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RESISTANCE OF SPHERICAL FILLS IN THE CASE OF FLOW OF SINGLE- AND TWO-PHASE MEDIA

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The results of experimental investigations of the hydrodynamic resistance in spherical fills as applied to the cores of nuclear reactors with spherical fuel elements are presented. The experimental setup and the procedures of preparation of models, measurement, and processing of experimental data are described. The criterial dependences satisfactorily describing data on resistance in motion of single- and two-phase media in spherical fills are obtained.

Keywords: *spherical fuel elements, single- and two-phase media, criterial dependences, model of internal separating flow, generalized coefficients of hydraulic resistance.*

Introduction. Spherical (ball-type) fuel elements with a fuel based on microparticles with a multilayer coating have attracted the recent attention of specialists engaged in designing cores of high-temperature gas-cooled nuclear reactors (HTGRs) and water-moderated water-cooled power reactors (WWERs) and of other power-stressed heat-exchange equipment [1–3]. Such fuel elements ensure keeping the fission products of a nuclear fuel to a temperature of 1600°C or higher, which makes it possible to obtain a gas with a temperature of 900°C or higher at exit from the cores and a superheated steam of supercritical parameters in WWERs manufactured in a single circuit and to increase the efficiency to 50%. This in turn diminishes the power consumption, i.e., the harmful environmental load promoting the "greenhouse effect" and the global climatic change. However the use of such a technology is retarded by the lack of data on heat-exchange and hydrodynamic processes in fuel elements and by the heat exchange of the equipment with the fill of spherical fuel elements in flow of two-phase media and boiling in such structures.

Formulation of the Problem and Experimental Investigations. To investigate hydraulic resistance in channels with spherical elements and in infinite spherical fills in isothermal and nonisothermal flow of air, water, and a water-air mixture, we have created an experimental setup (Fig. 1). The experiments were conducted with the use of plug-in working portions 6 in which these media moved from the bottom upward. The air source in the setup was a TG-42-1 blower 1 of output 1.5 nm^3/sec and head 0.04 MPa, which fed air via receiver 2 and a system of pipelines 3 and purifying nets 4 to the plug-in working portions 6. Distributor baffles 5 whose number and arrangement were selected experimentally, converging nozzles 8 and 13, and grids with nets holding a fill of spherical elements were installed at entry into the working portions to equalize the velocity profile and to more uniformly mix the gas and liquid phases. The air flow rate was controlled using a gate valve 14; its value was determined from the pressure difference on a standard DK-6-78-A-1 chamber diaphragm 7 with a set of precalibrated plates with orifices of diameter 0.025, 0.05, and 0.06 m. The pressure difference and the excess pressure (relative to atmospheric) on the chamber diaphragm and the working channels were measured by water U-manometers 10 or MMN-250 inclined alcohol manometers 9. The error of pressure measurement by the water U-manometers amounted to ±0.25%, whereas the error of measurement by the MMN-250 manometers was ±1%. Atmospheric pressure was determined by Fisher barometers of the 00003 type with an error of ±0.07%. When the working portions intended for investigation of the processes in regular packings and having a large flow section were installed, the air flow rate was measured using the total-head tube 15 ahead of the gate valve 14, which made it possible to diminish the loss in the feed lines and to obtain a mass rate of air flow through the working portion of to 1 kg/sec. Such a flow meter was calibrated by measuring the velocity profile on the converging-nozzle exit section. The standard deviation of the experimental data from the dependence

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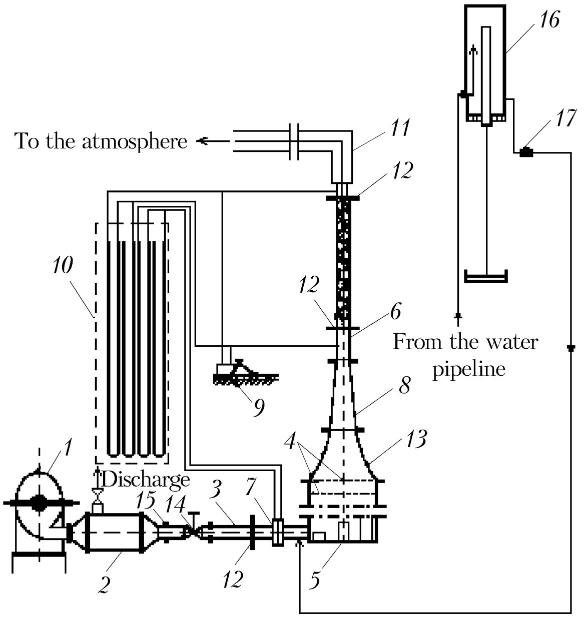

Fig. 1. Diagram of the experimental setup: 1) TG-42-1 blower; 2) receiver; 3) air duct; 4) purifying equalizing nets; 5) distributor baffles; 6) plug-in channels; 7) measuring diaphragm; 8) confuser; 9) MMn-250 micromanometer; 10) liquid U manometers; 11) discharge tube; 12) Chromel-Alumel thermocouples; 13) Vitoshinskii nozzle; 14) controlling gate valve; 15) total-head tube; 16) overflow pressure water tank; 17) valve for controlling the water flow rate.

