CALIBRATION OF A DRAG DISC TURBINE TRANSDUCER AND A GAMMA DENSITOMETER TO MEASURE THE MASS FLOW RATE IN SEPARATED HORIZONTAL TWO-PHASE FLOW

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ABSTRACT

The accurate measurement of two-phase mass flow rate is very important in experiments, such as the LOFT experiment, which investigate the hypothetical Loss-of-Coolant Accident (LOCA). This paper analyses experiments designed to determine the behavior of a LOFT free field drag disc turbine transducer (DTT) and a LOFT-type three-beam gamma densitometer in a steady state, horizontal high pressure steam-water flow. The experiments were conducted in a mass flow and void fraction range where a variety of separated flow regimes existed which strongly influenced the performance of the DTT. It is shown that the accuracy of the instruments is mainly a function of the void fraction. A simple calibration procedure is proposed using calibration factors which are only a function of the gamma densitometer reading. When two instruments are used to determine the mass flow rate, this procedure considerably improves the accuracy of the mass flow rate evaluation. If all three instrument readings are taken, this procedure gives much better results for slip and phase velocities than the void fraction, Aya, or Rouhani model.

In many nuclear safety experiments the mass flow rate is measured with a combination of a turbine meter and drag disc (DTT) and a gamma densitometer. In some of these experiments the turbine is a full flow device (Ball et al, (1)). In other experiments such as LOFT (2) free field DTT's are used. The performance, especially of a free field DTT, will be influenced significantly if separation of phases exists. Such phase separation occurs:

a. If the mass fluxes, qualities and transients are low so that the phases have time enough to separate; this may happen in a small area blowdown or in a large area blowdown at positions where flow reversal occurs.

b. At high mass fluxes, if the phases upstream of the measuring position are forced to separate, e.g. by flow obstructions or a bend in the pipe.

This paper analyses experiments designed to determine the accuracy of a LOFT DTT and a LOFT-type three-beam gamma densitometer in horizontal steam-water and air-water flow (3,4). Two different test sections with diameters of 103 mm ID (5" test pipe) and 66.6 mm ID (3" test pipe) were used, both providing free field calibrations. That is, the DTT is smaller than the inside diameters of the test sections. The gamma densitometer is a three-beam unit representative of the configuration used in LOFT, but modified to fit on a smaller pipe.

The reference mass flow rates were measured with orifices in single phase flow before mixing. The quality in the test section and the superficial velocities, respectively, were computed with an enthalpy balance.

Downstream of the mixing chamber outlet, a pipe (50 mm ID) was positioned which contained a junction to a bypass. To diverge from this pipe diameter to the test section diameter, eccentrical adapters were used which were made so that the bottom of the pipes were in line to prevent damming. The test sections had lengths of 5.2 m (5" pipe) and 5.93 m (3" pipe). Figure 1 illustrates both of these test sections.
Figure 1 also shows the additional instrumentation:

- The KfK radionuclide injection valves and the corresponding detectors for measuring the axial distribution of the phase velocities.
- The EG&G traversing reference gamma densitometer (scanning densitometer) for the measurement of a very accurate cross section averaged value of the density (void fraction).
- The KfK impedance probes: A vertically traversing probe in the 5" pipe for detection of flow regime and measurements of a vertical void fraction profile; two fixed built-in probes in the 3" pipe for detecting flow regime.

EXPERIMENTAL RESULTS

Figure 2 shows the test matrix for the 40 and 75 bar steam-water tests drawn in a flow chart. This flow chart was built up with the impedance probe data and fits quite well both the 5" and 3" pipe tests. In the 3" pipe tests, mostly slug flow or a wave flow with considerable droplet entrainment occurred; the 5" pipe tests were made in wave (wave droplet) flow regime and in the transition to annular droplet flow. Associated with the flow regime are the values for slip S: in the slug flow regime investigated the typical value was $S \approx 1.8$ whereas in the wave flow and transition to annular droplet flow slip values up to 6 existed.

The typical behavior of the single instruments can be shown by plotting the ratios of the measured values to the cross section averaged values in the flow chart. Another way is to present these data as a function of the height of the liquid level, whereby this interface level $(y/d)_{IF}$ is calculated from the gamma densitometer void fraction assuming a totally stratified flow. The latter procedure yields more information than the former and is described in the following.

Figure 3 shows the ratio of turbine velocity v_T to homogeneous velocity (equal volumetric flux) $(v_{sg} + v_{sl})$ as a function of the interface level. As long as the interface level is lower than the bottom of the turbine, the turbine measures about the phase velocity of steam v_g which is only slightly higher than the homogeneous velocity for the parameter range investigated. If the interface level is between the bottom and the top of the turbine, the turbine measures about 80% of the volumetric flux.

