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Advanced Two-Phase Flow Instrumentation Program Quarterly Progress Report for April–June 1979

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MASTER

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ADVANCED TWO-PHASE FLOW INSTRUMENTATION PROGRAM QUARTERLY PROGRESS REPORT FOR APRIL—JUNE 1979

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ADVANCED TWO-PHASE FLOW INSTRUMENTATION PROGRAM QUARTERLY PROGRESS REPORT FOR APRIL–JUNE 1979

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ABSTRACT

Experiments that were conducted in steam-water two-phase flow with a piping segment instrumented for making flow measurements are described. Results obtained with a triple-beam densitometer, a turbine flowmeter, and a drag flowmeter in the steam-water vertical upflow tests are presented. Comparisons between recorded turbine rotor velocities and velocities predicted by three turbine models are made, and two-phase mass flow models, applied to the recorded data, are compared with the mass flow metered into the steam-water system.

1. INTRODUCTION

The objective of the Advanced Two-Phase Flow Instrumentation Program is to improve the accuracy and precision of transient two-phase flow measurements required in reactor safety research. Instrumented piping spool pieces and other two-phase flow measurement devices are being studied.

A series of experiments with advanced spool piece I in air-water two-phase flow has been documented in previous quarterly reports.[1–4] During the current report period, a similar spool piece was tested in vertical upflow in the Advanced Instruments for Reflood Studies (AIRS) Test Stand, a steady-state steam-water flow system that produces environments typical of the reflood portion of a postulated loss-of-coolant accident. The AIRS Test Stand tests were conducted to examine how observations made in the air-water experiments regarding instrument response and mass flow rate determination translate to a steam-water flow system. In particular, these tests were designed to determine whether the mass flow rate in two-phase steam-water flow could be obtained with sufficient accuracy using only drag and turbine flowmeters. If so, useful instrumented spool pieces could be constructed without using relatively expensive gamma attenuation densitometers.

This report briefly describes the AIRS Test Stand and the methods of data acquisition and analysis used for the spool piece tests. Results from preliminary analysis of the data are discussed, and recommendations for future testing are made.

2. EXPERIMENTAL EQUIPMENT AND METHODS

The AIRS Steam-Water Test Stand[5] (Fig. 2.1) is used for testing instrument systems in flow conditions like those in a postulated nuclear reactor reflood. Superheated steam at 830 kPa (120 psia) and 440 K (340°F) and water at ambient temperature and pressure are mixed and passed vertically upward through piping where flow instruments are located. Each phase's input flow rates to the system are measured using rotameters for water input and a Gilflo steam flowmeter for steam input. Visual observations of the mixed flow stream may be made both upstream and downstream of the test sections. An instrumented piping spool piece is located near the top of the facility; measurements made with the spool piece instrumentation are compared to analogous measurements obtained with impedance probes or other devices installed in the lower sections.

The instrumented spool piece used for the steam-water testing (Fig. 2.2) consisted of a stainless steel pipe 91 cm (3.0 ft) long and 8.9 cm (3.5 in.) ID with fittings for a drag flowmeter and a turbine meter. A triple-beam gamma attenuation densitometer was installed on the spool piece at the location shown in Fig. 2.2. The turbine flowmeter had a full-flow 12-bladed rotor with untwisted blades and graphite bearings. Signals from the turbine transducers were processed both with Flow Technology, Inc., model FR-56I1000-L3 turbine monitor electronics and with the Oak Ridge National Laboratory (ORNL) turbine monitor electronics described in previous reports.[1,2] A full-flow perforated-plate drag body was used with the Ramapo, Inc., Mark V strain gauge—type drag transducer in the spool piece. The drag transducer had a zero-shift offset of ≈0.02 mV/V_{ex} or 1.0% of full scale at the temperatures used. An attempt to account for the zero shift was made in the data reduction procedure. No flow-dispersing screens were used in these tests.

Signal conditioning for the spool piece instrumentation was generally like that used for air-water spool piece testing, but the data acquisition and reduction were done somewhat differently. Time-averaged voltage outputs from the spool instrumentation and loop-process instrument data were recorded by hand from an integrating voltmeter and from process gauges. In addition, six channels of spool piece data were

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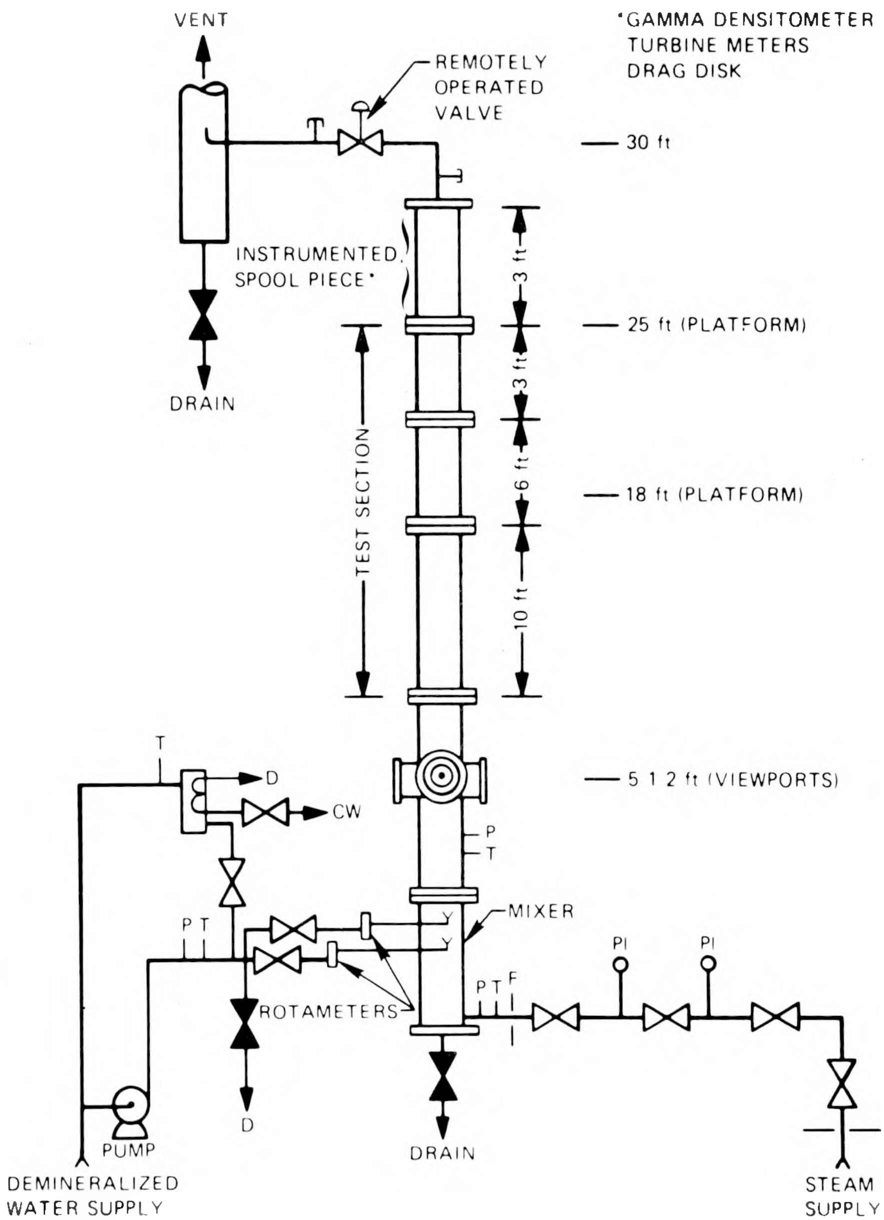

