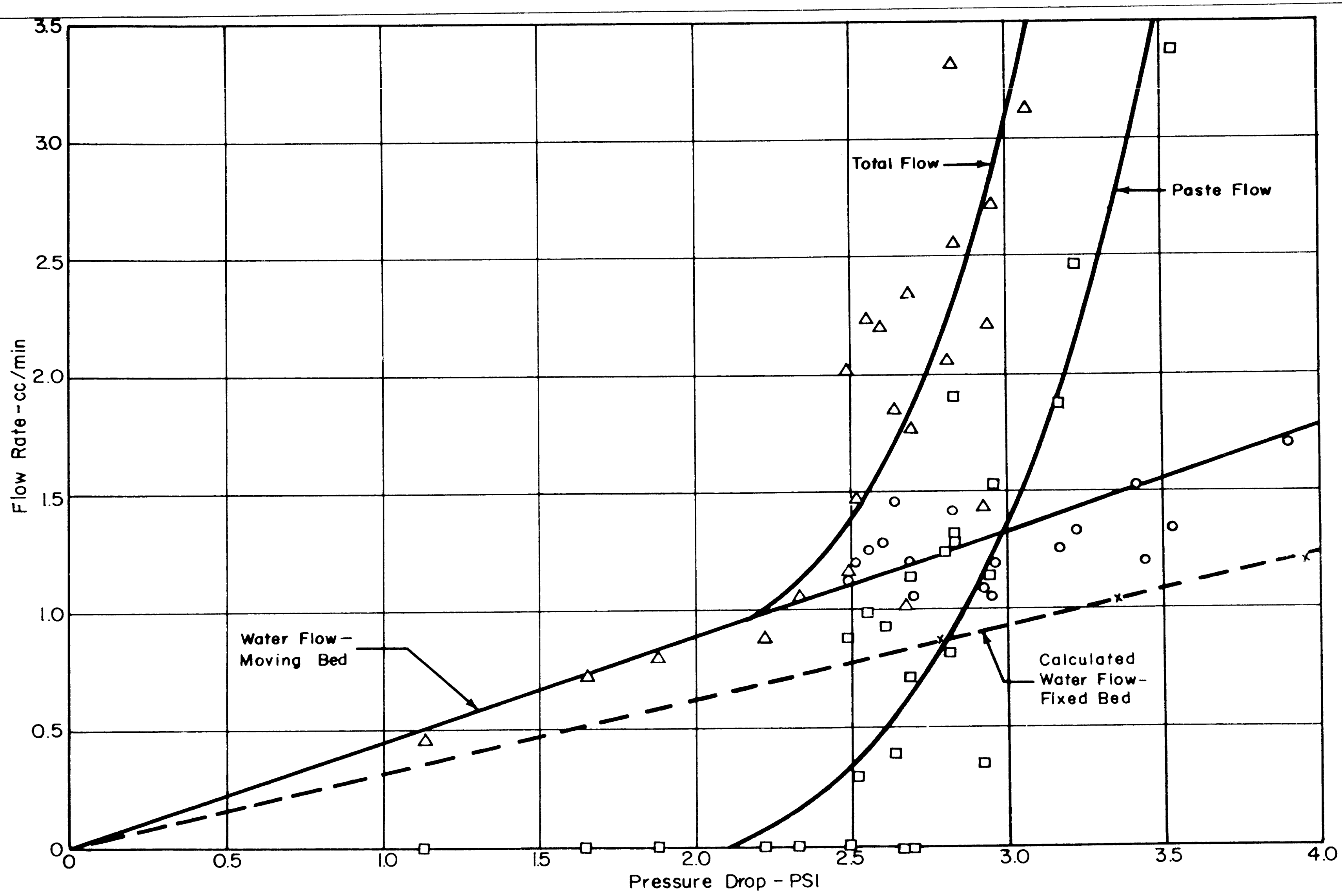


Fig. 6. Pressure drop vs flow rate for 100/150-mesh Ottawa silica sand flowing in a 2-ft-long hairpin of 10-mm-ID glass tubing