Figure 4 shows for the 5" pipe tests the ratio of drag disc reading $(\rho v^2)_{DD}$ to total two-phase momentum flux $(\rho v^2)_{tp}$ calculated by

$$(\rho v^2)_{tp} = (\rho v^2)_g + (\rho v^2)_l = \frac{\dot{G}_g v_g}{\alpha} + \frac{\dot{G}_l v_l}{(1-\alpha)}$$

At very low interface levels (very high void fractions) the ratio is about 1. With increasing interface level, caused by increasing liquid input, this ratio decreases because the water is mostly flowing below the drag disc and, therefore, is not measured. This fact is illustrated in Figure 4 when the drag disc reading is normalized with the steam momentum flux $\rho_g v_g^2$: where the ratio is about constant for all values of the interface level.

Figure 5 shows the corresponding results for the 3" pipe tests: the value of $(\rho v^2)_{DD}/(\rho v^2)_{TP}$ is considerably below 1 if the interface level is below the drag disc and above 1 if the interface level is above the drag disc.

The gamma densitometer density (respectively void fraction) was evaluated applying the length weighting method. This procedure gives rise to an error if a totally separated flow exists. It can be shown that this error is negligible for the high void fraction range investigated in the 5" pipe tests and larger (up to 10%) in the lower void fraction range occurring in the 3" pipe tests. However, it was shown in /4/ that this error is nearly compensated by the fact that the phase velocities make a change between the axial densitometer and the DTT position in the pipe. Therefore, in the following, the length weighted density or void fraction is always used.

Table 1: Comparison of Mean Values for Mass Flow Ratios (40 and 75 Bar Experiments)

		$\dot{G}_{\gamma-T}/\dot{G}_{Ref}$	$\dot{G}_{\gamma-DD}/\dot{G}_{Ref}$	$\dot{G}_{T-DD}/\dot{G}_{Ref}$
5" Pipe Tests	$\bar{x}$	1.60	1.03	0.69
	σ	0.39	0.20	0.18
3" Pipe Tests	$\bar{x}$	1.16	0.89	0.76
	σ	0.35	0.17	0.40

Table 1 shows the mean values $\bar{x}$ and standard deviations for the ratios of mass flow rates using a combination of two instrument readings to the reference values. The mass flow rates per unit area were calculated by

$$\dot{G}_{\gamma-T} = \rho_\gamma v_T \quad (1)$$

$$\dot{G}_{\gamma-DD} = \sqrt{\rho_\gamma (\rho v^2)} \quad (2)$$

$$\dot{G}_{T-DD} = (\rho v^2)_{DD}/v_T \quad (3)$$

These equations using two measuring parameters are called two-parameter equations, in contrast to a three-parameter equation which uses three measured quantities such as α, v_l and v_g and evaluates the mass flow rate by

$$\dot{G} = \alpha_\gamma \rho_g v_g + (1-\alpha_\gamma)\rho_l v_l \quad (4)$$

The two-parameter equations are, in contrast to eq.(4), only correct for $S \doteq 1$ (compare e.g. (5)). If it is assumed that the turbine measures the volumetric flux and the drag disc the total two-phase momentum flux, it can be shown that with increasing slip eq. (1) gives very high values and eq. (3) very low values, whereas, eq. (2) gives values only slightly too high for realistic values of slip.

From Table 1 it can be seen that for both the 5" and the 3" pipe tests the combination gamma densitometer - drag disc has the highest accuracy, caused to some extent by the relatively small errors of eq. (2) for $S > 1$.

MASS FLOW RATE EVALUATION WITH THE VOID FRACTION, ROUHANI AND AYA MODEL (THREE-PHASE PARAMETER)

If equation (4) is used, only the void fraction α is measured directly. The phase velocities v_g and v_l have to be evaluated using the other two independent readings v_T and ρv^2. To do this, there are three models which differ only in interpreting the turbine velocity.

The Void Fraction Model assumes that the turbine measures the volumetric flux

$$v_T = \alpha v_g + (1-\alpha) v_l = v_{sg} + v_{sl} \quad (5)$$

The Rouhani Model /6/ and the Aya Model /7/ are derived in different ways; they both give a turbine velocity between the liquid and steam phase velocity:

Rouhani Model

$$v_T = \frac{1 + \frac{\rho_l}{\rho_s}\frac{1-\alpha}{\alpha}}{\frac{1}{S} + \frac{\rho_l}{\rho_g}\frac{1-\alpha}{\alpha}} v_l \quad (6)$$

Aya Model (assuming that the turbine calibration coefficients in single-phase steam and water flow are the same)

$$v_T = \frac{S + \left(\frac{\rho_l}{\rho_g}\frac{1-\alpha}{\alpha}\right)^{0.5}}{1 + \left(\frac{\rho_l}{\rho_g}\frac{1-\alpha}{\alpha}\right)^{0.5}} \quad (7)$$