Fig. 2.1. Advanced Instruments for Reflood Studies (AIRS) Steam-Water Test Stand.

recorded using an analog FM tape recorder. The recorder had a maximum frequency response of 20 kHz. After the tests, the recorded data were transferred to the PDP-8 data acquisition system described previously[1] and then processed using an IBM FORTRAN computer progrm to yield the results shown in this report. The process used allowed application of

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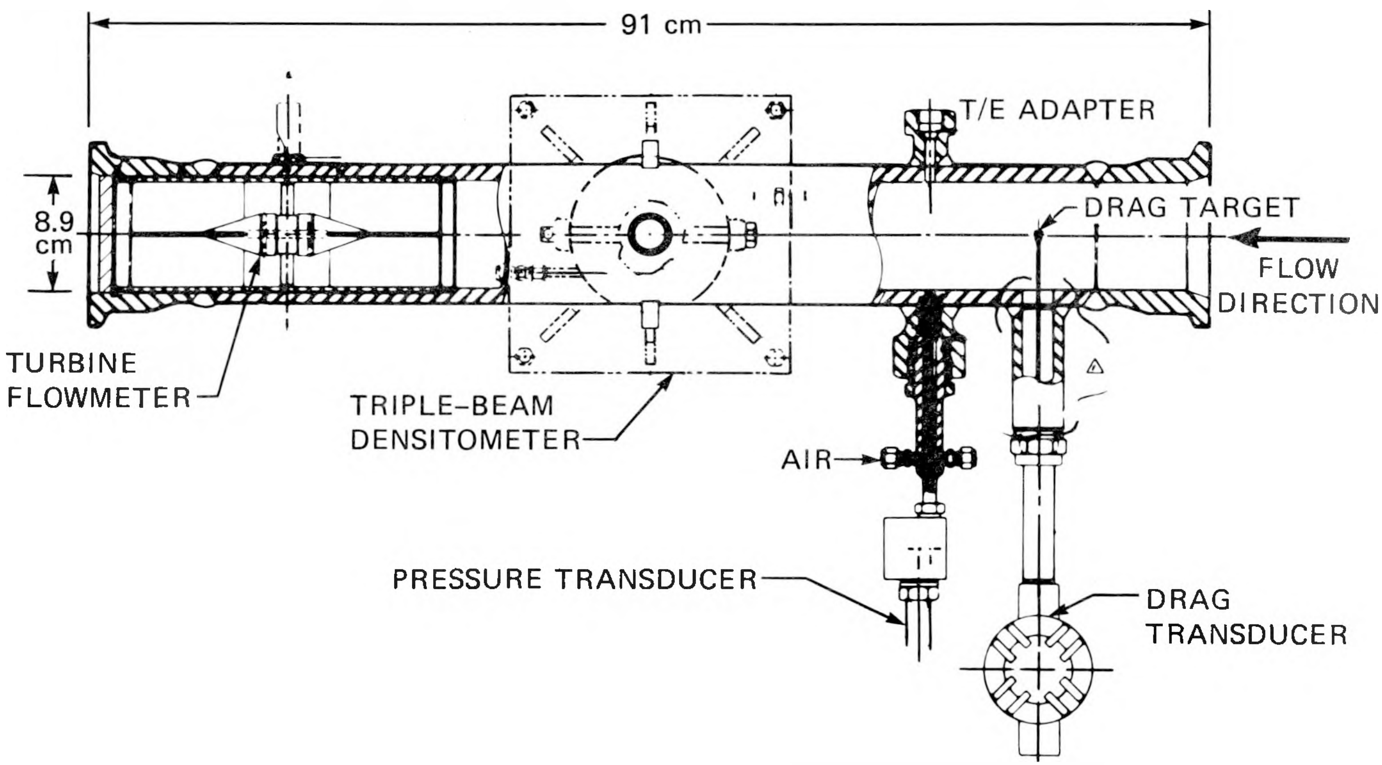

Fig. 2.2. Instrumented spool piece used in steam-water two-phase flow tests.

two-phase flow models to instantaneous readings with techniques developed in earlier experiments.

The two-phase flow tests described in this report are summarized in Table 2.1. The tests were performed at a spool piece pressure of ≃725 kPa (≃105 psia); thus, the phase densities in the test section were ≃0.90 and 0.0038 g/cm^3 (≃56 and 0.23 lb_m/ft^3). The ambient water input flow rates used ranged from 0.31 to 1.07 liters/sec (5 to 17 gpm). Superheated steam input rates ranged from 0.131 to 0.756 kg/sec (1040 to 5990 lb_m/hr). An energy balance was applied to the input flow rates and enthalpies to obtain the mixture quality at the spool piece. It was assumed that there was no heat lost from the fluid between the input metering stations and the test section. This assumption is reasonable because the loop piping is well insulated. At the lowest void fractions, the heat loss may have some effect on the calculated test section qualities and vapor phase velocities, because the amount of steam left after mixing with subcooled

