CONF-790455--6

MASTER

JAERI INSTRUMENTED SPOOL PIECE PERFORMANCE IN TWO-PHASE FLOW

J. B. Colson and J. V. Gilbert
EG&G Idaho, Inc.
P.O. Box 1625
Idaho Falls, Idaho 83401

ABSTRACT

Instrumented spool pieces to be installed in horizontal piping on the Cylindrical Core Test Facility (CCTF) at the Japanese Atomic Energy Research Institute (JAERI) have been designed and tested. The instrumented spool pieces will provide measurements from which mass flow rates can be computed.

The primary instruments included in the spool pieces are a full-flow turbine, a full-flow perforated drag plate, and a low energy three-beam photon densitometer. Secondary instruments are provided to measured absolute pressure, fluid temperature, and differential pressure across the full-flow perforated drag plate.

Single-phase (liquid-gas) calibrations were performed on the drag screen and turbine flowmeter in a prototype spool piece. Two-phase (water-steam) flow tests were conducted to determine the error bands for the spool piece measurements.

An analysis was performed on the two-phase flow data to optimize the computational method used to determine mass flow rates. The computed mass flow rates were compared with the known test loop inputs of steam and water; these comparisons were within 10% of the maximum flow rate tested.

1. INTRODUCTION

Instrumented spool pieces (flanged sections of pipe containing sensors) for installation in horizontal piping on the CCTF at JAERI have been designed and tested. These measurement systems are provided as part of a research program involving the U.S. Nuclear Regulatory Commission, JAERI, and the Federal Minister for Research and Technology of the Federal Republic of Germany (BMFI).

The objective of the instrumented spool pieces is to provide measurements from which the mass flow rate of steam and water can be computed. This paper provides a summary description of the hardware, calibration methods, and testing used for the instrumented spool pieces and discusses the analytical modeling and the methods for data analysis.

Section 2 provides a description of the instrumented spool pieces and associated instruments. Figure 1 shows a typical CCTF instrumented spool piece installed at the CCTF. The primary instruments included in the spool pieces are the turbine flowmeter, densitometer, and drag screen. Secondary instruments, not shown in detail, are provided to measure the differential pressure across the drag screen, absolute pressure, fluid temperature, and metal temperature. The instrument locations in the spool pieces are shown in Figure 2. The steam superheat temperature sensor (steam probe) was used only at Location CL-4. Instruments designed for Locations CL-1 through CL-3 were designed for higher density flow than those of Locations HL-1 through HL-4 and CL-4.

Section 3 discusses the single-phase (liquid-gas) flow calibrations performed on the drag screen and turbine motor in the spool pieces. A ballistic calibrator was used for the liquid calibrations and an air loop was used for the gas calibrations. These tests were performed at Flow Technology Inc., in Phoenix, Arizona.

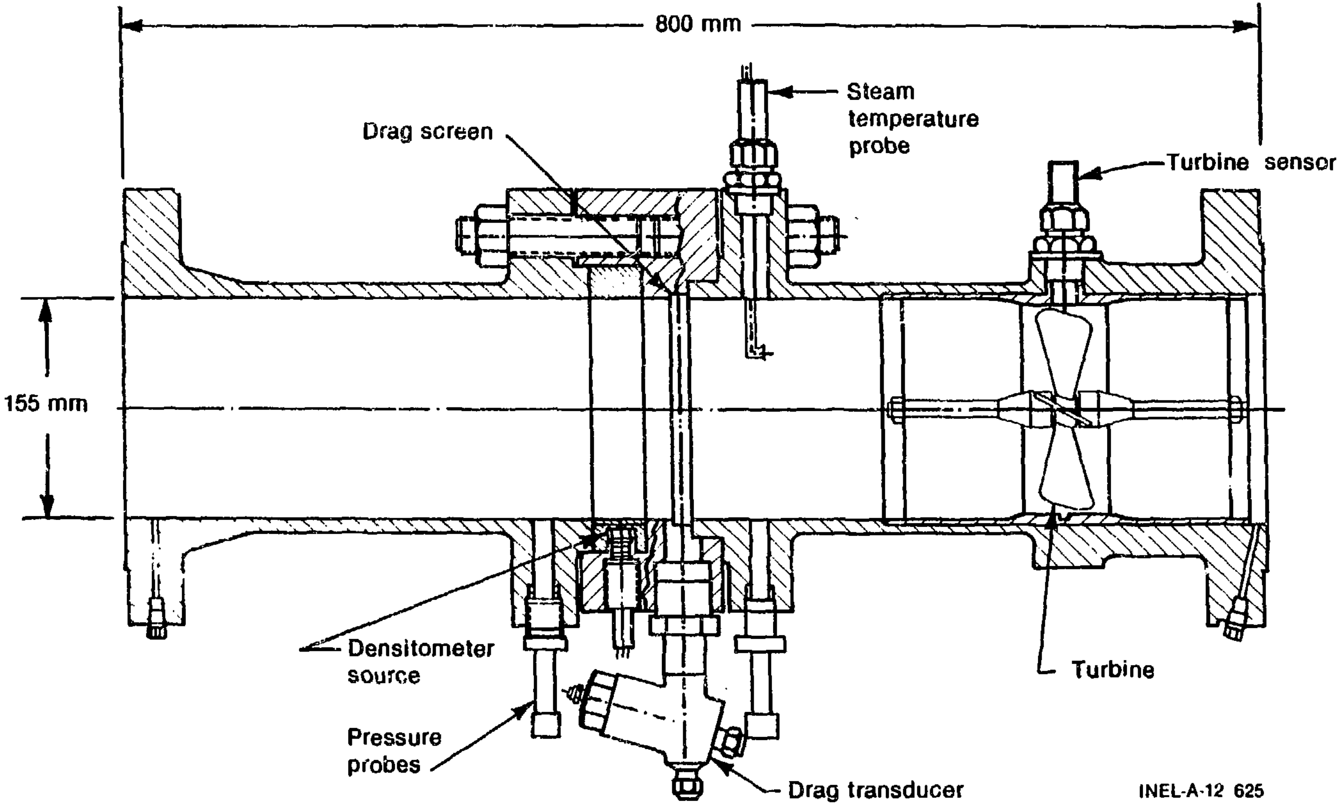


Fig. 1 CCIT instrumented spool piece.

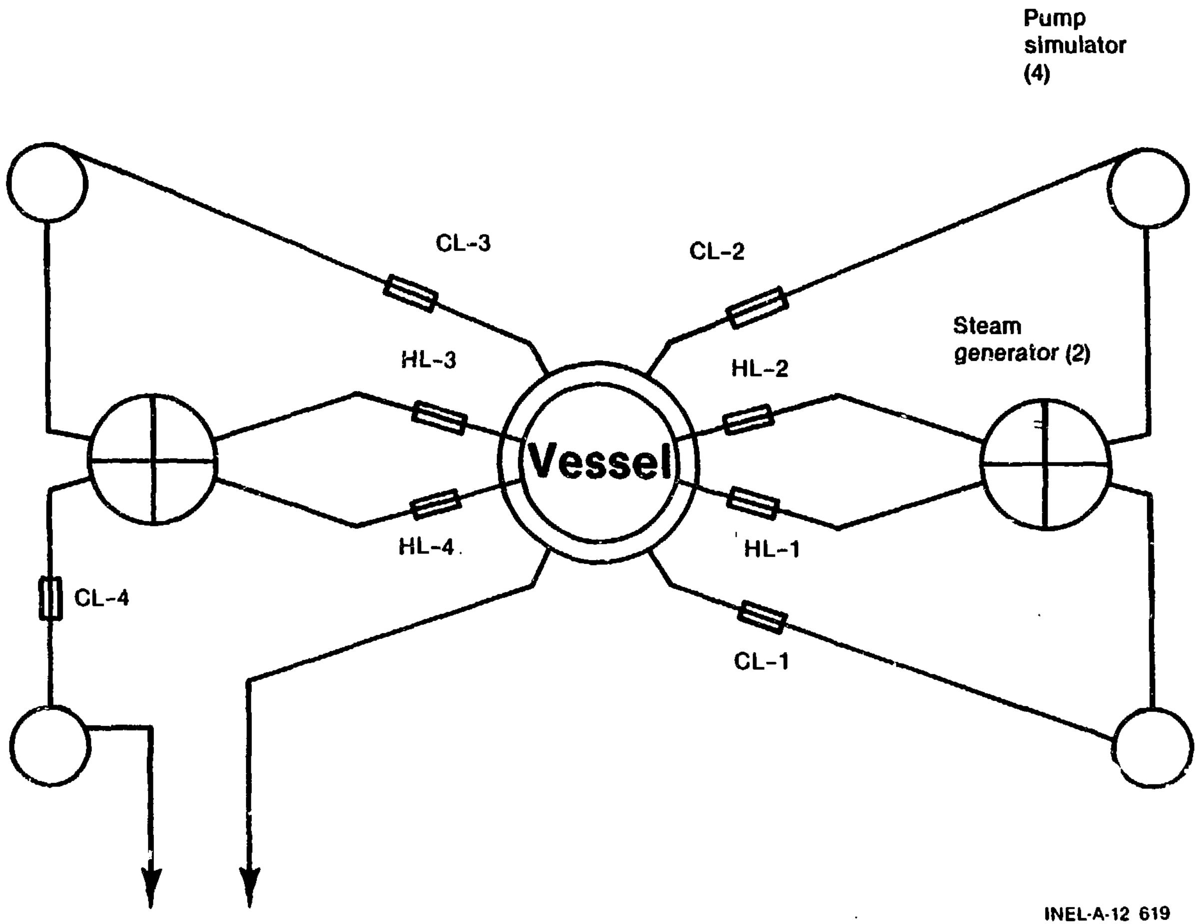


Fig. 2 Spool piece locations in CCTF.

Two-phase (water-steam) flow tests performed in a two-phase flow test loop located at Wyle Laboratory in Norco, California, are discussed in Section 4. The data obtained will be used to determine the accuracy to which the instrumented spool pieces can measure two phase steam-water mass flow rates.

The analytical models used for each instrument are provided and discussed in Section 5.

Mass flow rates have been computed using the analytical model and compared with the established two-phase (water-steam) test loop data. This information is found in Section 6.

Finally, conclusions are presented in Section 7.

2. HARDWARE DESCRIPTION

Harware utilized in these spool pieces includes commercial, prototypical, and instruments proven by EG&G Idaho, Inc., at the Idaho National Engineering Laboratory (INEL). The densitometers, drag screens, and pressure measurements are as developed and used at the Semiscale facility at the INEL.

