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EFFECTS OF FLOW DISPERSERS UPSTREAM OF TWO-PHASE FLOW MONITORING INSTRUMENTS

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Abstract—The effects of flow dispersing screens on the accuracy of two-phase flow monitoring instruments was studied with an air–water two-phase flow loop in which air and water flow rates were monitored separately. Flow dispersers were installed at the inlet of an instrumented spool piece containing a drag disk and a turbine meter. For the present tests, the spool piece was mounted vertically and flow was always down.

When the turbine was upstream of the drag disk, two-phase mass flow rates indicated by the instruments were approximately one-third actual mass flows both in the presence and absence of flow dispersers. However, when the drag disk was upstream of the turbine, the use of flow dispersing screens upstream of . the drag disk resulted in flow measurements within ±10% of actual flow rates over the range 0–160 kg/m^2 · s.

INTRODUCTION

Experimental studies of the hypothetical loss-of-coolant accident (LOCA) for water-cooled nuclear reactors are concerned with the transient thermal-hydraulic behavior of electrically-heated fuel rod bundles. Typically, a blowdown experiment lasts only a few tens of seconds during which time water flashes from single-phase liquid to relatively low quality steam. The experimental determination of transient heat transfer coefficients, mass, and energy balances requires an accurate measurement of two-phase flow rates during the blowdown. If the two phases were always uniformly dispersed across the piping cross section as they discharge from the system, standard flow monitoring techniques could possibly be utilized. However, two-phase flows are not typically homogeneous, and the existence of such flow regimes as annular, slug, or stratified may result in flow measurements of questionable accuracy.

A principal objective of this study was to test the effectiveness of flow dispersing screens in homogenizing the flow at the entrance of the spool piece and thus improve the accuracy of mass flow measurements. Screens or grids have been used for some time to regulate the structure of single-phase flow; for example, the study of single-phase turbulence has been simplified through the use of grid generated turbulence (Taylor 1935). However, little attention has been given to utilization of screens to homogenize two-phase flows and thereby improve the accuracy of flow measuring instruments.

BACKGROUND

The thermal hydraulic test facility (THTF), part of a separate effects blowdown heat transfer program at the Oak Ridge National Laboratory (Thomas 1976), utilizes instrumented piping spool pieces for flow monitoring. Each spool piece includes a turbine flowmeter, a drag disk flowmeter, a gamma densitometer, and pressure and temperature instruments. The first three instruments provide measurements of velocity, V_T, from the turbine meter, momentum flow, $(\rho V^2)_{DD}$, from the drag disk, and apparent density, ρ_a, from the gamma densitometer. Any two of the measured flow parameters can be used to estimate mass flow using a homogeneous, or one-velocity model. For example, at the loss-of-fluid tests (LOFT) facility (Aerojet Nuclear Co. 1974 and Coplen & Ybarrondo 1974) a turbine meter and drag disk are used in combination

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to monitor the total mass flow and average density according to the relationships

$$G = \frac{(\rho V^2)_{DD}}{V_T} \qquad [1]$$

$$\rho_a = \frac{(\rho V^2)_{DD}}{V_T^2}, \qquad [2]$$

where G is the mass velocity, $(\rho V^2)_{DD}$ is the momentum flux indicated by the drag disk, V_T is the velocity indicated by the turbine and ρ_a is the apparent density. Of course, the one-velocity model ([1] and [2]) is not sufficient to calculate the slip ratio or fluid quality from flow measurements alone. However, combination of three measurements (velocity, momentum, density) permits calculation of mass flow rate and fluid quality based on two-velocity, slip models, such as that of Aya (1975).

Using a two-velocity model, three independent flow parameters are required to calculate the mass flow rate,

$$G = \alpha\rho_G V_G + (1-\alpha)\rho_L V_L, \qquad [3]$$

where α is the gas phase volume fraction, V_G and V_L are characteristic velocities of the respective gas and liquid phases and ρ_G and ρ_L are gas and liquid densities, respectively. The void fraction is related to the apparent density by,

$$\alpha = \frac{\rho_L - \rho_a}{\rho_L - \rho_G}, \qquad [4]$$

and to the two-phase velocities by the continuity equations,

$$\alpha = V_G\alpha_h V_{Gh} \qquad [5a]$$

and

$$(1-\alpha)\cdot V_L = (1-\alpha_h)\cdot V_{Lh}, \qquad [5b]$$

where the subscript h indicates assumption of homogeneous flow.

