DEVELOPMENT OF A NOVEL NON-INTRUSIVE, ULTRASONIC FLOW METER FOR WET GAS PIPELINES

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ABSTRACT

A novel ultrasonic flow metering system been developed that has the capability of measuring liquid film thicknesses of the order of 0.1 mm and mist contents in gas flow of 4-5%. The principle of this nonintrusive technique is based on recording the transit time and attenuation of ultrasonic signals in both axial and radial directions using sets of upto eight transducers flush-mounted on the outside pipe wall at intervals around the pipe circumference and at two locations along the pipeline. The data from the meter is then used in existing multiphase flow models developed at the Corrosion in Multiphase Systems Center, to predict the quality of the gas and flow rate of the individual phases as a function of time.

INTRODUCTION

In the oil and gas industry, different flow regimes and patterns exist in horizontal multiphase pipelines at different gas and liquid velocities which include, stratified, slug, and annular flows. The flow characteristics are fundamentally different from one flow regime to the next. The flow is rarely homogeneous and the components can be distributed in any number of ways depending on the pipe diameter, inclination, and the relative proportions of the components and their velocities (Gold et al, 1991). It is therefore extremely important to measure both phase distribution and velocity profile of each phase as a function of position and time. The raw data then needs to be incorporated into physical multiphase flow models that can calculate the flow rate of the different phases to yield the macroscpic flow rate.

Many multiphase flow models fall under two categories, homogenous and non-homogeneous. Homogeneous models are applicable when one phase is present in such abundance relative to the other phases that slip between the different phases is negligible and can be neglected. For the flow regimes most relevant to this project, stratified, annular, and mist flows, a homogeneous flow model can be used only for the mist flow conditions. For both stratified and annular flows, non-homogeneous models that account for both, the variations of phase distribution and the local phase velocity, need to be used. Such models have already been developed at the Corrosion in Multiphase Systems Center.

A three phase oil/water/gas stratified flow model has already been developed (Neogi et al., 1994) which accurately predicts the phase distrbution and the velocity of the individual phases for a wide variety of input flow rates and for different fluids. A model has also been developed for the prediction of annular flow characteristics (Laurinet et al., 1985) for horizontal flow. From the above models, given the local velocities and phase distributions, it is possible to predict the liquid and gas flow rates.

Acoustic flow meters based on ultrasonics have been proposed and used for a wide variety of flows in the last ten years (Riezenman, 1989). Ultrasonic flow meters have a turndown ratio greater than 1000:1. They are nonintrusive, require little initial and maintanance costs and have been developed to yield accurate flow rate information. They are also being considered for gas transmission lines (Anon, 1990, Rogi, 1994, Thomas, 1994). Ultrasonic flow meters installed in one gas line yielded flow rates accurate to 0.5% compared to turbine flow meters (Anon., 1994).

Ultrasonic measurements have been used for safe, non-intrusive measurements in multiphase flows (Sidney et al, 1987). Cross-correlation coefficients of phase and amplitude modulations of ultrasonic signals in air/water pipes were used to determine the velocity in dispersed bubble flow. Results with accuracy within 10% were obtained. However, the results were only preliminary and further experiments were recommended. Ultrasonic measurements have been proven in oil/water measurements in the offshore separation platforms (Controlotron, 1995). By precisely matching the transducer dimensions with the pipe wall and material, a wide aperture for signal reception could be created. This resulted in highly enhanced sensitivity of the technique and density changes and aeration levels could be recorded. However, the technique has been used only for full pipe liquid flow and has not been tested in oil/water/gas flows. Morriss and Hill (1990) recently have used pulsed Doppler velocimetry to study vertical oil/water flows in oil pipelines. They determined that more theoretical and experimental work was needed. The transmission and/or reflection characteristics of ultrasonic signals can also be used to obtain a detailed picture of the flowing mixture. The theory underlying these mechanisms were recently outlined (Williams and Beck, 1995).

It is seen that instantaneous multiphase flow measurement is a challenging task. Existing instruments do not have the capability to measure the holdup or velocity of the individual phases in the complex multiphase flow regimes. New techniques are therefore required to accomplish this. Such a novel flow measurement system is described in this paper.

ULTRASONIC METHODS

The ultrasonic techniques used in this flow meter are, the measurement of time-of-flight (transit time) of the signal, and, attenuation and reflection of signal amplitude.

