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APPLICATION OF X-RAYS EXCITED BY β-SOURCES TO STUDYING HYDRODYNAMICS OF TWO-PHASE MEDIA

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Аннотация—Даётся обоснование метода определения истинных параметров циркуляции двухфазного потока в каналах малых сечений путём просвечивания рентгеновскими лучами, возбуждаемыми бетаисточниками в стенках канала.

Приводится описание экспериментальной установки. Определяются погрешности данного метода для тех случаев, когда структура потока является неопределенной.

NOMENCLATURE

φ, volume fraction occupied by gas (steam);
γ_{mix}, true specific weight of mixture, kg/m^3;
E_{eff}, average energy of X-rays, keV;
μ_{eff}, effective absorption coefficient, cm^{-1};
n, impulse counting recorded by the counter when the tube, filled with the mixture being investigated, is irradiated, 1/min;
n'', the same with gas (steam) in the tube;
γ', γ'', specific weight of steam and water under saturated conditions, kg/m^3;
x, steam quality (weight steam content);
δ, thickness of irradiated channel wall, mm.

METHODS based on absorption measurements of narrow or broad beams of γ-rays passing through a given medium [1, 2] are used for determining true circulation parameters (the fraction of the channel section occupied by steam, φ, or of true specific weight of mixture, γ) in tubes with sizes often employed in boilers.

When carrying out such measurements in channels with small sections it is necessary to employ low energy level γ-rays but this involves some difficulties as it is not always possible to choose suitable radioactive substances for this purpose; moreover a considerable proportion of soft radiation is absorbed in the channel walls.

For this purpose soft X-rays, obtained by bombardment of a target with β-rays, were used in the present work.

Two ways of obtaining X-rays are known: when X-rays pass through a target (transmission target) and when they are reflected from it (reflexion target) [3–9]. In the first case, the yield of X-rays with respect to β-radiation is 5–10 per cent with a target thickness 1 g/cm^2, and in the second case the yield is less, approximately by an order of magnitude [4, 5].

The energy of X-rays obtained depends on β-radiation energy, target material and its thickness. The energy of X-rays increases with the target thickness.

It is necessary to use soft X-radiation when measuring the density of a vapour–water mixture in channels with small sections, to ensure sufficient sensitivity of the method. At high pressure of the medium flowing inside the channel, the channel walls have appreciable thickness, therefore a considerable part of the radiation will be absorbed in metal walls. In this connexion we thought it advisable to carry out measurements in such a way that the metal wall of an irradiated channel itself may serve as the main transmission target. The beam of β-particles passing through a collimator bombards the part of the channel wall which faces the β-source and excites X-radiation in it, which then passes through the investigated medium filling the internal space of the channel, through the channel wall facing the counter and enters the γ-quantum counter through a diaphragm.

In the present paper $Sr^{90} + Y^{90}$ was used as a radiation source since it radiates only β-rays and has a great half-life period.

X-rays obtained have a polychromatic spectrum; therefore a density determination should be carried out after a calibration curve has been obtained for the conditions in which an experiment will be carried out. The calibration curve may be obtained by filling a channel with a homogeneous medium (liquid or superheated vapour) at different pressures and temperatures so that the calibration density change may cover the whole range of values anticipated when conducting experiments.

Experiments on irradiation of various metals were carried out in order to verify the influence of target metal and its thickness on generation of X-rays. Results of these experiments are given in Table 1.

Table 1

Metal	Relative no. of readings for given metal thicknesses (mg/cm²)										
	0	50	100	150	200	300	400	500	600	700	800
Iron	1	—	—	—	9·6	6·92	3·93	2·09	0·92	0·39	0·19
Copper	1	7·85	9·5	9·8	8·63	5·06	2·38	1·0	0·04	—	—
Lead	1	8·96	10·3	9·12	7·2	3·7	1·69	0·65	—	—	—

The table shows that the generation of rays predominates over their absorption for all the metals when the target thickness does not exceed a definite value whilst above a certain thickness an inverse relation prevails. These relations should be taken into account when choosing a target.

Experiments were carried out on the installation shown in Fig. 1 and intended for determining true circulation parameters by irradiating a tube with a narrow and broad beam of rays.*

The installation consists of a metal frame (4) formed by two bracing uprights which are fastened by plates. The frame travels along guides (5) by means of a screw (9). The junction between the movable and stationary parts of the frame is made in the form of a slot of a trapezoidal section. The distance between the bracing uprights may be altered making it possible to irradiate channels of various sizes. A metal ampoule with a radiation source (1) and counter tube (3) of the type MCT-17 are placed in the struts of the movable metal frame. The ampoule is made of aluminium, and the thickness of its wall is 0·2 mm from the side facing the irradiated object. Thus, in the given installation, X-rays are generated not only in the channel wall but also in the ampoule walls (transmission target and reflexion target); however the yield of γ-quanta is a negligible proportion of the γ-quanta generated in the wall of an experimental tube. The counter tube is connected with the counting assembly of type Б-2 by insulated cables. The collimator is placed in front of the isotope and the diaphragm (10) in front of the counter tube. The diaphragm consists of a set of aluminium and lead disks with slots 8 × 4 mm in size which serve to define a plane-parallel beam of rays so that it may span the internal section of a tube. Each disk is 15 mm in thickness. With such a thickness of collimator and diaphragm the background from the source is negligibly small. Provision is made for the protection of the counter tube from light, and from external radiation as well as the biological protection of personnel.