Aya's (1975) equation for separated flow through a turbine meter is,

$$C_{tG}\alpha\rho_G(V_G - V_T)^2 = C_{tL}(1-\alpha)\rho_L(V_T - V_L)^2, \qquad [6]$$

where C_{tG} and C_{tL} are drag coefficients for the two phases flowing past the rotor blades. Similarly, Aya's equation for the effect of the two phases on a drag disk assumes:

$$(\rho V^2)_{DD} = C_{dG}\alpha\rho_G V_G^2 + C_{dL}(1-\alpha)\rho_L V_L^2, \qquad [7]$$

where C_{dG} and C_{dL} are coefficients of drag of the two phases. When the void fraction is expressed in terms of densities [4], and the gas phase is much less dense than the liquid phase ($\rho_G \ll \rho_L$), then [7] becomes:

$$(\rho V^2)_{DD} = C_{dG}\left(\frac{\rho_L - \rho_a}{\rho_L}\right)\rho_G V_G^2 + C_{dL}(\rho_a - \rho_G)V_L^2. \qquad [8]$$

Clearly, as ρ_a approaches sufficiently close to either of the single-phase densities, the momentum flux for that phase will dominate the drag disk reading. The density ratio for the air–water system at substantially atmospheric pressure is $\rho_G/\rho_L \simeq 10^{-3}$. If the two-phase velocities are of the same order of magnitude and the apparent density is as much as an order of magnitude greater than the vapor phase density (0.017 kg/m^3), the expression for the drag disk measurement reduces to

$$(\rho V^2)_{DD} \simeq C_{dL}\rho_a V_L^{\,2}. \qquad [9]$$

If the gas phase density is small in comparison with either the homogeneous or apparent density, then combining [4] and [5] gives a relationship between the phase velocities and apparent density which reduces to

$$V_g = \frac{(\rho_L - \rho_h)}{(\rho_L - \rho_a)} V_{Gh}, \qquad (10a)$$

and

$$V_L = (\rho_h/\rho_a) V_{Lh}. \qquad (10b)$$

For this study, the known metered inputs of air and water were used in conjunction with [4], [5], [9] and [10] to determine the mean density and slip ratio. Mass flow rate was then determined from a modification of the Aya equation,

$$G = [\alpha\rho_G S + (1-\alpha)\rho_L] \cdot V_T \cdot \left[\frac{1 + \left[r_d\left(\frac{1-\alpha}{\alpha}\right)\right]^{1/2}}{S + \left[r_d\left(\frac{1-\alpha}{\alpha}\right)\right]^{1/2}}\right], \qquad (11)$$

which assumes the ratio, r_d, of drag coefficients of air and water on the turbine blade is unity. In [11] the velocity ratio, S, equals V_G/V_L.

EQUIPMENT

The air-water facility (figure 1) consisted of a recirculating water loop to which air was added upstream of the spool piece and removed down-stream of the spool piece. Water was

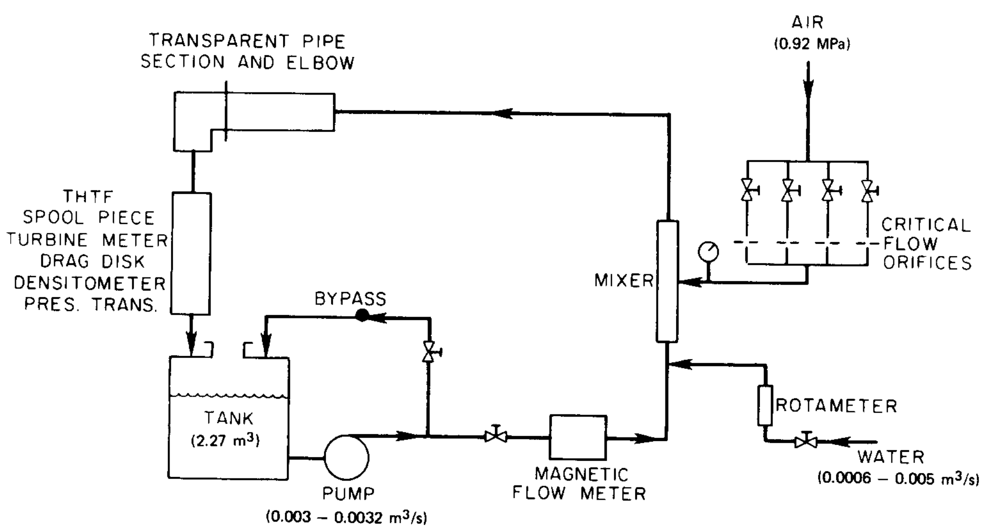

Figure 1. Air–water two-phase flow loop.

pumped through a magnetic flowmeter prior to mixing with air which was metered through critical flow orifices. Mixing of the two phases occurred in a 920-mm long vertical section of double wall pipe. Water flow was through the center of the pipe and air flow was from the annular outer section of the pipe through a permeable inner wall. Total length of this initial section of upward vertical flow was approximately 2.1 m, this was followed by a 5.5-m section of horizontal pipe (7.6-cm-ID) which then discharged through an elbow into the vertically oriented instrumented spool piece. The last 920 mm of the 5.5-m horizontal section was glass pipe which permitted observation of the nature of the flow discharging into the elbow and spool piece. Several critical flow orifices were used to give a range of air flows from 0.015 to 0.12 m^3/s which is 2.4 to 18.3 m/s superficial velocity in the spool piece. Maximum water flow was 0.011 m^3/s which corresponds to 1.74 m/s superficial velocity in the spool piece or a mass flow of approximately 160 $kg/m^2 \cdot s$.

