Int. J. Heat Mass Transfer. Vol. 12, pp. 713–726. Pergamon Press 1969. Printed in Great Britain

# EXPERIMENTAL DETERMINATION OF THE "SLIP RATIO" IN A VERTICAL BOILING CHANNEL, UNDER ADIABATIC CONDITIONS AT ATMOSPHERIC PRESSURE

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**Abstract**—An experimental method is presented for the determination of slip ratio in a tubular channel with two-phase flow in adiabatic conditions. The method is based on the measurement of the vapour velocity by means of statistical correlation functions. An example is given of a calculation from the data obtained in a small experimental loop.

## NOMENCLATURE

| | |
|---|---|
| $V$, | linear velocity; |
| $V_g(V_v)$, | linear velocity of the gas phase (vapour); |
| $V_l$, | linear velocity of the liquid phase; |
| $G$, | mass flow; |
| $G_v(G_g)$, | mass flow of the vapour phase (gas); |
| $G_l(G_t)$, | mass flow of the liquid phase (total mass flow); |
| $x$, | thermodynamic steam quality, $= G_v/G_t$; |
| $A_t$, | area of channel cross-section; |
| $A_l(A_g)$, | area of the portion of cross-section occupied by the liquid phase (gas); |
| $\rho_l(\rho_g)$, | density of the liquid (gas); |
| $\rho_v$, | vapour density; |
| $C(C_o)$, | electrical capacitance between the two plates of the capacitance probe in the presence of a two-phase mixture (all liquid); |
| $C_M(C_{oM})$ | average value of electrical capacitance between the two probes in the presence of a two-phase mixture (all liquid); |
| $\alpha$, | void fraction, $A_g/A_t$; |
| $\alpha_M$, | average value of void fraction; |
| $W_{il}$, | inlet velocity "all liquid", $= G_t/\rho_l \cdot A_t$; |
| $V_{ol}$, | superficial velocity of liquid phase, $= G_t(1 - x)/A_t \cdot \rho_l$; |
| $\Delta L$, | axial distance between centres of capacitor probes; |
| $\tau_R$, | transit time of the gas phase between the two probes; |
| $t$, | time; |
| $T$, | time period; |
| $\tau$, | delay time. |

## INTRODUCTION

THE EXPERIMENTAL work relating to this research was conducted on facility CFP-5 [1], an out-of-pile loop used at the Reactor Technology Laboratory of the Casaccia Nuclear Research Centre, for tests of thermohydraulics and instability under two-phase conditions. A substantial amount of experimental work was done lately with this facility in the field of void fraction measurements, first with integral methods [2] and then topical and local methods, such as the capacitance method [3, 4], which is based on the diversity of the dielectric constants of the liquid and gaseous phases of a certain medium. Using this method of measurement, a study was made of local sub-cooled voids using small annular probes (concentric cylindrical electrodes), and of voids in volume boiling, using as a probe the entire test section, consisting of two concentric tubes, suitably insulated from each other and arranged to make parasitic capacitances negligible.

Careful development work and an accurate analysis of the limitations of the techniques referred to above have made it possible to apply them to obtain an experimental measurement for the determination of the slip ratio $S = V_v/V_1$, defined as the ratio between the linear speeds of the vapour phase and of the liquid phase. This parameter is one of the most important in studying the motion of, and heat transfer in, two-phase mixtures; it is usually evaluated indirectly through certain relations which tie it to other magnitudes that can be determined experimentally, such as void fraction $\alpha$ and thermodynamic quality $x$ (see above).

Much data available in the literature concerning the values of the slip ratio at atmospheric pressure were obtained at the Argonne National Laboratory [5] through a series of experiments on air–water, nitrogen–Freon and nitrogen–mercury mixtures, in adiabatic test sections. In these experiments, $S$ was deduced indirectly on the basis of the determination of the mass quality, of the void fraction (assumed to be constant throughout the test section) and of the density of the gas and liquid used. Obviously, the use of such mixtures permits an extremely convenient dosage of the relative proportions of the two phases, and therefore a ready determination of the quality of the mixture.

Although the results obtained by us indicate that the validity of the proposed method is limited to the case of bubble motion, it is interesting to consider their main characteristics, because of their originality. As far as we know, even though throughout the world an enormous quantity of work has been done in the field of boiling, so far the slip ratio had never been measured by a direct determination of the linear velocity of the vapour phase. This method makes it possible, for instance, to carry out fairly simply a measurement of the slip ratio in a section of a vertical boiling channel under adiabatic conditions, in which, however, the distribution of steam and liquid is not constant over the height, due to the pressure gradient resulting from height variations and pressure losses, as well as from the imperfect adiabaticity due to the unavoidable outward heat losses.

## 1. TWO-PHASE FLOW PROBLEMS AND RELATED PARAMETERS

The phenomena connected with the motion of liquid–gas mixtures have been studied for several years, but despite the extensive literature available in this field, it cannot be said that all problems relating to this motion have been fully solved. The greatest incentive to an extensive range of research in the field of two-phase media was provided by the nuclear industry. This has created a need for knowing as accurately as possible the different parameters of importance in designing boiling-water nuclear reactors. Despite the very considerable progress made over the last few years towards an increasingly profound knowledge of the characteristics phenomena of two-phase motion several gaps and contradictions still exist in this field. There are, for instance, certain correlations providing the value of slip ratio $S$, valid with fair accuracy in the field of high flow rates, which fail completely in the low-field field [6]. One of the most important problems in this field is the determination of the type of motion prevailing in a channel through which a two-phase mixture is flowing: the predominant parameter becomes the distribution function of the gaseous phase in the liquid phase. Based on an extensive series of visual observations, we are listing below a few descriptive terms applicable to the various types of motion:

(a) *Bubble flow.* The gaseous phase moves intermittently, in the form of bubbles of different diameters, through the liquid phase.

(b) *Slug flow.* As the flow of the gaseous phase increases, the bubbles tend to group together forming new pseudo-cylindrical units, alternating with geometrically similar units consisting of the liquid phase only.

(c) *Churn flow.* The gaseous phase becomes more dispersed into the liquid phase, and a strong mutual interaction begins.

(d) *Semi-annular flow.* A stage of transition between churn motion and annular motion.

(e) *Annular flow.* The liquid phase flows almost completely on the duct wall in the shape of a hollow cylinder, the cavity of which is occupied by the gaseous phase, containing in suspension minute liquid masses.

(f) *Fog flow.* As the flow of the gaseous phase further increases, also the external crown of liquid enters into suspension and becomes dispersed into the gaseous mass in droplet form.

