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MEASUREMENTS OF TWO-PHASE MASS FLOW RATE: A COMPARISON OF DIFFERENT TECHNIQUES

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Abstract—The development of practical and accurate methods to measure two-phase mass flow rates is of prime interest to applied nuclear reactor safety research. This article summarizes a comparison and evaluation of four commonly used mass flow rate devices. The particular systems investigated include (a) the true mass flow meter (TMFM), (b) the radionuclide technique, (c) the combination of a free field drag disk-turbine meter-transducer (DTT) and a gamma densitometer, and (d) the combination of a venturi nozzle and a full flow turbine meter. The experiments were performed under similar conditions in steady-state steam–water flow. The flow direction upstream of the instruments was horizontal except for the last method. The pressures varied between 3 and 9 MPa, and the highest values of the mass flow rate, the quality were 5 kg/s and 90 per cent respectively. The test matrix included wave-, slug- and annular flow. The measuring techniques are described briefly and a classification is proposed, which is based on the different ways of mass flow rate evaluation. The experimental results show that the accuracy of some methods is distinctively dependent on phase distribution (flow regime). Simple calibration correlations were developed to account for these effects.

INTRODUCTION

The measurement of two-phase mass flow rates is of basic importance in many technical applications, e.g. for process control in chemical production plants or for transport of oil–gas mixtures in pipe lines. In the past, the mass flow rate was measured by separating, condensing or evaporating the phases which entailed a considerable technical effort.

Recently the development of two-phase mass flow rate instrumentation has been strongly influenced by nuclear reactor safety research. In many countries extensive experiments are being performed to investigate in detail loss of coolant accidents (LOCA). During these experiments the coolant is released as a two-phase mixture through a simulated break of a coolant pipe. This flow is in general strongly transient. Measuring techniques based on steady-state flow conditions are usually no longer applicable. There exists a large number of publications related to the development of such measuring techniques (for an overview, see e.g. Hewitt 1979). These techniques, however, were either not sufficiently tested or were tested only in special geometries so that a comparison and assessment of different techniques is not possible. Therefore a test facility for calibrating two-phase flow instrumentation under comparable conditions were constructed in the Institute for Reactor Components (IRB) at the Nuclear Research Center Karlsruhe (KfK), West Germany. Table 1 shows in chronological sequence the different mass flow instruments tested in this facility.

In the following four typical examples of the methods listed in table 1 are discussed in detail. The results presented were obtained with steam–water flow at approximately equal pressure, mass flow rate, and quality ranges.

DESCRIPTION OF MEASURING METHODS

The *radionuclide technique* (Löffel 1976, 1979) employs the transit time measurement of radioactive tracers and a void fraction measurement (figure 1). The liquid and gaseous phases are marked separately by different radioactive isotopes: for the gaseous phase Ar-41 with an energy E of the photons of 1.29 MeV and a half-live time $T_{1/2}$ of 1.83 h is used, for the liquid phase Mn-56 dissolved in water ($E = 0.85$ MeV, 1.81 MeV and 2.11 MeV, $T_{1/2} = 2.58$ h). After being injected, the tracers require a certain mixing length to reach the same velocity distributions as the corresponding phases. Then the radiotracer clouds are detected by detectors positioned in two or more measurement planes. The velocities of the gaseous phase v_{RG} and the

Table 1. Test of two-phase mass flow rate instrumentation

Instrumentation	Measured Quantities	Measurements Local	Measurements Global	Origin
a) Radiotracer Injection and Detection + Multibeam γ-Densitometer (Radionuclide Technique)	Phase Velocities + Density		×	KfK-LIT, West Germany
b) Drag Body	Momentum Flux	×		Battelle-Frankfurt, West Germany
c) Thermocouples	Velocity	×		TU-Berlin, West Germany
d) 2 Beam γ-Densitometer + Local Turbines + Drag Bodies	Density + Volume + Momentum Fluxes	×	×	Euratom-Ispra, Italy
e) 3 Beam γ-Densitometer + Drag Disk-Turbine-Transducer	Density + Volume + Momentum Fluxes	×	×	EG&G Idaho, LOFT, USA
f) 2 Beam γ-Densitometer + Full Flow Turbine + Drag Screen or Drag disk	Density + Volume + Momentum Fluxes	×	×	EG&G Idaho, Semiscale, USA
g) True Mass Flow Meter (TMFM)			×	KfK-IRE-IT, West Germany
h) Single Beam γ-Densitometer + Venturi Nozzle + Full Flow Turbine	Density + Differential Pressure + Volume Flux		×	CEN-Grenoble, France

liquid phase v_{RL} are calculated with the transit times determined by a cross correlation technique and the given axial detector distance.

