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FLOW OF AN AQUEOUS SLURRY THROUGH
A VERTICAL TUBE

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Flow of an Aqueous Slurry Through a Vertical Tube*

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Harold E. Wolfe and Glenn Murphy

ABSTRACT

The upward vertical flow of a slurry was investigated utilizing photographic techniques with the intention of obtaining data on solid phase concentration and velocity distribution and to evaluate the use of photography as a tool in slurry analysis.

An analytical expression for the ratio of the specific weight of the mixture in the tube to the specific weight of the mixture discharged was derived and used to verify certain assumptions indicated in the photographic study.

*This report is based on an M.S. thesis by Harold Wolfe submitted March, 1957, to Iowa State College, Ames, Iowa. This work was done under contract with the Atomic Energy Commission.

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I. INTRODUCTION

In recent years the use of slurries as a method of handling and transporting certain materials has gained considerable importance in industry. This increase in importance is due partially to the increased usage of materials which can be handled in slurry form.

In the chemical industry, slurries are used to a great extent in the catalytic process where the catalyst becomes the solid phase of the solid-fluid mixture. Other instances where slurries can be used to advantage are in the transportation of grain, coal, sand, gravel and cement. For all of these materials, the slurry provides a clean and rapid means of transportation.

In a general sense, a slurry can be defined as any solid-fluid suspension. This includes sizes of the solid phase ranging from less than one micron up to as large as can be maintained in suspension. For certain size ranges, the particles of the suspension will not settle out of the fluid phase and the mixture then is sometimes considered a colloidal suspension. This size range includes particles between 0.001 and 0.10 microns in diameter (4).

For the purposes of this report, the term slurry is used to indicate a mixture of water and a solid phase consisting of uniform spherical particles. In the investigation reported, the particles ranged in size from 0.0013-in. diameter up to 0.0314-in. diameter.

In the design of a slurry-handling system, several factors must be considered from the engineering standpoint. Of primary concern is the material to be handled, since its physical and chemical properties may govern the approach to the problem. The effect of these properties on the performance of the system must be weighed in regard to power consumption, efficiency, and amount of material transported, as well as the possible erosion of the equipment by the slurry. On the other hand, it may be necessary to study the probable effects of the system on the slurry itself if it becomes important that the slurry arrives at its destination in its original condition.

As a result, the design of slurry equipment depends on the ability to predict the behavior of slurries as affected by particle size, particle shape, particle density, fluid density, conduit diameter, conduit roughness, velocity and concentration.

Work done in the past few years has produced considerable data relating these variables with the prediction of head loss, mass rate of flow, power consumption, etc. At the same time, somewhat less attention has been given to the observation and recording of the characteristics of the type of flow.

This investigation was made in the interest of the latter aspect of slurry flow.

II. REVIEW OF LITERATURE

The major part of the literature review consisted of a search for information dealing with the application of photography to the study of fluid and slurry flow. This resulted in a general review of the various methods used in studying the characteristics of flow. At the same time, a brief survey was made of available literature on slurry behavior.

One of the most comprehensive articles found was a general survey of the techniques of flow visualization by Balint (1). Three methods of visualization which depend on the refraction of light were discussed. The first of these, described as the shadow pattern method, depends on the refraction of light emerging from the surface of a fluid to produce a pattern of light and shadow. The second method, called the "Schlieren", depends on the refraction of light rays by a medium in which density variations exist to produce a pattern of light and shadow. The third method discussed utilizes the property of double refraction exhibited by some fluids and colloidal suspensions. This method requires use of polarizing equipment to transform the doubly refracted light rays into a pattern of dark lines on a light background. Information regarding the shear stresses in the fluid can be obtained from this pattern of lines.

A method of studying flow patterns on the surface of a fluid was also discussed. This method involved the sprinkling of lycopodium powder or aluminum powder on the surface of the fluid. The particles align themselves with the direction of flow and act as tracers. Also mentioned

was the use of balsa wood particles and smoke as tracers in wind tunnel studies.

In conjunction with the study of the internal aspects of fluid flow, Balint discussed the introduction of air bubbles, droplets of oil, or other light reflecting particles to make possible the visualization of flow.

Prandtl and Tietjens (11) devoted a section to the visualization of flow which consisted mainly of pictures taken of the flow around an object using metallic powders sprinkled on the surface of the fluid.

Relf (12) conducted studies of flow around an airfoil using illuminated oil droplets in water. The drops used were a mixture of olive oil and nitrobenzene properly proportioned to result in a specific weight equal to that of water. These particles had a refractive index relative to water such that a ray of light striking a particle left at an angle of 90° to the original direction. Drops of an aniline-toluene mixture used required that the light enter at 71° to the direction in which it was required to emerge. Photographs were taken using one-second exposures on particles moving at approximately 0.5 in. per second. No attempts were made to determine actual particle velocities.

Jones and Hermges (9) used a photographic method to measure velocities in solid-fluid flow. They measured velocities in a 1-in. diameter pipe carrying 1/8-in. diameter gravel particles in air at speeds up to 40 fps. Two photographs were taken on the same negative by flashing two light units separately, with approximately one millisecond delay between flashes. Three methods of timing were used. The first method

consisted of two microswitches mounted horizontally and triggered by two setscrews in a falling lever. In the second method, the voltage across a relay having two pairs of contacts was varied to obtain time delay. The third method consisted of exposing a rotating disc simultaneously with the flow. The rotating disc speed was adjustable and was checked with a calibrated tachometer.

Jones and Hermges also measured the velocity of coal carried in water up to speeds of 20 fps.

Caffyn and Underwood (3) developed an ingenious method of determining velocity profiles using photographs of droplets of a mixture of benzene and carbon tetrachloride in water. The mixture was adjusted until the density was the same as water and then forced through a 0.015-cm. I.D. capillary tube to form droplets.

