Distribution Category:
Water Reactor Safety Research--
Systems Engineering (NRC-2)

ANL-76-75

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

A SUMMARY OF EXPERIMENTAL METHODS
FOR STATISTICAL AND TRANSIENT ANALYSIS OF
TWO-PHASE GAS-LIQUID FLOW

by

Jean-Marc Delhaye
Centre d'Etudes Nucléaires de Grenoble
Service des Transferts Thermiques
38 Grenoble, France

and

Owen C. Jones, Jr.*
Reactor Analysis and Safety Division
Argonne National Laboratory

June 1976

NOTICE
This report was prepared as an account of work
sponsored by the United States Government. Neither
the United States nor the United States Energy
Research and Development Administration, nor any of
their employees, nor any of their contractors,
subcontractors, or their employees, makes any
warranty, express or implied, or assumes any legal
liability or responsibility for the accuracy, completeness
or usefulness of any information, apparatus, product or
process disclosed, or represents that its use would not
infringe private, owned rights.

MASTER

*Now at Brookhaven National Laboratory, Dept. of Applied Science, Upton,
L. I., New York

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
7/2/76

TABLE OF CONTENTS

	<u>Page</u>
NOMENCLATURE	6
ABSTRACT	9
I. INTRODUCTION.	9
II. MICROTHERMOCOUPLE.	12
A. What Can Be Measured with a Microthermocouple.	12
B. Classical Microthermocouple	12
1. Pool-boiling Experiments.	12
2. Forced-convection Boiling Experiments	13
C. Microthermocouple Associated with a Phase-indicator Device.	14
III. OPTICAL PROBES.	18
A. What Can Be Measured with an Optical Probe.	18
B. Description of Optical Probes	18
1. Glass-rod System.	18
2. Fiber-bundle System.	19
3. U-shaped-fiber System	21
C. Signal Processing	21
1. Glass-rod System.	21
2. Fiber-bundle System.	22
3. U-shaped-fiber System	22
IV. HOT-FILM ANEMOMETRY	25
A. What Can Be Measured with a Hot-film Probe	25
B. Measurements in Two-component Two-phase Flow without Phase Change	25
1. Liquid Droplets in a Gas Flow.	25
2. Air-Water Flows	27
C. Measurements in One-component Two-phase Flow with Phase Change	32
1. Steam-Water Flow	32
2. Freon-Freon Vapor Flow.	33

BLANK PAGE

TABLE OF CONTENTS

	<u>Page</u>
V. ELECTRICAL PROBES	34
A. What Can Be Measured with Electrical Probes	34
B. Resistive-probes Technology	34
1. The Direct-current Supply	35
2. The Alternating-current Supply	35
C. Signal Processing	36
VI. PHOTON-ATTENUATION TECHNIQUES	42
A. What Can Be Measured by Radiation Attenuation	42
B. Transient Void Fractions	43
C. Statistical Measurements	47
VII. MISCELLANEOUS METHODS	49
VIII. CONCLUSIONS	51
BIBLIOGRAPHY	55

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Separation of Steam and Water Distributions According to Stefanovic et al.	13
2.	Separation of Steam and Water Distributions According to Barois .	14
3.	Subcooled Boiling-temperature Histograms.	15
4.	Different Hypotheses Concerning the Separation of Liquid and Steam Histograms	16
5.	Most Probable Liquid Temperature and Void Fraction above a Nucleus in Nucleate Boiling	17
6.	Glass-rod Optical Probe	18
7.	Principle of the Glass-rod Optical Probe	19
8.	Light Guidance by a Glass Fiber	20
9.	Fiber-bundle Optical Probe	20
10.	Principle of the Fiber-bundle Optical Probe	20
11.	U-shaped Fiber System	21
12.	Principle of the U-shaped-fiber Optical Probe.	21
13.	Typical Signal Delivered by the Optical Probe	22
14.	Signal Discrimination	23
15.	Void-fraction Profiles in Freon-Freon Vapor Flow	24
16.	Signal Processing by Goldschmidt and Eskinazi.	26
17.	Actual Impaction Rate	27
18.	The Hot-wire Anemometer as a Size Sampler	27
19.	Anemometer Signal Obtained with a Conical Probe in an Upward Air-Water Bubbly Flow	28
20.	Anemometer Signal Obtained with a 50- μ m-dia Cylindrical Probe in Upward Air-Water Slug Flow	28
21.	Amplitude Histogram of Signal Shown in Figs. 19 and 20	29
22.	Signal Processing Proposed by Resch et al.	29
23.	Typical Frequency Profiles of Interface Passage across the Small Dimension of a Thin Rectangular Duct for Air-Water Upflow as Measured with a Cylindrical Anemometer Probe	30
24.	Typical Liquid Volume Flux Profiles across the Small Dimension of a Thin Rectangular Duct for Air-Water Upflow as Measured with a Cylindrical Anemometer Probe	31

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
25.	Water-velocity Frequency Spectra for Air-Water Bubbly Flow with a Liquid Flux of 1.03 m/s and a Quality of 0.0511%	32
26.	Schematic Diagram of a Resistive Probe	34
27.	Miniaturized Resistive Probe	35
28.	Ideal Signal of a Resistive Probe.	36
29.	Signal Processing.	37
30.	Choice of the Trigger Level According to Iida et al.	37
31.	Comparison of Optical Probe, Resistive Probe, and Hot-film Probe for Air-Water Flow	38
32.	Measurement of Local Void Fraction	39
33.	Bubble-size and Slug- and Bubble-length Distributions for Bubbly and Slug Flows in a Mercury-Nitrogen System.	39
34.	Spectral and Cross-spectral Density of Film-thickness Fluctuations Measured with a Straight Conductivity Probe	40
35.	Signal Processing in Multichannel Technique for Bubble-velocity Measurement.	40
36.	Correlative Representation between Correlation Technique and Multichannel Technique	41
37.	Locus of Maximum Calculational Error in Void Fraction due to Nonlinear Averaging of Fluctuations as Dependent on Dimensionless Absorptivity and Density Ratio	43
38.	Void-fraction Response Amplitude as a Function of Power-modulation Frequency in Simulated SPERT-1A Rectangular Channels.	44
39.	Typical Transient Data of Schrock et al.	45
40.	Double Amplitude of the Average Void-fraction Oscillation	45
41.	Phase Lag of Void Fraction Relative to Test-section Power Input.	46
42.	Typical Void-fraction Distributions Obtained by Discrete-time Neutron Interrogation	47
43.	Profiles of Void-fluctuation Amplitudes and Probability Density Function of Void Fraction for Agglomerating Bubbly Flow	48
44.	Power Spectral Density and Probability Density Function of Void Fluctuations in Vertical Upflow of Air and Water in Slug Flow	48

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
45.	Local Particle -size Distributions	50
46.	Number vs Size at Different Qualities for Critical Flow	50
47.	Average Velocity vs Drop Size at Different Flow Rates	50

TABLE

<u>No.</u>	<u>Title</u>	<u>Page</u>
I.	Liquid-Vapor Systems with $n_g < 1.15$ and $n_l > 1.15$ That Are Adequate for Use with a 45°-tipped Optical Probe	19

NOMENCLATURE

D	Diameter
e	Signal voltage
i_0	Angle of incidence
i	Refraction angle
j_g	Volume flux of gas
k	Dimensionless absorptivity (Eq. 7)
n_0	Index of refraction of light carrier
n_i	Index of refraction
n	Index of refracting medium
$\bar{R}$	Time-averaged void fraction measured by X or gamma ray
r	Channel radius
s	Fluid path length
s_r, s_b	Adjustable optical-probe thresholds
T_L	Liquid temperature
T_{mes}	Measured temperature
T_{sat}	Saturation temperature
U	Optical-probe output voltage consisting of U_0 and u
U_0	Static component of optical-probe output voltage
u	Dynamic component of optical-probe output voltage
α	Void fraction
ρ_f	Liquid density
ρ_{fg}	Liquid-vapor density difference
μ_{fg}	Liquid-vapor linear-absorption-coefficient difference

A SUMMARY OF EXPERIMENTAL METHODS FOR STATISTICAL AND TRANSIENT ANALYSIS OF TWO-PHASE GAS-LIQUID FLOW

by

Jean-Marc Delhay and Owen C. Jones, Jr.

ABSTRACT

Much work has been done in the study of two-phase gas-liquid flows. Although 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. While the two points of view of a fully homogeneous or a fully separated flow are important in providing estimates of limiting system behavior, they do not provide sufficient detail to be of general design utility. Rather, improvements have been made in considerations of more realistic models such as the drift model or the slip model. Likewise, recent work has highlighted the importance of some of the statistical quantities of two-phase flows. As in analytical work, experimentation that examines only the most simple aspects of these flows may yield information that is inaccurate and/or misleading. Only relatively recently have fluctuating characteristics of two-phase flows been studied in detail. As a result, new experimental devices and techniques have been developed for use in measuring quantities previously ignored. This report reviews and summarizes most of 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.

1. INTRODUCTION

Much experimental and analytical work has been done in the study of two-phase gas-liquid flows with and without heat transfer. Although such flows have been recognized superficially not to be homogeneous in general, little attention has been paid to the inherent discreteness of two-phase systems due to the additional complexity this would entail. Typically, only the two extremes of fully mixed homogeneous flow or fully separated flow have been generally considered. Although such points of view in analyses are important in providing estimates of limiting behavior, they are of little use in providing sufficient detail to be of general design utility. Likewise in experimentation, neglect of the more detailed behavior of these flows yields information which may be incomplete or misleading or both. Although a slight amount

of consideration was given to the statistical characteristics more than a decade ago (Neal and Bankoff,⁸² Lackme,⁷¹ Akagawa,³ and Ishigai et al.⁵⁵), it has been a relatively recent development that fluctuating characteristics have been studied in detail. As a result, new experimental devices and techniques have been developed for use in obtaining measurements of quantities heretofore ignored. This report reviews and summarizes most of these methods so as to place emphasis on the importance of the fluctuating nature of two-phase flows and presents a guide to further research into these areas.

Some of the characteristics and problems associated with single-phase flow measurements are also experienced in two-phase instrumentation. On the other hand, many supplemental difficulties appear in experimentation of two-phase flow systems. Most of these difficulties are related to the presence of two phases, but some are also due to specific flow geometries. For instance, there are difficulties due to the presence of two phases:

1. The deformation of an interface by a sensor leads to a lag between the occurrence and the detection of the event due to a hydrodynamic response time.
2. Where pressures are measured with wall pressure taps, great care must be paid to purging all the gas from the pressure lines to ensure correct measurement.
3. Steady-state flow may contain significant fluctuations so that time-averaged quantities should be measured taking into account every damping factor and nonlinearity. As an example, we can take the line void fraction in slug flow measured with an X-ray absorption method, but care must be taken in time averaging to obtain correct results.
4. 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.
5. An in-stream probe or a wall pressure tap may destroy a metastable equilibrium or lead to cavitation effects.

