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Accuracy of various alternate methods of calculating total mass flow rate for PKL instrumented pipe spool prototype tests in single- and two-phase steam-water flows

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ABSTRACT

Instrumented spool pieces for installation in the piping of the German Primarkreislauf (PKL) test reactor have been designed and tested. The spools have been developed as part of a joint cooperative German, Japanese, and United States steam-binding study for the U. S. Nuclear Regulatory Commission, Division of Reactor Safety Research (NRC-RSR).

The primary objective of the spools is to provide measurements of two-phase steam-water flow parameters (pressure, temperature, velocity) from which mass flow rates can be calculated.

Each spool contains a three-beam densitometer, flow turbine, drag screen, and pressure and temperature sensors. The spools were prototype tested[1] in single- and two-phase steam-water flows and the results of the mass flow calculations were compared to known values.

The present software calculations of total mass flow in two-phase flows requires data from two instruments only: the flow turbine and drag screen. In this report, mass flow calculations based on other instrument combinations are investigated and compared to the programmed calculations. Instrument combinations considered included: densitometer and drag screen, densitometer and flow turbine, differential pressure sensor and flow turbine, and temperature and drag screen. The effect of changes in slip ratio on mass flow calculations also was investigated.

Results of the mass flow calculations show that the primary model involving the drag screen and turbine gives the most accurate results in most cases.

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ACCURACY OF VARIOUS ALTERNATE METHODS OF CALCULATING TOTAL MASS FLOW RATE FOR PKL INSTRUMENTED PIPE SPOOL PROTOTYPE TESTS IN SINGLE- AND TWO-PHASE STEAM-WATER FLOWS

INTRODUCTION

Instrumented spool pieces for installation in the piping of the German Primarkreislauf (PKL) test reactor have been designed and tested. The spools have been developed as part of a joint cooperative German, Japanese, and United States steam-binding study for the U. S. Nuclear Regulatory Commission, Division of Reactor Safety Research (NRC-RSR) under the 3-D Technical Support and Instrumentation Program.

The primary objective of the spools is to provide measurements of two-phase steam-water flow parameters (pressure, temperature, velocity) from which mass flow rates can be calculated.

Four spools were constructed. Each spool contains a 3-beam densitometer, flow turbine, drag screen, and pressure and temperature sensors. Both the computer system and the software are supplied with the four spools to record data and perform calculations to determine mass flow rates and related flow-parameters. A detailed description of the hardware and software is given in Ref. 1.

Three spools were prototype-tested in single-phase and two-phase steam-water flows. Reference 1 gives both the results and an error analysis for these prototype tests. The results indicated a very good capability of measuring single- and two-phase flows. For these tests, total two-phase mass flow rate is calculated based on measurements obtained from only the drag screen and flow turbine.

Alternate methods of calculating the total mass flow rate, in single- and two-phase flows, are possible. These methods involve using different instrument combinations, with certain combinations expected to give better accuracy in the various two-phase flow regimes. In this report, various alternate calculational procedures are investigated and their accuracies in determining mass flow rates are compared.

The results of the various two-phase alternate model calculations show that the primary model, which uses the drag screen and flow turbine, is definitely the best model over the range of flow conditions and flow regimes encountered in the PKL prototype tests.

In certain specific flow conditions one of the many models will give better accuracy. After review of all the alternate models, however, no modifications to the software calculational procedures are recommended.

DISCUSSION

In two-phase flows of steam and water, various flow regimes, which are dependent on the relative flow rates of steam and water, are possible. For PKL prototype tests, steam and water flow rates were adjusted to result in the following flow regimes: slug, annular mist, wave, and froth. In each of the flow regimes, the velocity of the steam may be different from the velocity of the water, with the ratio of steam velocity to water velocity defined as the slip ratio.

The drag screen and flow turbine are calibrated in single-phase flow (slip ratio equal to one). Operation of these instruments in two-phase flows with a slip ratio greater than one will result in a measured output that differs from the output predicted from single-phase calibrations[2]. An additional consideration for slip flows is the effect on mass flow calculations because of changes in slip ratio at the flow turbine that are due to disturbances caused by the upstream drag screen.

The primary method of calculating total mass flow involves the measurement of momentum flux by the drag screen and the measurement of velocity by the flow turbine. Dividing the momentum flux by the velocity and multiplying by the cross-sectional area of the spool gives the total mass flow rate.