In all models the drag disc measures the total two-phase momentum flux $(\rho v^2)_{tp}$ (assuming that the drag disc coefficients in single-phase steam and water flow are equal to 1):

$$(\rho v^2)_{DD} = \alpha \rho_g v_g^2 + (1-\alpha)\rho_l v_l^2 \quad (8)$$

From eq. (8) slip is evaluated:

$$S = \left(\frac{(\rho v^2)_{DD} - (1-\alpha) v_l^2}{\alpha \rho_g v_l^2}\right)^{0.5} \quad (9)$$

Combining equation (8) with (5), (6) or (7) the liquid velocity is given as follows:

Void Fraction Model

$$v_l = \frac{(1-\alpha)}{p} v_T + \left(\frac{(1-\alpha)^2 v_T^2}{p^2} + \frac{\alpha\left((\rho v^2)_{DD}/\rho_g - v_T^2\right)}{p}\right)^{0.5} \quad (10)$$

$$p = (1-\alpha)^2 + \alpha(1-\alpha)\rho_l/\rho_g$$

Rouhani Model

$$(1-\alpha)(1+y)^2\rho_l v_l^4 - 2y(1-\alpha)v_T\rho_l v_l^3 + \{\alpha\rho_g v_T^2 + (1-\alpha)\rho_l y^2 v_T^2 - (\rho v^2)_{DD}(1+y)^2\} v_l^2 + 2(\rho v^2)_{DD}\, y\, v_T v_l - y^2(\rho v^2)_{DD} v_T^2 = 0 \quad \text{with} \quad y = \frac{1-\alpha}{\alpha}\frac{\rho_l}{\rho_g} \quad (11)$$

Equation (11) has to be solved iteratively:

Aya Model

$$v_l = \frac{1}{2}p + \left(\frac{(\rho v^2)_{DD}}{\alpha\rho_g 2y} - \frac{1}{4}p^2\right)^{0.5} \quad (12)$$

$$\text{with} \quad p = \frac{1+y^{0.5}}{y^{0.5}} v_T, \quad y = \frac{1-\alpha}{\alpha}\frac{\rho_l}{\rho_g}$$

By insertin v_1 in eq. (9), S is computed and then $\hat{G}$ following from

$$\hat{G} = |\alpha \rho_g S + (1-\alpha)\rho_l| v_l \qquad (13)$$

Table 2 shows the results for the 5" pipe tests obtained with the different models.

The void fraction model does not give a real value for v_l for most of the test points although in the 5" pipe experiments the assumption of this model for the turbine reading is quite well fulfilled. The reason for the negative radical in equation (10) is the too small drag disc reading. The points where a real solution for v_l exists, belong to test points with a low liquid input where the steam momentum flux $(\rho v^2)_g$ is about the total momentum flux $(\rho v^2)_{tp}$. The liquid velocity is predicted too low, the slip too high.

The Aya Model gives no real solution at all because (i) the drag disc reading is generally too low, and (ii) the turbine reading is too high.

The Rouhani model gives a real solution for all test points, although this model often gives a too high value for v_l. As a consequence, the drag disc reading (which is too low), causes the value of slip to be much smaller than 1. This tendency is clearly seen in the 40 bar experiments where only one test point yields a slip greater than 1. In the 75 bar experiments there are three points with void fractions of about $\alpha = 0.99$. For these points v_l is significantly underpredicted and slip overpredicted, respectively. These values shift the mean value for all experiments to a value near to one which is then confusing. Of course, the high value of α indicates that any individual value of v_l may be in error. In spite of these difficulties, the agreement of evaluated mass flow rates with the reference values is surprisingly good.

Table 3 shows the results for the 3" pipe tests. Again the Rouhani model gives a real solution for all test points, the void fraction model for all test points except two. The accuracy of these two models in respect to mass flow evaluation is about the same and is worse than using the densitometer and drag disc together with equation (2). Slip is described quite well with the void fraction model but inadequately with the Rouhani model.

Summarizing the 5" and 3" pipe tests it can be stated that only the Rouhani model is applicable for all test points; the accuracy of the mass flow evaluation is comparable to the accuracy obtained with the drag disc gamma densitometer combination; slip is described very badly. The void fraction model gave better slip values but was not applicable to most of the 5" pipe tests. Generally it can be stated that the accuracy of the evaluated mass fluxes from all models (if a solution exists) is surprisingly good even though the DTT measures only a part of the horizontal, non-homogeneous flow.

MASS FLOW RATE FROM CALIBRATED GAMMA DENSITOMETER AND DRAG DISC (TWO-PARAMETER EQUATION)

If a two-parameter equation is used, the equation combining the momentum flux and density is most suited. As shown in Figure 5, in the 3" pipe tests the ratio of drag disc reading to total two-phase momentum flux was clearly different if the interface level was below or above the drag disc.

3" pipe tests: $(\rho v^2)_{DD} = 1.2\,(\rho v^2)_{tp}\ ;\ \left(\frac{y}{d}\right)_{IF} > 0.5$

$$(\rho v^2)_{DD} = 0.57\,(\rho v^2)_{tp}\ ;\ \left(\frac{y}{d}\right)_{IF} < 0.5$$

If the two-phase momentum flux mainly consisted of the gas momentum flux which is connected with low interface levels (5" pipe tests, Figure 4), the drag disc measured about the total momentum flux.