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

1. Two-phase flows are studied with a view of application to many engineering fields and 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.
2. Test-section geometries are often complex. In nuclear engineering, rectangular channels of narrow width (SPERT or ETR) or rod bundles (PWR, BWR, and LMFBR) are the rule.

An excellent review session of two-phase-flow instrumentation was organized for the ASME in 1969 by LeTourneau and Bergles.¹² 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 six years, both in instrumentation methods themselves and in the extent to which unsteady phenomena can be quantified. Nowhere to our 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. Due to space limitations, the earlier work shall not be summarized here, and the interested reader is directed to the summary of LeTourneau and Bergles,¹² and to the reviews by Delhayé,^{22,24} Gouse,³⁶ and Hewitt.⁴⁵

In the past, instrumentation for two-phase flow has been used to determine average and local void-fraction profiles. Recent methods have resulted in 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 will be described here. That these quantities are important there can be no doubt. 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 fuel element experiencing post-dryout conditions in a nuclear reactor.

Transient and statistical variations in void location 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 hypothetical accident situations. Measurement of instantaneous voids, temperatures, and velocities in critical flow situations are required to confirm current modeling efforts in this area. In addition, modeling efforts require local instantaneous measurements of void residence, velocity, and frequency in order 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. Efforts in these directions should continue and intensify over the next few years. This review should serve as a useful summary and critique of the current status and as a stimulus for workers in these areas.

II. MICROTHERMOCOUPLE

A. What Can Be Measured with a Microthermocouple

In the use of a microthermocouple in two-phase flow, we have to distinguish between two different types of apparatus:

1. The classical microthermocouple, which enables some statistical characteristics of the temperature to be measured.
2. The microthermocouple associated with a phase-indicator device, which enables the local void fraction and the instantaneous temperature of each phase to be determined. In this case, the phase-indicator device is an electrical device requiring a liquid that must be conducting.

In this section, we shall examine the use of a classical microthermocouple in pool boiling and in forced-convection boiling. Then we shall describe the microthermocouple associated with a phase-indicator device, which seems to us to be a more convenient technique in the statistical analysis of boiling two-phase flow.

B. Classical Microthermocouple

With a view to a more thorough understanding of boiling heat transfer, numerous experiments have been carried out to study temperature fluctuations near a heated surface. These investigations can be divided into two groups: pool-boiling experiments and forced-convection boiling tests.

1. Pool-boiling Experiments

The interest in temperature fluctuations, especially in pool boiling, is not new. Marcus and Dropkin⁷⁸ used a 50- μm -dia microthermocouple to evaluate the thickness of the superheated liquid layer in contact with a heated wall. They recorded the temperature fluctuations given by a thermocouple made up of Chromel-Alumel wires set in tension between two prongs. Results were given in terms of an average temperature obtained by damping out all the fluctuations. Other results concerned the average values of maximum and minimum temperatures. Although these experiments constituted a good progress in the knowledge of boiling phenomena, the results concerning the statistical aspects of the temperature fluctuations were to some extent inaccurate.

Bonnet et al.¹³ reported some 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 the thermal inertia led to extra vaporization of the liquid on the sensor so that the significance of the signal was not clear.

Lippert and Dougall⁷⁷ measured temperature profiles in the thermal sublayer of water, Freon 113, and methyl alcohol during pool boiling. The hot junction, 125 μm in diameter, of a Chromel-Alumel thermocouple was supposed to measure the liquid temperature. According to the authors, the results of the test data showed this assumption to be reasonable.

Jacobs and Shade⁵⁷ carefully examined the interaction between the bubbles and a microthermocouple, 20 μm in diameter. These authors, and also Van Stralen and Sluyter,¹⁰⁸ were primarily concerned with the thermocouple response time. These investigations on the response time were augmented by Subbotin et al.,¹⁰³ who examined the behavior of bubbles hitting different types of thermocouples.

Stefanovic et al.¹⁰² compared the thermocouple signal with the impact of a bubble on the hot junction. High-speed movies showed that the microthermocouple used by the authors, 40 μm in diameter, was suitable for studying temperature fluctuations in boiling heat transfer. 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 (see Fig. 1). Following the results obtained by Delhaye et al.,^{21,23} it seems that this assumption is generally misleading, although the method has been applied by Afgan et al.^{1,2}

Fig. 1
Separation of Steam and Water
Distributions According to
Stefanovic et al.¹⁰²

Wiebe and Judd¹¹¹ conducted measurements of superheat layer thickness in saturated and subcooled nucleate boiling. They used a Chromel-constantan microthermocouple of 75- μm diameter. A time-average temperature was determined by integrating the temperature signal.

2. Forced-convection Boiling Experiments

Treschov¹⁰⁵ carried out one of the first investigations into temperature profiles in forced-convection boiling. The results appear less

interesting than those obtained by Jiji and Clark⁵⁸ with a 250- μm -dia Chromel-constantan thermocouple. Despite the large size of their sensor, these authors succeeded in measuring an average temperature and average values of the temperature extremes.

Walmat and Staub¹¹⁰ studied local subcooled boiling, characterized by important nonequilibrium effects, with the help of several local measurements of pressure, void fraction, and temperature. For temperature measurement, they used a copper-constantan thermocouple, the size of which was rather large: 150 x 200 μm . The measured temperature T_{mes} was related to the average liquid temperature T_L by the relationship

$$T_L = \frac{1}{1 - \bar{R}}(T_{\text{mes}} - \bar{R}T_{\text{sat}}), \quad (1)$$

where T_{sat} is the vapor temperature assumed to be in saturated conditions and $\bar{R}$ the line void fraction measured with an X-ray absorption method.

In his study of flashing flow of water, Barois⁹ proposed to separate the distributions of steam and water by assuming that the steam-temperature histogram was symmetrical (see Fig. 2). This hypothesis, closely related to the method due to Stefanovic et al.¹⁰² and Afgan et al.,^{1,2} is generally incorrect, as Delhaye et al.^{21,23} have shown.

Fig. 2

Separation of Steam and Water
Distributions According to Barois.⁹
ANL Neg. No. 900-5421.

C. 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 of Delhaye et al.^{21,23} 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. The basic idea was to use a 20- μ m-dia hot junction of a Chromel-Alumel microthermocouple as an electrical probe that indicates the nature of the phase surrounding the sensing element.

Except for its hot junction, the microthermocouple is electrically insulated from the liquid with a varnish. The insulating resistance between the junction and the ground, which is a function of the phase (vapor or liquid) surrounding the junction, is measured with a Kohlrausch bridge. Both signals (phase and temperature) are received by a differential amplifier with a high common-mode rejection ratio. Only the differential signal (temperature) is processed by the amplifier. The common-mode signal (phase) is rejected and directed toward a logical switch circuitry. This phase signal is used to switch the liquid-temperature signal or the vapor-temperature signal into a first 1000-channel subgroup or into a second 1000-channel subgroup of a 4000-channel analyzer. The histograms of the vapor and of the liquid temperatures are thus obtained separately.

Figure 3 shows typical histograms obtained in subcooled boiling. The liquid-temperature histogram is represented in Fig. 3a. Superheated and

Fig. 3. Subcooled Boiling-temperature Histograms (Delhaye et al.)^{21,23} AML Neg. No. 900-5218 Rev. 1.

subcooled liquid can be distinguished on each side of the saturation temperature. The steam-temperature histogram is centered on the saturation temperature (see Fig. 3b). Figure 3c shows the histogram that would have been obtained with a classical thermocouple.

Figure 4 reveals the inconsistency of the separation rules proposed by Stefanovic et al.¹⁰² and Afgan et al.,^{1,2} or by Barois.⁹ The importance of this method may be seen by examining the details of typical results obtained near a vapor-generation cavity in pool boiling (see Fig. 5). Clearly, the temperature gradient in the liquid is sharply increased as the nucleation site is approached, but the local vapor fraction is a maximum away from the wall in support of the microlayer/microconvection hypotheses.

Fig. 4. Different Hypotheses Concerning the Separation of Liquid and Steam Histograms

Fig. 5. Most Probable Liquid Temperature and Void Fraction above a Nucleus in Nucleate Boiling

III. OPTICAL PROBES

A. What Can Be Measured with an Optical Probe

An optical probe is sensitive to the change in the refractive index of the surrounding medium. Consequently, bubbles and droplets can be detected at a given point in the flow. Among other information, the optical probe permits the measurement of local void fraction or of the arrival frequency of bubbles or droplets. Generally speaking, it is sensitive to the passage of an interface. Using two sensors and a cross-correlation method makes it possible to obtain some information on a transit velocity. The main advantage of the optical probe is its independence on the electrical conductivity of the ambient medium.

B. Description of Optical Probes

Up to now, three different optical-probe configurations have been proposed. We shall briefly depict the glass-rod and fiber-bundle systems, then the U-shaped optical probe.

1. Glass-rod System (Miller and Mitchie,^{79,80} Bell et al.,¹¹ Kennedy and Collier⁶⁷)

This probe (see Fig. 6) was made of a 2-mm-dia glass rod reduced to 0.3 mm at one end. The small tip of the rod was ground and polished to the form of a right-angled cone. The other end of the glass rod was glued to a Y-shaped light guide. The light from a quartz-iodine lamp was focused on one of the branched ends of the light guide. A phototransistor was located at the other branched end of the light guide.

Fig. 6

Glass-rod Optical Probe. ANL Neg.
No. 900-5424 Rev. 1.

Light was transmitted toward the tip of the probe. A light beam that strikes the surface at an angle of 45° 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 (see Fig. 7).

Fig. 7
Principle of the Glass-rod Optical Probe

According to Snell's law,

$$n \sin i = n_0 \sin i_0, \quad (2)$$

so that, for the light beam to emerge from the probe,

$$\sin i = \frac{n_0}{n} \sin i_0 \leq 1. \quad (3)$$

Thus, for a glass rod with $n_0 = 1.62$, if $i_0 = 45^\circ$, light is reflected back along the rod if n is less than 1.15 and exists from the rod if n is greater than 1.15. Table I gives possible combinations in which this probe can be successfully used.

TABLE I. Liquid-Vapor Systems with $n_g < 1.15$
and $n_l > 1.15$ That Are Adequate for Use with
a 45° -tipped Optical Probe

System	n_g	n_l
Steam-Water	1.00	1.33
Air-Water	1.00	1.33
Freon-Freon Vapor	1.02	1.25

2. Fiber-bundle System (Hinata⁴⁶)

The basic element of this probe is a $30\text{-}\mu\text{m}$ -dia glass fiber, which consists of a central core and an outer cladding (see Fig. 8). Due to a difference in the refractive indices between the core ($n = 1.62$) and the cladding ($n = 1.52$), total internal reflection takes place at the core-cladding interface for an angle of incidence higher than 69.7° , instead of 38.1° if there were no cladding. Consequently, the light loss is highly reduced if a coated glass fiber is used.

Fig. 8
Light Guidance by a Glass Fiber

A few hundred of such coated glass fibers are tied together in a 0.5-mm-dia Y-shaped bundle (see Fig. 9). One end of this bundle is glued to a 0.5-mm-dia, 1-mm-long small glass rod, itself coated with a glass of lower refractive index. The extremity of the glass rod is ground and polished. The two other ends of the fiber bundle are respectively connected to a light source (namely, a floodlight projector) and a phototransistor.

