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ORNL
CENTRAL FILES NUMBER

CF-57-1-49

DATE: January 10, 1957

COPY NO. 74

SUBJECT: The Pressure Bridge Density Meter for
Continuously Metering Densities of
Flowing Streams

TO: Distribution

FROM: R. P. Wichner, C. F. VandenBulck

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Summary

A new type of continuous density meter, applicable for use with ThO_2 slurry in high temperature-pressure systems, was tested successfully in a low temperature slurry loop. The slurry concentration was varied from 100 to 1100 gTh/Kg H_2O for which the average deviation between predicted density and that determined by sampling into a tared graduate cylinder was 0.019 g/ml, equivalent to an average percent deviation of 1.20%. A bias in the test data was found when the sample density was calculated from the chemical thorium content using 9.69 g/ml as the density of the ThO_2 particle.

The slurry velocity in the bridge was varied from 1 to $7\frac{1}{2}$ ft/sec (equivalent to throughputs of 5 to 40 gpm) without causing any noticeable error in the readings.

Introduction

The density of a static column of liquid can easily be determined from its known height and the difference in pressure from the base to the top. Similarly, the density of a moving column of liquid may be obtained from the differential pressure across a known vertical length of pipe provided that the portion of the differential pressure caused by friction losses is known.

P. R. Crowley¹ determined this frictional pressure drop by measuring the ΔP across a horizontal length of pipe identical with the vertical section (Fig. 1).

Hence referring to Fig. 1, if ΔP_V and ΔP_H are measured, the density of the flowing stream may be determined from the equation:

$$\Delta P_V - \Delta P_H = \rho Z \quad (1)$$

¹ Crowley, P. R., "Method for Metering Fluid Density in a Flowing Stream", unpublished (A. S. Kitzes' file).

Fig. 1 CONTINUOUS DENSITY METER, METHOD OF CROWLEY

where ΔP_V , ΔP_H = pressure drop across verticle and horizontal sections.

ρ = fluid density.

Z = height between pressure taps on verticle pipe and, hence,
also length between taps on horizontal pipe.

The quantities ΔP_V and ΔP_H are best determined by differential pressure instruments (manometers, d/P cells) in which case the static pressure at the taps A, B, C, and D must be transmitted via manometer lines to such instruments. Since the taps C and D are not in the same horizontal plane, the density of the manometer fluid must be accounted for as follows:

$$\Delta P'_V - \Delta P_H = (\rho - \rho_m)Z \quad (2)$$

where $\Delta P'_V$ = ΔP sensed by differential pressure instrument on vertical pipe.

ρ_m = density of manometer fluid.

Densities of various fluids were metered with some success, however, the project was abandoned when it became evident that this system would not be sufficiently precise at elevated temperatures and pressures. Note from equation (2) that the fluid density is linearly dependent on the difference between two readings which in high pressure systems is best determined from d/P cells. d/P cells, nevertheless, are not sufficiently stable to be used in this manner.

Description of Pressure Bridge

The pressure-bridge density meter, shown in Fig. 2, has the advantage that it can continuously record the density of a flowing stream by the use of a single differential pressure element, and hence at elevated temperatures and pressures, a substantial increase in precision is achieved over that inherent in the apparatus shown in Fig. 1.

4

Fig. 2 PRESSURE-BRIDGE DENSITY METER

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FIG. 2

In the pressure-bridge (as the name implies) the frictional losses are balanced against each other leaving the difference in pressure between the taps to be caused solely by the gravity head of the fluid. The equation for the bridge is, therefore, simply

$$\Delta P' = (\rho - \rho_m)Z \quad (3)$$

where again $\Delta P' = \Delta P$ between taps, sensed by differential pressure element.

Z = height between taps.

The dimensions given in Fig. 2 are those for the bridge constructed for the present test. Thus for $Z = 35\text{-}3/4$ inches and with water as the manometer fluid, equation 3 for the case in point becomes:

$$\begin{aligned} h_w &= (\rho - 0.998) 35.75 & \text{or} \\ h_w &= 35.75\rho - 35.70 & (4) \end{aligned}$$

where $h_w = \Delta P'$ in inches of water.