Flow was directed upward through a circular glass tube where the particles were illuminated by a flash tube. The light from the flash was rendered parallel by a cylindrical lens and then divided by two mirrors into two beams which entered the test section at 90° to one another. Using the two perpendicular beams and three other mirrors, one of which was semi-silvered, two particle images were formed and photographed. Each image was a different distance from a reference line in the photograph and gave x- and y-coordinates of the position of the particles in the flow area. Velocity was obtained by making two exposures on the same negative with a timed delay between exposures.

In order to reduce glare and distortion, a transparent rectangular box was built around the circular tube and filled with water.

Ferrel, Richardson and Beatty (5) used the displacement of a dye solution to measure velocity profiles in a fluid. They used a vertical tube filled to a certain level with a dye solution and the remaining volume filled with a dye-free solution. A spectrometer was built around the tube at a point below the interface of the solutions. As flow was started downward the interface moved downward and became stretched and distorted due to velocity variations across the diameter. The rate of distortion of the interface was measured with the spectrometer by the change in absorption of a beam of light passing across the diameter and the rate of distortion was used to calculate the velocity profile.

With this technique, the authors obtained velocity measurements to within 0.002 in. of the wall of a 1/2-in. diameter tube. The results agreed with the parabolic distribution predicted by laminar flow theory. Velocity measurements in the vicinity of the wall were limited by molecular diffusion of the dye.

Hariu and Molstad (6) investigated pressure drop in the vertical transport of solid particles by an air stream. From direct measurements of the dispersed solids' density (the total weight of solids in a given volume divided by that volume), the average particle velocity, slip velocity and the static pressure drop due to the column of solids in the test section were calculated.

The total pressure drop was assumed to consist of the sum of the three following effects: (a) the gas friction against the conduit walls, (b) gas friction on the particles being conveyed, and (c) the static head resulting from the column of solids in the test section. Subsequent data indicated

that this assumption was justified.

In calculating the pressure drop resulting from the gas friction on the particles, a particle moving at a uniform velocity was assumed to be held in equilibrium by the force of gravity and the friction of the gas on the particle.

Calculations made from the experimental data showed that the drag coefficients for the suspended particles agreed with those of single particles falling free in a still fluid.

Howard (7,8) investigated the flow of sand and water in a 4-in. horizontal pipe. In one series of tests data were obtained on the distribution of the solid in the mixture. A 7/16-in. diameter sampling tube which could be positioned at any point in the cross section of the pipe was used to obtain the data. The resulting data were plotted in the form of a series of diagrams containing contour lines to represent the percentage of the solid flowing above the contour lines. The contour lines indicated that the concentration was a function of vertical distance only and did not vary in the horizontal direction for a given contour line.

Burian (2) developed an expression for the ratio of the average velocity of the solid phase to the average velocity of the mixture. The problem was approached both experimentally and analytically and the results were compared. In order to arrive at the analytical expression, it was necessary to conduct a series of tests to determine the form of an equation for the solid distribution as a function of the vertical distance from the center of the conduit. These tests consisted of dividing the flow into two parts by a horizontal knife edge placed alternately at different heights

in the flow, and recording the percentage of the solid flowing above the knife edge. Data obtained on the velocity ratio indicated that it was independent of concentration and temperature. The experimental expression developed showed that the velocity ratio was a function of the ratio of the diameter of the particle to the diameter of the tube, the ratio of the density of the solid to the density of the fluid, and the Froude number.

III. OBJECTIVES

The objectives of this investigation were to obtain data on the velocity and concentration distribution of the solid phase in upward vertical flow and to study the use of photography as applied to the analysis of slurry flow.

IV. THEORETICAL ANALYSIS

From a study of the data obtained from the photographs, it was indicated that several assumptions might reasonably be made which would assist in an analytical approach to the flow of a slurry.

The first assumption made was that the number of particles contained in a unit volume of mixture was constant with respect to time, position along the length of the conduit, and location in the cross sectional area of the conduit. This assumption becomes invalid near the wall of the tube since it would require the particles to be dragged along the inside surface of the conduit. Observation of the flow and the photographs indicated that the particles are not in contact with the wall except in instances of certain particles having a lateral component of velocity large enough to cause impact with the wall. The data obtained indicate that the assumption is satisfactory for values of r (distance from the center of the tube) up to 0.95 of the tube radius.

Secondly, it was assumed that the velocity distribution of the fluid could be represented by the expression

$$v_r = v_o \left(\frac{R-r}{R} \right)^n \quad (1)$$

where v_r is the fluid velocity at a distance r from the center of the tube, v_o is the fluid velocity at the center of the tube, R is the tube radius and n is an exponent depending on the average velocity of flow. In the application of the equation (1), it was also assumed that the presence of

the particle does not affect the shape of the fluid velocity profile.

By plotting curves obtained from equation (1) on graphs of the velocity distribution of the particles, it was indicated that the difference between the fluid velocity and the average particle velocity was essentially constant. The difference agreed to within 10% of the calculated settling velocities of the particles. As a result, it can be said that

$$v_r - v_p = \text{constant } (v_r > v_p \text{ for upward flow}) \quad (2)$$

and

$$v_r - v_p = v_t \quad (2a)$$

where v_p is the velocity of a particle at a distance r from the center of the tube and v_t is the terminal settling velocity of the particle in a still fluid. Equation (2a) shows that at the wall where the fluid velocity is zero, the particle velocity becomes negative indicating that the particles travel downward along the wall. Since all particle velocities observed were positive and no particles were found at the wall, equation (2a) was assumed valid only in the region where particles appeared.