Fig. 9
Fiber-bundle Optical Probe

The probe basically works on the same principle as the glass-rod system. Depending on the refractive index of the surrounding medium, light emerges from the tip of the probe or is reflected back (see Fig. 10).

Fig. 10
Principle of the Fiber-bundle Optical Probe. ANL Neg. No. 900-5431.

3. U-shaped-fiber System (Danel and Delhaye¹⁸ and Delhaye and Galaup²⁵)

One major drawback of the glass-rod and fiber-bundle systems is the diameter of the sensitive part of the probe (respectively, 0.3 and 0.5 mm). This fact led to the development of a smaller optical sensor, which is depicted in Fig. 11. This probe consists of a single coated optical fiber, 40 μm in diameter. One end of the fiber receives the light emitted from a miniaturized lamp. The other end is centered on a phototransistor chosen for its high sensitivity. The sensitive element of the probe is obtained by bending the fiber into a U shape. The entire fiber, except for the U-shaped bend, is protected by a 2-mm-dia stainless steel tube. The active part of the probe has a characteristic size of 0.1 mm. Figure 12 shows an enlarged view of the probe extremity along with a light-beam transmission. Once again, the phase detection is based on Snell's law.

Fig. 11. U-shaped Fiber System

Fig. 12. Principle of the U-shaped-fiber Optical Probe. ANI, Neg. No. 900-5430.

point to the volume void fraction measured with quick-closing valves. This method seems to be rather approximate due to the known variations in axial

C. Signal Processing

1. Glass-rod System

All the investigators used a discriminator to transform the actual signal into a binary signal. A trigger level is set at a given value above the background level, corresponding to the case in which the probe is immersed in the liquid.

Miller and Mitchie^{79,80} set the trigger level at 10% of the pulse amplitude above the all-liquid level. They obtained this value by comparing the value of the local void fraction at a given

void fraction. A better comparison would seem to be a local void-fraction profile and a line void fraction, which could be measured with an X- or gamma-ray absorption method.

Bell et al.¹¹ set the trigger level halfway between the all-water and all-gas signal levels. They gave no justification to this procedure.

In a study of droplet jet flow, Kennedy and Collier⁶⁷ related the trigger level and the droplet time fraction with the sizes of the probe and of the droplets.

2. Fiber-bundle System

If the local void fraction is plotted against the trigger level, an S-shaped curve is obtained with a plateau corresponding to a given value of the void fraction. Hinata⁴⁶ chose a trigger-level value corresponding to this plateau, but gave no justification.

3. U-shaped-fiber System

A typical signal delivered by the probe is shown in Fig. 13. The voltage U can be divided into a static component U_0 and a fluctuating component u :

$$U = U_0 + u.$$

Fig. 13. Typical Signal Delivered by the Optical Probe

The static component U_0 varies with the local void fraction. In steady-state flow, U_0 does not change with time at a given point, but varies with the position of the probe in the test section. In a low-void-fraction bubble flow, we have, for instance, $U_0 \approx 3.2$ mV, whereas at a higher void fraction we obtain $U_0 \approx 3.0$ mV. The explanation of this change in U_0 lies in the physical significance of this component. Actually, U_0 corresponds to

a sensitive part of the probe completely immersed in the liquid. Consequently, the change in U_0 can be due to two effects:

- a. The response time inherent in hydrodynamic and optoelectronic phenomena when the interface is pierced by the probe.
- b. The scattering of light by the bubbles surrounding the probe.

The fluctuating component varies between 0 and 1.1-1.8 mV. It constitutes the interesting part of the signal. The maximum value $U_{\max}$ corresponds to the sensor completely immersed in the gas and does not depend on the local void fraction.

The above considerations directly lead to the following signal processing:

- a. Removal of the static component U_0 .
- b. Amplification and filtering.
- c. Discrimination with two adjustable thresholds, one for the rising part and the other for the falling part of the signal.
- d. Analog time-averaging.

Two adjustable thresholds, s_r and s_f , enable the signal to be transformed into a square-wave signal (see Fig. 14). Consequently, the local void fraction α is a function of s_r and s_f . If we assume that the optimum values of s_r and s_f do not depend on the position of the probe along a diameter, then the line-averaged void fraction $\langle \alpha \rangle$, defined by

$$\langle \alpha \rangle = \frac{1}{D} \int_D \alpha \, dr, \quad (4)$$

is a function of s_r and s_f , where D is the tube diameter. Both threshold levels are adjusted in order to obtain the equality

$$\langle \alpha \rangle = \bar{R}. \quad (5)$$

$\bar{R}$ being the time-averaged diameter void fraction measured with an X- or gamma-ray absorption method.

Fig. 14
Signal Discrimination. ANL Neg.
No. 900-5418 Rev. 1.

Experimental results for void profiles in Freon two-phase flow with phase change are given by Delhaye and Galaup²⁵ similar to that shown in Fig. 15. In addition, counting techniques can be used to give information on the interface passage frequency, while averaging of successive equal-time slices will provide histograms of void distributions.

	x_{ex}	$\bar{R}_G$	$\langle \alpha \rangle$
○	-0.05	0.03	0.02
▲	0.00	0.08	0.06
▼	0.05	0.21	0.24
□	0.10	0.37	0.38
●	0.15	0.47	0.48
△	0.20	0.56	0.58
▽	0.25	0.68	0.72
■	0.30	0.72	0.74

Fig. 15. Void-fraction Profiles in Freon-Freon Vapor Flow (Circular tube) from Delhaye and Galaup.²⁵ x_{ex} : exit equilibrium quality, $\bar{R}_G$: time-averaged line void fraction measured with gamma-ray absorption method; $\langle \alpha \rangle$: line-averaged local void fraction obtained with an optical probe.

IV. HOT-FILM ANEMOMETRY

A. What Can Be Measured with a Hot-film Probe

Hot-wire and hot-film anemometers have been used in gases for years, but little success has been reported on calibrated use of miniature cylindrical probes for accurate velocity measurement in liquids until recently and then only at relatively low velocities (for instance, in water: Ornstein,⁸⁵ < 0.5 m/s; Morrow and Kline,⁸¹ < 0.25 m/s; and Hollasch and Gebhart,⁴⁷ < 0.6 m/s; and in mercury: Hurt and Welby,⁵⁰ < 0.05 m/s). Jones⁶¹ and Jones and Zuber,⁶⁴ however, have recently reported measurement of void and volume-flux profiles with 50- μ m-dia cylindrical probes at liquid velocities up to 6 m/s. Use of the larger and much more sturdy wedge and conical probes has enjoyed greater success at velocities up to about 5 m/s (Rosler and Bankoff,⁹³ < 3.7 m/s; Bouvard and Dumas,¹⁴ < 5 m/s; Resch and Coantic,⁹⁰ < 4 m/s; and Resch,⁸⁹ < 4 m/s).

It has been found that hot-wire or hot-film anemometry can be used in two- or one-component two-phase flow with phase change. In the first case, for example, an air-water flow, 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 or the arrival frequency of bubbles or droplets. In the second case, for example, a steam-water flow, it has been so far impossible to obtain consistent results on the liquid velocity, although Jones⁶¹ suggested the use of a dual sensor probe to obtain transport times from cross correlations of the two sensor signals.

Although calibration of an anemometer for velocity is not practical in saturated or near-saturated fluids, there should be sufficient effect due to liquid velocity to obtain a measurable correlation maximum, separate from that obtained from interfacial motion. If sensors orientated perpendicular to the flow direction are separated by 5 mm, flow traveling at 50 m/s would have a transport time of 100 μ s. Sensors would be required to have a bandwidth of 10 kHz to resolve correlatable effects on this time scale, a not unreasonable requirement. At this time, however, only local void-fraction measurements have been reported in saturated flows.

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 that is characteristic of the flow pattern.

B. Measurements in Two-component Two-phase Flow without Phase Change

1. 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 and Eskinazi^{31,32} measured the arrival frequency of liquid droplets, 1.6-3.3 μm in diameter, with a constant-temperature anemometer and a cylindrical probe, 4.5 μm in diameter. After it hits the wire, a droplet stays on the wire by surface-tension effect. The droplet temperature increases and reaches the saturation temperature. Finally, the droplet evaporates while absorbing the heat of vaporization supplied by the hot wire. When the impaction frequency of the droplets is different from the energetic frequency range of the turbulent gas stream, the signal fluctuations due to droplet impacts can be distinguished from the fluctuations due to turbulence. The signal processing follows immediately from these considerations: A bandpass filter eliminates the turbulence frequencies, and an adjustable discriminator produces a binary signal (see Fig. 16). The threshold amplitude obviously has an important influence on the number of droplets than can be counted per unit of time. In the experiments carried out by Goldschmidt and Eskinazi,^{31,32} the results showed that the ratio of the impaction frequency to the maximum impaction frequency was insensitive to the threshold amplitude. Lackmé⁷² had also observed this fact for void-fraction measurements with a resistive probe. Ginsberg²⁹ used the same technique to study liquid-droplet transport in turbulent pipe flow.

Fig. 16
Signal Processing by Goldschmidt
and Eskinazi³¹

If we plot the number of impactions per unit of time counted on the hot wire against the number of particles collected per unit time through an area equal to that of the wire facing the stream, we observe (see Fig. 17) that both quantities are proportional for a given overheat ratio, wire diameter, and wire resistivity. Since the actual impaction rate is lower than the ideal one, one needs to calibrate the hot wire with another technique, such as a trapping cylinder or an isokinetic probe (Goldschmidt³⁰).

Goldschmidt and Householder^{33,34} undertook the determination of the droplet-diameter histogram. They found a linear relationship between

Fig. 17
Actual Impaction Rate

particle diameter and cooling-signal peak value, which they verified experimentally (see Fig. 18) for droplet diameters less than $200\text{ }\mu\text{m}$. This result was contradicted by the theoretical and experimental data produced by Bragg and Tevaarverk,¹⁵ who showed that the dependence between the voltage-spike amplitude and the droplet diameters is essentially nonlinear. These authors concluded that the hot wire was not suitable for drop-size sampling.

Fig. 18

The Hot-wire Anemometer as a Size Sampler

Hetsroni et al.⁴⁴ measured time-averaged gas velocities as well as gas turbulent intensities. They removed the spikes due to the impingement of the liquid droplets on the hot wire with the help of an amplitude discriminator and a somewhat simpler electronic circuit than that of Goldschmidt and Eskinazi.^{31,32}

Despite several difficulties arising in droplet granulometry determination, Goldschmidt et al.³⁵ have successfully used the hot wire for studying the turbulent diffusion of small particles suspended in turbulent jets.