The void fraction normaly is measured with a gamma densitometer. For the experiments reported in this article the three beam gamma densitometer belonging to the LOFT-instrumentation was used, which will be discussed later. With this instrument the length averaged density of the three beams is measured. To calculate the cross sectional averaged density ρ_γ the single beams are weighted according to their lengths. The relationship between the cross sectional density and the cross sectional void fraction is

$$\alpha = (\rho_L - \rho_\gamma)/(\rho_L - \rho_G)\,, \qquad [1]$$

with ρ_L is the liquid density and ρ_G is the gas (steam) density. Mass flux is calculated in the following way:

$$G_{R-\gamma} = \alpha_\gamma \rho_G v_{RG} + (1 - \alpha_\gamma)\rho_L v_{RL}\,. \qquad [2]$$

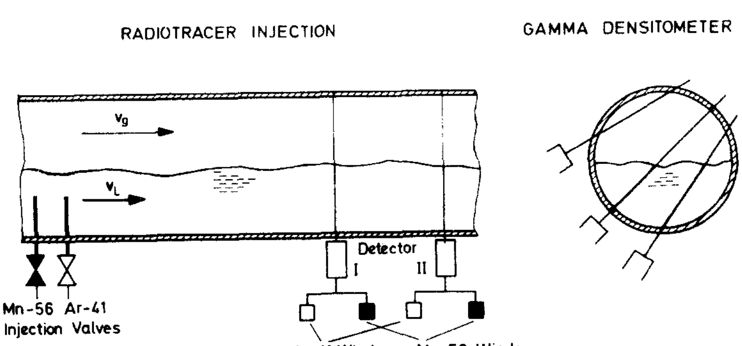

Figure 1. Radionuclide technique (KfK–LIT).

The radionuclide technique has been employed successfully in some nuclear safety experiments: the Marviken I and II experiments (Sweden) and the HDR-Experiments (West Germany). The use of this device during some experiments in the LOBI facility (Italy) is being prepared.

The *true mass flow meter* (*TMFM*) (Class & Cramer 1975, Barschdorff *et al.* 1976, Class *et al.* 1979a) is in principle a single stage turbomachine with a rotor and a stator (figure 2). The total mass flux G emerging from the rotor with a defined swirl, produces a torque M in the stator which is measured. For the idealized machine (blade efficiencies equal unity) the mass flux G is evaluated by the following equation:

$$G_{\mathrm{TMFM}} = M/(A\omega r^2)\,, \qquad [3]$$

where r is the rotor radius at the outlet, ω is the angular frequency and A is the pipe cross section.

The value of the existing blade efficiency can in principle be estimated by empirical correlations as known from literature on turbomachines or by measurement in single-phase flow.

The TMFM discussed in this paper was developed for a small scale blowdown facility (Cosima Facility, KfK). Results from transient experiments were presented by Class *et al.* (1978, 1979a).

The instrumentation shown in figure 3 consists of a *drag disk*, a *turbine meter*, and a 3 *beam gamma densitometer.* This kind of instrumentation has been employed in various reactor safety experiments using different designs of the single instruments. This paper deals with the instrumentation developed for the LOFT (Loss of Fluid Tests, EG&G, Idaho, U.S.A., see e.g. Reeder 1978). Here the drag disk and the turbine are combined in a single unit, the so-called *drag disk turbine transducer* (*DTT*) (compare e.g. Wesley 1977). This instrumentation is usually installed in pipes with larger diameters than the turbine shroud.

Therefore the DTT can measure only a portion of the pipe flow (free field configuration).

For the instrumentation shown in figure 3 it is generally assumed that the drag disk measures cross sectional momentum flux

$$(\rho v^2)_{DD} = \alpha \rho_G v_G^2 + (1-\alpha)\rho_L v_L^2\,, \qquad [4]$$

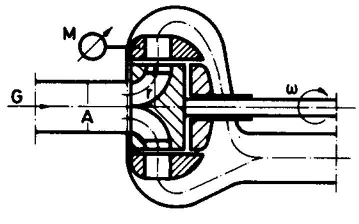

Figure 2. True mass flow meter (TMFM) (KfK-IRE-IT).

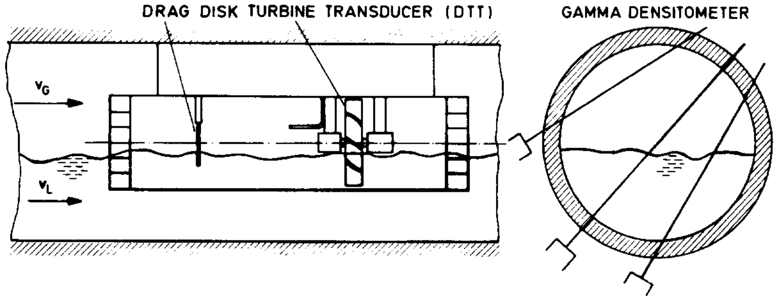

Figure 3. LOFT spool piece: Drag disk, turbine meter and gamma-densitometer (EG&G Idaho, U.S.A.).

and the gamma densitometer the cross sectional apparent density

$$\rho_\gamma = \alpha\rho_G + (1-\alpha)\rho_L\,. \qquad [5]$$

To interpret the rotational speed of the turbine meter, models were developed by Rouhani (1964) and Aya (1975). Another model, the void fraction model, assumes that the turbine measures the volumetric flux given by

$$v_T = \alpha v_G + (1-\alpha)v_L\,. \qquad [6]$$

The mass fluxes are often calculated by combining two of the three instrument readings in the following way:

$$G_{\gamma-T} = \rho_\gamma v_T\,, \qquad [7]$$

$$G_{\gamma-DD} = (\rho_\gamma(\rho v^2)_{DD})^{05}\,, \qquad [8]$$

$$G_{T-DD} = (\rho v^2)_{DD}/v_T\,. \qquad [9]$$

These relationships are very simple, however, [7]–[9] are correct only for homogeneous flow (compare, e.g. Reimann 1976).

