EXPERIMENTAL CHARACTERIZATION OF TWO-PHASE FLOWS

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Abstract. *This work discusses the application of three measuring techniques to two-phase flows: the electro-conductivity technique, hot-wire anemometry and termistors.The work discusses not only the principles of the techniques but also presents a full description of the hardware developed for the implementation of the measurements. Results will be presented for two different flow conditions in a vertical pipe.*

Keywords. *Two-phase flow, thermoanemometry, electro-conductivity sensor, hot-wire, thermistor.*

1. Introduction

Two-phase flow is a rich and complex subject. The frequent occurrence of this phenomenon in many branches of science and technology makes it an important costumer in relevant engineering problems. The obvious consequence is that huge efforts have been made in the past to enlighten the obscure knowledge we have of two-phase flows.

Of course, if any sense is to be made from flows that present different phases, unsteadiness and tri-dimensionality, among many other complicating factors, experiments are to play a central role. Indeed, the correct assessment of the flow properties is crucial for the development of any mathematical model that will be bound to provide any meaningful, and useful, engineering prediction. As such, many different techniques have been developed to measure mean and instantaneous properties of gas/liquid flows. These techniques are based on different principles, making use of optical diagnosis, chemical methods, ultrasonic attenuation, the electrical properties of the medium, and thermo-anemometry among others.

The purpose of this work is to discuss the application of the electrical conductivity probe technique and the thermo-anemometry technique to gas/liquid flows. In particular, the paper will focus on developments that took place at the Laboratory of Turbulence Mechanics of COPPE/UFRJ that led to the construction of conditioning modules for both techniques. In other words, the paper will show how both hardware and software were designed and built “in house” for the measurement of mean and fluctuating properties of turbulent gas/liquid flows. Results will be provided for two flow conditions: i) a vertical channel with a large Taylor bubble and, ii) a vertical channel with dispersed bubbles.

The thermo-anemometry system will consist of two distinct methods: i) the hot-wire technique and ii) thermistors. Both will be discussed in detail here.

At the present stage, we will show the application of those techniques to the evaluation of void fraction only.

2. The electro-conductivity technique.

The electrical conductivity technique has been explored in an accompanying paper by some of the present authors (Soto et al.(2003)). However, for the sake of completeness, its working principle will be repeated here.

The working principle of the experimental technique is based on the difference between the electrical conductivity (resistivity) of the phases. Since the electrical conductivity of water is much higher than that of air, it is assumed, for practical purposes, that only the continuous phase(liquid) is capable of conducting electrical current. Accordingly to Herringe and Davis(1974), resistivity sensors are the most suitable technique for measurements in two-phase mixtures where the continuous phase is conductive. The main adversity of the technique is the existence of an in-stream sensor, which affects the structure of the flow.

In a double channel system (whether AC or DC supply), the difference in electrical resistivity between the phases can be sensed by the electrodes in the two-phase flow so that parameters like the local time-averaged mean gas fraction, the rise velocity and the pierced length of bubbles can be obtained through an analysis of the output signal.

Electro-resistivity sensors built from small needles were simultaneously developed by Neal and Bankoff(1963) and by Nassos(1963). In these studies, almost all efforts were dedicated to the development of the experimental technique rather than to the investigation on the nature of some particular type of flow. Neal and Bankoff used a Nitrogen-Mercury system, whereas Nassos carried out measurements in an air-water system. Chesters et al.(1980) were the first to employ the resistivity technique in gas-liquid non-confined flows with a certain degree of success. The authors used electro-resistivity sensors together with laser-Doppler anemometry to describe the characteristics of the liquid and of the gas phases in a bubble plume.

Tacke et al.(1985), studying gas stirred steel making processes, used the electro-resistivity sensor technique to make some measurements of the gas phase properties in air-water, Helium-water and Nitrogen-Mercury systems. Castillejos and Brimacombe(1975), also aiming at the application of the bubble plume phenomenon in the steel making industry, developed a comprehensive instrumentation based on the resistivity technique to investigate the problem. In 1988, Teyssedou et al. presented a new AC probe system, together with an analysis of the effect of the geometry of the sensor tip and of other parameters on the performance of the system. More recently, Kocamustafaogullari and Wang(1991), Leung et al.(1992) and Liu and Bankoff(1993) used resistivity sensors to determine local time-averaged mean gas fraction, interfacial area concentration, bubble rise velocity and bubble pierced length in internal bubbly flows.

3. Hot-Wire Anemometry.

Hot-wire anemometry (HWA) is based on the convective heat transfer process that takes place when a heated wire is exposed to a fluid flow. Because typical sensors are less than 5 μm in diameter and are made to withstand high temperature, any change in fluid flow condition that affects the transfer of heat from the wire to the medium will be sensed immediately by a constant HWA system. HWA can then be used to measure the velocity and temperature of the flow, concentration and phase discrimination.

