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PECULIARITIES OF VOID FRACTION MEASUREMENT APPLIED TO PHYSICAL INSTALLATION CHANNELS COOLED BY FORCED HELIUM FLOW

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Особенности измерения паросодержания гелия в охлаждающих каналах физических установок

Показано, что для обеспечения высокой точности измерения целесообразно использовать высокочастотный метод, когда контроль паросодержания осуществляется по сдвигу резонансной частоты контура, в который включена сигнальная емкость датчика. Приведена информация о датчиках с каналами круглого и кольцевого сечений. Для обоих датчиков приведены теоретические соотношения и экспериментальные характеристики для сигнальных диапазонов и погрешностей измерения. Дано сопоставление результатов теоретических расчетов с полученными экспериментальными данными для гелия. Отмечены особенности процессов в каналах различных сечений.

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Peculiarities of Void Fraction Measurement Applied to Physical Installation Channels

The methods of optimizing the transducers designed for measurements of the void fraction of two-phase flows in the channels of round and annular cross section are presented. On the basis of the analysis performed concrete solution of relatively high technical characteristics are proposed. Rated and actual characteristics of signal ranges and measurement errors are given for both sensors. Influence of the mass velocity on the void fraction of adiabatic two-phase flows is theoretically analysed. Effects of friction and of liquid-into-vapour entrainment are shown. Calculation results are compared with the obtained experimental data for helium. Special attention is given to the specific features of the processes in channels with different cross section.

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INTRODUCTION

The use of two-phase flows for cooling the physical installations required the development of measuring systems to check the void fraction, ϕ, of such coolants like helium[1-4] and hydrogen[5]. Sensors of these systems consist mainly of the channels with round[5] and annular[1,3] cross section, though the channels of more complicated shape are also used[4]. The analysis of the available experimental data [1,2,6-8] shows that proper reliability of measurement is not necessarily ensured, since the results are not devoid of uncertainties, inaccuracies and sometimes they are quite unexpected. For example, it is not clear how some authors estimate measurement errors whose values may be too optimistic. The arguments in favour of the chosen geometry of the sensor flow section require convincing substantiation, because, for example, measurement of ϕ_t for tubes using the sensors with channels of annular cross section[3] ϕ_a, or of more complicated shape [8] is not evident in terms of adequacy of ϕ_t and ϕ_a (see Ref.[7]). It can also be stated that Refs.[1,4,8] do not allow for unambiguous conclusions as to the influence of the mass velocity $\dot{m}$ on the void fraction, in Refs.[1,2] it is significant, in Ref.[8] it is quite insignificant in a similar range of $\dot{m}$ variations, and in Refs.[3,4] it is not considered at all. In this paper we try to find out the reasons for the above discrepancies, starting with the theoretical analysis aimed at showing the influence of the channel geometry, mass velocity and thermodynamic parameters of the flow on the void fraction value.

THEORETICAL

To estimate the influence of the mass velocity of the flow on $\phi = A_g/(A_g + A_\ell)$ we shall use the principle of the minimum entropy gain[9], according to which the system tries to do as little work as possible to accelerate vapour and liquid to velocities satisfying the continuity relationship[10]. In other words, the value of the void fraction must correspond to the minimal total energy, which is a sum of the dissipation energy W and the flow kinetic energy E. Given below is an analysis of two typical cases: an annular-dispersed pattern of flow taking place[11] at relatively high mass velocities of helium $m \geq 200$ kg/m²s, and a stratified pattern observed[7,11] at relatively low $m \approx 20$-40 kg/m²s.

In the case of the annular-dispersed pattern it is suitable to express the dissipation energy $W = u_\ell S L \tau_w / A$ with the help of the relative hydraulic resistance $\overline{\Delta P}$ for which there are quite a lot of experimental data for helium [7,8,12,13]:

$$W_{ad} = N_{ad} \frac{m(u_\ell)^2}{2} (1-x)(1-K) , \qquad (1)$$

where $x = m_g/m$ is vapour quality, $K = x_{en}/(x_\ell + x_{en})$ - relative share of liquid-into-vapour entrainment, x_{en} - share of liquid-into-vapour entrainment, $x_\ell = 1 - x - x_{en}$ - share of liquid in two-phase flow, u - average velocities at saturation, τ - shear stress, L - channel lengh, S - moisted perimeter, A - area of channel. The friction factor is expressed as