For time-of-flight measurements, a pair of transducers at two points, separated by a known distance, is used. A pulse of ultrasonic signal is generated and received simultaneously from and at both points, and the time interval for the signal to travel in both upstream and downstream directions (t_1 and t_2) are noted (Ensminger, 1988).

Also, as the signal propagates through a medium, its amplitude decreases or attenuates (Kleppe, 1989). This is related to the absorption coefficient, and to the material properties of the medium.

When an ultrasonic wave encounters an interface between two media, the wave energy is partitioned in a manner that is controlled by the acoustic properties of the media. A plane logitudinal wave travelling from one medium into a second medium of normal incidence is partially reflected. The ratios of the incident sound pressure to the transmitted and reflected sound pressures are then related to the material properties of the two mdeia (Shutilov, 1988).

EXPERIMENTAL SETUP

The development of this novel flow metering system is carried out in a 10 cm diameter, 15 m long, horizontal, Plexiglass test flow facility shown in Fig. 1. A predetermined mixture of oil and water is placed in a 1.5 m^3 stainless steel tank (A) and is pumped by a 15 kW stainless steel pump (N). The liquid is pumped into a 7.5 cm diameter, 15 m long PVC pipe (E), where the liquid flow rate is measured using an office plate (F). The liquid flow rate is controlled by means of a bypass system and ball valves (C, D). Carbon dioxide gas is introduced into the system from a high pressure, 25000 kg storage facility (O) and mixed with the incoming oil/water liquid mixture. The gas flow rate is measured using variable area gas flow meters (P). The multiphase mixture then flows through the 10 cm diameter Plexiglass pipe, where all the measurements are made using a specially designed test section. The oil/water/gas mixture then flows into an inexpensive, in-line flow separator (J), where the gas is separated and the liquid flow rate is measured once again. The liquid then discharges into the storage tank (A) and is recirculated. The liquid storage tank is equipped with two induction coil heaters connected to a thermostat that is used to maintain a constant system temperature. A back-pressure regulator connected to a ball valve is used to maintain a constant system pressure.

A schematic of the test section with the existing instrumentation is shown in Fig. 2. This test section is used for extensive corrosion and multiphase flow monitoring in projects currently undergoing at the Center. Corrosion measurements are made at C and E. ST is a tube for extracting an isokinetic sample of the oil/water/gas mixture at different positions across the vertical diameter. From the sample, the local void fraction and/or oil/water compositions are determined. Pressure drop measurments are made using the pressure tappings P with Omega PX820 differential pressure transducers, and PX510 single point pressure transducers. At position S, a TSI hot film shear stress probe can be inserted for measurement of wall shear stress and turbulent levels at the top and bottom of the pipe. The sampling probe and the pressure transducers are utilized to obtain additional data concerning the multiphase flow characteristics to refine the mathematical models to be used for the flow meter.

The ultrasonic instrumentation system is added to the existing test section as shown in Fig. 3. Two sets of upto 8 ultrasonic transducers, spaced at regular intervals around the pipe cross section, are used. The two sets are separated by a certain distance for flow velocity measurements. The transducers are mounted flush with the pipe wall. They are positioned in pairs, both across the cross section and the length of the pipeline, so that they can be used in 8 transmitter-receiver arrangements or 16 single transmitter-receiver modes. The transducers are clamped on to the outside of the pipe wall using specially configured wedges, so that the whole instrument remains nonintrusive.

Finally, an existing flow visualization system, shown in Fig. 4, is used to obtain a detailed visual knowledge of the flow characterisitcs in the various multiphase flow regimes being investigated. This is used to obtain corroborating data to verify the results from the ultrasonic measurement system.

An inexpensive, inline separator is used to separate the phases at the end of the test section, where the volumetric flow rates are determined once more. This acts as a check for the ultrasonic flow measurements.

EXPERIMENTAL PROCEDURE

The oil used is similar to that found in gas condensate systems with a density of 800 kg/m^3 and a viscosity 2 cp at 40 C. The gas used is carbon dioxide. The pressure is 0.13 MPa (5 psig) for feasibility studies. Experiments are carried out at two different system temperatures, 25 C and 40 C. Experiments involving oil/water mixtures are conducted at two different input oil percentages of 20% and 60%.