The common factor to these various conditions is the existence of a difference between the average linear velocities of the two phases; this difference induces the phenomenon known as "slip" and is represented quantitatively by the related parameter $S$, defined as:

$$S = \frac{V_g}{V_l}. \qquad (1)$$

By definition we have:

$$\left.\begin{aligned} V_g &= \frac{G_g}{A_g \cdot \rho_g} \\ V_l &= \frac{G_l}{A_l \cdot \rho_l} \end{aligned}\right\} \qquad (2)$$

but

$$\left.\begin{aligned} A_g &= \alpha A_t \\ A_l &= (1 - \alpha) A_t. \end{aligned}\right\} \qquad (3)$$

The slip ratio is:

$$S = \frac{V_g}{V_l} = \frac{G_g}{G_l} \cdot \frac{1 - \alpha}{\alpha} \cdot \frac{\rho_l}{\rho_g}. \qquad (4)$$

The mass-flow rates ratio can be expressed as:

$$\frac{G_g}{G_l} = \frac{G_g}{G_t - G_g} = \frac{G_g/G_t}{1 - (G_g/G_t)} = \frac{x}{1 - x}. \qquad (5)$$

We have therefore:

$$S = \frac{V_g}{V_l} = \left(\frac{x}{1 - x}\right) \cdot \left(\frac{1 - \alpha}{\alpha}\right) \cdot \left(\frac{\rho_l}{\rho_g}\right). \qquad (6)$$

The latter relation clearly evidences the importance of the slip ratio, whose value conditions and defines the functional connection existing between void fraction and *mass quality* in a two-phase mixture.

## 2. AN EXPERIMENTAL METHOD FOR THE MEASUREMENT

The slip ratio between the two phases was measured by a method which we might define as "combined", being based on both a *dynamic-type measurement* (through the cross-correlation technique) for the direct determination of the vapour phase velocity, and a *static-type measurement* to obtain the stationary value of the void fraction, working back from the average value of the latter to the average velocity of the liquid phase.

In order to clarify the former part of the measurement, that of the average velocity of the vapour phases, we are referring to one type of measurement, the "sights measurement" which is common practice in various experimental fields. When we must study the velocity of propagation of a disturbance possessing certain well-defined characteristics, we measure the time taken by such disturbance to cover a certain distance collecting by suitable probes signals detecting the passage of the disturbance at the beginning and end of the said distance. To better illustrate this principle we shall refer to an example close to our case: measuring the travelling velocity of an air and vapour bubble in water. Let us position along a base of measured length two "sights", in this case being two probes capable of detecting the phase disturbance constituted by the bubble. The two probes, as in our case, can be of the capacitative type, or such as to detect by an electric signal the difference in capacitance due to the difference between the dielectric constants of the liquid and vapour. It is evident that from a plotting of the signals from the probes we can work back to the bubble transit time, and therefore to the average value of its velocity over the measured base. The shape and duration of the signals will depend on the relative dimensions of the bubble and probes, while in turn the transducer and detector trains will influence with their response times the signal rise times: a particular development study must be conducted case by case with a view to optimizing the various parameters which affect the measurement. The problem becomes considerably more complex if we wish instead to examine the transfer times of groups or "trains" of bubbles and vapour "slugs". In effect it is practically impossible to discriminate the pulse and waveform generated by the passing of the individual bubble under the probes forming the "sights", for such signals become confused with the similar ones generated by other bubbles. Moreover, the individual bubbles can recombine or change in volume, so that also the individual characters of the bubble can change during the time interval corresponding to the travel between the two "sights".

Recourse was therefore made to the *correlation functions*, utilizing their property of evidencing the common characteristics of two signals $x(t)$ and $y(t)$, whose behaviour in time can be described mathematically by statistical laws. We define as "auto-correlation function" the quantity

$$C_{xx}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{+T} x(t) \, . \, x(t+\tau) \, . \, \mathrm{d}t \qquad (7)$$

and as "cross correlation function" or "mutual correlation function" the quantity

$$C_{xy}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{+T} x(t) \, . \, y(t+\tau) \, \mathrm{d}t \qquad (8)$$

whose characteristics are discussed in detail in [7]. With the measurement system proposed by us, use is made particularly of the cross-correlation function between the signals $x(t)$ and $y(t)$ from two annular probes spaced 29·3 cm and connected to an electric circuit [4] which makes it possible to evaluate the void fraction at two points, at different levels, in a boiling channel. The cross-correlation function, asymmetrical with respect to $\tau = 0$, peaks at the value $\tau_R$ where the two signals show the greatest correlation. This occurs when the portion of disturbance on $y(t)$, which is connected with the disturbance detected by $x(t)$, is "in phase", i.e. coincides in time point by point, with the disturbance at $x(t)$.

It is evident that the value of $\tau_R$ represents the transit time of the disturbance between the two probes, and that therefore, we can work back from it to the velocity of the vapour phase. The auto-correlation function, instead, is a symmetrical or even function of $\tau$, i.e. $C_{xx}(\tau) = C_{xx}(-\tau)$, and it peaks at $\tau = 0$. Figure 1 shows an outline example of the path of such functions.

### 3. EXPERIMENTAL APPARATUS

As indicated early in this report, the measurements were carried out in the CFP-5 facility [1], in which an annular-type 150-cm long test section had been installed, consisting of an external pipe of clear Perspex of 32 mm i.d. and of an internal core being a steel pipe of 18 mm o.d.; a stainless steel bellows was fitted to take up the heat-expansion differences between the two pipes. The electrodes for measuring voids with the capacitance method were installed spaced 29·3 cm (at 100°C) along the test section, inside the Perspex pipe. The electrodes consist of 0·1 mm thick and of 40 mm high sheet-metal plates which, together with the internal pipe, form the capacitor plates. With this arrangement, two electric capacitors are positioned in the

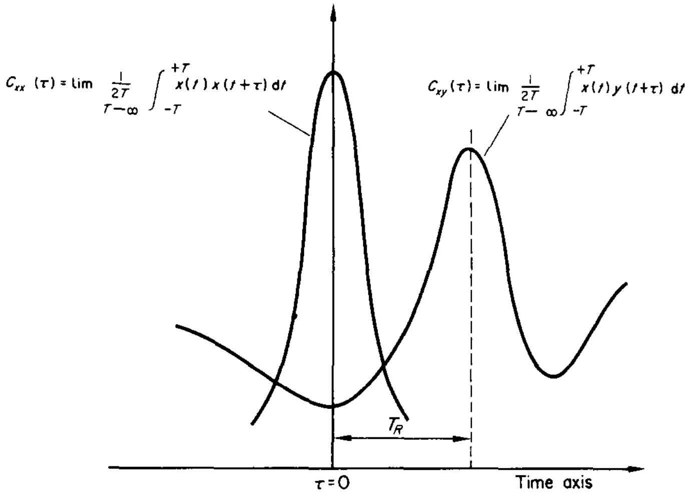


FIG. 1. Schematic trend of correlation functions with time.

