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TRANSIENT AND STATISTICAL MEASUREMENT TECHNIQUES FOR TWO-PHASE FLOWS: A CRITICAL REVIEW*

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Abstract—Much work has been expended in the study of two-phase, gas–liquid flows. While it has been recognized superficially that such flows are not homogeneous in general, little attention has been paid to the inherent discreteness of the two-phase systems. It has been a relatively recent development that fluctuating characteristics of two-phase flows have been studied in detail. As a result, new experimental devices and techniques have been developed for use in obtaining measurements of quantities previously ignored. This paper reviews and summarizes these methods in an effort to emphasize the importance of the fluctuating nature of these flows and as a guide to further research in this field.

INTRODUCTION

Considerable experimental and analytical work has been performed in the study of two-phase, gas–liquid flows with and without heat-transfer. While it has been recognized superficially that such flows are not homogeneous in general, little attention has been paid to the inherent discreteness of two-phase systems due to the additional complexity this would entail. Neglect of the more detailed behavior of these flows results in conclusions which may be incomplete, and or misleading. While slight consideration was given to the statistical characteristics more than a decade ago (Neal & Bankoff 1963; Lackmé 1964; Akagawa 1964; Ishigai *et al.* 1965), statistical or fluctuating characteristics have been studied in detail only recently. As a result, experimental devices and techniques have been developed for use in obtaining measurements of quantities ignored until now. This paper reviews and summarizes these methods to emphasize the importance of the fluctuating nature of two-phase flows, and serve as a guide to further research.

Some of the characteristics and problems associated with single-phase flow measurements are also experienced in two-phase instrumentation, while others are unique to two-phase systems. Most of these additional difficulties are related to the presence of two phases but some are also due to specific flow geometries. Difficulties due to the presence of two phases include:

(a) The deformation of an interface at a sensor leads to a lag between the occurrence and the detection of the event due to a hydrodynamic response time.

(b) Where pressures are measured with wall pressure taps, it must be insured that all the gas has been purged from the pressure lines.

(c) Steady-state flow may contain significant fluctuations so that time-averaged quantities should be measured taking into account every damping factor and nonlinearity.

(d) Bubbles or droplets, even at a rather low concentration, prevent a light beam from crossing the flow directly. Therefore, laser Doppler anemometry seems extremely difficult in contained two-phase flow.

(e) An in-stream probe or a wall pressure tap may destroy a metastable equilibrium or may lead to cavitation effects.

In addition to these, there are also difficulties due to flow geometries such as:

(a) Two-phase flows are studied with a view of application to many engineering fields and

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particularly to nuclear engineering. Temperature and pressure conditions are generally severe and require metallic channels, opaque to visible light. Even when X-rays are used, special design precautions are required to obtain a measurable response.

(b) Test section geometries are often complex. In nuclear engineering, rectangular channels of narrow width such as Special Power Excursion Reactor Tests (SPERT) or Engineering Test Reactor (ETR), or rod bundles such as Pressurized Water Reactor (PWR), Boiling Water Reactor (BWR) and Liquid Metal Fast Breeder Reactor (LMFBR) are the rule.

An excellent review session of two-phase flow instrumentation was organized by Le Tourneau & Bergles (1969). This session included a number of papers which discussed various aspects of steady-state instrumentation methods. Virtually no mention was made of measurement of transient or statistical quantities. Significant advances have been made in the last 6 years, both in instrumentation methods themselves, and in the extent to which unsteady phenomena can be quantified. Nowhere to the writers' knowledge has a summary of transient or statistical measurement techniques for two-phase, gas–liquid flows been published. This report is intended to fill this gap and will complement and update the works of Hewitt (1972) and Delhaye *et al.* (1973*a*) as well as that of Delhaye (1974).

Two-phase flow instrumentation has been utilized to determine average and local void fraction profiles. More recently, methods have progressed with resultant improvement in both accuracy and resolution. Recent work has been published describing measurement of local and integrated values for liquid and gas velocities, interfacial passage frequencies, and liquid and vapor temperatures and their statistical characteristics such as spectral densities, histograms, and probability density functions. These efforts are described here. Alterations in phase at a given location may give rise to pressure fluctuations which affect the stability of a system. The frequency and size of droplets in mist-annular flow have a direct bearing on the approach to burnout or on the deficient cooling of a post critical heat-flux fuel element in a nuclear reactor. Transient and statistical void location variations can have a marked effect on local heat-transfer coefficients. Likewise, transient void motion is of ultimate importance in the behavior of both water and liquid metal reactors during accident situations. Measurement of instantaneous voids, temperatures, and velocities in critical flow situations are required to confirm current modeling efforts. In addition, modeling efforts require local instantaneous measurements of void residence, velocity, and frequency to obtain data regarding interfacial area densities (important in describing interfacial transfer), one dimensional correlation coefficients expressing covariance of void and velocity, void and energy, etc., and verification of hypotheses regarding the shape of void and velocity profiles, their interrelations, and their statistical variations. It is thus expected that efforts in these directions shall continue and intensify over the next few years.

MICROTHERMOCOUPLE

What can be measured with a microthermocouple?

The classical microthermocouple enables measurement of some statistical characteristics of the temperature, and if combined with an electrical phase indicator, data regarding the local void fraction may also be obtained. Both are discussed below although the latter seems more appropriate in boiling two-phase flows.

Classical microthermocouple

Experiments on boiling heat-transfer include studies of temperature fluctuations near a heated surface with either pool boiling or forced convection.

Pool boiling experiments. A microthermocouple probe using wires 50 μm in dia was used by Marcus & Dropkin (1965) in measuring mean and fluctuating temperatures to evaluate the thickness of the superheated liquid layer in contact with a heated wall. The results, although timely, were somewhat inaccurate.

Bonnet & Macke (1966) reported results obtained with a microthermocouple imbedded in a resin block in such a way that only 20 μm of the hot junction was in the flow. Unfortunately the size of the probe, 80 μm, produced a disturbance in the flow and its thermal inertia led to extra vaporization of the liquid on the sensor so that the significance of the signal was not clear.

Temperature profiles using a 125 μm dia, chromel–alumel junction were measured by Lippert & Dougall (1968) in the thermal pool boiling sublayer. According to the authors, this large diameter thermocouple data was shown to be reasonable by the results of tests in water, Freon-113 and methyl alcohol.

The interaction between bubbles and a microthermocouple, 25 μm in dia was examined by Jacobs & Shade (1969). These authors, and also Van Stralen & Sluyter (1969) were primarily concerned with the thermocouple response time. These investigations of the response time were augmented by Subbotin *et al.* (1970) who examined the behavior of bubbles hitting different types of thermocouples.

Stefanovic *et al.* (1970) verified the adequacy of a signal from a 40 μm dia thermocouple by recording the impact of a bubble on the hot junction using high-speed movies. Amplitude histograms were obtained in pool boiling and in forced convection boiling. The authors separated steam and water temperature histograms by assuming that the predominant phase had a symmetrical distribution of temperature (figure 1). The identical assumption was used by Afgan *et al.* (1973a, b).

Superheat layer thickness measurements were conducted in saturated and subcooled nucleate boiling by Wiebe & Judd (1971) employing a 75 μm, chromel–constantan, microthermocouple. A time-average temperature was determined by integrating the temperature signal.

Forced convection boiling experiments. One of the first investigations into temperature profiles in forced convection boiling was carried out by Treschov (1957). The results appear less interesting than those obtained by Jiji & Clark (1964) with a chromel–constantan thermocouple, 250 μm in dia. Despite the large size of their sensor, these authors succeeded in measuring an average temperature and average values indicative of the temperature extremes.

Local subcooled boiling, characterized by important nonequilibrium effects, was studied by Walmet & Staub (1969) with the help of several local measurements: pressure, void fraction, and temperature. For temperature measurement the authors used a large, 150 × 200 μm copper–constantan thermocouple, and analytically related the measured value to the liquid temperature through the void fraction obtained using X-rays.

In his study of flashing flow of water, Barois (1969) proposed to separate the distributions of steam and water by assuming that the steam temperature histogram was symmetrical (figure 1), rather than the predominant phase as done by Stefanovic *et al.* (1970) and Afgan *et al.* (1973a, b).

Finally, Van Paassen (1974) did a detailed study of the microthermocouple as a droplet size sampler, showing good agreement between theory and experiment in determining droplet sizes between 3 and 1188 μm. Detection frequencies of up to 1 kHz were obtained for small droplets.

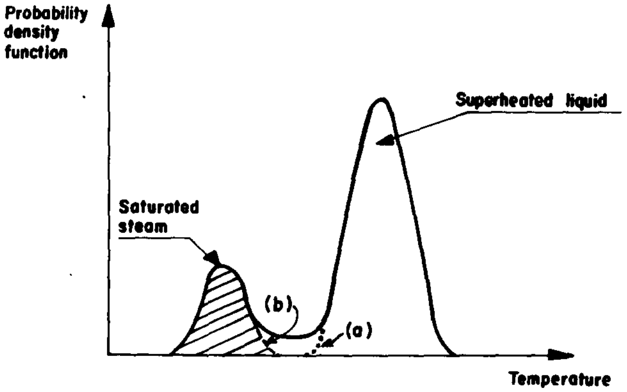

Figure 1. Separation of steam and water distributions: (a) according to Stefanovic *et al.* (1970), and Afgan *et al.* (1973a, b), (b) according to Barois (1969).

Microthermocouple associated with a phase indicator device

Although all the preceding works have contributed to a large extent to the understanding of the local structure of two-phase flow with change of phase, they have not provided any reliable statistical information on the distribution of the temperature between the liquid and the vapor phases.

The work done by Delhaye *et al.* (1972, 1973b) is based on the possibility of separating the temperature of the liquid phase from the temperature of the vapor phase, and of giving the statistical properties of the temperature of each phase as well as the local void fraction. These workers used an insulated 20 μm thermocouple both as a temperature measuring instrument and as an electrical phase indicator (see section on electrical probes) by using a Kohlrausch bridge to sense the presence of a liquid conductor between the noninsulated junction and ground. The phase signal is used to route the thermocouple signal to two separate 1000 channel subgroups of a multichannel analyzer thus providing separate histograms of liquid and vapor temperatures as shown in figure 2 for a subcooled boiling case. Comparison of these histograms with those in figure 1 clearly shows the inconsistency in the assumptions of Stefanovic *et al.* (1970), Afgan *et al.* (1973a, b), and of Barois (1969).

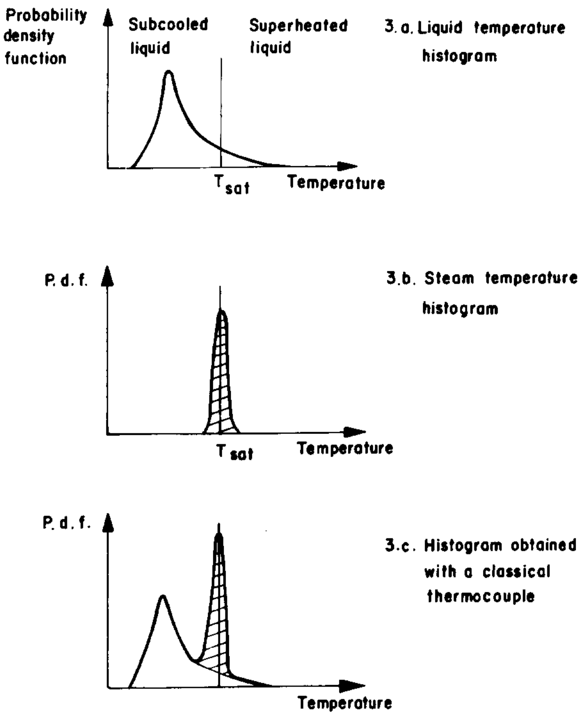

Figure 2. Subcooled boiling temperature histograms according to Delhaye *et al.* (1972, 1973b) (a) liquid temperature, (b) steam temperature, (c) coupled, classical temperature histogram.

OPTICAL PROBES

What can be measured with an optical probe?

An optical probe is sensitive to the change in the refractive index of the surrounding medium and is thus responsive to interfacial passages enabling measurements of local void fraction or interface passage frequencies to be obtained even in a nonconducting fluid. By using two sensors and a cross-correlation method, information may be obtained on a transit velocity (Galaup 1975).