No Flow Experiments

Experiments are initially conducted under no flow conditions, using oil only, gas only, water only, gas/oil, gas/water and gas/oil/water mixtures. In gas/liquid and gas/oil/water experiments, two levels of liquid in the pipe are studied. These experiments yield a detailed understanding of the range of frequencies and amplitudes of required ultrasonic signals and best configurations of the transducers for multiphase flow systems.

Single Phase Flow

Next, to obtain a calibration of the results from the ultrasonic measurements under flowing conditions, tests are conducted in single phase flow, involving gas only, water only, and oil only, respectively. The range of velocities for gas flow are 1, 5, and 20 m/s and for both oil and water are 0.5, 1.0, and 1.5 m/s. The highest velocity corresponds to 300,000 m^3/day.

Oil/Water Flows

Once the single phase flows have been thoroughly investigated, two phase oil/water flow tests are conducted. For the same total liquid velocities of 0.1, 0.5, and 1.0 m/s, experiments are carried out at two different input oil concentrations, 20% and 60%. Again, the ultrasound probes are tested in different orientations to determine the best configuration.

Two Phase Gas-Liquid and Three Phase Oil/Water/Gas Flow

After a detailed understanding of ultrasonic measurments of single phase and two phase oil/water flows has been obtained, the test matrix are extended to two phase water/gas and oil/gas flows and three phase oil/water/gas flow. In order to obtain stratified and annular/mist flows, the liquid velocities are kept below 0.05 m/s in the 10 cm diameter pipe. Starting from 0.05 m/s, the total liquid velocities in all cases (two phase gas/liquid and three phase gas/oil/water flow) are first reduced to 0.01 m/s. Subsequently, the total liquid velocity are reduced by an order of magnitude to 0.001, 1×10^{-4} m/s and so on, until the limit of ultrasound detection resolution is reached. Again, for three phase oil/water/gas flows, oil percentages of 20% and 60% in the liquid are investigated.

RESULTS

The results indicate that for homogeneous flows, such as mist flow, the transmission characteristics from bottom, top, and center positions are the same, as illustrated in Fig. 5. From the attenuation of the amplitude, the homogeneous mixture density is determined. The average velocity will be found from transit time measurements.

For stratified flows, the transmission/reflection characteristics are different from top and bottom of the pipe. Combining with the measurements of attenuation from the center position yield a height of the liquid film. In this case, the velocity is obtained from combinations of transducers (upstream and downstream) within the same medium.

The same principles as stratified flow are applied to annular flows. In this case, it is seen that more transducers are required around the pipe circumference due to the distribution of the liquid around the pipe.

In each case, once the phase distribution (or holdup) has been determined along with the average phase velocity, the volumetric flow rates are calculated using multiphase flow models.

The preliminary results using this novel ultrasonic technique show good agreement with experimental results determined using single phase flow measurements and data collected from the separator. The technique shows great promise as a unique multiphase flow measurement device and further experiments are continuing.

CONCLUSIONS

A novel ultrasonic multiphase flow metering technology is described that can measure both holdup and average phase velocity in stratified, annular, and mist flows. The device is nonintrusive, inexpensive, and can be used for any pipe diameter.