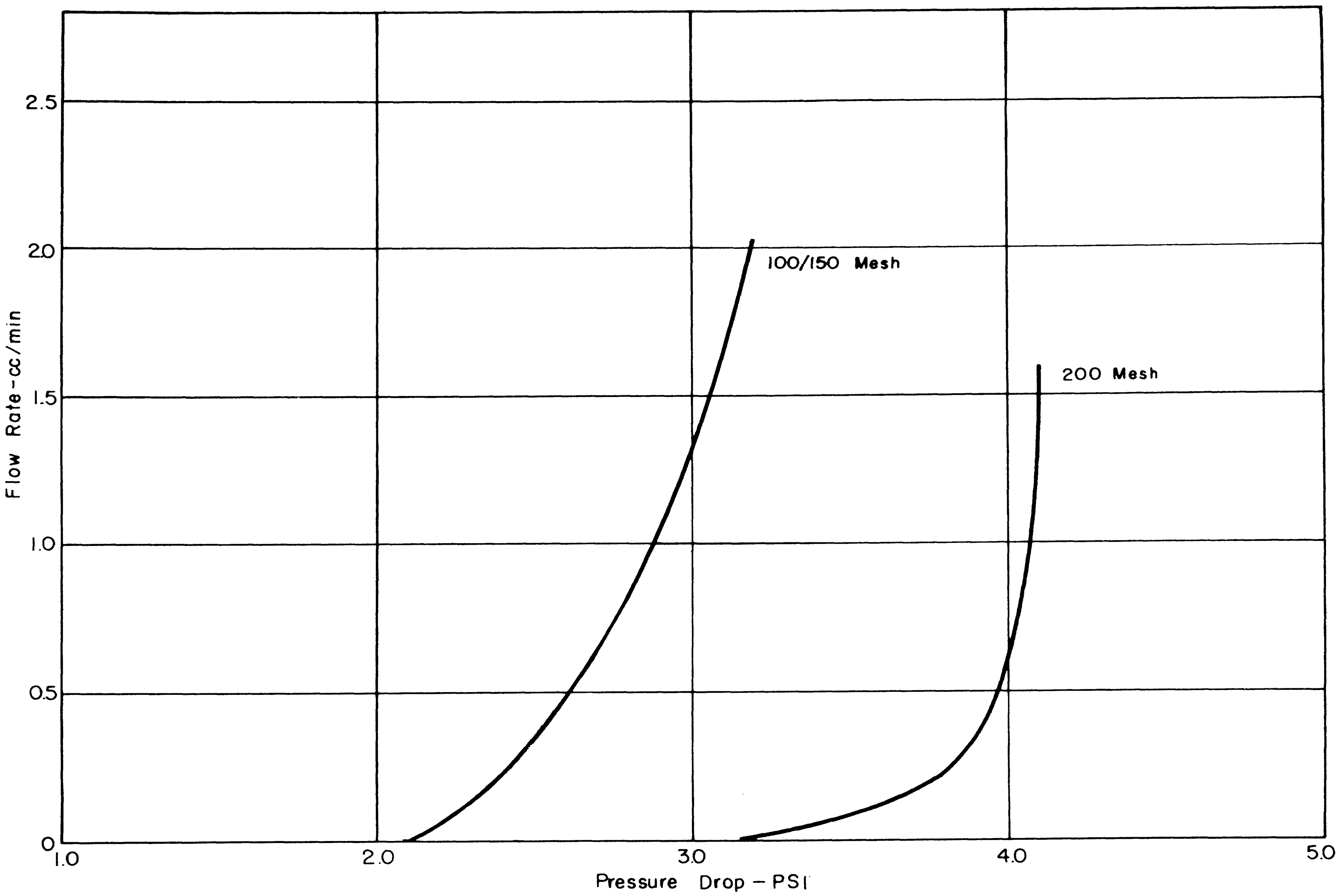


Fig. 7. Pressure drop vs flow rate for Ottawa silica-sand paste flowing in a 2-ft-long hairpin of 10-mm-ID glass tubing