Table 2.1. Two-phase flow conditions for AIRS Test Stand steam-water tests

Superficial liquid velocity [m/sec (ft/sec)]	Superficial vapor velocity [m/sec (ft/sec)]	Quality (%)	Void fraction[a] (%)
0.25 (0.81)	0.23 (0.74)	0.4	59
0.25 (0.83)	2.1 (7.07)	3.4	73
0.25 (0.82)	5.0 (16)	7.7	81
0.25 (0.82)	10.0 (33)	15.0	93
0.25 (0.81)	19.0 (63)	24.0	95
0.17 (0.57)	0.39 (1.3)	0.9	63
0.17 (0.57)	2.3 (7.6)	5.3	76
0.17 (0.57)	5.5 (18)	12.0	84
0.17 (0.57)	13.0 (42)	24.0	95
0.12 (0.38)	15.0 (50)	36.0	96
0.11 (0.36)	6.5 (21)	19.0	90
0.12 (0.38)	2.4 (8)	8.1	75
0.12 (0.38)	0.88 (2.9)	3.1	60
0.073 (0.24)	1.7 (5.6)	9.0	70
0.073 (0.24)	3.7 (12.0)	18.0	83
0.073 (0.24)	6.2 (20)	26.0	89
0.073 (0.24)	16.0 (52)	48.0	96

[a]Based on gamma densitometer data.

water is so small. For the flow rates used, the calculated test section quality was between 0.004 and 0.48, while the void fraction in the spool piece, derived using the densitometer data, ranged from 0.66 to 0.99. The flow rates were chosen to allow examination of unsteady slug-flow regimes (low-steam flow rates) as well as steady annular- and dispersed-flow regimes (high-steam flow rates). The nature of the flowing mixture was apparent both by visual observations made through the lower view ports and by the behavior of the output signals from spool piece instrumentation, particularly the densitometer (Fig. 2.3).

Tests were conducted using the following procedure: the water flow rate was set to the desired value, then steam was introduced in sufficient quantity to produce a two-phase mixture in the test stand. The lowest possible stable steam flow rate at each water flow rate was used while

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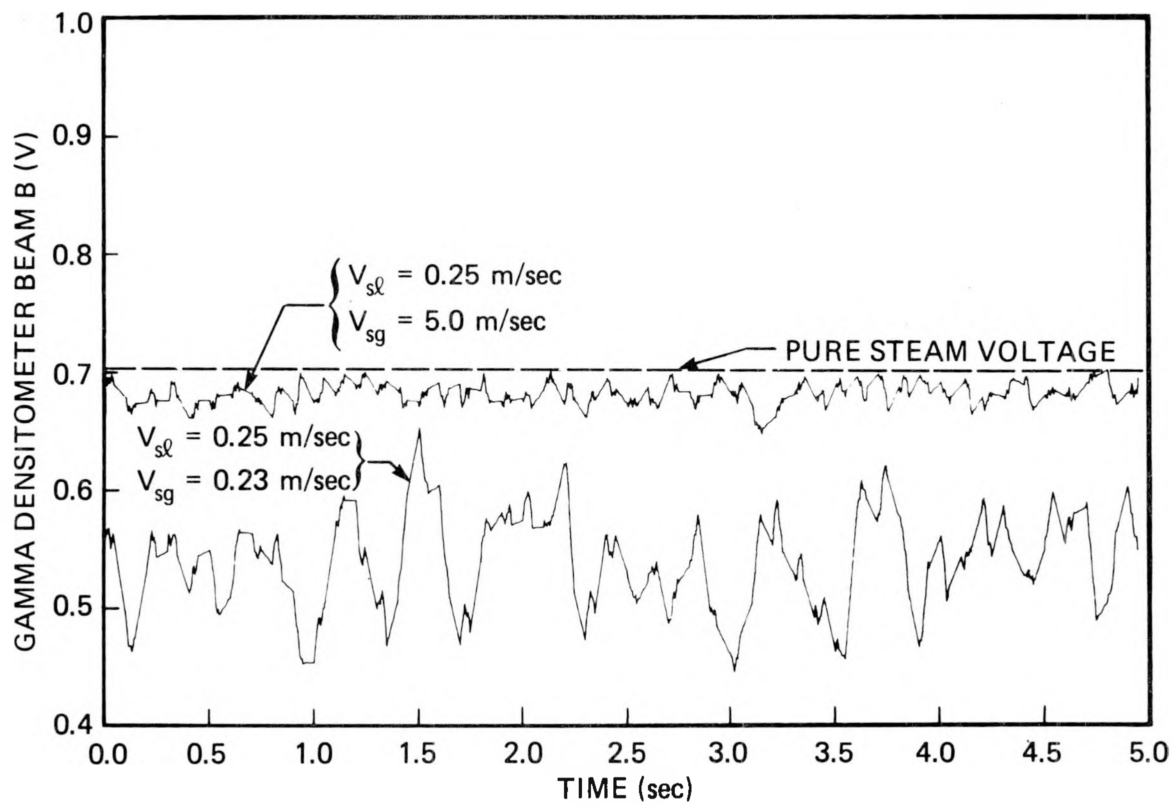

Fig. 2.3. Voltage outputs from beam B (diametrical beam) of densitometer in steam-water slug flow (lower trace) and annular mist flow (upper trace).

maintaining a two-phase mixture; these were the lowest void fractions and quality points shown in Table 2.1. Next, data were taken at higher steam flow rates, when significant changes in the densitometer or turbine output voltages were observed. The highest steam flow rates used produced turbine mean velocities of ≃20 m/sec (≃67 ft/sec), the highest turbine speed that could be interpreted by the turbine flowmeter electronics.

3. RESULTS AND DISCUSSION

Two-phase flow parameters determined from the drag flowmeter, densitometer and turbine meter outputs are presented here to illustrate the instruments' response to the flow.

The composite pipe-average density derived from the densitometer data is plotted in Fig. 3.1. The solid lines represent the density that would occur if the flow were homogeneous (no slip between phases). The predominance of data is at higher void fractions [densities less than 0.32 g/cm^3 (20 lb$_m$/ft^3)], and most of the points lie at higher values than the homogeneous densities, indicating slip ratios greater than unity. The mean liquid and mean vapor phase velocities (determined using volumetric flow rates of each phase in the spool piece and void fractions calculated from the densitometer data) are plotted vs quality in

