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MEASUREMENT OF TWO-COMPONENT FLOW USING ULTRASONIC FLOWMETERS (U)

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ABSTRACT

Calibration of transit-time and Doppler ultrasonic flowmeters under two-component flow conditions has been conducted on 400 mm (16-in.) pipe. Testing covered total flows of 0.19 to 1.89 m^3/s (3,000 to 30,000 gpm) and void fractions up to 40%. Both flowmeter types accurately measured total volumetric flow over a portion of their ranges. Pipe average void fraction, based on a three-beam gamma densitometer, was used to determine water component flow under stratified flow conditions, with similar results.

SUMMARY

A series of two-component flow calibrations was performed on nonintrusive, ultrasonic flowmeters mounted on large diameter piping. Thirteen ultrasonic flowmeters were calibrated. Agreement between flowmeter output and total volumetric flow was generally very good, with the following comments: (1) Doppler ultrasonic flowmeters correctly predicted flow over the entire void fraction range tested up to approximately 0.76 m^3/s (12,000 gpm) total volumetric flow. They underpredicted flow when it was above approximately 0.76 m^3/s. (2) The transit-time ultrasonic flowmeters were not expected to provide two-component flow results. However, they performed well at flows up to 0.47 m^3/s (7,500 gpm) when the void fraction was below 20%. (3) Care must be exercised to eliminate "drop outs" from the data of both types of ultrasonic flowmeters.

Comparisons were also made of actual water flow (during two-component tests) to water flow based on the flowmeters and void fraction derived from a three-beam gamma densitometer. Generally good agreement was obtained over the same ranges of flows as for the total flow results.

INTRODUCTION

Simulated loss of coolant accident (LOCA) tests were performed in the SRS L Reactor during the summer of 1989 (Menna and Whitehouse, 1990). The purpose of these tests was to provide hydraulic data from an SRS production reactor for normal and offnormal conditions. These data have been used to benchmark computer codes which will be used to determine reactor power limits. Due to severe limitations on direct access to the flow inside the reactor piping, it was necessary to select nonintrusive instruments for most of the flow measurements. The primary flow measurement instruments used during this test were ultrasonic flowmeters, of the "transit-time" and "Doppler" types. The majority of the flowmeters were placed on 400 mm (16-in.) stainless steel piping in the primary recirculation loops of the reactor.

The ultrasonic flowmeters supplied were originally designed for use in single-component, single-phase fluids, although the manufacturer (Controlotron Corp.) indicated that they were somewhat tolerant of "aeration". Based on manufacturer's information and experience with an earlier version of these meters, the test team decided to use both types of flowmeters in an attempt to measure air/water flows in the reactor piping.

Wyle Laboratories performed calibration testing in their large, high flow test facilities with two-component flow capabilities. Both single-component and two-component calibration tests were performed. However, only results from the two-component tests will be reported here.

TEST FACILITY

Piping Arrangement

The Wyle facility is designed to accommodate long straight test sections of various sizes, up to 30 m (100 ft) in length. The current test program used test sections constructed of 400 mm (16-in.) and 600 mm (24-in.) piping. Auxiliary tanks provide water and gas to the test section, and receive the effluent flow. Figure 1 is a schematic diagram of the piping arrangement used for these tests. Water is driven from the water tank under nearly constant head by air supplied, through a regulating valve, from a large air tank. Valve CV-1, located near the water tank exit, is provided for water flow control. For two-component flow tests, nitrogen gas is injected through a specially designed cross into the 600 mm water pipe. The gas injection cross consisted of two 75 mm (3-in.) pipes, each of which contains 46 6 mm (1/4-in.) diameter holes facing downstream.

During testing, the water or gas/water mixture flows through a pipe reducer into a 30 m (99-ft) length of 400 mm pipe where the SRS flowmeters are located. The fluid then passes through a 400 mm x

600 mm pipe expansion fitting and valve CV-2 before it enters the receiver tank. All test section piping is the same size and wall thickness as that used in L Reactor. In addition, all piping upon which ultrasonic flowmeters are mounted is 304 stainless steel. Two view ports are located near the end of the test section.