$$N_{ad} = \frac{f_\ell L}{D_e} \frac{1-\phi_1}{(1-x)^2(1-K)^2} \left[1 + \overline{\Delta P} \left(\frac{f_g \rho_\ell}{f_\ell \rho_g} - 1 \right) \right], \qquad (2)$$

$$\overline{\Delta P} = (\Delta P_{tp} - \Delta P_\ell)(\Delta P_g - \Delta P_\ell)^{-1} , \qquad (3)$$

where D_e is equivalent diameter, ΔP - pressure drop, f - friction coefficient, $\phi_1 = \phi(1 + \rho_g K(1-x)/\rho_\ell x)$, ρ - density; subscripts: ℓ - liquid phase, g - gas phase. tp - two-phase flow, w - wall. The derivation of relation (1) assumes that $\tau_w S/A = (dP/dL)_{tp}$ and the average velocities of both phases were determined as in Ref.[14]. Minimizing the total flow energy, $(E + W)_{ad}$, we find the relation for ϕ:

$$\phi = \left\{ 1 + K \frac{1-x}{x} \frac{\rho_g}{\rho_\ell} + \left(1 + \frac{1}{2} N_{ad}\right)^{1/3} (1-K) \frac{1-x}{x} \left(\frac{\rho_g}{\rho_\ell}\right)^{2/3} \left[\frac{1 + K \frac{1-x}{x} \frac{\rho_g}{\rho_\ell}}{1 + K \frac{1-x}{x}} \right]^{1/3} \right\}^{-1} . \qquad (4)$$

Relation (4) can be applied both to tubes and to annular channels.

In the case of stratified pattern the quantity N_{ad} in (4) can be replaced by

$$N_{st} = \frac{f_\ell L}{D_e} \frac{1-\phi_1}{(1-x)^2(1-K)^2} \left[1 + \overline{\Delta P} \left(\frac{f_g \rho_\ell}{f_\ell \rho_g} - 1 \right) \right] \left[1 + \frac{x(1-\phi_1)\rho_\ell}{\phi(1-x)(1-K)\rho_g} \right]. \qquad (5)$$

While deriving relation (5) it was taken into account that one can ignore the quantity of interfacial shear stress for the round and annular channels[15]. Thus, the proposed technique allows calculation of $\phi(m) = \phi(x, K, N)$ for the annular-dispersed and stratified patterns of two-phase flows. To do this, one must determine the relative hydraulic resistances $\overline{\Delta P}$, friction coefficients f_ℓ, f_g and the liqiud-into-vapour share K. For details of these procedures see Ref.[15].

To estimate the applicability limits of the proposed technique, the quantity ϕ was tentatively calculated, and the results were compared with the experimental data[1,2,6] at relatively high ($m > 100$ kg/m²s) and low ($m \approx 10$-40 kg/m²s) mass velocities. At high m the comparison shows good agreement of the results, the discrepancy does not exceed 3%. At low m the comparison showes that for $x \leq 0.4$ the results are also in good agreement, the maximum discrepancy does not exceed 3-6%. At the same time, for $x \geq 0.4$ the discrepancy between the calculated and experimental values of ϕ may amount to 8 and 18% for a tube and an annular channel respectively, e.g. at $x = 0.8$. In view of the above we adopted a higher value of u_ℓ, defined as $u_\ell = m(1-x)/\rho_\ell(1-\phi_1)$, for the calculations at $x > 0.4$. In this case only the quantities N_{ad} and N_s are changed into N_{ad_1} and N_{s_1}. The expressions for N_{ad_1} and N_{s_1} are structurally the same as (2) and (5) except for the quantities K in their denominator only, which should be taken equal to zero. This correction of u_ℓ resulted in reduction of above-mentioned discrepancy between the calculated and experimental values of ϕ from 8 and 18% to 3 and 6%.