Description of optical probes

Glass rod system. (Miller & Mitchie 1969, 1970; Bell *et al.* 1972; Kennedy & Collier 1974). This probe (figure 3) consists of a glass rod 2 mm in dia reduced to 0.3 mm at one end. The small tip of

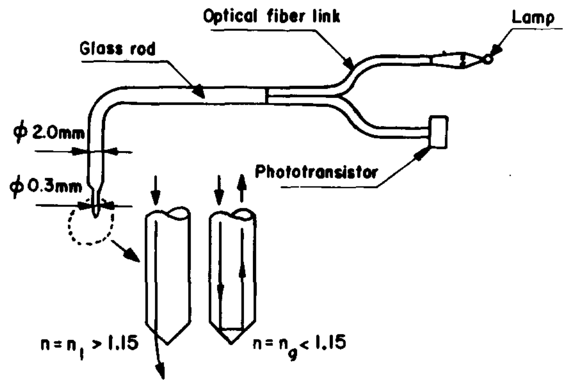

Figure 3. Typical optical probe system. Miller & Mitchie (1969, 1970).

the rod is ground and polished to the form of a right-angled guide. The light from a quartz–iodine lamp is focused on one of the branched ends of the light guide. A phototransistor is located at the other branched end of the light guide.

Light is transmitted parallel with the rod axis towards the tip of the probe. When light beam strikes the surface at an angle of 45°, it emerges from the probe or is reflected back, depending upon the refractive indices of the surrounding material n and of the probe material n_0 according to Snell's law. Thus for a glass rod when $n_0 = 1.62$, if the incident internal angle between the light and the polished tip is 45°, light is reflected back along the rod if $n < 1.15$ and exits from the rod if $n > 1.15$. Table 1 gives possible combinations in which this probe can be successfully used.

Table 1. Liquid vapor systems where $n_G < 1.15$ and $n_L > 1.15$. Adequate for use of a 45°-tipped optic probe rod

System	n_G	n_L
Steam–water	1.00	1.33
Air–water	1.00	1.33
Freon–Freon Vapor	1.02	1.25

Fiber bundle system (Hinata 1972). The basic element of this probe is a 30 μm dia glass fiber which consists of a central core and an outer cladding. Several hundred such elements are tied together in a Y-shaped bundle similar in appearance to that shown in figure 3, with a light source and a phototransistor. The active end of this bundle is glued to a glass rod, 0.5 mm in dia, 1 mm long, itself coated with a glass of lower refractive index (figure 4). The extremity of the glass rod is ground and polished. The operation of this device is similar to that of the glass rod system.

U-shaped fiber system (Danel & Delhaye 1971; Delhaye & Galaup 1975). One of the major drawbacks of the glass rod and fiber bundle systems is the large dimension of the sensitive part of the probe (respectively, 0.3 and 0.5 mm). An alternative sensor configuration developed by Danel & Delhaye (1971) has a distinct size advantage. This probe consists of a single coated optical fiber, 40 μm in dia. The overall configuration is similar to that shown in figure 3 with a miniaturized lamp and a phototransistor chosen for its high sensitivity. The active element of the probe is obtained by bending the fiber into a U-shape and protecting the entire fiber, except the U-shaped bend, inside a stainless steel tube, 2 mm in dia. The active part of the probe has a characteristic size of 0.1 mm as shown in figure 5.

Signal processing

Glass rod system. All the cited authors used a discriminator to transform the actual signal into a binary signal. A trigger level is set at a value above the background level corresponding to the

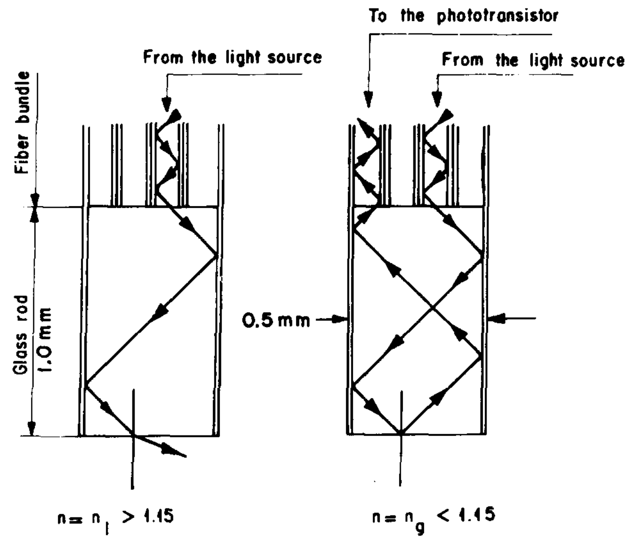

Figure 4. Fiber bundle optical sensor. Hinata (1972).

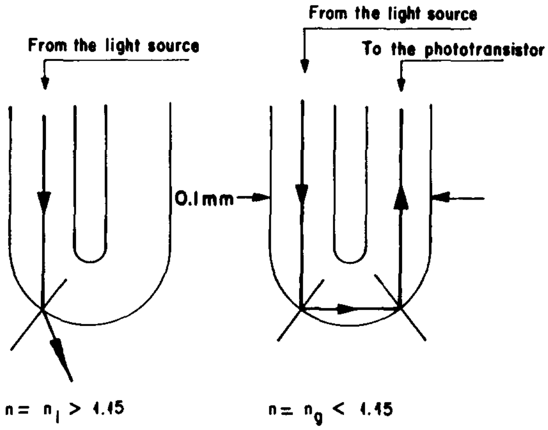

Figure 5. U-shaped fiber optical sensor. Danel & Delhaye (1971).

case where the probe is immersed in the liquid. Miller & Mitchie (1969, 1970) arbitrarily set the trigger level 10% of pulse amplitude above the all-liquid level obtained by comparing the value of the local void fraction at a given point to the volume void fraction measured with quick-closing valves. Without justification, Bell *et al.* (1972) set the trigger level half-way between the all-water and all-gas signal levels, while in a study of droplet jet flow, Kennedy & Collier (1974) related the trigger level and the droplet time fraction with the sizes of the probe and of the droplets.

Fiber bundle system. Hinata (1972) obtained an S-shaped curve of local void fraction measurement versus trigger level, with a plateau corresponding to a given value of the void fraction. He used the trigger level value corresponding to this plateau.

U-shaped fiber system. A typical signal delivered by the probe is shown in figure 6. The voltage U can be divided into a static component U_0 which varies with local void fraction, and a fluctuating component u.

Since U_0 corresponds to a sensitive part of the probe completely immersed in the liquid, the change in U_0 can be due to (a) the response time inherent in hydrodynamic and optoelectronic phenomena when the interface is pierced by the probe, and (b) the scattering of light by the bubbles surrounding the probe.

The fluctuating component constitutes the interesting part of the signal while the maximum value U_{max} corresponds to the sensor completely immersed in the gas and does not depend on the local void fraction. Signal analysis is accomplished through two adjustable thresholds, s_r and s_f which enable the signal to be transformed into a square-wave signal (figure 6). Consequently, the local void fraction α is a function of s_r and s_f which are adjusted and then held fixed during a traverse in order to obtain agreement between the profile average and a γ-ray measurement of void fraction.

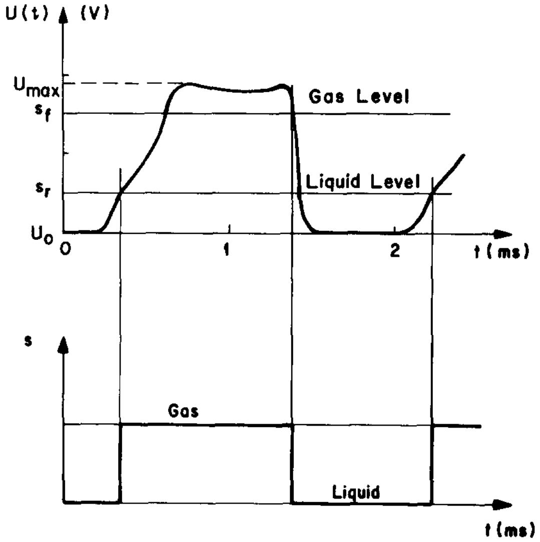

Figure 6. Typical optical probe signal and discrimination method. Delhaye (1974).

HOT-FILM ANEMOMETRY

What can be measured with a hot-film probe?

Hot wire and hot film anemometers have been widely used in gases. Little success has been reported on calibrated use of miniature cylindrical probes for accurate velocity measurement in liquids until quite recently, and then only relatively low velocities (for instance, in water, Ornstein (1970), < 0.5 m/s; Morrow & Kline (1971) < 0.25 m/s; Hollasch & Gebhart (1972) < 0.6 m/s, and Hurt & Welty (1973), < 0.05 m/s in mercury). Jones (1973) and Jones & Zuber (1975b), however, have recently reported measurement of void and volume flux profiles with 50 μm cylindrical probes with velocities up to 6 m/s. Use of the larger and more sturdy wedge and conical probes has enjoyed greater success at velocities up to the region of 5 m/s (Rosler & Bankoff (1963), < 3.7 m/s; Bouvard & Dumas (1967), < 5 m/s; Resch & Coantic (1969), < 4 m/s; Resch (1968), < 4 m/s). It has been found that hot-wire or hot-film anemometry can be used in two-component two-phase flow or in one-component two-phase flow with phase change. In the first case, an air–water flow, for example, it is possible to measure the local void fraction, the local liquid volume flux or instantaneous velocity and the turbulence intensity of the liquid phase in conjunction with the arrival frequency of bubbles or droplets. In the second case, a steam–water flow for example, it has been so far impossible to obtain consistent results on calibrated liquid velocity measurements.

Measurements in two-component two-phase flow without phase change

Liquid droplets in a gas flow. Hot-wire anemometry has been used for measuring the concentration flux and the diameter histogram of liquid particles moving in a gas stream. Goldschmidt & Eskinazi (1964, 1966) measured the arrival frequency of liquid droplets, 1.6 to 3.3 μm in dia, with a constant temperature anemometer and a cylindrical probe, 4.5 μm in dia. When the impaction frequency of the droplets is different from the energetic frequency range of the turbulent gas stream, the signal fluctuations due to impacts can be distinguished from the fluctuations due to turbulence. In experiments by Goldschmidt & Eskinazi (1964, 1966), results showed that the ratio of the impaction frequency to the maximum impaction frequency was insensitive to the threshold amplitude of a discriminator used to produce a binary chain of pulses due to droplet impactions. This fact has also been observed by Lackmé (1967) for void fraction measurements with a resistive probe. Ginsberg (1971) used the same technique to study liquid droplet transport in turbulent pipe flow. Goldschmidt (1965) determined that the measured impaction rate is lower than the true value but proportional, and should thus be calibrated against another technique.

In determining droplet diameter histograms, Goldschmidt & Householder (1968, 1969) theoretically found a linear relationship between particle diameter and cooling signal peak value which was verified experimentally for droplet diameters lower than 200 μm. Bragg & Tevaarverk (1971), however, contradicted these results and concluded that the hot wire was unsuitable for this purpose. This conflict has yet to be resolved.

Time-averaged gas velocities as well as gas turbulent intensities were measured by Hetsroni *et al.* (1969) in low concentration mist flow. The spikes due to the impingement of the liquid droplets on the hot-wire were eliminated with the help of an amplitude discriminator and a somewhat simpler electronic circuit than that of Goldschmidt & Eskinazi (1964, 1966). The resultant signal was used to obtain time averaged gas velocity and turbulent intensities.

Despite several difficulties arising in droplet granulometry determination, the hot-wire has successfully been employed for studying the turbulent diffusion of small particles suspended in turbulent jets by Goldschmidt *et al.* (1972).

Air–water flows. Following the studies done by Goldschmidt in aerosols and by Hsu *et al.* (1963) in steam–water flow, and the preliminary work of Jones (1966), a thorough investigation of the hot-film anemometry technique in two-phase flow was carried out by Delhaye (1968, 1969) using a conical constant temperature hot-film probe which has three major advantages over the cylindrical hot-film sensor: small particulate matter carried with the fluid does not attach to the tip, bubble trajectories are less disturbed, and the relatively massive geometry is less susceptible to flow damage at higher velocities. The maximum overheat resistance ratio of the probe of 1.05, (ratio of operating resistance to the resistance at ambient fluid temperature), was suggested by Delhaye (1968, 1969) to avoid degassing on the sensor. This corresponded to a difference of 17°C between the probe temperature and the ambient temperature, significantly below saturation temperature. Jones (1973), and Jones & Zuber (1975b) found little difference between resistance ratios of 1.05 and 1.10 insofar as degassing on their 50 μm dia cylindrical sensor was concerned, and chose the latter for increased sensitivity. Degassing in their system was found to occur in operation following failure of the 8000 Å-thick quartz coating over the platinum film. This failure occurred during forced resonant vibration of the sensor caused by vortex shedding at velocities over 1.5 m/s. Degassing caused the calibration to be unstable only at velocities less than ~30 cm/s.