5" pipe tests:

$$(\rho v^2)_{DD} = (\rho v^2)_{tp}\ ;\ \left(\frac{y}{d}\right)_{IF} < 0.2$$

Therefore, the following procedure is proposed:

$$\dot{G}_{\gamma-DD} = A\left(\rho_\gamma (\rho v^2)_{DD}\right)^{0.5}$$

with

$$A = 0.91\ ;\ \left(\frac{y}{d}\right)_{IF} > 0.5$$
$$A = 1.32\ ;\ 0.5 > \left(\frac{y}{d}\right)_{IF} > 0.2$$
$$A = 1.00\ ;\ 0.2 > \left(\frac{y}{d}\right)_{IF}$$

Table 4 shows a comparison of results with and without this calibration for the 3" pipe tests. An improvement is clearly seen. Factor A is equal to 1 for the 5" pipe tests; that means the original two-parameter equation is used; the results (shown again in Table 2) were very satisfactory.

The use of a similar calibration procedure for the other instrument combination is not so valuable because of the slip sensitivity of the corresponding equations.

The disadvantage of two-parameter equations is, that phase velocities and slip cannot be evaluated. This can only be done by using three-parameter equations. Such a model using calibration factors is discussed in the following.

MASS FLOW RATE USING THREE-PARAMETER EQUATIONS WITH CALIBRATION FACTORS

The correct equation for mass flow rate contains three parameters: α, v_l and v_g or α, S and v_l, which can be computed from three independent measurements. The models used so far were not very successful because for horizontal two-phase flow the drag disc and turbine readings were not modeled satisfactorily for either the 5" or the 3" tests.

In the model presented, the readings of the single instruments are corrected by calibration factors which are a function of the interface level.

It is assumed that:

a. The gamma densitometer measures the mean density ρ and the void fraction α. The density (void fraction) is evaluated according to the method used by Lassahn (8) or, if a length weighted method is used, with a correction for flow stratification.

b. Using a single phase calibration curve (thus assuming that the drag coefficients in single-phase and in two-phase flow are equal) the drag disc measures

$$(\rho v^2)_{DD} = \alpha \rho_g v_g^2 + A\,(1-\alpha)\rho_l v_l^2 \qquad (14)$$

c. Using a single-phase calibration curve the turbine measures

$$v_T = B\,(\alpha v_l S + (1-\alpha))\,v_l \qquad (15)$$

From equations (14) and (15) it follows

$$v_l = \frac{1-\alpha}{\rho}\,\frac{v_T}{B} + \left(\frac{(1-\alpha)^2}{\rho^2}\,\frac{v_T^2}{B^2} + \frac{\frac{\alpha(\rho v^2)_{DD}}{\rho_g} - \frac{v_T^2}{B^2}}{\rho}\right)^{0.5} \qquad (16)$$

with

$$\rho = \alpha (1-\alpha) A \, \rho_l/\rho_g + (1-\alpha)^2$$

and

$$S = \frac{V_T/B - (1-\alpha) V_l}{\alpha V_l} \tag{17}$$

A and B are taken from the experiments

$A = 1.2$ for $(y/d)_{IF} > 0.5$

$A = 0.5$ for $(y/d)_{IF} < 0.5$

$B = 0.8$ for $(y/d)_{IF} > (y/d)_{\text{bottom of turbine}}$

$B = 1.1$ for $(y/d)_{IF} < (y/d)_{\text{bottom of turbine}}$

The mass flow rate per area (mass flux) is evaluated from

$$\dot{G} = \left(\alpha \rho_g S + (1-\alpha) \rho_l \right) V_l \tag{18}$$

Table 4 and 5 also contain the results obtained with this method. For the 5" pipe tests the accuracy for mass flow rate is slightly reduced compared to the two-parameter equation and the Rouhani model, but slip and phase velocities are described much better than from the other three parameter models. In the 3" pipe tests the accuracy of this method is considerably higher as compared to the other three-parameter models both in mass flow rate, slip, and phase velocity. If the information on slip and phase velocity is not of great importance, the combination gamma densitometer - drag disc should be used together with the calibration factors, which gives the best accuracy for the mass flow rate.

CONCLUSIONS

The readings of drag disc and turbine meter in horizontal separated two-phase flow in general does not correspond to the cross section averaged values. It was shown that the dependency of these deviations is for all investigated flow regions nearly only a function of the height of the interface level which is evaluated from the gamma densitometer reading. Therefore, it is advantageous to use this dependency to derive calibration factors which are only a function of this interface level. This procedure considerably improves the accuracy of the mass flow rate evaluation for different test section geometries and gives good results for the phase velocities and slip.

The proposed method is similar to another method (9) in that both methods use the interface level as an important quantity. The latter method has the advantage that it does not need calibration factors - on the other hand, the range of application is more restricted. It is thought that both methods complement each other quite well.