2. Air-water Flows

Following the studies done by Goldschmidt et al. on aerosols, by Hsu et al.⁴⁹ on steam-water flow, and the preliminary work of Jones,⁵⁹

Delhaye^{19,20} carried out a thorough investigation of the hot-film-anemometry technique in two-phase flow. In his experiments, Delhaye used a conical hot-film probe, which had three major advantages over the cylindrical hot-film sensor: Dust did not attach to the tip, bubble trajectories were less disturbed, and the geometry was less susceptible to flow damage at high velocities. The conical hot-film probe was associated with a constant-temperature anemometer so that the sensor temperature could be adjusted below the saturation temperature.

In air-water flow, the probe temperature has to be properly chosen to prevent the formation of degassing air bubbles on the sensor and to avoid any shift of the output signal due to a change in the ambient fluid temperature. The maximum overheat ratio suggested by Delhaye^{19,20} was 1.05, which corresponded to a difference of 17°C between the probe temperature and the ambient temperature.

Figure 19 shows the signal obtained in an upward bubbly air-water flow with a conical probe. Delhaye examined the peculiarities of this signal in detail. When a cylindrical hot-film probe was used instead of a conical probe, the response was similar, as seen in Fig. 20 for air-water slug flow obtained by Jones⁶¹ with a 50- μm -dia sensor. It is evident that the turbulent structure for each phase could be obtained by separating the positions of the signal due to each phase alone. Chuang and Goldschmidt¹⁷ used 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.

Fig. 19. Anemometer Signal Obtained with a Conical Probe in an Upward Air-Water Bubbly Flow (Delhaye^{19,20})

Fig. 20

Anemometer Signal Obtained with a 50- μm -dia Cylindrical Probe in Upward Air-Water Slug Flow (Jones⁶¹). ANL Neg. No. 900-4923 Rev. 3.

With a view to determining local void fraction, liquid local velocity, and liquid turbulence intensity, the amplitude probability density function of the output signal $E(t)$ may be obtained with the help of a multichannel analyzer. The corresponding histogram is shown on Fig. 21. To a first approximation, the local void fraction is given by

$$\alpha = \frac{\text{hatched area}}{\text{total area}} \quad (6)$$

Fig. 21

Amplitude Histogram of Signal shown in Figs. 19 and 20. ANL Neg. No. 900-75-62.

This hypothesis is based on the signal analysis and was checked by comparing local void-fraction profiles with radiation-absorption methods (X or gamma rays). The time-averaged liquid velocity and the liquid turbulent intensity are calculated with the nonhatched area of the amplitude histogram (see Fig. 21) and the calibration curve of the probe immersed in the liquid. Serizawa⁹⁹ used the same method extensively for measuring the turbulent characteristics and local parameters of air-water two-phase flow in pipe.

Resch et al.^{91,92} proposed a different signal processing in a study of bubbly two-phase flow in hydraulic jump. The analog signal from the anemometer was characterized by a high turbulent intensity of the liquid phase. This signal was digitized, and the results stored on magnetic tape. According to the amplitude between two successive extremes of the signal compared to a fluctuation threshold level ΔE , a computer recognized a change of phase (see Fig. 22). This conditional sampling enables the discrimination of the phases

Fig. 22

Signal Processing Proposed by Resch et al.^{91,92} ANL Neg. No. 900-5219.

to be made. By taking the points of the digitized data corresponding to liquid, one can easily determine the liquid mean velocity and turbulent intensity by means of the calibration curve. The main problem remains the adjustment of the fluctuation threshold level ΔE to obtain the effective cutoff voltage.

In Resch et al.,⁹² the determination of the proper value of ΔE was based on the shape of the curve $\alpha(\Delta E)$. Jones⁶¹ and Jones and Zuber⁶⁴ found, for cylindrical hot-film anemometers, that the cutoff voltage (used to switch a binary circuit from zero to unity) must change with liquid velocity to a point just below the minimum value for a velocity fluctuation. By simply time-averaging the resulting signal, they could read the local void fraction in a traverse directly. 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. They found these errors to depend on the liquid volume flux and the mean void fraction. By counting the number of times the output of the discriminator changed from one level to another, they obtained local values for interface passage frequency, as seen in Fig. 23.

Fig. 23. Typical Frequency Profiles of Interface Passage across the Small Dimension of a Thin Rectangular Duct for Air-Water Upflow as Measured with a Cylindrical Anemometer Probe (Jones⁶¹). ANL Neg. No. 900-4929 Rev. 3.

Jones⁶¹ and Jones and Zuber⁶⁴ measured liquid volume fluxes directly. They time-averaged the linearized anemometer signal. This signal was equal to the liquid velocity when the sensor was in liquid, and theoretically equal to zero when the sensor was in gas, (similar to that shown in Fig. 20). Typical results are included in Fig. 24. Liquid velocity was obtained by point-wise division of the measured liquid flux by the measured void fraction. The results are somewhat questionable, however, since liquid velocities over ~ 1.5 m/s caused cracking of the 8000-Å-thick quartz coating on the 50- μ m-dia sensor, with resulting shifts in calibration. No attempt was made to measure the turbulent fluctuations.

Fig. 24. Typical Liquid Volume Flux Profiles across the Small Dimension of a Thin Rectangular Duct for Air-Water Upflow as Measured with a Cylindrical Anemometer Probe (Jones⁶¹). ANL Neg. No. 900-4928 Rev. 3.

Serizawa,⁹⁹ on the other hand, used a conical probe of much more sturdy construction and a larger size, similar to that of Delhay.^{19,20} In bubbly and slug flow in air-water mixtures, he used multichannel-analysis techniques

to obtain the frequency spectrum of the velocity signal, including fluctuations up to ~ 2 m/s for liquid fluxes of 1 m/s. Typical results are shown in Fig. 25.

Fig. 25. Water-velocity Frequency Spectra for Air-Water Bubbly Flow with a Liquid Flux of 1.03 m/s and a Quality of 0.0511% (Serizawa⁹⁹). ANL Neg. No. 900-4926.

Other applications of hot-film anemometry include the work of Chuang and Goldschmidt¹⁷ and of Ishigai et al.⁵⁶ Chuang and Goldschmidt theoretically investigated the behavior of the output signal due to the passage of an air bubble in water and used the hot-wire as a bubble-size sampler. Ishigai et al. used the hot-film anemometer to indicate liquid-film thickness. In conducting liquids, however, it seems that the more simple and less expensive resistance probe would be more suited for this purpose. (This type of probe is discussed in Sec. V below.)

C. Measurements in One-component Two-phase Flow with Phase Change

1. Steam-Water Flow

The earliest paper on hot-wire anemometry in two-phase flow seems to be that of Katarzhis et al.⁶⁵ This preliminary and crude approach was followed by the work of Hsu et al.⁴⁹ These authors, by comparing the signal with high-speed movies, concluded that hot-wire anemometry was a potential tool for studying the local structure of two-phase flow, in particular for determining the flow pattern and for measuring the local void fraction. The remarks made by Hsu et al. concerning the choice of a probe temperature were very important. In a steam-water flow, the only reference temperature is the saturation temperature. If water-velocity measurements are carried out, the probe overheat must be lower than 5°C in order to avoid nucleate boiling on the sensor. On the contrary, if no liquid-velocity measurements are required

and if a high sensitivity to phase change is looked for, then the overheat should range between 5 and 55°C. In these conditions, nucleate boiling occurs on the probe. Since the difference in the heat-transfer coefficient between nucleate boiling and steam alone is high, the sensitivity to a phase change is improved.

2. Freon-Freon Vapor Flow

Freons have a low electrical conductivity. This property enables bare wires to be used instead of conical probes or hot-film cylindrical probes.

Shiralkar¹⁰⁰ used a 5- μ m-dia tungsten wire with a very short active length (0.125 mm). This size was chosen so that the whole active zone was inside a bubble or inside a droplet. Nucleate boiling was deliberately occurring on the wire, as proposed by Hsu et al.⁴⁹ The local void fraction was determined by an amplitude discriminator with an adjustable threshold level. For a void fraction lower than 0.3, the threshold was set just under the liquid level, whereas for a 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 halfway between the liquid and vapor levels. The method was subsequently applied by Dix²⁶ and Shiralkar and Lahey.¹⁰¹

V. ELECTRICAL PROBES

A. What Can Be Measured with Electrical Probes

The first requirement to be met when using an electrical probe in two-phase flow is that one fluid must have a measurably higher electrical conductance than the other. The electrical probe described below will detect the passage of bubbles but not of droplets. Consequently, the use of a single electrical probe permits 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. A bubble velocity can be measured by using a double probe, but one has to be careful when giving a physical significance to this bubble velocity. A detailed survey of the use of electrical probes was given by Bergles.¹² We shall describe the recent developments of the probe technology as well as the new methods used to process the signal.

B. Resistive-probes Technology

Figure 26 shows the classical electrical diagram of an in-tube resistive probe. When the two electrodes are connected, either by a conducting liquid or by a gaseous medium, the impedance changes between the electrodes and produces a variation in the output signal. Resistive probes are based upon the change in the resistive component of the impedance (Lackmó⁷²).

Fig. 26. Schematic Diagram of a Resistive Probe. Part of ANL Neg. No. 900-5429.

The relative positions of the electrodes may differ according to the experimenters. Figure 27 shows the general scheme of a resistive probe. Differences may arise from the sensing-wire diameter and the insulation material. The tip of the probe constitutes the first electrode. The second electrode may be the metallic protecting sheath of the probe,

a second probe, or the general ground of the test section. The size of the sensor can be very small. Lecroart and Porte⁷⁴ developed a miniature probe, the sensing part of which was a 20 μm -dia tungsten wire, whereas Herringe and Davis⁴³ used sharpened needles with tips less than 16 μm in diameter. Probes may be either straight (Wallis¹⁰⁹) or angled as seen in Fig. 27.

The electrical circuit associated with the probe enables resistance changes to be transformed into voltage resistance. Figure 26 shows a common type of electrical circuit. Resistance changes lead to intensity fluctuations, which are transformed into voltage changes with the help of a resistance. One of the principal features that differentiates the electrical circuits shown in Fig. 26 is the type of electrical supply. Two distinct ways of energizing the sensor can be used.

Fig. 27. Miniaturized Resistive Probe (Lecroart and Porte⁷⁴). Part of ANL Neg. No. 900-5429.

1. The Direct-current Supply

On first examination, the use of a direct-current supply seems to be the easiest way of using an electrical probe. Such usage, however, requires low voltages in order to reduce electrochemical phenomena on the sensor to prevent the electronics from becoming troublesome. Despite low voltages, sensors may sustain alteration due to electrochemical deposits. These effects can be suppressed if the probe is used in high-speed flows which tend to clean the sensor. Lecroart and Porte⁷⁴ obtained interesting results 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. With such a device, capacitive effects of cables and of the surrounding medium were eliminated.

2. The Alternating-current Supply

With an alternating-current supply, phase changes are detected by amplitude modulation of the alternating output signal. This technique has been used by several investigators to eliminate the electrochemical phenomena on the sensor (Iida and Kobayasi,^{53,54} Kobayasi,⁶⁸ and Herringe and Davis⁴³). The current frequency must be higher than the frequency of the physical phenomenon 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 and Flamand⁸⁸ developed an alternative approach for such high-speed two-phase flows. The basic feature was to use a supply frequency lower than the frequency of the physical phenomenon. The advantages of such a device are twofold.