Chuang & Goldschmidt (1969) employed the hot-wire as a bubble size sampler by theoretically investigating the nature of the signal due to the traverse of an air bubble past the sensor. The peculiarities of the conical probe signal were examined in detail by Delhaye (1968, 1969). In the case where a 50 μm cylindrical hot film probe is used instead of a conical probe, the linearized response is similar to that seen in figure 7 near the interface in high velocity annular flow of air and water (Jones, 1973). It is evident that if the liquid and gas signals could be separated, the turbulent structure of the liquid phase could be obtained. Delhaye (1968, 1969) did this to a certain extent when he obtained the amplitude probability density function of the output signal $E(t)$, shown in figure 8. To a first approximation, the local void fractions were calculated as the ratio of the hatched area to the total area which then compared favorably with radiation absorption methods (γ-rays). The liquid time-averaged velocity and the liquid turbulent intensity are calculated with the nonhatched area of the amplitude histogram (figure 8) and the calibration curve of the probe immersed in the liquid. The same method has extensively been used by Serizawa (1974) for measuring the turbulent characteristics and local parameters of air–water two-phase flow in pipes.

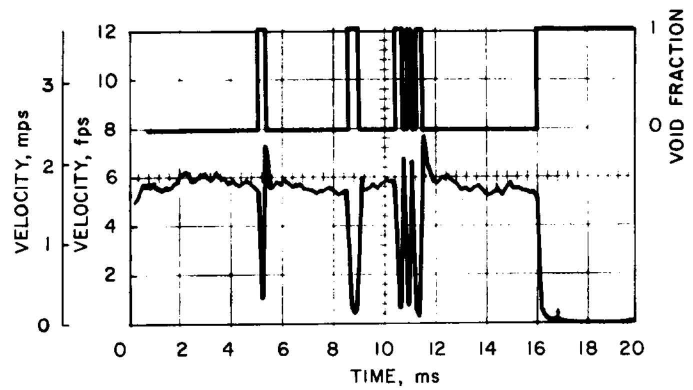

Figure 7. Linearized anemometer velocity signal. Jones (1973).

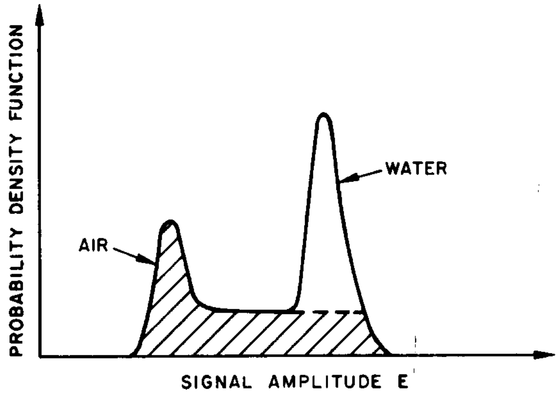

Figure 8. Typical amplitude histogram of anemometer bridge signal, Delhaye (1968, 1969).

A different processing method was proposed by Resch & Leutheusser (1972) and Resch *et al.* (1974) in a study of bubble two-phase flow in hydraulic jumps. The nonlinearized analog signal from the anemometer (figure 9) is digitally analyzed. A change of phase is recognized when the amplitude between two successive extremes of the signal is higher than a fluctuation threshold level ΔE. In this way the liquid mean velocities and turbulence levels were obtained along with bubble size histograms. ΔE was chosen to be in a plateau region of ΔE versus measured void fraction.

Jones (1973) and Jones & Zuber (1975b) used a discriminator applied to the raw anemometer signal to obtain a binary signal representative of local void fraction but found the cutoff level needed to be adjusted depending on the local velocity to a point just below the minimum value for a liquid. Even though the threshold value was set at every point in the traverse, errors in averaged void fraction were encountered when calibrated against an X-ray measurement. These errors were found to be dependent on the liquid volume flux and the mean void fraction.

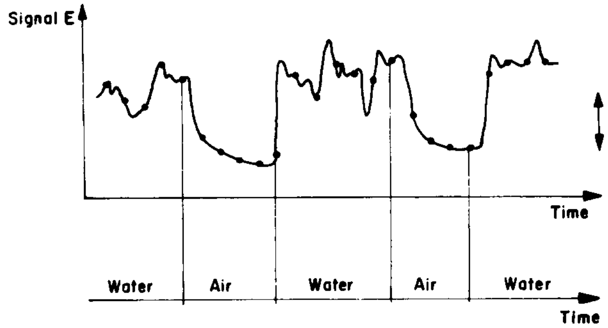

Figure 9. Signal analysis method of Resch *et al.* (1972, 1974).

By counting the number of times the output of the discriminator changed from one level to ıther, Jones (1973) also obtained local values for interface passage frequency (figure 10). He o measured the liquid-volume flux directly by time averaging the linearized signal equal to the uid velocity when the sensor was in liquid, and zero when the sensor was in gas (see figure 7). quid velocity was obtained by pointwise division of the measured liquid flux by the measured id fraction. The results were somewhat questionable, however, due to the cracking of the 00 Å-thick, quartz coating mentioned previously. No attempt was made to measure the rbulent fluctuations.

Serizawa (1974) used a conical probe of much more sturdy construction and larger size, milar to that of Delhaye (1968, 1969). In bubbly and slug flow in air-water mixtures he used ultichannel analysis techniques to obtain the frequency spectrum of the velocity signal cluding fluctuations up to ~2 m/s. Ishigai *et al.* (1972) used an anemometer to measure liquid ilm thicknesses.

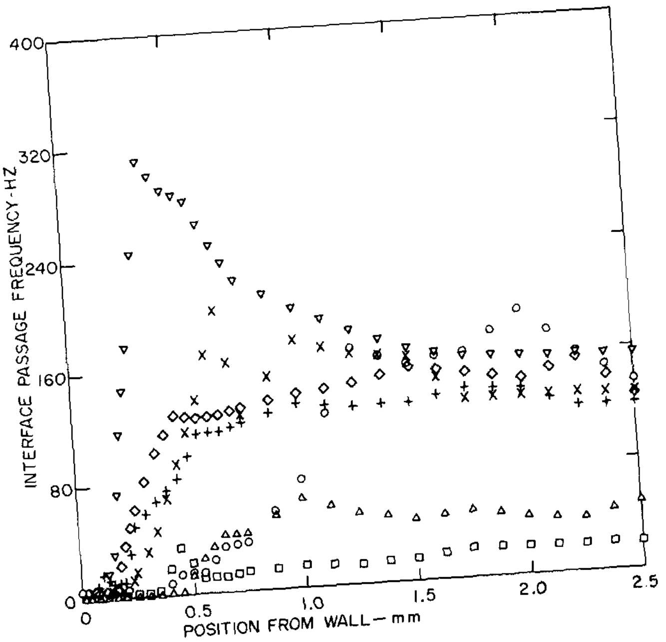

Figure 10. Typical interface passage frequency profiles for $j_L = 0.16$ m/s. Jones (1973) □ $j_G = 0.015$ m/s, bubbly flow; ○ $j_G = 0.070$ m/s, bubbly flow; △ $j_G = 0.036$ m/s, slug flow; + $j_G = 0.131$ m/s, slug flow; × $j_G = 0.494$ m/s, slug flow; ▽ $j_G = 6.34$ m/s, annular flow.

Measurements in one-component, two-phase flow with phase change

Steam–water flow. The earliest paper on hot-wire anemometry in two-phase flow seems to have been published by Katarzhis *et al.* (1955). This preliminary and crude approach wa followed by the work of Hsu *et al.* (1963). These authors, by comparing the signal with high-spee movies concluded that hot-wire anemometry was a potential tool for studying the local structur of two-phase flow, in particular for determining the flow pattern and for measuring the local voi fraction. Hsu *et al.* (1963) specified that in a steam–water flow the only reference temperature i the saturation temperature. If water velocity measurements are carried out, the probe temper ture must not exceed saturation temperature by more than ~5°C to avoid nucleate boiling on th sensor. Conversely, if only a high sensitivity to phase change is desired, then the superhe should range between 5°C and 55°C causing nucleate boiling to occur on the probe when the liqu phase is present, and a resultant shift to forced-convective vapor heat-transfer when the vap phase is present.

Freon–freon vapor flow. The low electrical conductivity of Freons enables bare wires to used instead of hot-film probes. Shiralkar (1970) used a 5 μm, boiling tungsten wire with a v short active length (0.125 mm) so that the whole active zone would generally be inside a bubble or droplet. Local void fraction was determined by an amplitude discriminator with an adjustable threshold level. For void fraction lower than 0.3 the threshold was set just under the liquid level whereas for high void fraction (0.8), it was set just above the vapor level. For void fractions ranging from 0.3 to 0.8 the threshold was set half-way between the liquid and vapor levels. The method was subsequently applied by Dix (1971) and Shiralkar & Lahey (1972).

ELECTRICAL PROBES

What can be measured with electrical probes?

The first requirement when using an electrical probe in two-phase flow is that the phases have significantly different electrical conductivities. Consequently, variations in conductance permit the measurement of the local void fraction and the arrival frequency of the bubbles at a given point in a continuous, conducting fluid. Statistical information can be obtained to characterize the flow pattern. By using a double probe, a bubble velocity can be measured but one has to be very careful when giving a physical significance to this bubble velocity. A detailed survey on the general use of electrical probes was given by Bergles (1969). This section concentrates on the recent developments of the probe technology as well as its use in statistical analysis.

Resistive probes technology

Figure 11 shows the classical electrical diagram of an in-tube resistive probe and a typical probe geometry. Impedance changes due to change of phase distribution between the electrodes produce a variation in the output signal. The relative position and shape of the electrodes differ according to different workers. For instance the tip of the probe may constitute the first electrode while the second electrode may be the metallic protecting sheath of the probe, a second probe, or the general ground of the test section. Lecroart & Porte (1971) developed a miniature probe, the sensing part of which was a tungsten wire, 20 μm in dia. One of the principal features which differentiates the electrical circuits shown in figure 11 is the type of electrical supply.

The direct current supply. Direct current supplies require low voltages in order to reduce electrochemical phenomena on the sensor. Resultant electronics may become troublesome and sensors may still sustain alteration due to electrochemical deposits at low flows. High speed flows clean the sensor. Interesting results were obtained by Lecroart & Porte (1971) in such flows with a special electronic device which maintained a constant voltage between the sensor and the general ground whatever the phase surrounding the tip of the probe thus eliminating external capacitance effects.

The alternating current supply. In this case, phase changes are detected by amplitude modulation of the alternating output signal. This technique has been used by several investigators

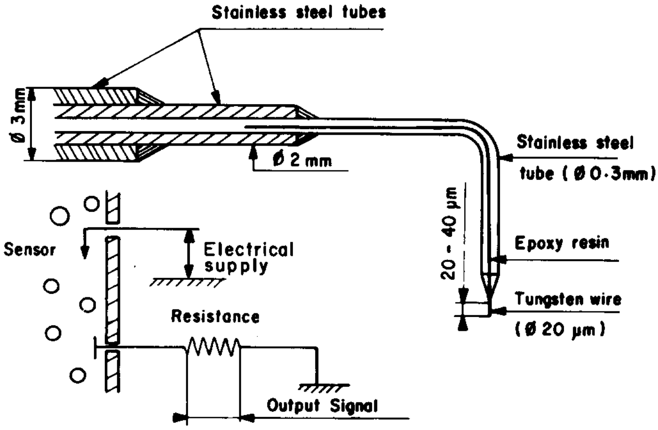

Figure 11. Characteristic resistance probe system. (a) miniature probe geometry of Lecroart & Porte (1971), (b) operating electrical schematic.

to eliminate the electrochemical phenomena on the sensor (Iida & Kobayasi 1969, 1970; Kobayasi 1974). It is necessary to have a current frequency significantly different than the frequency of the physical phenomenon which is to be observed. When high-speed flows are investigated the required supply frequency can be very high, e.g. 1 MHz, and many troubles occur with the electronic apparatus due to such things as stray capacitances. Réocreux & Flamand (1972), for such high-speed two-phase flows, instead used a supply frequency lower than the frequency of the physical phenomenon eliminating electrochemical effects and providing pseudo direct current operation in each half wave.

