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SUBJECT: SLURRY FLOW METERS AND DENSITY METERS
FOR THE HOMOGENEOUS REACTOR

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INTRODUCTION

Six types of instruments are being considered for the metering of flow and/or density in high temperature (300°C) and pressure (2000 psi) slurry flow systems. Three of these meters yield readings that depend only on the flow rate or the density, one (the Double Rotameter) yields two readings from which both the flow and the density may be determined while another (the venturi) yields a reading that depends on both the flow rate and the density and thus may be either a density-meter or a flowmeter depending on which variable is the unknown. The remaining instrument (the ultrasonic meter) may yield a signal dependent solely on the flowrate or the density depending on the physical setup. This memo briefly describes these instruments, listing their particular advantages, the difficulties that may arise in their use and the state of development of each.

A. Electromagnetic Flow Meter

1. Description. The well known principle of the electromagnetic flow meter is illustrated in Fig. 1. A potential (e) is produced across the fluid traversing the magnetic field. The induced EMF, magnetic lines of force and liquid flow are mutually perpendicular. For the arrangement shown in Fig. 1, where an insulating sleeve prevents the electrical short circuit from electrode to electrode via the pipe wall and where the electrodes themselves are electrically insulated, the induced EMF is related to velocity by the simple relation

$$e = cHdV \quad (1)$$

e = generated EMF, millivolts

c = constant = 10^5 for circular conduits

H = magnetic field, Gauss

d = distance between electrodes = diameter of pipe for flush electrodes, cm

V = average fluid velocity, cm/sec.

When the electrodes are simply tacked to the outside of the pipe and there is no insulating sleeve, the relation between generated EMF, fluid velocity, fluid and pipe resistivities and system geometry is given by the relation derived by Elrod and Fouse¹

$$e = cHvd \frac{\frac{d^2}{D}}{1 + \frac{d^2}{D^2} + \frac{\rho_f}{\rho_w} \left(1 - \frac{d^2}{D^2}\right)} \quad (2)$$

where,

e , c , H and V have the same meaning as in eq. (1)

d , D = tube ID and OD, cm

ρ_f , ρ_w = electrical resistivities of fluid and wall.

Note that when the ratio ρ_f/ρ_w is high (approximately 10^6 for dilute electrolytes in a steel pipe) e is correspondingly reduced and the electrodes must be insulated as in Fig. 1 to obtain sufficiently large readings. As the ratio ρ_f/ρ_w and the tube wall thickness is decreased, equation 2 approaches equation 1.

2. Status of Development. Development work on the electromagnetic flowmeter falls into two general categories; that associated with the design

of the electrical system and that associated with the materials of construction. James² describes the electrical system used at ORNL for the metering of low flows of radioactive liquids while Boeke³ lists the several electrical phenomena that yield spurious effects and how they were compensated for in the available Foxboro Magnetic Flowmeter.

Two of these flowmeters have been purchased by the Instrument Division, one of which was tested with satisfactory results in a low temperature slurry test loop.⁴ During this 100 hour test with 800 g Th/kg H₂O slurry, the flow rate was determined by the magnetic flow meter deviated from that determined by a venturi in series with the instrument by an average of $\pm 2\frac{1}{2}\%$. This uncertainty is within the precision of the venturi, the associated d/p cell and slurry density determination. The sleeve material is teflon and consequently the upper temperature limit of the transmitter is only 230°F. A satisfactory insulating material for high temperature (300°C) service remains the sole holdup. The Foxboro Co. is presently contacting both Norton Abrasives and the Corning Glass Co. in a search for a satisfactory insulating material.

3. Advantages. (a) The meter's reading is not a function of the flow profile nor of the physical properties of the fluid and so is unaffected by any changes in them. (b) There is no flow obstruction. (c) The meter's response is directly proportional to average velocity so that totalizing a varying flow-rate is a simple matter.