The instrumented spool piece, figure 2, was one fabricated for use in the THTF. The spool piece was a 920-mm long section of flanges 102 mm (IPS) stainless steel pipe machined to accommodate a turbine meter, drag disk and pressure and temperature sensors; gamma densitometers used with the THTF spool pieces were not available for the tests reported in this note. The drag disk was a Ramapo Instrument Company Mark V target flowmeter with a 12.7-mm-dia. cylindrical target supported on a 6.4-mm-dia. rod. The turbine was a nominal 89-mm-dia. full pipe turbine manufactured by Flow Technology, Inc.

All of the THTF flow meters, including those used for this test, were calibrated (Davis & Heilelmann 1975) in another facility for single-phase water flow in two different piping configurations. The "ideal" configuration had straight entrance and exit piping; whereas, the "worst case" had closely coupled elbows to distort the flow at the entrance and exit. Further, the calibration included tests in the vertical and horizontal position and tests with the direction of flow through the spool piece reversed (i.e. for some tests, the turbine was upstream of the drag disk and for other tests the drag disk was upstream of the turbine). The results (Thomas 1975) of the calibration showed that the turbine meters showed good agreement among each other for all flow configurations and were bidirectional. However, the signals from the drag disk showed some variation with respect to configuration. For values of momentum flux, ρV^2, greater than about 1042 $kg/m \cdot s^2$, measurements for all configurations were in good agreement except those associated with closely coupled entrance and exit elbows and, in addition, with the drag disk upstream of the turbine. In this "worst" configuration, the momentum flux for a given value of the output signal was about 35% greater than for the other configurations.

Several different flow dispersers were used; table 1 summarizes characteristics of dispersers used in this study (Sheppard & Tong 1977). The LS-15 + 1 disperser had fifteen 44-mesh screens stacked together with a single, 8-mesh, heavy wire backup screen; whereas, LS-3 + 4 consisted of a stack of alternate layers of fine mesh and coarse mesh screens. The 44-mesh screens were selected to finely divide the flow stream and the 5- to 8-mesh screens with heavier wire (0.89 to 1.57-mm dia.) were used primarily for structural support.

RESULTS

These tests were conducted with the spool piece oriented vertically and with flow downward. The air flow rate was set at a fixed value varying from 0.015 to 0.13 m^3/s and the water rate was varied from 0.0013 to 0.011 m^3/s at each air rate. Tests were conducted with no flow dispersers and with various types of dispersers located at the inlet flange of the spool piece ~ 150 mm upstream of the flow sensor.

Initially, the spool piece was oriented with the turbine meter upstream of the drag disk. Figure 3 shows typical instrument recordings at an air flow of 0.12 m^3/s and a water flow of 0.0097 m^3/s; results shown in figure 3(a) were obtained using a disperser designated as LS-3 + 4. The turbine meter signal is represented on a scale of 0 to 20 volts; liquid phase water calibration showed that 7 volts output was equivalent to 0.0227 m^3/s. The drag disk signal is shown as millivolts per 5 volts excitation of the strain gauge bridge. Fluctuations in the signals were not instrument noise, but illustrate the response of the instrumentation and associated electronics to fluctuations of the two-phase flow.

With the turbine meter upstream of the drag disk and no flow dispersers (figure 3a), the mean drag disk signal was equivalent to a momentum flux of $\rho V^2 = 57{,}000\,\mathrm{kg/m \cdot s}$; the mean turbine velocity was 12.4 m/s. Using [1] the mass flow rate indicated by the instruments was $433\,\mathrm{kg/s \cdot m^2}$. Inspection of figure 3(b) shows that use of the dispersing screens affected the signal only slightly, not enough to reduce the indicated mass flow by a factor of three. Other dispersers were used with the spool piece oriented the same as for the data shown in figure 3 with results similar to those of figure 3(b).

Then the spool piece was inverted so that the drag disk was positioned upstream of the turbine. When no dispersers were used in this orientation the signal from the turbine meter