Now we consider the influence of the mass velocity m both on separate components of relation (4) and on the void fraction. The functions showing the influence of the mass velocity on K and $N_{ad_1}(N_{s_1})$ are given in Fig. 1. As seen, the liquid-into-vapour entrainment increases with m, the increase being quite rapid up to $m \approx 80$ kg/m²s and at $m \geq 100$ kg/m²s practically all liquid is entrained into vapour. It is also seen from Fig. 1 that for tubes the friction effect is relatively small within the whole range of m, while for annular channels the friction effect is quite considerable at $m <$

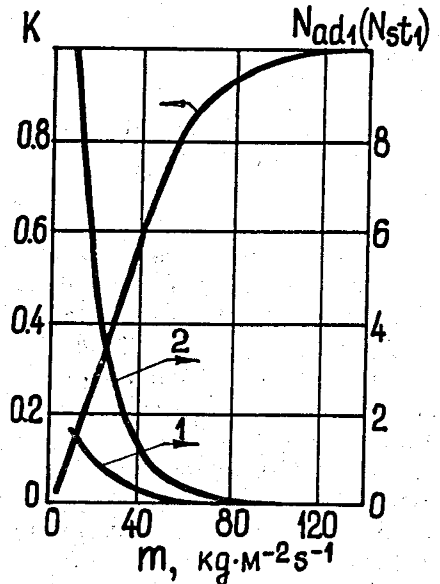

Fig. 1. Results of calculations of K and N at P = 0.12 MPa and x = 0.3 (horizontal orientation). 1 - for round tube, 2 - for annular cross section.

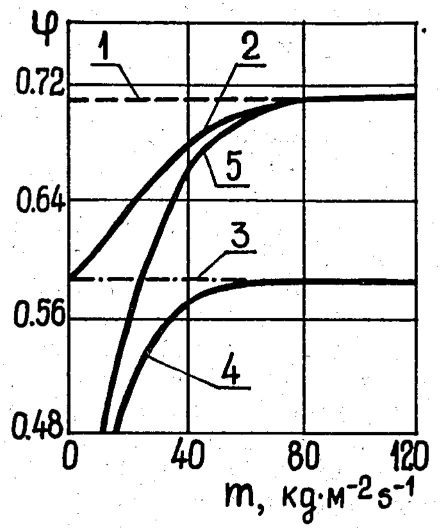

Fig. 2. Void fraction ϕ versus mass velocity m for horizontal annular channel at P = 0.12 MPa and x = 0.3. 1 - K = 1, N = 0 (homogeneous); 2 - 0 < K < 1, N = 0; 3 - K = N = 0 (eqn (6)); 4 - K = 0, N > 0; 5 - 0 < K < 1, N > 0.

< 40 kg/m s. Figure 2 shows the influence of values K and N, dependent on mass velocity m, on the void fraction ϕ. For example, at K = 1 and N = 0, when all liquid is entrained into vapour and friction can be ignored, the homogeneous model must be valid for the function $\phi(x)$ at high m. At K = N = 0 and $m \to 0$, i.e. when both effects can be ignored, ϕ is defined by the relation

$$\phi = [\,1 + \frac{1-x}{x}\,(\frac{\rho_g}{\rho_\ell})^{2/3}\,]^{-1}\,, \qquad (6)$$

obtained earlier [14]. Line 1 in Fig. 2 shows the limiting cases and curve 2 shows the intermediate states. Approximately the same influence of the mass velocity on ϕ can be typical for tubes as well. If there is no liquid-into-vapour entrainment (K = 0), the friction effect leads to a decrease in the value of ϕ obtained by formula (6), as shown by curve 4. For example, the reduction of the mass velocity in the

range $40 < m < 100$ kg/m^{2}s is characterized by a slight effect of friction on ϕ. However, at $m < 40$ kg/m^{2}s this influence becomes considerable. At low mass velocities, $m \approx 20$ kg/m^{2}s, the corresponding values of ϕ for annular channel are close to those calculated by the relation [7] (here μ is dynamic viscosity)

$$\phi = [\,1 + \frac{1-x}{x}\,(\frac{\rho_g}{\rho_\ell})^{4/7}\,(\frac{\mu_\ell}{\mu_g})^{1/7}\,]^{-1}\,. \qquad (7)$$

Combined influence of liquid-into-vapour entrainment and friction on ϕ is shown by curve 5. Similar dependence can be typical for narrow annular channels.

Thus, the theoretical analysis shows that the range of ϕ variations for annular channels can be wider than for tubes when the mass velocity of the two-phase helium flow decreases from 100-200 to 20 kg/m^{2}s, other conditions being the same.