The chief disadvantage of the electromagnetic flowmeter, aside from the difficulty of finding a suitable high temperature insulator, is that the deposition of slime or cake might tend to insulate the electrodes. A periodic measurement of the resistance across the electrodes when the unit is filled with slurry would indicate when scale or cake had formed on the electrode, but it would not correct the situation. The permissible resistance at the electrodes would depend on the by pass resistance between them, and on the impedance of the detecting instrument.

B. The Ultrasonic Flowmeter

1. Description.^a To measure flow, the ultrasonic flowmeter uses the effect of fluid motion upon the time in which a sonic impulse proceeds from one fixed point to another. The quartz crystal transducers are arranged on the pipe wall as shown in Fig. 2. The time required for the impulse to reach receiver (1) from transmitter (1) is given by

$$t_1 = \frac{d \csc 45^\circ}{c + v \cos 45^\circ} \quad (3)$$

while the time from transmitter (2) to receiver (2) is

$$t_2 = \frac{d \csc 45^\circ}{c - v \cos 45^\circ} \quad (4)$$

where:

c = characteristic sonic propagation velocity

v = fluid velocity

d = inside pipe diameter.

As variations in the sonic propagation velocity will usually be great in comparison to variations in the flow rate, the problem is to compensate for their effect on the time interval. This is accomplished by allowing each pulse to be triggered by the previous pulse as it impinges upon the receiving transducer, and thus the frequency of pulses is determined by the time intervals as follows:

^a The description of the Ultrasonic Flowmeter is taken from M. Koblenz, et al.⁵

$$f_1 = \frac{1}{t_1} = \frac{c + v \cos 45^\circ}{d \csc 45^\circ} \quad (5)$$

$$f_2 = \frac{1}{t_2} = \frac{c - v \cos 45^\circ}{d \csc 45^\circ} \quad (6)$$

The beat frequency ($f_1 - f_2$) then is independent of the sonic velocity and is proportional to the flow rate.

$$\text{beat frequency} = f_1 - f_2 = \frac{2v \cos 45^\circ}{d \csc 45^\circ} = \frac{v}{d} \quad (7)$$

2. State of Development. Koblenz et al. (of the Fischer-Porter Co.) state that hermetically sealed quartz transducers have been developed that are capable of withstanding pressures of 2500 psi and temperatures of 600°F, however, sales representatives of the Fischer-Porter Co. have not as yet been contacted as to the availability of this instrument. The performance and life of the crystals in a radiation field is another question mark.

3. Advantages and disadvantages. There is no mechanical obstruction in the pipeline and therefore low pressure drop and wear.

Chief disadvantages are: (a) Variations in the flow profile affect the readings. With a parabolic velocity distribution, the ratio of indicated to actual velocity is 0.75. In the transition region this ratio increases steadily to 0.9 while in turbulent flow the value lies between 0.9 and 1.0. (b) Drift in the system also limits accuracy. The source of the drift may be either mechanical deformation or changes in the electrical components.

4. Use as a Density Meter. By arranging the transmitters and receivers as shown in Fig. 3, the beat frequency becomes a measure of the fluid density.

The pulses are projected across the pipe perpendicular to the pipe axis and hence the time interval from transmitter to receiver and also the pulse frequency is independent of fluid velocity.

Therefore, the beat frequency, F , is given by

$$F = f - f_R = \frac{C - C_R}{d} \quad (8)$$

where the subscript R refers to the reference fluid contained in a pipe of the same diameter, d , as the slurry. The beat frequency then is inversely proportional to the difference in the sonic propagation velocity in the slurry and in the reference fluid. For a homogeneous fluid:

$$c = \sqrt{\frac{B}{\rho}} \quad (9)$$

where:

B = bulk modulus, change in fluid pressure/fractional change in volume

ρ = fluid density.