When a broad beam is used the irradiated tube is fastened to the unmovable frame (4). When irradiating the experimental tube with a narrow beam, in some sections the traverse of the frame and, consequently, that of the ray, is set by an indicator with scale divisions of 0·01 mm.

Both non-heated and heated tubes may be irradiated. In order to protect the counter tube

* The design of the installation was carried out by engineer J. Gonzàlez Martinez.

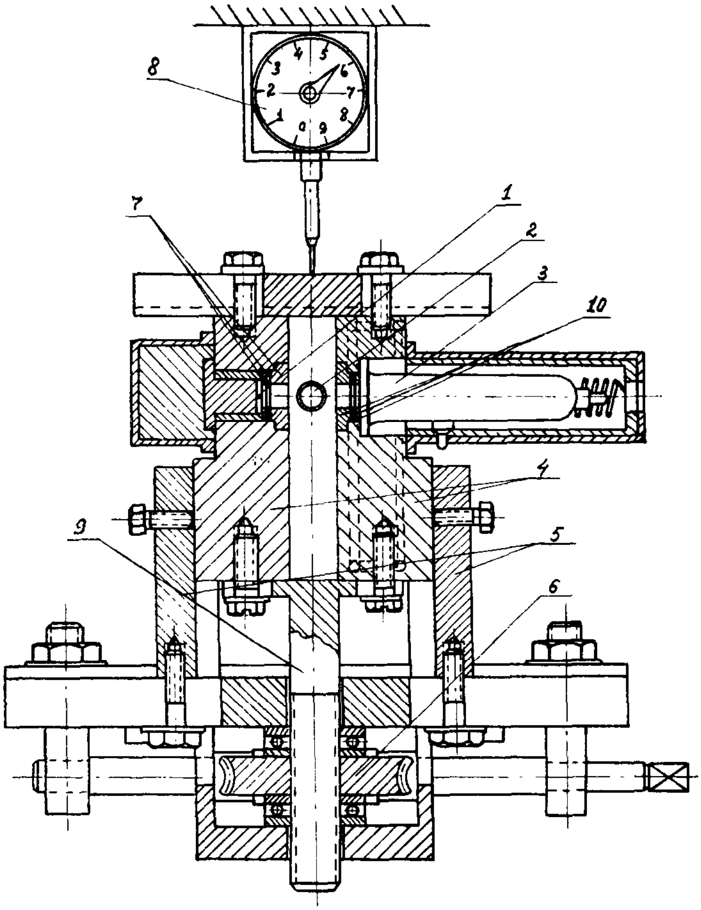

FIG. 1. Installation for irradiating steam-generating channels by X-rays.
(1) Ampoule with an isotope, (2) experimental tube, (3) counter, (4) movable frame, (5) guides, (6) worm gear drive, (7) collimator, (8) indicator, (9) screw, (10) diaphragm.

from heating, channels for water cooling it are made in the bracing struts of the stationary metal frame.

Experiments with the irradiation of flat cuvettes made of stainless steel 0·15 mm thick, filled with various amounts of water, were carried out for evaluating both the value of the effective absorption coefficient of generated X-rays in water and their mean energy. The covers of the cuvette which served as transmission targets were removable, and their thickness varied between 0·3 and 0·6 mm.

The effective values of μ_{eff} and E_{eff} measured in these experiments (values of E_{eff} were determined with respect to the measured values of μ_{eff} for water) are given in Fig. 2.

From Fig. 2 it follows that with the increase in target thickness from 0·3 to 0·6 mm and in the thickness of the water layer from 3 to 6 mm, decrease in μ_{eff} and increase in E_{eff} are observed, the values of μ_{eff} changing over a range from 8 to 4 cm^{-1} and of E_{eff} from 13 to 17 keV.

Thus, radiations were employed which increase the effective absorption coefficient in water by a factor of approximately one hundred in comparison with γ-sources used in the irradiation of large diameter tubes [1, 2].