boiling channel at two heights. Measuring their capacitance, with the section filled with liquid at different temperatures and extrapolating at 102°C, being the saturation temperature corresponding to the operating pressure ($p = 1{\cdot}11$ kg/cm$^2$), we obtained, as a value of the average capacitance between the two measuring probes for all liquid:

$$C_{OM} = 253\ pF.$$

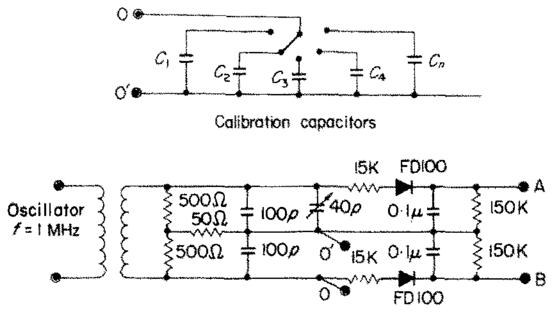
In our measurements, the capacitance in a two-phase medium fall to a minimum value of 30 $pF$, corresponding to a void fraction $\alpha = 80$ per cent, with a mass flow $G = 78$ g/s.

The test section is followed by a high-efficiency exchanger, capable of condensing over a short section (8–10 cm at a steam quality of 3·5 per cent and a mass flow rate of 78 g/s) all voids formed in the test section. The condenser is followed by a water–water backflow exchanger, whose function is to maintain below 80°C the temperature at the pump's delivery head. The loop is completed by the pump and a preheater having a maximum power of approx. 15 kW.

Boiling in the test section is obtained by inducing a pressure drop of about 2 atmospheres, by means of an orifice at the input end of the section and pre-heating above it the liquid in the preheater, in the absence of boiling, to a temperature above saturation temperature in the test section. Flash-boiling is thus achieved below the orifice: the thermodynamic inlet quality and hence the average void fraction in the test section are connected with the temperature drop from above to below the orifice. In order to regularize and stabilize this parameter, provision was made for automatically controlling the temperature immediately above the orifice, by means of a three-term regulator controlling the power delivered to the preheater by a special CGE controlled-diode supply. By this arrangement, temperature is controlled within $\pm 0{\cdot}1$°C. This value, quite acceptable in general, is still too high in the area where $\alpha$ varies very fast with the quality which is proportional to the temperature drop: this area is, in the $x$–$\alpha$ plane, the right-hand region near the origin where the curve has a practically vertical tangent [2].

The evaluation of the capacitance value is carried out by plotting the response of circuits of the type shown in Fig. 2.

In measuring the void fraction $\alpha$, the signal from the measuring device is taken through



The capacitance to be measured is connected between O and O' the umbalance is measured with a differential amplifier between A and B

FIG. 2. Capacitance meter circuit.

low-pass filters having 20–40 sec time constants. To determine transit times, under dynamic measurement conditions, the signal is taken directly off the output of the circuit, which has a pass band of about 10 cps, and sent via an amplifier to the recording section of the ISAC computer used to calculate the correlation functions. ISAC (Instrument for Statistical Analogical Computation) has a section in which the signals are recorded in closed loop on magnetic tape. The signals are then played back at higher than recording speed and processed automatically by the computer components. The operation performed by the computer is that indicated by formula (2), with the difference that the time interval to which the integral of the product $x(t)$, $y(t + \tau)$ is extended is obviously finite and of width suitably proportioned to the pass band and information density considered necessary: in our case between 120 and 240 sec. The delay $\tau$ is introduced in the ISAC by shifting the relative positions of the tape recording and playback heads. The moving head makes the movements corresponding to the $\Delta\tau$ during the off time between computations.

The cross-correlation function supplied by the ISAC and computed by points corresponds in reality to the equation:

$$C_{xy}(N\Delta\tau) = \int_0^T x(t)\, y(t + N\Delta\tau)\,\mathrm{d}t \qquad (9)$$

in which $T$ ranges from 120 to 240 sec, $N$ is progressive number of time intervals, $\Delta\tau$, for which computation is performed.

By means of the ISAC, an approximate evaluation can be made of the signal power spectra. Besides, the prior analysis of the frequency content of a signal and of the associated power of the individual frequencies can supply useful indications for the choice of the recording times, and therefore of the correlation times [8]. In actual computations $\Delta\tau = 0{\cdot}0254$ sec, $N$ ranges from 0, 1, 2 . . . to 100.

The maximum observable correlation time ranges from $\frac{1}{20}$ to $\frac{1}{80}$ of the recording time, depending on the length of the tape.

In addition to the apparatus described above, the instrumentation of the experiment comprises also a hot-pen Dynograph recorder used to amplify and visualize the signals from the electric void-fraction measuring circuits and a digital voltmeter for the reading of the calibration values and of the stationary capacitance values required for the evaluation of the average void fraction.

Figure 3 shows the recordings of the signals from the void measuring devices, for a given experimental point.

The following procedure was used to carry out the measurements. After allowing the circuit to warm up, a recording was made, on two adjoining tracks of the magnetic tape of the ISAC, of the signals from the two void-fraction measuring circuits connected to the two capacitance probes installed at 29·3 cm distance along the CFP-5 test section. On completion of the recording, the ISAC was set to compute the auto-correlation function of the first signal (the signal from the lower capacitance probe in the boiling channel) and the cross-correlation between the two signals. In effect, even though it is sufficient to identify the peak point of the cross-correlation function only, in order to determine the transit time $\tau_R$, for the purpose of preventing any errors due to the position of the recording head at the instant 0, it was preferred to establish with the utmost accuracy the