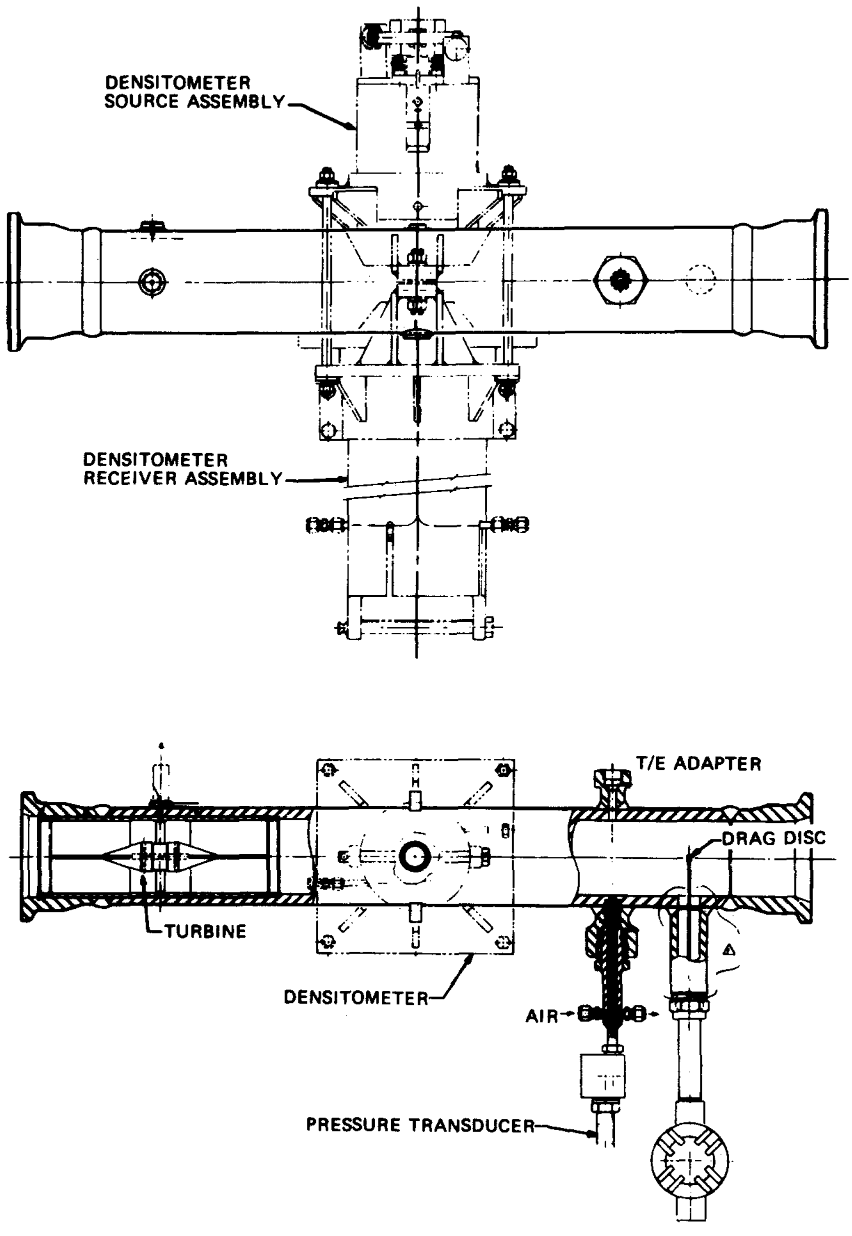

Figure 2. Thermal hydraulic test facility instrumental spool piece for monitoring transient two-phase flow.

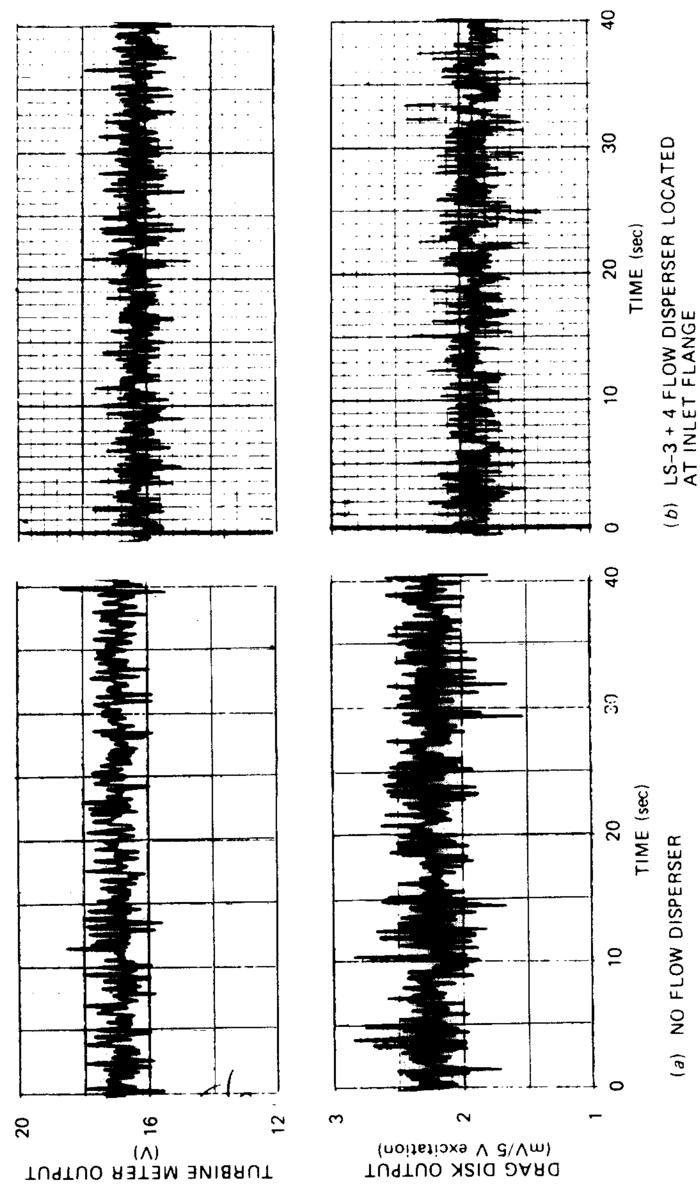

Figure 3. Turbine meter and drag disk signals from a THTF instrumented spool piece operating in an air–water, two-phase flow loop with (b) and without (a) a flow disperser located at the inlet flange (downward flow through the spool piece; turbine was upstream of the drag disk; superficial velocities: air, 19.5 m/s; water, 1.1 m/s; 89-mm-ID pipe).

