FLOW MEASUREMENT

An In-Situ Volume Fraction Sensor for Two-Phase Flows of Non-Electrolytes

G. A. GREGORY and L. MATTAR,
Department of Chemical Engineering,
The University of Calgary,
Calgary, Alberta

ABSTRACT

This paper provides a brief survey of methods which have been used to measure the in-situ volume fractions of two-phase mixtures flowing in pipes. A description is given of the development of an inexpensive device based on capacitance sensing which makes use of off-the-shelf electronics to yield a continuous monitoring of the in-situ volume fractions of flowing two-phase mixtures of non-electrolytes. The details of construction for the sensors are given and possible applications are suggested.

INTRODUCTION

The in-situ gas (or liquid) volume fraction is a major parameter of interest in the study of the cocurrent pipe flow of two-phase mixtures. Because the two phases do not generally flow at the same velocity, the in-situ volume fractions will almost invariably be different from those at the inlet of the pipe. In any case, the inlet conditions are often not known and a correlation based on inlet values has little consequence. Consequently, much effort has been devoted to the measurement of the phase volume fractions in the flowing system.

The earliest measurement technique used in laboratory or pilot studies involves the use of quick-closing valves. These may be either mechanically or electrically activated (e.g., see Govier and Omer, 1962). Two valves are located a known distance apart on the test section. Under steady flow conditions the valves are simultaneously closed, trapping a mixture of gas and liquid between them. The liquid is then drained from the trapping section, its volume recorded and the average in-situ liquid volume fraction is calculated knowing the total pipe volume between the valves. The advantages of this method are principally its simplicity and low cost, but there are some important and obvious disadvantages. It is time consuming to drain and measure the liquid for each determination, particularly for liquids of moderate to high viscosity which tend to cling to the pipe walls. Furthermore, this method is not suited for use with systems operated at elevated temperatures or pressures, or for single-component two-phase systems where the pressure change resulting from draining the liquid may have a significant effect on the phase behaviour of the material. To minimize equipment damage from the sudden flow stoppage, a test-section bypass is usually required. One is also limited to determining average volume fractions over a length of test section and hence detailed information related to the transient nature of various flow patterns is unattainable. Finally, unless it is possible to use plug-type valves with the flow passage exactly conforming to the inside diameter of the pipe, flow pattern disruptions occur at both ends of this test section and a sufficient length must be provided to minimize these end effects.

A number of methods which provide volume fraction measurements over a very short length of pipe have been successfully employed. These include the use of photographic and optical techniques (Hau et al., 1969; Miller and Mitchie, 1969), X-, beta- and gamma-ray attenuation devices (Srock, 1969), hot film anemometry (Delhaye, 1969), and various other physical (Schraub, 1969) and electrical probes for conductance and capacitance measurement (Bergles, 1969).

In general, these methods avoid many of the limitations of the quick-closing valves. Most provide a continuous monitoring of the in-situ volume fractions, often with no inherent disruption to the flow. In addition, most of the devices result in a measurement which is averaged over a very much shorter length of pipe than that required by the quick-closing valves for reproducibility. In general, a substantially greater capital investment is required, however, and the special characteristics of individual devices may preclude their use in given systems.

For example, the radiation attenuation devices require proper safety shielding, operating techniques, government licensing and inspection, etc., to protect both the operators and adjacent equipment. In some cases, radio-opaque tracer compound may have to be added to one of the phases to obtain a measurable reading. Also, unless a very wide beam, and hence very powerful source, or else a small-diameter pipe is used, some sort of traversing mechanism must be provided to obtain meaningful results on flow patterns which are not symmetrically distributed in the pipe.
Optical and photographic methods often give results that are difficult to interpret. Furthermore, they cannot be used with opaque pipe or opaque fluids, and photographic techniques may introduce a substantial time-lag into the availability of the data.

Capacitance measuring systems will not work with electrically conducting fluids, at least not where the conducting fluid forms a continuous phase. On the other hand, conductivity methods must have an electrolyte or similarly conducting medium in order to function.

Refractive index and hot film anemometry methods yield a local point value of the in-situ volume fraction. This may be useful for the study of radial variations in a given flow pattern, but, as with the radiation attenuation methods, a traversing mechanism must be provided to produce an average cross-sectional value.

CAPACITANCE METHOD

In many of the two-phase flows encountered in the petroleum, petrochemical and gas processing industries, the fluids involved are either both non-electrolytes or one phase is a weak electrolyte (water) present as a discontinuous phase in a continuous non-electrolyte medium. In these situations, capacitance-type measurement of the flowing-phase volume fractions can be considered. With a suitable sensing device the procedure is straightforward, power consumption is very low, there are no unusual safety hazards and there are numerous “off-the-shelf” instruments available for the continuous monitoring of capacitance.