In the study of two-phase flows, HWA can be used for measurements in flows containing a continuous liquid turbulent phase and dispersed bubbles. When bubbles hit the wire, the cooling process will be dramatically affected by the presence of the gas phase yielding a signal signature that upon analysis can be used to determine the void fraction. Moreover, HW probes can be used to measure velocity fluctuations in the liquid phase; this is a great advantage.

Much of the previous work on two-phase flow has led to the development of cylindrical or conical hot-film probes. These geometries have been vastly preferred over the classical one since they are supposed to give a better characteristic signal when immersed in a bubbly flow. However, since authors have offered a different signal interpretation to describe the passing of a bubble on the two different types of sensor, this matter will be discussed next.

The ideal probe output signal is an on-off signal in which the duration of the pulse equals exactly the passing time of a bubble over the sensing element of the probe. In fact, a “real” signal will present a finite rise time because a liquid film will remain on the sensing element following the impact of a bubble. Only when the film has drained, a full amplitude signal is reached. Partial amplitude signals also occur as bubbles hit the sensing element off the center. Two other causes of partial amplitude signals are bubbles that do not completely penetrate de probe or bubbles that are deflected by the probes.

In turbulent complex flows, the deflection and distortion of bubbles by their interaction with probes can seriously complicate the analysis of the output signal. The following comments will assume that the probes completely penetrate the bubbles. Bremhorst and Gilmore(1976) and Serizawa et al.(1983) showed this to be true when bubble diameter is greater than 2-3 mm. For smaller bubbles, $d < 2$ mm, imperfect penetration was observed. Serizawa et al.(1983) further observed that the large bubbles are remarkably unaffected by impact with the probe; they reported that full penetration may be difficult to achieve with a conical probe, and that the bubble trajectory is deflected by the probe.

The interaction between a cylindrical single normal hot-wire probe and a bubble produces a signal which is well-suited for analysis. Three events are clearly identified. Computing the passage of the undeformed bubble will furnish the can then be used to evaluate void fraction.

Conical probes give signals which are much more difficult to interpret. Since in a hot-film the sensing element is placed not in the tip of the probe but at a small downstream distance from the tip, this spatial difference results in the tip and not in the sensing element making its first contact with the bubble. Although conical probes still produce signals with three clearly identified events, none of these events are related to the position of the undeformed bubble. Consequently, correction methods must be devised to account for the void fraction. Some authors proposed the use of a probability density function method; others proposed to use the position of the bubble front and rear relative to the tip as a reference. In any case, all procedures were found to introduce some errors.

4. Experimental apparatus and instrumentation

The vertical tube where the tests were conducted had 20 mm in diameter and 1000 mm in length. The tube was filled with tap water up to 800 mm in length. The air injection system used a syringe and an volumetric pump to generate respectively the Taylor bubble and the dispersed bubbles regimes.

The data acquisition and analysis system consisted of a microcomputer with two interface data acquisition boards, an oscilloscope, the signal conditioner modules and the probes.

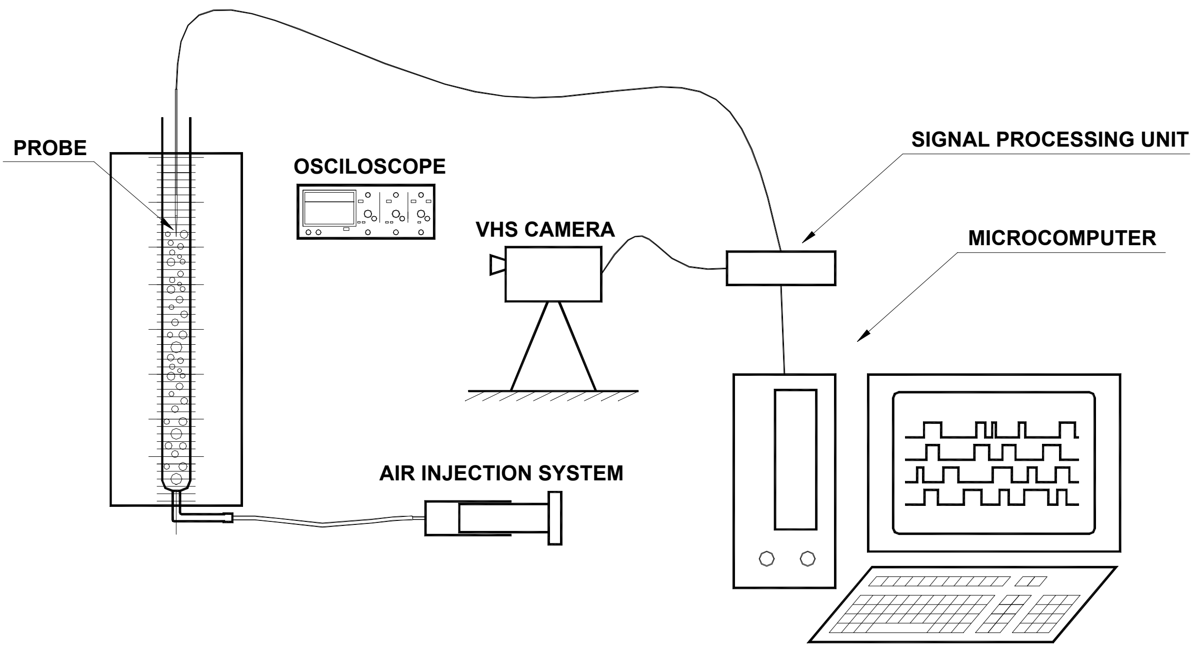
Measurements of void fraction for the conductivity and hot-wire probes were made in the central region of the pipe.