Alternate means of calculating total mass flow rate in two-phase flows that are investigated in this report involve the following instrument combinations:

- Densitometer and drag screen
- Densitometer and flow turbine
- Densitometer and differential pressure sensor across the drag screen
- Flow turbine and differential pressure sensor across the drag screen

The differential pressure sensor in two of the above models is used to measure the pressure drop across the drag screen, which is then related to momentum flux. Normally the momentum flux is determined from a calibration of drag force on the screen versus momentum flux. The force is obtained from three transducers holding the drag screen in place.

Alternate methods of calculating single-phase superheated steam mass flow rates were also investigated. Two methods are presently incorporated in the software. The instrument combinations involved in these two methods are:

- Flow turbine and pressure and temperature sensors
- Densitometer and drag screen

The instrument combinations for alternate calculations of superheated steam mass flow rates are:

- Drag screen and pressure and temperature sensors
- Drag screen and flow turbine
- Differential pressure probe and temperature and pressure sensors
- Densitometer and flow turbine

ANALYTICAL MODELS

The analytical models for single-phase and two-phase steam-water mass flow rate calculations are presented below.

SINGLE-PHASE SUPERHEATED STEAM FLOW

The mass flow rate in single-phase superheated steam flow (MS) is calculated using the following equation:

$$MS = A \times RHOS \times VT \tag{1}$$

where

RHOS = Steam density obtained from steam tables based upon measured temperature and pressure.

VT = Velocity obtained from the flow turbine based upon an air calibration.

A = Cross-sectional area of the spool.

The software has also been programmed to perform an additional calculation for total mass flow rate (MF) as given by equation (2).

$$MSX = A \times \sqrt{DB(3) \times DTT} \tag{2}$$

where

DB(3) = Steam density measured by the most accurate of the three densitometer beams in the steam density range.

DTT = Momentum flux as sensed by the three drag screen transducers.

Four alternate methods, using four different instrument combinations, were investigated, and the relationship for the steam mass flow rate (MS#) of each combination is given by equations (3) through (6).

- Drag screen and pressure and temperature sensors:

$$MS1 = A \times \sqrt{RHOS \times DTT} \tag{3}$$

- Drag screen and flow turbine:

$$MS2 = \frac{A \times DTT}{VT} \tag{4}$$

- Differential pressure sensor and pressure and temperature sensors:

$$MS3 = A \times \sqrt{RHOS \times PDTT} \tag{5}$$

where

PDTT = momentum flux obtained from a pressure drop calibration across the drag screen.

- Densitometer and flow turbine:

$$MS4 = A \times DB(3) \times VT \tag{6}$$

In addition to the values from the models above, average values of mass flow rates that were obtained by adding the results of various models were also investigated.

TWO-PHASE FLOW

Instrument Combinations

The primary model for calculating total mass flow rate (MF) is given by:

$$MF = \frac{A \times DTT}{VT} \tag{7}$$

Four alternate methods using four different instrumentation combinations were investigated. The relationship for total mass flow rate is given by equations (8) through (11).

- Densitometer and drag screen:

$$MFA = A \times \sqrt{RHOF \times DTT} \tag{8}$$

where

RHOF = average pipe cross sectional density determined from the densitometer beam measurements.

- Densitometer and flow turbine:

$$MFB = A \times RHOF \times VT \tag{9}$$

- Densitometer and differential pressure sensor:

$$MFC = A \times \sqrt{RHOF \times PDTT} \tag{10}$$

- Flow turbine and differential pressure sensor:

$$MFD = \frac{A \times PDTT}{VT} \tag{11}$$

Validity of Flow Turbine Data

Checks on the validity of the flow turbine data are made in the software coding. If the turbine data is rejected, the total mass flow rate calculations default to the calculation given in equation (8).