2.1 Turbine

A turbine flowmeter is used to measure the velocity of the fluid. The turbine (Figure 1), as manufactured by Flow Technology Inc., can be inserted into the end of the spool piece either during construction or while the spool piece is out of the piping for maintenance. Two magnetic sensors (one shown) are used to sense the blade velocity and to allow determination of direction. Stainless steel bearings and flow straightening vanes in the shroud are salient features of the design.

2.2 Densitometer

A densitometer is used to measure the averaged density of the fluid. The densitometer, as shown in cross section in Figure 3, uses a single, pure germanium detector cooled to liquid nitrogen temperature, three low-energy sources (Cd^{109}, Am^{241}, and Gd^{153}) of different photon energy, a beryllium ring insert for low photon attenuation in the pipe wall, and a cryogenically cooled preamplifier. Pulse height discrimination is used to separate the photon energies; the attenuation of each beam provides a measure of the chordal path density between the respective source and the detector.

2.3 Drag Screen

The force on a drag screen is measured to determine the area averaged momentum flux. Termed a drag screen, the full-flow perforated drag plate, shown pictorially in Figure 4, is a plate with large holes leaving a flow restriction of about 20% of the flow area. The plate is suspended by three drag transducers, one on the bottom and one on each side of the pipe, using ball pivots. Figure 5 illustrates a cross-sectional view of the drag transducer in which the drag screen force is transmitted by means of a pivot bearing to the core of the variable reluctance transducer (VRT). Core movement is restrained by a spring, whose stiffness or spring constant is selected such that the desired full-scale range is reached before the drag screen limits in travel. Water cooling is provided to maintain the temperature of the VRT and spring at a relatively constant temperature.

2.4 Secondary Instruments

The system pressure is measured by an absolute pressure transducer using water-cooled assemblies with a downward slope to ensure water-filled pressure lines. Such a connection ensures proper pressure measurements and a high-frequency response.

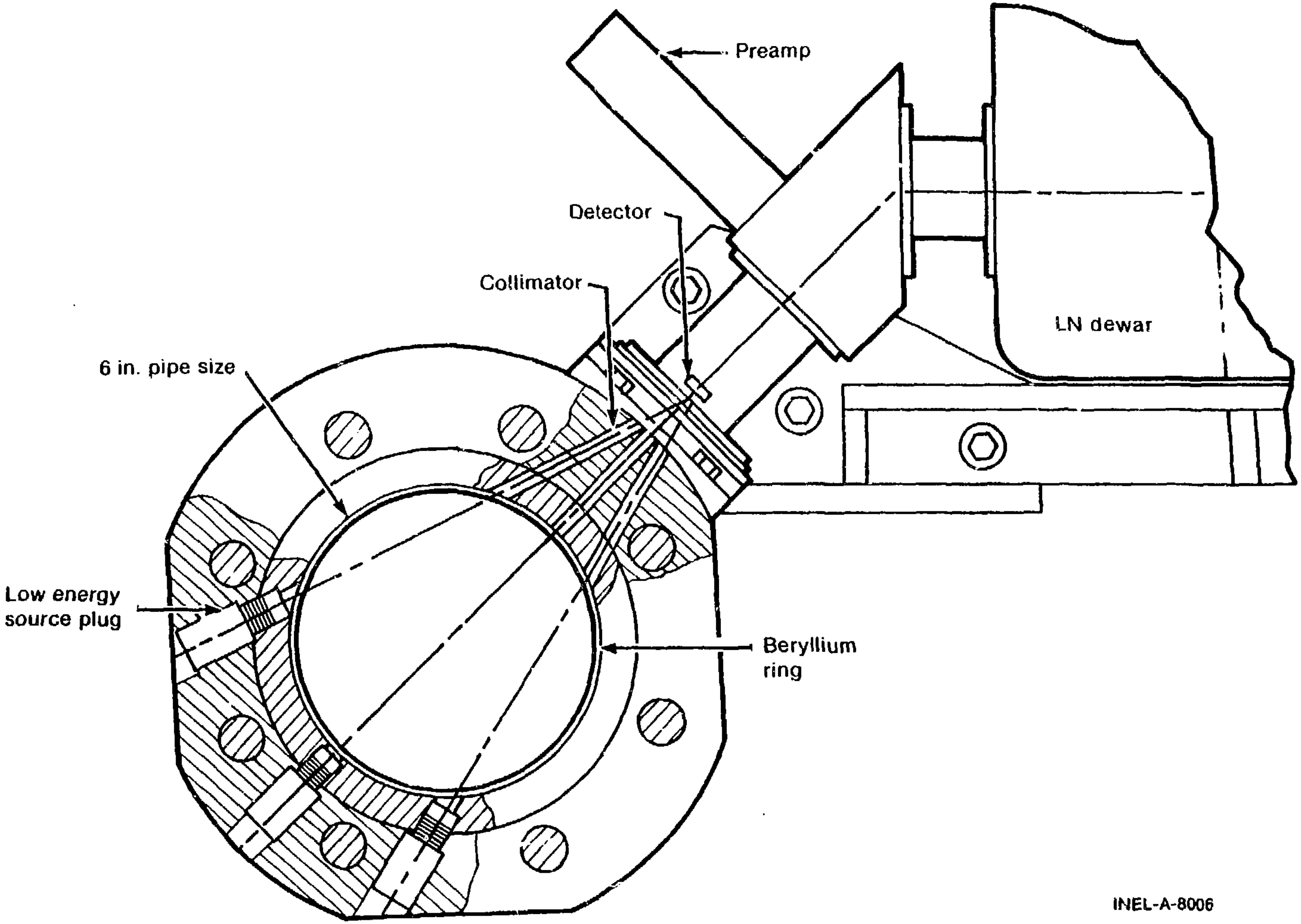
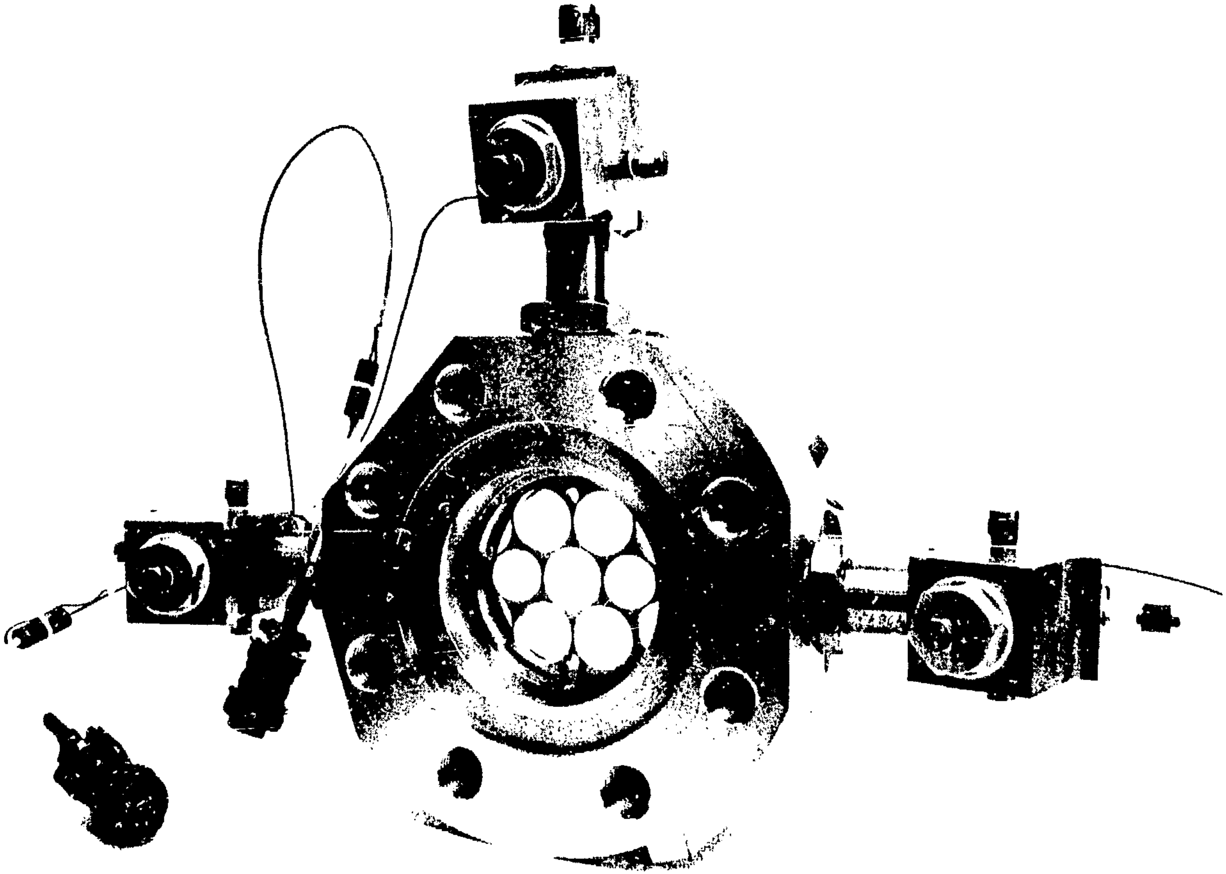


Fig. 3 Photon densitometer.



78-7468

Fig. 4 Drag screen assembly.