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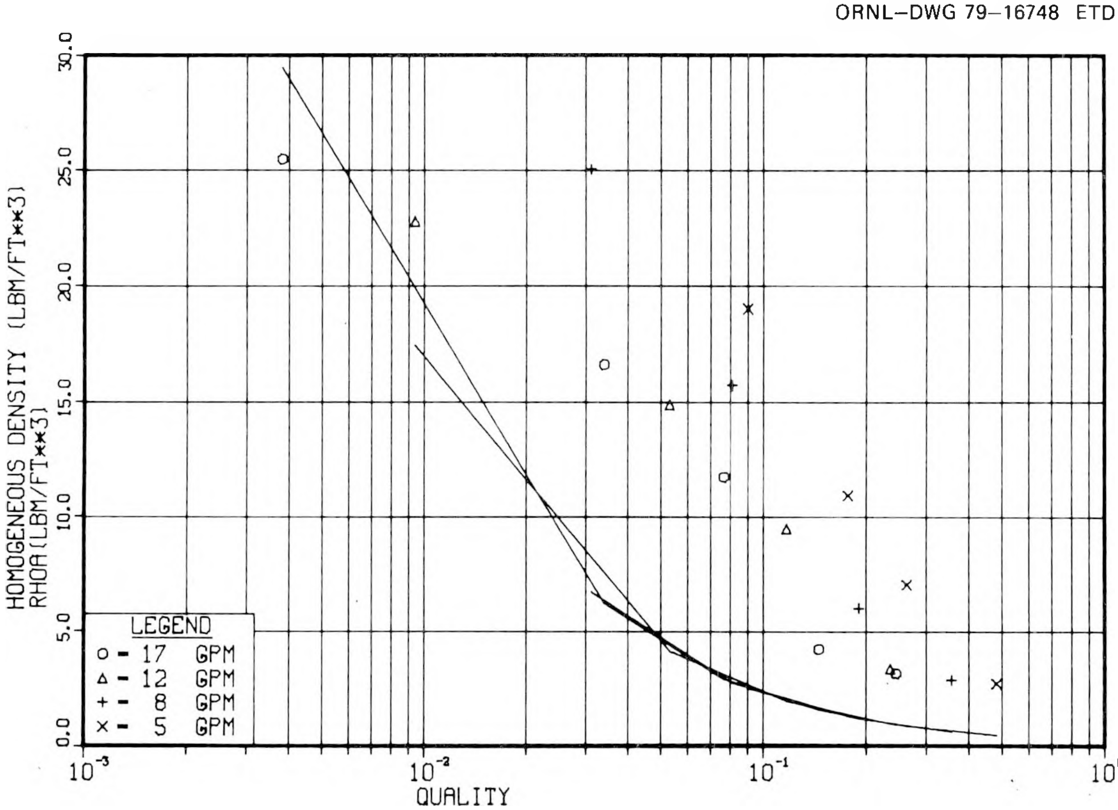

Fig. 3.1. Composite pipe-average densities derived from triple-beam densitometer data taken in steam-water tests. Solid lines represent homogeneous (no-slip) densities calculated from input flow rates.

Fig. 3.2. The vapor phase velocities [Fig. 3.2(a)] increase fairly uniformly with increasing steam flow at a given liquid flow rate. Also, at constant quality, the lower water flow rates produce lower steam velocities. The mean liquid phase velocity [Fig. 3.2(b)] increases rapidly at higher qualities as the flow regime changes from a froth or churn flow to annular or annular-mist flow. The quality calculated for the two points with lowest quality (<1%) may be seriously in error because of uncertainties in quantities used in the energy balance.

The time-averaged velocity of the 12-bladed turbine in the steam-water tests (Fig. 3.3) was almost always greater than the mean liquid velocity but less than the mean vapor velocity. For a given water flow rate, the ratio of turbine speed to mean liquid phase velocity is approximately constant, independent of steam flow [Fig. 3.3(b)]. At higher liquid flow rates, the turbine speed is closer to the liquid phase velocity but still exceeds it by a factor of ~3. On the other hand, the turbine speed lies relatively close to the mean vapor phase velocity at most of the flow rates tested [Fig. 3.3(a)]. At the highest steam flow rates, the turbine speed follows the steam velocity well; but at lower steam rates, in churn and slug flow, the turbine speed is appreciably less than the steam velocity. Generally, for these tests the turbine speed was much closer to the steam velocity than to the liquid velocity.

The turbine response models, which were compared with the 5-bladed turbine data from the air-water tests, have been compared with the 12-bladed turbine tested in the AIRS Test Stand. The phase velocities shown in Fig. 3.2 and the void fractions from densitometer data were substituted into equations that define the turbine velocity in terms of phase densities, phase velocities, and the void fraction.[2] The results are shown in Fig. 3.4. Generally, the volumetric[6] model slightly overpredicts the observed turbine velocities over the range of flow rates tested, while the Aya[7] and Rouhani[8] models underpredict the observed velocities. In contrast to the air-water vertical upflow results, however, the volumetric model predicts best turbine velocities of the three models tested. An exception is at the lowest steam flow rates, when the volumetric model prediction falls below the actual turbine velocity. (These points are at flow rates where calculation of the test section

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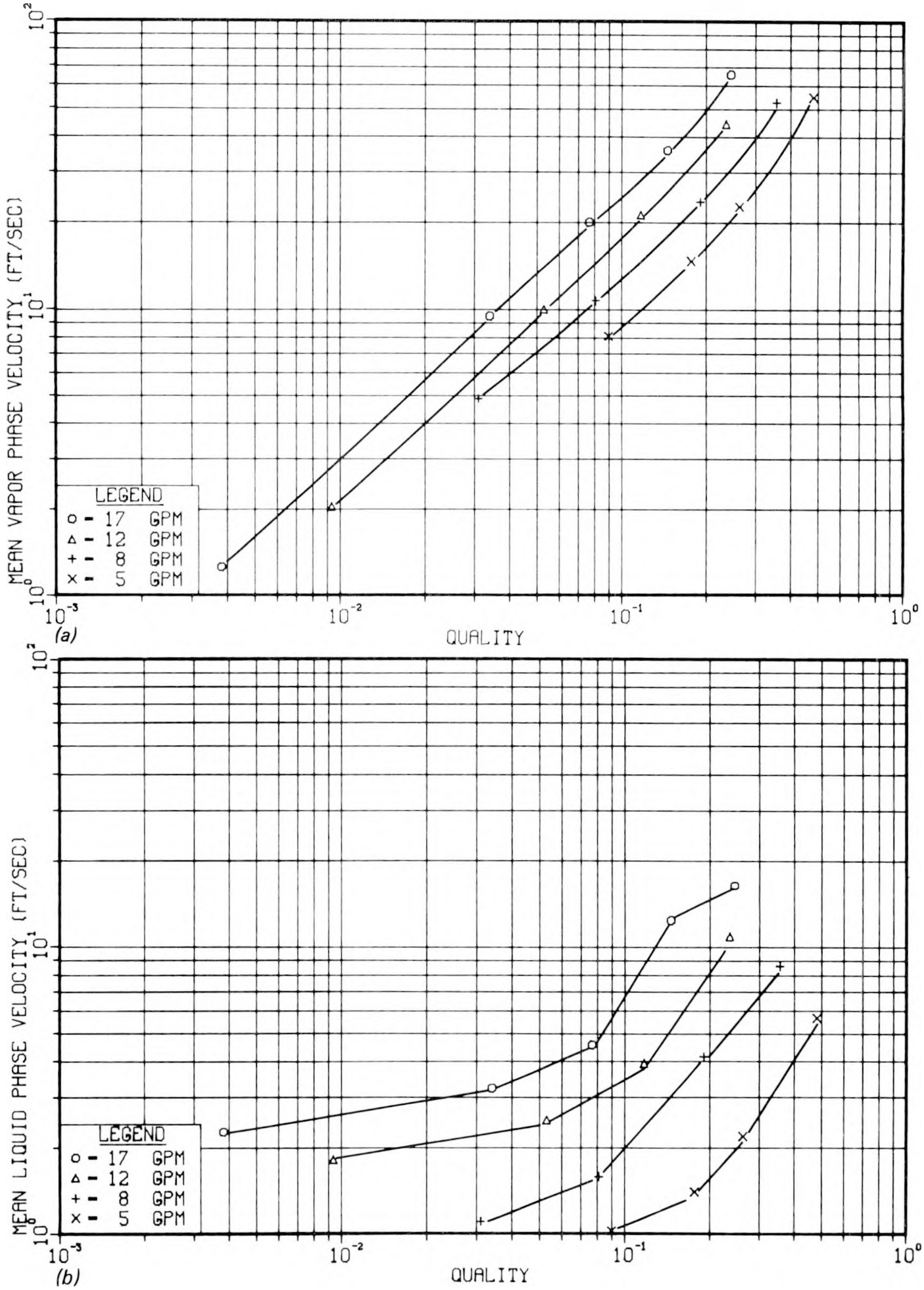