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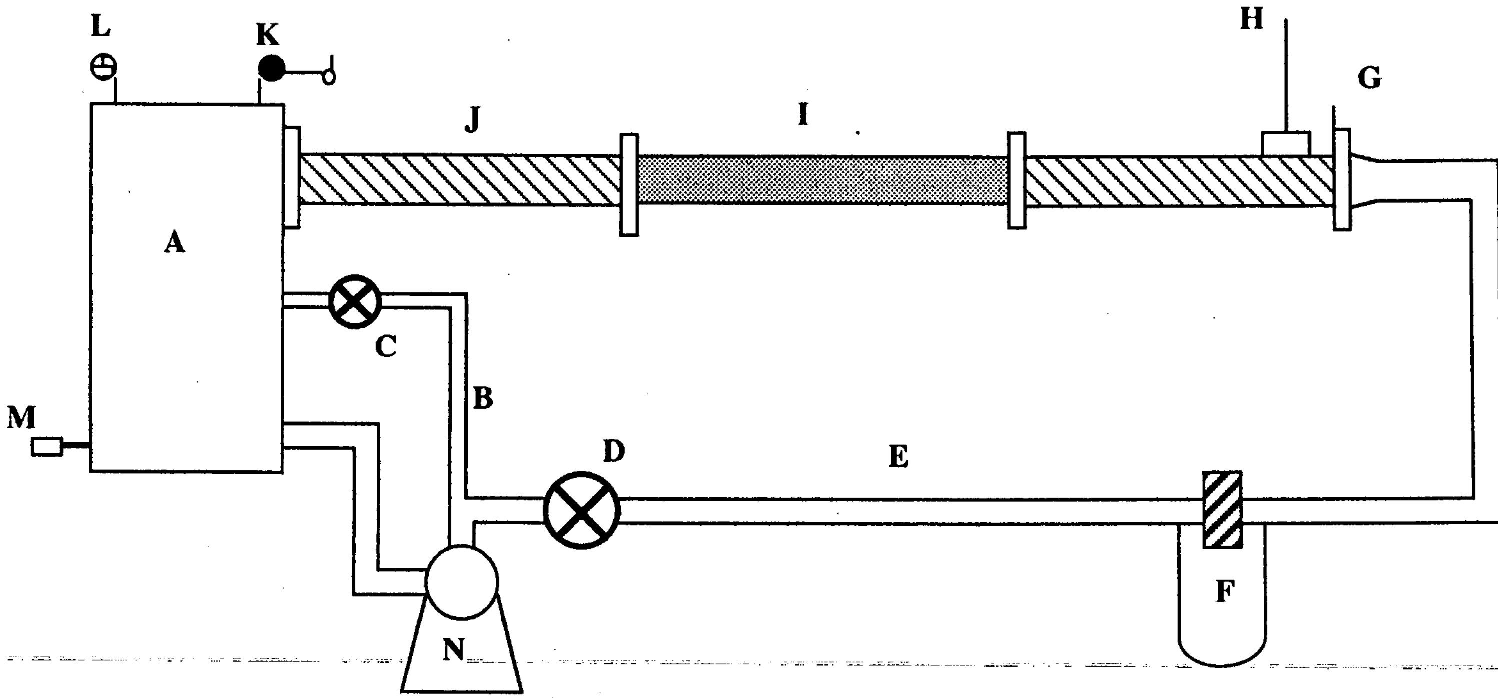

A. Liquid Tank
B. Liquid Recycle
C. Valve on Liquid Recycle
D. Valve on Liquid Feed
E. Liquid Feed- 7.5 cm PVC Pipe
F. Orifice plate, to pressure transducer
G. Flow Height Control Gate

H. Carbon dioxide Feed Line
I. Test Section- 10 cm Plexiglass pipe
J. 10 cm Plexiglass Section
K. Pressure Gauges & Back Pressure Regulator
L. Safety valve
M. Heater
N. Pump