When a two-phase medium moves in a channel,

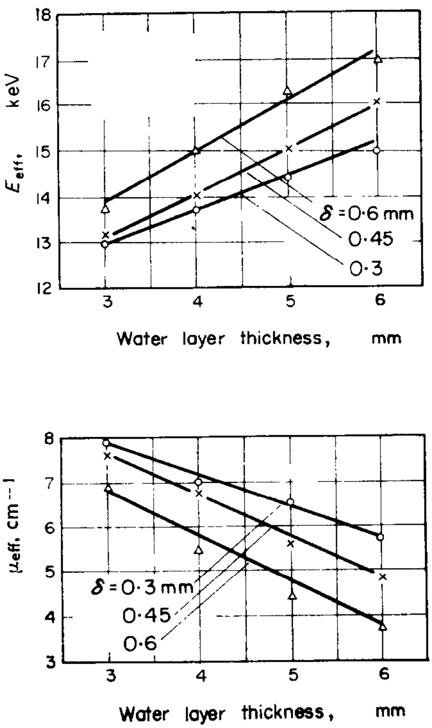

FIG. 2. Experimental values of effective absorption coefficients and energies of X-rays generated corresponding to them.

the absorption of X-rays in it may depend not only on the average density of the medium, but also on the distribution of both phases over the channel sections, i.e. on the flow structure.

Special methodological experiments were carried out to determine the influence of the flow structure of a two-phase mixture on the absorption of a broad beam of X-rays, i.e. on the uniqueness of determination of φ_{av}. For this purpose short straight sections of tubes with various wall thickness were used. Tubes were placed vertically and fastened firmly to the frame. Various regimes were simulated by using wooden inserts of various shapes inside the steel tube. Thus, emulsion, layered (stratified) and film regimes were simulated, the latter condition involving a vapour ring near the tube wall with water moving in the centre, and also annular regimes in which water flows near the tube wall with steam moving in the centre were simulated.

φ_{av} was determined as the ratio of volume occupied by wood to the internal tube volume:

$$\varphi = 1 - \frac{V_i}{V}$$

where V_i is the volume in cubic centimetres occupied by the wooden insert, V is the tube volume in the same units.

The specific weight of wood out of which inserts were made was 650 kg/m^3. Results of these experiments at various thicknesses of the irradiated tube are depicted in Fig. 3.

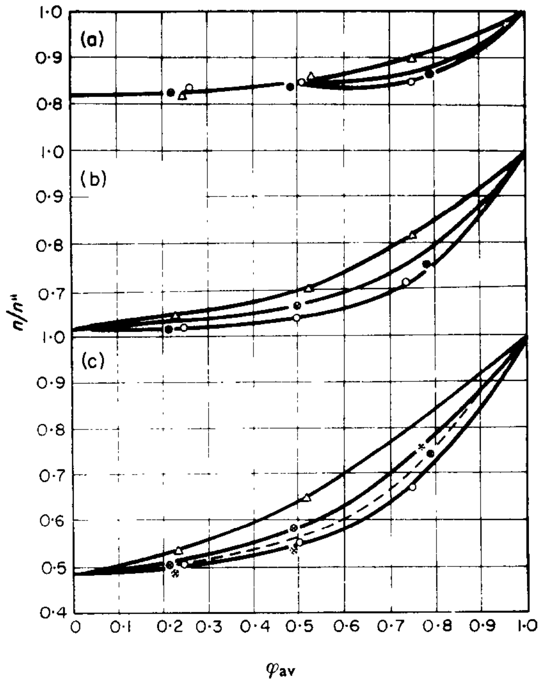

FIG. 3. Dependence of ratio n/n'' on φ_{av} for various flow structures. (a) δ = 0·4 mm, (b) δ = 0·315 mm, (c) δ = 0·2 mm. △—Annular regime, ⊗—laminated (stratified) regime, ○—film regime.

Since the absorption of X-rays by a substance depends not only on its density, but on its chemical composition as well, several experiments were carried out using ice inserts which simulated stratification perpendicular to the direction of irradiation, analogous to the emulsion flow regime. The use of water turned out to be inconvenient for this purpose, since the presence of the meniscus made it difficult to determine the proportion of the section of the tube filled with liquid. The data obtained (see dashed lines in Fig. 3a) differ negligibly from analogous data obtained in experiments with wooden inserts.

From Fig. 3 it follows that the less the thickness of an irradiated tube, the softer are the generated X-rays and the greater is the effect of the flow structure on results of measurement. Thus, when a radiation source is chosen, the material and thickness of the experimental tube should be taken into account.

It is also necessary to take into account the fact that in reality the error due to the uncertainty of the flow structure will be considerably smaller, since both in horizontal and in slightly inclined tubes the flow regimes are nearly always similar to the laminated (stratified) one, and the emulsion regime is the main regime (in particular, at high pressures) when a vapour–water mixture moves in vertical tubes. Under intensive heating of tubes the presence of a boiling boundary layer near a wall may create a structure similar to a film one.