The average solids velocity is defined by

$$v_s = \frac{\int_0^A k \cdot v_p \, da}{\int_0^A k \, da} \quad (3)$$

where k is the number of particles per unit volume of the mixture, and da is the incremental area of the cross section. From Figure 1 it can be seen that

Figure 1. Cross section of tube showing differential area of flow

$$da = r dr d\theta \quad (4)$$

If equations (1), (2a) and (4) are substituted in equation (3) there results

$$v_s = \frac{\int_0^{2\pi} \int_0^R k \left[v_o \left(\frac{R-r}{R} \right)^n - v_t \right] r dr d\theta}{\int_0^{2\pi} \int_0^R k r dr d\theta} \quad (5)$$

By removing k since it was assumed constant, equation (5) can be written as

$$v_s = \frac{v_o \int_0^{2\pi} \int_0^R \left(\frac{R-r}{R} \right)^n r dr d\theta}{\int_0^{2\pi} \int_0^R r dr d\theta} - v_t \quad (5a)$$

The average velocity of the fluid was defined by

$$v_f = \frac{\int_0^A v_r da}{\int_0^A da} \quad (6)$$

If equations (1) and (4) are substituted in equation (6) there results

$$v_f = \frac{v_o \int_0^{2\pi} \int_0^R \left(\frac{R-r}{R} \right)^n r dr d\theta}{\int_0^{2\pi} \int_0^R r dr d\theta} \quad (6a)$$

The right hand side of equation (6a) is the same as the first term in the right hand side of equation (5a). Substitution of equation (6a) in equation (5a) produces

$$v_s = v_f - v_t \quad (7)$$

or

$$v_f - v_s = v_t \quad (7a)$$

which states that the difference between the average fluid and average solids velocity is equal to the settling velocity of the particles.

The ratio of the average velocity of the fluid to the average velocity of the mixture (derived in the Appendix)* is given by

$$\frac{v_f}{v_m} = \frac{\rho_s - \rho_m}{\rho_s - \rho_{mt}} \quad (8)$$

where ρ_s is the density of the particles, ρ_m is the density of the mixture as collected and ρ_{mt} is the density of the mixture flowing in the conduit. The difference between the two densities arises as a result of the difference in average velocities of the fluid and solid phases. A more detailed discussion of the difference in densities is included in the Appendix.

The ratio of the average velocity of the solids to the average velocity of the mixture (also derived in the Appendix) is given by

$$\frac{v_s}{v_m} = \frac{\rho_m - \rho_f}{\rho_{mt} - \rho_f} \quad (9)$$

where ρ_f is the density of the fluid. Equations (8) and (9) can be written as

*The appendix for this report is included in the M.S. thesis "Flow of an Aqueous Slurry Through a Vertical Tube" by Harold Wolfe, which may be obtained from the Iowa State College Library, Ames, Iowa.

$$v_f = v_m \left(\frac{w_s - w_m}{w_s - w_{mt}} \right) \quad (8a)$$

and

$$v_s = v_m \left(\frac{w_m - w_f}{w_{mt} - w_f} \right) \quad (9a)$$

where the subscripts are the same as before and the w's indicate specific weights of the materials. If equations (8a) and (9a) are substituted in equation (7a) it becomes

$$v_t = v_m \left[\left(\frac{w_s - w_m}{w_s - w_{mt}} \right) - \left(\frac{w_m - w_f}{w_{mt} - w_f} \right) \right] \quad (10)$$

It was noted that all of the variables contained in equation (10) were variables which could be measured or controlled. The terms v_t and w_s become fixed when a material is chosen, v_m and w_m are capable of being accurately controlled, and the choice of the fluid fixes w_f . On this basis equation (10) was solved for w_{mt} which gives

$$w_{mt} = \frac{1}{2} \left[(w_s + w_f) - \frac{(w_s - w_f)v_m}{v_t} \right] \pm \sqrt{\frac{1}{4} \left[(w_s + w_f) - \frac{(w_s - w_f)v_m}{v_t} \right]^2 - \left[w_f w_s - w_m (w_s - w_f) \frac{v_m}{v_t} \right]} \quad (10a)$$

By dividing both sides of equation (10a) by w_m there results

$$\frac{w_{mt}}{w_m} = \frac{1}{2w_m} \left[(w_s + w_f) - \frac{(w_s - w_f)v_m}{v_t} \right] \pm \frac{1}{w_m} \sqrt{\frac{1}{4} \left[(w_s + w_f) - \frac{(w_s - w_f)v_m}{v_t} \right]^2 - \left[w_f w_s - w_m (w_s - w_f) \frac{v_m}{v_t} \right]} \quad (11)$$

It was decided to calculate values of the ratio w_{mt}/w_m for values of the other variables, to determine the ratio experimentally and compare the results to check the assumptions leading to equation (11).

V. MATERIALS AND EQUIPMENT

A. Materials

The solid phase materials used in this study consisted of spherical particles of glass and steel. The glass particles were used exclusively in all work involving photography, whereas in the tests to obtain data on the specific weight ratios, both the glass and the steel particles were used.

Since the solid-fluid concentration could be more accurately controlled in a closed system, only particles small enough to pass through the centrifugal pump were used.

1. Size determination

Two methods were used in determining the average diameter of the particles. One method consisted of actual measurement under a microscope with a traveling eye piece. The other method consisted of measurements taken from photomicrographs of the particles.

Representative samples of the particles used in the size determination were obtained by repeated quartering of a random batch until the quantity was reduced to that needed for the measurements. The samples used in the photomicrographs were mounted on standard microscope slides using Canadian Balsam as cement. The photographs were taken by means of a standard camera attachment for the microscope. The

magnification factors were determined from photographs of short lengths of Karma alloy and copper wire taken at the same camera focusing as that used for the glass specimen slides. Since the diameters of the wire samples had been previously determined by monocular microscope and checked with micrometers, the wire photographs provided a source containing a predetermined dimension from which magnification factors could be calculated.