PERCULIARITIES OF VOID FRACTION MEASUREMENT

The above analysis shows that correct measurement of the void fraction require such a design of the sensor that one could measure ϕ in the channel of a specific shape. The flow must come to the sensitive zone of the sensor from the hydrodynamic stabilization section only that is necessary for establishing velocity profiles of both phases typical for the given channel. This fact arises from the definition [16] of $\phi = \phi(u_g, u_\ell)$. Besides, to performe a detailed analysis of the experimental dependence of ϕ on the two-phase flow structure in a specific channel, one must ensure a quaranteed accuracy. These requirements were not regularly met by the authors whose data are available to us up to date and some void fraction transducers are not supplied with hydrodynamic stabilization sections. This lead us to the development of our own transducers with round and annular channels.

Since the physical properties of the liquid and vapour phases of helium at T = 3 ÷ 5 K have differ but to a little extent it seems reasonable to measure ϕ using the dependence of the dielectric susceptibility ϵ_{tp} of the two-phase flow on ϕ. Placing a flow in the electric field $\vec{E}$, one can determine the values of ϕ through the changes in the capacitance $C(\epsilon_{tp})$. The direct measurement of the capacitance is rather complicated [1], so we used a more convenient radio frequency method applied by other authors as well [3]. This method assumes that capacitor $C(\epsilon_{tp})$ is connected to a special oscillating circuit whose resonant frequency corresponds to a certain value of $\phi(\epsilon_{tp})$.

Now let us consider the main errors in measurements of ϕ by RF transducers and their relation with geometric dimensions, dielectric properties of the two-phase flow, etc. Using a common expression for the resonant frequency of the oscillator f_{tp} at a given value of ϵ_{tp} : $2\pi f_{tp} = (L_\Sigma C_\Sigma)^{-1/2}$, we obtain the following relation for the signal characteristic H of the sensor:

$$H = |df_{tp}/d\phi|/f_{tp} = a\Delta\epsilon/2, \quad a = |dC_\Sigma/d\phi|/C_\Sigma(\phi), \qquad (8)$$

where L_Σ, C_Σ - effective inductance and capacitance of transducer, $\Delta\epsilon$ - difference in dielectric susceptibility of liquid and vapour phases. When obtaining relation (8), the value of $\epsilon_{tp} = \epsilon_\ell - \phi\Delta\epsilon$ for the homogeneous flow case was used*. The geometric factor a significantly depends on the specific configuration of the channel and is always less than a unit. This is due to the fact that only a portion of the electric field $\vec{E}$ is generated within the measuring volume of the sensor.

When determining C_Σ, allowance for the real distribution of the field $\vec{E}$ in the sensor generally leads to the nonlinear characteristic $H(\phi)$ (8). It requires a rather complicated meter gauging which on its own part contributes to the measurement error. It the case of two-phase helium, however, the quantity $\Delta\epsilon$ is small ($\Delta\epsilon \approx 4\cdot 10^{-2}$ at $T \approx 4$ K) which allows one to determine ϕ using a simple linear relation

$$\phi = \frac{f_{tp} - f_\ell}{\Delta f_s} = 1 - \frac{f_g - f_{tp}}{\Delta f_s}; \quad \Delta f_s = f_g - f_\ell = f_g\, a\, \frac{\Delta\epsilon}{2}, \qquad (9)$$

where Δf_s is the signal range of the transducer. *The maximum error of this linear approximation* is $(\delta\phi)_{lin} = 3H/8$ at $a\Delta\epsilon \ll 1$. i.e. it does not exceed a certain fraction of a per cent for helium. So, in order to determine ϕ (9) one should experimentally measure only two easily fixed values of f_g and f_ℓ, which greatly simplifies the gauging. In this case the gauging error is reduced to the frequency measurement accuracy determined by the *instrumental error* $(\delta\phi)_{inst}$. According to (8) and (9), this error is $(\delta\phi)_{inst}/\phi = 2(\delta\phi)_{inst}/H\cdot f_g$, i.e. a better accuracy of linear approximation makes the requirements to the frequency measurement more severe.

Another important factor affecting the measurement error is the temperature dependence of $\Delta\epsilon(T)$. Using the relations (8), (9), one can show that near T = 4 K the corresponding *temperature error* is $(\delta\phi)_T \le \delta T/T$.