SLIP FLOW CORRELATIONS

Density

The average cross-sectional density, RHOF, is related to individual phase densities and the void fraction by:

$$RHOF = \alpha\rho_s + (1-\alpha)\rho_w \tag{12}$$

where

α = void fraction
ρ_s = steam density
ρ_w = water density

Flow Turbine

The flow turbine is calibrated in single-phase flow to obtain a calibration table of rotor turning rate versus average fluid velocity. In two-phase flow the velocity measured by the turbine (V_t) is assumed equal to the quality-weighted phase velocities.[3]

$$V_t = XVs + (1-X)V_w \tag{13}$$

where

X = flow quality
V_s = steam velocity
V_w = water velocity

Equation (13) can be rewritten as:

$$VT = \frac{\alpha\rho_s V_s^2 + (1-\alpha)\rho_w V_s^2}{\alpha\rho_s V_s + (1-a)\rho_w V_w} \tag{14}$$

<u>Drag Screen</u>

The measured drag force from the drag screen is related to momentum flux of single-phase flow by a DTT calibration table. The momentum flux in two-phase flows is given by:

$$DTT = \alpha\rho_s V_s^2 + (1-\alpha)\rho_w V_w^2 \tag{15}$$

<u>Slip Corrections</u>

The mass flux ($\frac{\dot{m}}{A}$) is given by:

$$\frac{\dot{m}}{A} = \alpha\rho_s V_s + (1-\alpha)\rho_w V_w \tag{16}$$

and the slip ratio (S) is given by:

$$S = \frac{V_s}{V_w} = \left(\frac{1-\alpha}{\alpha}\right) \frac{\rho_w}{\rho_s} \left(\frac{X}{1-X}\right) \tag{17}$$

Using equations 16 and 17, equation 14 can be written[2] as:

$$VT = \left(\frac{\dot{m}}{A}\right) \left(\frac{(1-X)S_T}{\rho_w} + \frac{X}{\rho_s}\right) \times \left(+\frac{1-X}{S_T}\right) \tag{18}$$

where

S_T = slip at the turbine

Using equations (14), (16), and (18), equation (15) can be rewritten as:

$$DTT = \left(\frac{\dot{m}}{A}\right)^2 \left(\frac{(1-X)}{\rho_W} S_{DS} + \frac{X}{\rho_S}\right)\left(x + \frac{1-X}{S_{DS}}\right) \qquad (19)$$

where

S_{DS} = slip at the drag screen

Substituting equations (19) and (18) into equation (7) gives:

$$\dot{m} = MF \left[\frac{\left(\frac{(1-X)S_T}{\rho_W} + \frac{X}{\rho_S}\right)\left(x + \frac{1-X}{S_T}\right)}{\left(\frac{(1-X)S_{DS}}{\rho_W} + \frac{X}{\rho_S}\right)\left(x + \frac{1-X}{S_{DS}}\right)}\right] \qquad (20)$$

where

$\dot{m}$ = slip-corrected mass flow rate

Equation (20) reduces to equation (7) for cases of unity slip or for equal values of slip at the turbine and drag screen. The slip ratio at the turbine downstream from the drag screen may be different from the slip at the drag screen due to flow disturbance caused by the drag screen.

RESULTS

The spools that were prototype-tested included the following:

- 80.8-mm diameter horizontal spool (designated spool no. 1).
- 113-mm diameter horizontal spool (designated spool no. 3).
- 80.8-mm diameter vertical spool (designated spool no. 4).

The fourth spool (spool no. 2) was not tested since it is essentially identical to spool no. 1.

Prototype testing involves testing the spools with the flow in the forward direction and also with the flow in the reverse direction. Changing the flow direction is accomplished by physically turning the spool around in the piping system. Various tests are repeated several times, on different days, and at essentially identical flow conditions to determine repeatability. Spool nos. 1 and 3 were tested under horizontal flow conditions, and spool no. 4 was tested under vertical flow conditions.

Each of the spools was tested in single-phase water flow, single-phase superheated steam (approximately 10 to 40^{o}F superheat), and two-phase water and steam flows. For two-phase horizontal flow, the flow regimes during testing included slug flow, stratified wavy flow, and annular mist flow. For two-phase vertical flow, the flow regimes during testing were slug flow, froth flow, and annular mist flow. The two-phase flow testing was done at saturation conditions and was conducted at three different fluid pressures, i.e., 620, 414, and 207 kPa (90, 60, and 30 psia, respectively).

SUPERHEATED STEAM FLOW

Applying equations (1) through (6) to data obtained from the PKL prototype superheated steam flow tests[1] gives the results shown in Table 1. Table 1 lists the average mass flow rate and the percentage difference relative to the known mass flow rate for each of the six models given by equations (1) through (6).