The capacitance of a parallel-plate condenser is known to vary linearly with the dielectric constant of the medium between the plates, following a relationship of the form

$$C = \varepsilon_0 K a$$  \hspace{1cm} (1)

where

- $C$ = capacitance of the condenser in appropriate units (i.e., farads, microfarads, picofarads)
- $K$ = dielectric constant for the medium between the plates
- $a$ = proportionality constant determined by the geometry of the device

The effective dielectric constant for a compound medium, formed say by sandwiching layers of different materials together, is known to be the linearly weighted average of the dielectric constants of the pure components. Thus, for the case of a two-phase mixture occupying the space between the plates, such that the entire cross section of the space occupied by the two-phase mixture is “seen” by the plates, we can write

$$K_a = K_{Li} + (1 - \varepsilon) K_{Pa}$$  \hspace{1cm} (2)

where

- $K_a$ = effective dielectric constant of the two-phase mixture
- $K_{Li}$, $K_{Pa}$ = dielectric constants of the pure liquid and pure gas respectively (note: The term “gas” is used for convenience; in fact, both phases could be liquids)
- $\varepsilon$ = in-situ volume fraction of the liquid phase

This relationship may be rearranged to give

$$K_a = (K_{Li} - K_{Pa}) \varepsilon + K_{Pa}$$  \hspace{1cm} (3)

where

$$\varepsilon = \frac{(K_{Li} - K_{Pa})}{K_{Pa}}$$ and is constant at a given temperature

Then

$$C = \frac{\varepsilon K_a}{\varepsilon_0}$$  \hspace{1cm} (4)

I.e., the capacitance is a linear function of the in-situ volume fraction of the liquid phase.

The above argument is strictly true only for a simple parallel-plate capacitor. The objective of the present study was to develop a simple device which would behave in a pipe geometry as a parallel-plate capacitor and hence retain the linear relationship between the measured capacitance and the desired quantity, $\varepsilon$.

The basic requirements of the sensing device are that:

(a) it provides volume fraction measurements averaged over a relatively short length of pipe (maximum of 5 to 10 pipe diameters);
(b) it creates no disturbance to the flow field;
(c) it gives reliable volume fraction measurements for any of the possible flow patterns (i.e., stratified, slug, annular, etc.);
(d) it must be relatively cheap to construct, as it is desirable to install a number of them in a test length to observe downstream changes.

EXPERIMENTAL WORK

In order to meet the requirements for the sensing device listed above, it was found necessary to examine a variety of configurations for the two-capacitor plates. These included:

(i) a pair of parallel plates mounted on the outside pipe wall;
(ii) a pair of concave plates mounted on the outside pipe wall;
(iii) a series of pairs of concave plates staggered spirally around the outside pipe wall;
(iv) a pair of continuous helices mounted on the outside wall; and
(v) three pairs of continuous helices mounted on the outside pipe wall and connected alternately in parallel.

These configurations are shown schematically in Figure 1.

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**FIGURE 1 — Trial Configurations for Capacitor Plates.**
Of all the above, only the continuous helix pair, (iv), was found to give consistent results, regardless of the flow pattern.

A typical sensor as finally constructed is shown schematically in Figure 2. A short section of acrylic pipe, identical to that used in the test section, forms the basis of the sensor. The plates of the capacitor, constructed from brass shimstock, were wound helically around the outside of the pipe section and cemented in place. A section of larger-diameter acrylic pipe covered with a layer of brass shimstock and cemented into the end flanges coaxially with the sensor section was found to be necessary to shield the capacitor plates from unwanted interference. Spring-loaded coaxial cable connectors were screwed into threaded ports in the shield section in such a way that the center wire of the coaxial cable made contact with the capacitor plate, and the outer sensor shield was connected with the coaxial cable shield. With this arrangement, the measured capacitance is not dependent on the length of the coaxial leads, and the sensor is minimally affected by external fields.

Capacitance Instruments

Two different instruments were used to power the sensors in this study.

The first is the IKOR Model 545 Vapor-Liquid meter, which is specifically designed for this type of application*. This instrument will give a reading in percent liquid volume directly, provided that (a) it is possible to operate initially with alternate flows of pure gas and pure liquid to perform the required in-place calibrations and (b) the capacitance of the sensing device is a linear function of the in-situ volume fraction of liquid. It operates at a fixed frequency of 20 KHz, has a capacitance measuring range of from 0.2 to 200 μF and has a response time of about 5 milliseconds.

The second instrument was a Hewlett-Packard Model 4270A automatic capacitance bridge**. This device provides a digital readout of the measured capacitance, can be operated at frequencies of 1, 10, 100 and 1000 KHz, and has a response time of about 0.5 sec. It has a measuring range of from about .001 of 1000 μF. Although the data presented in this paper were obtained using the above instruments, preliminary trials showed that equally satisfactory results could be obtained with an oscilloscope plug-in capacitance bridge and an instrument designed for following titration analyses using capacitance measurements.