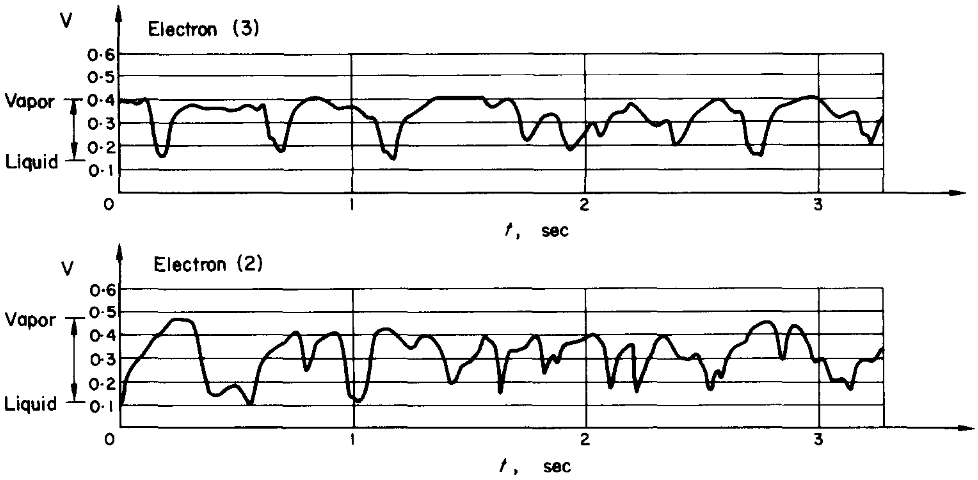


FIG. 3. Voids noise on the electrodes (2) and (3). Void fraction $\alpha_M = 0{\cdot}438$ and slip ratio $= 4{\cdot}85$.

reference point of the time axis, taking advantage of the property (as mentioned above) of the auto-correlation function, i.e. peaking at the origin. Thus, $\tau_R$ was evaluated on the basis of the distance between the peaks of the two correlation functions, minus an appropriate scaling factor due to the expansion of the time scale. At the same time, in the CFP-5 facility under the same operating conditions, an evaluation was made of the average void fraction between the two electrodes. This measurement was carried out by filtering with a strong time constant the fluctuations of the signal, and then evaluating the average capacitance, in time, registered by the two-phase mixture in the section of boiling channel comprised between the two capacitance probes. The measurement was preceded and followed by the calibration of the void-fraction measuring system, done by a series of capacitors of known capacity (accurate within better than 0·1 per cent) and covering a range of capacitance variations certainly comprising the capacitance value measured in the facility.

From an operational standpoint, the average time required for the plotting of all experimental parameters required for the computing of the slip ratio was in the order of 25–30 min.

## 4. PROCESSING THE EXPERIMENTAL DATA

Following our approach, the measurement made makes it possible to compute the average velocity of the vapour phase in the section comprised between two capacitance probes, since from the distance between the cross-correlation function peak we can work back to the transit time of the vapour phase between two capacitor probes. Since the void fraction is not strictly constant along the vertical in the area considered, due to outward heat losses and to the influence of the pressure gradient along the channel, under our working conditions ($p = 1{\cdot}11$ kg/cm$^2$) it was considered sufficiently correct, given the shortness of the section, to regard as linear the variation of $\alpha$ between the two probes.

The velocity of the liquid phase between the two probe stations is then obtained as an average value between the two local velocities at the beginning and end of the measured base, computed on the basis of the liquid flow and of the narrowed section $A_1 = (1 - \alpha) A_t$. The formulae adopted are the following:

$$V_v = \Delta L/\tau_R \tag{10}$$

$$\begin{aligned} V_l &= [W_{il} - (\rho_v/\rho_l)\,\alpha_M V_v]/(1 - \alpha_M) \\ &= \{[V_{ol}/(1 - x)] - \rho_v/\rho_l \cdot \alpha_M V_v\}/(1 - \alpha_M) \end{aligned} \tag{11}$$

where $W_{il}$ is the inlet velocity "all liquid" deduced by the equation $W_{il} = G_t/\rho_l A_t$.

The value indicated as $\alpha_M$ is the average value of the void fraction as measured with the two probes, while velocity $V_{ol}$ (or superficial velocity of the liquid phase) is defined on the basis of equation $V_{ol} = G_l/A_t\rho_l$.

Calling $\Delta L$ the axial distance between the two capacitance probes, the slip ratio will be expressed by the following equation:

$$S = \frac{V_v}{V_l} = \frac{\Delta L}{\tau_R} \frac{1 - \alpha_M}{W_{il} - (\rho_v/\rho_l)\,\alpha_M\ (\Delta L/\tau_R)} = \frac{1 - \alpha_M}{[(W_{il} \cdot \tau_R)/\Delta L] - (\rho_v/\rho_l)\,\alpha_M} \qquad (12)$$

This relation, in the case of constant mass flow rate (and therefore liquid inlet velocity) and constant pressure, can be written as:

$$S = \frac{V_v}{V_l} = \frac{1 - \alpha_M}{K_1\tau_R - K_2\alpha_M} \qquad (13)$$

in which $K_1 = W_{il}/\Delta L$ and $K_2 = \rho_v/\rho_1$

The relative error committed in evaluating the slip ratio, at constant pressure and flow rate, will be:

$$\frac{\Delta S}{S} = \frac{\Delta(1 - \alpha_M)}{1 - \alpha_M} + \frac{\Delta(k_1\tau_R + K_2\alpha_M)}{K_1\tau_R - K_2\alpha_M)} = \frac{\Delta\alpha_M}{1 - \alpha_M} + \frac{\Delta\tau_R}{\tau_R - (K_2/K_1)\,\alpha_M} + \frac{\Delta\alpha_M}{(K_1/K_2)\,\tau_R - \alpha_M} \qquad (14)$$

Now, under the conditions of geometry (32 × 18 mm annulus), flow rate (78 g/s) and pressure (1·11 kg/cm$^2$) prevailing in our experiment, we will have:

$$K_1 = 0{\cdot}505\ \text{sec}^{-1}$$
$$K_2 = 6{\cdot}89\ \ 10^{-4}$$

As we can assume [4]:

$$(\Delta\alpha_M)_{\max} = 0{\cdot}02$$
$$(\Delta\tau_R) \quad = 1 \div 4\ \text{msec},$$

and since the various experimental observations have shown:

$$\alpha_M = 0{\cdot}30 \div 0{\cdot}80$$
$$(1 - \alpha_M) = 0{\cdot}20 \div 0{\cdot}70$$
$$\tau_R = 0{\cdot}080 \div 0{\cdot}260\ \text{sec}$$

we obtain:

$$\frac{\Delta S}{S} = 4\% \div 15\%. \qquad (15)$$

This quantity provides a tentative indication of the dispersion of the experimental points obtainable with the method proposed, or an evaluation of the accidental error which affects $S$. If we wish to consider the total error in $S$, the second member should be increased, due to inaccuracy in our knowledge of the parameters such as the channel length comprised between the two probe stations ($\Delta L$), the superficial velocity of the liquid phase ($V_{ol}$) and the densities of the vapour phase and liquid phase ($\rho_v$ and $\rho_l$). However, the value expressed by (20) is still acceptable in this particular experimental field.