$m_{\text{air}} = 0.0253\sqrt{\rho_{\text{air}}\Delta h}$ was no higher than ±1.7%. Precalibrated Chromel-Alumel thermocouples 12 allowing measurements of the air temperature with an error of ±0.1% were installed at entry and exit from the working portions.

The plug-in working portions 6 were manufactured from organic glass (Plexiglas) or ebonite, which made it possible to bring the spherical-element temperature to 300°C. In experiments with heating, we installed an inductor (heater) on a working portion, and water traversed the heat exchanger according to the diagram given in [4]. The inside diameter of the working portions ranged from 30 to 180 mm, whereas their length varied from 75 to 420 mm. A support grid with orifices covered with a high-porosity net was installed in the lower part of the working portions; a fill of spherical elements of diameter 3 to 60 mm manufactured from aluminum alloy, lead, or steel was arranged above the grid. For its fixation the spherical elements were held down from above by a grid analogous in structure. For spherical elements of diameter 3 and 3.8 mm, the surface temperature was measured using one Chromel-Alumel thermocouple installed in it; for spherical elements of diameter 60 mm on which we investigated resistance in the case of flow of single-phase media, the average temperature of the sphere surface was determined using the Chromel-Alumel thermocouples (arranged at an angle of 60°) whose hot junctions were flush caulked and joined with the spherical-element surface. The experiments were conducted in air, water, and a mixture of water and air in their different proportions.

Water entered the working portions 6 from an overflow pressure tank 16, which made it possible to maintain constancy of flow in the process of each specific experiment (for a certain air flow rate), and its change was controlled by sinking or lifting the overflow pipe and by the corresponding valve 17. The use of the open circulation circuit enabled us to determine the water flow rate with a measuring tank at which water arrived through a discharge tube 11. Resistance was investigated in channels with a spherical fill in the case of flow of air, or a water-air mixture modeling the boiling resistance in them for Reynolds numbers $\text{Re}_0 = 4.545\text{–}7.2 \cdot 10^4$. The hydraulic-loss factor was determined from the pressure difference on the working portion with a spherical fill; from the pressure difference, we subtracted the pressure difference on the working portion without a spherical fill under the same operating conditions as those in the case of a filled portion.

In describing resistance in a spherical-element fill, we used the model of internal separating flow [3] according to which flow of the heat-transfer agent occurs under the conditions of periodic contraction of its flow from the maximum flow section $F_{\max}$ to the minimum $F_{\min}$ (a unit cell of the spherical bed is considered). On passage to the relative values of these sections the relative flow-section area determined as the ratio of the running value of the cross section of the geometric clearance F_r to the cross-sectional area of the spherical unit cell F changes from the maximum value $\psi_{\max} = F_{r\max}/F$ to the minimum value $\psi_{\min} = F_{r\max}/F$ with a period equal to the relative height of the spherical unit cell h_m. The governing parameter for such channels is the expansion ratio of the flow section $\overline{F} = \psi_{\max}/\psi_{\min}$.

The hydraulic resistance of the channel with a variable cross section without allowance for the friction resistance is determined by the expression

$$\Delta p = \xi_g f(\overline{F}) \frac{H_b}{h_m d_{sph}} \frac{\rho W_0^2}{2}, \tag{1}$$

where $f(\overline{F})$ is the empirical coefficient allowing for the expansion ratio of the flow section. Passing to the filtration velocity $W = \psi_{\min} W_0$, we obtain

$$\frac{\Delta p}{H_b} = \xi_g f(\overline{F}) \frac{\rho W^2}{\psi_{\min}^2 h_m d_{sph} 2}.$$

In the case of the two-phase water–air medium the filtration velocity and the density were determined from the following dependences:

$$W = W_{mix} = \frac{m_{mix}}{\rho_{mix} S} = \frac{m_w + m_{air}}{\rho_{mix} S}; \quad \rho = \rho_{mix} = (1 - x)\rho_w + x\rho_{air}; \quad x = \frac{m_{air}}{m_w}.$$

We can find the expansion ratio $\overline{F}$, using the dependence [3]

$$\overline{F} = \frac{1}{\psi_{\min}} - 4(1 - \psi_{\min})(1 - h_{\min}) \frac{h_m}{\psi_{\min}}.$$

From expression (1), we determine the dependence for the coefficient of hydraulic resistance within the framework of the model of internal separating flow

$$\xi_g = \frac{2\Delta p \psi_{\min}^2 h_m d_{sph}}{\rho W^2 H_b f(\overline{F})}.$$

Taking into account that $h_m = H_b/(n_b d_{sph})$ we obtain an expression analogous in structure to the equation for the coefficient of hydraulic resistance of channels with a channel diameter-to-sphere diameter ratio $n \le 3$ [3]

$$\xi_g = \frac{2\Delta p \psi_{\min}^2}{\rho W^2 f(\overline{F}) n_b} = \xi \psi_{\min}^2,$$

in which the function $f(\overline{F})$ is equal to $1 + 33/\overline{F}^4$.