INSTRUMENTATION

Flowmeter Instruments

Two types of ultrasonic flowmeters were calibrated, transit-time and Doppler. The operation of the transit-time flowmeter is based on the time-of-flight principle. Two transducers are placed on the outside of the pipe, 180 degrees apart and axially displaced. An ultrasonic signal is alternately transmitted between the transducers so that it travels with and against the flow. Average velocity of the fluid through which the pulses travel is calculated from the difference in time required for the pulses to travel the path between the transducers. Average velocity is then multiplied by the internal pipe area and reported as flow. The transducers are maintained a fixed distance apart by mounting tracks. Due to the large difference in sonic impedance between water and air, the ultrasonic beam is unable to penetrate the gas component. The meter is somewhat tolerant of signal loss caused by gas bubbles. However, interruptions of the signal greater than about one second will cause the meter to drop out and report zero flow.

Six transit-time flowmeters were calibrated. All were mounted so that their beams traveled in a horizontal plane, through the center of the pipe. The range of the flowmeters was 0 to 18 m/s (0 to 60 ft/s), which corresponds to 0 to 2.1 m^3/s in 400 mm pipe (0 to 33,000 gpm in 16-in. pipe).

The second type of ultrasonic flowmeters tested use the Doppler principle of the frequency shift of reflected sound waves off moving objects. Two transducers are placed on the outside of the pipe; one serves as a transmitter, the other as a receiver. Ultrasound is transmitted into the fluid resulting in reflections from moving particles (such as air bubbles) or gas/water interfaces. The receiver signal is analyzed using fast fourier transformation (FFT) techniques to resolve the signal into its frequency components, which are directly related to the velocity of the moving reflectors. The mean value of the resulting spectrum of velocities, corrected for flow profile, is the average velocity. This velocity is multiplied by the internal pipe area and reported as flow.

Seven Doppler flowmeters were calibrated. The transducers for each instrument were mounted in the same axial plane of the pipe at various locations around the circumference of the pipe. Relative transducer location is much less critical for Doppler flowmeters. However, an effort was made to place the transducers on the pipe in the same orientation as used for the L Reactor tests. The range of the Doppler flowmeters was 0 to 12 m/s (0 to 40 ft/s), which corresponds to 0 to 1.4 m^3/s in 400 mm pipe (0 to 22,000 gpm in 16-in. pipe).

Facility Instruments

Instrumentation was provided for the measurement of fluid pressure, differential pressure, fluid temperature, water flow, gas flow, and control valve position.

Average water flow was based on the time required for the level in the water tank to drop between two level sensors (Figure 1). The volume between the two sensors was calibrated before the tests. The time taken for the level to drop through the calibrated volume ranged from 10 to 130 s, depending on water flow required, and was measured to within ± 0.03 s. To ensure that the flow is constant during the calibration interval (i.e. when the water level is between the level sensors), a differential pressure instrument was added. The maximum uncertainty for water flow is ± 0.34% or ± 0.006 m^3/s (± 100 gpm).

Gas (nitrogen) flow is determined by measuring the pressure and temperature of compressed gas upstream of a group of five sonic nozzles (Figure 2). These nozzles, of various sizes, were calibrated before the tests to determine their discharge coefficients. Any one of the nozzles, or a combination of up to five, is selected for a given flow. The upstream pressure is adjusted so that the nozzle(s) will operate in a choked flow regime. Upstream pressures are selected so that the pressure drop across the nozzle(s) is adequate to ensure choked flow. The maximum uncertainty for gas flow is ± 0.85% or ± 0.003 m^3/s (± 44 gpm).