Figure 1: Layout of The Experimental System

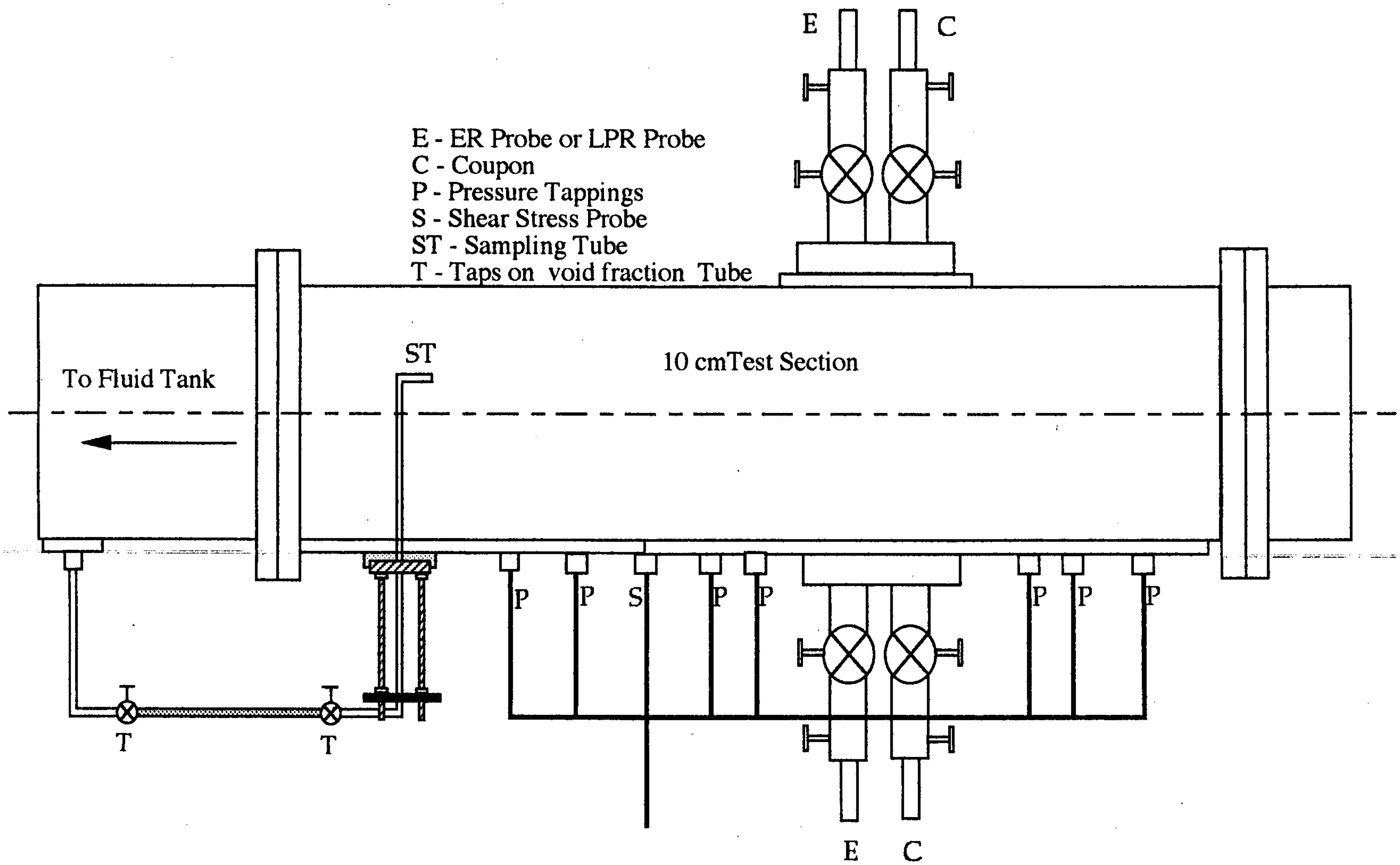

Figure 2: Test section

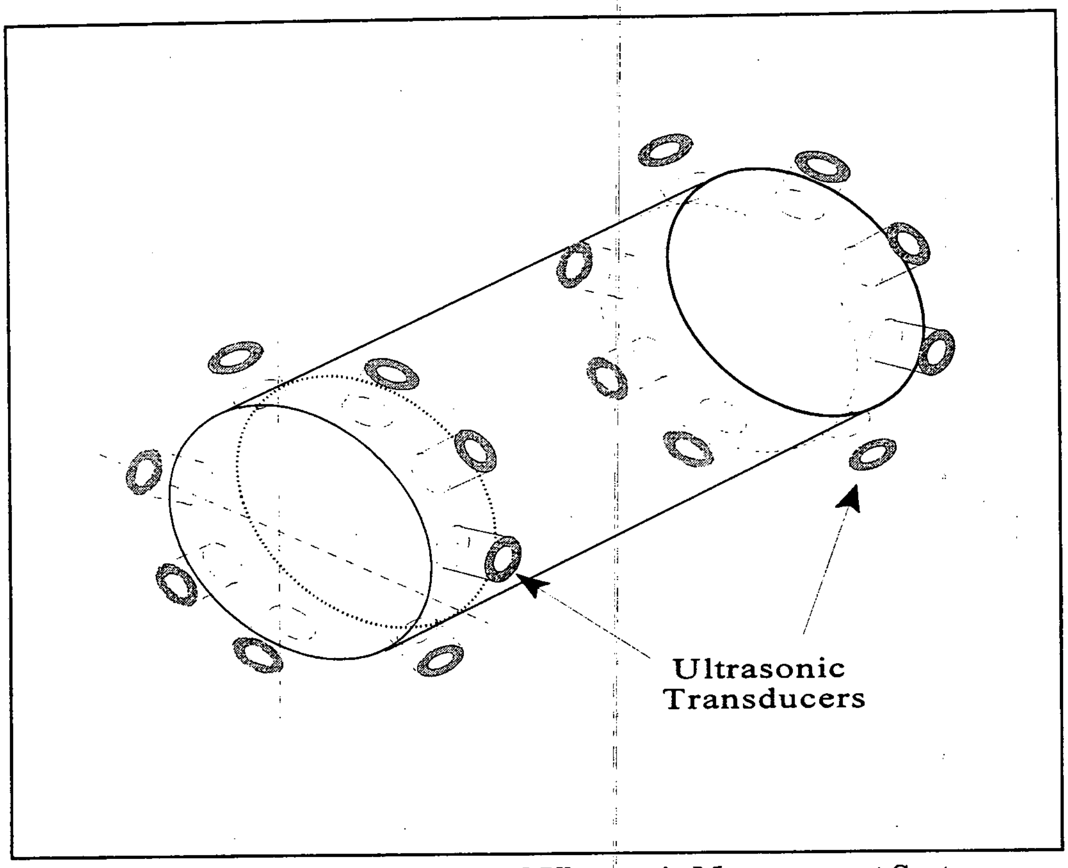

