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HOT-FILM ANEMOMETRY IN AIR-WATER FLOW

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ABSTRACT

The paper presents local measurements of void fraction and liquid velocity in a steady-state air-water bubbly flow at atmospheric pressure. Use is made of a constant temperature anemometer and of a conical hot-film probe.

The signal is processed with a multi-channel analyzer. Void fraction and liquid velocities are determined from the amplitude histogram of the signal.

The integrated void fraction over a diameter is compared with the average void fraction along the same diameter obtained with a γ-ray absorption method.

The liquid volumetric flow-rate is calculated from the void fraction and liquid velocity profiles and compared with the indication given by a turbine flowmeter.

INTRODUCTION

Two-phase flow instrumentation is of the utmost importance to back up the theoretical investigations which have been carried out for nuclear or chemical engineering purposes (Delhaye and Jones. 1975).
Technically sound measurement techniques are needed to provide information on the local structure of two-phase flows characterized by the flow pattern, the specific area and the bubble or droplet diameter probability function.
A fairly accurate knowledge of void fraction, velocity and temperature profiles is also required for checking different hypotheses usually appearing in the litterature.

In this paper, local measurements provided by a conical hot-film probe are compared to overall measurements for three different flow patterns : bubbly, transition and slug flow.

1. The local void fraction $\alpha(x)$ is determined along a diameter D of a vertical pipe where an air-water mixture is flowing upward. The results are compared with the time-averaged void fraction $\bar{R}_G$ measured along the same diameter with a γ-ray absorption method (Fig. 1). The following identity must be satisfied :

$$\bar{R}_G \equiv \frac{1}{D}\int_0^D \alpha(x)\,dx \qquad (1)$$

2. On the other hand, the hot film probe enables the liquid time-averaged velocity $\bar{v}_L$ to be measured. A supplementary comparison is introduced with the liquid volumetric flow rate $\bar{Q}_L$ measured with a turbine flowmeter.

In effect, assuming the flow to be axisymmetric, the following identity must be satisfied :

$$\bar{Q}_L \equiv \int_0^{D/2} (1-\alpha)\bar{v}_L \; 2\pi r\,dr \qquad (2)$$

PREVIOUS WORK ON HOT-FILM ANEMOMETRY IN TWO-PHASE FLOW

Measurements in Two-Component Two-Phase Flow without Phase Change

Liquid Droplets in a Gas Flow. Hot-wire anemometry has been used for measuring the concentration flux and the diameter histogram of liquid particles moving in a gas stream. Goldschmidt and Eskinasi (1964,1966) measured the arrival frequency of liquid droplets, 1.6 to 3.3 µm in diameter, with a constant temperature anemometer and a cylindrical probe, 4.5 µm in diameter. When the impaction frequency of the droplets is different from the energetic frequency range of the turbulent gas stream, the signal fluctuations due to impacts can be distinguished from the fluctuations due to turbulence.
Ginsberg (1971) used the same technique to study liquid droplet transport in turbulent pipe flow. Goldschmidt (1965) determined that the measured impaction rate is lower than th[illegible] value but proportional, and should thus be calibrated against another technique.

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

Time-averaged gas velocities as well as gas turbulent intensities were measured by Hestroni et al. (1969).

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

Air-water Flows. Following the studies done by Goldschmidt in aerosols and by Hsu and his colleagues (1963) in steam-water flow, and the preliminary work of Jones (1966), a thorough investigation of the hot-film anemometry technique in two-phase flow was carried out by Delhaye (1968, 1969) who used a conical constant temperature hot-film probe which has three major advantages over the cylindrical hot-film sensor: dust does not attach to the tip, bubble trajectories are less disturbed, and the relatively passive geometry is less susceptible to flow damage at high velocities. The maximum overheat resistance ratio suggested by Delhaye to avoid degassing on the sensor was 1.05, which corresponded to a difference of 17°C between the probe temperature and the ambient temperature, significantly below saturation temperature.