Signal processing

According to the way that the sensor is energized, the ideal output signal of a resistive probe is either a binary wave sequence, or a sequence of bursts of constant amplitude oscillations separated by zero voltage areas. Actually, the output signal is misshapen with respect to the ideal signal as thoroughly investigated by Lackmé (1967) and by Réocreux & Flamand (1972). The true signal is quite similar in shape to that shown for the optical probe in figure 6. It is generally transformed into a binary sequence with the help of a single trigger level near the liquid voltage. It is found that if the local void fraction is plotted versus the trigger level, an S-shaped curve is obtained with a plateau corresponding to a given value of the void fraction (Iida *et al.* 1967). Iida *et al.* (1967) chose a trigger level value corresponding to this plateau but no justification was given. Serizawa (1974) adjusted the threshold level just under the average liquid level whereas Lecroart & Porte (1971) used a level adjustment based upon an integral comparison with a γ-ray absorption method. This latter seems more practical but requires the assumption that this level is independent of position. It is encouraging that the results from three separate instruments, optical probe, anemometer, and resistance probe all give comparable results as shown by Galaup (1975) in figure 12.

Following this first signal processing, different characteristics of the flow can be determined including a subjective observation of flow pattern, local void fraction by averaging, counting, or histogram methods, and interface frequencies. Bubble diameter distribution functions can also be

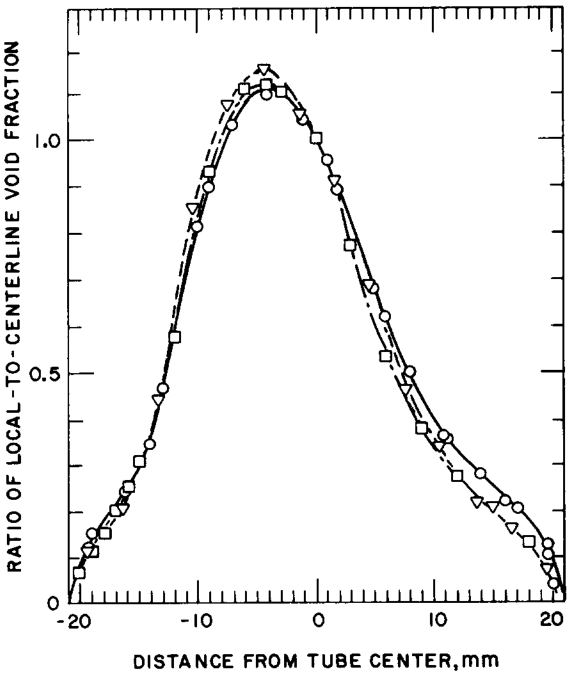

Figure 12. Comparison of results of optical, resistance, and anemometer measurement methods in air-water flow due to Galaup (1975). Optical probe—average $\alpha = 0.35$; resistance probe—average $\alpha = 0.31$; anemometer probe—average $\alpha = 0.37$.

obtained if local velocity is measured (Neal & Bankoff 1963; Sekoguchi *et al.* 1974; Galaup 1975), as well as gas and liquid slug length distributions as shown in figure 13.

Uga (1972) obtained histograms of bubble sizes in the riser and downcomer sections of a BWR. However, he used average values of bubble velocities rather than instantaneous values corresponding to the dewetting signals so that his size distributions were really normalized inverse dry-time distributions where a constant value of velocity was the normalized factor. Similarly, Ibragimov *et al.* (1973) used miniature traversing probes to obtain bubble frequency profiles in water–nitrogen flow similar to those obtained by Jones (1973) with the anemometer. Sekoguchi *et al.* (1974) reported histograms of bubble sizes using a double-tipped probe with tips 4 mm apart and 30 μm in dia. Using the transport time averaged over 10 observations, the bubble rise velocity was obtained which was then used to obtain the bubble size from the dewetting time. Similar to the method of Uga (1972), this method requires the assumption that there is no correlation between bubble size and rise velocity. While this may be true for the >1 mm bubble observed by Sekoguchi (1974), it certainly is not in general. It is interesting to note, however, that these workers obtained excellent agreement between void residence time profile and the volume fraction profile calculated from the bubble diameter and frequency measurements, in agreement with the theoretical analysis by Serizawa (1974) for long sampling times.

In their studies of thin film characteristics of annular two-phase flow, Telles & Dukler (1970), Dukler (1972), and Chu & Dukler (1974) have used the straight electrical probe to determine

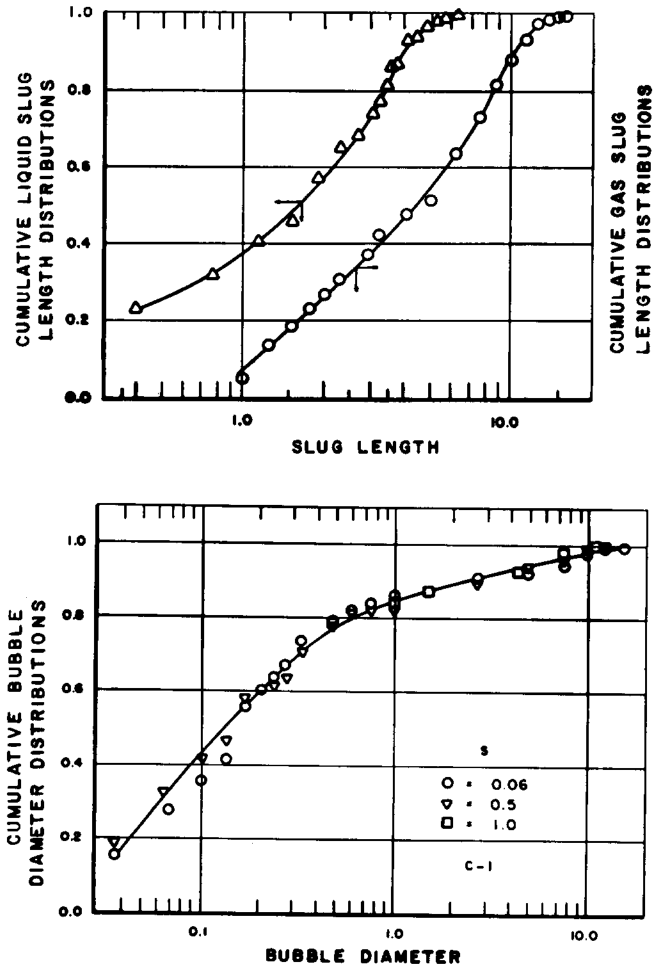

Figure 13. Bubble and slug size distributions according to Neal & Bankoff (1963). (a) Typical slug and bubble length distributions. (b) Typical bubble diameter distributions at different dimensionless radial positions.

information on wave structure. Such information has included probability density functions for wave height where the contributions due to the film substrate and due to large waves have been identified along with wave frequency. Also the spectral and cross spectral densities of film thickness fluctuations were determined as shown in figure 14.

Other statistical data can be obtained by using a double probe. Several authors tentatively described the granulometry of bubbly flows with sophisticated models (Uga 1972; Lecroart & Lewi 1972; Serizawa 1974). A bubble displacement velocity has been looked for by the same authors and also by Lecroart & Porte (1971), Kobayasi (1974), and Galaup (1975).

Serizawa (1974), using a double-tip probe with tips 5 mm apart utilized both correlation and pulse-height methods to determine bubble velocity spectrums. His signal analysis method is shown in figure 15. Correlation of the outputs of the two probes after passing through Schmitt

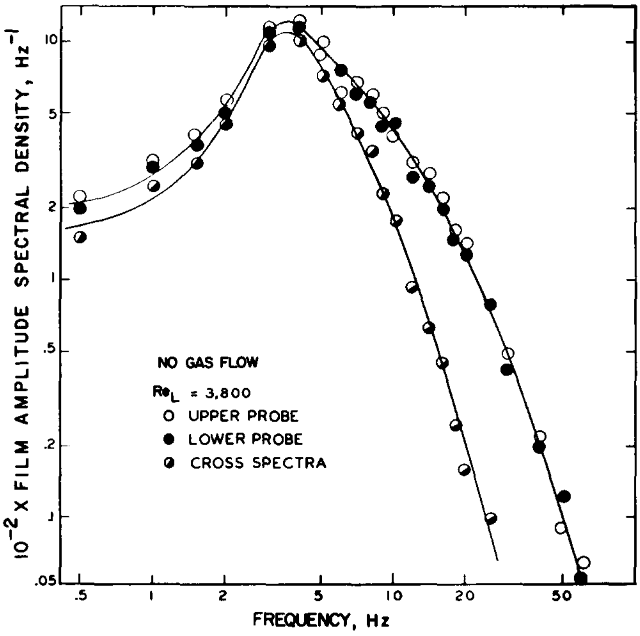

Figure 14. Film thickness fluctuation spectra at two locations. Telles & Dukler (1970).

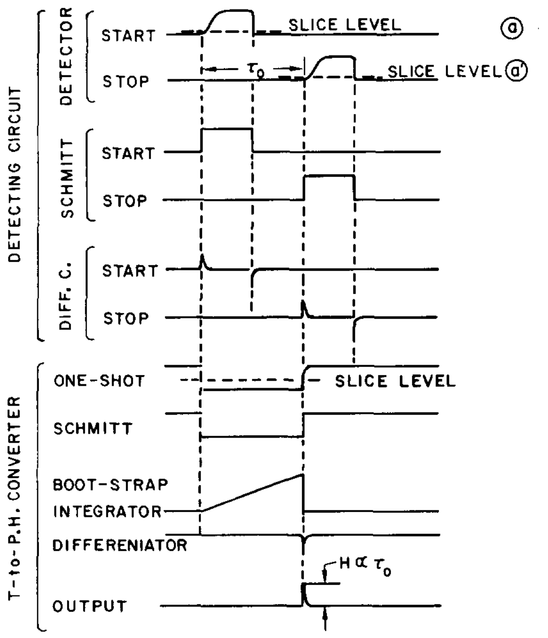

Figure 15. Signal processing method of Serizawa (1974).

triggers provides a function which exhibits a well defined maximum at a time delay corresponding to the transport time between probes. Dispersion of the amplitude of the correlation function is representative of the probability distribution of this velocity, and hence of the fluctuations. Also, by using one probe signal as a starter and the other as a stopper, ramp functions are generated during the transport time which, when stopped and differentiated yield pulses whose heights are proportional to the transport time delay. Height analysis of this pulse train yields the bubble velocity spectra. Results of the two methods are pictured in figure 16. Problems associated with this method include those due to probe wettability and surface tension, and bubble trajectory. Boundary contact times were noted by Sekoguchi *et al.* (1972), to be 100–200 μs resulting in errors of up to 10% in void measurements and Jones (1973) and Jones & Zuber (1975b) measured similar boundary times and errors with a 50 μm hot film anemometer. Generally speaking, more work is needed on this difficult problem, especially on the physical significance of the delay times measured with a double probe.

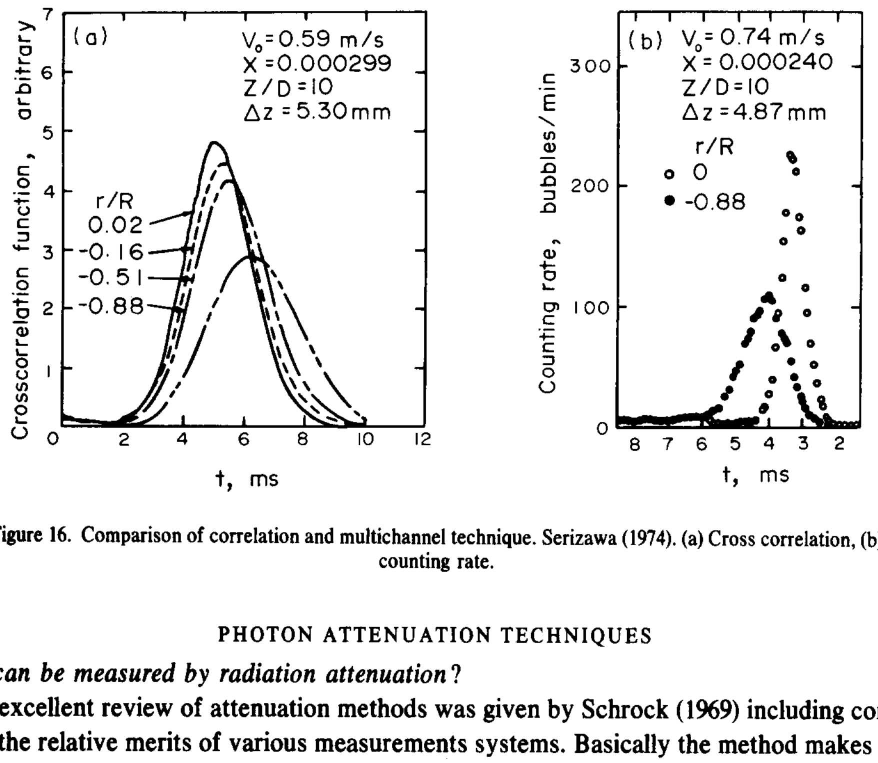

Figure 16. Comparison of correlation and multichannel technique. Serizawa (1974). (a) Cross correlation, (b) counting rate.