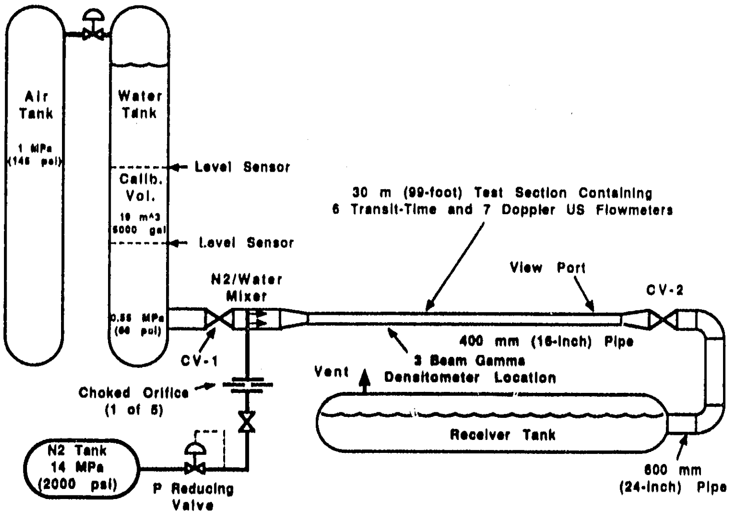

Figure 1. Nitrogen - Water Flow Calibration Loop at Wyle Laboratory (Norco, CA)

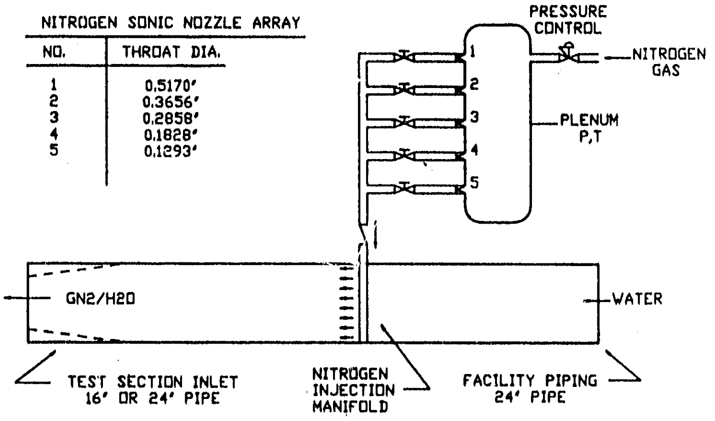

Figure 2. Gas Flow Nozzles and Injection System

One three-beam gamma densitometer was used for each of the test series. The units used were designed and fabricated by the Idaho National Engineering Laboratory (INEL), and were the same units used during the L Reactor tests. Their principle of operation is covered in detail elsewhere (Meyer and Averill, 1990).

Additional data acquired during testing included video images of the flow made through ports near the end of the test section.

Data Acquisition and Reduction

Data were acquired by an HP-9000 at 30 samples per second. The raw data file for each test was written to a write once read many (WORM) optical disk, then taken to INEL and SRS for post-test processing. At SRS a data extraction and reduction program was used to extract a minimum of 100 data points from each test for the time interval that the water level took to pass through the calibrated volume. The program averaged the data and reported the mean, minimum, maximum, and standard deviation of the data. Data for each flowmeter was collated for all the appropriate tests of a given void fraction range and plotted.

Test Matrix

The test matrix covered 0.19 to 1.89 m^3/s (3,000 to 30,000 gpm) total volumetric flow and 0% to 40% void fraction. Thirty-five test matrix points were planned. A test acceptance criteria of ± 0.06 m^3/s (± 1,000 gpm) and ± 2% void was set. To meet this requirement, it was sometimes necessary to repeat tests two or three times. As a result, over 60 tests were performed which covered all of the original conditions plus many intermediate combinations of flow and void fraction.

TEST RESULTS

Data from 40 two-component flow tests were extracted and averaged in the manner just described. Flow ranged from 0.167 to 2.136 m^3/s (2,641 to 33,858 gpm) total volumetric flow. Void fractions (calculated as the ratio of gas flow to total flow) ranged from 1.3 to 37.8%. Average flow values for the flowmeters are plotted versus total average volumetric flow (sum of gas and water flow). Different symbols are used for ranges of void fraction to identify any flowmeter dependence on this parameter. Uncertainty estimates of ± 0.06 m^3/s (± 1,000 gpm) are plotted with the results from each flowmeter.

The plots presented compare the performance of the flowmeters to the actual time-averaged total volumetric flow, based on measurement of injected gas and water flow. Since the ultrasonic flowmeters are velocity measuring devices, this implies that they must accurately measure, and spatially average, the velocity field of the two-component mixture to obtain good agreement with total volumetric flow. Alternately, they can obtain the correct total volumetric flow if they measure the correct velocity of one of the components (water in this case) and the two-components are moving at nearly the same average velocity (slip ratio = 1). Both ultrasonic flowmeter types correct the reported flow based on an assumed flow profile (fully developed turbulent flow) which the meter calculates. Flow rates of the individual components, gas and water, can be obtained from the total volumetric flow if the void fraction is known. This topic is discussed later.