The experimental apparatus is shown in Figure 1; including the vertical pipe and the support instruments.

The mean gas fraction at a point in the flow is a time-averaged property given by,

$$f(r,x) = \frac{1}{T}\int_0^T I(r,x,t)\,dt \qquad (1)$$

where T is the total sampling time, I is the digital output signal from the conditioning module and r and x are the co-ordinates shown in Figure 1. The output signal, I, consists of a series of pulses which correspond to the transit of bubbles through the probe. Further details concerning the output signal, I, are available in Barbosa and Bradbury(1996) and in Barbosa(1997).



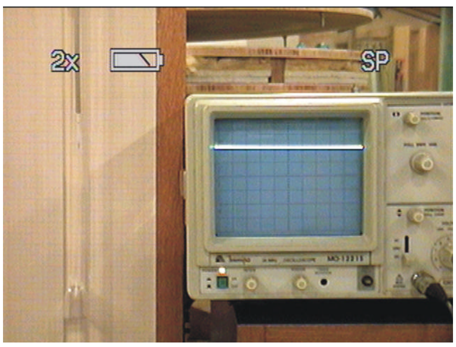


Figure 1. Diagram showing the testing apparatus.

4.1. The electro-conductivity device

The circuit of the electro-conductivity device was designed by Bradbury; its complete description is given in Barbosa and Bradbury(1996) and Barbosa(1997). The signal conditioning module was entirely built at the Laboratory of Turbulence Mechanics of PEM/COPPE/UFRJ.

The measuring system used in this work comprises a signal conditioning module and a single channel needle probe. The signal conditioning module is composed a electronic circuits connected to some electrical reference (that can be either the probe sheath or a third electrode immersed in the single phase region). Illustrations of two probes together with the electronic circuit are shown in Figures 2 and 3. The circuits are fed by a *12 V AC* signal and their main component used to be the monolithic bipolar integrated circuit *LM 1830 N*, which was devised for use in fluid measurement and detection systems. Because this component had its production terminated, it was substituted by the discrete elements that defined it. An *AC* supply system was chosen because, in agreement with Teyssedou *et alli*(1988), it is superior to the *DC* method. *DC* systems are subject to problems such as polarization and electrochemical attack.

The principle of operation can be stated very simply. When the so-called resistance of flow, R_f, increases above a pre-set value, the oscillator signal is coupled to the base of the open-collector output transistor.

The frequency of the oscillator is inversely proportional to the external capacitor value, C_1. A *220 pF* capacitor was chosen so that an oscillation frequency of *25 KHz* could be provided. The output amplitude from the oscillator is approximately $4\ V_{BE}$. Thus, when R_f equals the reference resistance, R_{ref}, the detector (which is an emitter base junction) is turned on by a $2\ V_{BE}$ voltage. The probe is also excited with $2\ V_{BE}$. The reference resistance, R_{ref}, is coupled to R_f by a blocking capacitor ($C_2 = 0.047\ mF$) to avoid net *DC* on the probe.

The collector of the detecting transistor is brought out to pin 9 enabling a filter capacitor ($C_3 = 0.047\ mF$) to be connected so that the output will be a digital on/off signal depending on the value of R_f. The on/off signal is then brought to a shifter where the voltage is transferred to the level of the digital card input

The measuring probes were constructed in the following way (Figure 2). A *0.2 mm* diameter stainless steel wire (upstream electrode) is electrically insulated, with exception of its tip, and embedded in a *0.4 mm* OD *0.2 mm* ID hypodermic tubing (downstream electrode), whose tip is also free of insulation. The length of the electrodes free of insulation is approximately *0.1 mm* and the probe tips were shaped to minimize their interference in the flow field.

The meaning of the parameter R_f (resistance of the flow) is discussed on the following lines. The actual value of R_f results from the combination of two factors, the resistance of the probe (that depends on the material from which the probe was made, on the effective electrical contact area and on the distance between the needles and the reference electrode) and the resistivity of the fluid that surrounds it. Each channel has its own R_f, which will be named from this point on as R_{f1} and R_{f2}. The channels are calibrated separately and, due to the reasons explained above (geometry, distance to the reference electrode), their resistances (R_{f1} and R_{f2}) often assume different values. A detailed calibration procedure is described in Barbosa, Jr. and Bradbury(1997).