PHOTON ATTENUATION TECHNIQUES

What can be measured by radiation attenuation?

An excellent review of attenuation methods was given by Schrock (1969) including comparison of the relative merits of various measurements systems. Basically the method makes use of the observation that a stationary, homogeneous material will absorb a monochromatic beam of constant intensity, short wave-length radiation exponentially with increasing absorption length at constant material density. By using empty and full calibration conditions this method has been the basis of numerous experiments reporting void fraction in single- and two-component, two-phase systems with and without phase change. Its attractiveness lies in its ability to produce reasonable results without disturbing the flow in visually opaque geometries.

Difficulties sometimes occur in reducing parasitic attenuation due to high pressure boundaries. In addition, unfortunately, two phase flow is neither stationary nor homogeneous. Effects due to lack of homogeneity in the form of parallel layers of gas and liquid orientated parallel with the photon beam so that "photon streaming" errors as high as 40% may occur was discussed by Hooker & Popper (1958) and verified by Petrick & Swanson (1958). These errors can be significantly reduced by reducing the size of the beam relative to the size of the voids.

Potentially serious, and until quite recently unrecognized, fluctuation errors can arise due to the coupled effects of fluid motion and nonhomogeneity. The attenuated intensity varies nonlinearly with the gas content of the test section which the beam traverses. Thus, fluctuation amplitudes also vary nonlinearly with fluctuations in gas content. If these fluctuations are themselves averaged by counting, rate meter, low pass filter, or like methods, significant inaccuracies could result when converting the averaged signal back to the desired quantity of mean density or void fraction. These errors were recognized and analyzed by Jones (1970, 1973), Harms & Forrest (1971), Harms & Laratta (1973), and Laratta & Harms (1974). Maximum theoretical errors for idealized, slug-type flow were reported by Jones (1973) as shown in figure 17. These errors for the mixture density are in terms of the gas–liquid density ratio and the dimensionless absorption-coefficient given by $k = s\rho_L\mu_{LG}/\rho_{LG}$ where s is the water gap thickness, μ_{LG} is the difference between liquid and gas linear-absorptivity coefficients, and ρ_L and ρ_{LG} are the liquid density and gas–liquid density differences respectively. The error will generally increase with increasing sensitivity of the signal. Methods of eliminating these errors include linearization of the void signal prior to averaging (Jones 1970, 1973), and short-time sampling, conversion, and averaging of the desired results (Hancox & Harms 1971; Hancox *et al.* 1972).

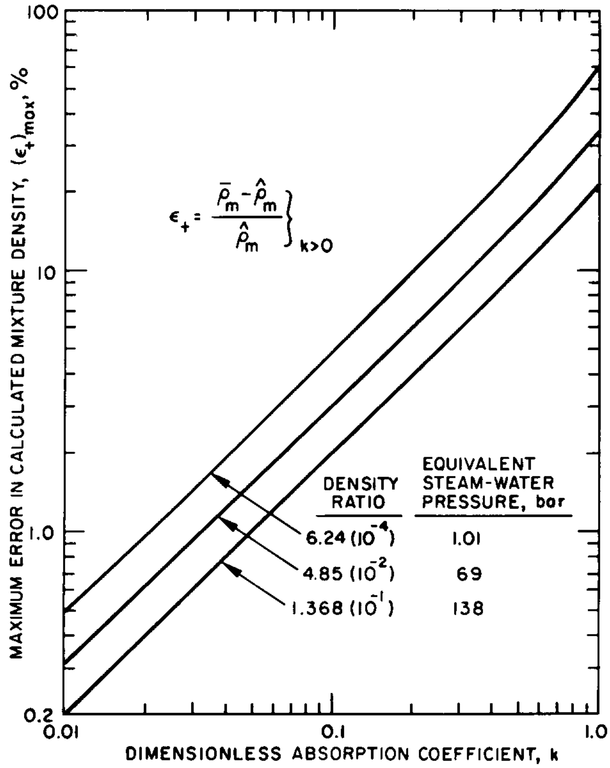

Figure 17. Maximum error in calculated mixture density, $\bar{\rho}_m$, compared with the true value, $\hat{\rho}_m$, due to nonlinearities. Jones (1973).

Transient void fractions

Early reports of the transient measurement of void fraction included those of Ball *et al.* (1958), and Kemp *et al.* (1960). This work was closely followed by that of Schrock & Selph (1963). Both systems could follow relatively rapid transients, the former capable of following a void rate of 0.0076 void fraction/ms while the system of Schrock & Selph (1963) was capable of responding to passage of a 0.1 mm dia void in 1 ms. The system of Kemp *et al.* (1960) was not a linearized system while that of Schrock & Selph (1963) appeared to be close to linear based on comparison between the stated thicknesses of their polystyrene calibrator and their system response to the calibrator. Both systems suffered from severe 60 Hz groundloop noise although Schrock & Selph (1963) took pains to reduce 60 Hz noise by carefully balancing three-phase power supply sources. D.C. drift was also a problem amounting to over 0.20 voids per hour in the system of Kemp *et al.* (1960) so that they reported only variations in void fraction in their studies of dynamic response of a simulated SPERT-1A rectangular, reactor channel. Schrock *et al.* (1966) obtained data for transient void volume in pool boiling similar to those shown in figure 18.

More recently, Zuber *et al.* (1967) used a similar system to those described above but low-pass filtered to eliminate 60 Hz noise. They obtained data for void oscillation amplitude and phase lag with respect to power oscillations. Nyer (1969) reported on an X-ray system having 2.2 ms response times and 60 Hz ripple of ~0.10 voids for studying rapid power transients in a rectangular channel. Jones (1970) determined that the 60 Hz noise was due mostly to the A.C. component of the rectified and filtered high voltage applied to the X-ray tube. Installation of a solid state, full-wave rectifier in the tube current supply circuit along with the 80,000 μF across these lines resulted in a signal having ripple less than 0.03 voids while maintaining better than 1.0 ms response times under optimal conditions. (Increasing the parasitic attenuation, however, severely reduced the system bandwith.) D.C. drift was also reported to be a problem but was later found (Jones 1973) to be due to very long-term thermal drift of the system. Continuous operation after 12 h was found to limit this cyclic drift to less than 0.005 voids/h.

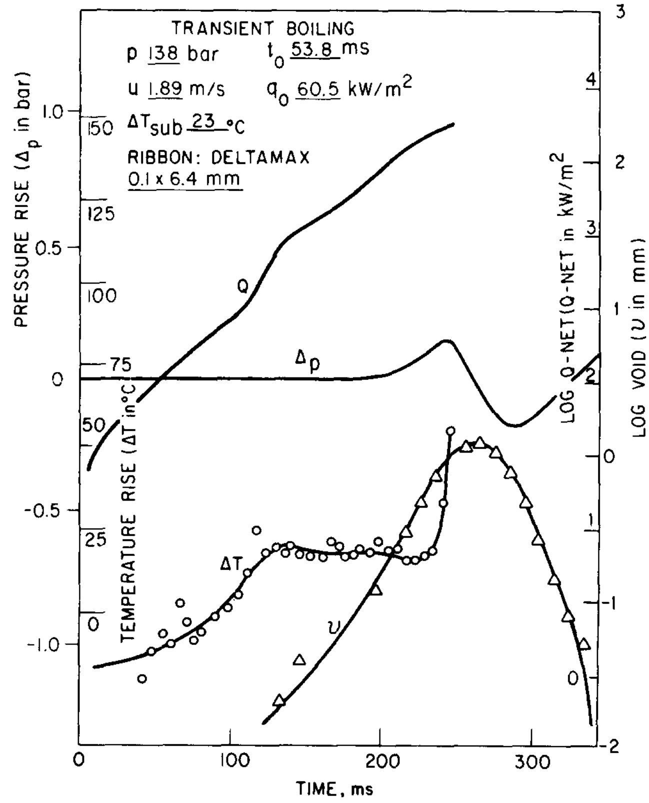

Figure 18. Typical transient pool boiling data of Schrock *et al.* (1966).

Statistical measurements

There are little reported data for statistical quantities measured by radiation techniques. Hancox & Harms (1971), and Hancox *et al.* (1972) used a 7000 neutron per s beam to make short interval, discrete time void measurements to construct histograms (figure 19). Their measurements indicated that a detection period of 0.05 s was sufficiently small to maintain fluctuation errors less than 0.10. However, since the errors are due to the fluctuations occurring in the observation period, this conclusion would not be true where fluctuation periods are significantly smaller than those investigated. Also, sampling times longer than the fluctuation period eliminate some of the fine structure of the flow. This is probably why only a single peak is observed for the churn flow histogram rather than a double peaked histogram, one peak for the bubbly slugs and one for the major bubbles (Jones & Zuber 1974, 1975a).

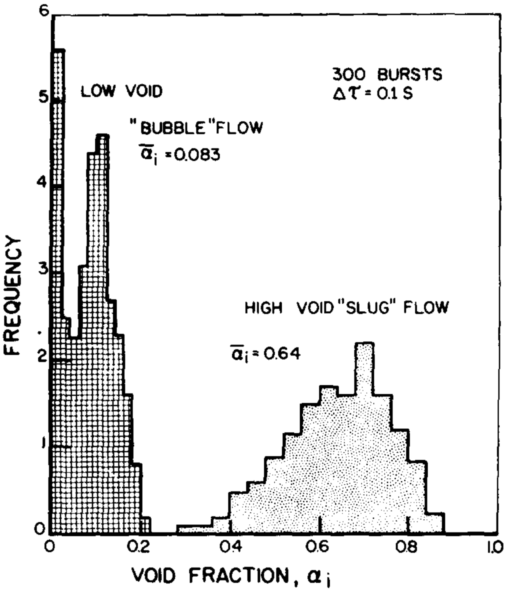

Figure 19. Void fraction frequency distributions of Hancox *et al.* (1971).

Kölbel *et al.* (1972) measured void fraction and void fluctuation profiles in a bubble column, and obtained probability distributions of the fluctuations. Jones (1970, 1973), and Jones & Zuber (1974, 1975a) reported on a linearized X-ray system having millisecond response times. Probability density functions and fluctuation spectra were obtained for the void fraction similar to those shown in figure 20. No attempt was made to eliminate the statistical system noise from their system since this amounted only to a standard deviation of 0.022 voids. In more opaque systems the results become less definitive unless care is taken to subtract out the extraneous noise component from these measurements.

MISCELLANEOUS METHODS

Recent developments of interest which do not fit any of the previously discussed categories should be mentioned because of the potentially important information they may yield regarding the statistical or transient structure of two-phase flows.

Ishigai *et al.* (1965) demonstrated that fluctuations in pressure are directly related to the individual component flows in an air-water system. Hubbard & Dukler (1966) studied pressure fluctuations below 10 Hz in horizontal air–water flow and showed that the type of flow pattern could be characterized by the fluctuation spectra of the pressure signal. In fact, they showed there to be little difference between various subgroups of flow patterns and suggested a simplification in the overall classification such that dispersed, intermittant, and separated regimes be those considered dominant. Akagawa *et al.* (1971) studied differential pressure fluctuations below 50 Hz in vertical air–water flow in a round tube with electrical probes and quick closing valves for direct measurement of mean void fraction, and reported probability distributions, power spectra, and amplitude ratios for the pressure drop fluctuations, as well as probability distributions for bubble lengths.