The table also shows the mass flow rate (MA) (and percentage difference) given by the average of the results from equations (1) and (2):

$$MA = \frac{MS + MSX}{2} \qquad (21)$$

TABLE 1. Total superheated steam mass flow rate (kg/s) and percentage differences (%).

Test[a] no.	W[b]	MS	%	MSX	%	MS1	%	MS2	%	MS3	%	MS4	%	MA	%	Flow dir.
38	0.604	0.614	1.68	0.588	-2.65	0.605	0.17	0.596	-1.27	0.569	-5.75	0.579	-4.28	0.601	-0.50	F
47	0.490	0.530	8.22	0.523	6.73	0.532	8.67	0.535	9.18	0.508	3.60	0.510	4.12	0.527	7.45	F
48	0.607	0.632	4.19	0.613	0.99	0.630	3.80	0.629	3.57	0.594	-2.07	0.597	-1.66	0.623	2.55	F
61	0.609	0.626	2.75	0.606	-0.50	0.622	2.17	0.619	1.63	0.595	-2.33	0.594	-2.51	0.616	1.15	F
62	0.205	0.203	-1.01	0.207	0.98	0.208	1.46	0.214	4.44	0.216	5.55	-0.199	-2.93	0.205	0.0	F
63	0.097	0.095	-2.23	0.123	26.80	0.107	10.00	0.120	23.66	0.129	33.46	0.126	29.49	0.109	12.37	F
64	0.211	0.223	5.74	0.192	-9.00	0.192	-9.03	0.165	-21.40	0.213	0.79	0.220	4.35	0.208	-1.66	F
71	-0.204	-0.204	0.23	-0.244	19.60	0.214	5.08	0.225	10.35	0.350	71.60	0.267	30.70	0.224	9.80	R
72	-0.608	-0.626	3.02	-0.690	13.49	0.637	4.80	0.649	6.70	0.721	18.50	0.731	20.24	0.658	8.22	R
73	-0.102	-0.078	-23.17	-0.138	35.29	0.108	6.31	0.150	46.96	0.081	-20.79	0.124	21.92	0.108	5.88	R
88	-0.212	-0.221	4.29	-0.218	2.83	0.230	8.58	0.240	13.08	0.271	27.90	0.198	-6.44	0.220	3.54	R
89	-0.610	-0.640	4.89	-0.618	1.31	0.654	7.21	0.668	9.50	0.731	1[illegible].87	0.573	-6.06	0.629	3.11	R
90	-0.462	-0.477	3.34	-0.471	1.95	0.497	7.53	0.517	11.90	0.564	22.08	0.430	-6.95	0.474	2.60	R
97	-0.607	-0.618	1.82	-0.586	-3.46	0.629	3.60	0.640	5.48	0.721	18.72	0.526	-11.74	0.602	-0.82	R
148	1.138	1.191	4.65	0.837	-26.45	1.173	3.06	1.157	1.66	1.319	15.89	0.605	-46.81	1.014	-10.90	F
157	1.174	1.212	3.25	1.115	-5.03	1.203	2.47	1.192	1.53	1.186	1.06	1.040	-11.42	1.164	-0.89	F
172	1.157	1.205	4.16	1.118	-3.37	1.190	2.89	1.174	1.44	1.204	4.08	1.064	-8.04	1.162	0.39	F
183	-1.161	-1.246	7.33	-1.147	-1.21	1.237	6.58	1.227	5.71	1.183	1.89	1.065	-8.23	1.197	3.05	R
194	-1.175	-1.258	7.08	-1.184	0.77	1.242	5.71	1.228	4.52	1.157	-1.53	1.136	-3.33	1.221	3.91	R
252	0.609	0.616	1.23	0.588	-3.45	0.643	5.64	0.671	10.16			0.516	-15.28	0.602	-1.15	F
264	0.611	0.621	1.64	0.560	-8.35	0.644	5.45	0.669	9.48			0.471	-22.92	0.591	-3.36	F
293	-0.613	-0.701	14.35	0.577	-5.87	0.645	5.29	0.594	-3.18			0.560	-8.60	0.639	4.24	R
300	-0.617	-0.701	13.65	0.574	-6.97	0.645	4.47	0.592	-4.04			0.560	-9.22	0.638	3.32	R

[a] represents prototype test number as given in Ref. 1.