One more contribution to the error of ϕ measurements is due to the uncertainty of the flow pattern and, consequently, to the inaccuracy of relation for $\epsilon_{tp}(\phi)$. The corresponding error, the *limiting intrinsic error* $(\delta\phi)_{intr}$, is associated with the possibility of the liquid or vapour being in the region of maximum (or minimum) values of the sensor field $\vec{E}$. The difference in the resonant frequencies $(\delta f)_{intr}$ of the sensor resulted from such phase redistribution at fixed ϕ determines the error: $|(\delta\phi)_{intr}| \approx (\delta f)_{intr}/2\Delta f_s$. For example, in the case of annular channels this error will be [2]: $|(\delta\phi)_{intr}| \approx d/4r_{in}$, at $d/r_{in} \ll 1$, where d-gap width, r_{in} - internal radius (the relation is valid when $E(r) \propto 1/r$).

The above requirements were taken into account in the transducers designed by us; their parameters are listed in the Table. Described below are some details of the design and its main features. Annular channel sensors Nos 1, 2 are themselves the signal capacitors [2]. By connecting these capacitors to an inductive element, i.e. to short-circuited coaxial lines, one obtains a measuring resonator. On both sides of the sensor there are flow-stabilizing sections. The absence of such sections is a natural disadvantage of practically all known devices of similar type [1,3,4].

Another principle [17] is used in round channel void fraction sensors Nos 3, 4. For its realization a meander-type

Table. Parameters of the designed transducers

Sensor type	No.	ℓ_m, mm	ℓ_{st}, mm	d, mm	$2r_{in}$, mm	f_ℓ MHz	Δf_s, MHz*	a_{exp}	$\delta\phi$ intr	$\delta\phi$ inst	$\delta\phi$ total
annular	1	50	100	0.65	14.7	213.6	3.3	0.7	2.2	0.5	1.5
	2	80	100	1.0	11.0	212.00	3.63	0.7	5.0	0,5	1.5
round	3	60	140	-	7.93	394.4	1.6	0.25	1 ÷ 2	1.0	2.0
	4	90	140	-	7.68	205.51	0.8	0.3	1 ÷ 2	1.0	2.0

* In Ref. [4] the capacitance of the sensor is determined trough the volume-related quality, but it is valid for a particular case only.

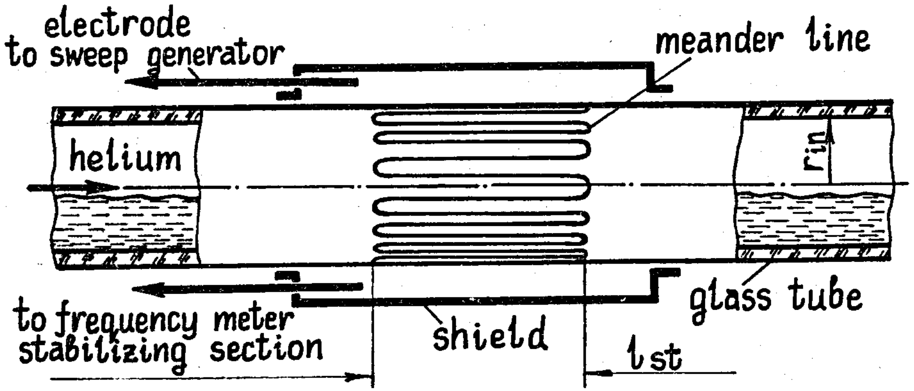

Fig. 3. Void fraction transducer with round cross section.

"long line" (see Fig. 3) of a wire (No. 3) or a band (No. 4) is put on the surface of the glass tube. With a standing wave in this line, the distribution of field potential on the tube surface is close (for the first harmonic) to a sinusoid. It ensures high field homogeneity in the measurement volume at a sufficiently long meander and relatively large number of conductors in the line. The limiting intrinsic error $(\delta\phi)_{intr}$ (according to Ref. /17/) does not exceed 1-2 per cent in this case. The flow-stabilizing sections are in front and behind the meander line part. Noteworthy are relatively high values of the signal range Δf_s (9) of these transducers (see the Table); they exceed the corresponding parameter of the resonator-type meters approximately by one order of magnitude (e.g. see Ref. /5/).