The transit-time flowmeters were not expected to provide two-component flow information. However, as shown in Figures 3 (one meter, typical of all meters tested) and 4 (all meters), the meters did an excellent job at flows below about 0.47 m^3/s (7,500 gpm) and void fractions below 20%. The points plotted on the x-axis represent drop out, where the meter did not function properly, usually reporting zero flow for all, or a significant portion of, the calibration interval. The tolerance of the meter to void fraction decreased with increasing flow. This was particularly evident in data from other tests conducted at 1.1 m^3/s (18,000 gpm) where the void fraction was decreased to 2.5% and 1.3% (not plotted). At these conditions, none of the transit-time flowmeters operated correctly. The results can be explained by considering the flow regimes which probably occurred over this range of conditions, as follows. The transit-time flowmeters cannot operate if the ultrasonic beam is interrupted by air for a significant time (on the order of 1 second). However, the flowmeters were located on the pipe such that their beams bisected the middle of the pipe horizontally. Under stratified flow conditions (in the range of void fractions tested) most of the air will be above the beam path, allowing the flowmeter to operate. Under dispersed or bubbly flow conditions, more air will be present in the beam path, potentially causing the flowmeter to drop out or fault. Under fault conditions the meter will report zero flow. Visual observations confirmed stratified flow for those tests where the transit-time meters correctly reported flow.

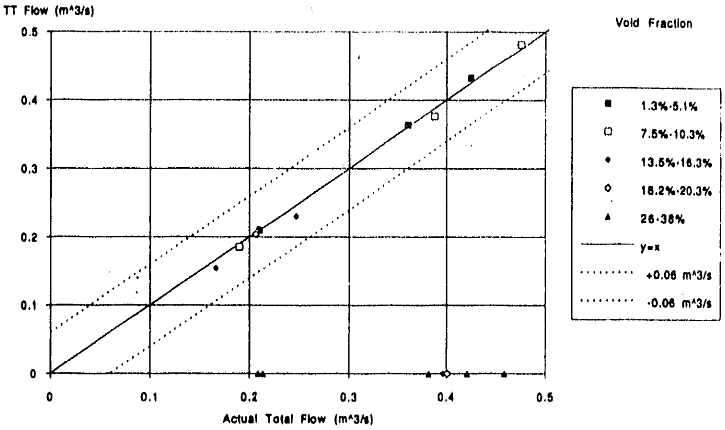

Figure 3. Ultrasonic Transit-Time 110 (avg) vs Total Volumetric Flow

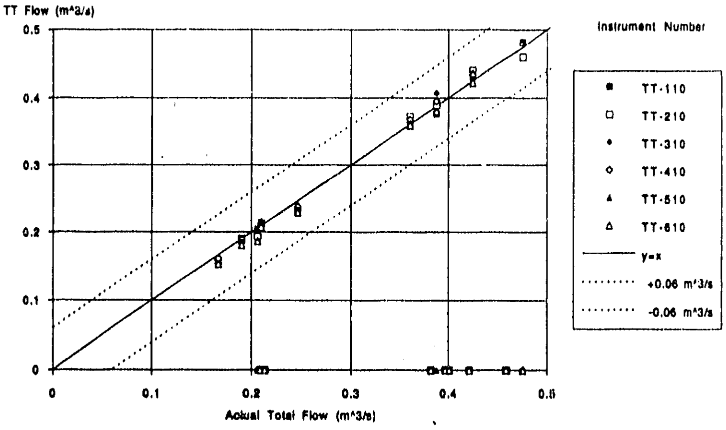

Figure 4. All Ultrasonic Transit-Times vs Total Volumetric Flow

The Doppler flowmeters were designated to cover a range of 0 to 12 m/s, which corresponds to a volumetric flow of 0 to 1.4 m^3/s. In practice, their upper range was limited to about 1.1 m^3/s (18,000 gpm) or less. This limitation was due to the nature of the two-component flow and the averaging technique used. At high flows the upper portion of the measured velocity spectra exceeded the upper limit of the flowmeter. In this case, the computed average was lower than the true value because velocity samples greater than 12 m/s were not included. As a result, the flowmeter underpredicted flow when the mean flow was greater than approximately 0.76 m^3/s (12,000 gpm). This is clearly shown in Figures 5 (one meter) and 6 (all meters). The amount of underprediction is a function of void fraction. Below 0.76 m^3/s the agreement is excellent, and nearly independent of void fraction. This applies to all the Doppler flowmeters, even though they were mounted differently, and located at different positions along the pipe.