In taking particle measurements, readings were obtained from two perpendicular diameters, and in cases of ellipsoidal particles, the major and minor axes were measured. The arithmetic average of the diameter measurements gave the average particle diameter.

Photomicrographs taken of samples of the materials after circulation through the pump indicated that little or no damage to the particles had occurred.

Most of the data in Table 1 originally appeared in Murphy, Young, and Burian (10) and in Burian (2).

2. Specific weight determination

The specific weight of each size of particles was determined by the method of displaced volume. A representative sample of the particles was thoroughly dried and then added to a graduated cylinder partially filled with a fluid. The change in the volume reading and in the gross weight of the cylinder enabled calculation of the specific weight of the particles. Two fluids were used in the specific weight determination, water and carbon tetrachloride. The results are tabulated in Table 1.

Table 1. Summary of particle size and specific weight determinations*

Material	Method of size determination	Number of observations	Maximum observed inches	Minimum observed inches	Average inches	Specific weight pcf.
Glass	microscope	35	0.0134	0.0060	0.0114	177.9
	photographs	80	0.0136	0.0091		
	microscope	-	--	--	0.0314	156.9
	photographs	161	0.0474	0.0215		
	by manufacturer	-	--	--	0.0013	158.0
	photographs	50	0.0039	0.0016		
Steel	microscope	37	0.0199	0.0103	0.0149	465.0
	photographs	28	0.0175	0.0100		

* Most of these data appeared originally in Murphy, Young and Burian (10).

3. Determination of settling velocities

Experimental data obtained by Hariu and Molstad (6) showed that the drag coefficients of the particles of a slurry in vertical flow agree very well with those of single particles falling free in a still fluid. Calculation of the settling velocities used was based on the assumption that the particles had reached terminal settling velocities and the fluid drag on the particle was opposed by the difference between the particle weight and the buoyant force. Drag coefficients were obtained from Figure 2 which was taken from Prandtl and Tietjens (11). Where possible, actual measurement of settling velocity was made by timing the free fall of single particles in water through a known distance. The settling velocities of the materials used are tabulated in Table 2.

B. Equipment

The equipment used in the test work was, except for minor alterations and additions, the same apparatus used to conduct head loss studies on slurries.

The main items included the following: supply tank, agitator, cooling coil, centrifugal pump and motor unit, scales, stopwatch, two-liter graduated cylinder, a centigrade thermometer, and two test sections. One test section was used to conduct the specific weight ratio tests and the other to obtain the photographic data. In conjunction with the latter, a camera, film, synchronous motors and a floodlamp were used. A schematic diagram of the flow equipment is shown in Figure 3.

Table 2. Summary of settling velocity determination

Material	Method of settling velocity determination	Number of readings	Maximum observed fps	Minimum observed fps	Average fps
Glass					
0.0314-in. diam.	(experimental)	20	0.336	0.237	0.310
	(calculated)	-	--	--	0.365
0.0114-in. diam.	(experimental)	10	0.161	0.114	0.144
	(calculated)	-	--	--	0.131
0.0028-in. diam.	calculated	-	--	--	0.0114
Steel					
0.0149-in. diam.	calculated	-	--	--	0.520

Figure 2. Drag coefficients for a sphere in a still fluid*

*Taken from Prandtl and Tietjens (11)

Figure 3. Schematic diagram of flow equipment

Since it was decided to use particles which could pass through the pump, a fixed quantity of mixture could be used, resulting in a closed circuit system.

With the proper quantity of solids and fluid in the supply tank (A) and with the agitator motor (J) operating, a supply of slurry was available. The mixture was drawn from the supply tank and passed through pump (G) after which it was directed through valve (B) and the nozzle at (D) or through the large valve at (C).

At the union (E) it was possible to establish flow through the 0.314-in. I.D. glass tubing (F) or by joining union (E') with union (E), the flow could be passed through the 1-in. galvanized pipe.

In the tests utilizing test section (L), both the glass tubing (F) and the 1-in. pipe were used, according to the flow rates desired.

With the glass tubing (F) in the circuit, the flexible tubing (P) was attached to the lower end of section (L) and the flow passed upward through the section and back to the supply tank via tubing (Q). By adjusting the clamp (H) on tubing (T) to by-pass a portion of the flow and send it directly to the supply tank, accurate control of the flow rate through the test section was gained.

If higher velocities in the section (L) were desired, the 1-in. galvanized pipe was connected in the system at union (E) and at the lower end of (L). Flow was then routed through valve (B) and the nozzle at (D) to obtain velocity control. Precalibrated nozzles (D') were used to give the proper flow rate, and were installed by clamping them in the short length of rubber hose at (D).

The flow circuit for the specific weight ratio tests was the same as that described above for use of the glass tubing (F), except that the flexible tubing (P) was connected to the lower end of test section (K). The flow then traveled upward through the section (K) and back to the supply tank via tubing (R).

A sketch of section (K) is shown in greater detail in Figure 4. It consisted of a length of 0.314-in. I. D. glass tubing with a glass stopcock attached at each end. The length between stopcocks was approximately 60 in. A male portion of a ball-and-socket joint was attached to each stopcock as shown in the sketch. These joints permitted easy removal and installation of the test section (K) during the tests.

Figure 5 includes a sketch of the apparatus used to obtain pictures of the flow. The essential elements were the light source to illuminate the flow area, a light collimating slit, timing disc, and a light source to illuminate the timing disc.

The light source used to illuminate the tube diameter was a General Electric Photoflood Lamp No. RFL-2, operating on 110-120 volts. The lamp was enclosed in a can lined with asbestos sheeting to isolate the light source and to prevent radiation of heat.