[b] "W" represents known values of mass flow rate.

Analyzing the results of Table 1 shows that the primary model given by equation (1) appears to give the best results for forward flows and the model given by equation (21) appears to give the best results for reverse flows.

The present software prints out the results of calculations based on equations (1) and (2). To obtain the results of equation (21), an average of the results of equations (1) and (2) must be taken.

TWO-PHASE FLOWS

The results from applying equations (7) through (11) to the PKL prototype test data[1] give the total mass flow rate data in Tables 2, 3, 4, and 5 for the slug, annular mist, froth, and wave flow regimes. Negative mass flow rate values indicate flows in the reverse direction.

For the slug flow regime data of Table 2, the primary model gives better results than all the other models for reverse flows. For forward flows, the model (MFA) given by equation (8) appears to be better for spool number 3.

For the annular mist flow regime data of Table 3, the primary model, shown by equation (8), appears to be best.

For the froth and wave flow regime data given in Tables 4 and 5, the primary model equation (8) gives the best results.

SLIP CORRECTIONS IN TWO-PHASE FLOWS

The effect of slip on mass flow calculations is given by equation (20). From this relation one can see that if the slip ratio at the turbine is smaller than at the drag screen, the corrected mass flow rate will be increased, as well as the converse.

TABLE 2. Slug flow regime total mass flow rates (kg/s) and percentage differences (%).

Test no.	Flow dir.	Spool no.	W	MF	%	MFA	%	MFB	%	MFC	%	MFD	%
36	F	1	4.351	3.939	-9.5	4.467	2.7	4.898	12.6	5.435	24.9	6.031	38.6
41	F	1	4.335	3.656	-15.7	4.324	-0.26	5.093	17.5	5.347	23.3	5.613	29.5
56	F	1	3.156	2.651	-16.0	3.611	14.4	4.916	55.8	4.672	48.0	4.440	40.7
57	F	1	4.376	3.997	-8.7	4.601	5.1	5.175	18.3	5.866	34.1	6.650	52.0
59	F	1	3.020	2.891	-4.3	3.936	30.3	5.370	77.8	5.063	67.7	4.774	58.1
75	R	1	-4.393	-4.835	10.1	4.994	13.7	4.788	9.0	7.465	70.0	11.641	165.0
79	R	1	-3.077	-3.860	25.4	4.241	37.8	4.665	51.6	6.037	96.2	7.812	153.9
84	R	1	-3.086	-2.937	-4.8	4.115	40.1	6.057	96.3	6.144	99.1	6.232	101.9
94	R	1	-4.340	-4.548	4.8	4.637	6.8	4.727	8.9	6.895	58.9	10.060	131.7
99	R	1	-4.438	-4.143	-6.7	4.451	0.29	4.788	7.9	6.968	57.0	10.141	128.5
146	F	3	8.470	6.205	-26.7	9.049	6.8	13.190	55.7	12.016	41.9	10.947	29.2
155	F	3	5.758	4.287	-25.5	7.318	27.1	12.497	117.0	9.308	61.7	6.932	20.4
161	F	3	8.398	6.232	-25.8	9.051	7.8	13.150	56.6	12.105	44.1	11.143	32.7
164	F	3	5.929	4.592	-22.6	6.758	14.0	9.937	67.6	9.145	54.2	8.416	41.9
170	F	3	8.414	6.267	-25.5	9.139	8.6	13.347	58.6	12.179	44.8	11.113	32.1
178	R	3	-8.543	-7.791	-8.8	9.507	11.3	11.613	35.9	14.201	66.2	17.364	103.3
182	R	3	-5.849	-6.001	2.6	7.271	24.3	8.820	50.8	9.105	55.7	9.399	60.7
190	R	3	-5.858	-5.283	-9.8	6.777	15.7	8.695	48.4	10.465	78.7	12.597	115.0
192	R	3	-8.422	-7.436	-11.7	9.156	8.7	11.290	34.1	13.945	65.6	17.225	104.5
251	F	4	7.384	5.950	-19.4	5.958	-19.3	3.640	-50.7				
260	F	4	1.458	1.655	13.5	1.640	12.5	0.602	-58.7				
286	R	4	-7.350	-6.810	-7.4	6.790	-7.6	4.732	-35.6				
289	R	4	-1.509	-2.057	36.3	2.041	35.3	1.612	6.9				

TABLE 3. Annular mist flow regime total mass flow rates (kg/s) and percentage differences (%).