Another equation for calculating the mass flux is based on the mass balance:

$$G = \alpha\rho_G v_G + (1-\alpha)\rho_L v_L\,. \qquad [10]$$

This relationship is correct without restriction for any flow regime. In this equation, the three variables α, v_G, and v_L are computed with the three independent measurements α_γ, v_T, and $(\rho v^2)_{DD}$ using [4] and one of the turbine models. However, this procedure assumes that the phase distribution and slip is constant across the pipe.

An instrumented pipe spool, which is used in the PHEBUS-experiments (Cadarache, France) is shown in figure 4. This instrumentation which was developed by Frank *et al.* (1977) consists of a ***full flow turbine meter***, a ***symmetrical venturi nozzle***, and a ***single beam gamma densitometer.*** The instrumentation was installed in a pipe geometry containing several bends. The pipe geometry used in our tests was identical to that used in the PHEBUS facility.

In the present article only the differential pressure Δp measured between inlet and throat of the venturi nozzle and the turbine meter frequency f were used for the determination of the mass flux given by the following relationship:

$$G_v = K_v\sqrt{[\rho_v(\Delta p \pm g\Delta h(\rho_0-\rho_a))]} \qquad [11]$$

$$G_T = K_T\rho_T f\,. \qquad [12]$$

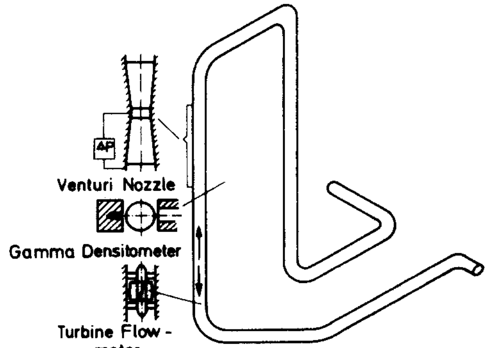

Figure 4. PHEBUS spool piece: venturi nozzle, gamma-densitometer, turbine flow meter.

Here K_V, K_T are flow coefficients of the instruments obtained in single phase flow, $g\Delta h(\rho_0 - \rho_a)$ is the static head correction term with g the acceleration of gravity, Δh the vertical differential height of the pressure taps, ρ_0 the density of the fluid in the manometer and ρ_a the apparent density (defined in [5]) in the test section. The positive sign in [11] holds for vertical upward flow and the negative sign for vertical downward flow. ρ_V and ρ_T are two-phase densities at the venturi nozzle and the turbine meter. Murdock (1962) and Chisholm (1967) have shown that the appropriate density for orifices and venturi nozzles is the momentum density ρ_i given by the relation

$$\rho_i = (x^2/\alpha\rho_G + (1-x)^2/(1-\alpha)\rho_L))^{-1} \qquad [13]$$

where x is the quality.

Rouhani (1964) has shown that the appropriate density for the turbine meter is also the momentum density.

The following assumptions are made to evaluate mass flux from [11] and [12]:

(1) The apparent density is equal to the momentum density.

(2) The turbine meter momentum density ρ_T is equal to the venturi nozzle momentum density ρ_v.

The first assumption concerns only the static head correction which is generally small compared to the value of Δp. The second assumption is not *a priori* true because the void fraction α may change due to a change of the phase distribution although the quality x will not change significantly between the two measurement locations.

With the above assumptions, the density can be eliminated. This procedure then leads to the following expression

$$G_{v-T} = (\Delta p \pm \Delta h g \rho_0) f \Big/ \left(K_v \left(\left(\frac{K_v}{K_T} \right)^2 f^2 \pm \Delta h g \right) \right). \qquad [14]$$

CLASSIFICATION OF MEASURING METHODS

It is proposed to classify the measuring methods listed in Table 2 according to the evaluation procedure for the flow rate, following an idea by Reimann (1976). According to this procedure the measuring methods can be subdivided basically into two classes, a so-called "comprehensive class" and a so-called "restricide class".

A method shall be termed "comprehensive" if

—the relationship for the mass flux is correct without any limitation to flow regime and if

—the properties occuring in this relationship are measured directly.

A method is termed "restricted" if either

—the mass flux relationship is only correct for special cases (e.g. special flow regimes) or if

—the measured quantities are expressed in terms of the quantities occuring in the mass flux relationship by means of certain models where the region of validity of these models is not generally verified.