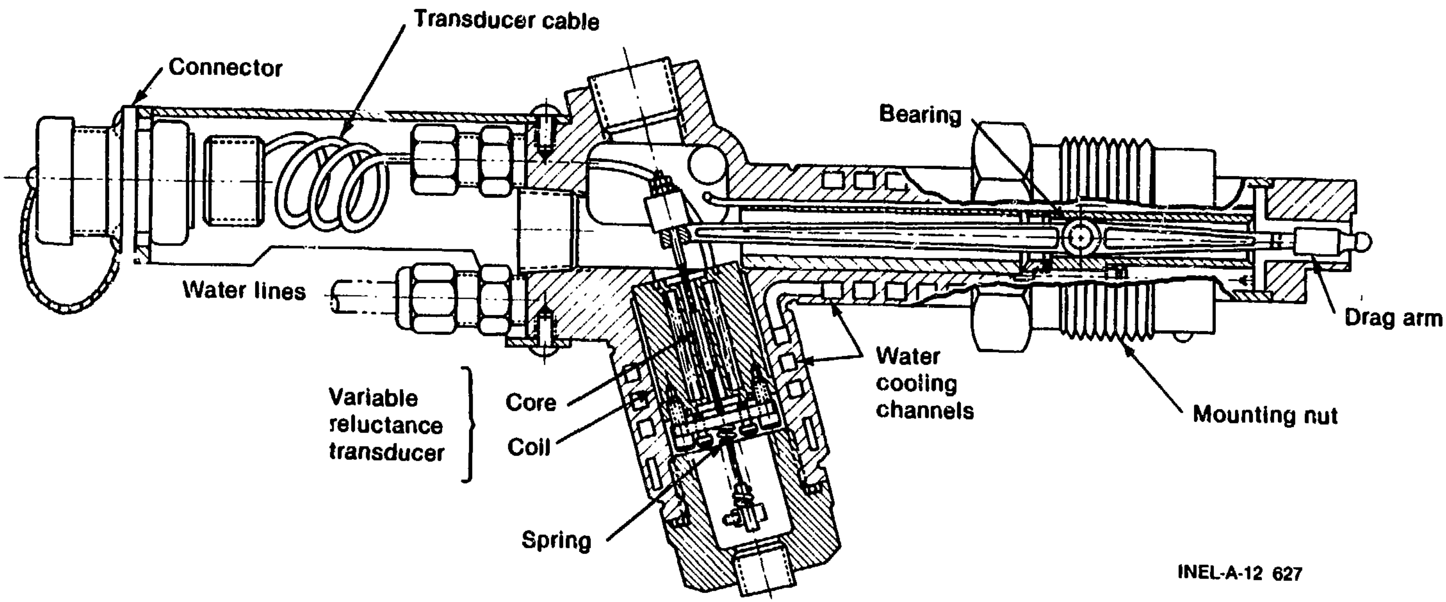


Fig. 5 Drag transducer.

Differential pressure is measured across the drag screen with a commercial transducer and water-cooled lines as an alternate method of measuring momentum flux. Commercial grounded junction Type-E thermocouples with a stainless steel sheath are used; the fluid temperature thermocouple extends into the fluid, and the metal temperature thermocouple is spring loaded into a thermal well near the inside pipe wall.

A steam temperature probe is used to measure the temperature of superheated steam in high-quality, two-phase flow. The steam probe (Figure 1) is a prototypical, vented EG&G Idaho Inc., design with an entrance port pointing downstream and is similar to the steam probe developed by Westinghouse Electric Company. Only steam is vented when the void fraction is low. An internal thermal shield is used around the thermocouple to minimize heat transfer errors.

Figure 6 shows the prototype spool piece during preliminary calibration tests.

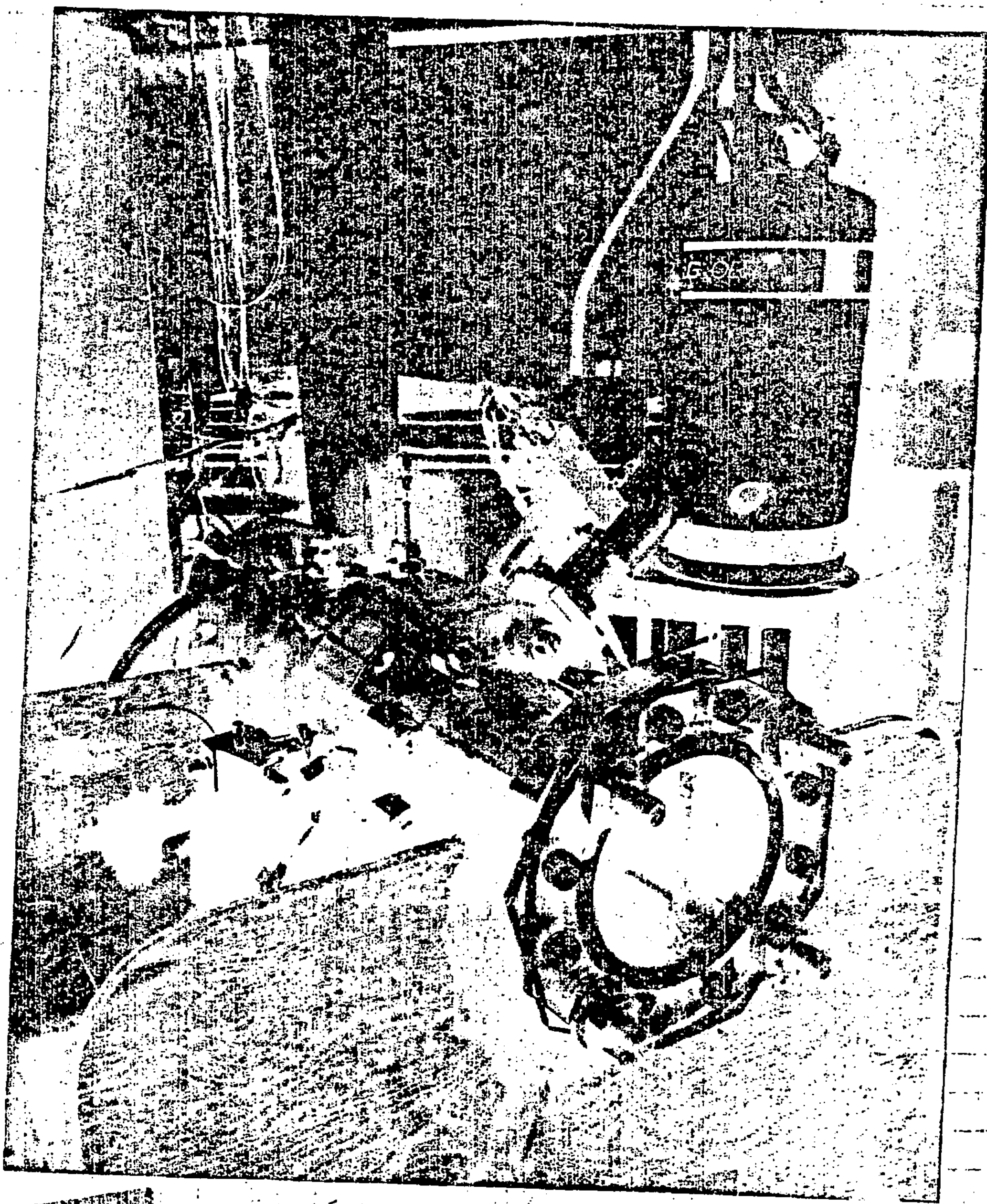


Fig. 6. Spool piece densitometer calibration setup.

3. SINGLE-PHASE CALIBRATION

Single-phase air and water calibrations were performed at Flow Technology, Inc., through the use of a ballistic calibrator. Figure 7 is a plot of the calibration data in both gas and liquid for the turbines used in the low-density flow spool pieces (Locations HL-1 through HL-4 and CL-4). The data indicated that the same calibration constant can be used for both gas and liquid, a prerequisite for successful use in two-phase flow. Similar results were obtained with the turbine used in the high-density flow spool pieces (Locations CL-1 through CL-3). All data points are accurate within 1% of full scale.

Figures 8 and 9 show the calibration data taken at Wyle Laboratories for the calculated momentum flux from the drag screen force and differential pressure responses, respectively. Calibration was consistent over 2-1/2 decades of range for both the hot and cold leg spool pieces. Data points are accurate within 2% of full scale.

Densitometer calibration was performed over the high range of density, as shown in Figure 10, using water levels in the spool pieces and over the very low range of density using nitrogen at various pressures, as shown in Figure 11. Data points are accurate within 2% of full scale.

Standard calibration techniques were used for temperature and pressure.

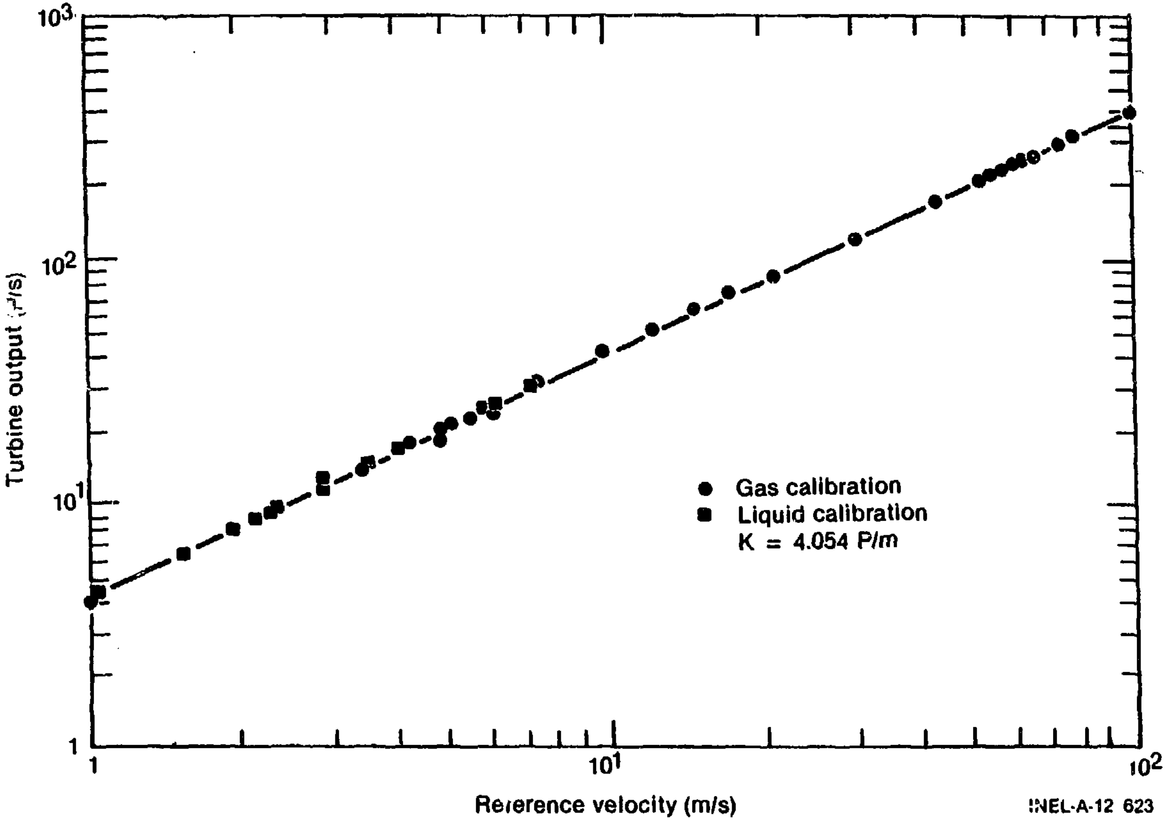


Fig. 7 Hot leg spool turbine calibration.