Thus, the coefficient of hydraulic resistance is a function of the Reynolds number determined from the parameters of the narrow section $\mathrm{Re}_0 = \mathrm{Re}_{sph}/\sqrt{\pi \psi_{\min}}$.

As a result of processing of a certain amount of experimental data, the generalized coefficient of hydraulic resistance determined from the parameters of the internal-separating-flow model as functions of the Reynolds number in a narrow section can satisfactorily be described by two dependences: for $\mathrm{Re}_0 = 4.545$–10^2, by

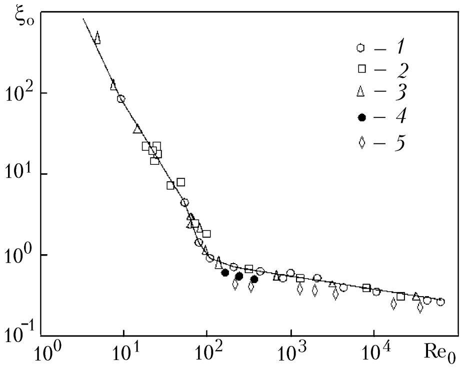

Fig. 2. Generalized coefficient of hydraulic resistance ξ_g vs. Reynolds number Re_0: 1) air; 2) water; 3) water + air; 4) [10]; 5) [11].

$$\xi_g = \exp\left[1.96\,(4.6 - \ln Re_0)\right], \tag{2}$$

and for $Re_0 = 10^2$–$7.2 \cdot 10^4$, by

$$\xi_g = 0.276\left(\frac{33}{Re_0^{0.6}} - \frac{Re_0^{1.6}}{10^9} + 1\right). \tag{3}$$

Formulas (2) and (3) describe well the experimental data given in Fig. 2 and can be recommended for calculation of the generalized coefficient of hydraulic resistance in regular and irregular monodisperse spherical fills in the range of $Re_0 = 4.545$–$7.2 \cdot 10^4$ in the case of air, water, and gas-liquid flows in them. Blocking of the clearances in a rhombohedral regular spherical fill causes an additional bending of the heat-transfer-agent flow and leads to an increase in the bed's resistance, which can be allowed for by introducing, into the expansion ratio, the correction coefficient $\overline{F} = k\overline{F}'$, where $\overline{F}'$ is the expansion ratio of the flow section of the spherical monodisperse bed with free clearances, which is determined from the above dependence. We have $k = 1$ for the irregular bed and regular structures with free clearances and $k = 0.71$ for the rhombohedral packing with blocked clearances.

An analysis of the data on hydraulic resistance and heat transfer in nonisothermal flow [3–5] has made it possible to single out a number of factors influencing the final form of the dependences in describing these processes. They include the factors related to both the qualitative and quantitative changes (nonisothermicity proper of the flow across the boundary gas layer and hence the displacement of the point of its separation) and the procedure of processing of experimental data (allowance for the pressure loss by acceleration or deceleration of the gas flow; selection of the determining temperature in calculation of the criterial parameters).

Let us consider the influence of the flow nonisothermicity in the transverse direction. In the case of gas flow in a spherical-element fill the boundary layer redevelops on each sphere; the thickness of the boundary layer does not exceed 100–200 μm because of the small length [3, 5]. The boundary layer is laminar on most of the sphere. The results of numerical calculation of the heat exchange in the laminar boundary layer and experimental data for laminar gas flow in a tube and on its initial portion demonstrate the extremely weak influence of the temperature factor on the hydraulic resistance and heat transfer [3, 6, 7]. In the case of gas flow about a sphere the influence of the temperature factor representing the ratio of the surface temperature of the sphere T_w to the temperature of the medium T_f flowing about it on the hydrodynamic pattern manifests itself as the counter-streamwise displacement of the point of separation of the boundary layer [3, 8], which leads to an increase in the width of the wake of the sphere and to another distribution of the local heat-transfer coefficients in the afterbody of the sphere. As a result the coefficients of both resistance and heat transfer change [9]. However, the investigations carried out with a unit sphere in a channel with $n = 1.27$ have shown that the temperature factor has little or no influence on the average coefficient of heat transfer from the sphere in the range of variation in $T_w/T_f = 1.08$–2.2 and the Reynolds numbers $Re_{sph} = (10$–$444) \cdot 10^3$ [3]. Clearly, the displacement of the point of separation of the boundary layer within a few degrees does not lead to substantial changes in the hydrodynamic pattern of flow near the sphere and exerts no influence on the hydrodynamic resistance.