A formal representation of this classification together with typical examples is given in Table 2.

Typical examples belonging to the "comprehensive" measuring methods are the radionuclide technique and the true mass flow meter.

An example for the restricted class is the mass flux evaluation with the three measured values from drag disk, turbine meter and gamma densitometer. Here the mass flux equation is generally valid but the models for the drag disk and the turbine meter are unsatisfactory since the instruments measure a local value and the flow is generally nonhomogeneous.

Table 2. Two-phase mass flux evaluation.

	Comprehensive Evaluation of Mass Flux		Restricted Evaluation of Mass Flux	
Examples	TMFM	Radionuclide Technique	Drag Disk + Turbine Meter + Gamma Densitometer	Drag Disk + Gamma Densitometer
Measured Variables	M	α, V_G, V_L	$(\rho V^2)_{DD}, V_T, \alpha$	$\rho_\gamma, (\rho V^2)_{DD}$
Evaluation Equation	$G = M(A\omega r^2)^{-1}$	$G = \alpha \rho_G V_G + (1-\alpha)\rho_L V_L$		$G = (\rho_\gamma (\rho V^2)_{DD})^{0.5}$
Region of Validity	All Flow Regimes			Homogeneous Flow
Evaluation Procedure	Direct, without Modeling		Indirect, with Modeling e.g. $V_T = \alpha V_G + (1-\alpha)V_L$	Direct, Model in Evaluation Equation
Requirement for Two-Phase Flow Calibration	Two-Phase Flow Calibration not Absolutely Necessary		Two-Phase Flow Calibration Required for Every Geometry	

The mass flux evaluation with two of the three measured values (for example as shown in Table 1 the combination gamma densitometer—drag disk) belongs also to this group. Here a homogeneous flow is implicitely assumed.

The mass flux determination with the measured values from turbine meter and venturi nozzle has also to be considered as restricted. Here the model is used that the densities for both instruments are equal.

As consequence of the classification as shown in Table 2 it can be argued that a calibration of the "comprehensive methods" in two-phase flow is in principle not necessary. The measurement range and accuracy could be checked satisfactorily from measurement in single phase flow. A calibration in two-phase flow is primarily necessary for the "restrictide methods"; here it is important that the same test conditions exist as in the experiments where these methods are to be applied.

TEST FACILITY AND TEST CONDITIONS

The experiments were performed in the KfK-Two-Phase Instrumentation Test Facility (for details see John & Reimann 1979). This facility consists of a steam–water and air–water loop. Figure 1 shows schematically the set-up of the steam–water loop. Two operating modes are possible: In the first mode slightly subcooled water flows through one boiler and slightly superheated steam flows through the other boiler. In the second mode water flows through both boilers and steam is generated by flashing in the throttling valves. The total flow rate is determined by measuring the individual single-phase flow rates with orifice meters which are located downstream of the boilers. Before entering the mixing chamber, the two streams pass through sinter metal filters and the throttle valves. Downstream from the mixing chamber, the mixture flows through the horizontal test section (length 8 m) where the instruments to be tested are installed. For flow regime detection and measurement of phase distribution, the test section instrumentation includes a five beam gamma densitometer (John *et al.* 1979) and local impedance probes (Reimann & John 1978). The horizontal test section is followed by an electrically actuated pressurizer valve controlling automatically the pressure in the test section. The depressurized mixture flows to two parallel condensers. Finally the condensate is pumped back to a condensate tank and the cycle is completed. The boiler system is equipped with a demineralization and degasing unit.

The test of the different measuring methods were performed with steam–water flow in a pressure range between 3 and 9 MPa. The maximum mass flow rate was about 5 kg/s, quality was varied between 0.1 and 0.9. The two-phase test matrix included wave, slug and eccentrical annular droplet flow. These flow regimes are characterized by distinct phase and velocity

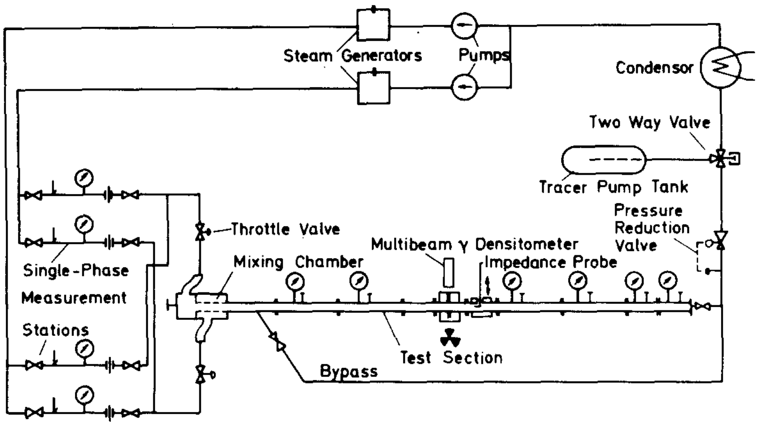

Figure 5. Steam–water loop.

differences in the cross section. Besides the two-phase flow tests, single phase water and steam flow tests were also carried out to establish the required single phase calibration curves of several instruments.