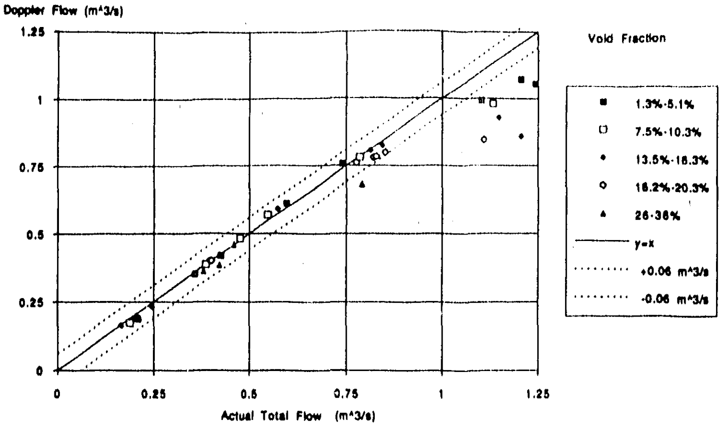

Figure 5. Ultrasonic Doppler 660 (avg) vs Total Volumetric Flow

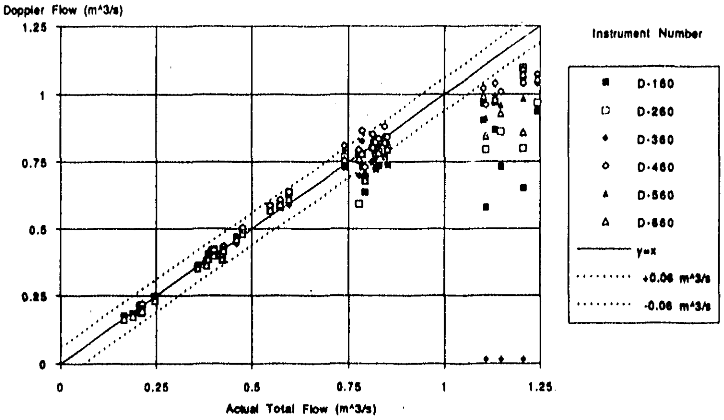

Figure 6. All Ultrasonic Dopplers vs Total Volumetric Flow

DATA ANALYSIS

Test results were presented which compared the output of the flowmeters to total volumetric flow. Generally, good agreement was obtained, at least up to a well-defined flow limit. If the void fraction at the flowmeter is known, the liquid and gas flows can be calculated from the total volumetric flow, using the equations:

$$Q_w = (1 - \alpha)\, Q_{tot} \qquad (1)$$

$$Q_g = \alpha\, Q_{tot} \qquad (2)$$

where the flows (Q) are in m^3/s and α is void fraction. If Q_{tot} is the output of the flowmeter, then:

$$Q_{tot} = Q_{US} = v_m\, A_{pipe} \qquad (3)$$

Where v_m is the measured fluid velocity, in m/s corrected for an assumed flow profile (based on Reynolds number), as computed by the flowmeter. A_{pipe} is the internal cross-sectional area of the pipe, 0.114 m^2 (1.227 ft^2) for 16-in. schedule 40 pipe. Assuming that v_m accurately represents the average fluid velocity of the water component and that the components are moving at nearly equal velocities, equations 1 and 2 can be used to arrive at the individual component flows if α (at the flowmeter) is known.

The value of void fraction to be used in equations 1 and 2 can be arrived at in several ways. The simplest is to use the void fraction calculated from the injected gas and water flows, α_{inj}. However, this quantity would not typically be known in an experimental situation.