Chuang and Goldschmidt (1969) employed the hot-wire as a bubble size sampler by theoretically investigating the nature of the signal due to the traverse of an air bubble past the sensor. The peculiarities of the conical probe signal were examined in detail by Delhaye (1968, 1969). It is evident that if the liquid

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and gas signals could be separated, the turbulent structure of the liquid phase could be obtained. Delhaye did this to a certain extent when he obtained the amplitude probability density function of the output signal E(t), as shown in Fig. 2. To a first approximation, the local void fractions were calculated as the ratio of the hatched area to the total area which then compared favorably with radiation absorption methods (γ-rays). The liquid time-averaged velocity and the liquid turbulent intensity are calculated with the nonhatched area of the amplitude histogram (Fig. 2) and the calibration curve of the probe immersed in the liquid. The same method has extensively been used by Serizawa (1974) for measuring the turbulent characteristics and local parameters of air-water two-phase flow in pipes.

A different processing method was proposed by Resch et al. (1972,1974) in a study of bubble two-phase flow in hydraulic jumps. The nonlinearized analog signal from the anemometer (Fig. 3) is digitally analysed. A change of phase is recognized when the amplitude between two successive extremes of the signal is higher than a fluctuation threshold level ΔE. In this way the liquid mean velocities and turbulence levels were obtained along with bubble size histograms. ΔE was chosen to be in a plateau region of ΔE versus measured void fraction.

Jones (1973,1975) used a 50 μm cylindrical hot-film probe and a discriminator applied to the raw anemometer signal to obtain a binary signal but found the cutoff level needed to be adjusted depending on the local velocity to a point just below the minimum value for a liquid. Even though the threshold value was set at every point in the traverse, errors in averaged void fraction were encountered when calibrated against an x-ray measurement. These errors were found to be dependent on the liquid volume flux and the mean void fraction.

By counting the number of times the output of the discriminator changed from one level to another, Jones (1973) also obtained local values for interface passage frequency. He also measured the liquid volume flux directly by time averaging the linearized signal equal to the liquid velocity when the sensor was in liquid, and zero when the sensor was in gas. Liquid velocity was obtained by pointwise division of the measured liquid flux by the measured void fraction.

Serizawa (1974) used a conical probe similar to that of Delhaye (1968, 1969). 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.

Measurements in One-Component Two-Phase Flow with Phase Change

Steam-Water Flow. The earliest paper on hot-wire anenometry in two-phase flow seems to have been published by Katarzhis et al. (1955). This preliminary and crude approach was followed by the work of Hsu, Simon, and Graham (1963). These authors, by comparing the signal with high-speed movies concluded that hot-wire anenometry 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. Hsu, Simon and Graham specified that in a steam-water flow the only reference temperature is the saturation temperature. If water velocity measurements are carried out, the probe temperature must not exceed saturation temperature by more than about 5°C to avoid nucleate boiling on the sensor. Conversely, if only a high sensitivity to phase change is looked for, then the superheat should range between 5°C and 55°C causing nucleate boiling to occur on the probe.

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

EXPERIMENTAL SET-UP (Galaup, 1975)

Air-Water Loop

An air-water mixture is flowing upward in a vertical pipe of circular cross-section, 42 mm in diameter. Air is injected at the bottom of the pipe through 0.5 mm holes drilled in the pipe wall. Measurements were carried out at 30 diameters downstream of the air injection zone.

The air-water mixture temperature was measured with a chromel-alumel thermocouple, the cold junction of which was maintained at 0 ± 0,02°C by means of an automatic temperature controller.

Water volumetric flowrates $\overline{Q}_L$ were measured with a turbine flowmeter with a total relative accuracy of about 10^{-2}.

Air volumetric flowrates $\overline{Q}_G$ were measured with a rotameter associated with a thermometer and a Bourdon manometer.

Overall void fraction measurement

The void fraction over a diameter $\overline{R}_G$ is measured using a γ-ray absorption technique. The γ-ray emitter is an Americium 241 source whose contained activity is about 40 GBq. This value does not take into account either the source self-absorption or the absorption due to protection claddings. The energy peak is at 60 keV ensuring a good contrast between air and water.

The absorbed γ-ray intensity is measured with a NaI scintillator, a photomultiplier and a counting assembly. Collimators, 2 mm in diameter, provide a narrow γ-ray beam in order to avoid any bias due to the void distribution across the beam.
The overall void fraction is given by the following formula :

$$\overline{R}_G = \frac{\mathrm{Log}\,(I/I_L)}{\mathrm{Log}\,(I_G/I_L)} \qquad (3)$$

where :

I : emergent γ-ray beam intensity with the air-water mixture flowing in the pipe.
I_G : emergent γ-ray beam intensity with air alone flowing in the pipe.
I_L : emergent γ-ray beam intensity with water alone flowing in the pipe.