The radionuclide technique was tested together with the LOFT spool piece in horizontal test sections with inner diameters of 66.6 and 104 mm. Radiotracer velocity measurements were made at three axial positions in the test section. The LOFT gamma densitometer and the radiotracer detector units were located at slightly different axial positions of the test section. For the 66.6 mm diameter test section detector units were located up and downstream of the densitometer and for the 104 mm dia. test section all detectors were upstream of the densitometer. Therefore it was necessary to interpolate (smaller diameter pipe) and extrapolate (larger diameter pipe) the phase velocities to the position of the densitometer for the evaluation of the mass flux. The LOFT spool piece was about 3.3 m downstream of the test section entrance (for details see Reimann *et al.* 1980b).

The TMFM, whose axis had to be orientated vertically, was positioned at the end of a horizontal test section of 8 m length and 50 mm inner diameter. The PHEBUS instrumentation was installed in the PHEBUS piping with an inner diameter of 66.6 mm (see figure 4). This piping was positioned 1.4 mm downstream of the mixing chamber, connected by a horizontal pipe piece of 80 mm inner diameter.

RESULTS

The measured mass fluxes obtained by the different measuring methods are given in figures 6–8 and 12. These mass fluxes are plotted vs the reference mass flux G_{ref} which is the actual

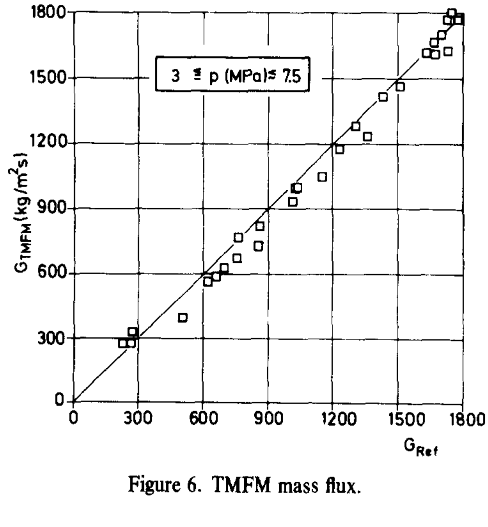

Figure 6. TMFM mass flux.

flux and is obtained from the individual single-phase measurements. Figure 6 contains the TMFM results. The scattering of the results is very small, the deviation of the arithmetic mean value of the ratios TMFM mass flux to reference mass flux is about 3 per cent, the standard deviation is about 10 per cent. The deviations of the measured mass flux from the actual mass flux are dependent on neither the actual mass flux nor the quality (for details see Wagner *et al.* 1979). It can therefore be concluded that these deviations are independent of the flow regimes in the horizontal test section. The mean deviation is essentially caused by the fact that for mass flux evaluation a blade efficiency of unity was assumed.

Figure 7 shows the results obtained by the radionuclide technique. The agreement between evaluated and reference mass fluxes is also very satisfying. The mean deviation of the mass flux ratio is +5 per cent, the standard deviation 7 per cent. The largest deviations occur at higher mass fluxes. This is essentially caused by the evaluation of the cross sectional void fraction with the length weighting method using the three beam gamma densitometer as shown by Reimann *et al.* (1979). Improvements may be achieved if the signals of the single gamma beams are first used to determine the flow regime and then the cross sectional void fraction is calculated as a function of flow regime according a procedure developed by Lassahn (1976).

Figure 8 shows corresponding results obtained by the LOFT spool piece. The symbols with vertical primes indicate those test points where measurements with the radionuclide technique were also made (figure 7). The scattering of the values is considerable. Deviations up to a factor of two occur. The following mean values $\bar{x}$ and standard deviations σ for the different instrument combinations were determined:

	$\bar{x}$	σ
$G_{\gamma-T}/G_{\mathrm{Ref}}$	1.36	0.43
$G_{\gamma-DD}/G_{\mathrm{Ref}}$	0.95	0.20
$G_{T-DD}/G_{\mathrm{Ref}}$	0.73	0.32.

The combination gamma densitometer–drag disk gives the best results. The measurements shown in figure 8 do not include any points which were obviously in error due to amplifier drift or due to not falling into the measuring range.

The deviations are caused by the fact that (a) the mass flux equation are only correct for homogeneous flow, and (b) the drag disk and turbine meter measure to a certain degree local values only.

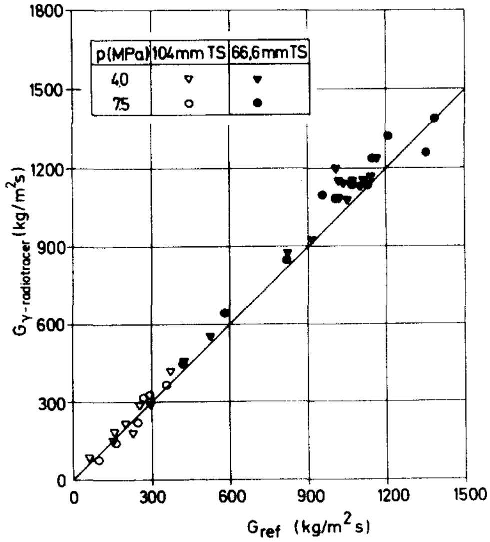

Figure 7. Radionuclide mass flux.