Where detailed time-dependent in-situ volume fractions are required (for slug flow, for example), a fast-response time instrument must be used, e.g., the IKOR instrument referred to above.

Static Testing

Blank flanges which enabled the sensors to be easily filled with liquid or drained were mounted on the sensors. The total volume thus enclosed was then measured. In the calibration tests the capacitance of the air-filled sensor was first measured, following which oil was added in increments of about 10% of the sensor volume. After each addition, the sensor was placed in a horizontal position and the capacitance, or IKOR meter reading, noted. The effect of orientation was examined by rotating the sensor about its axis, and, while in the horizontal position, and observing the changes, if any, in the measured capacitance. Such a rotation is really a test of whether or not the liquid distribution affects the observed results. That this is true can be noted from Figure 3, because the effective flow pattern, relative to a fixed point of the sensor periphery, changes quite drastically with the rotation.

Typical results of the static calibration tests are shown in Figures 4 and 5. In all cases, the data show that the sensors are compatible with the IKOR Vapor-Liquid meter, and the meter reading can be used directly with no correction applied. The actual capacitance of the sensors is seen to exhibit a small but

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*IKOR, Incorporated, Northwest Industrial Park, Burlington, Mass. 01803, U.S.A.
**Hewlett-Packard (Canada) Ltd., 275 Hymus Blvd., Pointe-Claire, Quebec.
significant frequency effect. The lower capacitance of the 2-in. sensor is expected because the separation distance of the plates is quite large, and, in the interests of maintaining as short a measuring length as possible, only a single spiral was used. Two spirals were used on all of the other sizes.

In all cases, the effect due to rotation of the sensor was found to be less than 2% of the measured capacitance. As this is approaching the order of accuracy of the capacitance measuring instrumentation, it was not considered to be significant, and the sensors were concluded to be liquid-distribution insensitive.

**Dynamic Testing**

A small test loop was built to confirm the observation from the static tests that the sensors were not sensitive to the liquid distribution. This was simply a standard flow loop utilizing the quick-closing valve approach discussed earlier in this paper. Solenoid valves were used as the trapping elements and a kerosene was used as the liquid phase. The kerosene and air flow rates were adjusted so as to produce widely differing flow patterns (stratified, elongated bubble, slug and annular), and the resulting dynamic capacitance signal from the IKOR meter was continuously recorded. When the flow appeared to become stabilized, the solenoid valves were closed, trapping the gas-liquid mixture. This of course quickly assumed the same stratified configuration as used in the static tests. The capacitance of this condition was also recorded, following which the trapping section was drained and the actual liquid volume fraction measured. The continuous fluctuating capacitance signal was then graphically averaged, and this average was compared with the reading obtained after the flow had been trapped. These values were found to agree to within ± 2 per cent. Furthermore, the calibration obtained in this system was found to be in such good agreement with the much faster and easier static calibration that the latter was used exclusively for all subsequent tests.

**CONSTRUCTION DETAILS OF SENSORS USED IN THIS STUDY**

At the present time, we do not have an analytical design criterion for constructing the sensors. Figure 6 gives the particular sets of dimensions which were found by trial and error to give satisfactory results in this study. To eliminate the liquid distribution effect, it is important to have an exact integer number of spirals for each electrode, and to have these properly lined up opposite one another. This is equivalent to wrapping the two spirals exactly 180 degrees out of phase. Both the sensor tube and the shield tube were short lengths of clear acrylic cast or extruded tubing. Several oils were used in this study; the capacitance values reported in Figure 6 may be regarded as typical for the construction materials used and for oil with a dielectric constant of about 2. Not shown in Figure 6 are the flanged ends on the sensors, but these were simply standard couplings. The tubing sections were cemented into appropriately machined seats in the flanges.

**APPLICATIONS**

Sensors of the type described have been used successfully in sizes of up to 2-in. (I.D.) in laborator, studies of air-oil flow (Agrawal, 1971; Yu, 1972). In these studies, the fluctuating capacitance output signal was sent through a simple filtering circuit which yielded a smooth time-averaged value of the in-situ volume fraction as well as the original time-dependent signal.

The direct measurement of gas-to-liquid ratio should be possible using such sensors on producing gas wells, provided that the liquid phase is not aqueous. The construction is straightforward and the cost is minimal. The sensors can be made sturdy enough for industrial application by encasing the electrodes in a setting resin and using an appropriate pipe section to serve as the shield.
Another possible application is in the metering of pneumatically transported solids in small-diameter lines. Provided the transport velocity is known (and this is usually slightly above the settling velocity for economic reasons), the measurement of in-situ volume fraction enables the solids flow rate to be readily calculated.

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