The validity and accuracy of Eq. (3) are discussed at length in Galaup (1975).

Hot Film Probe Calibration

A conical hot-film probe (DISA 55 R 42) was energized by a constant temperature anemometer (DISA 55 M). The calibration of the probes was carried out in a rotating tank. The overheat ratio was fixed at 1.05.

SIGNAL PROCESSING

The output signal of the constant temperature anemometer is depicted in Fig. 4. Delhaye (1969) thoroughly investigated the use of a hot film conical probe in air-water flow. High-speed movies enabled the interaction between the probe and a bubble to be visualized while simultaneously recording the anemometer output signal. The main results are summarized in Fig. 4.

Before a bubble is pierced by the probe the signal amplitude increases due to the slip velocity of the bubble with respect to the surrounding liquid.

The most important feature to be drawn from Fig. 4 is the nonsuitability of a threshold discriminator to measure the local void fraction. Actually, Fig. 4 shows that the bubble residence time τ_G is given by :

$$\tau_G = t_F - t_B \qquad (4)$$

whereas a threshold discriminator would give :

$$\tau_G\,(S) < t_E - t_C < \tau_G \qquad (5)$$

Delhaye (1969) proposed that measurements of local void fractions and local liquid velocities be made by means of the signal amplitude probability density function.

Local void Fraction Measurements

The histogram of the signal amplitude (Fig. 5) shows two peaks separated by a plateau.

According to Delhaye's method, the following values of the amplitude are recorded :

u_1 and u_5 : histogram extreme amplitudes,

u_3 and u_4 : plateau extreme amplitudes,

u_2 : amplitude of the intersection point of the histogram with the extrapolated plateau.

If S_G denotes the cross-hatched area, the local void fraction is given by :

$$\alpha = \frac{S_G}{S_G + S_L} = 1 - \frac{S_L}{S_G + S_L} \qquad (6)$$

Calling p(u) the probability density function, we get:

$$\alpha = 1 - \frac{\int_{u_2}^{u_3} p(u)\,du - P(u_3 - u_2)}{\int_{u_1}^{u_5} p(u)\,du} \qquad (7)$$

where P is the height of the plateau defined by :

$$P = \frac{1}{u_4 - u_3} \int_{u_3}^{u_4} p(u)\,du \qquad (8)$$

Local Liquid Velocity Measurements

The time-averaged local liquid velocity is given by :

$$\overline{v}_L = \frac{\int_{u_2}^{u_3} \overline{v}_L(u) \left[p(u) - P\right] du}{\int_{u_2}^{u_3} \left[p(u) - P\right] du} \qquad (9)$$

where $\overline{v}_L(u)$ is obtained from the probe calibration curve.

RESULTS

The output signal of the anemometer was processed by a multichannel analyzer with a 256 channel format. The sampling period was chosen equal to 500 µs according to the contraints imposed by the signal power spectral density and by the Shannon theorem. The storage time was 60 s, a value selected to obtain a time-independent local void fraction.

Local Void Fraction Data

Most histograms did not show a well defined plateau (Fig.6). In a first attempt, the height P of the plateau was determined with the following formula :

$$P = \frac{1}{u_4 - u_3} \sum_{u_3}^{u_4} p(u_i) \qquad (10)$$

where u_3 is selected visually.

The local void fraction is then calculated by :

$$\alpha_1 = 1 - \frac{\sum_{u_2}^{u_3} \left[p(u_i) - P_1\right]}{\sum_{u_1}^{u_5} p\,(u_i)} \qquad (11)$$

Local void fractions calculated with Eq. (11) underestimated the overall void fraction $\overline{R}_G$ measured by the γ-ray absorption method. The calculated $\{\alpha\}$ were systematically 0.05 to 0.06 lower than the measured $\overline{R}_G$.

Hence a new choice for the height of the plateau :

$$P_2 = p(u_3) \qquad (12)$$

In this case the local void fraction is given by :

$$\alpha_2 = 1 - \frac{\sum_{u_2}^{u_3} \left[p(u_i) - p(u_3)\right]}{\sum_{u_1}^{u_5} p(u_i)} \qquad (13)$$

Local void fraction profiles are given in Fig. 7 to 9. A comparison between $\{\alpha\}$ and $\bar{R}_G$ is given in Fig. 10. The determination of P by means of Eq.(12) seems to be correct except at low velocities where higher values of P are necessary.