The collimating slit was fabricated from plexiglass and painted on all surfaces with flat-black paint to prevent reflection of stray light. It was 1/8-in. wide, 3-in. long and 3-in. high, and served the purpose of admitting a 1/8-in. wide beam of light across the diameter of the test section.

The collimating slit was mounted in one wall of a water-tight

Figure 4. Details of specific weight ratio test section

Figure 5. Details of photographic apparatus

plexiglass box which was built around the outside of the test section. All internal and external surfaces of the box, except one wall, were coated with flat-black paint to absorb stray light. The wall of the box left transparent was perpendicular to the wall containing the light slit and thus was parallel to the sheet of light crossing the tube diameter. Photographs of the flow were taken through this window. In order to eliminate image distortion caused by the curvature of the tubing, the plastic box was filled with water.

Two synchronous speed motors were used to drive perforated rotating discs which were photographed simultaneously with the flow and provided an accurate exposure-time source.

One of the motors was a Model M4E, No. MCE/738 Westclox electric clock motor and turned at a synchronous speed of 7.5 rps. It was used to obtain shutter speeds slower than $1/30$ sec.

The other motor was a $1/100$ hp Robbins and Meyers 115 volt, 60 cycle A. C. motor turning at a speed of 1800 rpm and was used to obtain shutter speeds faster than $1/30$ sec.

Plexiglass discs painted flat-black were mounted on the shafts of both motors and small box-like enclosures containing light sources were built around the discs. The enclosures were constructed with back lighting in order to make the rotating discs appear as a group of whirling, concentric pinpoints of light when viewed from the front. These pinpoints of light were exposed as circular arcs during the time the camera shutter was open.

The camera used was a standard 4 by 5-in. professional model

mounted on an adjustable tripod and fixed with a f 4.5 lens calibrated for various shutter speeds.

Kodak Royal Pan High Speed film was used for all pictures. This film had the feature of having a very high tungsten exposure index which was most desirable for this type of work since a relatively small amount of light was admitted to the test section.

VI. EXPERIMENTAL PROCEDURE

The preliminary procedure followed in readying the equipment for test runs was the same for both the photographic method and the specific weight ratio tests.

First, the supply tank was filled with water to a level well above the pump intake and the cold water supply to the cooling coil submerged in the supply tank was turned on. The cooling coil was used more in the interest of maintaining a constant mixture temperature than in attempting to reach a specified temperature since the work done on the mixture by the pump caused a gradual increase in temperature of the uncooled mixture.

The agitator motor was then turned on and a flow of water to the water-seal on the pump shaft was established.

At this point, the procedure followed depended on the type of test to be performed.

A. Photographic Method

In order to obtain photographs of the flow pattern, the initial step was the location and focusing of the camera. This was done by first locating the camera in an approximate position in front of the test section. Then the return line from the outlet of the test section to the supply tank was disconnected for access to the inside of the test section. For sharp focusing, a piece of coordinate paper mounted on plexiglass was lowered

into the test section and positioned to receive the maximum illumination from the light slit. The camera was then adjusted to give the largest magnification of the test section and still include the rotating disc in the picture. At this point, the test section was filled with water to a level above the viewing area and the camera was focused to obtain sharpest definition of the grid on the coordinate paper. The coordinate paper was then removed and the return line reconnected.

If it was desired to photograph the flow at a velocity less than 1.5 fps, connections were made at the union (E), Figure 3, to direct the flow through the glass tubing. After closing valve (B) and opening valve (C) the pump was started. Several adjustments of the clamp (H) on the flexible bypass line were necessary to divide the flow. Velocities were determined from data obtained by noting the time required to collect a two-liter sample of the mixture passing through the test section. The quantity collected per second divided by the cross sectional area of the tube gave the average velocity.

If velocities greater than 1.5 fps were to be used, the one-inch galvanized pipe was connected in the system and a pre-calibrated copper nozzle was installed in the rubber hose at (D) to give the desired velocity. Valve (C) was then closed, and valve (B) was opened to divert the flow through the nozzle and the pump was started.

After the desired velocity had been obtained, a small quantity of the solid phase was added to the supply tank and the flow was observed in the test section. Repeated additions of solids and observations of the flow were usually necessary to prevent over concentration of the particles.

Once the flow appeared satisfactory, the film was inserted in the camera, shutter speed and diaphragm opening were set, and the rotating disc was started. The light source was switched on and left burning only long enough to permit the picture to be snapped.

After the picture had been taken, the disc was stopped and the film was removed from the camera. An additional check on the velocity was then made and at the same time the temperature of the slurry was recorded.

Pictures were taken of the 0.0314-in. diameter particles at velocities of 1.0, 1.5, 2.0, 2.5, and 3.0 fsp. The 0.0114-in. diameter particles were photographed at velocities of 0.5 and 0.6 fps and the 0.0028-in. diameter particles were photographed at velocities of 0.13 and 0.18 fps.

After a group of pictures, usually six or eight, had been exposed they were taken to the darkroom for developing. Darkroom procedure was standard in regard to steps followed, developing chemicals, and developing times.

When the film had been developed, washed, and dried, the exposure times were determined. This was done by measuring, with a protractor, the angle through which the rotating disc had turned while the shutter was open. In all cases there were at least two circular exposed streaks from which the angles could be measured. The fraction of a revolution through which the disc had turned was determined from the average of the individual arc readings. The average fraction of a revolution was divided by motor speed in revolutions per second to give the time in seconds.

With the time interval known, the next step was to obtain data from the negatives relative to particle positions and particle velocities. The negative was placed under a magnifying lens and the particles leaving the darkest streaks (those most brilliantly lighted during exposure) were chosen to use as a data source.