Recent studies regarding safety aspects of fast breeder reactors have led to the use of liquid metals rather than water or organic fluids as coolants. The advantage that liquid metals are electrically good conductors has led to some interesting methods for dynamic analysis of simulated loss of flow accidents without scram. Henry *et al.* (1974a, b) report the use of voltage taps located axially along the outer wall of the hexagonal can holding a seven-pin bundle with high temperature liquid sodium flow. Measurement of the relative voltage drop between these taps compared with full and empty reference values and the one-dimensional electrical current flow assumption allowed the calculation of instantaneous void volume within the bundle. Similarly,

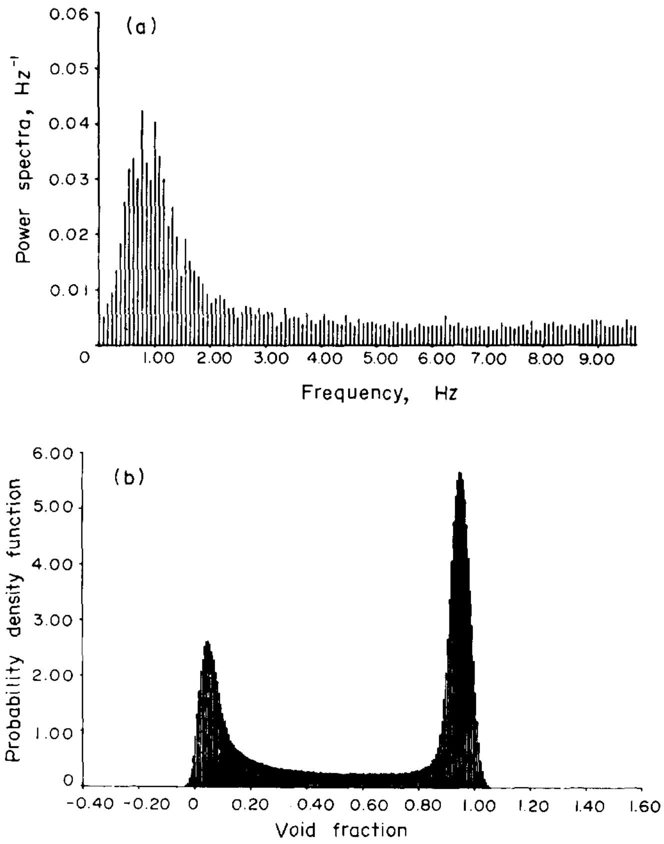

Figure 20. Statistical X-ray void data of Jones (1973), and Jones & Zuber (1974, 1975a), in slug flow. (a) Fluctuation spectra; (b) void probability distribution function.

Kottowski *et al.* (1974) attached pairs of voltage taps along tubes having walls 0.1 mm thick. Using NaK eutectic at ambient temperature they measured film thicknesses within 2% for 0.1 mm-thick films.

The use of laser scattering techniques for statistical analysis of two-phase dispersed flows was recently reported by Zimin *et al.* (1973) who obtained measurements of the local particle distribution for dusty gas flows. No estimation for the accuracy of their system was given. It is noted, however, that Popper *et al.* (1974) used a laser-Doppler system calibrated to known references within 3% to measure velocity profiles of droplets in a two-phase jet. The laser method has the obvious drawback that light transmission is required and that partial concentrations cannot become so large as to severely reduce the strength of the light beam. Use in fully dispersed mist flow would be a distinct possibility at the exit of an internal geometry but the presence of an annular film would be difficult to overcome. Durst & Zaré (1975) recently undertook a detailed analysis of laser-Doppler anemometry in systems with interfaces of large curvature which were either totally reflecting or partially transparent. They showed that the general considerations using Mie's light scattering principle yield analytical results which are contrary to experimental results. Instead, they developed a method which uses interference fringes from reflection of two separate laser beams to obtain sizes and velocities of bubbles and droplets. In all cases their theory appears to be validated by their experiments. Still, the method seems to require a discrete phase which is generally of isolated nature rather than swarms of bubbles or droplets in close proximity with each other.

Two recent papers have described the use of laser holography in two-phase gas–liquid flows. Alad'ev *et al.* (1973) determined that two beam holography could be most effective in mist flows where the droplets were 20 μm or larger in dia as well as with thin films of 5–35 μm (interferometry) or greater than 150 μm (shadowgrams). Use was described for measurement of droplet accelerations from 1 to 50 m/s as well as pressure distributions from interferograms of the gas phase in the core. Lee *et al.* (1974) used a single ruby laser to measure size and velocity of drops for air–water critical two-phase flows over 95% quality. Results included the determination of size and velocity distributions based on particle size (figure 21) as well as the particle velocity histograms.

Finally, Nishihara (1974) has used statistical correlation of the signals from acoustic detectors to determine the location of boiling of < 50 ms duration in a simulated reactor vessel by triangulation techniques. Use of this method to obtain void information may be difficult in geometries where reflections occur, or at moderate and high void levels. Its primary use would be to detect boiling incipience in reactors, or for transient tests where obscuration of later results could be tolerated.

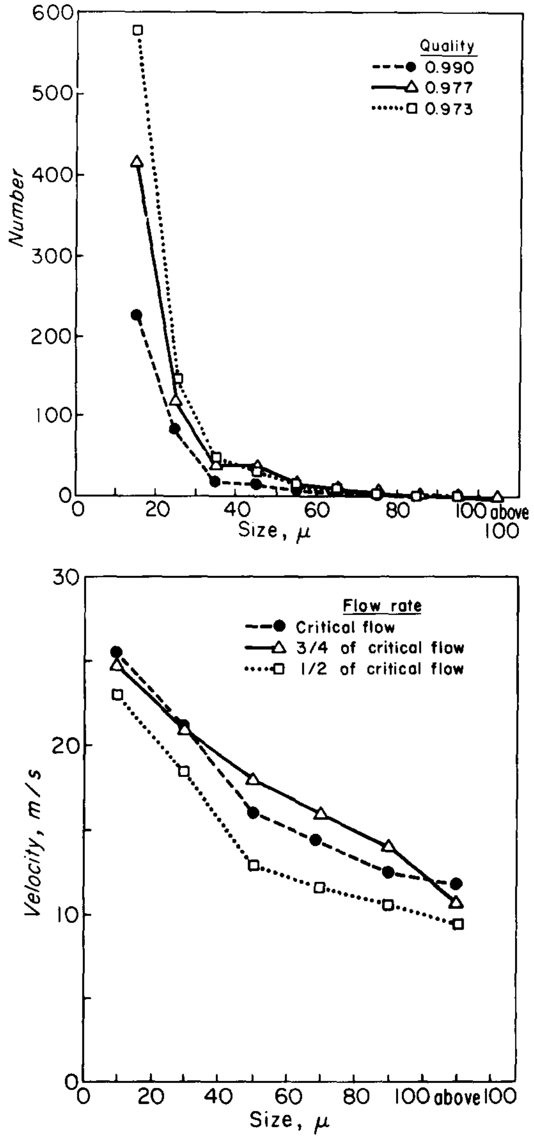

Figure 21. Droplet size (a) and velocity distributions (b) obtained by Lee *et al.* (1974). (a) number vs. size at different qualities for critical flow (1.5 cm from the exit plane), (b) average velocity vs. drop size at different flow rates.

CONCLUSIONS

Instrumentation methods capable of yielding transients or statistical information in two-phase flows have been reviewed. These instruments include microthermocouples, optical probes, hot-film anemometers, electrical (conductivity) probes, and photon attenuation methods, as well as several miscellaneous techniques which are capable of providing a wide range of information regarding the statistical or transient structure of two-phase, gas—liquid flows. Such information includes local and chordal void fluctuation spectra and probability density functions, liquid and vapor mean velocity and turbulent fluctuations, interface passage frequencies, and void and droplet sizes among others. Through the use of these and other techniques a coherent picture of the interactions of the phases will eventually be accomplished, allowing more detailed and realistic models of multiphase phenomena.

The *optical probe* system theoretically gives an on–off signal corresponding to phase change due to the passage of an interface, the only requirement being a sufficient difference between the indices of refraction of the liquid and gaseous states. This is generally true for most fluids, one exception being hydrogen where $n_G = 1.00$ and $n_L = 1.10$. Recent improvements in these systems include miniaturization of the sensor to 100 μm dia, integration of the electronics, and use of dual sensors for velocity determination. In practice, stretching of interfaces around the sensitive portion of the probes yield other than a true binary signal, resulting in the need for interpretation of the results. This is usually accomplished by means of a single or double trigger arrangement where threshold(s) must be adjusted to yield accurate results. To date these thresholds have been adjusted so that the line-averaged void fraction will agree with that measured by a γ-ray densitometer. There is no guarantee, however, that these thresholds should be held fixed during a traverse. Thus, since the baseline signal, U_0, also varies with position, significant errors might be expected to occur in local void measurement. On the other hand, agreement has been noted in local measurements using the optical probe in comparison with electrical probes and anemometers. This question will have to be settled by further work.

The small size of the U-shaped fiber system presents the least disturbance to the flow of any system reported. The small size makes it ideal for use in dual-sensor systems where cross correlation of the signals would be expected to yield information regarding the average interfacial velocities and their fluctuations. Unlike the thermocouple, this system would not be applicable to corrosive environments such as high pressure steam–water flows which readily dissolve the glass.

The electrical probe is probably the simplest device, next to the thermocouple, for obtaining statistical information in two phase flows. It has obvious disadvantages in requiring the liquid to be both conducting, and continuous, at least between two points in the fluid. Further, electrochemical effects occur in the most simple, D.C. excitation mode which tend to alter the response in time. Alternating current supplies can circumvent this problem but may lead to others. Jones (1973) has shown that the frequencies characteristic of two phase flows may range from less than 1 Hz for slug flows at low velocities, to near 5 kHz for droplet passage in annular mist flows. High frequency supplies which would be significantly above this upper range present problems due to stray capacitance effects. Very low frequencies make it difficult to separate the signal from the carrier. Cleanliness of the system is an important consideration in D.C. systems as is variation in fluid resistivity. The latter may be difficult to account for in fluids such as water where resistivity decreases due to electrolytic dissociation with increasing temperatures. Recent improvements, similar to the optical probe, include decreased size (to 20 μm), and use of dual probes to measure velocities and obtain velocities histograms.

Similar comments regarding the signal analysis may be made for the conductivity probe as were made for the optical systems. Signals are not ideal so that discrimination methods may be inaccurate and require a standard such as an X- or γ-ray measurement of overall void fraction. Histogram analysis appears to present a better possibility although much more costly. One final note of caution is indicated by those workers who have used average velocities to get bubble sizes. Instantaneous velocity values should be used to insure the correlative effects of size on velocity are properly included.

The wedge and conical hot film *anemometer probes* are sufficiently massive so as to be somewhat resistant to some of the operational difficulties associated with cylindrical hot films and hot wires. On the other hand their frequency response is an order of magnitude lower than their cylindrical counterparts and they cannot be used in small geometries as can the cylindrical sensors and hot wires. Anemometers have the advantage over electrical and optical probes in that they can measure mean and fluctuating characteristics of the fluid velocity as well as temperature and void fractions. Accuracy of the signal processing has recently improved but still needs further work. The adequacy of the hot wire as a droplet size sampler is still questionable and requires more work. The cylindrical quartz-coated, hot-film sensors have the problem of calibration instability in the low velocity range (< 30 cm/s) once they have experienced velocities over the range of 1.5 m/s, this instability due to failure of the coating. It is unclear whether this would be a problem in organic fluids but in this case, bare hot wires can be used. No instance has been found of reported use of these types of sensors in high temperature corrosive environments such as those experienced in pressurized or boiling water reactors or high temperature liquid metal systems. It is well known that quartz is easily dissolved in high temperature water, as are most ceramic materials suitable for thin coating of the sensors. The difficult problem of obtaining statistical information of phase velocities in one-component, two-phase flows has yet to be solved. As for local void fraction measurements, a major advantage of hot-film anemometry is that this method can be used regardless of the electrical conductivity of the liquid. In both cases, the anemometer gives a signal which is characteristic of the flow pattern. A major drawback, however, is the cost of the electronics, and the extreme fragility of the sensors.

Microthermocouples have come into increasing use in recent years and have combined phase indication through electrical conductivity with instantaneous temperature signals. The manner in which the probability density functions (PDF) of fluctuations due to vapor and those due to liquid in nonequilibrium conditions combine to yield the total time PDF has been clearly demonstrated. While it has not yet been reported, there seems no reason why dual microthermocouples cannot be used to yield simultaneous information on interfacial velocities along with temperature and void signals. Discrimination of the phase signal and phase separation is subject to the same problems associated with the other probes and again, histogram analysis appears to present the best albeit the most expensive choice for the same reasons. Determination of the actual vapor temperature, especially the maximum in bubbly flow, and determination of the liquid temperature in mist flow, especially the minimum, is a strong function of the sensor size and the fluid temperatures. This has been clearly demonstrated by Van Paassen (1974) who used a microthermocouple as a droplet size sampler.