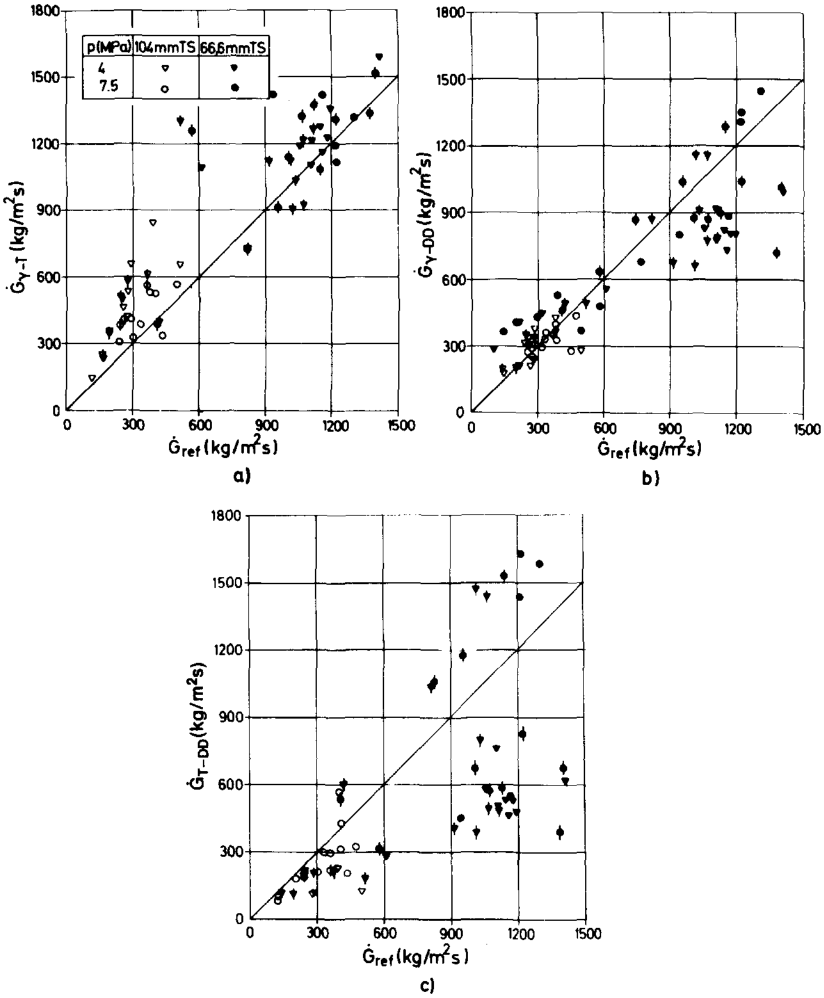

Figure 8. Mass flux from (a) gamma-densitometer and turbine meter, (b) gamma-densitometer and drag disk, (c) turbine meter and drag disk.

The deviations caused by employing [7]–[9] which are only valid for homogeneous flow are shown in figure 9 (Reimann *et al.* 1979). For this purpose [4]–[6] were inserted in [7]–[9] and mass flux ratios were formed dividing these expressions by the correct mass flux equation [10]. Finally v_G was replaced by $S \cdot v_L$ where the slip S is the ratio of gas phase velocity to liquid phase velocity. The mass flux ratios calculated are plotted in figure 9 vs the slip S with the void fraction α as a parameter.

The equation which combines the density ρ_γ and the volumetrix flux v_T and the combination of momentum flux $(\rho v^2)_{DD}$ and volumetric flux v_T are strongly dependent on the slip. On the other hand, the combination of density ρ_γ and momentum flux $(\rho v^2)_{DD}$ is dependent on slip to a much lesser degree.

These circumstances explain to some extent the better agreement for the measured mass fluxes when employing the combination drag disk and gamma densitometer rather than any other combination of the three instruments.

As already mentioned, the test matrix covered flow regimes with a distinct stratification influence due to gravity. That means that the fluid quantities are dependent essentially on the vertical coordinate.