Finally, the total error can be estimated as follows. In the course of measurements the real values of temperature can be checked with an accuracy of $\delta T \leq 2\cdot 10^{-2}$ K, which yields temperature error $(\delta\phi)_T \leq 0.5\%$ for all sensors. The error of linear approximation for annular sensors is also $(\delta\phi)_{lin} \approx 0.5\%$, and is about three times smaller for round sensors. Frequency f_{tp} was measured by a CAMAC system. The instrumental error was $(\delta f)_{inst}/f_g \leq 5\cdot 10^{-5}$, which leads to the error $(\delta\phi)_{inst}/\phi \approx$ $\approx 0.5 \div 1\%$. Thus, the total experimental error of void fraction measurements $(\delta\phi)_{tot} = (\delta\phi)_{lin} + (\delta\phi)_{inst} + (\delta\phi)_T$ for all transducers did not exceed 2%, which is approximately equal to their limiting intrinsic error $(\delta\phi)_{intr}$ (except for meter No. 2). On the contrary, it is this value of $(\delta\phi)_{intr}$ that brings the greatest contribution to the total error in the case of large-gap-annular sensors, e.g. for the meter /1/ the value of $(\delta\phi)_{intr}$, according to the estimations /2/ is about 16%.

RESULTS AND DISCUSSIONS

The transducers with round and annular channels were horizontally installed in the test bench circuit /11/, a fragment of which is shown in Fig. 4. A 300 W refrigerator was used to maintain helium circulation. The experimental results were obtained at the following parameters of two-phase helium flows: $x = 0 \div 1$, $m = 20 \div 110$ kg/m^{2}s, $P = 0.13 \div 0.18$ MPa. It should be stressed that in each series of experiments the dependence $\phi(x)_{m = const}$ was registered at a strictly fixed pressure, which requires much time nevertheless it eliminates distortions of the results due to variability of the thermodynamic properties of the flow. Since generalization of the results in the whole range of the investigated parameters is not the subject of this paper, we only dwell upon some typical parameters.

The experimental data for both transducers at P = (137 ± 1) kPa are given in Fig. 5. As is seen, at mass velocities about 100 kg/m^{2}s the experimental points for both round and annular channels lie near homogeneous dependence, and further increase in m does not practically affect the position of points. It agrees with the results of Refs. /1,2/. This fact prompts an idea of using the void fraction transducer as an instrument whose readings are proportional to the mass flow rate. For example, if the cryogenic system contains a controllable source of energy gain ΔQ leading to a change in the vapour quality by Δx, then the mass flow rate should be determined by the ratio of $G = \Delta Q/\Delta x h$, where h is latent heat of vaporization. Reduction of the flow mass velocity to the values at which the flow patterns change over to stratified ones /7/ leads to a corresponding reduction of ϕ for both transducers. Yet, for the round channel this reduction is

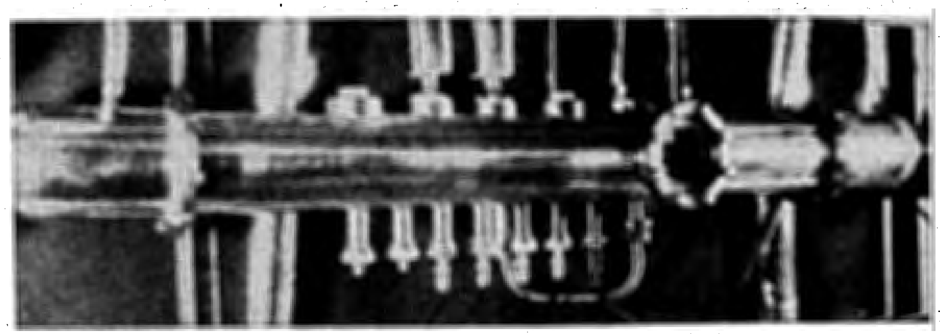

Fig. 4. Cryostat for transducer No.4 with visual section.