- a. The probe runs with a direct-current supply during each semialternance.
- b. The voltage level can be high without any shift due to electrochemical deposits on the sensor.

C. Signal Processing

According to the way in which the sensor is energized, the ideal output signal of a resistive probe has one of the shapes represented in Fig. 28. Actually, the output signal is misshapen with respect to the ideal signal. The signal distortions were thoroughly investigated by Lackmé⁷² and by Reocreux and Flamand.⁸⁸ Such distortions are caused by hydrodynamical, electrical, and chemical phenomena.

Fig. 28. Ideal Signal of a Resistive Probe

The actual signal is generally transformed into a binary sequence with the help of a trigger level, as shown in Fig. 29. The main problem arises with the choice of trigger level. If the local void fraction is plotted against the trigger level, an S-shaped curve such as in Fig. 30 is obtained, with a plateau corresponding to a given value of the void fraction (Iida et al.⁵²). Iida et al. chose a trigger-level value corresponding to this plateau, but gave no justification. Herringe and Davis⁴³ obtained a similar S-shaped curve, but the plateau was not at a constant value of void fraction. Instead the plateau had a slope which spanned about 5% in void fraction. They also used the minimum plateau trigger level that maximized the void-fraction measurement, also without justification.

Fig. 29
Signal Processing

Fig. 30
Choice of the Trigger Level
According to Iida et al.⁵²

Serizawa⁹⁹ adjusted the threshold level just under the average liquid level, whereas Lecroart and Porte⁷⁴ used a level adjustment based upon an integral comparison with a gamma-ray-absorption method. This latter seems more practical, but requires the assumption that this level does not depend on position. Herringe and Davis⁴³ also compared their results with measurements taken with an anemometer probe, and concluded that a single needle probe with small area and continuity detection between the tip and the sheath was superior for flows in which the liquid was the continuous phase. The results, however, appear questionable, especially when the averaged void fractions determined by averaging the data agree well with the kinematic void fraction, in opposition to the well-known results of Armand,⁶ Bankoff,⁸ and Zuber and Findlay.¹¹³

Galaup²⁸ also compared the results obtained with optical, hot-film, and resistive probes, with the results shown in Fig. 31. It is encouraging to note that the results from all three methods gave comparable results within 4% of the gamma-ray-measured, line-averaged void fraction.

In addition to the methods described above, different characteristics of the flow can be determined.

Fig. 31

Comparison of Optical Probe, Resistive Probe, and Hot-film Probe for Air-Water Flow. ANL Neg. No. 900-5427 Rev. 1.

1. The flow pattern can be determined by a direct observation of the signal.
2. The local void fraction can be determined by an electronic counter, by the use of the signal-amplitude histogram, or by the gas-residence-time histogram (see Fig. 32).
3. The arrival frequency of the bubbles can be determined.
4. Bubble-diameter distribution functions can be obtained if local velocity is measured (Neal and Bankoff⁸² and Sekoguchi et al.⁹⁸), as well as gas and liquid slug-length distributions, as shown in Fig. 33.

Uga¹⁰⁶ also obtained histograms of bubble sizes in the riser and down-comer 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 in which a constant value of velocity was the normalizing factor. Similarly, Ibragimov et al.⁵¹ used miniature traversing probes to obtain bubble-frequency profiles in water-nitrogen flow similar to those obtained by Jones⁶¹ with the anemometer.

Sekoguchi et al.⁹⁸ reported histograms of bubble sizes also using a double-tipped probe with tips 4 mm apart and 30 μm in diameter. Using the transport time averaged over 10 observations, they obtained the bubble-rise velocity, which was then used to obtain the bubble size from the dewetting times. This method requires the assumption that there is no correlation

Fig. 32
Measurement of Local
Void Fraction

Fig. 33. Bubble-size and Slug- and Bubble-length Distributions for Bubbly and Slug Flows in a Mercury-Nitrogen System (Neal and Bankoff⁸²)

between bubble size and rise velocity. Although this may be true for the >1 -mm bubbles observed by Sekoguchi et al.,⁹⁸ it certainly is not true in general. Note, however, that these workers obtained excellent agreement between void-residence-time profiles and the volume-fraction profiles calculated from the bubble-diameter and frequency measurements. This agrees with the theoretical analysis of Serizawa⁹⁹ for long sampling times.

In their studies of thin films characteristic of annular two-phase flow, Telles and Dukler,¹⁰⁴ Dukler,²⁷ and Chu and Dukler¹⁶ have used the straight electrical probe to determine information on wave structure. Such information has included probability density functions for wave height where the contributions due to the film substance 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 Fig. 34.

Other statistical data can be obtained by using a double probe. Several authors tentatively described the granulometry of bubbly flows with sophisticated models (Uga,¹⁰⁶ Lecroart and Lewi,⁷⁵ Serizawa⁹⁹). A bubble displacement velocity has been looked for by the same investigators, and also by Lecroart and Porte⁷⁴ and by Kobayasi.⁶⁸

Serizawa,⁹⁹ using a double-tip probe with tips 5 mm apart, utilized both correlation and pulse-height methods to determine the bubble-velocity spectrum. His method of signal analysis is shown in Fig. 35. Correlation of the outputs of the two probes after passing through Schmitt triggers provides a function that 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 the stopper, ramp functions are generated during the transport time which, when stopped and differentiated, yield pulses whose heights are

Fig. 34. Spectral and Cross-spectral Density of Film-thickness Fluctuations Measured with a Straight Conductivity Probe (Telles and Dukler¹⁰⁴). ANL Neg. No. 900-5428.

Fig. 35. Signal Processing in Multichannel Technique for Bubble-velocity Measurement (Serizawa⁹⁹). ANL Neg. No. 900-5426 Rev. 1.

proportional to the transport-time delay. Height analysis of this pulse train yields the bubble-velocity spectrum. Results of the two methods are pictured in Fig. 36. Problems associated with this method include those due to probe wettability and surface tension, and bubble trajectory. Boundary contact times were noted by Sekoguchi⁹⁷ to be 100-200 μ s, resulting in errors of up to 10% in void measurements. (Jones⁶¹ measured similar boundary times and errors with a 50- μ m 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.

Fig. 36. Correlative Representation between Correlation Technique and Multichannel Technique (Serizawa⁹⁹). ANL Neg. No. 900-5420 Rev. 1.

VI. PHOTON-ATTENUATION TECHNIQUES

A. What Can Be Measured by Radiation Attenuation

Schrock⁹⁶ gave an excellent review of attenuation methods, including a comparison of the relative merits of various measurements systems. Basically, an attenuation method uses the observation that a stationary, homogeneous material will absorb a monochromatic beam of constant-intensity, short-wavelength electromagnetic radiation exponentially with increasing absorption length at constant material density. By measuring the emergent intensity at two extreme conditions, say gas-filled and liquid-filled, one can make calculations for intermediate conditions of beam-averaged gas volume fraction or mixture density based on these assumptions. 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. The attractiveness of such a method 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. 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 oriented parallel to the photon beam were discussed by Hooker and Popper⁴⁸ and verified by Petrick and Swanson⁸⁶ who showed that errors as high as 40% could be possible. These errors are due to "photon streaming" preferentially through the gas such that the emergent attenuation is the sum of two separate exponentials rather than the exponential of the sum of two linear terms. 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 content of the test section 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,^{60,61} Harms and Forrest,³⁹ Harms and Laratta,⁴⁰ Laratta and Harms,⁷³ and most recently by Barrett.¹⁰

Maximum theoretical errors for completely separated slug flow for α in the range from zero to unity were obtained by Jones⁶¹ as shown in Fig. 37. These errors for the mixture density are in terms of the gas-to-liquid density ratio and the dimensionless absorption coefficient given by

$$k = s \frac{\mu_{fg}}{\rho_{fg}} \rho_f, \quad (7)$$

where s is the water-gap thickness, μ_{fg} is the difference between gas and liquid linear-absorptivity coefficients, and ρ_f and ρ_{fg} are the liquid-density and gas-liquid-density differences, respectively. The general expression for the error at any void fraction was shown to be

$$\epsilon \equiv \frac{\rho_{\text{calc}} - \rho_{\text{true}}}{\rho_{\text{true}}} = \frac{\ln[\alpha e^{k\rho_g/\rho_f} + (1-\alpha)e^k]}{k[(1-\alpha) + \alpha\rho_g/\rho_f]} \quad (8)$$

where α is the true void fraction "seen" by the X- or gamma-ray beam. This expression is literally true only for perfectly separated, sluglike flow producing

Fig. 37. Locus of Maximum Calculational Error in Void Fraction due to Nonlinear Averaging of Fluctuations as Dependent on Dimensionless Absorptivity and Density Ratio (Jones⁶¹). ANL Neg. No. 900-5432.

those of Ball et al.⁷ and Kemp et al.⁶⁶ This work was closely followed by that of Schrock and Selph.⁹⁴ The systems used could follow relatively rapid transients; the earlier work was capable of following an 0.0076/ms void rate, and the system of Schrock and Selph was capable of responding to passage of a 0.1 mm-dia void in 1 ms. The system of Kemp et al. was not a linearized system, whereas that of Schrock and Selph 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

a series of binary-wave void signals. However, if the density fluctuates between two extremes, say ρ_1 and ρ_2 , then these values may be used to replace ρ_f and ρ_g , respectively, to calculate the error involved. 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^{60,61}), and short-time sampling, conversion, and averaging of the desired results (Hancox et al.^{37,38}). Barrett¹⁰ has shown that, for the latter method, it is necessary to compromise between (1) increased calculational accuracy, which arises with decreasing sampling interval, and (2) the decreased accuracy resulting from the decreasing number of random nuclear events that are measured in the shorter interval. Linearization does not require such a compromise.

B. Transient Void Fractions

Early reports of the transient measurement of void fraction included

severe 60-Hz groundloop noise, although Schrock and Selph took pains to reduce the 60-Hz noise by carefully balancing the three-phase power-supply sources.

Direct-current drift was also a problem, amounting to over 0.20 void/hr in the system of Kemp et al. For this reason, Kemp et al. reported only variations in void fraction in their studies of dynamic response of a simulated SPERT-1A rectangular reactor channel. Typical results for void-fraction response are shown in Fig. 38. Using the system of Schrock and Selph,⁹⁴ Schrock et al.⁹⁵ obtained data for transient void volume in pool boiling similar to those shown in Fig. 39.

More recently, Zuber et al.¹¹⁴ used a system similar to those described above. They low-passed the signal with a bandwidth of 40 Hz and a 40-dB/decade rolloff, which eliminated most problems associated with 60-Hz ripple in their nonlinearized signal. They thus obtained data for void-oscillation amplitude and phase lag with respect to power oscillations such as shown in Figs. 40 and 41. Nyer⁸⁴ described a system in which he modulated his

Fig. 38. Void-fraction Response Amplitude as a Function of Power-modulation Frequency in Simulated SPERT-1A Rectangular Channels (Kemp et al.⁶⁷). ANL Neg. No. 900-4930 Rev. 1.

