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INFLUENCE OF DISTURBANCES IN THE GEOMETRY OF THE ELEMENTS OF A REGULARLY POROUS SYSTEM ON THE HYDRODYNAMIC CHARACTERISTICS OF THE CLUSTERS OF FUEL ELEMENTS OF A NUCLEAR REACTOR

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The results of an experimental investigation of the hydraulic characteristics of clusters of twisted self-spaced rods on initiation of possible damages of their integrity are presented. For some probable breakdowns of clusters in their flow region the influence of these disturbances on the coefficient of hydraulic resistance of a packet of rods and on the distribution of velocities of the working body in the cross section of a cluster are investigated. The data obtained can be used for predicting the change in the thermal state of the active zone of the reactor, in particular, of the reactor of power plants under conditions of possible failure of fuel elements.

Introduction. The active zone of a thermally stressed gas-cooled reactor, in particular of the reactor of a nuclear rocket engine (NRE), operates under the conditions of high temperatures (~3000 K) and heat loads (~30 kW/cm^3) [1, 2], thus imposing heavy demands on the reliability of its cooling system.

The most thermomechanically stressed unit of the active zones is the cluster of fuel elements (CFE) that incorporates heating sections (HS) consisting of fuel elements. The section is assembled from self-spaced rods with a complex profile of cross section (e.g., cruciform) twisted around a longitudinal axis [3, 4]. Fuel elements are made from solid solutions of carbides of U–Zr–Nb–Ta (uranium–zirconium–niobium–tantalum). The characteristic property of such compositions is brittleness and the probabilistic distribution of strength properties [5]. Since one active zone of the NRE reactor houses several hundreds of thousands of rod-shaped ceramic fuel elements and the thermomechanical stresses appearing in them are known to exceed the lower level of strength, the appearance of numerous fractures is inevitable. The joint effect of thermal stresses and different types of side loads on the rods (hydraulic, vibrational, bandage, etc.) leads to mutual displacement of the fragments of the rods and to the appearance of hydraulic disturbances in the flow region of the heating sections. The self-spacing of twisted rods and of their fragments restricts the scale of these disturbances and preserves the permeability of the heating sections. At the same time, it is necessary to know the general laws governing the hydrodynamics and heat transfer and the characteristic features of the working body flow under conditions of possible disturbances of the hydraulic circuit of the reactor units, which will make it possible to rather accurately predict the admissible (without loss of the structure efficiency) temperature of gas heating and the heat release density in a reactor.

Statement of the Problem. An analysis of the results of electrothermal tests and reactor examination [5–7] shows that more than 70% fractures of the rods occurs in the plane perpendicular to the rod axis; the remaining splinters are oblique or stepwise. In multiblade fuel elements splintering of blades is also observed; there are virtually no such destructions in two-blade fuel elements.

The frequency of rupture of fuel elements in a packet may differ along the length of a cluster of fuel elements and over its radius, since the curves of the heat load and the thermal strength properties of fuel elements along the length and over the radius of a cluster are dissimilar. For example, for a cluster of fuel elements with concentration-based profiling of heat release along the length and over the radius of the cluster the different-concentration zones

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are assembled from fuel elements of different batches and therefore they can have different strengths; moreover, these zones are loaded by thermal stresses of different levels.

In order that the cluster of fuel elements preserve its performance capability, the following demands on it must be met:

a) the fuel elements must be kept in a gas flow. The determining factor is the mobility of individual elements in a packet. The problem is solved by selecting the constructional shape of fuel elements, packets, and means of their fastening in the channel of a cluster;

b) uniform heating of the working body in a cluster of fuel elements. The possible nonuniformities are determined by the character of hydraulic disturbances appearing as a result of both the mobility of individual fuel elements and of their fragments in the channel and deviations in the geometrical and technological parameters of the cluster.

A change in the hydraulic properties of a cluster of fuel elements leads to two main effects:

1) the disturbance of the reactor scale occurs because all of its clusters of fuel elements are loaded by the same pressure head, and a change in the resistance of some of the clusters leads to the redistribution of the working body flow rate between the clusters and, consequently, to the possible overheating of the groups of fuel elements. This effect can be lessened or eliminated by installing devices at the inlet to each cluster that would ensure a constant rate of flow of the working body through the cluster on change in its hydraulic characteristics (in a particular case, this can be a nozzle with a high pressure recovery coefficient);

2) the disturbance of the scale of a cluster of fuel elements is attributed to the fact that the superposition of tolerances or displacement of splinters and of the fuel elements themselves causes redistribution of the rate of the working body flow within the limits of the packet of fuel elements of one cluster and correspondingly the nonuniformity of the temperature field of fuel elements.

The limiting cases of the destruction of packets from the viewpoint of hydraulic disturbances seem to be destruction of fuel elements of a packet into fragments of the same length. If the fractures of all fuel elements lie in one plane, the disturbance is maximum, but if the fractures of neighboring fuel elements are staggered, then the disturbance is minimal. All the remaining possible variants of breakdown occupy an intermediate position.

