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Mass Velocity Measurement in Steam-Water Flow by Pitot Tubes

SANJOY BANERJEE

Department of Engineering Physics
McMaster University
Hamilton, Ontario, Canada

and

D. M. NGUYEN

Systems Development
Westinghouse Canada Ltd.
Hamilton, Ontario, Canada

Pressure, temperature, void fraction, and mass velocity must be measured in transient steam-water flow experiments related to reactor safety. Void fraction and mass velocity measurement techniques are still being developed. Multibeam γ ray attenuation techniques to measure void fraction (Banerjee et al., 1976; Heidrick et al., 1976) appear promising for practical applications. Mass velocity is more difficult to measure, and many devices have been used. Of these, Pitot tubes are particularly attractive because they are rugged and stand up well in high pressure steam-water environments.

Banerjee et al. (1976) have measured mass velocity in transient steam-water flow with Pitot tubes which were not directly calibrated. Reproducible results and good response to flow transients were obtained over several months operation. Pitot tubes have also been used by Anderson and Mantzouranis (1960), Adorni et al. (1961), Gill et al. (1963), Delhaye (1966), and Dzakowic and Dix (1969) to investigate steady gas-liquid flow and by Dussourd and Shapiro (1955) and Dalmon and Lowe (1957) for gas-solid flow. Generally, reasonable agreement with input flow was obtained by integrating the total phase flow across the channel.

To develop the technique further, Pitot tubes should be directly calibrated in steady and transient steam-water flows covering a wide range of mass velocities, void fractions, and pressures. To interpret the measurements, simultaneous void fraction measurements are required. This note describes the first stage of such a program. The main objective was to determine whether it was feasible to use Pitot tubes to measure mass velocity in high pressure, high mass velocity steam-water flows.

EXPERIMENTS

To determine the feasibility of measuring cross section averaged mass velocity with Pitot tubes, experiments were done in the facility shown in Figure 1. The flow rate, temperature, and pressure of the hot water and superheated steam were monitored before they entered the mixer. The mixer consisted of a single pass shell and tube heat exchanger with one end cut off. The steam and water flowed concurrently along the heat ex-

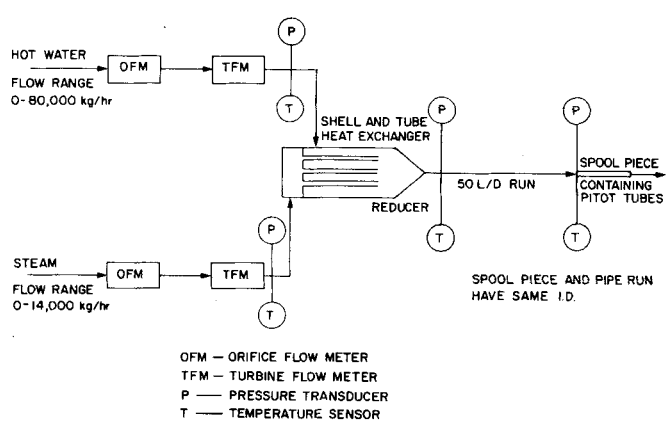

Fig. 1. Schematic of experimental facility.

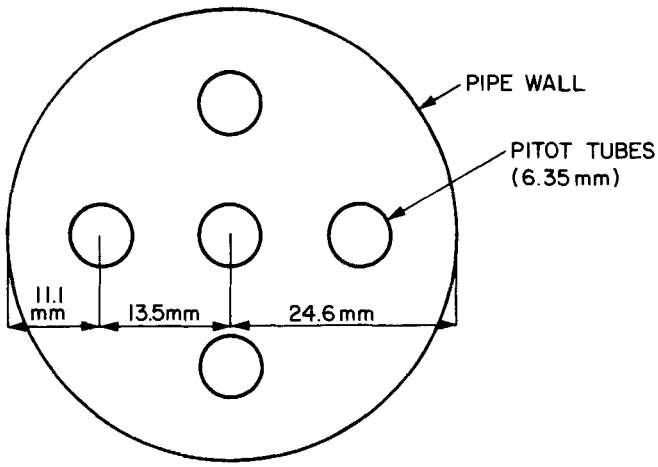

Fig. 2. Diagram showing placement of Pitot tubes in pipe.

changer and came close to thermal equilibrium before the phases were mixed at the cut off end. The temperature and pressure were monitored at the mixer outlet to verify that the phases were in thermal equilibrium.