Figure 3: Schematic of Proposed Ultrasonic Measurement System

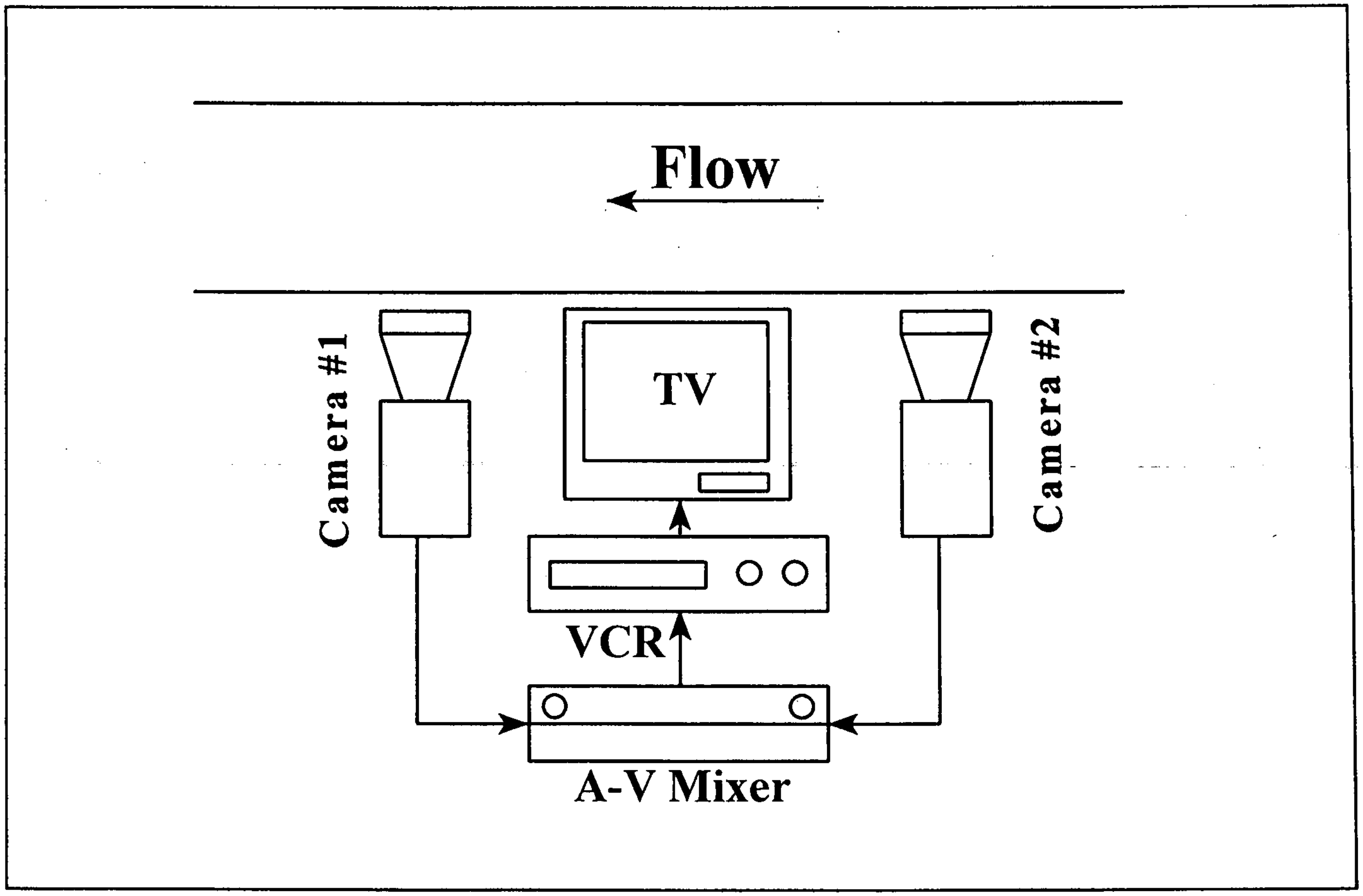