(figure 4a), at the same flow rate used previously, was essentially the same as shown in figure 3 with a mean value of approximately 16 volts while the mean drag disk signal was reduced from 2.25 mV per 5 volts excitation in figure 3a to 1.5 mV per 5 volts excitation. Further, then the same disperser (LS-3 + 4) used to obtain the results of figure 3b was inserted in the upstream flange, the drag disk signal was reduced to 0.75 mV per 5 volts excitation while the turbine signal remained at ~ 16 volts, figure 4(b). It is notable that when the values of the mean turbine and drag disk signals shown in figure 4(b), which involved the use of the flow disperser immediately upstream of the drag disk, are substituted in [1], the indicated mass flow rate is 145 kg/s · m^2, essentially the same as the metered input of 146 kg/s · m^2.

Whereas figures 3 and 4 show data at a single flow condition, figure 5 shows the variation in mass flow calculated by [1] at 0.12 m^3/s air flow and with the water rate varying from 0.0013 to 0.0095 m^3/s; the solid line represents the actual mass flow metered into the system. The circles and squares represent data with and without flow dispersers and with the turbine upstream of the drag disk. With this orientation the mass flow indicated by the instruments was about a factor of three greater than the actual flow over the total range of water rates with or without dispersers. When the spool piece was inverted so that the drag disk was upstream of the turbine a distinct improvement between indicated and metered mass flow rate was observed even when no disperser was used (figure 5, triangles). However, the only spool piece configuration that gave good agreement between the indicated and metered mass flow rate was when the flow disperser immediately upstream of the drag disk (figure 5, diamonds).

Figure 6 shows typical results using flow disperser LS-3 + 4 upstream of the drag disk and air flows of 0.030 to 0.12 m^3/s and water flows from 0.0013 to 0.0095 m^3/s; mass flow was calculated from the modified Aya model, [11]. Since the mass flow rate of 0.12 m^3/s air is only

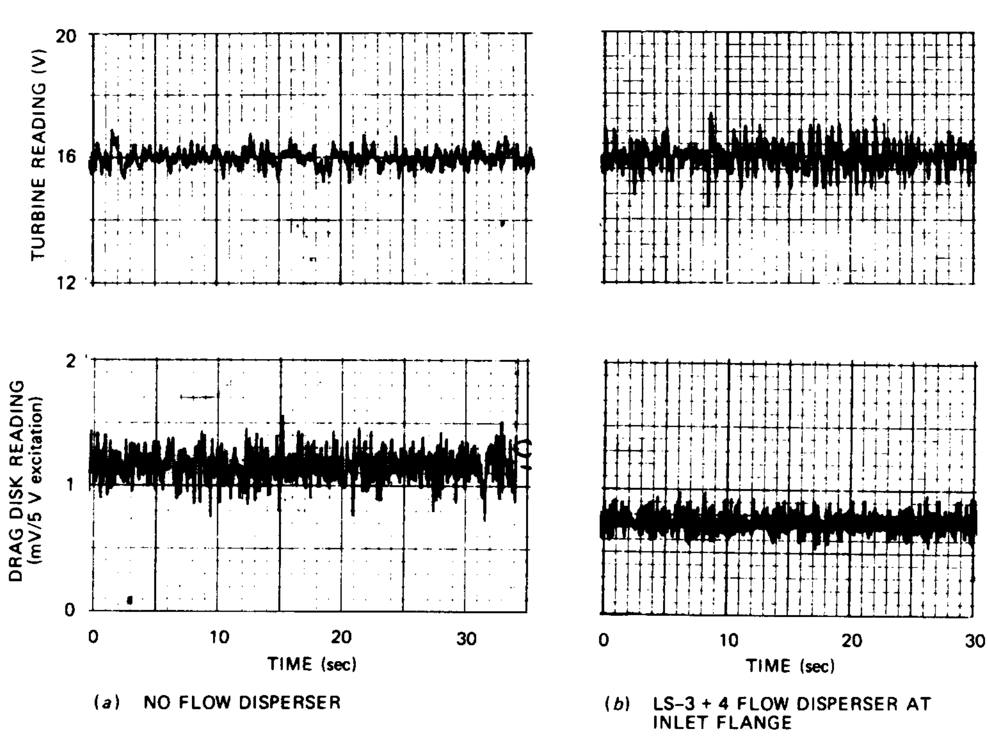

Figure 4. Turbine meter and drag disk signals from a THTF instrumented spool piece operating in an air–water, two-phase flow loop with (b) and without (a) a flow disperser located at the inlet flange (downward flow through the spool piece; drag disk was upstream of turbine; superficial velocities: 19.5 m/s air, 1.55 m/s water; 89-mm-ID pipe).