The data were acquired at a sampling rate of approximately 2.5 kHz and about 50 sampling blocks of 10,000 readings (Barbosa and Bradbury(1996), Barbosa(1997)) were shown to be sufficient to describe the flow at each measured point. In fact, in Barbosa(1997), the shape, size and velocity of the rising bubbles was detailed studied; also, the influence of the injection geometry on plume development and the existence of any lateral wandering motion of the plume were investigated.

The probe calibration was made in the very own testing pipe. After the pipe had been filled with water taken from the tap and the probe had been placed in position, a large bubble was carefully introduced at its bottom through a syringe. As the bubble raised and hit the probe, the recordings from a RedLake high speed video camera were digitalized and analyzed. The pictures which were taken at a frequency of 250 frames per second were then compared with the signal of the conditioning module. The resistance of the flow in the conditioning module was then set so as to furnish the same response in both systems.

An uncertainty analysis of the data was performed according to the procedure described in Kline(1985). Typically the uncertainty associated with the mean gas fraction measurements was: f = 0.00035 precision, 0 bias (P=0.95).

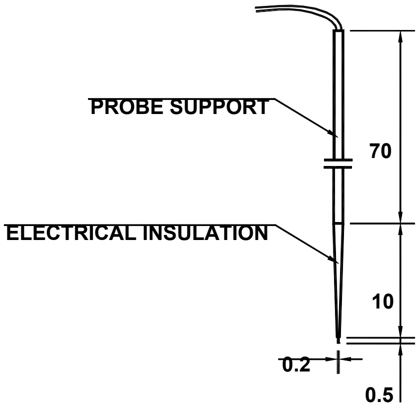


Figure. Electro-conductivity probe.

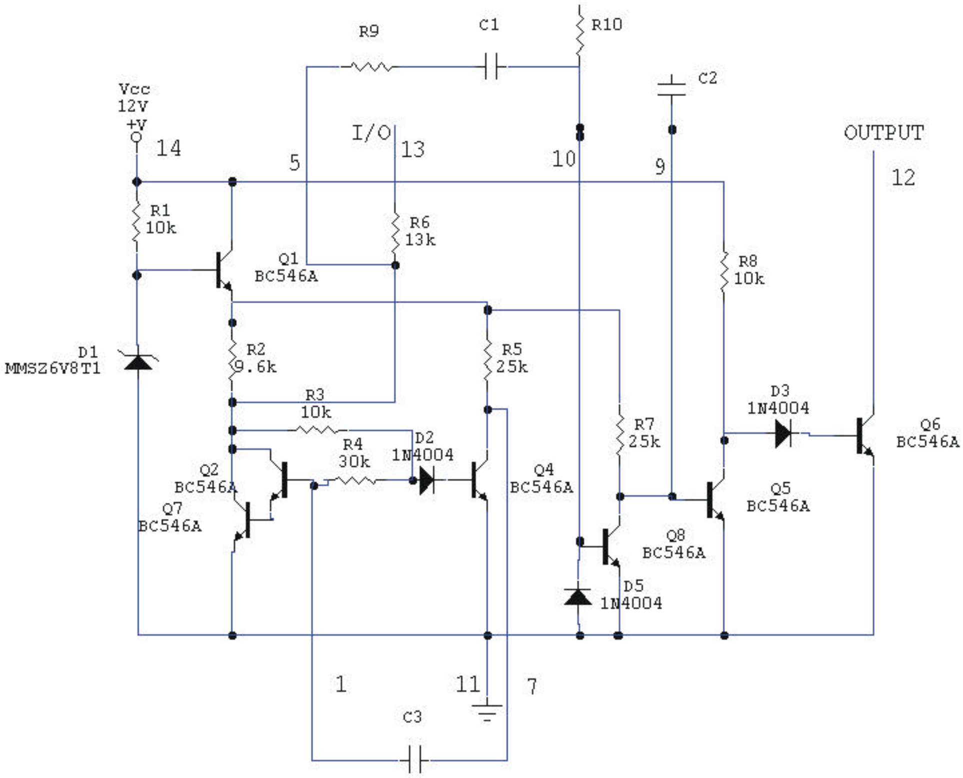


Figure 3. Diagram of circuit for the electro-conductivity technique.

4.2 The hot-wire anemometer

The hot-wire anemometer was entirely designed and constructed in the Laboratory of Turbulence Mechanics of PEM/COPPE/UFRJ. Operating in the constant temperature mode, the hot-wire unit presents the circuit shown in Figure 4. The hot-wire probe is placed in a Wheatstone bridge .As the flow velocity changes, the voltage readings by the operational amplifier will measure the change in wire resistance. The amplifier has an output current inversely proportional to the resistance charge of the wire. Feeding this current back to the top of the bridge restores the wire resistance to its original value. The CTA has the following controls:

a) low pass filter;
b) high pass filter;
c) amplifier gain;
d) stability circuit.