Herringe and Davis (1974) carried out similar experiments with conical and cylindrical probes. They proposed a splitting of the histogram according to the tangent AT (Fig. 6). Although their results were not compared with overall void fraction measurements, it seems that their local void fraction data must be seriously underestimated.

Local Liquid Velocity Data

The time-averaged local liquid velocity is calculated with the following equation :

$$\bar{v}_L = \frac{\sum_{u_2}^{u_1} \bar{v}_L(u_i) \left[p(u_i) - P \right]}{\sum_{u_2}^{u_1} \left[p(u_i) - P \right]} \qquad (14)$$

where P is given by Eq. (12)

Time-averaged liquid velocity profiles are given in Fig.11 to 13. These figures show also gas velocity profiles measured with double optical or resistive probes according to a method described by Galaup (1975).

Knowing α and $\bar{v}_L$, we can calculate the volumetric flux $\bar{j}_L$ defined by :

$$\bar{j}_L = (1 - \alpha)\, \bar{v}_L \qquad (15)$$

By integrating over the cross section A, we get for an axisymmetric flow :

$$\{ \bar{j}_L \} = \frac{1}{A} \int_A (1 - \alpha)\, \bar{v}_L \, dA = \frac{\bar{Q}_L}{A} \qquad (16)$$

Consequently, in order to assess the validity of our method, we must verify the identity :

$$\{ \bar{j}_L \} \equiv \frac{\bar{Q}_L}{A} \qquad (17)$$

where $\bar{j}_L$ is measured with the hot-film probe and $\bar{Q}_L$ with the turbine flowmeter. The results of the comparison are given in the following table :

Flow pattern	Bubbly	Bubbly	Transition
$\bar{R}_G$	0.05	0.21	0.28
$\bar{Q}_L/A$ (m/s)	1.50	2.01	1.50
$\{\bar{j}_L\}$ (m/s)	1.47	1.82	1.56
$\dfrac{\{\bar{j}_L\} - \bar{Q}_L/A}{Q_L/A}$	-0.02	-0.09	0.04

CONCLUSIONS AND FUTURE WORK

Hot-film anemometry has been proved a valuable measurement technique in two-component two-phase flow. Local void fractions were measured and successfully compared with overall void fraction data. Comparisons with other local probes were also reported by Galaup (1975). The shape of the amplitude histogram has been shown to be a function of the probe type and no universal recommendation can be made for a proper division of the histogram between a liquid part and a gas part. Cross-checking with an overall method must be used in each case. Time-averaged local liquid velocities were also measured and compared fairly well with the liquid volumetric flow-rate.

Improvements in the method could be achieved by using smaller probes and by integrating the profiles over the whole cross section to get rid of any non-symmetric effects within the flow.

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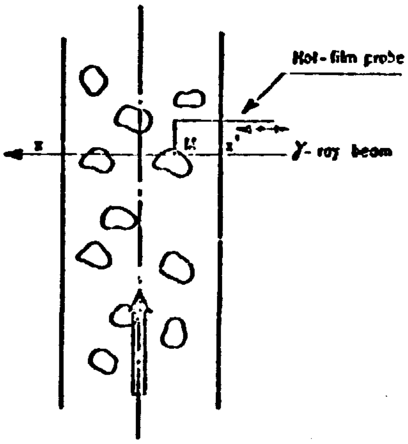

Figure 1
Comparison between hot-film measurements and γ-ray absorption measurements.

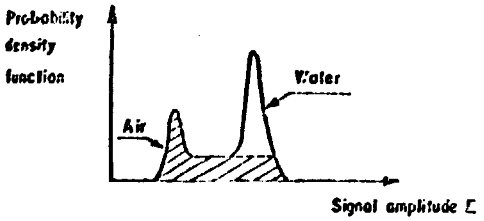

Figure 2
Typical amplitude histogram of anemometer signal. Delhaye (1968, 1969)

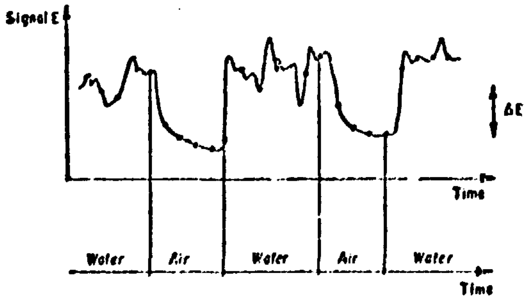

Figure 3
Signal analysis method of Resch et al. (1972, 1974).