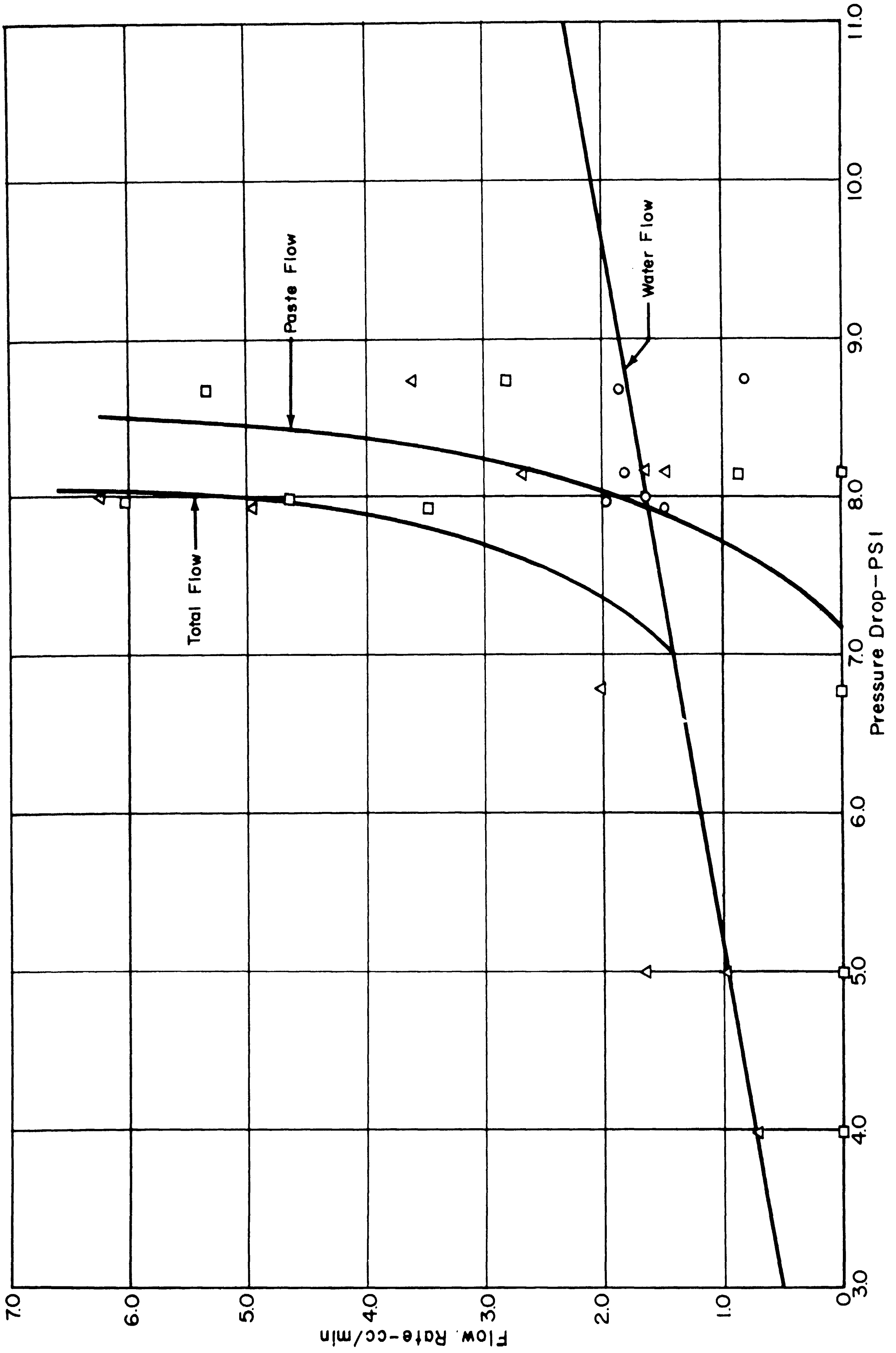


Fig. 8. Pressure drop vs flow rate for 100/150-mesh Ottawa silica sand flowing in a 4-ft-long hairpin of 10-mm-ID glass tubing