An alternative approach is to use the void fraction based on an analysis of the gamma densitometer beams. Each beam provides a chordal average density, which can be converted into a chordal average void fraction. By comparing these void fractions, a determination of flow regime can be made, at least in principle. If the three beams yield equal void fractions, the flow at the gamma densitometer is homogeneous. If the top beam has a higher void fraction than the middle and lower beams the flow is probably stratified. Variation of the chordal densities with time can be used to identify flow regimes such as wavy stratified and slug flow. Since the data used for the present analysis are time averaged, only the stratified and homogeneous flow regimes were identified. A simple geometrical model for stratified flow was developed. Void fraction, determined from the gamma densitometer and the stratified model (α_{strat}), is used in the plots which follow to calculate water flow from flowmeter output for two-component flow.

The analysis performed is based on the following assumptions: (1) flow regimes are homogeneous or stratified, (2) the stratified model used assumes complete separation of phases, (3) temporal variations in flow structure have been averaged out, and (4) the effects of changes in flow profile have been ignored.

Water Flow Calculation Results

Water flow, based on transit-time flowmeter output, was calculated from equation 1 using stratified model void fractions. Results are presented in Figure 7 for a typical transit-time flowmeter and in Figure 8 for a Doppler flowmeter. The agreement with actual water flow is similar to that achieved in comparisons to total volumetric flow (Figures 3 and 5). Problems with the Doppler at flows above 0.76 m^3/s (12,000 gpm) are still evident as are other data trends noted before.

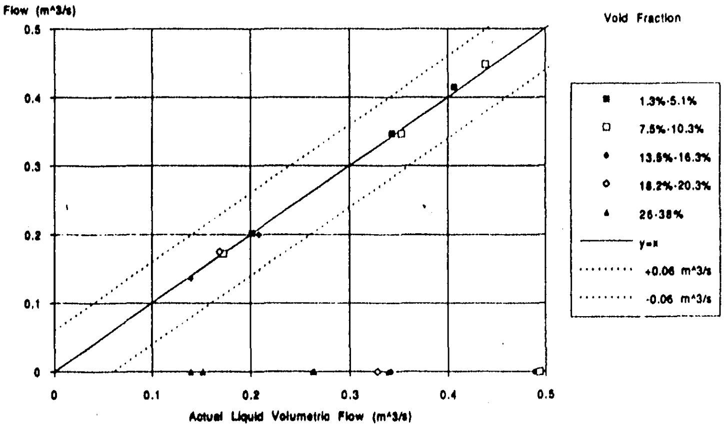

Figure 7. Transit-Time 110 * (1 - Strat. VF) vs Actual Water Flow

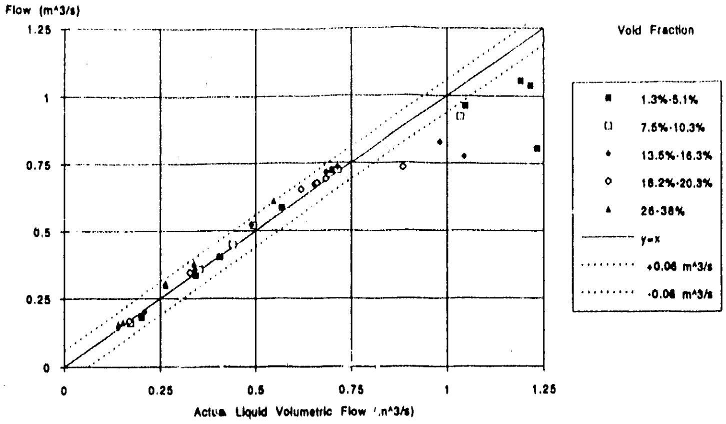

Figure 8. Doppler 660 * (1 - Strat. VF) vs Actual Water Flow

CONCLUSIONS

Ultrasonic flowmeters have been successfully calibrated over a range of two–component flows. Transit–time flowmeters provided accurate flow indication up to 0.47 m^3/s total volumetric flow for void fractions less than 20%. Doppler flowmeters accurately measured total flows up to 0.76 m^3/s for all void fractions tested (up to 40%). A simple flow stratification model, based on analysis of a three–beam gamma densitometer, allowed calculation of individual component flows. Good agreement was obtained for each flowmeter type when actual water flow was compared to measured flow over the same ranges just stated.

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