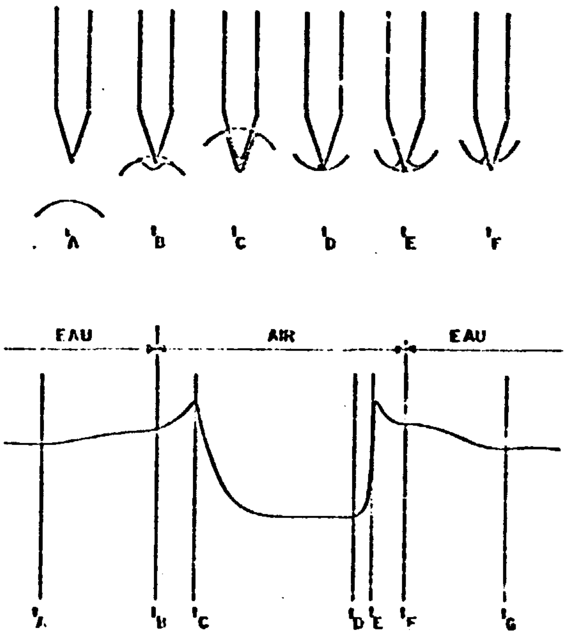

Figure 4
Passage of a single air bubble past a conical probe. Delhaye (1969)

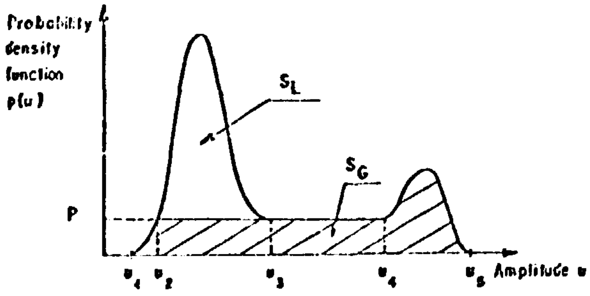

Figure 5
Typical amplitude histogram. Delhaye (1969)

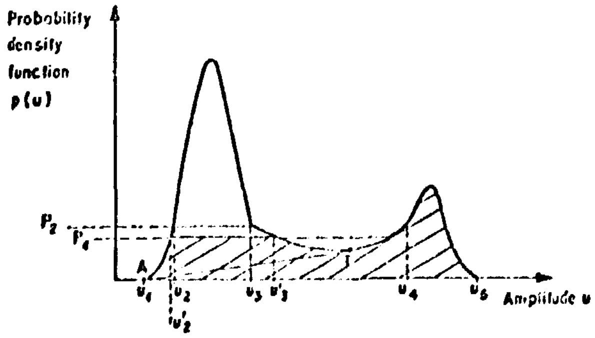

Figure 6
Typical amplitude histogram. Galaup (1975)

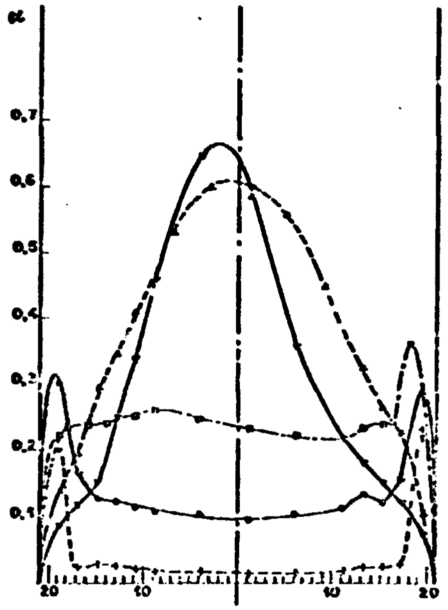

Figure 7
Local void fraction profiles. Galaup (1975)(x≡air mass quality)

	$\overline{Q_L}/A$ (m/s)	$10^4 x$	$\overline{R_G}$	$\{\alpha\}$
--+ --+- bubbles	1.01	1.0	0.05	0.05
—o——o- "	1.01	3.1	0.18	0.05
-·□----□- "	1.01	4.4	0.27	0.24
—▽——▽- transition	1.01	6.0	0.36	0.32
---△---△-- slugs	1.01	8.0	0.40	0.39