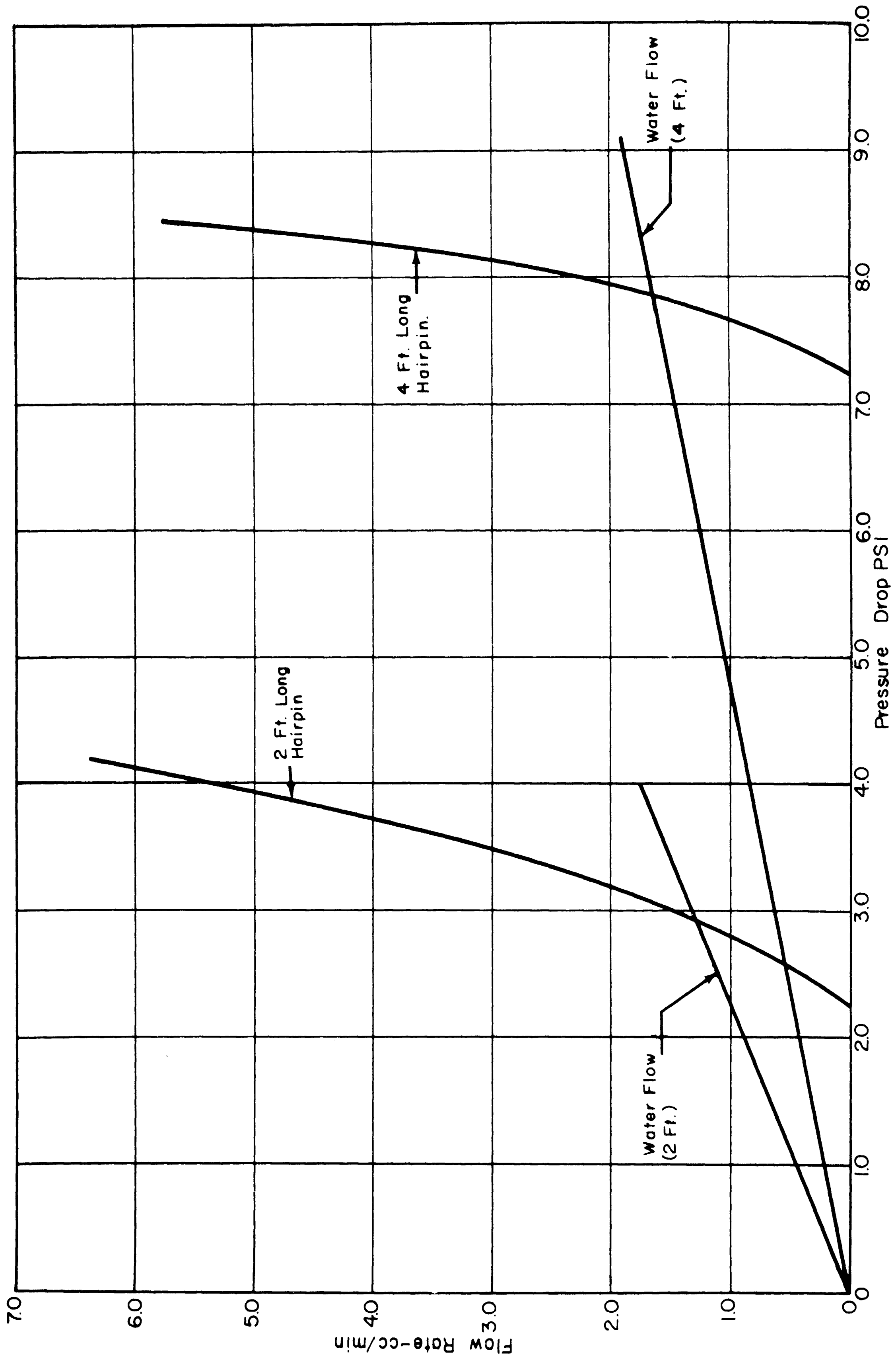


Fig. 9. Pressure drop vs flow rate for 100/150-mesh Ottawa silica-sand paste flowing in 10-mm-ID glass tubing