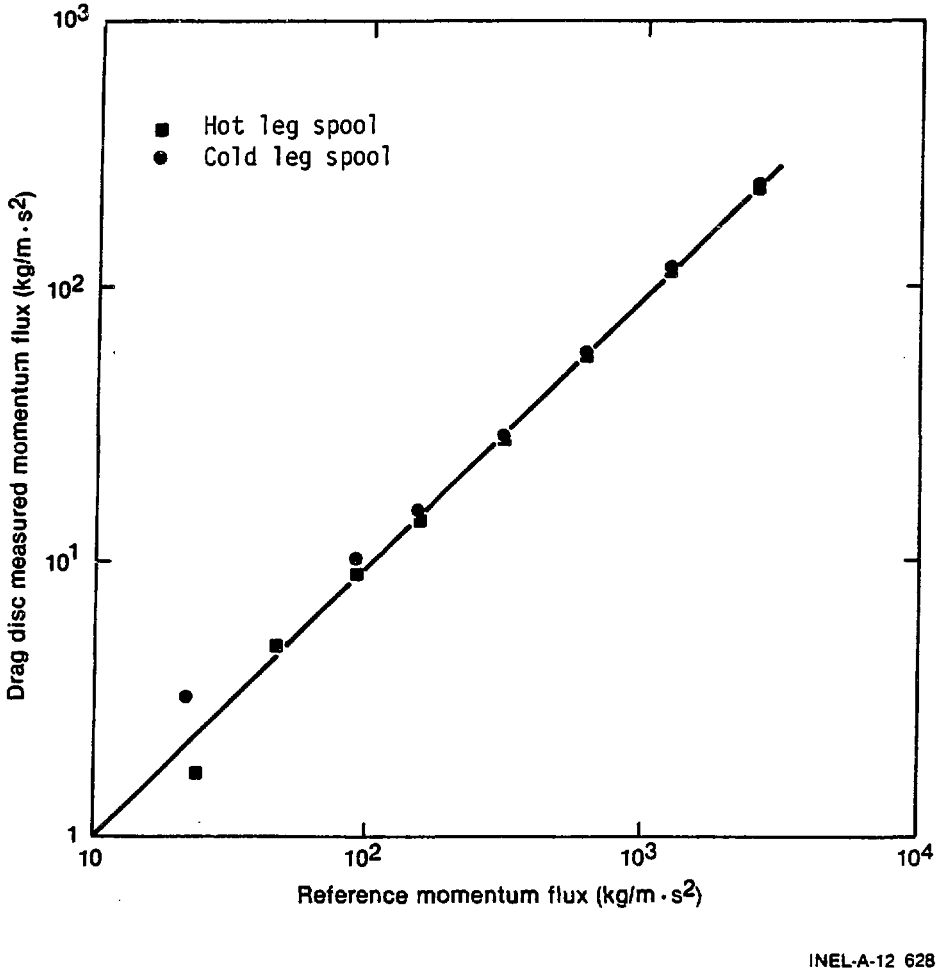


Fig. 8 Drag screen force momentum flux calibration.

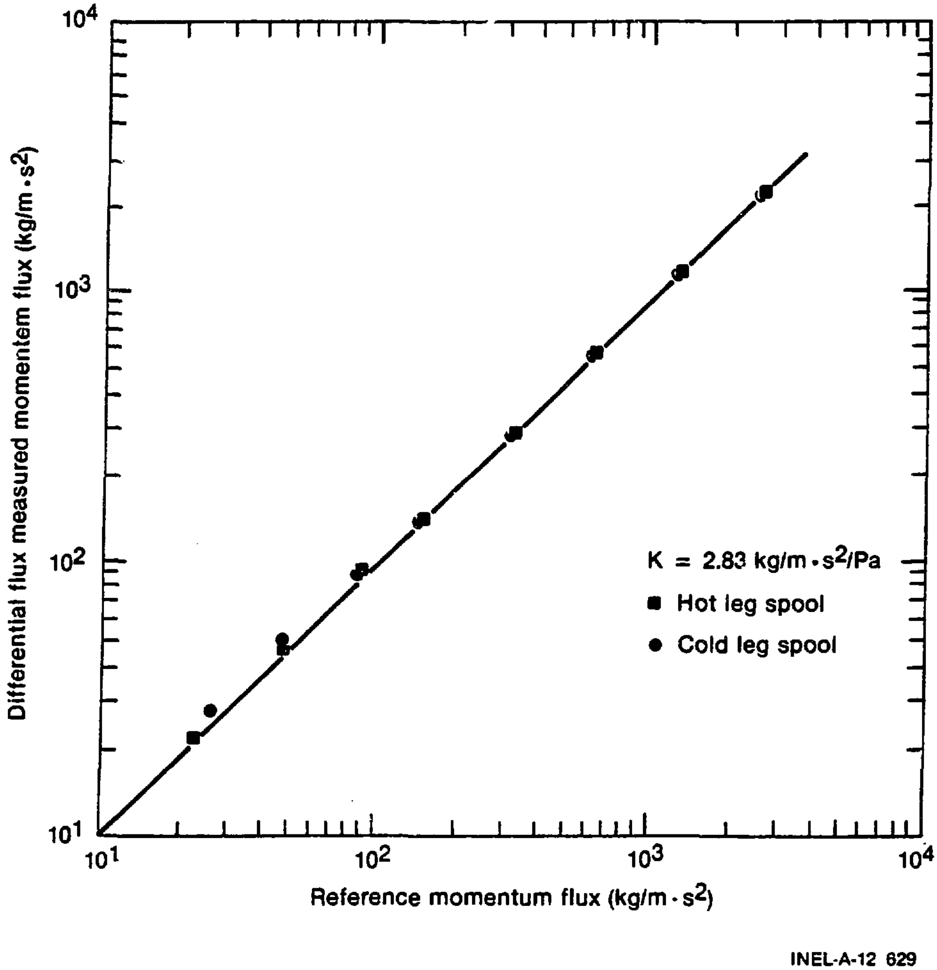


Fig. 9 Drag screen differential pressure momentum flux calibration.

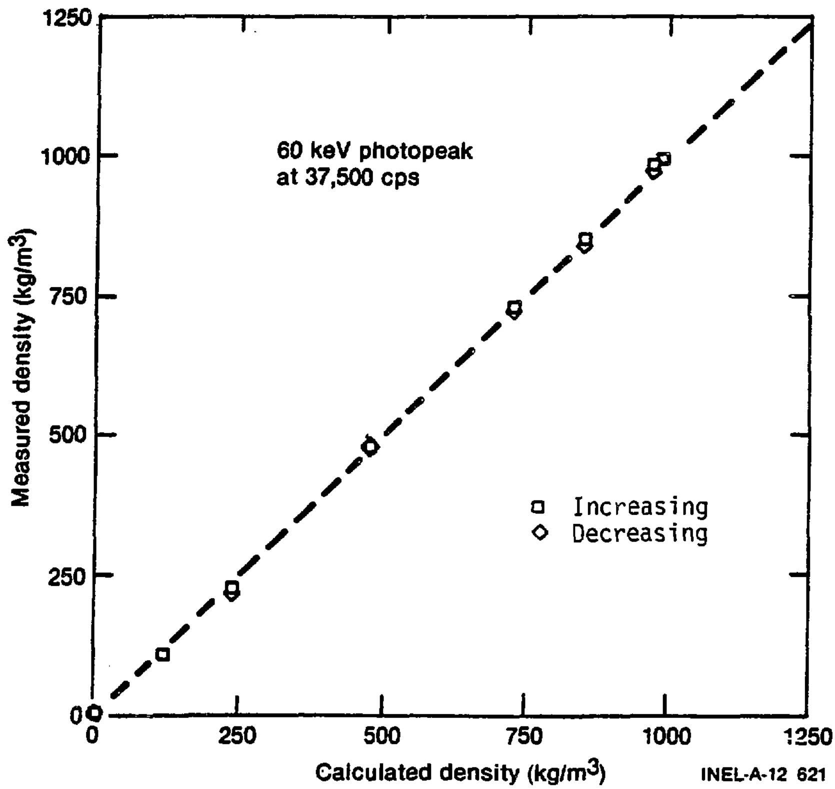


Fig. 10 Densitometer high density air-water calibration.

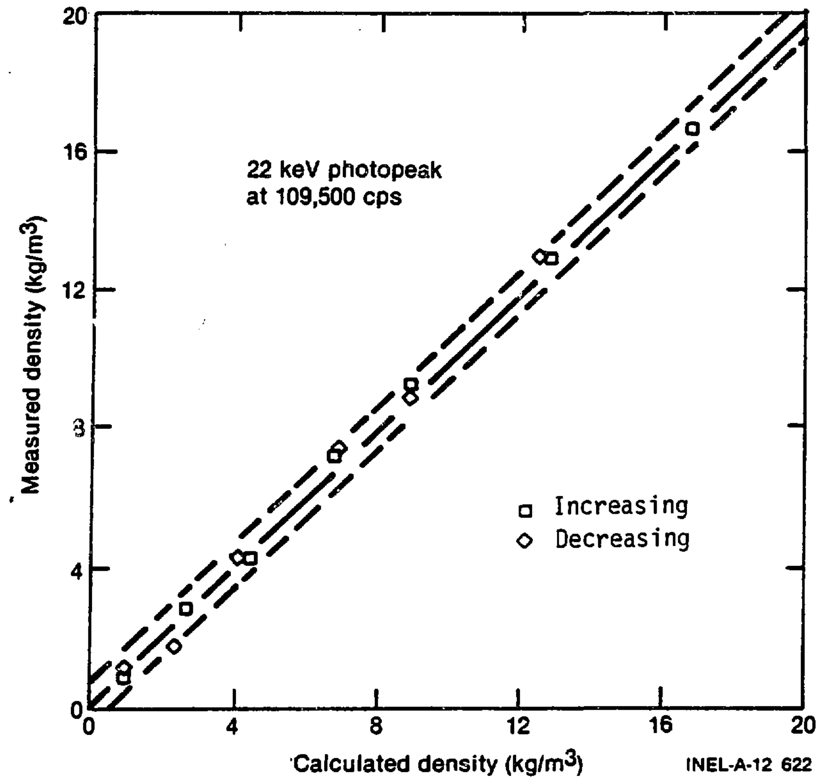


Fig. 11 Densitometer low density nitrogen calibration.