Fig. 39

Typical Transient Data of Schrock et al.⁹⁵
 ANL Neg. No. 900-4906 Rev. 2.

RUN NO S0177 VII 6
 $p_r = 0.65$
 $G = 620,000 \text{ lb/hr-ft}^2$
 $\Delta T_{\text{sin}} = 6.6 \text{ }^\circ\text{F}$

Fig. 40. Double Amplitude of the Average Void-fraction Oscillation. Zero-frequency oscillations are those calculated assuming thermodynamic equilibrium (Zuber et al.¹¹⁴). ANL Neg. No. 900-4922 Rev. 1.

Fig. 41. Phase Lag of Void Fraction Relative to Test-section Power Input. Qualities at each void station assume thermodynamic equilibrium at the average power level (Zuber et al.¹¹⁴). ANL Neg. No. 900-4921 Rev. 1.

40 kV X-ray power supply to within 3.5% and measured the anode current from a photomultiplier fed by a thallium-activated sodium iodide crystal. The 3.5% amplitude in the supply voltage, coupled with slight variations in the photomultiplier supply, resulted in 10-15% ripple on the output at a frequency of 60 Hz. The accuracy of the time-averaged signal was stated to be within 5% with a time constant of 2.2 m/s.

Jones⁶⁰ reported that the 60 Hz noise in signal output was found to be due mostly to the ac component of the rectified and filtered high voltage applied to the X-ray tube. This problem was virtually eliminated by installation of a solid-state, full-wave rectifier in the current-supply circuit to the tube along with 80,000 μF across these lines. The resultant signal had ripple less than ± 0.03 void while maintaining < 1.0 -m/s response times. Direct-current drift

was also reported to be a problem, but was later found (Jones⁶¹) to be due to very long-term thermal drift of the system. Continuous operation after 12 hr was found to limit this cyclic drift to less than 0.005 void/hr, probably due to thermal vagaries in the surroundings.

C. Statistical Measurements

There are few reported data for statistical quantities measured by radiation techniques. Hancox et al.^{37,38} made short-interval, discrete time

Fig. 42. Typical Void-fraction Distributions Obtained by Discrete-time Neutron Interrogation (Hancox and Harms³⁷). ANL Neg. No. 900-5419.

measurements of void fraction to construct histograms of void-fraction observations (see Fig. 42) in a 1.36-cm-square duct. Instead of using photons, they employed neutrons from a reactor at rates to the test section of 7000 neutrons per second. Their measurements indicated that a detection period of 0.05 s was sufficiently small to maintain fluctuation errors less than 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 and Zuber^{62,63}).

Kobel et al.⁶⁹ used a transient X-ray system to measure void fraction and void-fluctuation profiles in a bubble column, and to obtain probability distributions of the fluctuations (see Fig. 43).

Finally Jones⁶¹ and Jones and Zuber^{62,63} reported on an X-ray system having a linear output proportional to the void fraction and millisecond response times. Probability density functions and fluctuation spectra were obtained for the void fraction on the centerline across the small dimension of a 0.51 x 6.35-cm rectangular Plexiglas duct. Typical results are shown in Fig. 44. No attempt was made to eliminate the statistical system noise from their system since this amounted only to a standard deviation of 0.022 void. In more opaque systems, such as those required for high-pressure experimentation, this noise would be expected to increase as the percentage of parasitic attenuation increases and signal-to-noise ratio decreases. The results would become less definitive, unless care was taken to subtract out the extraneous noise component from these measurements.

Fig. 43. Profiles of Void-fluctuation Amplitudes (a) and Probability Density Function of Void Fraction for Agglomerating Bubbly Flow (b) (Kobel et al.⁶²)

Fig. 44. Power Spectral Density (a) and Probability Density Function (b) of Void Fluctuations in Vertical Upflow of Air and Water in Slug Flow (Jones and Zuber⁶³). ANL Neg. No. 900-4925.

VII. MISCELLANEOUS METHODS

Recent new developments of interest that do not fit any of the previously discussed categories should be mentioned because of the potentially important information they may yield regarding the statistical structure of two-phase flows. Therefore a few selected studies will be discussed without any attempt at completeness.

Ishigai et al.⁵⁵ demonstrated that fluctuations in pressure would be directly related to the individual component flows in an air-water system. Akagawa et al.⁴ studied differential pressure fluctuations in vertical air-water flow in a round tube in conjunction with electrical probes; quick-closing valves were used for direct measurement of mean void fraction. Specially designed pressure transducers had built-in throttles to provide known measurement response amplitude versus frequency between 0 and 50 Hz (down 5 dB at 50 Hz). Probability distributions, power spectra, and amplitude ratios for the pressure-drop fluctuations were reported, 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 of 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.^{41,42} reported the use of voltage taps located axially along the outer wall of the hexagonal can holding a seven-pin bundle through which liquid sodium at high temperature flowed. 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, Kottowski et al.⁷⁰ attached pairs of voltage taps along tubes having 0.1-mm-thick walls. Using NaK eutectic at ambient temperature, they measured film thicknesses within 2% for 0.1-mm-thick films.

Zimin et al.¹¹² reported the use of laser-scattering techniques for statistical analysis of two-phase dispersed flows. Measurements showed that for particle mass concentrations up to 0.5, even nonuniform particle sizes yielded linear relationship between the intensity of the scattered light and the condensed-phase flow rate for scattering angles from 0.0083-0.0367 radian. Measurements were thus made of the local particle distribution (see Fig. 45) for dusty gas flows containing mixed oxides of silicon, iron, aluminum, calcium, and magnesium in decreasing order of concentration. No estimate of the accuracy of their system was given.

Popper et al.⁸⁷ used a laser-Doppler system to measure velocity profiles of droplets in a two-phase jet. Their system was calibrated to known references within 3%. The laser method has the obvious drawback that light transmission is required and that partial concentrations cannot become so

Fig. 45

Local Particle-size Distributions:
 (1) $r = 0$ mm; (2) $r = 6$ mm;
 (3) $r = 12$ mm; (4) Calculated
 from Scattering Indicatrix Aver-
 aged over Jet Diameter.
 (Zimin et al.¹¹²)

large as to severely reduce the strength of the light beam. Use in fully dispersed mist flow would be a distinct possibility, but in the presence of an annular film, use would be questionable.

Two papers have described the use of laser holography in two-phase gas-liquid flows. Alad'ev et al.⁵ determined that two-beam holography could be most effective in mist flows for which the droplets were $20\text{ }\mu\text{m}$ or larger in diameter as well as with thin ($5\text{--}35\text{-}\mu\text{m}$) films (interferometry) and $>150\text{-}\mu\text{m}$ -thick films by 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.⁷⁶ used a single ruby laser to measure sizes and velocities of drops for air-water critical two-phase flows over 95% quality. Results included the size and velocity distributions based on particle size (see Figs. 46 and 47) as well as the particle-velocity histograms.

Finally, Nishihara⁸³ has used statistical correlation of the signals from acoustic detectors to determine the location of boiling of $<50\text{-m/s}$ duration

in a simulated reactor vessel by triangulation techniques. Use of such a method to obtain void information may be difficult in geometries in which 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.

Fig. 46. Number vs Size at Different Qualities for Critical Flow (1.5 cm from the exit plane).⁷⁶ ANL Neg. No. 900-5212.

Fig. 47. Average Velocity vs Drop Size at Different Flow Rates.⁷⁶ ANL Neg. No. 900-5213.

VIII. 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 instruments based on photon-attenuation methods. There are also instruments, based on 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. Through the use of these and other techniques a coherent picture of the interactions of the phases will eventually be accomplished to allow more detailed and realistic models of multiphase phenomena.

The optical-probe system theoretically gives an on-off signal corresponding to a 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, for which $n_g = 1.00$ and $n_l = 1.10$. Recent improvements in these systems include miniaturization of the sensor to a 100- μm diameter, integration of the electronics, and use of dual sensors for velocity determination.

In practice, stretching of interfaces around the sensitive portion of the probes yields 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 whereby 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 gamma-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.

Of any system reported, the small size of the U-shaped fiber system presents the least disturbance to the flow. The small size makes this system 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.

Next to the thermocouple, the electrical probe is probably the simplest device, 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, dc-excitation mode that tend to alter the response in time. Alternating-current supplies can circumvent this problem, but may lead to others.

Jones⁶¹ has shown that the frequencies characteristic of two-phase flows may range from less than 1 Hz for slug flows at low velocities to more than 5 kHz for droplet passage in annular mist flows. High-frequency supplies that 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 dc 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 gamma-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 ensure that 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 hot films and hot wires. On the other hand, the frequency response of such a probe is lower by an order of magnitude 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 mean and fluctuating characteristics of the fluid velocity may be measured, as well as temperature and void fractions. Accuracy of the signal processing has improved, but still needs further work.

There is still some question as to the adequacy of the hot wire as a droplet-size sampler, and more work also needs to be done in this area. 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 is due to failure of the coating. It is unclear whether this would be a problem in organic fluids, but in such cases, bare hot wires can be used.

In no instance has there been 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 measurements of local void fraction, 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. Major drawbacks, however, are the cost of the electronics and the extreme fragility of the sensors.

Microthermocouples, which have come into increasing use in recent years, give combined phase indication through electrical conductivity with instantaneous temperature signals. The manner has been clearly demonstrated in which the probability-density functions (PDF's) of fluctuations due to vapor and those due to liquid in nonequilibrium conditions combine to yield the total time PDF. Although 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 are subject to the same problems associated with the other probes; 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, are strong functions of the sensor size and the fluid temperatures. This has been clearly demonstrated by Van Paassen,¹⁰⁷ 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, to be effective, the former must have sampling times shorter than the fluctuation period. The latter method seems easier, less expensive, and perhaps more accurate.

The 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 dc 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 of the order of 0.02 standard deviation in void fraction, and of drift less than 0.005 void/hr. 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 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 in which 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.