For each group of pictures, it was necessary to determine the scale between the actual test section and its size as shown on the film. The scale was determined by measuring the diameter of the test section or the diameter of the rotating disc on the negative and comparing it with the known true dimension. All of the measurements taken from the negatives were corrected to true size.

Two measurements were required to determine particle data, one to fix the particle position on the diameter and the other to calculate particle velocity.

The first measurement was taken from a point designated as the inside wall of the test section to the center of the streak left by the particle. This dimension positioned the particle on the diameter illuminated by the light source. The second measurement consisted of finding the length of the particle streak, from which the velocity was calculated by dividing the streak length by the exposure time.

B. Specific Weight Ratio Tests

The specific weight ratio tests were all conducted using flow directed through the 0.314-in. diameter glass section. After the glass stop-cocks on the test section had been carefully adjusted to offer minimum

resistance to flow, the test section was clamped in the socket joints and the pump was started.

Solid phase material was added to the supply tank and allowed to circulate through the system until equilibrium was reached. A two-liter sample was then collected from the return line emptying into the supply tank and the time to collect the sample was recorded. The specific weight of the mixture collected was calculated from the volume and the weight of the mixture. Weights were determined by weighing the two-liter graduate and contents on a scale accurate to 0.02-kg. and subtracting the tare of the graduate.

Velocities were determined in the same manner as that used for the photographic method tests.

Adjustment of the specific weight was accomplished by adding or removing solid phase material, or by adding or draining water from the system.

After the desired velocity and specific weight values were established the run was ready to be made. The time required to collect a two-liter sample was checked with a stopwatch. The weight of the graduate and contents, the exact volume collected and the time to collect the sample were recorded. A centigrade thermometer was used to determine the mixture temperature.

Then, with the help of an assistant and following a count-down procedure, the two glass stopcocks on the test section were simultaneously closed, at which time the entire flow was directed through the flexible by-pass line back to the supply tank. The test section was

unclamped, removed, and weighed on balance scales accurate to 0.10 gm. Subtraction of the tare weight of the glass tubing from the total weight resulted in the weight of the mixture isolated between the stopcocks. The volume trapped between the stopcocks was constant and was determined by measuring, with a graduated cylinder, the quantity of water necessary to fill the section and by filling the section with water, weighing it and converting the weight of the water to a volume figure. The volume was found to be 79.4 cc.

The specific weight of the mixture flowing through the tube was calculated by dividing the weight collected by the volume of the section.

After the data were recorded, the test section was drained, the stopcocks were readjusted and the section was again clamped in the circuit ready for another run.

Specific weight ratio tests were run on the 0.114-in., 0.0028-in., and 0.0013-in. diameter glass particles and on the 0.0149-in. diameter steel particles. Data for these particles were taken at velocities ranging from less than 1 fps to 18 fps and for weight concentrations ranging from 5% to 30%.

VII. DISCUSSION OF RESULTS

A. Photographic Method

The results obtained from the experimental work are shown in Figure 6 through Figure 19.

In Figure 7 through Figure 15, each point plotted represents the velocity and position of a particle along the diameter of the test section at the time of exposure. The region photographed was a volume of the flow measuring 1/8-in. by 1.47-in. by 3-in.. The 1.47-in. dimension corresponded to the diameter of the test section and the 1/8-in. dimension was the width of the beam of light extending across the diameter. The 3-in. dimension was arbitrary. Particles traveling through the illuminated region during the time the shutter was open were exposed as streaks on the negative. Circular symmetry was assumed since the test section was in a vertical position and the conduit was circular in shape. As a result, the data obtained represent the conditions existing along any diameter of the cross section.

In order to study particle concentration distribution, the diameter was divided into twenty equal increments (twenty equal volumes when the 1/8-in. thickness and the 3-in. height are considered). The percentage of the total number of particles photographed, which happened to be in each increment, was plotted vs. the increment position. The data obtained are shown in Figure 6 where the dashed curve represents

Figure 6. Average distribution of particles photographed

Figure 7. Velocity distribution of 0.0314-in. diameter glass beads in water flowing vertically upward in a 1.465-in. I.D. glass tube

Figure 8. Velocity distribution of 0.0314-in. diameter glass beads in water flowing vertically upward in a 1.465-in. I. D. glass tube

Figure 9. Velocity distribution of 0.0314-in. diameter glass beads in water flowing vertically upward in a 1.465-in. I.D. glass tube

Figure 10. Velocity distribution of 0.0314-in. diameter glass beads in water flowing vertically upward in a 1.465-in. I.D. glass tube

Figure 11. Velocity distribution of 0.0314-in. diameter glass beads in water flowing vertically upward in a 1.465-in. I. D. glass tube

Figure 12. Velocity distribution of 0.0114-in. diameter glass beads in water flowing vertically upward in a 1.474-in. I.D. glass tube

Figure 13. Velocity distribution of 0.0114-in. diameter glass beads in water flowing vertically upward in a 1.474-in. I.D. glass tube

Figure 14. Velocity distribution of 0.0028-in. diameter glass beads in water flowing vertically upward in a 1.474-in. I.D. glass tube

Figure 15. Velocity distribution of 0.0028-in. diameter glass beads in water flowing vertically upward in a 1.474-in. I.D. glass tube

Figure 16. Comparison of experimental results with data obtained from analytical expression for w_{mt}

Figure 17. Comparison of experimental results with data obtained from analytical expression for w_{mt}

Figure 18. Comparison of experimental results with data obtained from analytical expression for w_{mt}

Figure 19. Comparison of experimental results with data obtained from analytical expression for w_{mt}

the arithmetic average of the percentage values found in each of the twenty increments previously mentioned.