0.14 kg/s, a single curve is a good representation of all present tests with different air flow rates. The dashed lines indicate that the calculated mass flow was within ± 10% of actual mass flow. Similar results were obtained using a variety of stacked or layered screens, table 1 and figure 7.

Finally, while the use of several different dispersers resulted in equally accurate measurement of mass flow rates (figure 5), there were substantial differences in pressure drop characteristics. At the highest flow rates shown in figure 5 (0.12 m^3/s air, 0.0096 m^3/s), pressure drop across the dispersers with two, three and fifteen 44-mesh screens was 0.41, 0.55 and 1.45 MN/m^2 respectively. Qualitatively, we have found that increased resistance to flow due to different disperser designs frequently results in increased pulsating flow upstream. This observation is consistent with a two-phase flow stability analysis of Wallis & Heasley (1961). Their study of the effect of a constriction at the exit of a two-phase flow section showed that the ratio of constriction pressure drop to a characteristic velocity head in the section was a principal parameter in determining system stability. The Nyquist locus scaled directly with this pressure

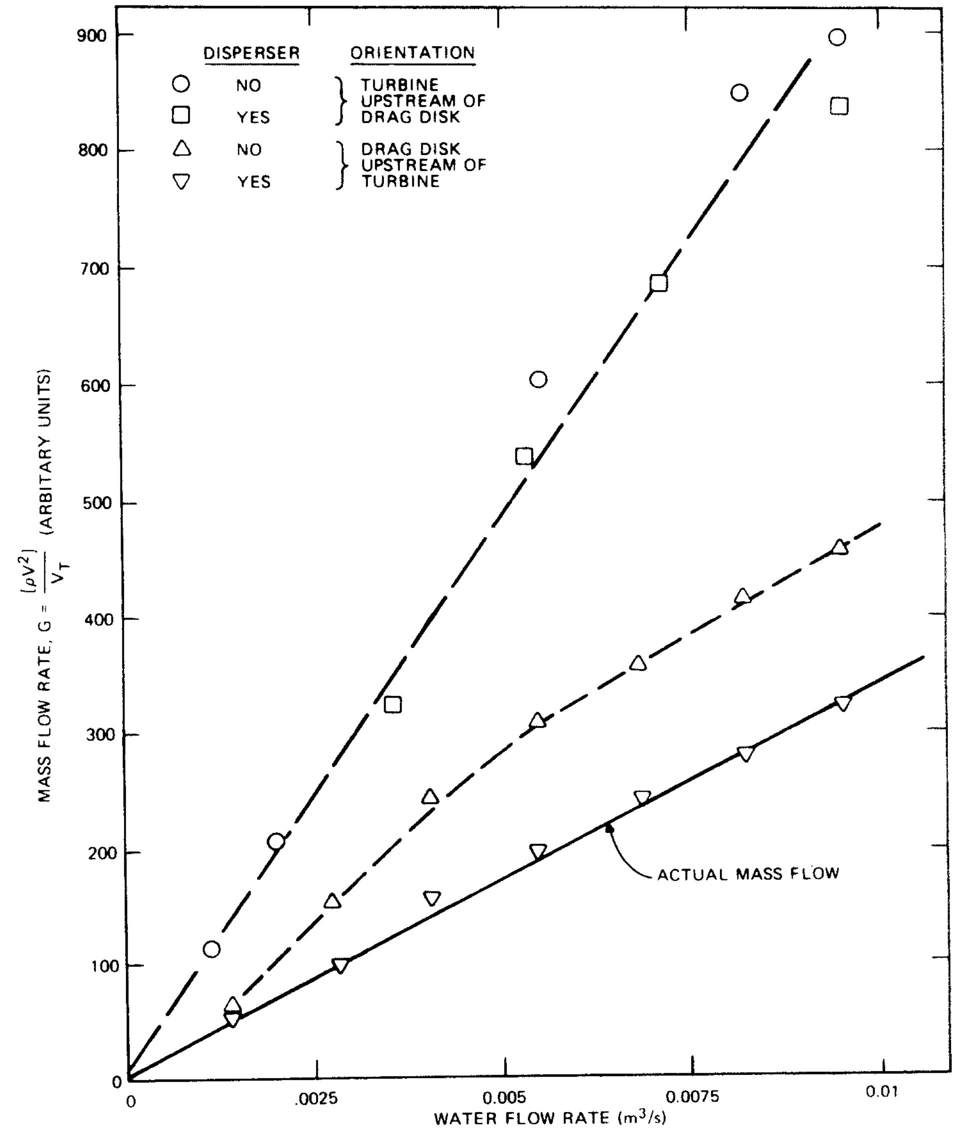

Figure 5. Variation in mass flow rate indicated by instrumented spool piece with water flow rate for operation with and without a disperser (LS-3 + 4) and for different orientations of the same piece (89-mm-ID pipe, 0.12 m^3/s air flow).

coefficient so that sufficiently high constriction pressure drops at a given velocity head resulted in an inherently unstable system.