At low pressures and high vapour content, structures similar to an annular one may also appear. However, at high vapour content the error due to uncertainty of structure becomes negligible. With the increase in pressure the influence of the flow structure on the results of measurement also decreases, since values of the absorption coefficients for water and vapour μ' and μ'' converge.

In the determination of the true volume vapour content φ, the error includes two values: $\Delta\varphi_{count.}$, due to inaccuracy of impulse counting, and $\Delta\varphi_{str.}$, due to uncertainty of a flow structure, i.e.

$$\Delta\varphi_{total} = \Delta\varphi_{count.} + \Delta\varphi_{str.}.$$

Figure 4 illustrates the values of $\Delta\varphi_{total}$ depending on weight mixture content x for a vertical tube 8 mm i.d. at $P = 1$ atm, obtained on analysing the curves plotted in Fig. 3. $\Delta\varphi_{str.}$ was determined as the difference between values of φ for emulsion and film regimes for constant values of n/n'', and

$$\Delta\varphi_{count.} = \frac{\Delta(n/n'')}{(d/d\varphi)(n/n'')}$$

was calculated for the case when $\Delta(n/n'') = 0{\cdot}01$.

$\Delta\varphi_{count.}$ has the greatest values at small values of φ where the curves of the dependence $n/n'' = f(\varphi)$ approach the x-axis at a small angle of inclination. The angle of inclination of the curves to the abscissa $[(d/d\varphi)(n/n'')]$ increases with φ, and $\Delta\varphi_{count.}$ decreases.

$\Delta\varphi_{str.}$ has the greatest value at mean or average values of φ and decreases to zero when $\varphi \to 0$ and $\varphi \to 1$. $\Delta\varphi_{total}$ increases with tube wall thickness, especially at small values of φ, due to the increase in $\Delta\varphi_{count.}$.

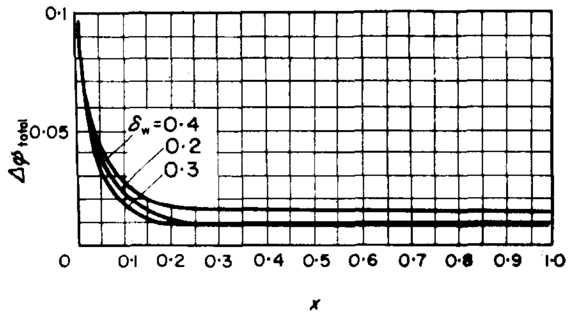

FIG. 4. Error when determining φ at $P = 1$ atm as a function of weight steam content of medium.

From Fig. 4 it follows that when determining φ, considerable errors are encountered only in the region of small weight vapour contents ($\Delta\varphi_{total} > 0{\cdot}05$ only at $x < 0{\cdot}04$).

When plotting the curves given in Fig. 4 it was assumed that

$$\varphi \simeq \left[\frac{\gamma''}{\gamma'}\,\frac{1-x}{x} + 1\right]^{-1}.$$

With increase in pressure, $\Delta\varphi_{str.}$ will decrease as a result of diminishing difference in densities of vapour and liquid phases, and this is mainly due to the fact that at high pressures the emulsion flow regimes predominate.

CONCLUSIONS

(1) A method is proposed of measuring true circulation parameters in channels of small sections using X-radiation excited by a β-source. The channel walls themselves are used as the main transmission target to reduce radiation energy attenuation by the channel walls.

(2) By varying the wall thickness of an irradiated channel it is possible to change the average energy of the generated rays, and, consequently, the effective absorption coefficient in the two-phase medium investigated.

(3) The influence of the two-phase flow structure on the unique determination of true circulation parameters was experimentally investigated. Errors in the determining φ_{av} due to the uncertainty of flow structure and inaccuracy of impulse counting were determined.

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Abstract—The principles of a method of determining true circulation parameters of a two-phase flow in channels of small cross section by means of X-rays excited by β-sources in the channel walls is given.

The description of an experimental installation is presented. For those cases when the flow structure is indefinite, the errors of the method are determined.

Résumé—Cet article présente les principes d'une méthode de détermination des vrais paramètres de circulation pour un écoulement à deux phases, dans des conduites de petite section. Cette méthode utilise des rayons X excités par des sources β sur les parois.

L'installation expérimentale est décrite. Les erreurs de la méthode sont déterminées dans le cas où la structure de l'écoulement est indéfinie.

Zusammenfassung—Nach der hier angegebenen Methode können die wahren Zirkulationsparameter der Zweiphasenströmung in engen Kanälen mit Hilfe von Röntgenstrahlen bestimmt werden, die von β-Strahlen innerhalb der Kanalwände ausgehen.

Die Versuchsanordnung ist beschrieben. Für unbestimmte Strömungsstrukturen sind die Fehler der Methode angegeben.