Transient and statistical photon attenuation techniques remain constrained to the streaming errors inherent in steady state systems. Further, errors due to improper averaging of the signal nonlinearly related to the quantity desired have recently been identified as inherent in any two phase system since void fluctuations are the rule rather than the exception. Care must be taken to avoid these errors, especially in systems of high sensitivity. Two basic methods have been devised to circumvent the error due to fluctuations: short term sampling and signal linearization. Both appear equally capable in theory although the former must have sampling times shorter than the fluctuation period to be effective. The latter method seems easier, less expensive, and perhaps more accurate.

Major advances in recent years have resulted from identification of the source of 60 Hz noise inherent in almost all X-ray systems, and the elimination of D.C. drift as a significant problem. It is currently possible to design an X-ray measurement system having a 1 ms response time with time averaged noise on the order of 0.02 standard deviation in void fraction, and drift less than 0.005 voids/h. Significant increases in parasitic attenuation, however, severely decrease the bandwidth and increase the noise of the system. It is doubtful whether these optimum conditions could be achieved, for instance, in a system required to contain a two-phase mixture at high pressure due to decreasing signal-to-noise ratio. Flow pattern determination in these conditions would be more difficult due to possible overlapping of the probability density functions of the bubbly-like, and annular-like components of slug flow.

All of the probe-type sensors discussed have a common problem in discrimination of the signal to separate the phases. Yet to be developed is a method for finding a proper trigger level so as to eliminate the need for comparison with a photon measurement as a standard. Laser-Doppler anemometry shows some promise in cases where the discrete phase is sufficiently dilute to be able to target individual interfaces with no intervening discontinuities. This may prove particularly useful in measuring interfacial turbulence and film velocity profiles and spectra in annular flows, a subject of wide interest.

Finally, more work must be done to determine the interactive effects between the phases, especially instantaneous shear, momentum fluctuation profiles, objective flow pattern transitions, interfacial area densities, constitutive laws for one-dimensional void and velocity profiles, and constitutive laws for the phase interaction terms. Instrumentational methods are now capable of providing this information.

REFERENCES

AFGAN, N., JOVANOVIC, L. J., STEFANOVIC, M. & PISLAR, V. 1973a An approach to the analysis of temperature fluctuation in two-phase flow. *Int. J. Heat Mass Transfer* **16**, 187–194.

AFGAN, N., STEFANOVIC, M., JOVANOVIC, L. J. & PISLAR, V. 1973b Determination of the statistical characteristics of temperature fluctuation in pool boiling. *Int. J. Heat Mass Transfer* **16**, 249–256.

AKAGAWA, K. 1964 Fluctuations in void ratio in two-phase flow. *Bull. J.S.M.E.* **7**, 122–128.

AKAGAWA, K., HAMAGUCHI, H., SAKAGUCHI, T. & IKARI, T. 1971 Studies of the fluctuation of pressure drop in two-phase slug flow. *Bull. J.S.M.E.* **14**, 447–469.

ALAD'EV, I. T., GINSBERG, V. M , GAVRILOVA, N. D., KUZNETSOVA, E. A., SOLUYANOV, Yu. S. & TSARFIN, Y. Ya. 1973 Investigation of the possibility of using holography in the study of two-phase flows. *Teploenergetika* **20**, 66–68.

BALL, W. P., LANGMUIR, D. B. & WRIGHT, R. W. 1958 X-ray measurements of time varying steam void fraction in a thin water channel. *Trans. A.N.S.* **1**, No. 2, 59; also TRW Report RW-RL-137 (1959).

BAROIS, G. 1969 Etude expérimentale de l'autovaporisation d'un écoulement ascendant adiabatique d'eau dans un canal de section uniforme. Thèse de docteur-ingénieur, Faculté des Sciences de l'Université de Grenoble.

BELL, R., BOYCE, B. E. & COLLIER, J. G. 1972 The structure of a submerged impinging gas jet. *J. Br. Nucl. Energy Soc.* **11**, 183–193.

BERGLES, A. E. 1969 Electrical probes for study of two-phase flows, *Two-Phase Flow Instrumentation* (Edited by LE TOURNEAU, B. W & BERGLES, A. E.) pp. 70–81. A.S.M.E.

BONNET, C. & MACKE, E. 1966 Fluctuations de température dans la paroi chauffante et dans le liquide au cours de l'ébullition nucléée. EUR 3162f.

BOUVARD, M. & DUMAS, H. 1967 Application de la méthode du fil chaud à la mesure de la turbulence dans l'eau. *Houille Blanche* **3**, 257–270.

BRAGG, G. M. & TEVAARVERK, J. 1971 The effect of a liquid droplet on a hot-wire anemometer probe. *Flow—Its Measurement and Control in Science and Industry* (Edited by DOWDELL, R. B.) Vol. 1, Part 2, pp. 599–604. I.S.A.

CHU, K. J. & DUKLER, A. E. 1974 Statistical characteristics of thin, wavy films. *A.I.Ch.E. J.* **20**, 695–706.

CHUANG, S. C. & GOLDSCHMIDT, V. W. 1969 The response of a hot-wire anemometer to a bubble of air in water. *Turbulence Measurements in Liquids* (Edited by PATTERSON, G. K. & ZAKIN, J. L.) University of Missouri, Rolla, Continuing Education Series.

DANEL, F. & DELHAYE, J. M. 1971 Sonde optique pour mesure du taux de présence local en écoulement diphasique. *Mesures-Régulation-Automatisme*, Août-Septembre, pp. 99–101.

DELHAYE, J. M. 1968 Measurement of the local void fraction in two-phase air–water flow with a hot-film anemometer. CEA-R-3465(E).

DELHAYE, J. M. 1969 Hot-film anemometry, *Two-phase flow instrumentation.* (Edited by LE TOURNEAU, B. W. & BERGLES, A. E.) pp. 58–69. A.S.M.E.

DELHAYE, J. M. SÉMÉRIA, R. & FLAMAND, J. C. 1972 Mesure du taux de vide local et des températures du liquide et de la vapeur en ecoulement diphasique avec changement de phase à l'aide d'un microthermocouple. CEA-R4302.

DELHAYE, J. M., GALAUP, J. P., RÉOCREUX, M. & RICQUE, R. 1973a Métrologie des écoulements diphasiques-Quelques procédés. C.E.A. R-4457.

DELHAYE, J. M , SÉMÉRIA, R. & FLAMAND, J. C. 1973b Void fraction, vapor and liquid temperatures: local measurements in two-phase flow using a microthermocouple. *J. Heat Transfer* **95C**, 365–370.

DELHAYE, J. M. 1974 Les techniques de mesure dans les écoulements diphasiques, *Techniques de Mesure dans des Écoulements.* Collection de la Direction des Etudes et Recherches de l'E.d.F., Eyrolles, Paris.

DELHAYE, J. M. & GALAUP, J. P. 1975 Measurement of local void fraction in Freon-12 with a 0.1 mm optical fiber probe. Private communication.

DIX, G. E. 1971 Vapor void fractions for forced convection with subcooled boiling at low flow rates. General Electric Co., NEDO-10491.

DUKLER, A. E. 1972 Characterization, effects, and modeling of the wavy gas-liquid interface. *Progress in Heat and Mass Transfer* (Edited by HETSRONI, G., SIDEMAN, S. & HARTNETT, J. P.) Vol. 6, pp. 207–234. Pergamon, Oxford.

DURST, F. & M. ZARÉ 1975 Laser doppler measurements in two-phase flows. University of Karlsruhe Report SBF 80/TM/63.

GALAUP, J. P. 1975 Contribution à l'étude des méthodes de mesure en écoulement diphasique. Thèse de docteur-ingénieur, Université Scientifique et Médicale de Grenoble, Institut National Polytechnique de Grenoble.

GINSBERG, T. 1971 Droplet transport in turbulent pipe flow. ANL-7694.

GOLDSCHMIDT, V W. 1965 Measurement of aerosol concentrations with a hot-wire anemometer. *J. Colloid Sci.* **20**, 617–634.

GOLDSCHMIDT, V. W. & ESKINAZI, S. 1964 Diffusion de particules liquides dans le champ retardataire d'un jet d'air plan et turbulent. *Les Instabilités en Hydraulique et en Mécanique des Fluides*, pp. 291–298. Société Hydrotechnique de France,8 èmes journées de l'Hydraulique. Lille, France.

GOLDSCHMIDT, V. W. & ESKINAZI, S. 1966 Two-phase turbulent flow in a plane jet. *J. Appl. Mech.* **33**, 735–747.

GOLDSCHMIDT, V. W. & HOUSEHOLDER, M. K. 1968 Measurement of aerosols by hot-wire anemometry. *Advances in Hot-Wire Anomometry*, (Edited by MELNIK, W. L. & WESKE, J. R.) pp. 134–152. Dept of Aerospace Eng., University of Maryland.

GOLDSCHMIDT, V. W. & HOUSEHOLDER, M. K. 1969 The hot-wire anemometer as an aerosol droplet size sampler. *Atmospheric Environment.* Vol. 3, pp. 643–651.

GOLDSCHMIDT, V. W., HOUSEHOLDER, M. K., AHMADI, G. & CHUANG, S. C. 1972 Turbulent diffusion of small particles suspended in turbulent jets. *Progress in Heat and Mass Transfer*, (Edited by HETSRONI, G., SIDEMAN, S. & HARTNETT, J. P.) Vol. 6, pp. 487–508. Pergamon, Oxford.

HANCOX, W. T. & HARMS, A. A. 1971 Discrete-time neutron interrogation of liquid flow systems. *Trans. ANS* **14**, 699.

HANCOX, W. T., FORREST, C. F. & HARMS, A. A. 1972 Void determination in two-phase systems employing neutron transmission. ASME Paper 72-HT-2.

HARMS, A. A. & FORREST, C. F. 1971 Dynamic effects in radiation diagnosis of fluctuating voids. *Nucl. Sci. Engng* **46**, 408–413.

HARMS, A. A. & LARATTA, F. A. R. 1973 The dynamic-bias in radiation interrogation of two-phase flow. *Int. J. Heat Mass Transfer* **16**, 1459–1465.

HENRY, R. E., SINGER, R. M., QUINN, D. J. & JEANS, W. C. 1974a Incipient superheat in a convective sodium system. Paper B7.1 presented at the Fifth International Heat Transfer Conf., Tokyo, 3–7 Sept 1974, 305–309.

HENRY, R. E., SINGER, R. M., LAMBERT, G. A., MCUMBER, L. M., QUINN, D. J., SPLEHA, E. A., ERICKSON, E. G., JEANS, W. C. & PARKER, N. E. 1974b Sodium expulsion tests for the seven-pin geometry. *Proc. Fast Reactor Safety Mtg.*, Beverly Hills, CA., 2–4 Apr CONF-740401 (in 3 parts), 1188–1201.

HETSRONI, G., CUTTLER, J. M. & SOKOLOV, M. 1969 Measurements of velocity and droplets concentration in two-phase flows. *J. Appl. Mech.* **36E**, 334–335.

HEWITT, G. F. 1972 The role of experiments in two-phase systems with particular reference to measurement techniques. *Progress in Heat and Mass Transfer.* (Edited by HETSRONI, G , SIDEMAN, S., HARTNETT, J. P.) Vol. 6, pp. 295–343. Pergamon, Oxford.

HINATA, S. 1972 A study on the measurement of the local void fraction by the optical fibre glass probe. *Bull. J.S.M.E.* **15**, 1228–1235.

HOLLASCH, K. & GEBHART, B. 1972 Calibration of constant-temperature hot-wire anemometers at low velocities in water with variable fluid temperature. *J. Heat Transfer* **94C**, 17–22.

HOOKER, H. H. & POPPER, G. F. 1958 A gamma-ray attenuation method for void fraction determination in experimental boiling heat transfer test facilities. ANL-5766.

HSU, Y. Y., SIMON, F. F. & GRAHAM, R. W. 1963 Application of hot-wire anemometry for two-phase flow measurements such as void-fraction and slip-velocity. *Multi-Phase Flow Symposium*, (Edited by LIPSTEIN, N. J.) 26–34. ASME.

HUBBARD, M. G. & DUKLER, A. E. 1975 The characterization of flow regimes for horizontal two-phase flow. *Proc.* 1966 *Heat Trans. and Fluid Mech. Inst.* (Edited by SAAD, M. A. & MILLER, J. A.) Stanford University Press, 100–121.

HURT, J. C. & WELTY, J. R. 1973 The use of a hot-film anemometer to measure velocities below 5 cm/sec in mercury. *J. Heat Transfer* **95C**, 548–549.