4. TWO-PHASE TESTING

The prototype spool piece was tested in a two-phase, steam-water loop at Wyle Laboratories in Norco, California. The loop flow diagram is shown in Figure 12. Two-phase flow was obtained by mixing steam from a storage tank into a circulating water loop. The steam was separated from the loop at a receiver and vented to the atmosphere, and the water was recirculated. The steam supply had the capacity to deliver up to 0.63 kg/s under steady state conditions and 3 kg/s for short periods of time. Water flow could be varied up to 52 kg/s. Loop design and instrumentation made mass and energy balance possible to within 5% through inlet and outlet flow measurements in the steam-water tests. Both high- and low-density flow versions of the spool piece were tested over the entire range of flows expected in the CCTF in forward and reverse directions.

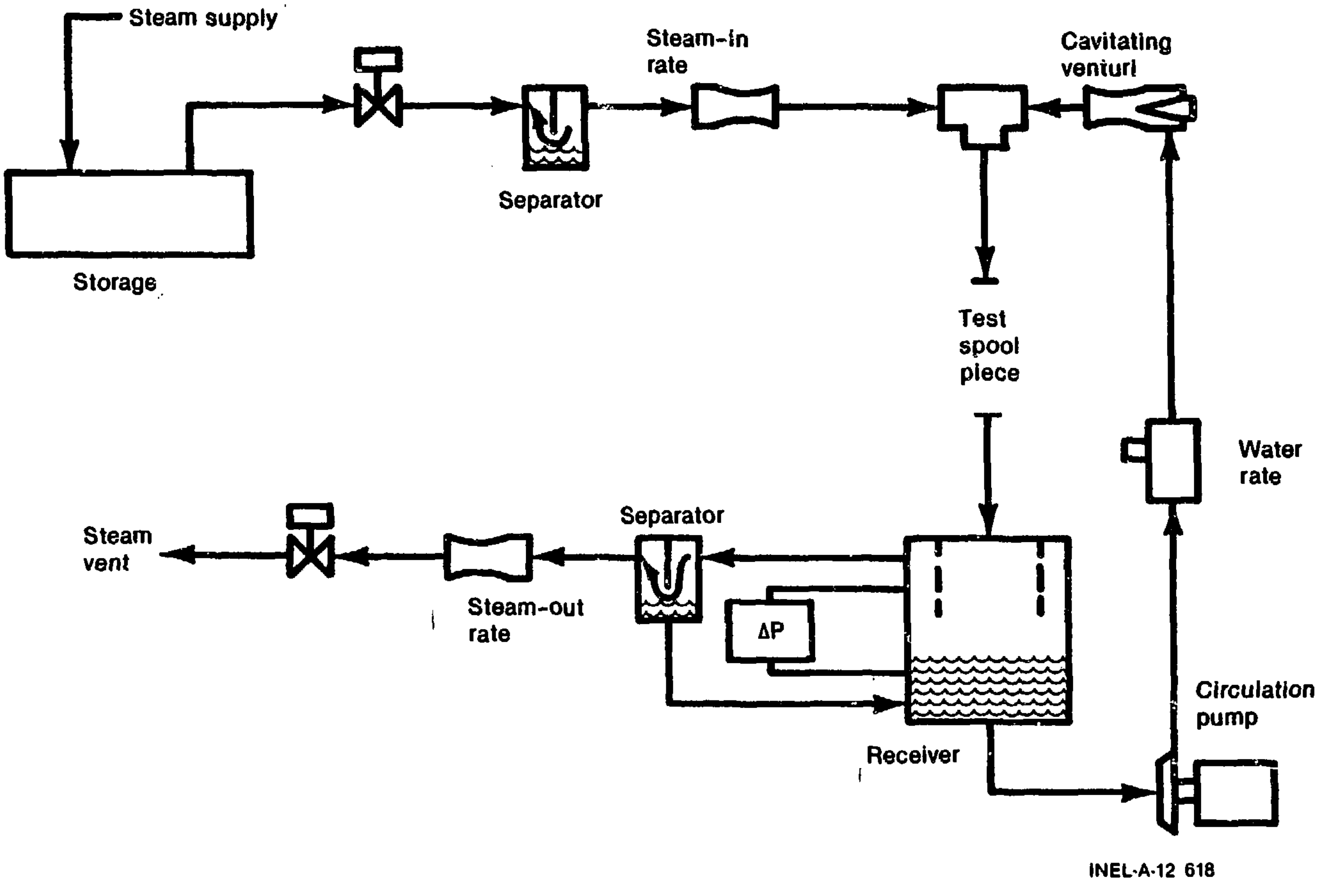


Fig. 12 Two-phase facility flow diagram.

5. ANALYTICAL MODELS

Analytical modeling was based on a two-component model with the water and steam flowing at different velocities.

5.1 Density and Void Fraction

The area-averaged density of the fluid was determined from the three chordal densities by the method developed by Lassahn[1]. The average density is related to the void (steam) fraction and phase densities by

$$\bar{\rho} = \rho_s + (1 - \alpha) \rho_w \tag{1}$$

where

α = void fraction

ρ_s = steam density

ρ_w = water density.

Using the fluid temperature and pressure, the steam density and water density can be computed. From these results, the void fraction can then be determined by solving Equation (1) for α:

$$\alpha = \frac{\rho_w - \bar{\rho}}{\rho_w - \rho_s}. \tag{2}$$

5.2 Turbine

The turbine flowmeter turns at a rate determined by the phase velocites. The turbine response to two-phase flow has been modeled by various investigators. One such model[2] pressumes that the turbine turns at an axial blade velocity equal to the quality weighted phase velocities as given by the following equation:

$$V_t = xV_s + (1 - x)\ V_w \tag{3}$$

where

x = flow quality

V_s = steam velocity

V_w = water velocity.

Flow quality is defined as the ratio of the mass flow rate of the steam to the total mass flow rate. Using this definition, the turbine velocity can also be written as

$$V_t = \frac{\rho_s V_s^2 + (1 - \alpha)\ \rho_w V_w^2}{\rho_s V_s + (1 - \alpha)\ \rho_w V_w} . \tag{4}$$

5.3 Drag Screen

The drag force on the drag screen is proportional to the total momentum flux through the pipe. Using the two-component model, the force can be represented by

$$F = \frac{Cd}{2} \left[\alpha \rho_s V_s^2 + (1 - \alpha)\ \rho_w V_w^2\right] \tag{5}$$

where Cd is the drag coefficient of the screen as determined from the calibration tests. This force is measured by the algebraic summation of the three drag transducer forces.

The force on the drag screen can also be measured by the differential pressure across the screen. Therefore, the differential pressure is assumed to be

$$\Delta P = K \left[\alpha \rho_s V_s^2 + (1 - \alpha)\ \rho_w V_w^2\right] \tag{6}$$

where K is a constant determined from the calibration tests.

6. DATA ANALYSIS

Using the analytical models discussed in Section 5, the mass flow rates were computed for the prototype test data and compared to the reference mass flow rates measured by the test facility.

The total mass flow rate ($\dot{m}$) can be determined by several alternate methods. The turbine flowmeter velocity can be combined with the momentum flux from the drag screen forces or differential pressure. Also, the area-averaged density can be used in conjunction with the turbine flowmeter velocity or the momentum flux from the drag screen. Since the effect of the relative velocities of the water and the steam can contribute a significant error in the mass flow rate measurement, care must be taken to minimize these effects.

Slip (S) in two-phase flow is defined as the ratio of the steam velocity to water velocity:

$$S = \frac{V_s}{V_w} = \left(\frac{1-\alpha}{\alpha}\right)\frac{\rho_w}{\rho_s}\left(\frac{x}{1-x}\right) . \qquad (7)$$

The void fraction can then be expressed in terms of the flow quality and slip as

$$\alpha = \frac{x\rho_w}{S(1-x)\,\rho_s + x\,\rho_w} . \qquad (8)$$

Using Equation (8) in conjunction with the analytical models, the models can be rewritten as

$$\bar{\rho} = \frac{x + S(1-x)}{\frac{S(1-x)}{\rho_w} + \frac{x}{\rho_s}} \qquad (10)$$

$$V_t = \frac{\dot{m}}{A}\left[\frac{(1-x)\,S}{\rho_w} + \frac{x}{\rho_s}\right]\left[x + \frac{(1-x)}{\rho_s}\right] \qquad (11)$$

$$F = \frac{Cd}{2}\left(\frac{\dot{m}^2}{A}\right)\left[\frac{(1-x)S}{\rho_w} + \frac{x}{\rho_s}\right]\left[x + \frac{(1-x)}{S}\right] \quad (12)$$

$$\Delta P = K\left(\frac{\dot{m}^2}{A}\right)\left[\frac{(1-x)S}{\rho_w} + \frac{x}{\rho_s}\right]\left[S + \frac{(1-x)}{S}\right]. \quad (13)$$

These equations show the effect of slip on the measurement at each location. As an example, in forward flow, if the slip is modified by the drag screen, the turbine flowmeter will turn at a different velocity than predicted by the densitometer. The magnitude of this effect is demonstrated by defining

$$K_d = \frac{V_t}{V_{t1}} = \frac{F}{F_1} = \frac{\Delta P}{\Delta P_1} \quad (14)$$

where the subscript 1 denotes S = 1.

$$K_d = \frac{\left[\frac{(1-x)S}{\rho_w} + \frac{x}{\rho_s}\right]\left[S + \frac{(1-x)}{S}\right]}{\left[\frac{(1-x)}{\rho_w} + \frac{x}{\rho_s}\right]}. \quad (15)$$