As regards the void fraction, it was not possible to work with voids under 27 per cent, since under these conditions the results obtained were not quantitatively appreciable, since the bubble dimensions and number produced a void noise too low to be appropriately processed by the ISAC. In Fig. 4 we have shown the average value of the void fraction measured with the two capacitance probes as a function of the thermodynamic mass quality at the input end of the test section.

It appears clear from the figure that, with very low quality values, given the near-verticality of the tangent to curve $\alpha = \alpha(x)$, fluctuations can easily occur in the void conditions, and such fluctuations, due to even minimal variations of the temperature drop across the orifice, make the measurement a precarious operation.

As regards the processing of the data relating to the average void fraction in the section of boiling channel between the capacitance probes,

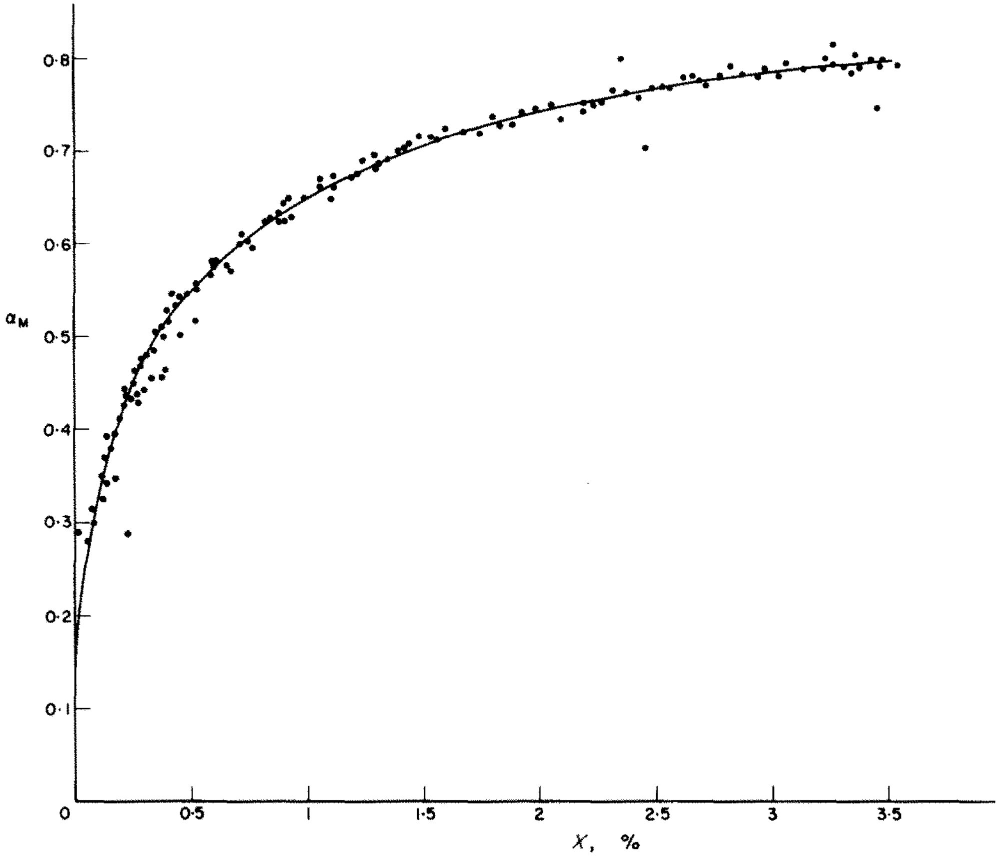


FIG. 4. Void fraction vs. steam quality.
$p = 1{\cdot}11$ kg/cm$^2$, annulus = 32 × 18 mm, $G = 78$ g/s.

we have worked back from ratio $C_M/C_{oM}$ to the values of $\alpha_M$ through the equation:

$$\alpha_M = 0{\cdot}926 - 1{\cdot}202\left(\frac{C}{C_o}\right) + 0{\cdot}276\left(\frac{C}{C_o}\right)^2$$

obtained—under the conditions of mass flow rate ($G = 78$ g/s), geometry (32 × 18 mm annulus) and pressure ($p = 1{\cdot}11$ kg/cm$^2$) characterizing our experiment—by an experimental comparison between the expansion method and the impedance method [4]. The curve corresponding to this equation is shown in Fig. 5 and compared with the calibration curve obtainable on the basis of the Maxwell equation. Figure 6 shows the correlation functions computed for the case illustrated by the Dynograph

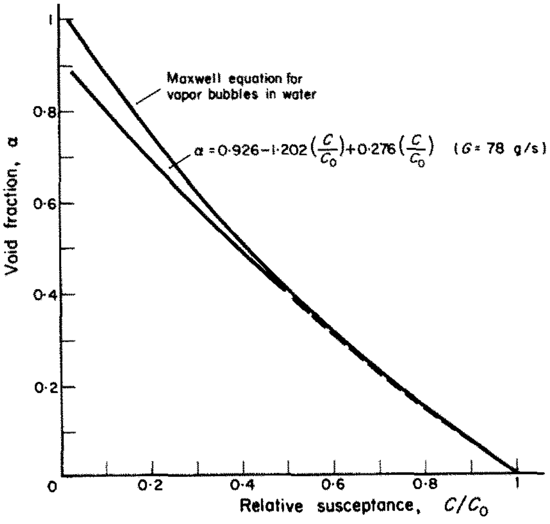


FIG. 5. Void fraction vs. relative susceptance, $C/C_o$.