Fig. 3.2. Velocities calculated from spool piece volumetric flow rates and void fractions determined from densitometer data: (a) mean vapor phase, (b) mean liquid phase.

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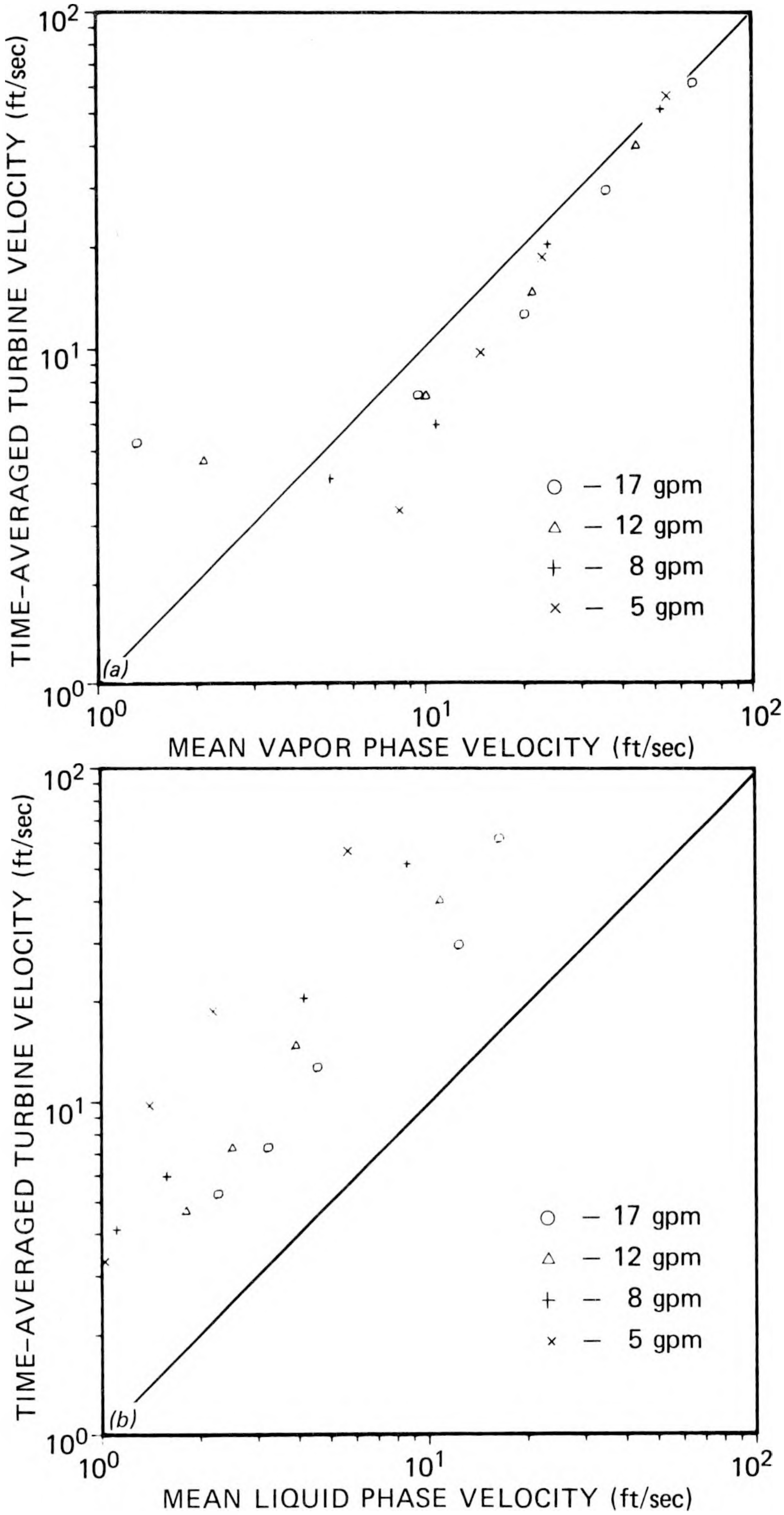

Fig. 3.3. Time-averaged velocity indicated by 12-bladed turbine in steam-water two-phase flow tests plotted vs (a) vapor and (b) liquid velocities.