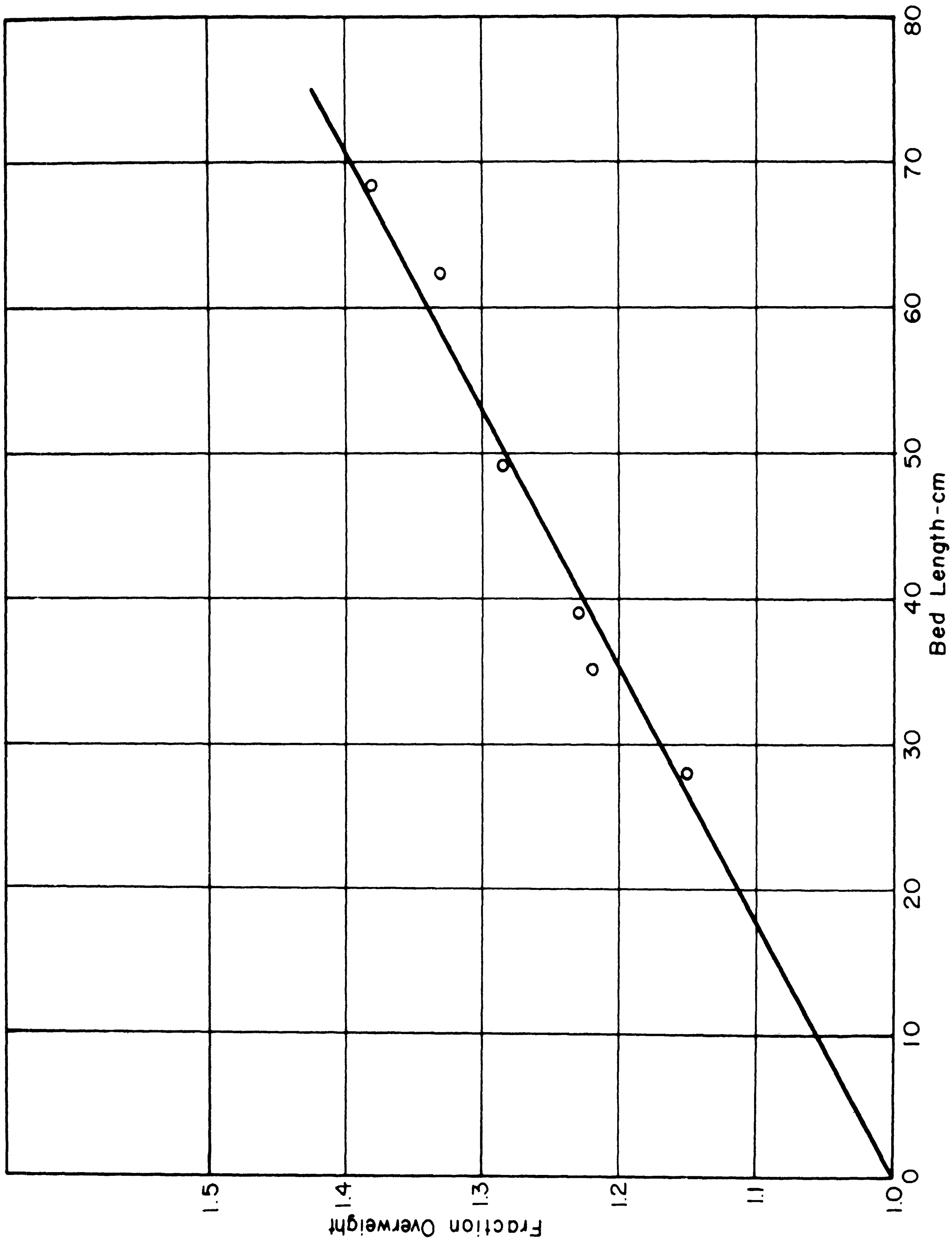


Fig. 10. Fraction overweight vs bed length for vertical, upward flow of water in beds of 200-mesh Ottawa sand

DISCUSSION OF EXPERIMENTAL RESULTS

While the data obtained are too sparse to permit any quantitative generalization, they do provide order-of-magnitude values and a basis for some insight into the mechanism of flow. Apart from noting that pressure drop and density variations are within reasonable magnitudes, we may make the following observations concerning the nature of this type of flow.

1. Sedimentation is an unavoidable feature of this type of flow where velocities are low, particle size is comparatively large, and the difference between solid and liquid densities is high. Because of this, the particles are in intimate contact and are capable of transmitting force in a predominant direction. Mechanical force exerted on the particles along a plane perpendicular to the tube axis will be transmitted to the tube walls and dissipated in a few diameters of length. Only by the application of force distributed along the tube axis can this unfavorable effect of dissipation be overcome and motion obtained through long tubes.

2. Upward flow can be obtained only when the pressure drop exceeds the weight of the solids in the upward section. The excess pressure drop per unit length required to overcome friction seems to be a linear function of tube length. Since the packed density is lower in an upward section than in a downward section, a greater liquid-flow rate is required to produce a given pressure drop in an upward section than in a downward section.

Then, when one considers flow through a vertical hairpin, it might be said that the upward leg sets the requirement for liquid rate so that its bed weight and friction are balanced by pressure drop. This liquid rate is much higher than is required by the downward leg and it produces a higher pressure drop than required in the downward leg, and this must be dissipated as friction against the tube wall. So the downward leg seems to play a passive role, extracting what pressure drop it must in accordance with its permeability and the liquid flow rate. It appears possible at this stage of the study that this analysis may point the way for future generalization of flow data on hairpins.

3. The instantaneous flow rate is not constant in the region of average rate equal to 10 ft/day. It appears that this is in the transition region between static and sliding (or rolling) friction and that all portions of the bed are not doing the same thing at the same time. The effect that particle-size distribution and tube diameter will have on this remains to be seen.

ESTIMATION OF PRESSURE DROP FOR URANIUM-PASTE FLOW

The data obtained in this study can be used to estimate an order-of-magnitude pressure drop for the flow of uranium particles plus liquid sodium. We make the following assumptions.