Assuming that Eq. (9) also applies to a slurry and substituting in equation (8):

$$F = \frac{\sqrt{\frac{B}{\rho}} - \sqrt{\frac{B_R}{\rho_R}}}{d}$$

or

$$\rho = \frac{B}{\left(\sqrt{\frac{B_R}{\rho_R}} + dF\right)^2} \quad (10)$$

Thus, the fluid density is determined from the beat frequency, F , the known values of the bulk moduli, and the reference fluid density. The precision that may be obtained with this principle is not known.

It should be noted that the Chemical Technology Division has a sub-contract with the Houdry Process Corporation for the development of ultrasonic equipment for use on slurry systems, with the major interest being in an interface follower for settling rate determinations.

C. The Double Rotameter^a

1. Description. This system consists of two rotameters in series equipped with bobs of different density. The tapered rotameter tubes are metallic, and the position of the bobs, which contain a soft iron core, are determined by differential transformers around the tubes. The number of turns per unit length of the secondary coil of each transformer varies with height so that the output voltage is a function of bob height.

$$G = c_D A_2 \sqrt{\frac{2g V_b (\rho_b - \rho) \rho}{A_b \left\{ 1 - \frac{A_2}{A_1} \right\}^2}} \quad (11)$$

where:

G = mass flow rate, lb m/sec

c_D = discharge coefficient

A_2 = area at constriction between rotameter bob lip and tube wall, ft²

A_1 = cross-sectional area of flow upstream from A_2 , ft²

g = acceleration of gravity, ft/sec²

^a System conceived and constructed by R. N. Lyon

V_b = volume of rotameter bob, ft^3

ρ_b = density of rotameter bob, lb m/ft^3

ρ = fluid density, lb m/ft^3

A_b = maximum cross-sectional area of bob perpendicular to flow, ft^2 .

Usually the ratio $(A_2/A_1)^2$ is small and equation (7) may be written:

$$G = c_D A_2 \sqrt{\frac{2gV_b}{A_b} (\rho_b - \rho)\rho} = c'_D A'_2 \sqrt{\frac{2gV_b}{A'_b} (\rho'_b - \rho)\rho} \quad (12)$$

where the primed quantities refer to the second rotameter in series with the first. The values of A_2 and A'_2 , which are functions of the bob height, are obtained from the voltages of the transformers around the tubes (from a calibration), and if the values of the discharge coefficients and the size and weight of the bobs are known, the above simultaneous equations may be solved for the flow rate and density. If c_D and c'_D are equal (as would be the case if flow passing the bob lip were turbulent) and if both bobs are of the same size and shape a simple, rapid graphical solution of equation (12) can be made.

2. State of Development. Development work on the double rotameter involves obtaining a satisfactory electrical system which determines the position the bobs and obtaining a satisfactory bob-tube geometry.

At present a system built around 1-1/4" thin walled pipe is on hand. In water tests a desirable linear dependence of transformer output voltage with bob height was found, however the rapidity of response was less than satisfactory. Possibly going to a higher transformer excitation frequency and hence allowing use of smaller sized filter condensers in the electrical circuit will aid in this respect.

Thus far, in the single test in a slurry stream, the double rotameter did not function as predicted by the rotameter equations but by no means should any final judgment be made based on the result of that single test. However, it is a distinct possibility that satisfactory functioning of the double rotameter requires that the slurry be Newtonian or near Newtonian.

3. Advantages. The double rotameter system indicates both flow rate and density without any mechanical breaching of the pipe wall.

D. The Venturi

1. Description. A venturi system employing a continuous purge of the pressure taps to prevent entry of slurry into the manometer lines has given approximately 2830 hours (~2100 with slurry) of trouble free service since its installation in S-loop.⁶ A flow diagram of the unit is shown in Fig. 4. Pressurizer condensate is collected in the surge tank and then flows through two high pressure rotameters into the venturi pressure traps. The purge rates may be regulated by valves whose stems extend through the loop shield. The d/p cell is connected across the two purge lines.

2. Development. S-loop experience has shown that a purge rate of 2 cc/min into each tap is easily maintained and suffices to maintain the manometer system slurry free. The new 200A loop (loop 200AM) which will have several venturis and pressure taps will be equipped with a more elaborate purge system employing the same principle.