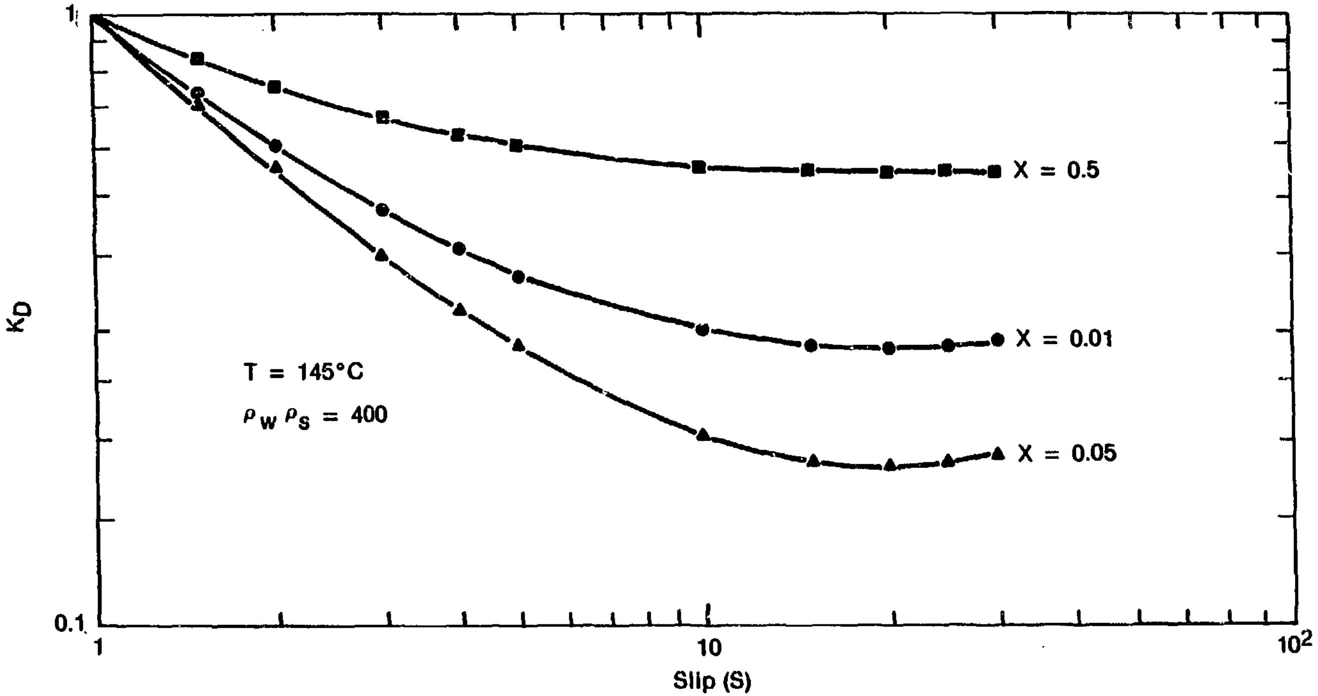
This equation is plotted in Figure 13.

The largest effect is in low quality flows with slips from 1 to 10. This condition normally exists in slug flow.

If the slips at the drag screen and the turbine flowmeter are assumed equal, Equations (11) and (12) or (11) and (13) can be solved for mass flow rate yielding

$$\dot{m} = \frac{2F}{Cd\ V_t} \quad \text{or} \quad \dot{m} = \frac{P}{KV_t} \quad (16)$$

where Cd and K were determined from the single-phase calibration tests. These equations are independent of slip except for effects described above. These data from the hot leg spool piece during the two-phase flow tests are plotted in Figures 14 and 15.



INEL-A-12 632

Fig. 13 Slip effects on momentum flux.

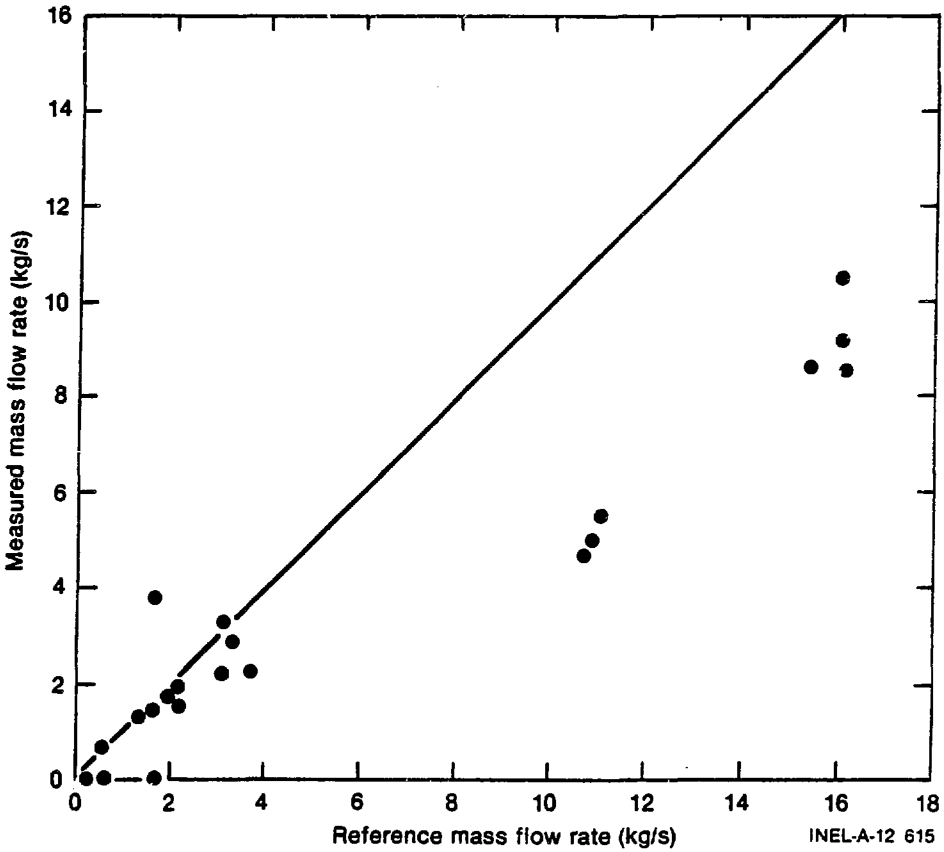


Fig. 14 Total mass flow rate from drag screen-turbine combination.

The effect of the disturbance to the flow caused by the drag screen can be seen very pronounced at the high mass flow rate where slug flow exists.

The technique of combining the densitometer with either the momentum flux or the turbine velocity is based on the assumption that the slip is unity as demonstrated by combining Equation (10) with Equations (11), (12), or (13) which yields

$$m = \frac{A - V_t}{K_s} \qquad (17)$$

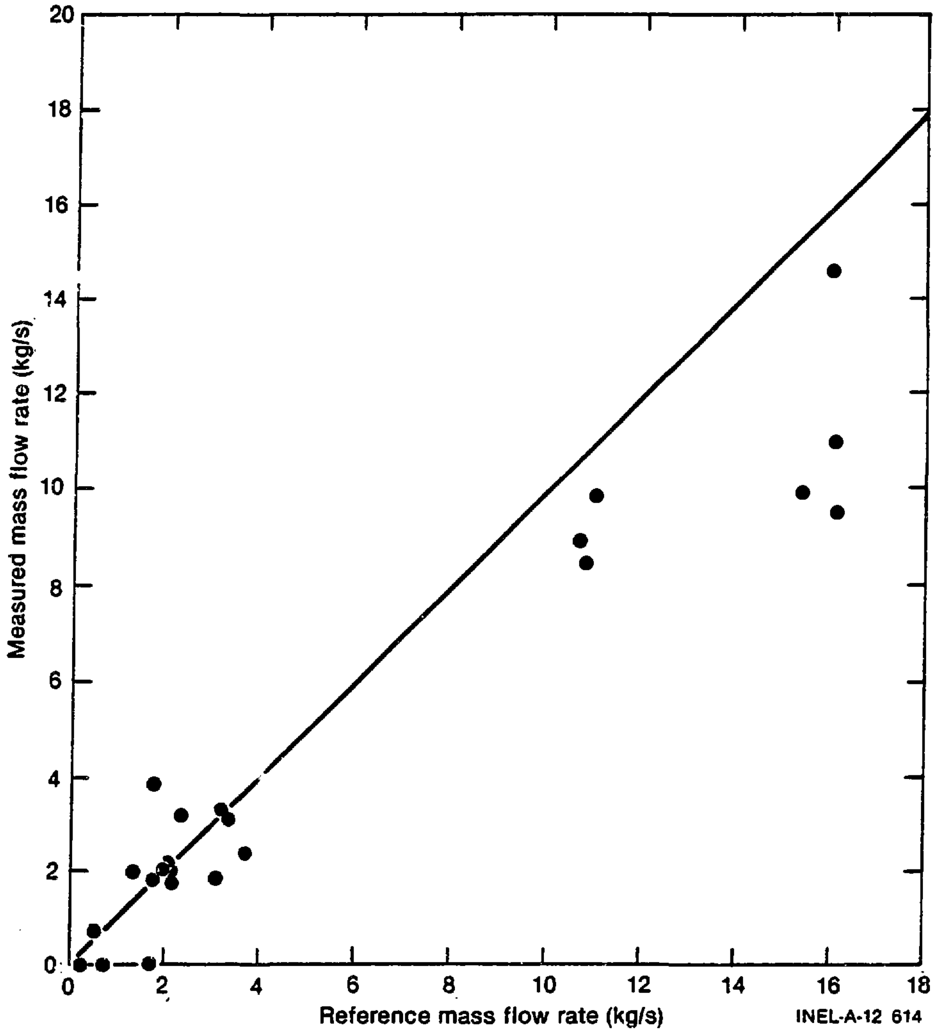


Fig. 15 Total mass flow rate from differential pressure-turbine combination.

$$m = A\left[\frac{2F}{Cd}\frac{\bar{\rho}}{K_s}\right]^{1/2} \tag{18}$$

$$m = A\left[\frac{\Delta P}{K}\frac{\bar{\rho}}{K_s}\right]^{1/2} \tag{19}$$

where

$$K_S = \left[x + S\,(1 - x)\right]\left[x + \frac{(1 - x)}{S}\right] \qquad (20)$$