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Table 2 Results from Void Fraction, Aya and Rouhani Model (5" Pipe Tests)

Test Nr.	p bar	γ-Densitometer + Ref.-Values V_l (m/s)	γ-Densitometer + Ref.-Values S (1)	Void Fraction Model V_l (m/s)	Void Fraction Model S (1)	Void Fraction Model C_{VF}/C_{Ref} (1)	Aya Model V_l (m/s)	Aya Model S (1)	Aya Model C_A/C_{Ref}	Rouhani Model V_l (m/s)	Rouhani Model S (1)	Rouhani Model C_R/C_{Ref} (1)
5001		3.14	3.35	S<0			S<0			6.63	0.[illegible]	1.05
5002		2.14	2.36	"			"			7.62	0.19	0.83
5004		2.06	3.03	"			"			7.38	0.40	1.21
5005		1.75	5.73	"			"			8.78	0.40	1.31
5037		2.04	2.48	0.43	12.1	0.64	"			3.39	0.34	0.94
5038	40	1.52	3.29	.25	4.16	0.97	"			3.97	0.47	1.13
5039		7.34	2.19	S<0			"			1.57	3.18	0.88
5043		1.41	6.15	"			"			7.49	0.30	1.50
5044		2.07	1.34	"			"			2.67	0.17	0.54
5034		4.27	2.34	"			"			7.01	0.41	0.[illegible]0
5055		2.60	2.02	0.43	12.48	0.46	"			2.71	0.23	0.76
5056		1.78	2.74	0.99	5.03	0.78	"			2.99	0.29	0.96
5057		1.05	4.76	1.67	2.76	1.10	"			3.49	0.38	1.17
5058		1.61	6.14	S<0						7.71	0.48	1.31
5059		2.36	4.19	"			"			6.95	0.41	1.18
5014		4.56	1.27	S<0			S<0			0.64	9.16	0.92
5015		2.18	2.41	"			"			3.83	1.19	1.03
5016		2.85	1.88	"			"			4.57	0.73	0.97
5021		3.67	1.40	"			"			7.04	0.84	0.91
5022	75	4.16	1.91	"			"			8.36	1.09	1.01
5023		4.33	1.79	"			"			0.88	9.21	0.93
5026		6.72	1.14	"			"			0.87	9.23	0.96
5025		3.02	1.73	"			"			4.14	0.50	0.86
5066		2.40	2.20	"			"			3.76	0.40	0.91
5067		3.04	2.48	"			"			4.60	0.39	1.03
5071		1.23	4.62	0.88	6.65	0.97	"			4.96	0.65	1.18

Mean Values	Void Fraction Model			Aya Model			Rouhani Model		
p (bar)	40	75	40 + 75	40	75	40 + 75	40	75	40 + 75
$V_{l\,Model}/V_l$	0.67	0.73	0.68	-	-	-	2.31	1.44	2.06
σ	0.58	-	0.53	-			1.49	1.13	1.43
S_{Model}/S	2.95	1.44	2.69	-	-	-	0.20	2.12	1.01
σ	2.44	-	2.27				0.35	3.09	2.2
C_{Model}/C_{Ref}	0.79	0.97	0.82	-	-	-	1.03	0.97	1.01
σ	0.25	-	0.36				0.23	0.09	0.1[illegible]
N/N_{total}	5/15	1/11	6/26	0	0	0	15/15	11/11	26/26

Table 3 Results from Void Fraction, Aya and Rouhani Model (3" Pipe Tests).