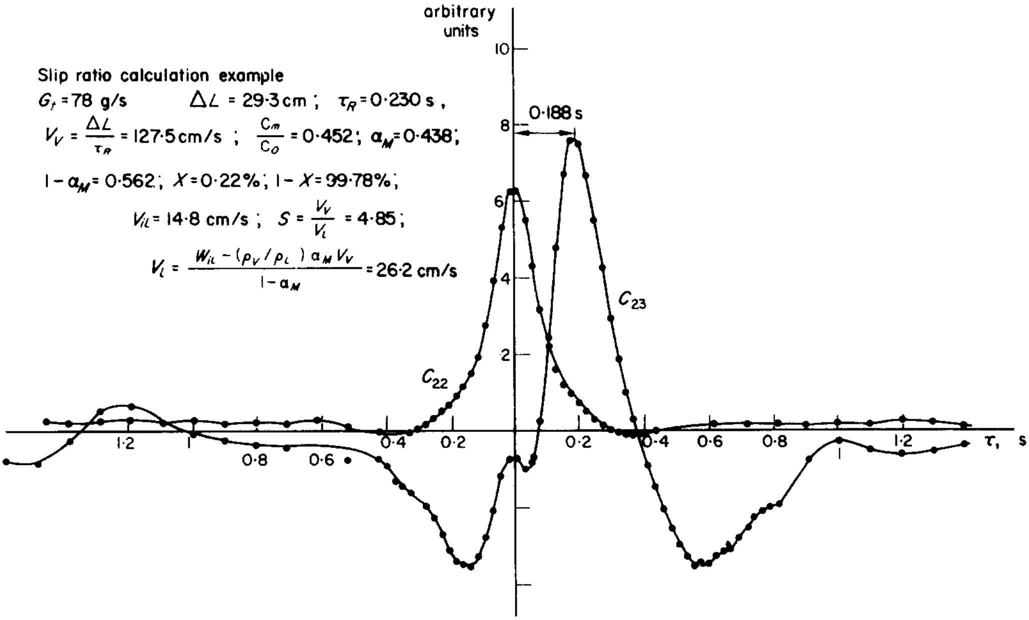


FIG. 6. Experimental auto- and cross-correlation functions.

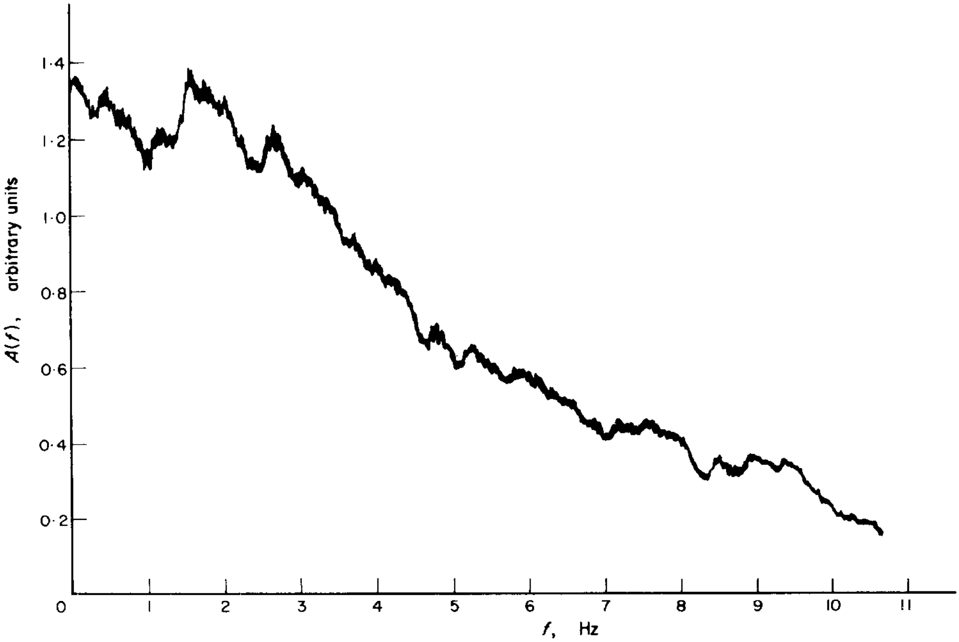


FIG. 7. Power spectral density of the signal from electrode ($\alpha_M = 0{\cdot}438, S = 4{\cdot}85$).

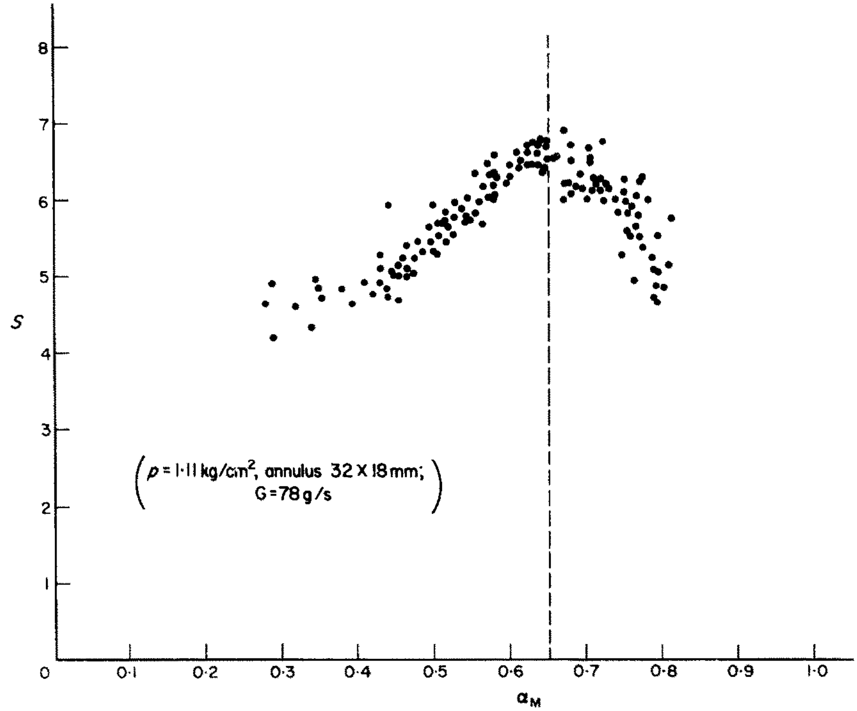


FIG. 8. Slip ratio vs. void fraction.

recordings shown in Fig. 3; Fig. 6 also summarizes the computation method adopted to obtain the slip ratio $S$. Figure 7 shows the power spectrum of one the two signals recorded in Fig. 3. The experimental values obtainable by this process for the quantity $S$ are shown, presented in $\alpha_M$–$S$ coordinates, in Fig. 8, and in $x$–$S$ coordinates in Fig. 9. We have computed the slip ratio values by the equation (11) from the chart in Fig. 6, i.e. on the basis of the experimental values of void fraction $\alpha_M$.

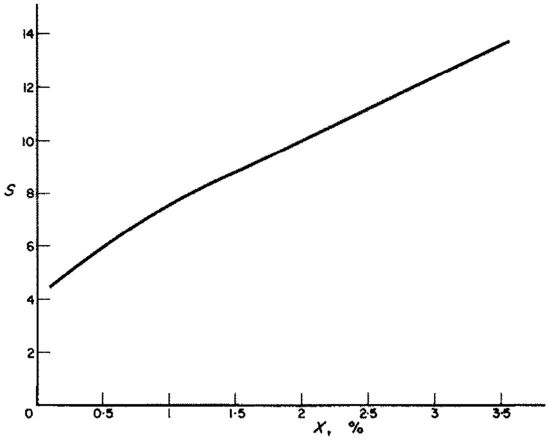


FIG. 9. Slip ratio, calculated from the mass conservation, [equation (6)], vs. steam quality. Annulus = 32 × 18 mm, $G$ = 78 g/s, $p$ = 1·11 kg/cm².