In interpreting the data in Figure 6, two factors affecting the shape of the curve were taken into consideration. The first of these factors was created by the method used to illuminate the region photographed. As the light progressed through the slurry it was decreased in intensity and the particles on the side of the tube away from the light source were only partially illuminated or not illuminated at all because of interference of other particles. The second factor was due to the use of a circular flow area. In order to reach the camera lens, light from an illuminated particle had to travel through a thickness of mixture that was a function of the position of the particle on the diameter. As a result, the mixture thickness increased from a minimum at both ends of the diameter to a maximum at the center of the tube, leading to a corresponding interference to light transmission.

Figure 6 reflects the influence of the two factors just discussed since the curve indicates a greater concentration of particles at the side nearer the light source (negative values of Y/R) and a minimum near the center of the tube. After considering these effects on the shape of the dashed curve and the appearance of the other data in Figure 6 it was assumed that the number of particles per unit volume of mixture was constant across the diameter and was not affected by mixture velocity.

In slurry tests performed by the author and others a flow condition termed "coring" (explained in section X, Suggested Topics for Further

Investigation) has been observed to exist under certain combinations of mixture velocity, particle size, and tube diameter. As a result, it becomes necessary to limit the constant concentration assumption to flow where "coring" does not occur.

In Figure 7 through Figure 13, turbulent flow was reached due to the mixture velocities required to keep the 0.0314-in. diameter particles in suspension. The dashed lines representing the average velocity profiles for the particles were obtained from smooth curves drawn through the arithmetic average of the velocities of the particles found in each of the twenty diameter increments.

For comparison purposes, the velocity profile for water flowing in the same section at the same average velocity as that of the mixture was drawn on each plot of the particle data. Equation (1) was used to determine the water profile. The maximum fluid velocity was determined by using the curve in Figure 20 which was taken from Stanton and Pannel (13). A value of $1/7$ was used for the exponent n and it gave results which agreed to within 6% for a velocity of 0.50 fps and 2.5% for a velocity of 3.0-fps of data in Stanton and Pannel (13) for the velocity distribution for fully developed turbulent flow.

When the fluid profile was compared with the particle velocity profile, it was noted that the two curves were separated by a distance (velocity) that was essentially constant for a given size particle. The distances between the fluid and particle profiles for the 0.0314-in. and 0.0114-in. diameter particles were compared with the calculated settling velocities of the particles. These distances agreed to within

Figure 20. Relationship between average velocity and maximum velocity as a function of Reynolds number*

* Taken from Stanton and Pannel (13.)

10% of the calculated settling velocities except for the tests at flow rates of 2.5- and 3.0- fps where agreement was within 40% of the calculated settling velocity.

As a result of the similarity of shape between the fluid and particle velocity profiles it was assumed that the presence of the particles does not affect the shape of the velocity profile of the fluid phase. It was also assumed that the particle velocity profile is separated from the fluid profile by a velocity equal to the settling velocity of the particles.

Figures 14 and 15 represent data on the 0.0028-in. diameter glass particles which had a settling velocity small enough to permit flow rates which would normally insure laminar flow of water. Due to the small settling velocity of the particles, the difference between the fluid and particle velocity profiles is small and the particle velocity profile represents, with close approximation, the mixture velocity profile.

The solid lines in Figures 14 and 15 represent the velocity profile of water in laminar flow at the same average velocity as the mixture. Good agreement is indicated in Figure 14 except for the inner half of the tube where the mixture profile lags the fluid profile by a considerable amount. One explanation for this is the fact that in the test section used, the length of approach to the viewing area was only about 33 diameters. In addition, entrance conditions to the test section were not ideal. Normally, a minimum of 50 diameters and good entrance conditions are recommended before fully developed laminar flow can be expected.

The possibility of error in the determination of the average mixture

velocity on which the solid line is based was investigated. This would require an error of 20% based on the 0.131-fps velocity figure to cause the recorded difference in the curves. As will be discussed later, the normal expected errors were well below this figure. It is also possible that the presence of the particles alters the properties of the fluid sufficiently to prevent prediction of laminar flow velocity profiles in the normal manner.

Figure 15 represents a higher average mixture velocity than that of Figure 14. The value of the Reynolds number, entrance conditions, and approach length suggest the possibility that the flow entered the section in a turbulent state and did not have sufficient length of travel for laminar conditions to develop to the same point as in Figure 14. Calculations show that the flow was well into the turbulent region (Reynolds number = 3400) in the tubing leading to the test section for a test section velocity of 0.182-fps.

There were several factors influencing the data taken from the negatives which account for some of the spread in the results. The first of these factors, and one which does not lend itself to control by the experimenter, is the normal fluctuations of velocity components in the direction of flow as well as in a direction normal to the flow. These fluctuations could be expected to become evident in the velocities of the particles and this was borne out by the fact that in many cases the particle streaks measured did have components of velocity normal to the direction of flow.

Another factor influencing the data was the variation in particle size. In the stock of 0.0314-in. diameter glass particles used, particles were included which had diameters ranging from 0.0474-in. to 0.0215-in.

diameter, which resulted in calculated settling velocities of 0.550-fps and 0.242-fps, respectively. This is a spread of 0.308-fps in the settling velocity of the particles used and would account for a large portion of the scatter in the data for the 0.0314-in. diameter glass.

For the 0.0114-in. diameter glass, the diameters ranged from 0.0136-in. to 0.0060 in. resulting in settling velocities of 0.166-fps and 0.051-fps, respectively. This is a spread of 0.115-fps and it would account for most of the scatter in the 0.0114-in. diameter glass data.