Test no.	Flow dir.	Spool no.	W	MF	%	MFA	%	MFB	%	MFC	%	MFD	%
37	F	1	0.804	0.756	-6.0	1.074	33.6	1.526	89.8	1.088	35.4	0.776	-3.5
42	F	1	0.811	0.785	-3.2	1.093	34.8	1.522	87.7	1.101	35.8	0.796	-1.8
43	F	1	1.025	1.363	33.0	2.075	102.4	3.159	208.2	2.201	114.7	1.533	49.5
45	F	1	0.554	0.632	14.1	1.080	95.0	1.850	233.9	1.198	116.2	0.776	40.0
46	F	1	0.932	0.916	-1.7	1.154	23.9	1.455	56.1	1.165	25.0	0.933	0.1
54	F	1	0.382	0.494	29.3	0.906	137.1	1.663	335.3	0.957	150.5	0.551	44.2
55	F	1	0.655	0.684	4.4	1.190	81.7	2.072	216.3	1.212	85.0	0.709	8.2
58	F	1	0.795	0.769	-3.2	1.096	37.8	1.561	96.3	1.123	41.3	0.808	1.6
69	R	1	-0.752	-0.800	6.4	1.013	34.7	1.282	70.5	1.243	65.3	1.205	60.2
70	R	1	-1.044	-1.590	52.3	1.587	52.0	1.408	34.8	2.225	113.2	3.519	237.0
80	R	1	-0.542	-0.731	34.3	0.873	61.0	1.045	92.8	1.246	129.8	1.485	174.0
81	R	1	-0.878	-0.930	5.9	1.087	23.8	1.272	44.9	1.311	49.3	1.352	54.0
82	R	1	-0.667	-0.818	22.6	1.152	72.8	1.625	143.6	1.395	109.1	1.197	79.5
83	R	1	-0.391	-0.687	75.7	0.877	124.2	1.171	199.5	1.077	175.3	0.990	153.1
91	R	1	-0.799	-0.882	10.3	1.108	38.7	1.393	74.3	1.355	69.6	1.318	65.0
92	R	1	-1.042	-1.523	46.2	1.521	46.0	1.277	22.6	2.122	103.6	3.525	238.3
93	R	1	-0.763	-0.836	9.6	1.062	39.2	1.351	77.1	1.282	68.0	1.216	59.3
98	R	1	-0.761	-0.829	9.0	1.064	39.8	1.364	79.3	1.309	72.0	1.256	65.1
147	F	3	1.438	1.190	-17.2	1.187	-17.5	1.183	-17.7	1.227	-14.7	1.273	-11.5
152	F	3	1.095	1.194	9.0	2.411	120.2	4.875	345.2	2.684	145.1	1.478	35.0
153	F	3	1.111	1.208	8.7	2.470	122.3	5.056	355.0	2.733	146.0	1.478	33.0
154	F	3	1.765	1.439	-18.5	1.969	11.5	2.693	52.6	2.053	16.3	1.566	-11.3
158	F	3	2.049	1.909	-6.8	2.904	41.7	4.416	115.5	2.987	45.8	2.020	-1.4
159	F	3	1.426	1.185	-16.9	1.768	49.2	2.640	85.1	1.844	29.3	1.289	-9.6
162	F	3	1.298	1.110	-14.5	1.859	43.3	3.114	139.9	1.919	47.9	1.183	-8.9
163	F	3	0.771	0.715	-7.3	1.646	113.5	3.795	392.3	1.902	146.7	0.953	23.6
171	F	3	1.455	1.201	-17.5	1.768	21.5	2.604	79.0	1.841	26.5	1.301	-10.6

TABLE 3. Annular mist flow regime mass flow rates (kg/s) and percentage differences (%) (Contd).