1. The pressure drop in any upward-flow section of a tube is equivalent to the weight of the bed in that section. Since the solids must be supported by fluid drag, it seems unlikely that solid density will have much influence on frictional losses here. Thus, the excess pressure (above that equivalent to bed weight) should be about the same as for sand, and this is not very significant when compared to the weight of a uranium bed. In other words, it does not seem proper to apply the overweight ratio found for sand to the flow of uranium.

2. The flow-rate vs pressure-drop data for molten sodium flowing through uranium can be approximated by that determined for water flowing through sand.

3. The porosity of the uranium powder would be about the same as that of the sand used in our experiments. Actually, it will probably be lower since a wider range of sizes is envisioned for the uranium powder.

COMPUTATIONS

Density of uranium = 18.7 g/cc = 0.675 lb/cu in.

Approximate density of sodium = 1.0 g/cc = 0.03613 lb/cu in.

Weight of uranium paste in 1 ft of tube $= \frac{W}{\Delta L} = \left(\frac{\pi D^2}{4}\right) 12(0.675-0.036)0.62(\text{lb/ft})$.

Pressure equivalent to weight of paste $= \frac{W}{\Delta LA} = 12(0.639)0.62 = 4.75$ psi/ft.

This gives an approximation of the pressure drop in the upward leg. To estimate the pressure drop in the downward leg, use the data of Fig. 5, which shows a ratio of pressure drop in downward leg to pressure drop in upward leg equal to 1.05. Thus, the total pressure drop would be 2.05 x 4.75 = 9.75 psi/ft of hairpin (a foot of hairpin includes one foot in each leg).

If a 10-ft-long hairpin is used, the pressure drop will be approximately 100 psi. Since it has been assumed that frictional effects in the upward leg are negligible, this estimation shows no effect of tube size.

The sodium flow rate required to produce a pressure drop of 4.75 psi/ft is estimated from the data for a moving bed in Fig. 2. Since the relationship is linear, one can extrapolate to 4.75 psi/ft, or 19 psi/4 ft. The flow rate indicated is 33.2 cc/min in a 10-mm-ID tube. This corresponds to a linear rate of 33.2/.785 = 42.3 cm/min. Thus, in a 1-in.-ID tube the required sodium flow rate would be equal to 42.3 $(\pi 2.54^2/4)$ = 214(cc/min).

The pressure drop for uranium oxide flow (ρ = 10.9 g/cc) has been estimated by the same procedure as 5.45 psi/ft of hairpin. The estimated sodium flow rate is 23.6 cm/min.

The pressure drop probably could be cut in half by taking advantage of the fact that the paste will move down under the influence of its own weight. If the liquid were introduced at the bottom of a hairpin and the downward leg were longer than the upward leg, then paste flow should occur in the proper direction. Since the porosity in the downward leg is lower than that in the upward leg, its resistance to fluid flow would be higher and most of the fluid should go through the upward leg. Variations on this scheme, such as sealing the downward leg so that no fluid flows in it or providing a small volume of flow from the top of the downward leg, also can be considered.

CONCLUSIONS

The principal conclusion drawn from this study is that it is possible to move high-density sediments through vertical tubes under the influence of fluid drag forces. Frictional effects do not give rise to excessive pressure drops; a sediment will flow downward under the influence of its own weight. The pressure drop required to produce upward flow is primarily determined by the weight of the sediment which must be lifted.

In order to understand fully or at least have reliable data on this type of flow, it will be necessary to extend the study to cover a wider range of variables. Some of the general questions which have yet to be answered are:

1. What is the mechanism which produces resistance to sediment flow and how can it be described in terms of the system's variables?

2. How does the permeability of a sediment bed change with bed flow rate and how is it related to the other variables such as particle size, shape, and density?

3. Is all the potential energy of the solids in a downward-flow section

lost as friction or can some be used to move solids up through a hairpin?

4. Why does the pressure drop per unit length increase with tube length in an upward-flow section?

5. What are the geometric limitations on this type of flow?

6. What factors influence the steadiness of flow?

Finding the answers to these and other questions will require a program of at least one year's time. In submitting (separately) a proposal for a three-month extension of this study, we do not mean to infer that the problem can be understood with the completeness described above. We should, however, be able to arrive at reliable design data covering a range of variables wide enough to permit a process design and economic evaluation to be made with an acceptable degree of confidence.