The steam-water mixture then flowed through straight horizontal pipe about 50 L/D ratios in length before entering a horizontal spool piece containing five Pitot tubes. The arrangement of the Pitot tubes is shown in Figure 2, which also shows the important dimensions. The dynamic pressure hole was 3.2 mm diameter, the static pressure holes added up to the same area, and the outside diameter of the Pitot tubes was 6.35 mm. The dynamic pressure was measured by Validyne DP15TL differential pressure transducers. Each transducer was dead weight calibrated at the beginning of the series of experiments and checked for drift by zeroing the pressure difference before each run. Drift was found to be negligible for the experiments described here.

A three-beam γ densitometer (see Heidrick et al., 1976) was placed immediately downstream of the spool piece containing the Pitot tubes. The mean density and phase distribution were measured with the γ densitometer.

For the experiments described in this note, the flow was maintained steady, and the axis of the spool piece was horizontal. No attempt was made, however, to ensure a fully developed symmetric velocity profile, as the technique should be applicable to complex flow situations to be of practical use.

RESULTS

Experiments were done with mass velocities ranging from about 1 100 to 4 200 kg/(m^{2}s). These mass velocities are high and are in the range of interest for blowdown and emergency cooling experiments. For these mass fluxes, the cross section averaged mixture density measured by the γ densitometer was close to the homogeneous mixture density (in agreement with previous work by Banerjee et al., 1976).

To interpret the Pitot tube measurements in terms of cross section averaged mass velocity, the simplest expression with a theoretical basis, which is of the form

$$<G> = C\sqrt{\overline{\Delta P}<\rho>} \qquad (1)$$

was tried. C is a coefficient which depends on the distribution of density, mass, and momentum flux when $\overline{\Delta P}$ is the arithmetic average of the dynamic pressures measured and $<\rho>$ is the cross section averaged density measured. Other effects such as the local momentum transfer coefficients for each phase are also lumped into C. The cross section averaged mass velocity is related to the local mass velocity G by

$$<G> = \frac{1}{A}\int_A GdA$$

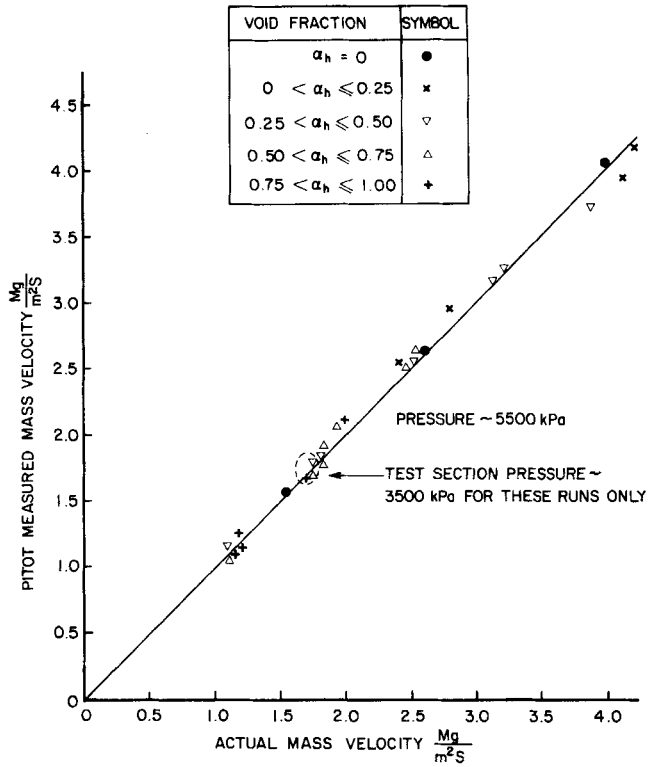

Fig. 3. Actual and Pitot measured mass velocities. The Pitot measured mass velocities were calculated from Equation (1) with C = 0.74.

A set of single-phase water experiments were done, and we found

$$C = 0.74 \qquad (2)$$

This is near the expected value for flow through rough tubes for our placement of Pitot tubes.