Test Nr.	p (bar)	γ-Densitom. +Ref.-Values v_l (m/s)	S (1)	Void Fraction Model v_l (m/s)	S (1)	C_{VF}/C_{Ref}	Aya Model v_l (m/s)	S (1)	C_A/C_{Ref}	Rouhani Model v_l (m/s)	S (1)	C_R/C_{Ref}
6003		3.07	2.34	[illegible]	1.51	0.78	R<0			2.67	0.03	0.77
6004		5.34	2.21	[illegible]	1.94	0.71	-			4.35	0.07	0.70
6005		6.29	1.79	[illegible]	[illegible]	0.65	-			4.82	0.09	0.63
6013		8.04	1.44	[illegible]	[illegible]	0.61	-			4.00	0.15	0.83
6014		3.23	1.88	2.21	2.19	0.77	-			2.59	0.05	0.75
6015		1.55	1.44	[illegible]	[illegible]	1.07	1.67	0.36	1.07	1.68	0.01	1.01
6016		0.94	1.91	[illegible]	[illegible]	1.19	1.14	0.45	1.19	1.16	0.01	1.18
6017	40	2.13	3.23	[illegible]	2.50	0.63	R<0			2.49	0.07	0.93
6018		5.43	1.95	2.33	[illegible]	0.68	-			8.37	0.20	0.87
6019		1.99	1.74	2.18	0.47	1.08	2.17	0.92	1.08	2.19	0.01	1.08
6020		2.02	1.72	2.33	0.66	1.14	2.32	0.91	1.14	2.33	0.01	1.13
6021		4.4.	1.77	3.03	2.07	0.69	R<G			3.42	0.05	0.69
6022		2.75	1.79	2.44	[illegible]	0.88	2.28	2.59	0.85	2.50	0.02	0.87
6023		3.81	1.81	2.69	2.02	0.71	R<0			2.98	0.04	0.71
6024		5.51	1.62	3.20	1.93	0.69	-			4.27	0.07	0.61
6025		7.61	1.37	4.37	2.0	0.64	-			3.39	0.11	0.60
6026		4.94	1.67	3.27	1.89	0.68	-			3.65	0.34	0.67
6027		3.01	1.68	[illegible]	1.42	0.83	1.95	4.88	0.72	2.59	0.02	0.82
6048		4.08	2.09	2.80	2.18	0.69	R<0			3.04	0.03	0.69
6035		1.83	3.83	1.03	1.78	1.11	2.03	1.17	1.11	2.05	0.00	1.11
6036		2.10	1.89	2.35	0.19	1.10	2.34	0.61	1.10	2.35	0.01	1.10
6037		2.36	1.92	2.47	0.70	1.07	2.63	0.26	1.07	2.63	0.02	1.06
6051		3.75	1.92	2.37	3.31	0.74	R<0			3.40	0.13	0.81
6052		5.10	1.88	3.32	2.46	0.69	-			4.77	0.15	0.71
6053		2.16	1.70	2.43	0.73	1.08	4.47	0.17	1.07	2.47	0.03	1.06
6054	75	0.99	1.88	1.18	0.67	1.12	1.70	0.06	1.10	1.20	0.03	1.10
6055		1.76	1.38	1.53	0.56	1.05	1.94	0.13	1.04	1.94	0.02	1.04
6056		2.31	2.82	R<0			R<0			3.57	0.17	1.03
6057		2.74	2.02	2.41	1.66	0.86	-			3.62	0.05	0.84
6058		3.39	2.06	2.62	2.18	0.75	-			3.15	0.08	0.78
6059		4.84	1.64	3.42	2.18	0.75	-			4.52	0.13	0.75
6060		3.22	1.95	2.78	1.56	0.84	-			2.98	0.05	0.62
6061		2.33	1.73	2.49	0.53	1.12	2.70	0.16	1.11	2.71	0.02	1.13
6062		5.00	1.63	3.34	2.06	0.69	R<0			4.08	0.09	0.69
6063		11.00	1.04	R<0			-			6.72	0.35	0.49

Mean Values	Void Fraction Model			Aya Model			Rouhani Model		
p(bar)	40	75	40 + 75	40	75	40 + 75	40	75	40 + 75
$v_{l\,Model}/v_l$	0.77	0.93	0.84	1.0	1.14	1.07	0.90	1.04	0.97
σ	0.23	0.22	0.23	0.22	0.04	0.16	0.16	0.20	0.20
S_{Model}/S	1.09	0.77	0.95	1.01	0.15	0.55	0.03	0.05	0.04
σ	0.64	0.50	0.61	1.02	0.11	0.80	0.03	0.06	0.06
C_{Model}/C_{Ref}	0.79	0.93	0.85	1.01	1.09	1.05	0.81	0.91	0.86
σ	0.19	0.18	0.19	0.18	0.03	0.13	0.18	0.19	0.19
N/N_{total}	19/19	14/16	33/35	6/19	7/16	13/35	19/19	16/16	35/35

Table 4 Mass Flow Rate Evaluation with Calibration Factors (5" Pipe Tests).

Test Nr.	p (bar)	TPE* $G_{\gamma-DD}/G_{Ref}$	γ-Densitometer + Ref.-Values v_l (m/s)	S (1)	Three Parameter Equations with Calibration Factors v_l (m/s)	S (1)	G_{3P_c}/G_{Ref}
5001		1.13	3.14	3.35	3.80	2.78	1.06
5003		0.87	2.14	2.56	1.61	3.24	0.82
5004		1.30	2.04	5.03	4.35	2.19	1.28
5005		1.32	1.75	5.73	5.85	1.70	1.36
5037		1.01	2.04	2.48	2.22	2.20	1.01
5038	40	1.16	1.52	3.29	2.96	1.37	1.28
5039		0.98	2.34	2.19	3.94	1.20	0.99
5043		1.30	1.61	6.15	5.21	3.08	1.23
5044		0.57	4.07	1.34	1.46	3.94	0.49
5054		0.97	4.27	2.34	4.07	2.36	0.93
5055		0.78	2.60	2.02	1.80	1.63	0.78
5056		1.02	1.76	2.74	2.22	2.00	1.09
5057		1.25	1.05	4.76	2.98	1.39	1.41
5058		1.35	1.61	6.14	4.85	1.97	1.39
5059		1.24	2.36	4.19	4.13	2.31	1.23
5014		0.97	4.54	1.27	5.20	1.08	1.02
5015		1.03	2.14	2.41	2.75	1.88	1.03
5016		0.97	2.85	1.88	1.86	2.94	0.90
5021		0.93	1.62	1.40	4.55	1.78	0.93
5022	75	1.02	4.16	1.93	5.41	1.45	1.05
5023		1.02	1.33	1.79	8.60	0.80	1.04
5026		0.99	6.72	1.14	9.09	0.82	1.08
5025		0.90	3.02	1.23	1.99	2.69	0.84
5066		0.95	2.40	2.20	2.02	2.57	0.92
5067		1.07	2.04	2.44	3.13	1.55	1.12
5071		1.19	1.21	4.62	3.93	1.31	1.21