The CTA characteristics are shown in Table 1.

The single-sensor hot-wire probes were made of a 12 μm-diameter wire attached to two steel prongs 90.3 mm in diameter) distant 1.25 mm of each other (Figure 5). The wire material was tungsten. The wire was attached to the prongs through a spot-welding technique developed in the Laboratory of Turbulence Mechanics.

For measurements in liquids, normally hot-film probes are chosen for their extended durability. The use of thermal-anemometry in water is complicated by probe fouling, bubble formation on film elements, and the sensitivity of the calibration relationship to small changes in water temperature due to a low overheat ratio of about 1.05 to 1.08 (Bruun(1995)).

Here, we will use hot-wire probes in water to measure void fraction. We know electrolysis to be a major problem for unprotected wires. The potential drop across the wire causes electrolysis of the water, resulting in the formation of bubbles or even a film on the sensing element. More significantly, electrolysis results in a continuous reduction of wire diameter, provoking a shift in calibration that deems the measurements useless. To avoid the problem of electrolysis, wires have been coated with a thin layer of quartz, 1-2 μm. However, sensor failure due to cracking of the coating has been frequently observed by researchers.

Here, since we will be only measuring void fraction, temperature drift and probe contamination will not be a problem.

Table 1 – Characteristics of the CT anemometer.

Parameter	Min	Tip	Max	UNID
LCD Voltimeter	-20.0	-	+20.0	Volt
LCD Precision Voltimeter	-	-	0.01	Volt
Resistance waffle precision	-	0.1	-	Ω
Reference resistance precision	-	-	1	%
Wire resistance @ 25 ^{o}C under an overheat ratio of 70%.	0.60	-	58	Ω
Deviation in cut-off frequency	-	-	± 0.5	kHz
Output impedance	-	-	50	Ω
Output noise	-	-	500	µV
Output thermal stability	-	-	100	ppm / C

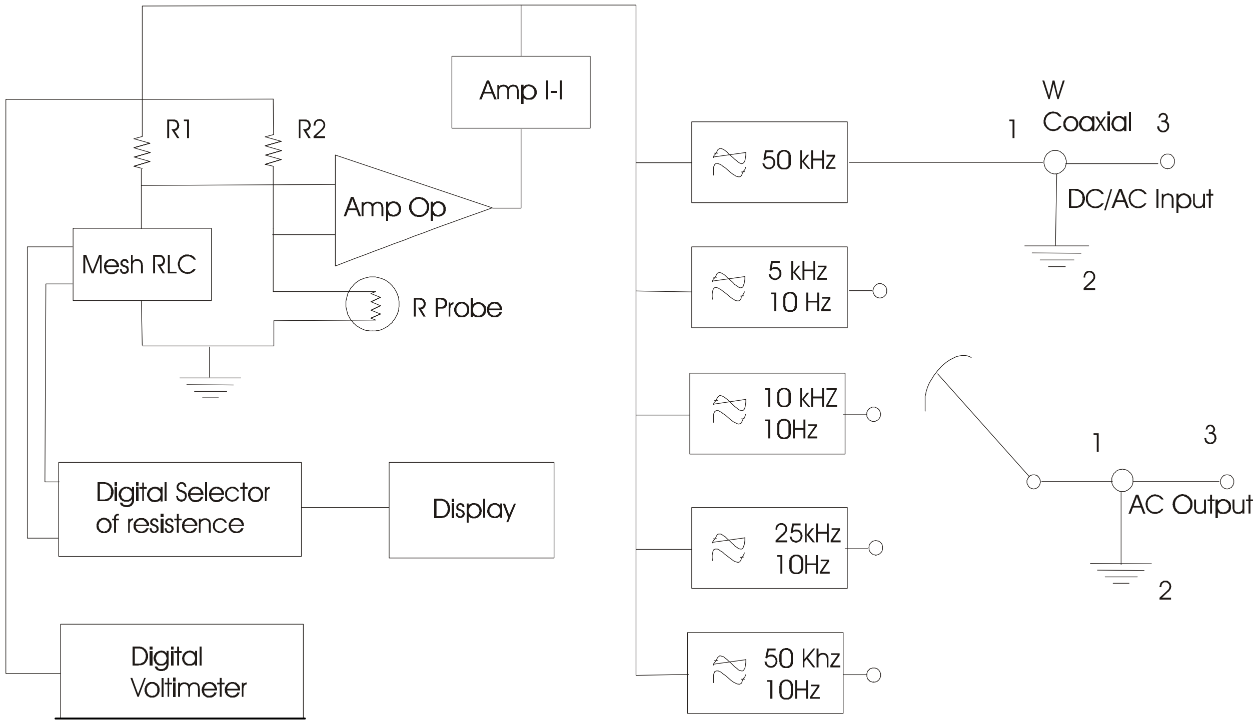
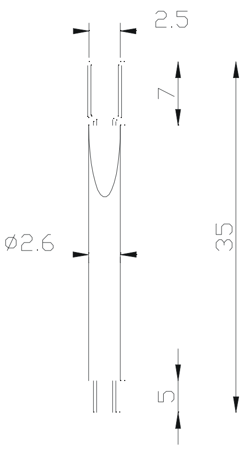


Figure 4. Circuit of CT anemometer.