DISCUSSION

A comparison was made of the effectiveness of the one-velocity model [1] and the two-velocity (modified Aya) model [11] in calculating mass flow rates. When the experimental conditions were those shown to be necessary for accurate flow monitoring by the spool piece (i.e. with drag disk upstream of the turbine and with flow dispersers), both models gave reasonable agreement between calculated and metered mass flow rates (figure 8). This suggests

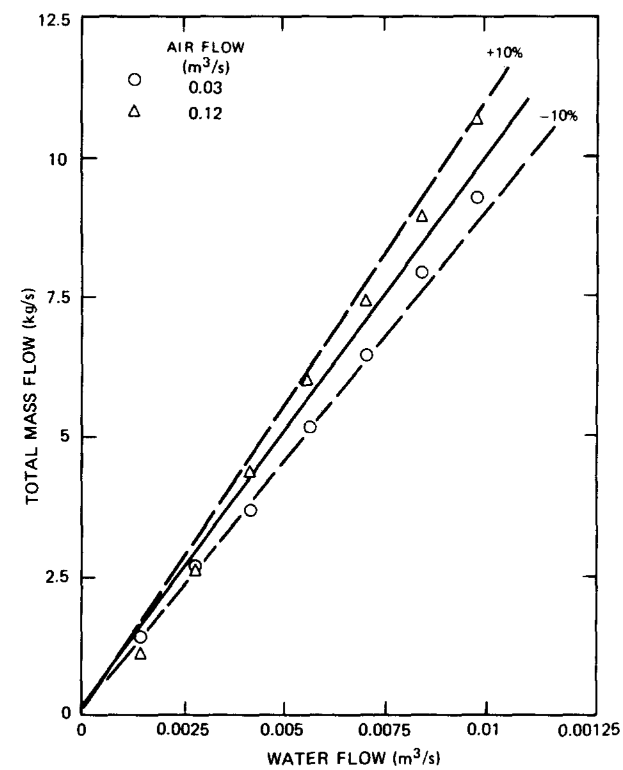

Figure 6. Mass flow rate calculated from output of turbine and drag disk meters when drag disk was upstream of turbine and flow disperser made with three 44-mesh screens spaced by four 5-mesh screens (air-water, ~310 K; vertical position, 89-mm-ID pipe).

Table 1. Characteristics of flow dispersers used to homogenize two-phase flow at entrance to instrumented spool piece

Designation	Type	Characteristics
LS-2+3	Layered screen	Three 44-mesh (0.13-mm wire, 61% open area) screens layered between three 7-mesh (0.89-mm wire, 52% open area) screens
LS-15+1	Stacked screen	Fifteen 44-mesh (0.13-mm wire, 61% open area) screens stacked with one 8-mesh (1.57-mm wire, 24.6% open area) screen
LS-3+4	Layered screen	Three 44-mesh (0.13-mm wire, 61% open area) screens layered between four 5-mesh (0.89-mm wire, 68% open area) screens

that, for the conditions used in this test, the flow dispersing screens were quite effective in homogenizing the flow approaching the drag disk. This is consistent with the order of magnitude analysis [9] which showed that over a wide range of low quality flows the two-velocity model for momentum flux given by the drag disk effectively reduces to a single-velocity model based on the mean density and the liquid phase velocity. Other studies (Baumeister *et al.* 1973 and Andeen & Griffith 1968) have also shown that experimentally determined momentum fluxes are sometimes more accurately represented by homogeneous models than by two-velocity, slip models.

In all probability the homogenizing effect of the flow dispersers occurred for several different flow regimes. This is supported by superimposing the present range of flow rates on the flow regime map developed by Oshinowo & Charles (1974) for vertical downflow of air–water and air–water–glycerol mixtures in a 2.54-cm-dia. pipe, figure 9. The dashed curves in the figure show that in the THTF spool piece an air flow of 0.030 m^3/s and a range of water flow from 0.0013 to 0.0095 m^3/s involves traversing through the falling bubbly film and froth regimes while the same water rates with 0.12 m^3/s air flow should involve the froth and annular mist regimes. However, the regime of flow in the spool piece is not in general independent of the flow regime in other parts of the system. Although visual observation indicates that the 90-degree elbow upstream of the spool piece mixes the flow considerably, nevertheless pulsation generated upstream of the spool piece is transmitted throughout the system. Despite this, comparison of figures 6 and 9 shows little effect of different possible flow regimes and pulsation of the resulting calculated mass flow rate.