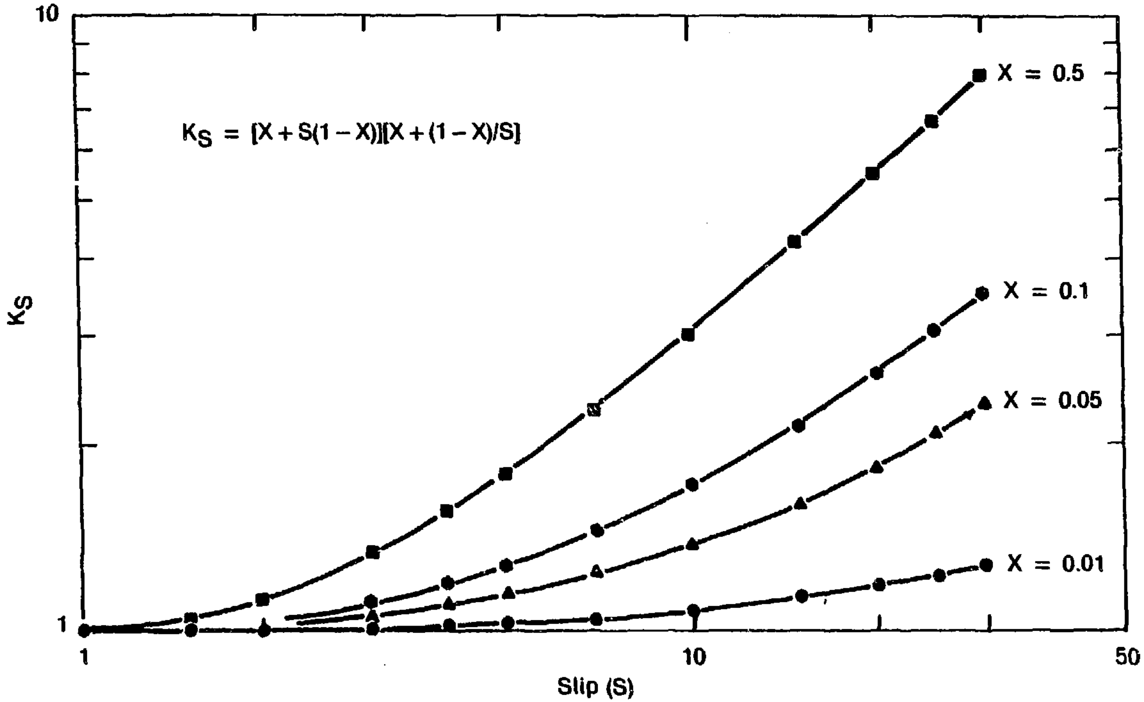
for unity slip, $K_S = 1$, which is assumed for this technique. Figure 16 shows a plot of K_S for various qualities and slips. This effect can be very pronounced in high-quality and high- slip flows. This condition normally exists in the highly separated flow regimes such as stratified, wavy, and annular mist.

Figures 17, 18, and 19 are plots of the hot leg spool data using the densitometer measurement in the preceeding equations with the drag transducer, differential pressure, and turbine flowmeter, respectively. The data can be corrected for slip, as seen by the densitometer, from the following equation:

$$S = \frac{(1 - \alpha)}{\alpha}\,\frac{\rho_W}{\rho_S}\,\frac{\dot{m}_S}{\dot{m}_W}$$

where the mass flow rate of the steam ($\dot{m}_S$) and the mass flow rate of the water ($\dot{m}_W$) are the rates determined from the test facility instrumentation. The void fraction (α) is measured by the densitometer. This correction was applied to the data and the corrected values shown in Figures 17, 18, and 19. The slip correction is very significant at the very low flow rates where stratified, wavy, or annular mist flow exists. The slip data is not normally available from the spool piece instrumentation; hence, an empirical correlation is required to make this correction. If no correction is used, this model should be avoided for these flow regimes.

By properly selecting the appropriate data processing technique for the various flow conditions, an improved measurement can be obtained. The analysis of the data from the hot leg instrumented spool piece has lead to the following analysis criteria:



INEL-A-12 631

Fig. 16 Slip correction factor.

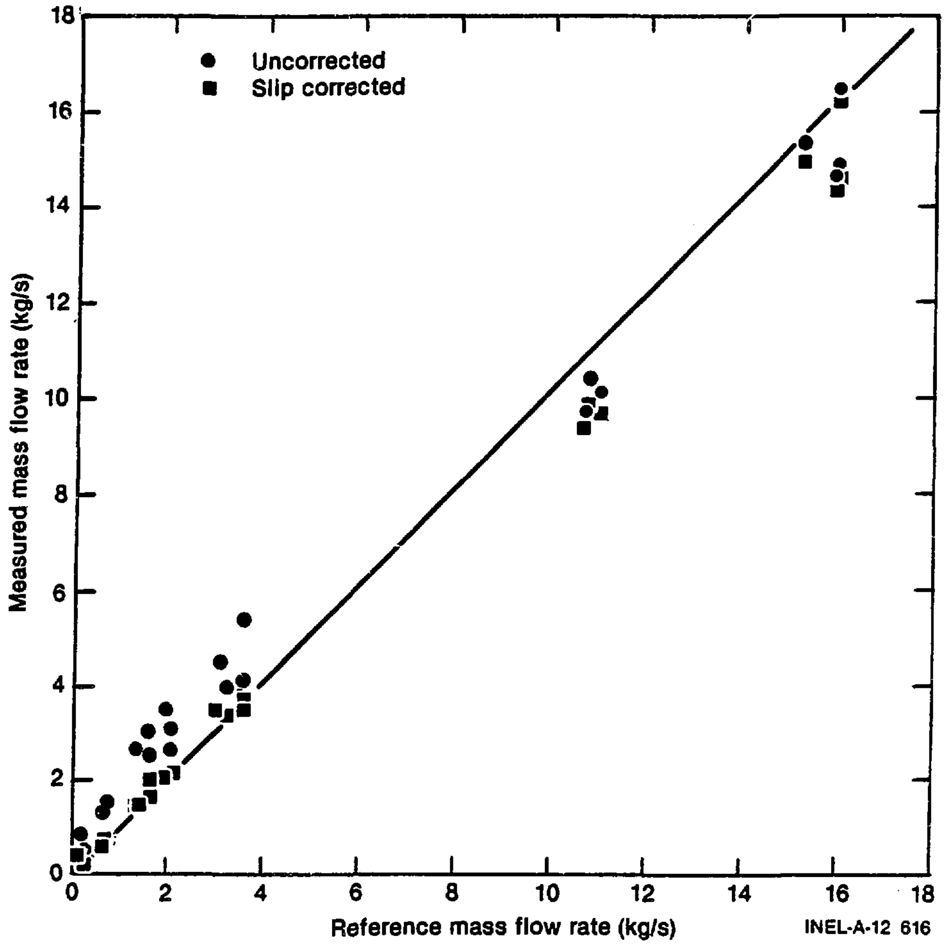


Fig. 17 Total mass flow rate from drag screen-densitometer combination.

(1) For $\dot{m}_w > 3$ kg/s,

use $\dot{m} = A\left[\bar{\rho}(\rho V^2)\right]^{1/2}$.

(2) For $\dot{m}_w < 3$ kg/s and $V_t > 0.5$ m/s,

use $\dot{m} = \frac{A(\rho V^2)}{V_t}$.

(3) For $\dot{m}_w < 3$ kg/s, $V_t < 0.5$ m/s, and $\bar{\rho} > 90$ kg/m^3,

use $\dot{m} = A\left[\bar{\rho}(\rho V^2)\right]^{1/2}$.

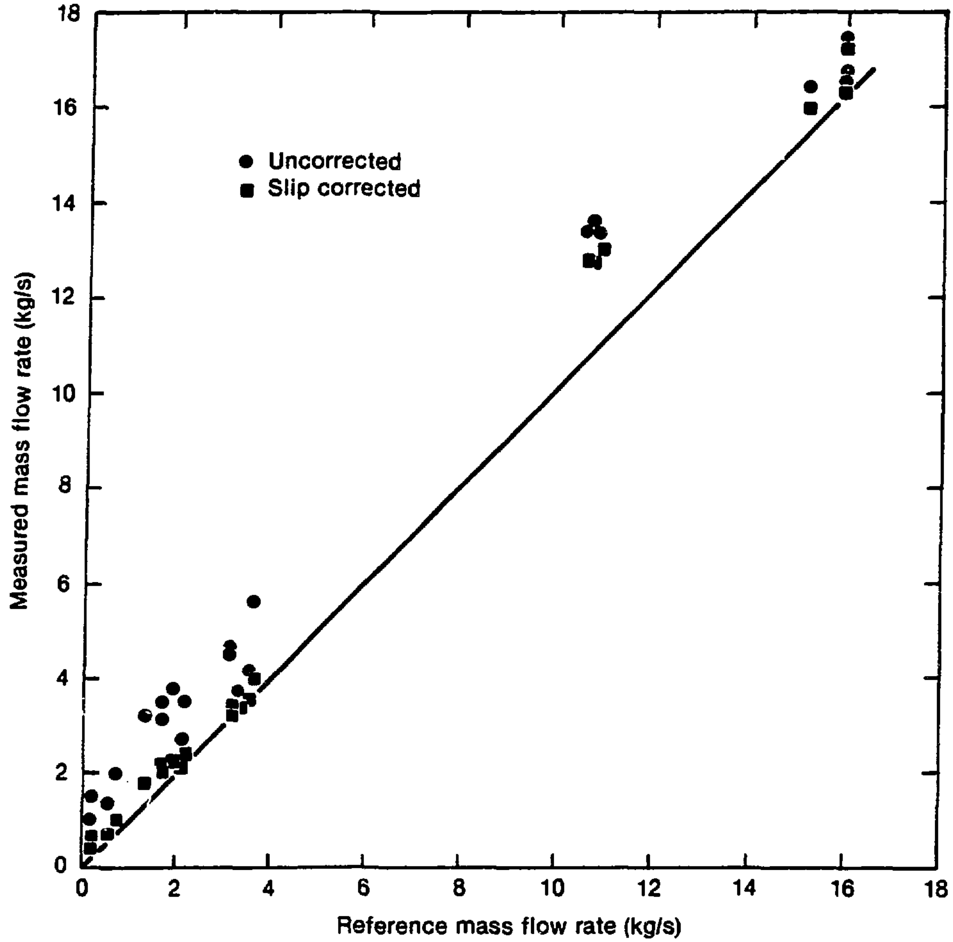


Fig. 18 Total mass flow rate from differential pressure-densitometer combination.

(4) For $\dot{m}_W$ < 3 kg/s, V_t < 0.5 m/s, and $\bar{\rho}$ < 90 kg/m^2,

use $\dot{m}$ = 0.

(5) For ρV^2 < 3000 kg/m·s^2,

use ρV^2 from drag transducers.