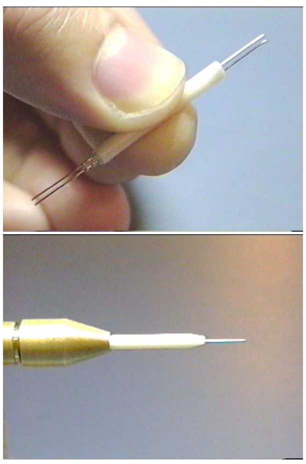


Figure 5. HW-probe. Dimensions in mm.

4.3 Thermistor

The application of thermistors to measurements in moving fluids is now a well-established technique. Papers that were published almost half a century ago have become classical references. Typical examples are the works of Smith(1950a, 1950b) and of Rasmussen(1961). When operating at constant temperature, thermistors present much shorter response times resulting in a dynamic behaviour that can be used to characterize phase change. A self-heated thermistor flowmeter, based on a tiny, glass-encapsulated, NTC thermistor probe was used here for measuring the liquid flow.

A diagram of the thermistor circuit together with a probe is shown in Figure 6.

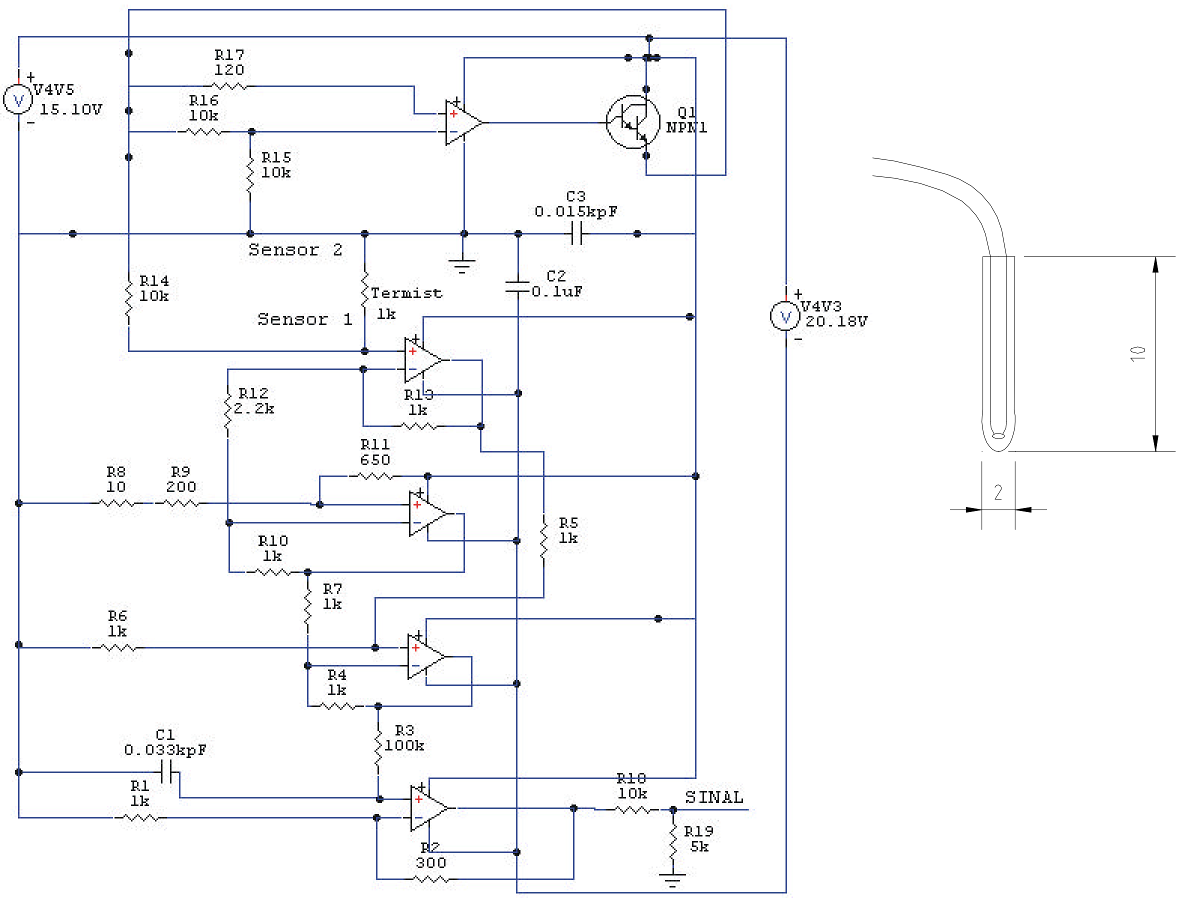


Figure 6. Thermistor circuit and probe. Dimensions in mm.