In Fig. 10 such values are shown as compared to the $S$ values obtained by our method and to the values obtained by Smissaert at the Argonne National Laboratory. Considering the high degree of uncertainty involved in such measurements, it can be said that the agreement is reasonably good, with both Smissaert's experimental results and with those deriving from the application of equation (11) up to quality values of 1 per cent, or up to void fraction values of approx. 65 per cent. For higher qualities, as the "slug flow" condition arises in the channel, the experimental method proposed loses its validity. In effect, beyond this limit the voids

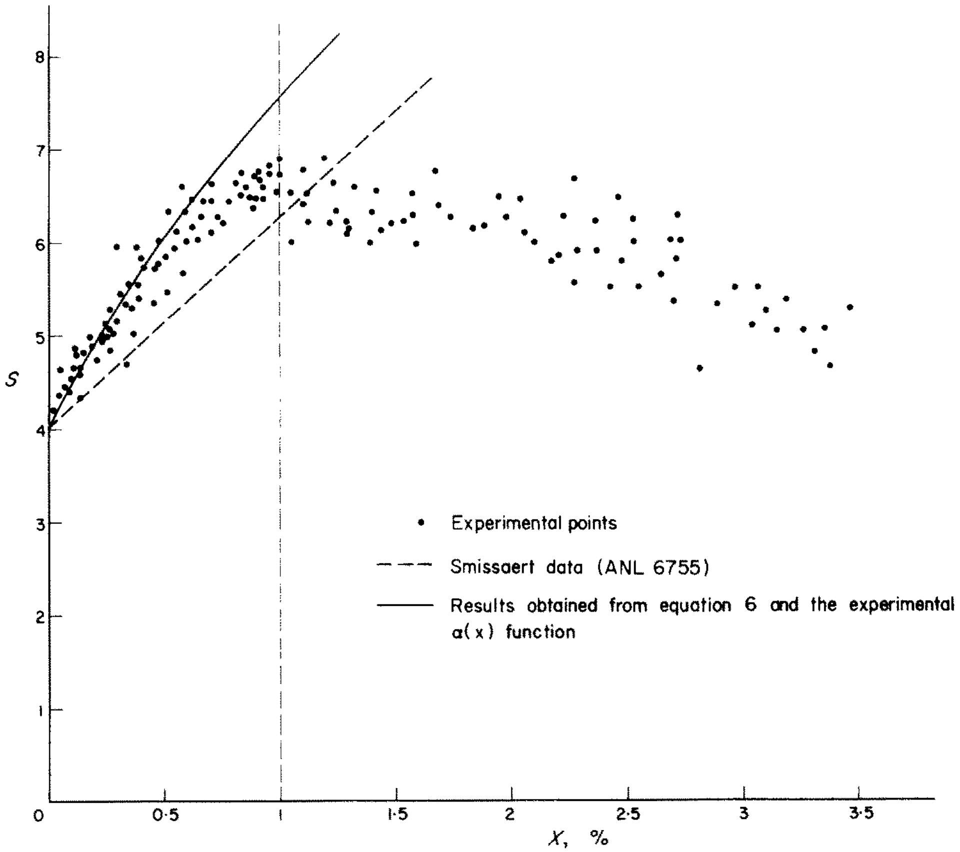


FIG. 10.

continue to increase and with them, on equal flow, the quantity $V_l$ (Fig. 11), while the distance between auto-and-cross correlation function peaks tends to become stabilized on a certain value, and therefore as steam quality increases, $V_v$ assumes an asymptotic path, resulting in a seeming decrease of the slip ratio (see Figs. 10 and 12). The phenomenon may be explained in the following terms: when the bubble-motion condition gives way to slug motion, the plugs are those which, as the mass quality increases, become the major vapour carriers. Their dimensions, however, are such that they cannot be properly scanned by the electrodes, which instead continue to detect correctly the bubble motion. In computing the correlation function, the ISAC is then almost exclusively affected by the bubbles which accompany the slug motion. The results obtained by us (see Fig. 12) indicate indeed that the velocity of such bubbles tends to an asymptotic value, as disclosed by the fact that, from a certain point on, the transit time is almost constant as $\alpha$ varies. This results in an $S$ value seemingly decreasing with $\alpha$, for the method proposed by us is no longer valid for this type of measurement. At the same time, while it is true that the contribution made by the plugs to the correlation functions disappears almost completely, there remains the effect which they have on the reduction of the section of area $A_1 = (1 - \alpha)\ At$, and therefore on the increase of the magnitude $V_1$ (see Fig. 11).

Obviously, the method proposed fails even worse when moving to the "churn flow" and

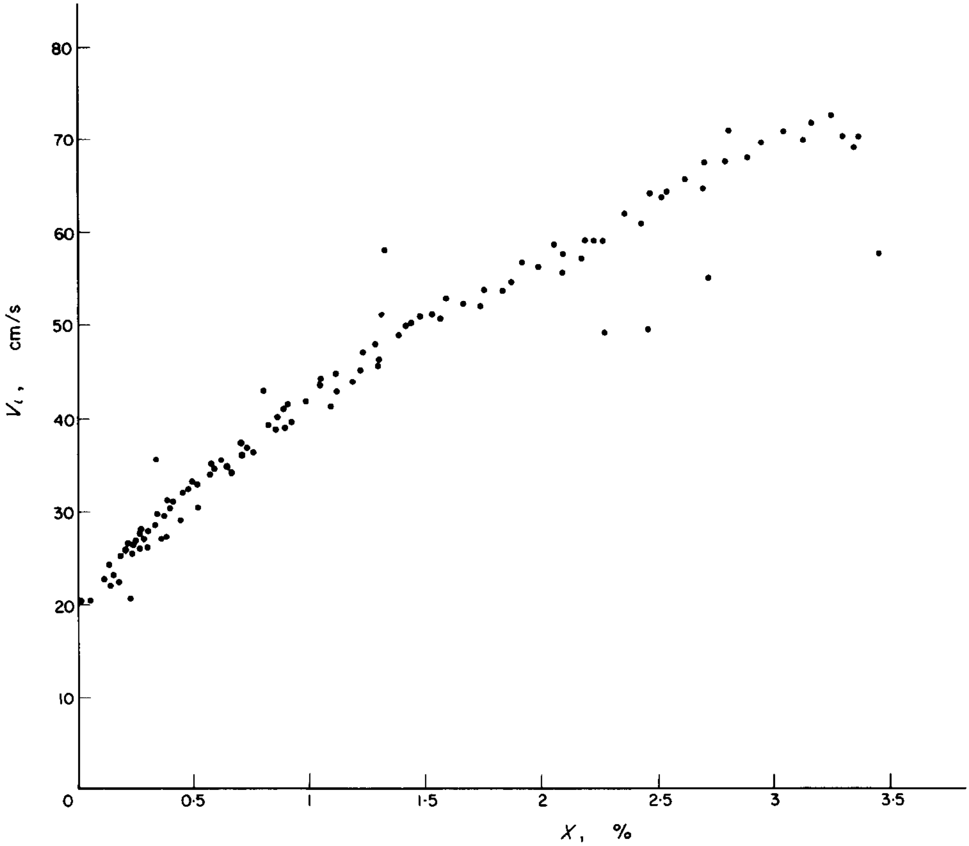


FIG. 11. Liquid phase velocity vs. steam quality.