3. Advantages and Disadvantages. The primary advantage of the venturi system is that it is a system of proven reliability that is available for installation now.

E. The Pressure Bridge Density Meter⁷

1. Description. The principle of the Pressure Bridge is illustrated in Fig. 5. The flow entering the loop divides equally as shown, and the differential pressure between the upper and lower legs is measured. In proper operation the fluid friction loss from the inlet to the upper pressure tap equals that to the lower tap, and the relation between the fluid density and the measured pressure difference is given by

$$\Delta P = (\rho - \rho_m)Z \quad (13)$$

where

ΔP = differential pressure

ρ = fluid density

ρ_m = manometer fluid density

Z = height between taps.

2. Development. The pressure bridge tested in a low temperature slurry loop was constructed of 1-in. pipe with screwed fittings and had a height between taps of 35-3/4 inches. Water was the manometer fluid in which case equation (13) for this special case becomes:

$$h_w = 35.75\rho - 35.70 \quad (14)$$

where

h_w = ΔP in inches of water

ρ = fluid density, g/cc.

Figure 6 shows the results of this test. The average deviation between the density predicted by equation 10 from h_w (the straight line in Fig. 6) and the density obtained by sampling into a tared graduate cylinder was 0.019 g/cc, or equivalent to average deviation of 1.2%.

The pressure bridge will receive its initial test in a high temperature-pressure slurry circulating system in the forthcoming 200AM loop.

3. Advantages and Disadvantages. The chief advantage of this instrument is its simplicity and ruggedness. It is also potentially an extremely accurate density meter; its precision apparently limited only by the differential pressure element.

A disadvantage is the relatively large pressure drop (~ 2 velocity heads) through the instrument.

F. Gamma-ray Density Meter

In this instrument, the degree of attenuation of a γ -ray beam passing through a slurry conduit is used as a measure of the density of the slurry. An extensive description of the apparatus used during the past year by the Engineering Research Section on both the 200A loop and the Slurry Blanket Mockup is given by Richardson and Kitzes.⁸ A 66 millicurie Co^{60} source was generally useful for a wide range of slurry concentrations and pipe sizes, while a 181 millicurie Co^{60} source was used for the Slurry Blanket where the γ -beam passes through approximately 13 inches of slurry.

The γ -ray absorption technique has been found to be extremely useful as a service for loop operation. The qualitative distribution of thorium in a high pressure, closed system can be found as can slurry-water and water-gas interfaces. Although there was no effort to determine with what precision

the slurry density may be measured it seems that an accuracy of at least that of sampling can be attained. It does not seem, however, that this system is applicable in a highly radioactive area.

SUMMARY AND CONCLUSIONS

The flowmeters and density meters that are presently being considered are listed in Table I.

TABLE I

PRESENTLY CONSIDERED FLOW METERS AND DENSITY METERS

Measured Variable	Density	Either Density or Flow	Density and Flow	Flow
Instrument	Pressure Bridge	Venturi	Double Rotameter	Electro-Magnetic Flowmeter
	^{Fig. 1} γ-Ray Attenuation			Ultrasonic Flowmeter Fig. 2
	Ultrasonic Meter - Fig. 3			

Of the above instruments, the electromagnetic flowmeter and pressure bridge are potentially the most accurate, however, the electromagnetic flowmeter coupled with the ultrasonic density meter yields the smallest pressure drop.

Of the instruments listed in Table I only the venturi has been tested in a high pressure loop and is applicable for reactor use.

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Fig 1

Electromagnetic Flow Meter

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Fig 2

The Ultrasonic Flow Meter

(Ref. 5)

Fig. 3

Ultrasonic Device Used as a Density Meter

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Fig. 4 "S" LOOP MANOMETER PURGE SYSTEM

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Fig. 5 - The pressure bridge density meter

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Fig. 6 - Pressure bridge measurements ΔP vs P

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