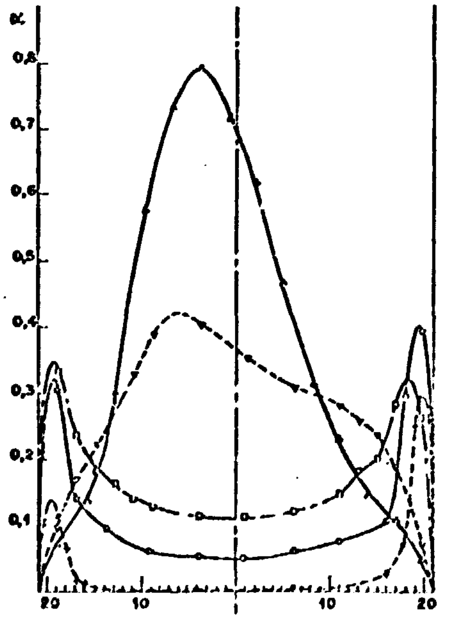

Figure 8
Local void fraction profiles. Galaup (1975)(x≡air mass quality)

	$\overline{Q_L}/A$(m/s)	$10^4 x$	$\overline{R_G}$	$\{\alpha\}$
—·+—·—+- bubbles	1.50	0.7	0.05	0.03
—o——o- "	1.50	2.1	0.13	0.11
--□—-□- "	1.50	3.0	0.19	0.17
--▽- - ▽- "	1.50	4.1	0.28	0.28
—△——△- transition	1.50	5.4	0.35	0.37

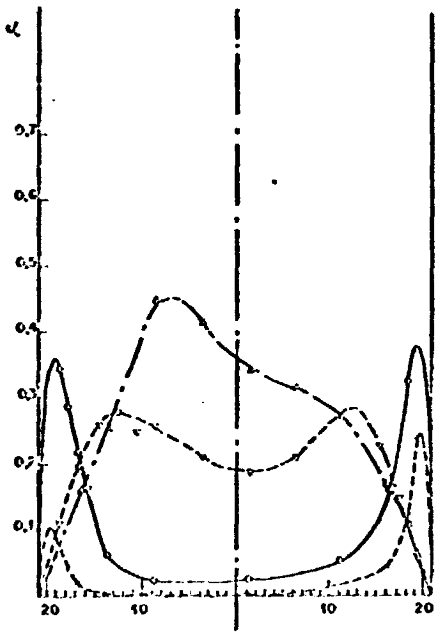

Figure 9
Local void fraction profiles. Galaup (1975)(x= air mass quality)

	$\overline{Q_L}/A$ (m/s)	$10^4 x$	$\overline{R_G}$	{α}
-+--+- bubbles	2.01	0.5	0.035	0.04
—o—o- "	2.01	1.6	0.10	0.10
-∇-∇- "	2.01	3.0	0.22	0.21
-Δ-Δ- "	2.01	4.0	0.26	0.28

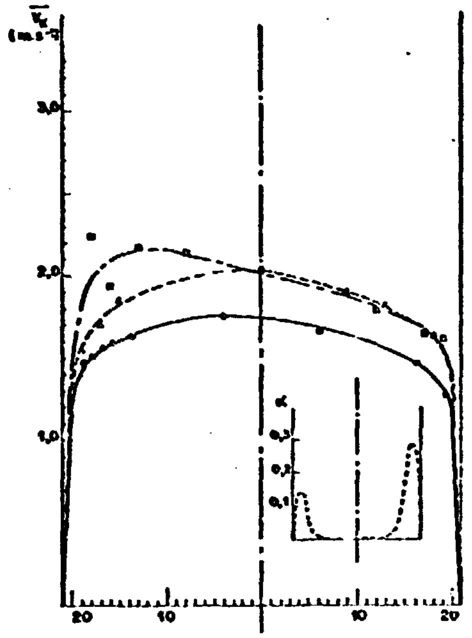

Figure 11
Velocity profiles in a bubbly flow. Galaup (1975)
$\overline{Q_L} = 2.08 \ 10^{-3} \ m^3/s$; $\overline{Q_G} = 0.12 \ 10^{-3} \ m^3/s$