With the multibeam gamma densitometer a comparative good cross sectional average of the void fraction and density, respectively, can be determined. Moreover, the gamma densitometer can give information to calculate density distributions in a horizontal pipe (Lassahn 1976). For

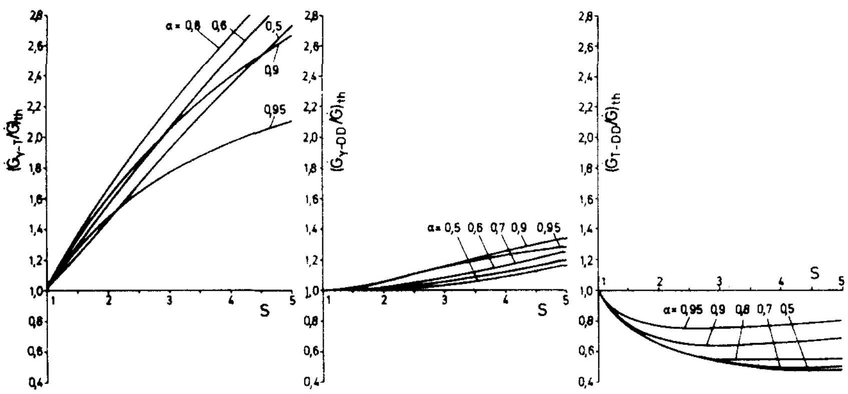

Figure 9. Theoretical ratios of mass fluxes (steam–water flow, $p = 4$ MPa).

the experiments discussed in this article it proved to be advantageous to calculate the height of the dimensionless liquid level y/d assuming an ideal stratified flow in the following way

$$\alpha = 1 - \frac{1}{2\pi}(\theta - \sin\theta), \qquad [15]$$

$$y/d = 0.5\left(1 - \cos\frac{\theta}{2}\right), \qquad [16]$$

where θ is the angle between the pipe radii and the secant which represents the interface level. It was seen that this interface level y/d is well suited to establish a simple interrelation between the local values of the drag disk and turbine meter and the corresponding cross sectional values (Reimann *et al.* 1979):

If the combination drag disk–gamma densitometer is taken, the following calibration relation is used:

$$G_{(\gamma-DD)_{cal}} = C(\rho_\gamma(\rho v^2)_{DD})^{0.5}, \qquad [17]$$

where the factor C is depending in the following way on the interface level

$$C = 0.91 \quad \text{for} \quad y/d > 0.5$$

$$C = 1.32 \quad \text{for} \quad 0.5 \geq y/d \geq 0.2$$

$$C = 1.0 \quad \text{for} \quad 0.2 > y/d.$$

The mass fluxes calculated in this way are shown in figure 10. The scattering of the values is reduced considerably, the mean deviation of the mass flux ratios is about 4 per cent, the standard deviation about 15 per cent.

The mass flux evaluation using [10] together with [5] and any one of the turbine models was not superior to the evaluation with [8] (Reimann *et al.* 1979, 1980). The reason is that the assumption of constant slip and phase distribution was poorly fulfilled in our experiments.

The results obtained with the PHEBUS spool piece are shown in figure 11. Besides the variation of mass flux, quality and pressure, the flow direction was additionally varied. The accuracy for vertical upward flow is very good. The deviation of the mean value is about 1 per cent, the standard deviation about 6 per cent. For downward flow the mean deviation is −16 per cent, the standard deviation 12 per cent.

The deviations in the latter case are caused mainly by assuming identical densities in the two measurement cross sections. The void fraction and therefore the densities may differ due to the

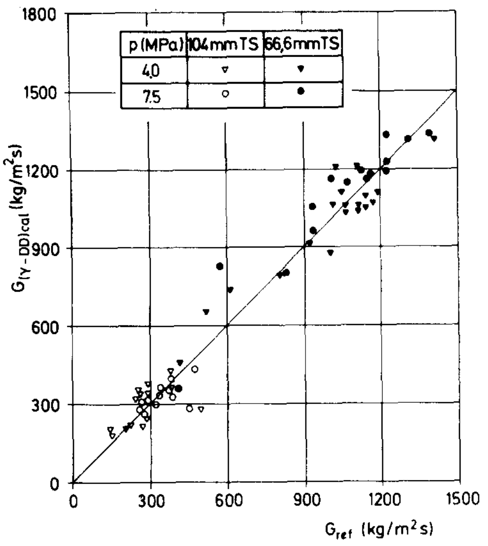

Figure 10. Calibrated mass flux from gamma-densitometer and drag disk.

influence of the pipe bends and the instruments themselves. This is quantified by evaluating the slip S_V, S_T both from the venturi nozzle and the turbine meter reading using mass flux and quality from the reference instrumentation (for details see Frank *et al.* 1980). It was shown that for each instrument the slip was only weakly dependent on mass flux and quality but dependent to a much higher degree on pressure and flow direction. Figure 12 shows the slip S_V and S_T averaged for each pressure vs the density ratio and pressure, respectively.

For instrumentation calibration this dependency was considered in the mass flux evaluation: the void fraction was replaced by the slip, in the momentum density [12], yielding

$$\rho_{V,T} = \left(\left(x\frac{\rho_L}{\rho_G} + (1-x)S_{V,T}\right)\left(\frac{1-x}{S_{V,T}} + x\right)\right)^{-1}\rho_L. \qquad [18]$$

The mass flux can be computed iteratively by inserting [18] in [11] and [12]. Figure 13 shows the results obtained in this way. The results for downward flow which were considerably less accurate than the upward flow results, are improved distinctly, the mean deviation is 3 per cent, the standard deviation 13 per cent.