BIBLIOGRAPHY

1. N. Afgan et al., *An Approach to the Analysis of Temperature Fluctuation in Two-Phase Flow*, Int. J. Heat Mass Transfer 16, 187-194 (1973).
2. N. Afgan et al., *Determination of the Statistical Characteristics of Temperature Fluctuation in Pool Boiling*, *ibid.*, 249-256.
3. K. Akagawa, *Fluctuations in Void Ratio in Two-Phase Flow*, Bul. JSME 7, 122 (1964).
4. K. Akagawa, H. Hamaguchi, T. Sakaguchi, and T. Ikari, *Studies of the Fluctuation of Pressure Drop in Two-Phase Flow*, Bul. JSME 14, 447-469 (1971).
5. I. T. Alad'ev, V. M. Ginsberg, N. D. Gavrilova, Ea. Kuzretsova, Yu S. Soluyanov, and Y. Ya Tsarfin, *Investigation of the Possibility of Using Holography in the Study of Two-Phase Flows*, Teploenergetika 20, 66-68 (1973).
6. A. A. Armand, *The Resistance During the Movement of a Two-Phase System in Horizontal Pipes*, AERE-Trans-828, from Izvestia Vsesoyuznogo Teploekhnicheskogo Instituta 1, 16-23 (1946).
7. W. P. Ball, D. B. Langmuir, and R. W. Wright, *X-ray Measurements of Time Varying Steam Void Fraction in a Thin Water Channel*, Trans ANS 1(2), 59 (1958); also TRW Report RW-RL-137 (1959).
8. S. G. Bankoff, *A Variable Density, Single-Fluid Model for Two-Phase Flow with Particular Reference to Steam/Water Flow*, J. Heat Trans. 82(4), 265 (1960).
9. G. Barois, *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 (1969).
10. P. R. Barrett, *Systematic Errors in the Discrete Time-Interval Transmission Method for the Estimation of Void Statistics in Boiling Channels*, Nucl. Eng. Des. 30, 316-327 (1974).
11. R. Bell, B. E. Boyce, and J. G. Collier, *The Structure of a Submerged Impinging Gas Jet*, J. Br. Nucl. Energy Soc. 11(2), 183-193 (1972).
12. A. E. Bergles, "Electrical Probes for Study of Two-Phase Flows," in *Two-Phase Flow Instrumentation*, B. W. LeTourneau and A. E. Bergles, Ed., ASME, pp. 70-81 (1969).
13. C. Bonnet et al., *Fluctuations de température dans la paroi chauffante et dans le liquide au cours de l'ébullition nucléée*, EUR 3162f (1966).
14. M. Bouvard and H. Dumas, *Application de la méthode du fil chaud à la mesure de la turbulence dans l'eau*, La Houille Blanche 3, 257-270 (1967).
15. G. M. Bragg and J. Tevaarverk, "The Effect of a Liquid Droplet on a Hot-Wire Anemometer Probe," Paper No. 2-2-19, *First Symposium on Flow--Its Measurement and Control in Science and Industry*, Pittsburgh (1971).
16. K. J. Chu and A. E. Dukler, *Statistical Characteristics of Thin, Wavy Films*, AIChE J. 20, 695-706 (1974).
17. S. C. Chuang and V. W. Goldschmidt, "The Response of a Hot-Wire Anemometer to a Bubble of Air in Water," *Turbulence Measurements in Liquids*, G. K. Patterson and J. L. Zakin, Ed., Dept. of Chem. Eng., University of Missouri, Rolla, Continuing Education Series (1969).

18. F. Danel and J. M. Delhay, "Sonde optique pour mesure du taux de présence local en écoulement diphasique," *Mesures-Régulation--Automatisme*, Août--Septembre, 99-101 (1971).
19. J. M. Delhay, *Measurement of the Local Void Fraction in Two-Phase Air-Water Flow with a Hot Film Anemometer*, CEA-R-3465(E) (1968).
20. J. M. Delhay, "Hot-Film Anemometry," in *Two-Phase Flow Instrumentation*, B. W. LeTourneau, and A. E. Bergles, Ed., ASME (1969).
21. J. M. Delhay, R. Séméria, and J. C. Flamand, *Mesure du taux de vide local et des températures du liquide et de la vapeur en écoulement diphasique avec changement de phase à l'aide d'un microthermocouple*, CEA-R4302 (1972).
22. J. M. Delhay, J. P. Galaup, M. Réocreux, and R. Ricque, *Métrologie des écoulements diphasiques--Quelques procédés*, CEA-R-4457 (1973).
23. J. M. Delhay, R. Séméria, and J. C. Flamand, *Void Fraction, Vapor and Liquid Temperatures: Local Measurements in Two-Phase Flow Using a Microthermocouple*, *J. Heat Transfer* 95, 365-370 (1973).
24. J. M. Delhay, "Les techniques de mesure dans les écoulements diphasiques," *Techniques de Mesure dans les Écoulements*, Collection de la Direction des Etudes et Recherches de l'E.d.F., Paris (1974).
25. J. M. Delhay and J. P. Galaup, *Measurement of Local Void Fraction in Freon-12 with an 0.1 mm Optical Fiber Probe*, European Two-Phase Flow Group Meeting, Harwell (1974).
26. G. E. Dix, *Vapor Void Fractions for Forced Convection with Subcooled Boiling at Low Flow Rates*, NEDO-10491, General Electric Co. (1971).
27. A. E. Dukler, *Characterization, Effects, and Modeling of the Wavy Gas-Liquid Interface*, *Prog. Heat Mass Transfer* 6, G. Hetsroni, S. Sideman, and J. P. Hartnett, Ed., Pergamon Press, 207-234 (1972).
28. J. P. Galaup, *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 (1975).
29. T. Ginsberg, *Droplet Transport in Turbulent Pipe Flow*, ANL-7694 (Nov 1971).
30. V. Goldschmidt, *Measurement of Aerosol Concentrations with a Hot-Wire Anemometer*, *J. Colloid Sci.* 20(6), 627-634 (1965).
31. V. Goldschmidt and S. Eskinazi, "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*, Société Hydrotechnique de France, 8èmes journées de l'Hydraulique, Lille, France, 291-298 (1964).
32. V. W. Goldschmidt and S. Eskinazi, *Two-Phase Turbulent Flow in a Plane Jet*, *J. Appl. Mech.* 33(4), 735-747 (1966).
33. V. W. Goldschmidt and M. K. Householder, "Measurements of Aerosols by Hot-Wire Anemometry," *Advances in Hot-Wire Anemometry*, W. L. Melnik and J. R. Weske, Ed., Dept. of Aerospace Eng., University of Maryland, pp. 134-152 (1968).
34. V. W. Goldschmidt and M. K. Householder, *The Hot-Wire Anemometer As an Aerosol Droplet Size Sampler*, *Atmospheric Environment* 3, 643 (1969).
35. V. W. Goldschmidt, M. K. Householder, G. Ahmadi, and S. C. Chuang, *Turbulent Diffusion of Small Particles Suspended in Turbulent Jets*, *Prog. Heat Mass Transfer* 6, G. Hetsroni, S. Sideman, and J. P. Hartnett, Ed., Pergamon Press, 487-508 (1972).

36. S. W. Gouse, *Void Fraction Measurement*, MIT Report DSR 8734-2 (1964).
37. W. T. Hancox and A. A. Harms, *Discrete-Time Neutron Interrogation of Liquid Flow System*, Trans. ANS 14, 699 (1971).
38. W. T. Hancox, C. F. Forrest, and A. A. Harms, *Void Determination in Two-Phase Systems Employing Neutron Transmission*, ASME Paper 72-HT-2 (1972).
39. A. S. Harms and C. F. Forrest, *Dynamic Effects in Radiation Diagnosis of Fluctuating Voids*, Nucl. Sci. Eng. 46, 408-413 (1971).
40. A. A. Harms and F. A. R. Laratta, *The Dynamic-bias in Radiation Interrogation of Two-Phase Flow*, Int. J. Heat Mass Transfer 16, 1459-1465 (1973).
41. R. E. Henry, R. M. Singer, D. J. Quinn, and W. C. Jeans, *Incipient Superheat in a Convective Sodium System*, Paper B7.1 presented at the Fifth Internatl Heat Transfer Conf., Tokyo, Sept 3-7 (1974).
42. R. E. Henry et al., "Sodium Expulsion Tests for the Seven-Pin Geometry," *Proc. Fast Reactor Safety Meet.*, Beverly Hills, Calif., April 2-4, 1974, CONF-740401, pp. 1188-1201.
43. R. A. Herringe and M. R. Davis, *Detection of Instantaneous Phase Changes in Gas-Liquid Mixtures*, J. Phys. E. 7, 807-812 (1974).
44. G. Hetsroni, J. M. Cuttler, and M. Sokolov, *Measurements of Velocity and Droplets Concentration in Two-Phase Flows*, J. Appl. Mech. 36, 334-335 (1969).
45. G. F. Hewitt, *The Role of Experiments in Two-Phase Systems with Particular Reference to Measurement Techniques*, Prog. Heat Mass Transfer 6, G. Hetsroni, S. Sideman, and J. P. Hartnett, Ed., Pergamon Press, 295-343 (1972).
46. S. Hinata, *A Study of the Measurement of the Local Void Fraction by the Optical Fibre Glass Probe*, Bull. JSME 15, 1228-1235 (1972).
47. K. Hollasch and B. Gebhart, *Calibration of Constant-Temperature Hot-Wire Anemometers at Low Velocities in Water with Variable Fluid Temperature*, J. Heat Transfer 94, 17-22 (1972).
48. H. H. Hooker and G. F. Popper, *A Gamma-ray Attenuation Method for Void Fraction Determination in Experimental Boiling Heat Transfer Test Facilities*, ANL-5766 (Nov 1958).
49. Y. Y. Hsu, F. F. Simon, and R. W. Graham, "Application of Hot-Wire Anemometry for Two-Phase Flow Measurements Such as Void-fraction and Slip Velocity," *Multi-phase Flow Symposium*, Nov 17-22, 1963, ASME, N. J. Lipstein, Ed., pp. 26-34.
50. J. C. Hurt and J. R. Welby, *The Use of a Hot-film Anemometer to Measure Velocities Below 5 cm/sec in Mercury*, J. Heat Transfer 95, 548-549 (1973).
51. M. Kh. Ibragimov, V. P. Bobkov, and N. A. Tychinskii, *Investigation of the Behavior of the Gas Phase in a Turbulent Flow of a Water-gas Mixture in Channels*, Teplofizika Vysokikh Temp. 11, 1051-1061 (1973); (Consultants Bureau, New York) High Temp. 11, 935-944 (1973).
52. Y. Iida, K. Kobayasi, and S. Kumagai, *A Study on the Measurement of Void Fraction by Probe Method*, J. Atomic Soc. Japan 9(1), 2-9 (1967).
53. Y. Iida and K. Kobayasi, *Distributions of Void Fraction Above a Horizontal Heating Surface in Pool Boiling*, Bull. JSME 12(50), pp. 283-290 (1969).