When experimental data are processed, different authors take either the temperature of the incident gas or the mean-mass temperature as the determining temperature of the flow and calculate the physical properties of the gas from either the incident-flow temperature or the mean-mass temperature and from the wall temperature, the arithmetic mean between the wall and gas temperature, or from the set of these quantities. This presents certain difficulties when the obtained experimental results are analyzed.

Investigations of transverse unconstrained air flow past a cylinder [10] have shown that the heating of air was very small in this case, which enabled Aérov et al. to process experimental data on the incident-flow temperature. When the cylinder is transferred to a narrow channel with a lower mass rate of air flow (all other things being the same), the heating of air grows and the influence of the temperature factor virtually disappears as a result of the processing of data on the mean-mass flow temperature. We have obtained the same result in investigating the resistance and heat transfer from a single sphere in a channel with $n = 1.27$ and 2.72. Thus, to eliminate the group T_w/T_f as the flow temperature and the determining temperature of the medium flowing about spherical elements from the generalized coefficient of hydraulic resistance we should use the mean-mass temperature, which was determined as the arithmetic mean of the temperatures at the working-portion inlet and outlet. Measurements of the velocity and temperature profile at the working-portion outlet demonstrate that the outlet temperature profile is virtually uniform, apparently because of the intense mixing of the medium flowing about a spherical fill in its traversal.

The pressure loss by acceleration and deceleration of the flow should be determined from the mean-mass velocity of the medium in a fill or a rod bundle. Otherwise this gives rise to the dependence of the coefficient of hydraulic resistance on the temperature factor. Thus, the performed analysis of the influence of individual factors has shown that the empirical dependences for calculation of hydraulic resistance can be represented in final form without terms allowing for the temperature factor, which, apparently, makes it possible to use formulas (2) and (3) for calculation of the generalized coefficient of hydraulic resistance in the case of water boiling in regular and irregular spherical fills, too.

CONCLUSIONS

1. We have proposed the internal-separating-flow model adequately reflecting the hydrodynamic processes in spherical-element fills in the case of flow of single- and two-phase media in them.

2. The generalized coefficient of hydraulic resistance for regular and irregular monodisperse spherical fills can be described by unified criterial dependences in the case of flow of both single-phase and two-phase media in them.

NOTATION

d_{sph}, diameter of a spherical element, m; F, cross-sectional area of a unit spherical cell, m^2; F_r, running value of the cross section of a geometric clearance, m^2; $F_{r\min}$ and $F_{r\max}$, minimum and maximum values of the cross section of a geometric clearance, m^2; Δh, dynamic head, millimeters of water column; h_m, relative height of a unit spherical cell; H_b, height of a spherical-fill bed; m_{wat}, mass rate of water flow, kg/sec; m_{air}, mass rate of air flow, kg/sec; m_{mix}, mass rate of flow of a two-phase medium, kg/sec; n, channel diameter-to-sphere diameter ratio; n_b, number of spherical-element beds in a fill throughout the height; p_{atm}, atmospheric pressure, mm Hg; p_{st}, static pressure at the site of installation of the total-head tube, mm Hg; $\mathrm{Re}_{sph} = Wd_{sph}/\nu$, Reynolds number calculated from the sphere diameter; Re_0, Reynolds number calculated from the parameters of internal separating flow; S, cross-sectional area of the channel without a spherical-element fill, m^2; T_f, temperature of the medium flowing about spherical elements, K; T_w, surface temperature of spherical elements, K; W, velocity of flow of the medium in an empty channel; W_0, velocity of flow of the medium in a narrow channel cross section; x, mass content of air in the two-phase medium, kg/kg; ν, coefficient of kinematic viscosity of the medium, m^2/sec; $\rho_{air} = \rho_0 \frac{273}{273 + T_f} \frac{p_{st} + p_{atm}}{760}$, air density at temperature T_f, kg/m^3; $\rho_0 = 1.293$ kg/m^3, air density under normal conditions; ρ_{mix}, density of the two-phase medium flowing about spherical elements; ξ_g, generalized coefficient of hydraulic resistance; ψ_{min}, relative minimum flow section; ψ_{max}, relative maximum flow section. Subscripts: atm, atmospheric; wat, water; air, air; g, generalized; b, bed; mix, mixture; st, static; r, running value; sph, spherical; f, medium (fluid) flowing about spherical elements; m, relative value; min, minimum; max, maximum; w, spherical-element surface.

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