Mean Values	*Two-Parameter Equation			Three Parameter Equations with Calibration Factors		
p (bar)	40	75	40 + 75	40	75	40 + 75
$v_{l\,Model}/v_l$	-	-	-	1.47	1.34	1.53
σ	-	-	-	0.89	0.73	0.84
S_{Model}/S	-	-	-	0.83	0.94	0.87
σ	-	-	-	0.67	0.40	0.56
C_{Model}/C_{Ref}	1.08	1.00	1.05	1.09	1.03	1.06
σ	0.23	0.04	0.18	0.26	0.13	0.21
N/N_{total}	15/15	11/11	26/26	15/15	11/11	26/26

Table 5 Mass Flow Rate Evaluation with Calibration Factors (3" Pipe Tests).

Test Nr.	p (bar)	TPE* $G_{\gamma-DD}/G_{Ref}$	TPE** $(G_{\gamma-DD})_c/G_{Ref}$	γ-Densitometer +Ref.-Values v_l (m/s)	S (1)	Three Par. Equations with Cal Factors v_l (m/s)	S (1)	G_{3P_c}/G_{Ref}
6003		0.79	0.85	3.07	2.34	3.20	1.71	1.01
6004		0.72	0.95	5.34	2.21	4.63	2.00	0.87
6005		0.70	0.93	6.29	1.79	6.53	2.41	0.76
6013		0.66	0.87	8.04	1.44	8.36	1.45	0.81
6014		0.74	0.99	3.23	1.88	3.88	2.20	0.90
6015		1.07	0.97	1.55	1.44	1.51	1.45	0.98
6016		1.19	1.08	0.94	1.91	1.03	1.28	1.09
6017	40	0.96	1.27	2.13	3.23	3.09	3.30	0.99
6018		0.91	1.20	5.43	1.95	6.89	2.27	0.97
6019		1.08	0.98	1.99	1.74	1.98	1.31	0.99
6020		1.14	1.04	2.02	1.72	2.11	1.22	1.05
6021		0.71	0.94	4.47	1.77	3.75	2.09	0.85
6022		0.88	1.17	2.75	1.79	3.26	1.15	1.17
6023		0.73	0.97	3.81	1.81	3.75	1.20	0.95
6024		0.71	0.94	5.51	1.62	4.50	1.99	0.84
6025		0.64	0.90	7.61	1.37	4.87	2.25	0.70
6026		0.68	0.91	4.94	1.67	4.11	1.88	0.85
6027		0.83	1.10	3.01	1.68	3.33	1.29	1.10
6048		0.70	0.93	4.08	2.09	3.60	2.11	0.88
6035		1.10	1.00	1.83	3.83	1.57	1.70	0.88
6036		1.10	1.00	2.10	1.89	2.10	1.46	1.01
6037		1.07	0.97	2.36	1.92	2.32	1.83	0.98
6051		0.85	1.12	3.75	1.92	3.91	1.64	1.02
6052		0.76	1.01	5.10	1.88	5.16	1.31	0.92
6053		1.08	1.98	2.16	1.70	2.17	1.50	0.99
6054	75	0.95	0.87	0.99	1.88	1.05	1.36	1.03
6055		1.06	0.95	1.76	1.38	1.72	1.39	0.97
6056		1.09	1.44	2.31	2.82	2.66	2.59	1.11
6057		0.87	1.15	2.74	2.02	3.05	1.60	1.09
6058		0.81	1.07	3.39	2.06	2.98	2.45	0.91
6059		0.80	1.06	4.84	1.64	3.19	3.03	0.77
6060		0.82	1.09	3.22	1.95	3.59	1.48	1.08
6061		1.12	1.01	2.33	1.73	2.41	1.46	1.02
6062		0.72	0.95	5.00	1.63	3.75	2.34	0.79
6063		0.52	0.69	11.00	1.04			