54. Y. Iida and K. Kobayasi, "An Experimental Investigation of the Mechanism of Pool Boiling Phenomena by a Probe Method," *Heat Transfer* 1970, Vol. 5, Paper B1.3, Elsevier (1970).
55. S. Ishigai, M. Yamane, and K. Roko, *Measurement of the Component Flows in a Vertical Two-Phase Flow by Making Use of the Pressure Fluctuations*, Bull. JSME 8, 375 (1965).
56. S. Ishigai et al., *Hydrodynamics and Heat Transfer of Vertical Falling Liquid Films (Part 1: Classification of Flow regimes)*. Bull. JSME 15, 594-602 (1972).
57. J. Jacobs and A. H. Shade, *Measurement of Temperatures Associated with Bubbles in Subcooled Pool Boiling*, J. Heat Transfer 91, 123-128 (1969).
58. L. M. Jiji and J. A. Clark, *Bubble Boundary Layer and Temperature Profiles for Forced Convection Boiling in Channel Flow*, J. Heat Transfer 86, 50-58 (1964).
59. O. C. Jones, *Preliminary Investigation of Hot Film Anemometer in Two-Phase Flow*, TID-24104 (1966).
60. O. C. Jones, *Determination of Transient Characteristics of an X-ray Void Measurement System for Use in Studies of Two-Phase Flow*, KAPL-3859 (1970).
61. O. C. Jones, *Statistical Considerations in Heterogeneous, Two-Phase Flowing Systems*, Ph. D. thesis, Rensselaer Polytechnic Institute (1973).
62. O. C. Jones and N. Zuber, "Statistical Methods for Measurement and Analysis in Two-phase Flow," Paper B5.4, *Proc. 5th Int. Heat Transfer Conf.*, IV, 200, September 3-7 (1974).
63. O. C. Jones and N. Zuber, *The Interrelation between Void Fraction Fluctuations and Flow Patterns in Two-phase Flow*, Int. J. Multiphase Flow 2, 273-306 (1975).
64. O. C. Jones and N. Zuber, *Use of a Cylindrical Hot-film Anemometer for Measurement of Two-phase Void and Volume Flux Profiles in a Narrow Rectangular Channel*, AIChE Paper No. 47, National Heat Transfer Conference, San Francisco (1975).
65. A. K. Katarzhis, S. I. Kosterin, and B. I. Sheinin, *An Electric Method of Recording the Stratification of the Steam-Water Mixture*, *Izvestiya Akademii Nauk S.S.S.R., Otdelenie Tekhnicheskikh Nauk* 2, pp. 132-136, A.E.R.E. Lib./Trans. 590 (1955).
66. R. F. Kemp, A. L. Morse, R. W. Wright, and S. M. Zivi, *Kinetic Studies of Heterogeneous Water Reactors*, RWD-RL-167 (1960).
67. T. D. A. Kennedy and J. G. Collier, "The Structure of an Impinging Gas Jet Submerged in a Liquid," *Multi-Phase Flow Systems Symposium*, Inst. Chem. Eng. Symp. Ser. No. 38, II, Paper J4 (1974).
68. K. Kobayasi, *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 (1974).
69. H. Kobel, R. Beinhauer, and H. Langemann, *Dynamische Messung des relativen Gasgehaltes in blässensaulen mittles Absorption von Rontgensbrahlen*, Chem.-Ing. Tech. 44(11), 697-704 (1972).
70. H. M. Kottowski et al., "Measurement of the Liquid Metal Residual Film Left behind Coolant Expulsion in Narrow Channels," *Proc. Fast Reactor Safety Meet.*, Beverly Hills, Calif., April 2-4, pp. 1173-1187 (1974).

71. C. Lackmé, *Statistical Analysis of the Local Structure of a Two-phase Flow*, Grenoble Notes TT-162 and TT-176; also ANL-Trans. 171 and 172 (1964).
72. C. Lackmé, *Structure et cinématique des écoulements diphasiques à bulles*, CEA-R3203 (1967).
73. F. A. R. Laratta and A. A. Harms, *A Reduced Formula for the Dynamic-Bias in Radiation Interrogation of Two-phase Flow*, Int. J. Heat Mass Transfer 17, 464 (1973).
74. H. Lecroart and R. Porte, *Electrical Probes for Study of Two-Phase Flow at High Velocity*, Presented at the Int. Symp. Two-phase Systems, Haifa, Israel (1971).
75. H. Lecroart and J. Lewi, *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 (1972).
76. Y. J. Lee, M. E. Fournery, and R. W. Moulton, *Determination of Slip Ratios in Air-water Two-phase Critical Flow at High Quality Levels Using Holographic Techniques*, AIChE J. 20, 209-219 (1974).
77. T. E. Lippert and R. S. Dougall, *A Study of the Temperature Profiles Measured in the Thermal Sublayer of Water, Freon-113, and Methyl Alcohol during Pool Boiling*, J. Heat Transfer 90, 347-352 (1968).
78. B. D. Marcus and D. Dropkin, *Measured Temperature Profiles within the Superheated Boundary Layer Above a Horizontal Surface in Saturated Nucleate Pool Boiling of Water*, J. Heat Transfer 87, 333-341 (1965).
79. N. Miller and R. E. Mitchie, "The Development of a Universal Probe for Measurement of Local Voidage in Liquid/Gas Two-phase Flow Systems," in *Two-Phase Flow Instrumentation*, B. W. LeTourneau and A. E. Bergles, Ed., ASME, pp. 82-88 (1969).
80. N. Miller and R. E. Mitchie, *Measurement of Local Voidage in Liquid/Gas Two-phase Flow Systems*, J. British Nucl. Energy Soc. 9(2), 94-100 (1970).
81. T. B. Morrow and S. J. Kline, *The Evaluation and Use of Hot-wire and Hot-film Anemometers in Liquids*, Stanford University Report MD-25 (1971).
82. L. S. Neal and S. G. Bankoff, *A High Resolution Resistivity Probe for Determination of Local Void Properties in Gas-liquid Flow*, AIChE J. 9, 490-494 (1963).
83. H. Nishihara, *Triangulation of Local Coolant Boiling by Cross-Correlating Acoustic Noise Signals*, Nucl. Tech. 23, 222-232 (1974).
84. M. Nyer, *Etude des phénomènes thermiques et hydrauliques accompagnant une excursion rapide de puissance sur un canal chauffant*, CEA-R3497 (1969).
85. H. L. Ornstein, *An Investigation of Turbulent Open Channel Flow Simulating Water Desalination Flash Evaporators*, Ph.D thesis, University of Connecticut (1970).
86. M. Petrick and B. S. Swanson, *Radiation Attenuation Method for Measuring Density in a Two-phase Fluid*, Rev. Sci. Inst. 29, 1979 (1958).
87. J. Popper, N. Abuaf, and G. Hetsroni, *Velocity Measurements in a Two-Phase Turbulent Jet*, Int. J. Multiphase Flow 1, 715-726 (1974).

88. M. Réocreux and J. C. Flamand, *Etude de l'utilisation des sondes résistives dans des écoulements diphasiques à grande vitesse*, CENG, STT, Rapport interne. No. 111 (1972).
89. F. Resch, *Etudes sur le fil chaud et le film chaud l'eau*, CEA-R3510 (1968).
90. F. Resch and M. Coantiec, *Etude sur le fil chaud et le film chaud dans l'eau*, La Houille Blanche 2, 151-161 (1969).
91. F. J. Resch and J. H. Leutheusser, *Le ressaut hydraulique; mesures de turbulence dans la région diphasique*, La Houille Blanche 4, 279-293 (1972).
92. F. J. Resch, H. J. Leutheusser, and S. Alemu, *Bubbly Two-phase Flow in Hydraulic Jump*, J. Hydraulics Division, ASCE 100, 137-149 (1974).
93. R. S. Rosler and S. G. Bankoff, *Large Scale Turbulence Characteristics of a Submerged Water Jet*, AIChE J. 9, 672-676 (1963).
94. V. E. Schrock and F. B. Selph, *An X-ray Densitometer for Transient Steam Void Measurement*, SAN-1005 (1963).
95. V. E. Schrock, H. A. Johnson, A. Gopalakrishnan, K. E. Lavezzo, and S. M. Cho, *Reactor Heat Transfer Research Final Report: Transient Boiling Phenomena*, Vol. 1, SAN-1013 (1966).
96. V. E. Schrock, "Radiation Attenuation Techniques in Two-phase Flow Measurements," in *Two-Phase Flow Instrumentation*, B. W. LeTourneau and A. E. Bergles, Ed., ASME, pp. 24-35 (1969).
97. K. Sekoguchi, H. Fukui, T. Matsuoka, and K. Nishikawa, *Ninth Japan Heat Transfer Symp.*, 435 (as taken from Serizawa [1974]) (1972).
98. K. Sekoguchi, H. Fukui, T. Matsuoka, and K. Nishikawa, *Investigation into the Statistical Characteristics of Bubbles in Two-phase Flow*, Trans. JSME 40, 336, 2295-2310 (1972).
99. A. Serizawa, *Fluid-dynamic Characteristics of Two-Phase Flow*, Institute of Atomic Energy, Kyoto University (1974).
100. B. S. Shiralkar, *Local Void Fraction Measurements in Freon-114 with a Hot-Wire Anemometer*, NEDO-13158, General Electric Co. (1970).
101. B. S. Shiralkar and R. T. Lahey, *Diabatic Local Void Fraction Measurements in Freon-114 with a Hot-Wire Anemometer*, Trans. ANS 15(2), 880 (1972).
102. N. Stefanovic et al., "Experimental Investigation of the Superheated Boundary in Forced Convection Boiling," *Heat Transfer 1970*, Vol. 5, Paper B4.12, Elsevier (1970).
103. V. I. Subbotin, D. N. Sorokin, and A. A. Tsiganok, "Some Problems on Pool Boiling Heat Transfer," *Heat Transfer 1970*, Vol. 5, Paper B1.9, Elsevier (1970).
104. A. S. Telles and A. E. Dukler, *Statistical Characteristics of Thin, Vertical Wavy Liquid Films*, Ind. Eng. Chem. Fund. 9, 412 (1970).
105. G. G. Treschov, *Experimental Investigation of the Mechanism of Heat Transfer with Surface Boiling of Water*, Teploenergetika 3, 44-48 (1957).
106. T. Uga, *Determination of Bubble Size Distribution in a BWR*, Nucl. Eng. Design 22, 252-261 (1972).

107. C. A. A. Van Paasen, *Thermal Droplet Size Measurements Using a Thermocouple*, Int. J. Heat Transfer 17, 1527-1548 (1974).
108. S. J. D. Van Stralen and W. M. Sluyter, *Local Temperature Fluctuations in Saturated Pool Boiling of Pure Liquids and Binary Mixtures*, Int. J. Heat Mass Transfer 12, 187-198 (1969).
109. G. B. Wallis, *Joint US-Euratom Research and Development Program--Quarterly Progress Report* (1963).
110. G. E. Walmet and F. W. Staub, "Pressure, Temperature, and Void Fraction Measurement in Nonequilibrium Two-phase Flow," in *Two-Phase Flow Instrumentation*, B. W. LeTourneau and A. E. Bergles, Ed., ASME (1969).
111. J. R. Wiebe and R. L. Judd, *Superheat Layer Thickness Measurements in Saturated and Subcooled Nucleate Boiling*, J. Heat Transfer 93, 455-461 (1971).
112. E. P. Zimin, O. V. Inozemitsev, A. M. Krugerskii, and Z. G. Mikhnevich, *Optical Measurement of the Parameters of the Dispersed Condensed Phase in a Two-phase Flow*, Teplofizika Vysokikh Temperatur 11, 1037-1043 (1973), also Heat Trans. Sov. Res., 924-928 (1973).
113. N. Zuber and J. A. Findlay, *Average Volumetric Concentrations in Two-phase Flow Systems*, J. Heat Transfer 87(4), 453 (1965).
114. N. Zuber, F. W. Staub, G. Bijwaard, and P. G. Kroeger, *Steady-state and Transient Void Fractions in Two-phase Flow Systems*, GEAP-5417 (1967).