Investigation of the entire set of possible destructions that may occur in a cluster of rods during reactor operation is practically impossible. This would require a very great number of clusters to be tested in a reactor.

In selecting experimental objects that would model the possible characteristics of the destruction of rods the following notions have been adopted:

1. The scale of the influence of a defect: the minimum distance between two defects in the material, when they are perceived separately from the point of view of destruction, can be estimated qualitatively based on the following arguments. In the case of thermoelastic loading, twisting, and bending, about 30% of splinters are oblique, i.e., the planes of fractures make an angle of about 45^o with the axis of the fuel elements. This fact allows the assumption that defects spaced at a distance of one diameter of the rod are indiscernable.

2. The scale of a fragment: in the case of thermoselastic destruction of fuel elements the surface of fractures is unloaded. The effect of unloading of the rod end face exerts its influence on the length of several diameters; therefore it might be expected that the defect located within the limits of two-three diameters of the rod from the fracture surface does not participate in further destruction of fuel elements. Consequently, the minimum distance between two defects that participate in fragmentation of a fuel element approximately corresponds to two to three diameters.

3. Mutual disposition of fractures: to study the influence of possible regular failures, for example, at the scale of one concentration zone over the radius of a cluster, it is advisable that for each cluster models be constructed with the same dimensions of fragments and with fractures lying in one plane; the very planes of the fractures should be perpendicular to the packet axis. Such variants seem to be limiting as to the disturbances introduced, since a group of fragments may shift over the cluster radius.

Objects of Experiments. These were clusters of four-lobe twisted rods: the number of rods 151; the circumscribed diameter of a rod 2.2 mm; the lobe thickness ~0.5 mm; the material of the rods — coated graphite (with pyrographite as the coating); the cluster length 100 mm, and the twisting pitch 100 mm. The scale of the fragments is from 5 to 20 mm. Longer fragments cannot be displaced mutually.

A cluster rested on a specially made honeycomb lattice of the following structure: one rod of a cluster is inscribed into the cross section of each hexahedral channel. The axial alignment of the rods of a packet and of the lat-

TABLE 1. Characteristics of Prepared Clusters of Twisted Rods

No. of cluster	Composition of cluster fuel element + filler	ε_{gas}	d_h, mm	d_{cir}, mm	ψ	State of cluster	z	Position of group	Character of fractures	L, mm
2	151+12	0.48	1.036	2.175	3.37	Fractured group	7	Central	Ratio of oblique-to-straight splinters 1:3	20
3	151+12	0.48	1.036	2.175	3.37		7			20
6	151+18	0.47	1.083	2.17	3.37		19			20
7	151+18	0.47	1.083	2.17	3.37		19			20
8	151+18	0.47	1.083	2.17	3.37		19			20
13	151+18	0.47	1.083	2.17	3.37		19			10
14	151+18	0.49	1.083	2.18	3.37		19			10
15	151+12	0.48	1.036	2.17	3.37		19			10
"00"	151+12	0.48	1.036	2.175	3.37	Integral cluster	—	—	—	—
"0"	151+18	0.48	1.083	2.175	3.38		—	—	—	—
"П"	151+18	0.44	0.966	2.26	3.36	Fractured group	127	Outer row — integral rods	1:3	See Fig. 2
29	151+12	0.48	1.036	2.175	3.38	Complete destruction	163	All rods are destroyed	1:3	Dissimilar
30	151+12	0.48	1.036	2.175	3.38	Fractured group	19	Central	Only sstraight fractures	5
31	151+12	0.48	1.036	2.175	3.38		19			5
32	151+12	0.48	1.036	2.175	3.38	Integral cluster	—	—	—	—

tice cells was provided by the side semi-cylindrical rods-fillers common for the packet and the lattice (the lattice porosity is ~0.9, the turnkey-based size of the hexahedral channels is equal to the circumscribed diameter of a rod of about 2.2 mm, with the channel wall thickness being ~0.05 mm).

For the creation of the needed initial conditions and force loading on the cluster investigated, at its inlet a cluster of integral rods was installed, which by size and composition was similar to that tested (buffer cluster).

The models of the heating sections with possible defects were prepared as follows:

a) rods were broken at specified places into measured fragments;

b) the fragments of one rod were then glued into an integral rod, preserving carefully their angular orientation;

c) with the fractures located chaotically, the rods were broken by applying radial bandage stresses to the side surface of the heating sections, and the fragments were fixed by filling paraffin into the hydraulic circuit of the heating sections.

The heating sections investigated and the buffer cluster were then installed into the working part of the experimental setup so that it could rest on the above-described lattice, and the paraffin that had fixed the fragments was removed by blowing hot air.

In the process of blowing the fractures were open, and thus we had a packet with introduced defects which was ready for hydraulic tests. This technique rather adequately models natural processes of cracking of fuel elements.