"semi-annular flow" conditions. It is instead, fully valid in the range of the "bubble flow", and therefore particularly observed in thermohydraulics research under subcooled boiling conditions. It is also very usefully applied to volume boiling in a broader range of thermodynamic quality variance, when the operating pressure increases considerably, resulting in bubble motion persisting up to steam quality values much higher than at atmospheric pressure.

## REFERENCES

1. L. CORNAGGIA, M. DI BARTOLOMEO and A. PREMOLI, Circuito sperimentale ad acqua da 25 kW, C.N.E.N., RT/Ing (64) 1.
2. R. EVANGELISTI and A. PREMOLI, Misure di vuoti in un canale bollente verticale in condizioni adiabatiche, Il calore, February 1965, No. 2.
3. L. CIMORELLI and A. PREMOLI, Measurement of void fraction with impedance gauge technique, *Energia Nucl.* **13**, 1 (1966).
4. L. CIMORELLI and R. EVANGELISTI, The application of the capacitance method for void fraction measurement in bulk boiling conditions, *Int. J. Heat Mass Transfer* **10**, 277–288 (1967).
5. G. E. SMISSAERT, Two-component two-phase flow parameters for low circulation rates. Argonne National Laboratory Report No. ANL-6755.
6. J. F. MARCHATERRE and B. M. HOGLUND, Correlation for two-phase flow, *Nucleonics* **20** (1962).
7. L. CIMORELLI, Metodi statistici per lo studio della dinamica dei sistemi, Report C.S.N. Casaccia, DI.TE. DR (63).
8. L. CIMORELLI, Determinazione sperimentale di funzioni di transferimento e sintesi di modelli analogici mediante metodi statistici, C.S.N. Casaccia Doc. Int. 64/IN (9), MI. D.A.S. No. 5, CNEN Report.

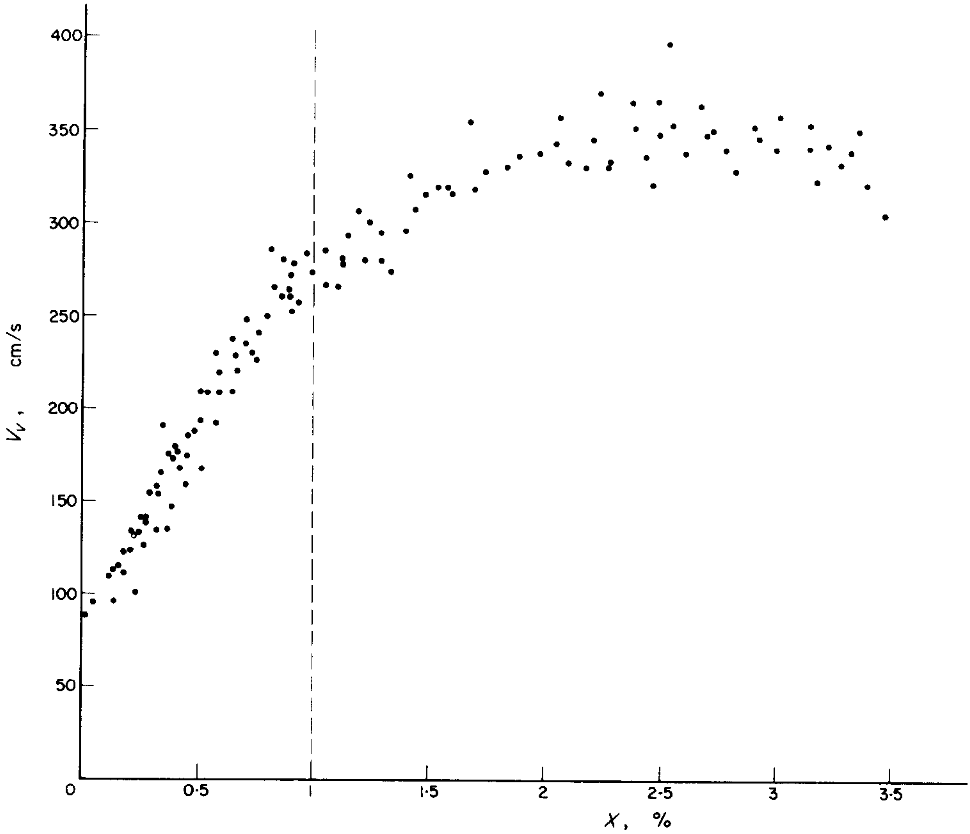


FIG. 12. Vapour phase velocity, obtained by the correlation functions, vs. steam quality.

**Résumé**—On présente une méthode expérimentale pour la détermination du rapport de glissement dans une conduite tubulaire avec un écoulement diphasique dans des conditions adiabatiques. La méthode est basée sur la mesure de la vitesse de la vapeur au moyen de fonctions de corrélation statistiques. On donne un exemple d'un calcul à partir des résultats obtenus dans une petite boucle experimentale.

**Zusammenfassung**—Eine experimentelle Methode zur Bestimmung des Schlupffaktors bei der Zweiphasenströmung in einem Ringkanal bei adiabaten Bedingungen wird angegeben. Die Methode stützt sich auf die Messung der Dampfgeschwindigkeit mit Hilfe statistischer Funktionen. An Hand von Daten, die in einer kleinen Versuchsschleife gewonnen werden, ist ein Berechnungsbeispiel gegeben.

**Аннотация**—Представлен экспериментальный метод определения отношения скольжения в трубчатом канале при двухфазном течении в адиабатических условиях. Метод основывается на измерении скорости пара с помощью статистических корреляционных функций. Приведен пример расчёта по данным, полученным в небольшой экспериментальной петле.