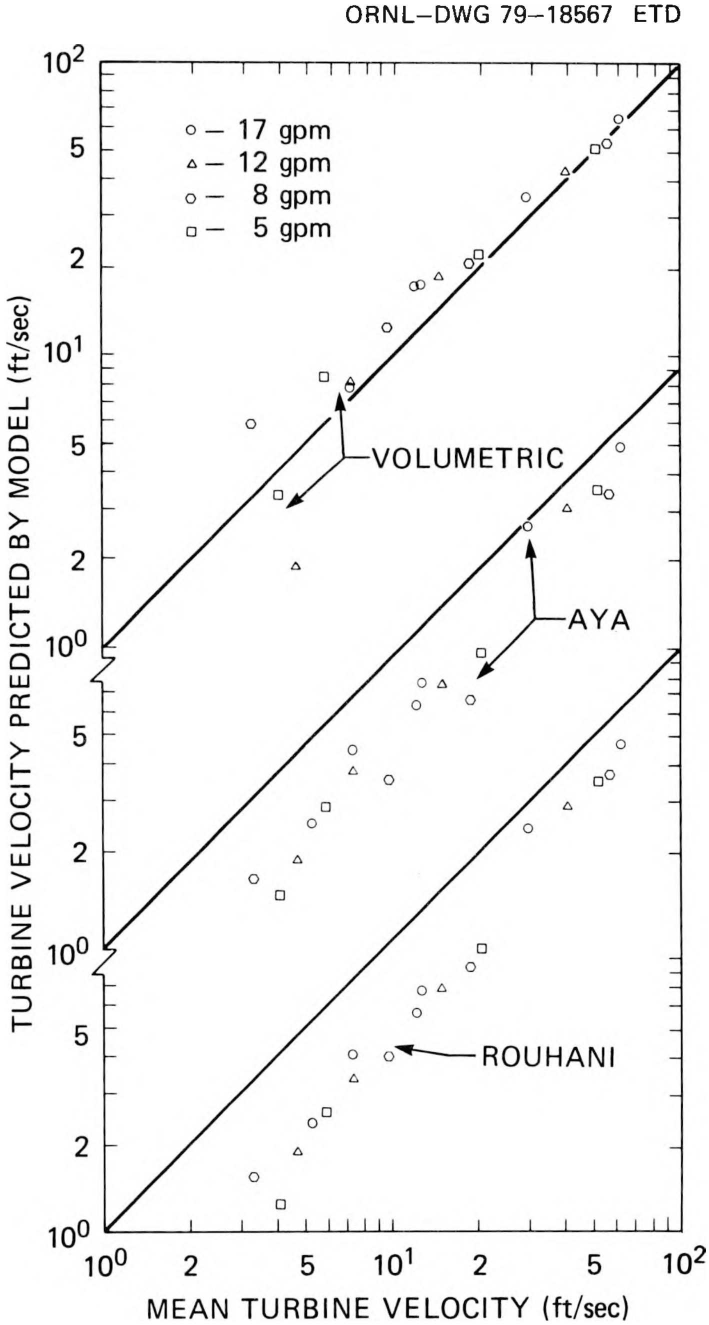

Fig. 3.4. Turbine velocities predicted by volumetric, Aya, and Rouhani turbine models for steam-water two-phase upflow plotted vs 12-bladed turbine data taken in AIRS Test Stand. Solid lines represent perfect agreement for each model.

quality and, thus, the phase velocities have the greatest uncertainty.) The performance of the Aya and Rouhani models is quite similar. The error between their predictions and the actual turbine meter velocity is slightly less at the highest velocities, when the flow regime is annular mist.

A 12-bladed turbine identical to the one used in the steam-water tests was run in vertical upflow in the air-water system. Results of model comparisons to the 12-bladed turbine data using air-water void fractions and phase velocities (Fig. 3.5) are qualitatively like those from the steam-water tests, that is, at high void fraction, the volumetric model overestimates the turbine velocity, while the Aya and Rouhani models underestimate it. (The air-water tests included data at void fractions lower than 50% — points not obtainable in the AIRS Test Stand.) For given air and water flow rates, the 12-bladed turbine indicates higher velocities in two-phase flow than the 5-bladed turbine did. Air-water tests with the 5-bladed turbine showed that the turbine speed approximated the mean liquid velocity when the void fraction was low. Even at low void fractions, however, the 12-bladed turbine's speed exceeds the mean liquid velocity by a significant amount. Thus, the 12-bladed turbine is apparently more responsive to the presence of the faster moving gas phase in the pipe, registering higher speeds than the 5-bladed turbine. None of the turbine models examined accurately predicts the behavior of the 5- or 12-bladed turbines in vertical upflow for all flow regimes.

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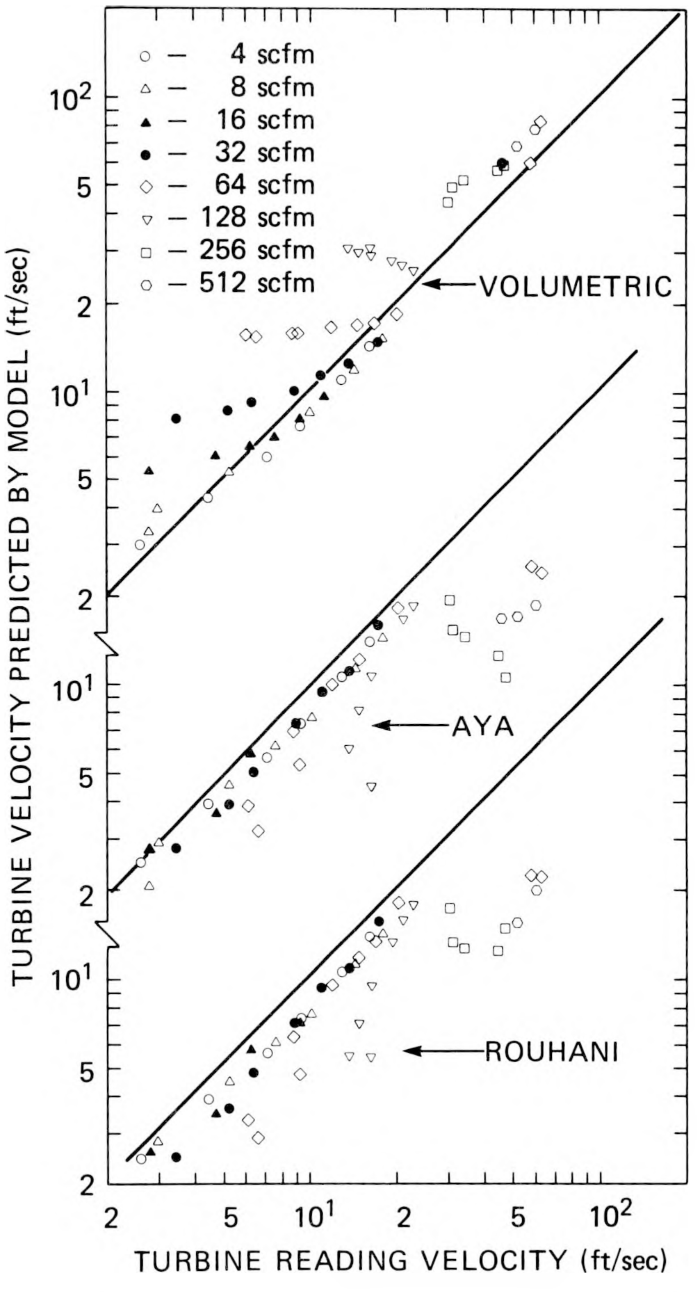

Fig. 3.5. Turbine velocities predicted by volumetric, Aya, and Rouhani turbine models for air-water two-phase upflow plotted vs 12-bladed turbine data taken in air-water test facility. Solid lines represent perfect agreement for each model.