Figure 4: Schematic of Flow Visualization System

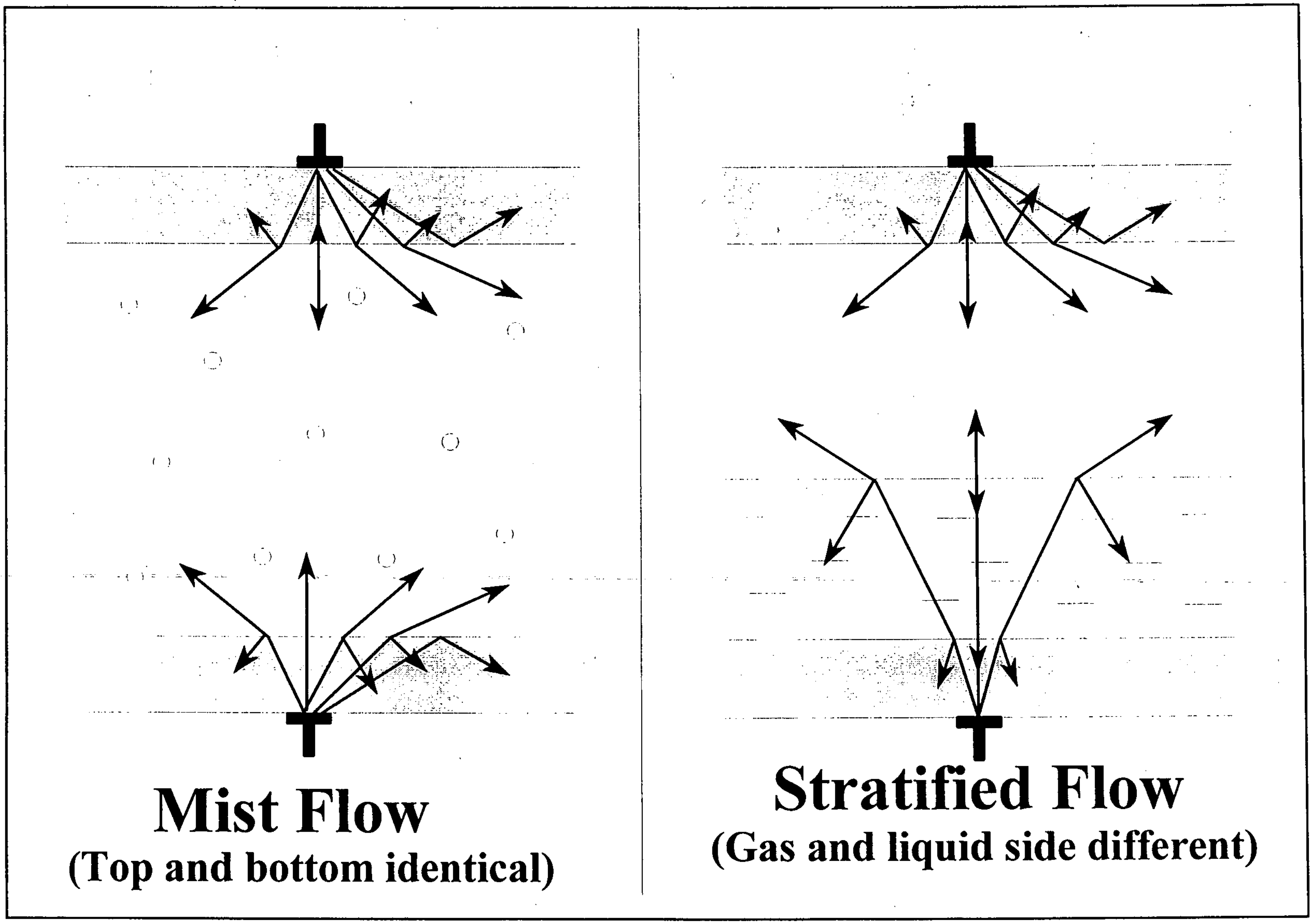

Figure 5: Ultrasonic signal response in different flow regimes