Error in velocity determination also influenced the spread of the data. Representative figures for the error in time were approximately 2%, although by using shutter speeds of 1/50-second or slower, the error was in some cases reduced to 1% or less. Measurements of particle streak lengths were accurate to 0.01-in. which in most cases introduced an average error of approximately 3% with cases as high as 10% and others as low as approximately 1%. The 0.01-in. error in streak length measurements was due more to the difficulty in ascertaining the actual end points of the streaks rather than in the scales used to obtain the lengths. The condition of the end points of the streaks was due to the gradual increase and decrease of exposure at the beginning and end of the shutter cycle, and as a result it left each end of the streak with a gradation in exposure from the negative background to the fully exposed streak. The shutter used was spring operated and, having mass, it required a certain period of time to reach full open position and a certain period of time to close again. At higher shutter speeds (over 1/100 sec.) this opening and closing time can become very

significant, sometimes requiring 20 to 30% of the shutter time cycle to open and the same to close.

The percent error in determining mixture velocities and specific weights was approximately 1% based on the accuracy in timing, sensitivity of the scales used, and the error in reading volumes from the graduated cylinder.

Figure 21 is a typical picture of the flow and the timing device.

B. Specific Weight Ratio Tests

In Figure 16 through Figure 19 are shown results of the specific weight ratio tests used to verify the assumptions based on the photographic data. The solid lines in each figure represent the calculated values of the ratio w_{mt}/w_m . In Figure 16 and Figure 17 good agreement between calculated and experimental values was obtained. In these curves, variation from the calculated values was less than 1%.

Figure 18 indicates fair agreement for Froude numbers greater than 20. For values of the Froude number less than 20 there appears a definite trend for the tube concentration to be less than that collected at the discharge end. This indicates that the average velocity of the solid is greater than that of the fluid. This correlates with visual observations of the flow made during the tests where the "coring" characteristics become evident. With "coring" present the solid phase travels up the center core of the tube and thus takes advantage of the opportunity to maintain a higher average velocity than the fluid. This condition

Figure 21. Typical photograph showing flow and timing disc

existed for the range of Froude numbers from about 1 to 20, as is shown by the dip in the curve through this range. Below a Froude number of 1 the flow tended to revert to an evenly distributed appearance but still showed evidence of ragged and turbulent behavior.

In Figure 19 the "coring" behavior existed throughout the velocity range tested and as a result these data cannot be used to support the assumptions made. The trend of the data suggests that the "coring" would possibly dissipate for Froude numbers less than 2 and greater than 150 or 200.

VIII. CONCLUSIONS

As a result of this investigation, the following conclusions were reached.

A. Photographic Method

- (1) The photographic method of slurry investigation can be an important tool in obtaining data on slurry behavior.
- (2) The photographic method can be adapted to the investigation of a three-dimensional flow problem without reducing it to a two-dimensional configuration.
- (3) This method would lend itself particularly well to the situation requiring flow study without disturbing the flow pattern by the addition of foreign bodies into the flow stream.
- (4) Use of the photographic approach requires very close attention to details of lighting, timing, and particles used as tracers.
- (5) From the time standpoint, reduction of data obtained from the photographic method is rather time consuming and tedious.
- (6) The method offers the advantage of providing a permanent and portable history of the flow patterns.
- (7) As used in this report, the photographic method cannot be depended on to give more than an indication of the pattern of particle distribution.

B. Specific Weight Ratio Tests

- (1) The assumptions made on the basis of the data obtained from the photographs are valid only for flow conditions where "coring" of the solid phase does not occur.

IX. SUGGESTED CHANGES IN THE EQUIPMENT

The experience gained during use of the equipment indicated certain changes could be made in various items to improve their performance.

Two basic improvements could be made in the specific weight ratio test section. The first of these would be the addition of an approach section at least 50 times the inside diameter of the test section in length and having the same internal diameter as the test section. This would provide a length in which stable flow conditions could develop before the mixture entered the test section.

The second change indicated involves redesign of the method of trapping the flow in the removable length of tubing. The primary aims of the improvement would be the following: (a) to assure rapid cutoff of the flow without a "pinching-off" effect taking place and (b) to provide simultaneous operation of the valving at each end. A possible design might be that utilizing two sliding doors mounted in watertight slots at each end of the section. The doors would lie in the plane of the cross sectional area of the tube and could be operated on a push-pull basis. This method of operation would lend itself to interconnection between ends of the section to permit simultaneous operation of the doors.

The photographic apparatus was lacking in two respects. The first of these was in the amount of light available to illuminate the particles. The amount was satisfactory at the side of the tube where it entered, but in traveling through the mixture its strength was weakened some-

what, and as a result an uneven exposure was obtained. The addition of another light source in a symmetrical position on the opposite side of the section would remedy this.

The inherent inertia of the shutter system, as mentioned in the Discussion of Results, causes a variation of the amount of exposure given a moving object. This defect could possibly be corrected by the use of a focal plane shutter traveling in a direction perpendicular to that of the moving particles.

X. SUGGESTED TOPICS FOR FURTHER INVESTIGATION

The results obtained using the photographic method described in this paper have indicated other topics which might be investigated using the same basic technique.

Recent data on the vertical flow of slurries obtained by the author and others have indicated that several conditions of flow are possible. Of particular interest is that condition in which the solid phase in upward flow collects at the center of the conduit in a core leaving an annulus of pure fluid between this core and the conduit wall. This phenomena would lend itself to a photographic study of velocity distribution, core diameter, and annulus thickness as related to particle size and mixture velocity.

The data have also indicated that conditions of flow analogous to turbulent and laminar flow of a pure fluid exist in both upward and downward vertical flow. These phenomena could also be investigated photographically.

The photographic approach could be applied to the study of horizontal flow of a slurry, particularly in the velocity ranges where the solid phase is deposited along the bottom of the conduit and remains there or is moved along at a velocity significantly less than that of the mixture flowing above.

Problems of conduit erosion in bends, restrictions or expansion sections could be studied with this method of analysis.

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