Test no.	Flow dir.	Spool no.	W	MF	%	MFA	%	MFB	%	MFC	%	MFD	%
175	R	3	-1.443	-1.360	-5.8	1.725	19.5	2.188	51.7	1.829	26.8	1.529	6.0
176	R	3	-2.020	-2.625	29.9	3.050	51.0	3.549	75.7	3.709	83.6	3.875	91.8
180	R	3	-1.709	-1.580	-7.6	1.909	11.7	2.307	35.0	2.008	17.5	1.748	2.3
181	R	3	-1.105	-1.792	62.2	2.058	86.2	2.368	114.3	2.712	145.4	3.106	181.1
189	R	3	-0.779	-1.413	81.4	1.675	115.0	1.986	40.6	2.449	214.3	3.019	287.5
191	R	3	-1.312	-1.311	-0.1	1.900	44.8	2.753	109.9	2.089	59.2	1.585	20.8
193	R	3	-1.471	-1.361	-7.5	1.811	23.1	2.411	63.9	1.929	31.1	1.543	4.9
245	F	4	0.653	0.644	-1.4	1.257	92.5	2.454	275.7				
246	F	4	0.843	0.960	13.9	1.473	74.8	2.269	169.1				
249	F	4	1.016	1.086	6.9	1.657	[illegible].1	2.530	149.0				
250	F	4	0.747	0.723	-3.2	1.066	42.7	1.572	110.4				
262	F	4	1.404	1.467	4.5	2.039	45.2	2.840	102.3				
263	F	4	0.890	0.840	-5.7	1.124	26.3	1.503	68.9				
282	R	4	-0.660	-0.770	16.7	1.054	59.6	1.446	119.1				
283	R	4	-0.867	-1.261	45.5	1.456	67.9	1.685	94.4				
287	R	4	-1.039	-1.310	26.1	1.511	45.5	1.752	68.7				
288	R	4	-0.755	-0.706	-6.4	0.972	28.7	1.340	77.5				
291	R	4	-1.413	-1.897	34.3	2.048	44.9	2.211	56.5				
292	R	4	-0.867	-0.802	-7.5	0.998	15.2	1.296	49.5				

TABLE 4. Froth flow regime total mass flow rates (kg/s) and percentage differences (%).

Test no.	Flow dir.	Spool no.	W	MF	%	MFA	%	MFB	%	MFC	%	MFD	%
247	F	4	0.374	0.496	32.5	0.711	90.0	1.020	172.7				
248	F	4	1.550	1.884	21.6	1.899	22.5	1.285	-17.1				
258	F	4	0.371	0.521	40.5	0.693	86.8	0.922	148.4				
259	F	4	1.559	1.627	4.4	1.692	8.6	1.102	-29.3				
261	F	4	1.592	1.973	23.9	2.018	26.7	1.357	-14.7				
284	R	4	-0.374	-0.357	-4.5	0.928	148.1	2.461	558.1				
285	R	4	-1.625	-1.882	15.8	1.941	19.5	1.802	10.9				
290	R	4	-1.564	-1.861	19.0	1.933	23.6	1.737	11.0				
298	R	4	-0.385	-0.395	2.6	0.914	1.4	2.149	458.1				
299	R	4	-1.520	-2.060	35.5	2.106	38.6	1.793	18.0				

TABLE 5. Wave flow regime total mass flow rates (kg/s) and percentage differences (%).

Test no.	Flow dir.	Spool no.	W	MF	%	MFA	%	MFB	%	MFC	%	MFD	%
44	F	1	0.202	0.135	-33.3	0.354	75.3	0.937	363.7	0.867	329.3	0.803	297.4
60	F	1	0.493	0.617	25.3	0.953	93.3	1.472	198.5	0.768	55.7	0.401	-18.7
156	F	3	0.954	0.572	-40.1	1.815	90.3	2.76	189.4	1.815	90.3	1.194	25.2
177	R	3	-0.379	-0.533	41.8	0.993	162.0	1.839	385.1				
179	R	3	-0.947	-0.557	-41.1	1.188	25.5	2.552	169.5				
188	R	3	-0.642	-0.611	-4.8	0.933	45.4	1.425	121.9				

The amount of change in slip ratio between the drag screen and the turbine is not a known quantity; however, assumptions as to this value can be made and applied to the data to discern a possible empirical relationship.

The mass flow data for the prototype spool tests given in Ref. 1 have been analyzed with equation (20). Mass flow rates in the forward flow direction for the three spools are randomly larger or smaller than the reference values; for reverse flows the same situation exists.

Applying the slip correction, with various assumptions of change in slip ratio between the turbine and drag screen, did not result in increased accuracy.

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