The stream-water flow measurements were then interpreted from Equation (1) with $C = 0.74$ to determine whether it was adequate. $\overline{\Delta P}$ was obtained from the Pitot tube measurements and $<\rho>$ from the γ densitometer measurements. The Pitot measured mass velocity calculated in this way is compared with the actual input mass velocity in Figure 3. Most of the experiments were done at a pressure of about 5 500 kPa, with three runs at 3 500 kPa. The higher pressure experiments covered the whole range of mass velocities and void fractions. The lower pressure runs were done at a single intermediate mass velocity but covered a wide range of void fractions.

DISCUSSION

The results shown in Figure 3 indicate that mass velocities calculated from Pitot tube measurements using Equation (1) with C determined from single-phase experiments are adequate to predict the actual mass velocity over the range studied. This conclusion is now being checked in a set of transient calibration experiments to determine whether the steady state calibration is sufficient.

The results presented here are sufficiently encouraging that a more extensive program to develop Pitot tubes for mass velocity measurements has been undertaken. The effect of spool piece diameter, lower mass velocities, and transient steam-water flows on the interpretation of Pitot tube measurements is being investigated.

In parallel, a more fundamental study of Pitot tube response in low pressure air-water flow has been started.

The Pitot tube measurements are being compared directly with averaged water linear velocity measurements made with a hot film anemometer.

ACKNOWLEDGMENT

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NOTATION

A = cross-sectional area of pipe, m^2
C = calibration coefficient, Equation (1)
$\langle G \rangle$ = cross section averaged mass velocity, $kg/(m^2s)$
$\overline{\Delta P}$ = arithmetic average of dynamic pressures measured by Pitot tubes, Pa
$\langle \rho \rangle$ = cross section averaged mixture density, kg/m^3 $\frac{1}{A}\int_A \rho dA$
ρ = local mixture density, kg/m^3

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Comments on Polymerization of Styrene in a Tubular Reactor

SCOTT LYNN

Department of Chemical Engineering
University of California
Berkeley, California 94720

In a recent two-part paper, Wallis et al. (1975*a*, *b*) presented the results of an experimental investigation and a modeling study of the polymerization of styrene in a tubular reactor. From their work they concluded that a tubular reactor is a technically feasible replacement for a stirred-tank reactor for carrying out the first 30 to 40% of the polymerization. In this communication, a simple method is developed for estimating temperature and composition gradients in a tubular polymerizer. For the reasons outlined below, it does not appear that either the experimental work or the mathematical model of Wallis et al. justifies their conclusion.

Kwon (1976) pointed out the nature of the problem in qualitative terms, explaining that the higher residence time of the solution flowing near the wall, and the resulting increase of polymer concentration there, would result in a significant distortion of the velocity profile relative to the parabolic profile assumed by the authors. In his response, Wallis (1976) disagreed that this effect would be significant. Also relying on qualitative arguments, he maintained that the effect of a nonparabolic velocity profile on monomer conversion to polymer is small; that the combination of high shear stress at the wall and molecular diffusion would prevent a buildup of polymer near the wall; that no polymer buildup was observed when their reactor was dismantled; that the agreement between the experimental results and the predictions of the model justifies the assumed velocity profile; and that the duration of the experimental runs assured that steady state operation had been attained. Since this matter is of potential industrial interest, a more quantitative discussion would appear to be worthwhile.

The experimental reactor (Wallis et al., 1975*a*) had an inside diameter of 23.62 mm and a nominal length of 6.10 m. The method of operation was to feed styrene monomer to the reactor for a period of time equal to three average residence times, which varied from 4 309 to 9 569 s. Samples were then taken over a period of 1 800 s, after which the reactor was shut down and flushed with 2.5 times its volume of toluene. The authors did not reveal the reasoning by which three residence times were deemed to assure attainment of steady state operation.

For their mathematical model, Wallis et al. (1975*b*) used two equations of change of importance to this discussion. When x_m is defined as weight fraction monomer and R_p is expressed in terms of weight fraction, they become

$$V_{zo}\frac{\partial x_m}{\partial z} = -R_p + \frac{D}{r}\frac{\partial}{\partial r}\left(r\frac{\partial x_m}{\partial r}\right) \qquad (1)$$

and

$$\rho_o C_p V_{zo}\frac{\partial T}{\partial z} = -\Delta H_r R_p + \frac{k}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) \qquad (2)$$