5. Results

5.1 Electro-conductivity device

Figure 7 shows the output signal from the conditioning module when the sensor is immersed in a bubbly flow. The system was devised to give a digital output signal consisting of the local and instantaneous gas-fraction (intermittent function),

$$I_{A,B}(z,r,t)=\begin{cases}0, \text{if water,}\\ 1, \text{if air.}\end{cases} \qquad (2)$$

The subscripts A and B stand for the upstream and downstream electrodes, respectively. One can observe the time delay between the passage of bubbles through the electrodes. The signal from the channels are not identical, since the probe interferes in the structure of the flow, distorting the surface of the bubbles and making them deflect away from it. As a matter of fact, when a bubble hits the downstream electrode it had already been deformed by the upstream electrode. An analysis of the output signal and the interpretation of the flow properties are presented in the succeeding sub-sections.

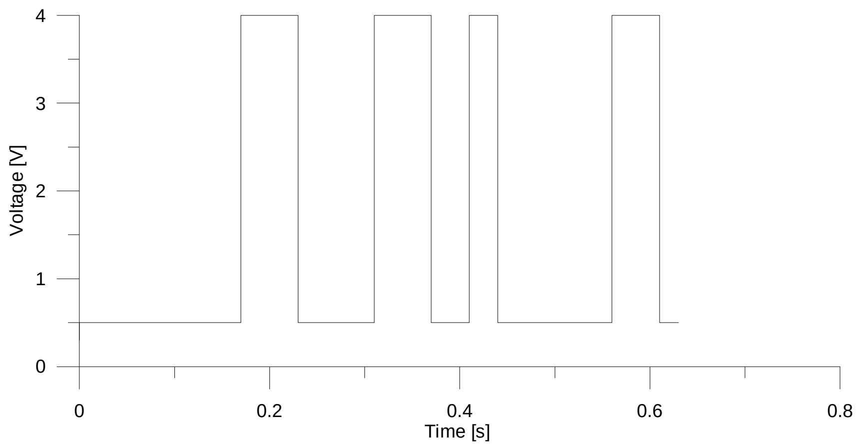


Figure 7. Output signal for an electro-conductivity device.

5.2 Hot-wire anemometer

Figure 8 shows the hot-wire anemometer output signal when the sensor is hit by the bubbles.

The passage of a single bubble is shown in more detail in Figure 9. Here is a description of the signal interpretation.

A moment prior to the bubble hitting the wire, the anemometer signal will increase due to the water acceleration provoked by the presence of the bubble. As the bubble hits the wire, a steep drop in the anemometer signal occurs with the duration of the bubble passage time. When the back of the bubble reaches the wire, the signal starts to increase until the bubble has completely left the wire. As the bubble leaves the wire the signal peaks a maximum, dropping slowly to towards the average velocity of the liquid phase.

In fact, the process just described has been observed by several other authors, being explained in more detail in Bruun(1995).

Thus, Figure 9 is plain evidence that the signal from a cylindrical hot-wire is well-suited for the void fraction analysis of two-phase flows. The passage of a bubble corresponds to the time interval between the first voltage peak and the lower voltage level when the back of the bubble reaches the wire.