IBRAGIMOV, N. Kh., BOBKOV, V. P. & TYCHINSKII, N. A. 1973 Investigation of the behavior of the gas phase in a turbulent flow of a water–gas mixture in channels. *Teplofiz. Vysok. Temp.* **11**, 1051–1061. Also *High Temperature*, **11**, 935–944, Consultants Bureau, New York.

IIDA, Y., KOBAYASI, K. & KUMAGAI, S. 1967 A study on the measurement of void fraction by probe method. *J. Atomic Energy Soc. Japan* **9**, 2–9.

IIDA, Y. & KOBAYASI, K. 1969 Distributions of void fraction above a horizontal heating surface in pool boiling. *Bull. J.S.M.E.* **12**, 283–290.

IIDA, Y. & KOBAYASI, K. 1970 An experimental investigation of the mechanism of pool boiling phenomena by a probe method. *Heat Transfer*, Vol. 5, pp. 1–11. Elsevier, Amsterdam.

ISHIGAI, S., YAMANE, M. & ROKO, K. 1965 Measurement of the component flows in a vertical two-phase flow by making use of the pressure fluctuations. *Bull. J.S.M.E.* **8**, 375–382.

ISHIGAI, S., NAKANISI, S., KOIZUMI, T. & OYABU, Z. 1972 Hydrodynamics and heat transfer of vertical falling liquid films (Part 1: Classification of flow regimes). *Bull. J.S.M.E.* **15**, 594–602.

JACOBS, J. & SHADE, A. H. 1969 Measurement of temperatures associated with bubbles in subcooled pool boiling. *J. Heat Transfer*, **91C**, 123–128.

JIJI, L. M. & CLARK, J. A. 1964 Bubble boundary layer and temperature profiles for forced convection boiling in channel flow. *J. Heat Transfer*, **86C**, 50–58.

Jones, O. C. 1966 Preliminary investigation of hot-film anemometer in two-phase flow. USAEC Report TID-24104.

Jones, O. C. 1970 Determination of transient characteristics of an X-ray void measurement system for use in studies of two-phase flow. KAPL-3859.

Jones, O. C. 1973 Statistical considerations in heterogeneous, two-phase flowing systems. Ph.D. Thesis, Rensselaer Polytechnic Institute, Troy, N.Y.

Jones, O. C. & Zuber, N. 1974 Statistical methods for measurement and analysis in two-phase flow. Paper B5.4, Proc. 5th Int. Heat Transfer Conf., *IV*, 200, 3–7 Sept.

Jones, O. C. & Zuber, N. 1975a The interrelation between void fraction fluctuations and flow patterns in two-phase flow. *Int. J. Multiphase Flow* **2**, 273–306.

Jones, O. C. & Zuber N. 1975b Use of a cylindrical hot film anemometer for measurement of two-phase void and volume flux profiles in a narrow rectangular channel. A.I.Ch.E. Paper No. 45, presented at the National Heat Transfer Conf., San Francisco, 11–13 Aug.

Katarzhis, A. K., Kosterin, S. I. & Sheinin, B. I. 1955 An electric method of recording the stratification of the steam–water mixture. *Izv. Akad. Nauk SSSR* **2**, 132–136, A.E.R.E. Lib./Trans. 590.

Kemp, R. F., Morse, A. L., Wright, R. W. & Zivi, S. M. 1960 Kinetic studies of heterogeneous water reactors. RWD-RL-167.

Kennedy, T. D. A. & Collier, J. G. 1974 The structure of an impinging gas jet submerged in a liquid. *Multi-Phase Flow Systems.* Inst. Chem. Engng Symp. Ser. No. 38, **II**, Paper J4.

Kobayasi, K. 1974 Measuring method of local phase velocities and void fraction in bubbly and slug flows, Presented at the *Fifth Int. Heat Transfer Conf.*, Round Table RT-1.

Kölbel, H., Beinhauer, R. & Langemann, H. 1972 Dynamische Messung des relativen Gasgehaltes in Blasensäulen mittles Absorption von Röntgenstrahlen. *Chemie-Ingr-Tech.* **44**, 697–704.

Kottowski, H. M., Mol, M. J., Morandi, A., Pancaldi, E. & Zurli, A. 1974 Measurement of the liquid metal residual film left behind coolant expulsion in narrow channels. Proc. Fast Reactor Safety Mtg., Beverly Hills, CA., 2–4 Apr. 1173–1187.

Lackmé, C. 1964 Statistical analysis of the local structure of a two-phase flow. C.E.N.G. Notes TT-162 and TT-176. Also ANL-Trans-171 and 172.

Lackmé, C. 1967 Structure et cinématique des écoulements diphasiques à bulles. CEA-R3203.

Laratta, F. A. R. & Harms, A. A. 1974 A reduced formula for the dynamic-bias in radiation interrogation of two-phase flow. *Int. J. Heat Mass Transfer* **17**, 464.

Lecroart, H. & Porte, R. 1971 Electrical probes for study of two-phase flow at high velocity. Presented at the Internat. Symposium on Two-Phase Systems, Haifa, Israel.

Lecroart, H. & Lewi, J. 1972 Mesures locales et leur interprétation statistique pour un écoulement diphasique à grande vitesse et taux de vide élevé. Société Hydrotechnique de France, Douzièmes journées de l'Hydraulique, Paris, 1972, Question IV, Rapport 7.

Lee, Y. J., Fourney, M. E. & Moulton, R. W. 1974 Determination of slip ratios in air-water two-phase critical flow at high quality levels using holographic techniques. *A.I.Ch.E. J.* **20**, 209–219.

LeTourneau, B. W. & Bergles, A. E., Ed. 1969 *Two-phase Flow Instrumentation.* ASME, Proceedings of a session held at the 11th National Heat Transfer Conf., Minneapolis, MI, 3–6 Aug.

Lippert, T. E. & Dougall, R. S. 1968 A study of the temperature profiles measured in the thermal sublayer of water, Freon-113, and methyl alcohol during pool boiling. *J. Heat Transfer* **90C**, 347–352.

Marcus, B. D. & Dropkin, D. 1965 Measured temperature profiles within the superheated boundary layer above a horizontal surface in saturated nucleate pool boiling of water. *J. Heat Transfer* **87C**, 333–341.

Miller, N. & Mitchie, R. E. 1969 Electrical probes for study of two-phase flows, *Two-Phase Flow Instrumentation* (Edited by LeTourneau, B. W & Bergles, A. E.) pp. 82–88. ASME.

Miller, N. & Mitchie, R. E. 1970 Measurement of local voidage in liquid/gas two-phase flow systems. *J. Br. Nucl. Energy Soc.* **9**, 94–100.

Morrow, T. B. & Kline, S. J. 1971 The evaluation and use of hot-wire and hot-film anemometers in liquids. Stanford University Report MD-25.

Neal, L. S. & Bankoff, S. G. 1963 A high resolution resistivity probe for determination of local void properties in gas–liquid-flow. *A.I.Ch.E. J.* **9**, 49–54.

Nishihara, H. 1974 Triangulation of local coolant boiling by cross-correlating acoustic noise signals. *Nuc. Tech.* **23**, 222–232.

Nyer, M. 1969 Etude des phénomènes thermiques et hydrauliques accompagnant une excursion rapide de puissance sur un canal chauffant. CEA-R3497.

Ornstein, H. L. 1970 An investigation of turbulent open channel flow simulating water desalination flash evaporators. Ph.D. Thesis, University of Connecticut.

Petrick, M. & Swanson, B. S. 1958 Radiation attenuation method for measuring density in a two-phase fluid. *Rev. Scient. Instrum* **29**, 1079–1085.

Popper, J., Abuaf, N. & Hetsroni, G. 1974 Velocity measurements in a two-phase turbulent jet. *Int. J. Multiphase Flow* **1**, 715–726.

Réocreux, M. & Flamand, J. C. 1972 Etude de l'utilisation des sondes résistives dans des écoulements diphasiques à grande vitesse. CENG, STT, Rapport interne No. 111.

Resch, F. 1968 Etudes sur le fil chaud et le film chaud dans l'eau. CEA-R3510.

Resch, F. & Coantic, M. 1969 Etude sur le fil chaud et le film chaud dans l'eau. *Houille Blanche* **2**, 151–161.

Resch, F. J. & Leutheusser, J. H. 1972 Le ressaut hydraulique; mesures de turbulence dans la région diphasique. *Houille Blanche* **4**, 279–293.

Resch, F. J., Leutheusser, H. J. & Alemu, S. 1974 Bubbly two-phase flow in hydraulic jump. *J. Hydraul. Div. Am. Soc. Civ. Engrs* **100**, No. HY1, Proc. Paper 10297, 137–149.

Rosler, R. S. & Bankoff, S. G. 1963 Large-scale turbulence characteristics of a submerged water jet. *A.I.Ch.E. J.* **9**, 672–676.

Schrock, V. E. & Selph, F. B. 1963 An X-ray densitometer for transient steam void measurement. SAN-1005.

Schrock, V. E., Johnson, H. A., Gopalakrishnan, A., Lavezzo, K. E. & Cho, S. M. 1966 Reactor heat transfer research final report: transient boiling phenomena, Vol. I, SAN-1013.

Schrock, V. E. 1969 Radiation attenuation techniques in *Two-phase Flow Measurements* (Edited by LeTourneau, B. W. Bergles, A. E.) pp. 24–35. ASME.

Sekoguchi, K., Fukui, H., Matsuoka, T. & Nishikawa, K. 1972 Ninth Japan Heat Transfer Symp., 435 (as taken from Serizawa, 1974).

Sekoguchi, K., Fukui, H., Matsuoka, T. & Nishikawa, K. 1974 Investigation into the statistical characteristics of bubbles in two-phase flow. *Trans. J.S.M.E.* **40**, 336, 2295–2310.

Serizawa, A 1974 *Fluid-Dynamic Characteristics of Two-Phase Flow.* Institute of Atomic Energy, Kyoto University, Ph.D. thesis.

SHIRALKAR, B. S. 1970 Local void fraction measurements in Freon-114 with a hot-wire anemometer. NEDO-13158, General Electric Co.

SHIRALKAR, B. S. & LAHEY, R. T. 1972 Diabatic local void fraction measurements in Freon-114 with a hot-wire anemometer. *ANS Trans.*, **15**, No. 2, p. 880.

STEFANOVIC, N., AFGAN, N., PISLAR, V. & JOVANOVIC, L. J. 1970 Experimental investigation of the superheated boundary in forced convection boiling. *Heat Transfer*, Vol. 5. Elsevier, Amsterdam.

SUBBOTIN, V. I., SOROKIN, D. N. & TSIGANOK, A. A. 1970 Some problems on pool boiling heat transfer, *Heat Transfer*, Vol. 5. Elsevier, Amsterdam.

TELLES, A. S. & DUKLER, A. E. 1970 Statistical characteristics of thin, vertical wavy liquid films. *I/EC Fundamentals* **9**, 412–421.

TRESCHOV, G. G. 1957 Experimental investigation of the mechanism of heat transfer with surface boiling of water. *Teploenergetika* **3**, 44–48.

UGA, T. 1972 Determination of bubble size distribution in a BWR. *Nucl. Engng Design* **22**, 252–261.

VAN PAASSEN, C. A. A. 1974 Thermal droplet size measurements using a thermocouple. *Int. J. Heat Mass Transfer* **17**, 1527–1548.

VAN STRALEN, S. J. D. & SLUYTER, W. M. 1969 Local temperature fluctuations in saturated pool boiling of pure liquids and binary mixtures. *Int. J. Heat Mass Transfer* **12**, 187–198.

WALMET, G. E. & STAUB, F. W. 1969 Electrical probes for study of two-phase flows, *Two-Phase Flow Instrumentation.* (Edited by LETOURNEAU, B. W & BERGLES, A. E.) pp. 84–101. ASME.

WIEBE, J. R. & JUDD, R. L. 1971 Superheat layer thickness measurements in saturated and subcooled nucleate boiling. *J. Heat Transfer* **93C**, 455–461.

ZIMIN, E. P., INOZEMITSEV, O. V., KRUGERSKII, A. M. & MIKHNEVICH, Z. G. 1973. Optical measurement of the parameters of the dispersed condensed phase in a two-phase flow. *Teplofiz. Vysok. Temp.* **11**, 1037–1043; (Also *High Temperature*, **11**, 924–928, Consultants Bureau, New York).

ZUBER, N., STAUB, F. B., BIJWAARD, G. & KROEGER, P. G. 1967 Steady-state and transient void fraction in two-phase flow systems. Final report for the program on two-phase flow investigation. GEAP-5417.