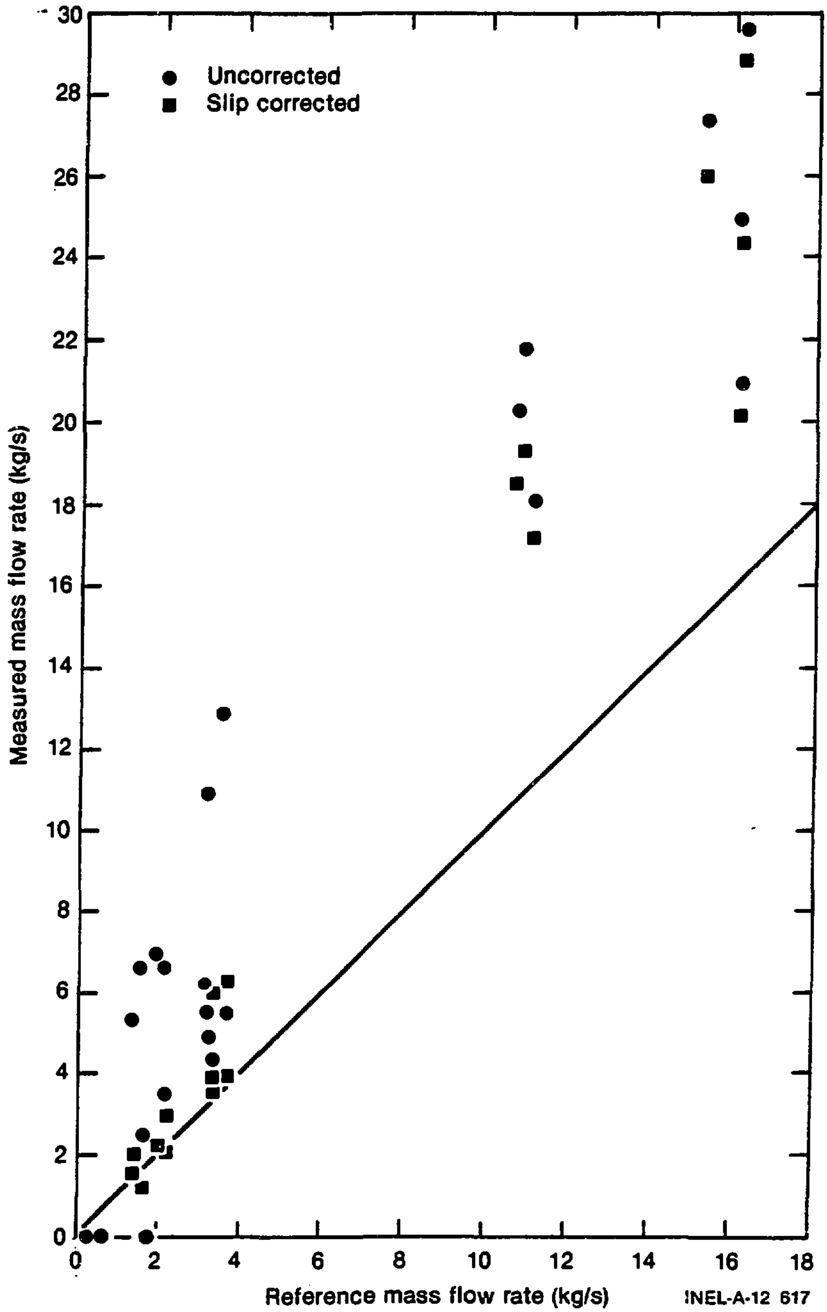


Fig. 19 Total mass flow rate from turbine meter-densitometer combination.

(6) For $\rho V^2 > 3000$ kg/m·s^2,

use ρV^2 from differential pressure.

The data from the hot leg spool piece in the forward direction was processed using the above criteria. No attempt was made to use a slip correction of the data. The combined results are shown in Figure 20. The data are accurate within 10% of the maximum flow rate tested.

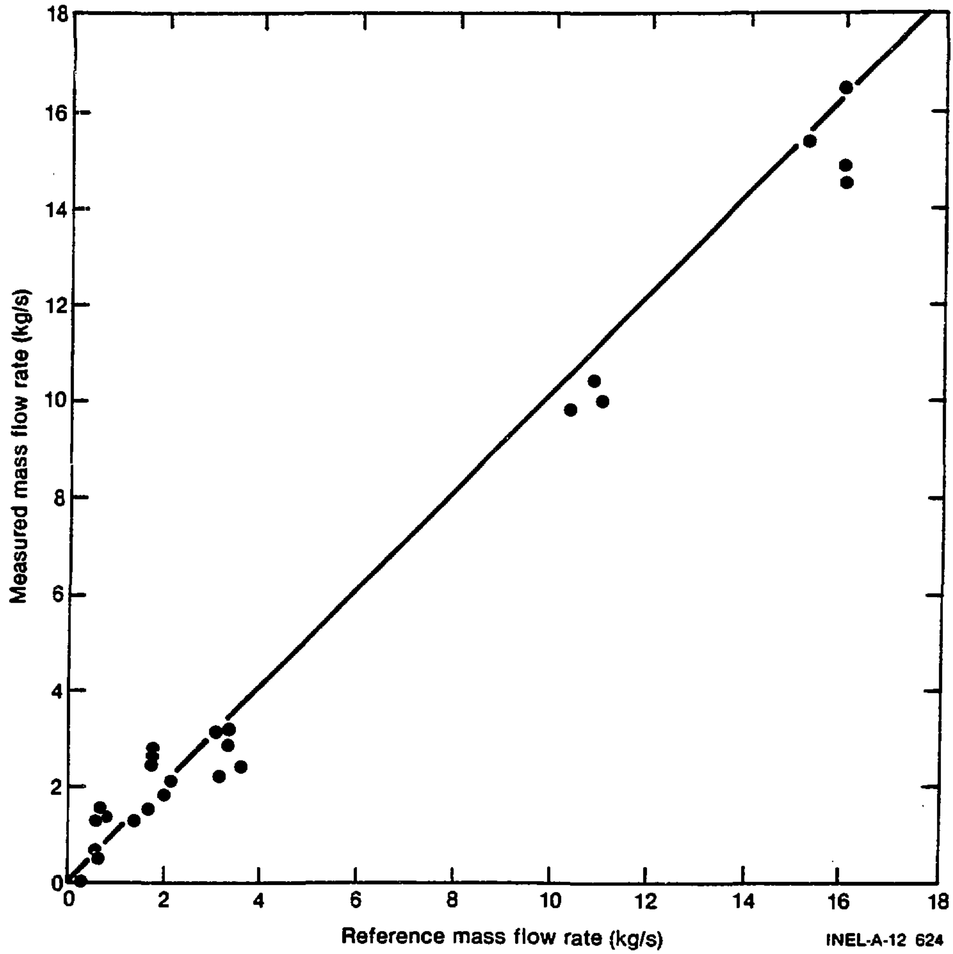


Fig. 20 Total mass flow rate combined results for hot leg spool in forward direction.

Figure 21 shows the combined results of the instrumented spool piece in the reverse direction. The data are improved at the low flow rates, since the turbine performance is improved. The higher flow rates have degraded performance due to the effect of the drag screen on the densitometer readings.

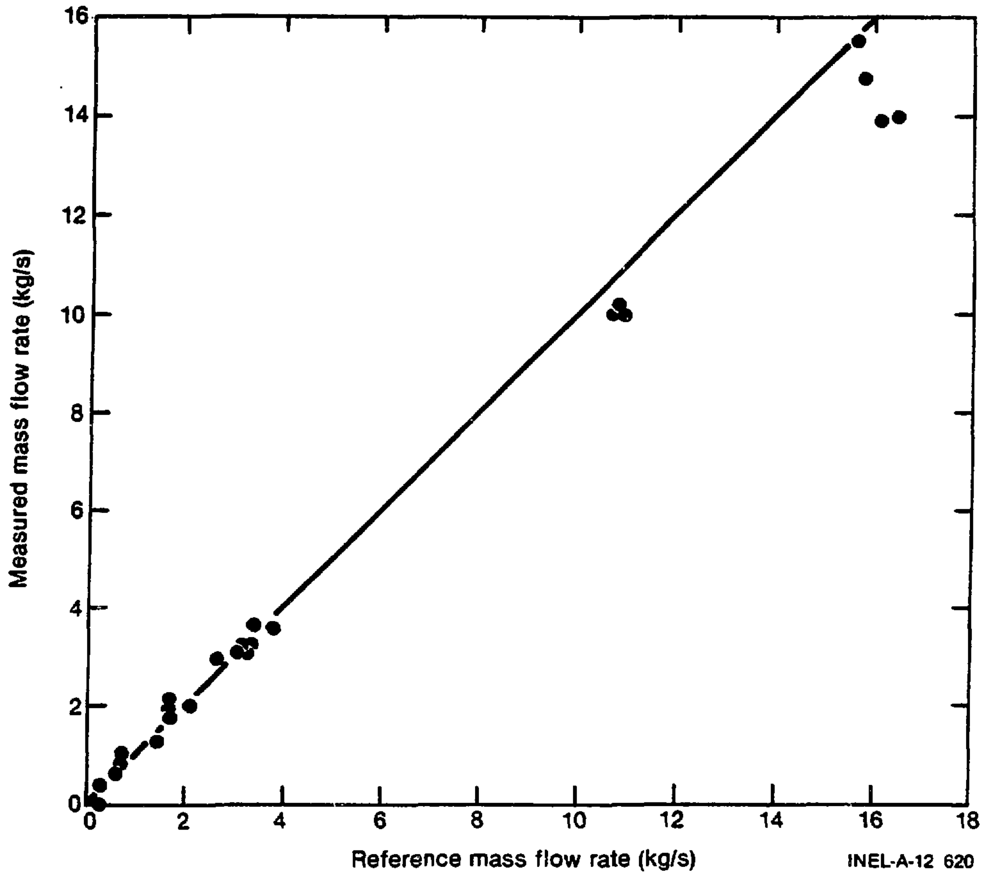


Fig. 21 Total mass flow rate combined results for hot leg spool in reverse direction.

7. CONCLUSIONS

The results of the two-phase flow analysis indicate that the effects of slip on the measurement of two-phase flow must be considered. For the more separated flow regimes of stratified, wavy, and annular mist, where the slip is high, the use of the drag screen-turbine combination is more accurate. For the more mixed flow regimes of slug, elongated bubble, and blubbly flow, where the slip is lower, the drag screen-densitometer combination is more accurate.

When both of the above combinations are used in the analysis of data, the instrumented spool piece accuracy is much improved over the use of any one measurement combination for all flow regimes and give satisfactory performance.

8. REFERENCES

1. G. D. Lassahn, LOFT Three-Beam Densitometer Data Interpretation, TREE-NUREG-1111 (October 1977).

2. Rouhani, "Application of Turbine Type Flow Meters in the Measurement of Steam Quality and Void," Symposium on In-Core Instrumentation, Oslo, Norway, June 1964.