4. TWO-PHASE MASS FLOW MODELS

Models involving simple algebraic combinations of the reduced readings from the turbine and drag flowmeters and the densitometer have been applied to the data taken in the AIRS Test Stand. Comparisons of the model calculations with the metered input mass flow rates are presented in this section.

The pipe-average density from the densitometer ρ_a and the mean turbine velocity V_t may be combined to give

$$G_1 = \rho_a V_t \; . \tag{4.1}$$

G_1 is plotted vs the actual mass flux in Fig. 4.1. The mass flow rates

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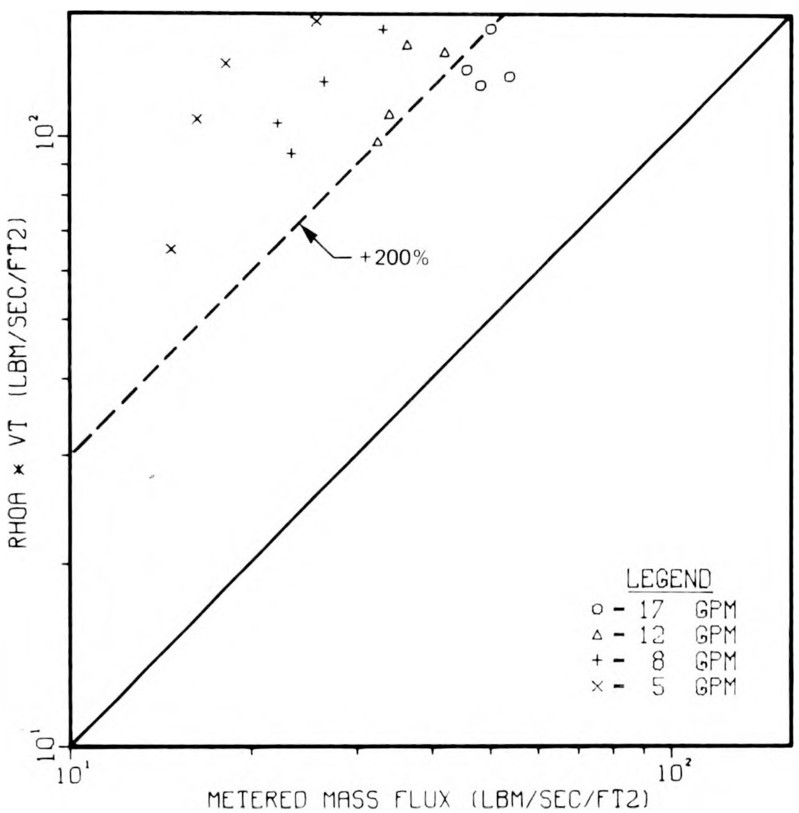

Fig. 4.1. Mass flux predicted using densitometer and turbine flowmeter readings (G_1) plotted vs mass flux metered into AIRS Test Stand.

predicted by G_1 grossly overpredict the correct mass flux over the entire range of flow rates. In the air-water tests, G_1 had predicted the actual flux reasonably well at lower void fractions because, in those cases, the turbine speed had approximated the mean liquid phase velocity. The void fractions and slip ratios obtained in the steam-water system were relatively high, however, and the turbine rotor was more responsive to the vapor velocity than were the five-bladed rotors used previously.

Figure 4.2 is a similar graph for the model

$$G_2 = \sqrt{\rho_a I_d} \; , \tag{4.2}$$

where I_d is the momentum flux indicated by the drag flowmeter. Again,

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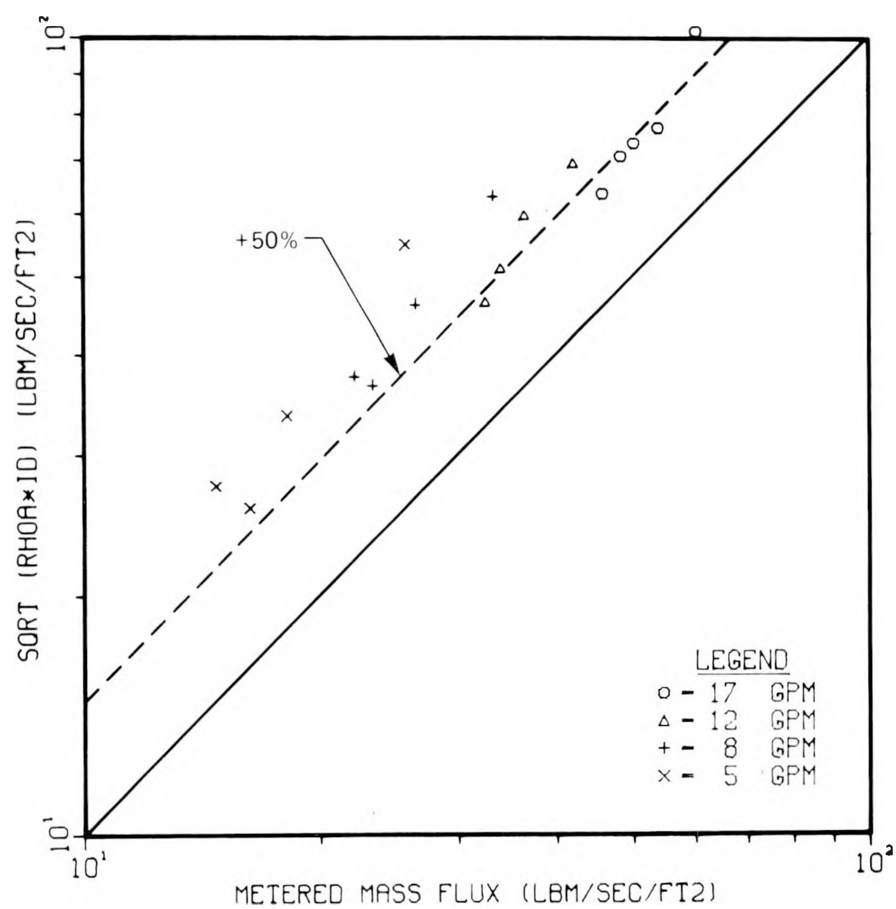

Fig. 4.2. Mass flux predicted using densitometer and drag flowmeter readings (G_2) plotted vs mass flux metered into AIRS Test Stand.

the mass flow rates predicted by the model overestimate the correct mass fluxes over the entire range but by a lesser amount than G_1. A previous report[3] showed that G_2 will overestimate the mass flux at high slip ratios if the drag flowmeter reading conforms to a two-velocity model. Thus, G_2 appears unsuitable for application in flows of this nature unless correction factors are applied.