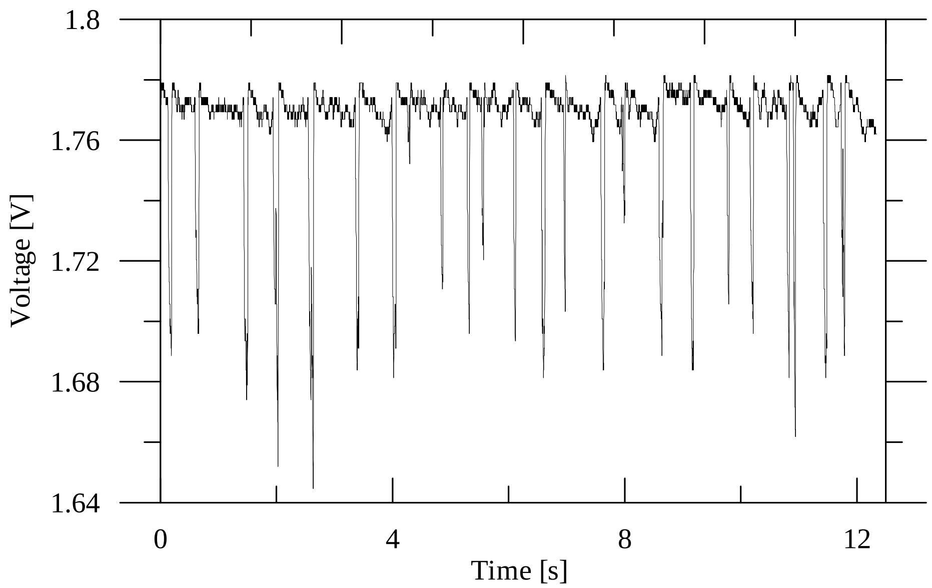


Figure 8. Output signal for a hot-wire anemometer:

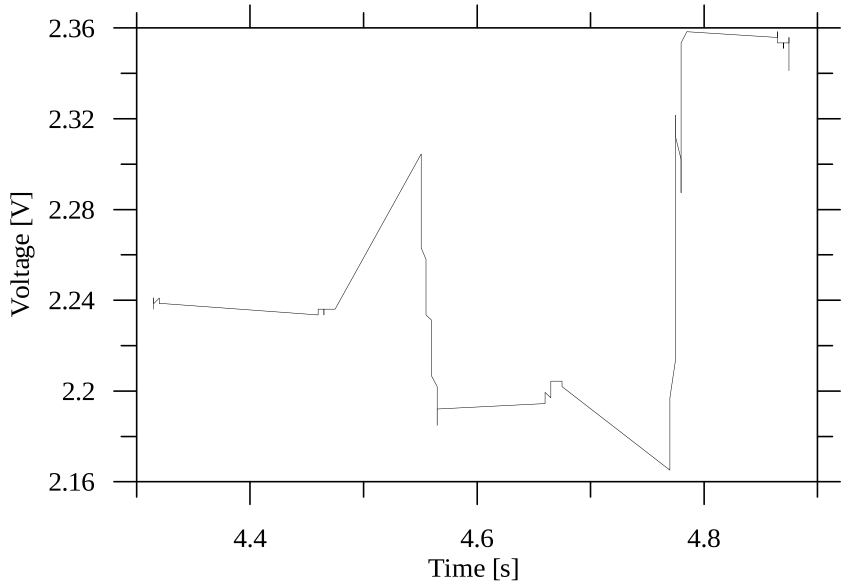


Figure 9. Output signal for a single bubble hitting the hot-wire sensing element.

5.3 Thermistor

Figure 10 shows the thermistor output signal for bubbly flows.

All three events identified for the hot-wire signal can be observed here. The voltage initially increases due to the approaching bubble. Next, a voltage decrease is observed thanks to the passage time of the bubble. Finally, a large increase in voltage is observed due to the departure of the bubble and the exposition of the wire to the liquid phase. As for the hot-wire case, the void fraction can be calculated from the time interval between the first voltage peak and the lower voltage level.

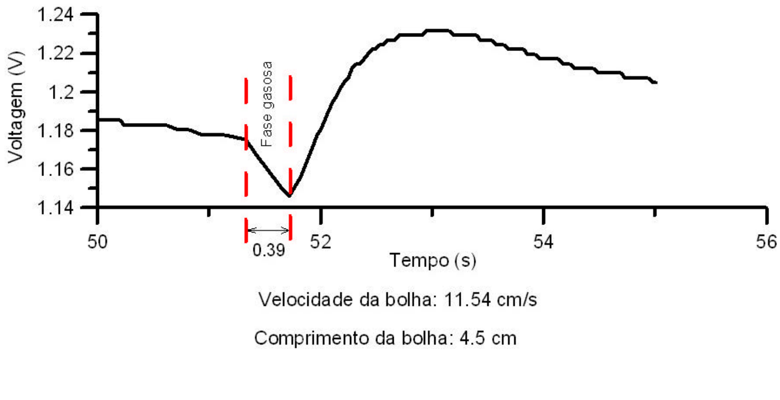


Figure 10. Output signal for a single bubble hitting the thermistor.

6. Conclusion

We have show how three different measurement techniques can be used to measure void fraction in two-phase flows. These techniques have all their own peculiarities serving for different purposes. The electro-conductivity device and the thermistor were observed to be very robust and easy to operate. They can be made out of cheap parts and are easy to maintain. The thermistor in addition can be used to determine the mean velocity of the liquid phase.

The hot-wire anemometer, however, is a more sophisticate apparatus that requires much more training for its competent use. Of course it has the advantage of providing turbulence data.

The major point of the paper, however, has been the presentation of all hardware and software that were used in the development of the research. This has been, to my mind, a great accomplishment of the Laboratory of Turbulence Mechanics. The complete domain of all experimental techniques described in this work places the Laboratory in a good position to perform original research in two-phase flow in the future.

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