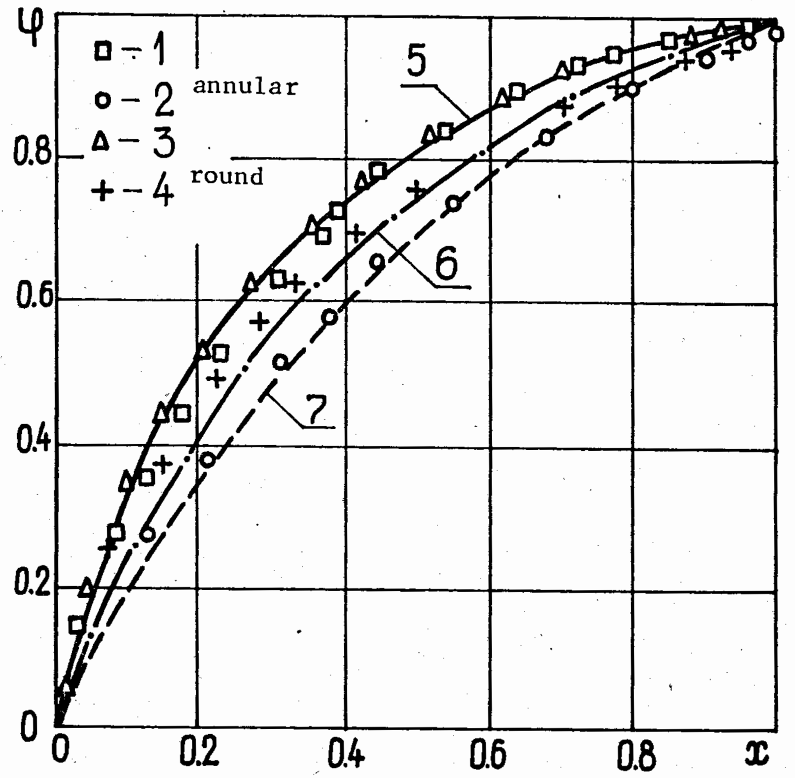

Fig. 5. Void fraction ϕ versus quality x at $P = 0.137$ MPa. $1 \div 4$ - experimental data at different m, kg/m^{2}s: 1 - 110, 2 - 34, 3 - 71, 4 - 21. $5 \div 7$ - calculation results: 5 - by homogeneous model, 6 - by relation (6), 7 - by relation (7).

smaller than for the annular one. This is well seen in Fig. 5, where the relevant data for the tube are in satisfactory agreement with the calculations by expression (6), while the experimental points for the annular channel are in good agreement with the calculation based on (7). Figure 5 shows that the curves calculated by relations (6) and (7) notably differ from each other. It confirms the above-mentioned restrictions of the use of annular channel sensors (or with channels of more complicated shape) for obtaining correct information on processes taking place in the tubes.

Among the experimental data obtained by other authors at small m we point out the indirectly obtained results /6/ for vertical tubes at $m = 6 \div 12$ kg/m^{2}s, $P = 100$ kPa, $x = 0 \div 0.15$

and $x = 0.8 \div 1$. These data are in good agreement with the calculations by (6), which does not contradict the theoretical conclusions made to the effect that under these conditions the channel orientation may not influence the form of the relation /15/ $\phi(x)_m$. The data /1/ for a vertical transducer with a relatively large annular gap* at $P \approx 120$ kPa, $x = 0 \div 1$ and $m \approx 8$ kg/m^{2}s lie mainly between the dependences calculated by (6) and (7). However, it is difficult to analyse this fact, since the absence of the hydrodynamic stabilization sections and a relatively high possible error $(\delta\phi)_{intr}$ do not ensure the revealing of the true reasons for it.

Finally, besides the main function of the helium void fraction transducer, i.e. mesurement of ϕ, and the above-mentioned additional one - measurement of the mass flow rate of two-phase flow, we note some more possible applications. Used in the single-phase region, the meters can measure the flow density /3/ which is unambiguously related to the signal range Δf_s. Since the dielectric susceptibility of the medium depends on P and T, the void fraction sensor can also be gauged as a thermometer at the proper pressure control. For example, the experiments showed that the sensitivity of the annular channel transducer No.2 in the subcooled liquid region is 300 kHz/K at $P = 130$ kPa, which ensures the measurement accuracy of $(1\text{-}2)\cdot 10^{-2}$ K. Evidently, other applications of the void fraction transducers are also possible, which makes them attractive for the application in cryogenics, though it requires additional investigations.

CONCLUSIONS

The value of the void fraction ϕ significantly depends on the channel geometry, mass velocity and thermodynamic properties of the flow. Other conditions being equal, the variation of ϕ for annular channel is larger than for tubes in those cases when the two-phase flow pattern changes from the stratified to homogenized one.

The designed transducers with round and annular channels are simple, reliable, and allow for a comparatively high accuracy of measurements. When used with helium, they have practically linear operating characteristic, and their gauging is very simple. Besides measuring ϕ, the transducers

* The data /1,6/ are not shown in Fig. 5 to avoid encumbering.

can be used in the single-phase region to check the mean integral temperature and density of the flow. If the two-phase flow pattern is homogenized and the energy applied is controlled, the meters can be used to measure the mass flow rate.

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