The behavior of the third model,

$$G_3 = I_d/V_t \ , \tag{4.3}$$

is shown in Fig. 4.3. At times when the drag flowmeter reading was below ≃300 kg/m•sec² (≃200 lb_m/ft•sec²) or ≃1% of full scale, the data

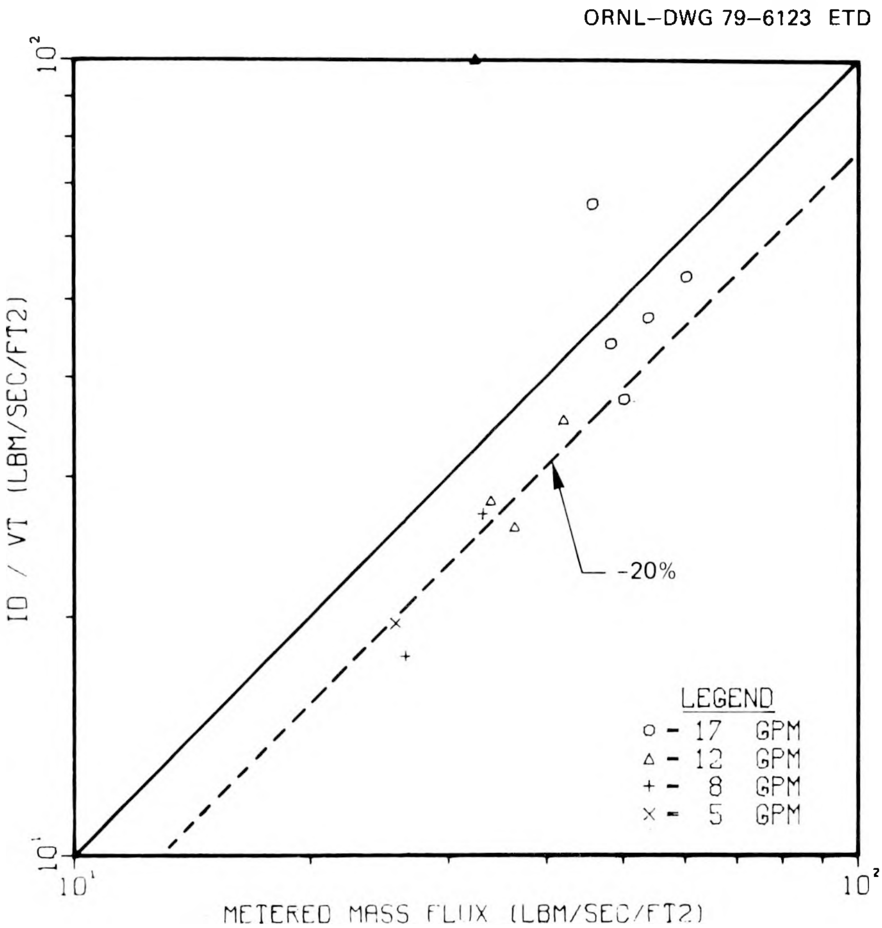

Fig. 4.3. Mass flux predicted using turbine flowmeter and drag flowmeter readings (G_3) plotted vs mass flux metered into AIRS Test Stand.

were deemed unsuitable for model comparison, and those are not plotted in Fig. 4.3. In general, the model results lie some 10 to 30% less than the correct values. Air-water vertical upflow tests demonstrated that the drag coefficient of the full-flow targets in two-phase flow were not appreciably less than the single-phase drag coefficients. Therefore, the underestimate is most likely because the turbine speed V_t is greater than that predicted by the Rouhani turbine model.

5. CONCLUSIONS

An experimental study was performed using an instrumented piping spool piece in the AIRS Test Stand, a steam-water flow system. Flow through the spool piece was vertically upward. The steam and water flow rates produced several flow regimes; the void fraction in the spool piece was always greater than 50%.

Analysis of the densitometer data showed that the pipe-average slip ratios for the steam-water flow points were high, ranging from ~3 to ~10. The turbine velocity was found to greatly exceed the mean liquid phase velocity; its velocity was fairly close to the mean steam velocity over most of the flow range. Consequently, the Aya and Rouhani turbine models seriously underestimated the turbine velocities for these tests. The volumetric model, however, predicted the turbine velocity reasonably well, except at the lowest steam flow rates used. (The 12-bladed turbine used in the steam-water tests was also found to greatly overestimate the liquid velocity in the air-water system, in contrast to the 5-bladed turbine used previously.)

Comparisons of the data calculated using the mass flow models $G_1 = \rho_a V_t$, $G_2 = \sqrt{\rho_a I_d}$, and $G_3 = I_d/V_t$ with the actual two-phase mass flux in vertical upflow have suggested the following points.

1. At the flow rates and void fractions used in the steam-flow tests, G_1 grossly overestimates the mass flux, largely because of turbine speeds well in excess of the mean liquid velocity.

2. G_2 overestimates the mass flux at the high slip ratios characteristic of the steam-water tests, though not as badly as G_1.

3. When the drag flowmeter output was high enough to be significant, G_3 was found to yield consistent results but fell somewhat below the true mass flux because of the turbine overspeed problem mentioned above.

Recommendations made with respect to further steam-water testing of instrumented spool pieces of the type described here are:

1. use of drag transducers ranged to more accurately measure fluid momentum fluxes below ≈300 kg/m·sec^2 (≈200 lb$_m$/ft·sec^2);

2. use of a 5-bladed turbine so that the Rouhani model is more appropriate, or, alternately, development of a two-phase mass flow rate model that incorporates the volumetric turbine model assumption for use with data from the 12-bladed turbine;
3. extension of the testing to include higher water flow rates and lower void fractions, so that the transitions in instrument behavior to single-phase liquid flow could be studied.

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