ρ = slurry density, g/ml.

Possible Sources of Error

A. Friction Loss Imbalance

The most obvious source of error would be for the bridge to be in friction-loss imbalance; that is, for the pressure drop due to friction from the inlet to the upper tap to differ from the friction loss from the inlet to the lower pressure tap. Naturally, the smaller the value of the friction losses in the bridge, in comparison with the gravity head, the smaller will be the effect of any imbalance of it. Therefore, for homogeneous fluids, where there is no concern regarding phase separation or settling, the bridge

can always be constructed of such size pipe and of such height so that friction loss imbalance will have negligible effect.

B. Velocity Imbalance

Unequal fluid velocity in each of the two legs would create an error in the readings as in such a case the pressure difference between the taps would be effected by not only the gravity head of the fluid, but also by differences in kinetic energy per unit volume. The magnitude of this error for Newtonian fluids in laminar flow is given by

$$\Delta h_w = \frac{\rho}{K g_c} (v_1^2 - v_2^2) \quad (5)$$

where ρ = fluid density, lb m/ft³

g_c = dimensional constant, poundals/lb_f = 32.2

K = dimensional constant, $\frac{\text{lb}_f/\text{ft}^2}{\text{inches water}} = 5.20$

v_1, v_2 = velocity in each leg, ft/sec

Δh_w = error in ΔP caused by the kinetic effect, inches water.

If it is assumed for purposes of illustration that ρ is 1.5 g/ml, then by equation (5) the attendant error would be 3.0 in H₂O for a 1% difference in velocity in the two legs at a nominal fluid velocity of 20 ft/sec. At 7 ft/sec a 1% difference in velocity would cause an error 0.37 in H₂O. The magnitude of the resulting error in determining the density is dependent on the height of the bridge, the relation being:

$$\text{error in } \rho = \frac{\text{error in } \Delta P}{Z} \quad (6)$$

For a 3 ft. bridge the error in the density is for these two cases 0.083 g/ml and 0.010 g/ml, respectively.

C. Phase Separation

In heterogeneous systems composed of phases of differing density, there is the possibility of phase separation at the inlet tee or in the vertical section of the bridge. This in itself will create no error as the bridge will simply determine the average density in the vertical sections. However, accompanying such a separation in phases would be also a separation of physical properties (density, viscosity, etc.) and, hence, unbalance the bridge with respect to velocity. Such separation should, therefore, be avoided by maintaining a sufficiently high velocity.

In ThO_2 slurry systems, the particle settling rates are so small in comparison with ordinary pipe velocities that this possibility may be ignored.

Experimental System

The bridge used for this test was constructed from 1-inch, schedule 40 pipe using screwed fittings. The dimensions are shown in Fig. 2

Figure 3 shows the bridge set in the test loop and manometer purge system. The differential pressure element used was a 60" Taylor d/P cell which was connected across the water purge lines. Continual checks on the calibration and zero point of the d/P cell were made during the course of the runs.

No attempt was made to precisely determine the fluid velocity in the loop, however, the position of the throttling valve served to differentiate between low (~ 5 gpm), medium (~ 20 gpm), and high (~ 40 gpm) throughputs.

Experimental Data

Throughout the course of the test, slurry density was determined either by sampling into a tared graduate cylinder or by the more indirect means of calculation from the chemical thorium content, using 9.69 g/ml as the density

Fig. 3 PRESSURE BRIDGE IN LOW TEMPERATURE SLURRY TEST LOOP

of the ThO_2 particle. Occasionally simultaneous samples were withdrawn and the two methods of density determination were checked against each other. Table I shows this comparison. It is seen that in all cases except one, the density obtained directly from the volume of the sample in a tared graduate cylinder exceeded that obtained by calculation from chemical analysis.