Mean Values	*Two-Par. Equation			**Two-Par. Equation with Cal. Factor			Three-Par. Equations with Cal. Factors		
p (bar)	40	75	40 + 75	40	75	40 + 75	40	75	40 + 75
$v_{l\,Model}/v_l$	-	-	-	-	-	-	1.02	0.98	1.00
σ							0.40	0.14	0.31
S_{Model}/S	-	-	-	-	-	-	0.99	1.12	0.99
σ							0.27	0.34	0.27
C_{Model}/C_{Ref}	0.83	0.92	0.87	1.01	1.02	1.02	0.73	0.97	0.95
σ	0.18	0.18	0.18	0.11	0.15	0.13	0.12	0.10	0.11
N/N_{total}	19/19	16/16	35/35	19/19	16/16	35/35	19/19	15/16	34/35

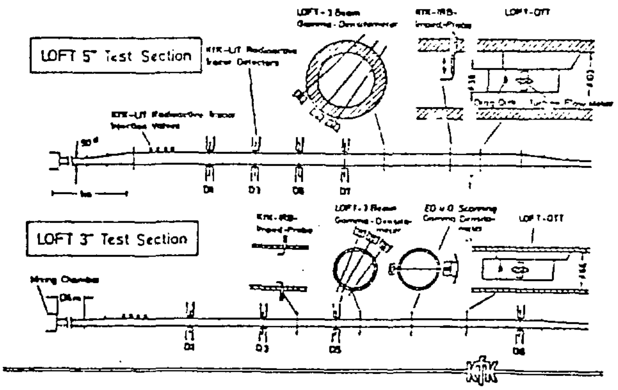

Figure 1 Schematical Set Up of Test Section Geometry and Mass Flow Rate Instrumentation

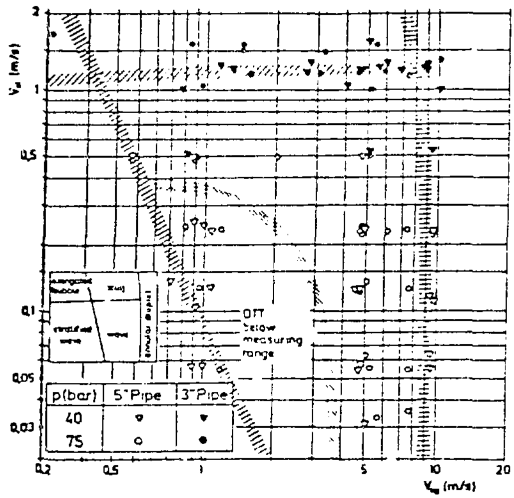

FIGURE 2 TEST MATRIX FOR 5" AND 3" PIPE TESTS (STEAM-WATER FLOW, 40 AND 75 BAR)

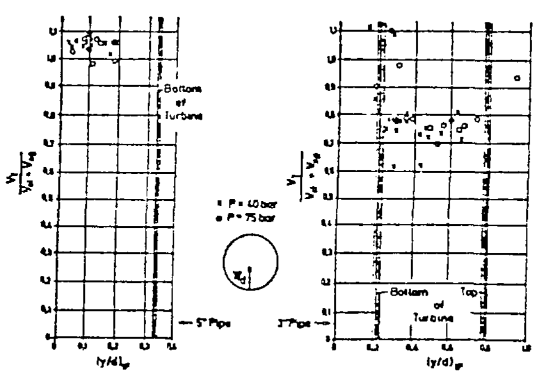

FIGURE 3 TURBINE METER READING AS FUNCTION OF INTERFACE LEVEL

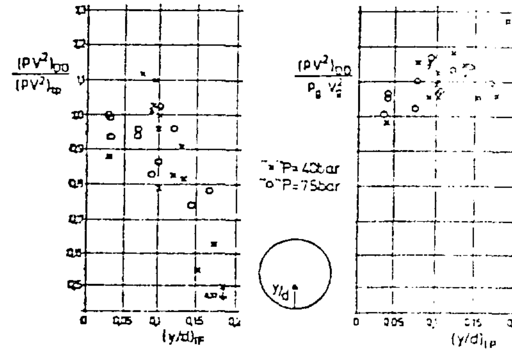

FIGURE 4 DRAG DISC READING AS FUNCTION OF INTERFACE LEVEL (5" PIPE TESTS)

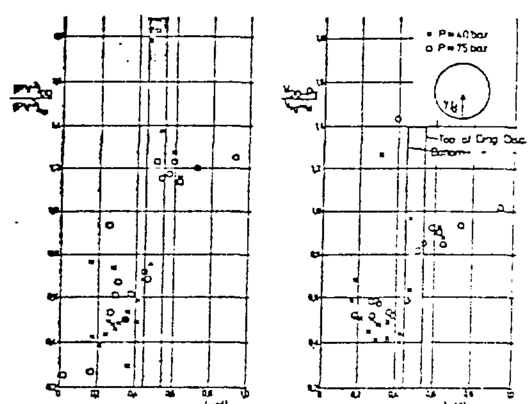

FIGURE 5 DRAG DISC READING AS FUNCTION OF INTERFACE LEVEL (3" PIPE TESTS)