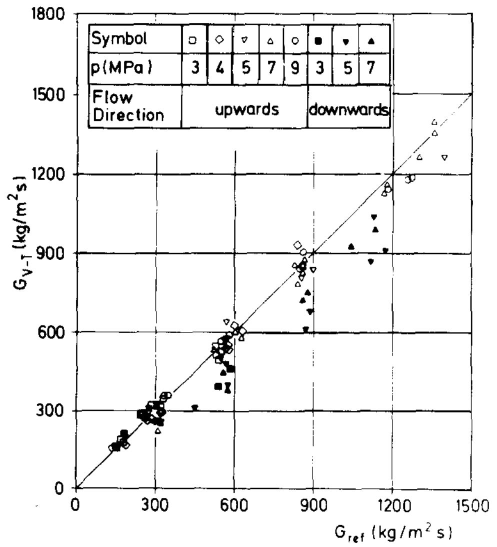

Figure 11. Mass flux from venturi nozzle and turbine meter.

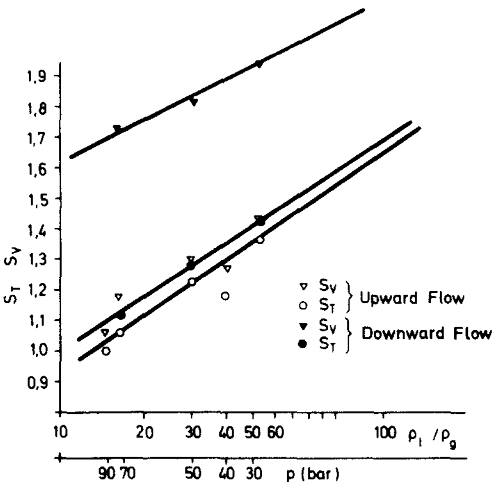

Figure 12. Average slip.

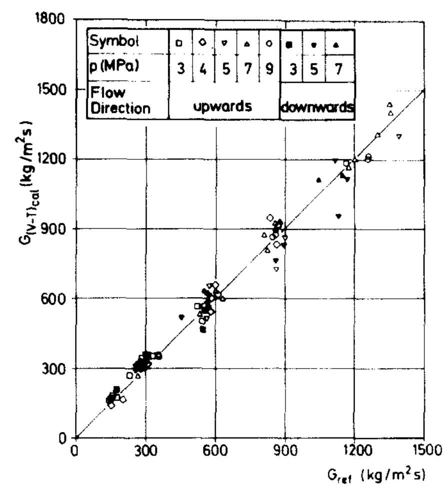

Figure 13. Calibrated mass flux from venturi nozzle and turbine meter.

CONCLUSIONS

In conclusion the results are briefly summarized and some typical characteristics are given which have not been discussed yet:

The true mass flow meter (TMFM) is the only device which measures directly the two-phase mass flow rate. The results are independent on flow regime or phase distribution. The instrument disturbs the phase distribution downstream and can cause a considerable pressure drop (in our experiments up to 1 MPa). The mechanical design of the instrument is complex. Presently, design data for TMFM's with other mass flow rate ranges and a maximum pressure drop below 0.4 MPa are being established. These data will be available to all interested research groups. A TMFM for a mass flow rate up to 50 kg/s was built and will be tested in the near future.

The radionuclide technique also yielded results essentially independent of the flow regime. With this technique the phase velocities are measured directly. This capability could be of great use for quite different investigations, e.g. measurement of the development of phase velocities downstream of changes in pipe geometry (contractions, bends) etc. The use of radiotracers is limiting the range of application: isotopes are not available everywhere and isotope handling and radiation protection require a considerable technical effort. A multi-beam gamma densitometer, which is mostly used for void fraction measurement if the mass flow rate is to be determined can give a lot of detailed information on phase distribution but such an instrument requires an experienced experimentator.

The results given by the drag disk turbine transducer (DTT) and the gamma densitometer are strongly dependent on phase distribution. The DTT is a local (free field) measuring instrument and is therefore not giving cross sectional averaged values if the flow is not homogeneous. A detailed calibration is therefore necessary if homogeneity of phase and velocity distributions cannot be assured in the experiments. The DTT tested proved to be a quite rugged instrument with simple data acquisition. It can be installed in geometries which are not accessible to the other instruments (downcomer, core plate of a reactor simulator). The gamma densitometer was already discussed in the preceeding paragraph.

The tested combination of venturi nozzle and turbine meter is also uncomplicated in its design and data acquisition. The fact that both instruments are full flow instruments and are vertically mounted results in considerably improved conditions compared to the use of a free field instrument in horizontal flow which can be strongly stratified at the same mass flow rate and quality. Nevertheless a calibration is necessary because the upstream pipe geometry and the interaction of the instruments themselves can influence the readings.

In the present article only steady-state experiments were performed. In reactor safety experiments the flow can be strongly transient. To test in a similar way two-phase flow instrumentation in transient flow, a blowdown facility is under construction (Reimann & John 1980) which will use the large TMFM, mentioned above as transient reference two-phase mass flow rate instrument.

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