—o——o— $\overline{v_L}$ (anemometer probe)
--Δ---Δ-- $\overline{v_G}$ (double optical probe)
--□---□-- $\overline{v_G}$ (double resistive probe)

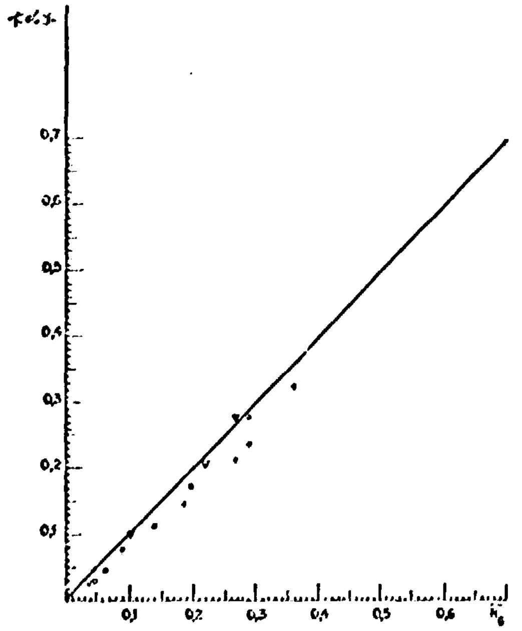

Figure 10
Comparison between hot-film and γ-ray measurements
Galaup (1975)

	$\overline{Q_L}/A$ (m/s)
+	1.01
o	1.50
∇	2.01

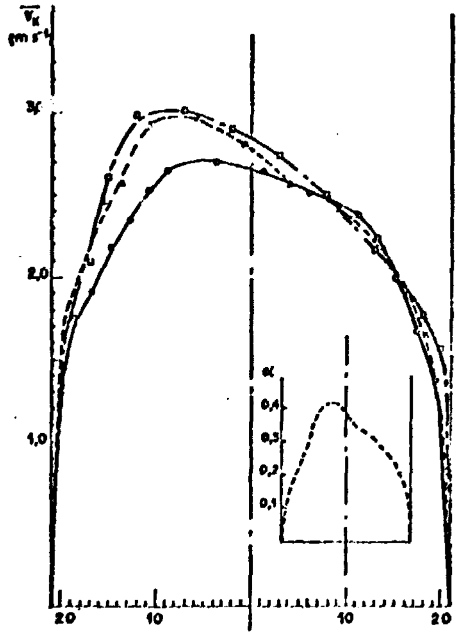

Figure 12
Velocity profiles in a transition flow
Galaup (1975)
$\overline{Q_L} = 2.08 \ 10^{-3} \ m^3/s$; $\overline{Q_G} = 0.71 \ 10^{-3} \ m^3/s$

—o——o— $\overline{v_L}$ (anemometer probe)
--Δ---Δ--- $\overline{v_G}$ (double optical probe)
—□---□--- $\overline{v_G}$ (double resistive probe)

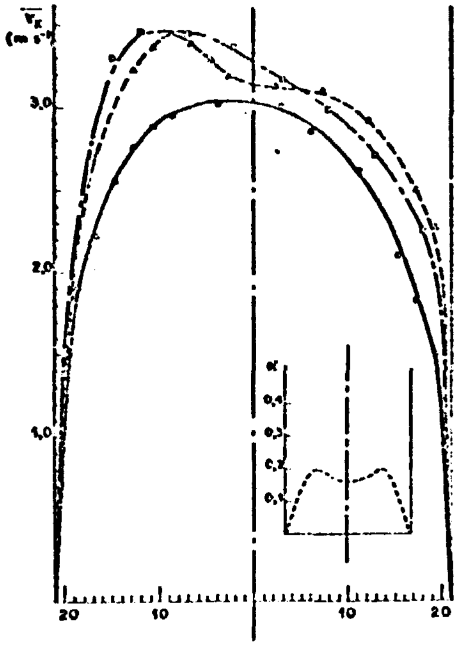

Figure 13
Velocity profiles in a bubbly flow
Galaup (1975)
$\overline{Q_L} = 2.78\ 10^{-3}\ m^3/s$; $\overline{Q_G} = 0.71\ 10^{-3}\ m^3/s$

—○——○--- $\overline{v_L}$ (anemometer probe)
--△---△--- $\overline{v_G}$ (double optical probe)
—·□—·-□··· $\overline{v_G}$ (double resistive probe)