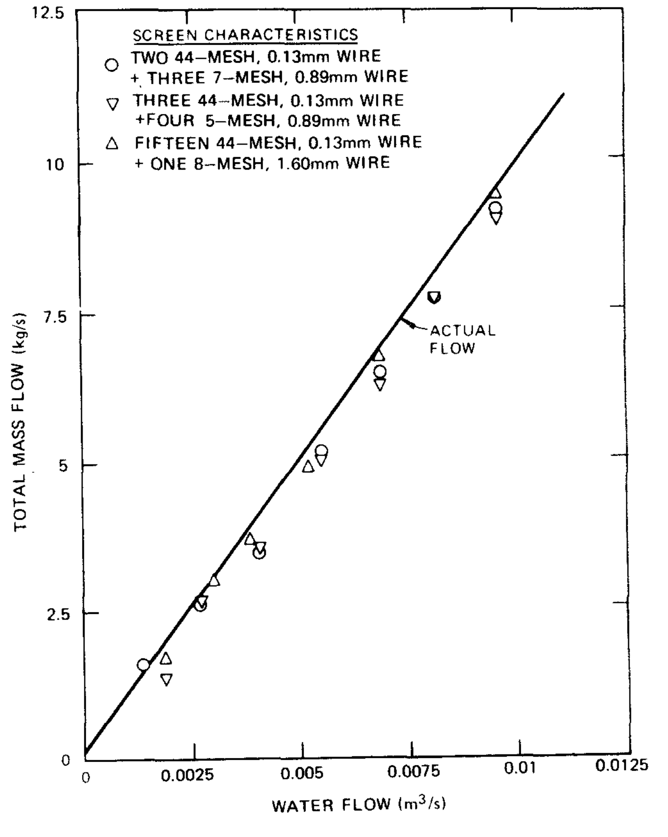

Figure 7. Mass flow rate calculated from output of instrumented spool piece with drag risk upstream of turbine for three flow dispersers (air–water, ~310 K; vertical position, 89-mm-ID pipe, variable water flow, 0.12 m^3/s air flow).

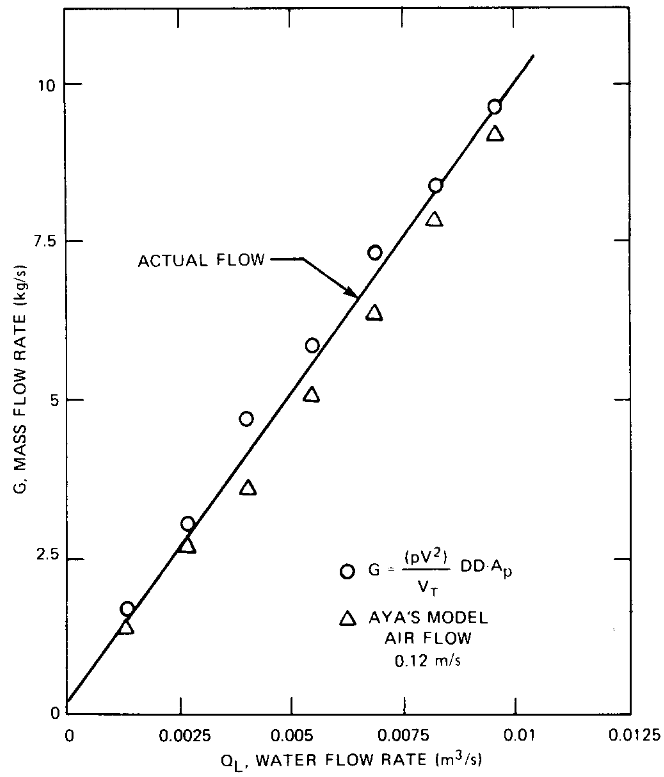

Figure 8. Mass flow rate in instrumented spool piece with superficial air velocity of 19.5 m/s (drag disk upstream of turbine; flow dispersers—three 44-mesh + four 5-mesh screens; air-water; ~310 K; 89-mm-ID pipe).

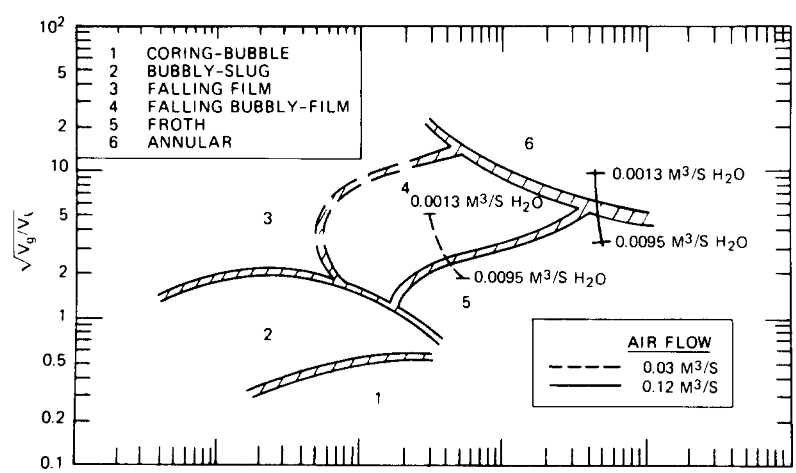

Figure 9. Two-phase flow regime diagram for vertical downflow of air–water mixtures shows the transition between flow regimes encountered during experimental studies (after Oshinowa & Charles 1974; present study involved 89-mm-ID pipe, V_G, V_l superficial phase velocities).

CONCLUSIONS

In vertical downflow of two-phase air–water mixtures, wire screen flow dispersers placed upstream of a drag disk markedly improve the accuracy of a drag disk-turbine meter combination in determining the mass flow rate in steady flows. The results suggest that the flow dispersers homogenize the flow approaching the drag disk almost independent of the flow regime upstream of the flow disperser.

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