Three series of slurry runs were made the data points of which are indicated in Fig. 4 as circles, squares, and triangles. The dark points, those in which the density was determined by the more direct means described above, are seen to be in excellent agreement with the predicted value given by the straight line, which is simply a plot of equation (4). In Table II are listed the deviations of the experimentally determined densities from that predicted by the d/P cell reading and equation (4). The average absolute deviation is 0.019 g/ml or an average percent deviation of 1.20%.

As is expected from the comparisons in Table I, the data using the value of ρ calculated from chemical analysis are biased. This is readily seen in Fig. 4 where nearly all of the light points fall above the theoretical line. In Table III are recorded, for these points, the density deviations from that predicted by the d/P cell readings. In spite of the bias, the average deviation is only 0.036 g/ml or 2.3%.

The slurry velocity was varied in each series of runs. This is indicated in Fig. 4 by flags on the data points, a downward flag signifying low velocity, horizontal and upward flags signifying medium and high slurry velocities. As seen from Fig. 4, the pressure-bridge was insensitive to throughput variations between 5 and 40 gpm (equivalent to a range of 1 to $7\frac{1}{2}$ ft/sec in the bridge) within the experimental error.

Fig. 4 Pressure Difference VS Slurry Density

TABLE I

COMPARISON BETWEEN THE VALUE OF THE SLURRY DENSITY OBTAINED BY
CALCULATION FROM CHEMICAL THORIUM CONTENT WITH THAT OBTAINED
BY SAMPLING INTO A TARED GRADUATE CYLINDER

ρ_A g/ml	ρ_B g/ml	$\rho_B - \rho_A$
Chemical Analysis	Graduate Cylinder	
1.726	1.793	+0.067
1.464	1.533	+0.069
1.480	1.484	+0.004
1.344	1.370	+0.026
1.172	1.194	+0.022
1.696	1.766	+0.076
1.543	1.594	+0.051
1.329	1.354	+0.025
1.281	1.258	-0.023

TABLE II

DEVIATION BETWEEN SLURRY DENSITY PREDICTED BY d/P CELL READINGWITH THAT DETERMINED BY SAMPLING INTO A TARED GRADUATECYLINDER (DARK POINTS, FIG. 4)

Predicted Slurry Density, g/ml	ρ Sampling - ρ Predicted	Percent Deviation
1.936	+0.068	+3.52
1.881	+0.008	+0.42
1.810	-0.017	-0.94
1.743	+0.018	+1.03
1.608	-0.014	-0.87
1.552	-0.019	-1.23
1.495	-0.010	-0.07
1.386	-0.017	-1.23
1.340	+0.015	+1.12
1.252	+0.007	+0.56
1.239	-0.013	-1.05
1.217	-0.022	-1.80
Average absolute value:	0.019 g/ml	1.20%

TABLE III

DEVIATION BETWEEN SLURRY DENSITY PREDICTED BY d/P CELL READING
WITH THAT DETERMINED BY CALCULATION FROM THE CHEMICAL ANALYSIS
OF A SAMPLE USING 9.69 g/ml AS THE DENSITY OF ThO₂

(LIGHT POINTS, Fig. 4)

Predicted Slurry Density, g/ml	ρ Chem. Anal. - ρ Predicted	Percent Deviation
1.981	-0.045	-2.27
1.948	-0.052	-2.66
1.810	-0.082	-4.53
1.803	-0.073	-4.05
1.776	-0.053	-2.99
1.748	-0.052	-2.97
1.608	-0.065	-4.05
1.552	-0.098	-6.30
1.513	-0.042	-2.78
1.494	-0.014	-0.94
1.488	+0.006	+0.40
1.494	-0.036	-2.40
1.483	-0.011	-0.74
1.483	-0.011	-0.74
1.386	-0.042	-3.03
1.377	-0.029	-2.11
1.349	+0.013	+0.97
1.347	-0.003	-0.22
1.337	-0.009	-0.08
1.255	+0.026	+2.07
1.216	-0.043	-3.55
1.214	-0.044	-3.63
1.185	0.000	0.00
1.185	-0.014	-1.18
Average absolute value: 0.036 g/ml		2.30%

0-13