The geometrical dimensions of the clusters tested corresponded to the presumed natural clusters on the basis of four-lobe twisted rods. The kinematic and dynamic similarity of flows was provided by realization of the range of Reynolds numbers corresponding to those natural for the IRGIT reactor [2].

In processing experimental data on hydraulic resistance the definitions adopted for the coefficient of hydraulic resistance and for hydraulic diameter in flow through clusters of rods was used [2]. The Reynolds number was based on the hydraulic diameter and average velocity in the section of the cluster transverse to flow passage.

The degree of accuracy of measured parameters of flow and geometric characteristics of the cluster make it possible to estimate the uncertainty of the determination of hydraulic diameter, coefficient of hydraulic resistance, and gas velocity, which is equal to 1.5%, 10%, and 15%, respectively.

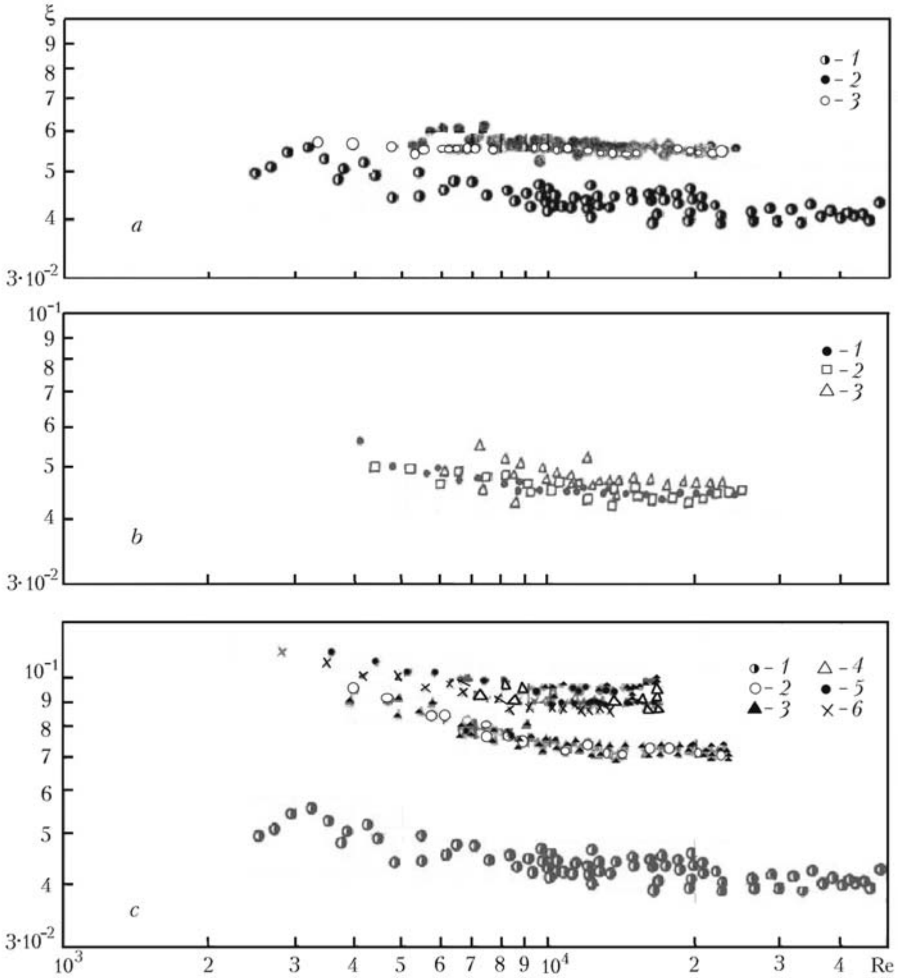

Fig. 1. Coefficients of hydraulic resistance for clusters of rods "0", Nos. 30 and 31 (1–3 respectively for 2 and 3, 19 central rods are fractured, lumps of length 5 mm) (a); Nos. 13, 14, and 15 (1–3 for 19 central fractured rods, with lumps of length 10 mm) (b); "0", No. 29, "Π" (1, 2 and 3, 4–6 respectively for 1 (the cluster "0" of integral rods), for 2 and 3 cluster No. 29 and for 4–6 cluster "Π" typical of which are multiple destructions of rods within the cluster; 3, 5, 6, the results of repeated tests) (c).

Analysis of Experimental Results. Figure 1 shows the variation of the average coefficients of hydraulic resistance ξ depending on Reynolds number for the packets (clusters) of rods investigated (the parameters of the packets are given in Table 1). The packets were assembled from rods of the same batch (they have the same geometric dimensions and were manufactured following the same technology) and differ only by the number of rods with the defects introduced.

Figure 1a presents data for one of the packets examined; it was composed of integral rods (for the remaining rods the results coincide to within experimental accuracy). Data for each packet in which the central group of 19 rods has defects of different scales along the length (in each specific cluster the central rods are composed of fragments of the same length) are presented in Fig. 1a and b. The rod fragment was of length 20 mm for clusters Nos. 6 and 8, 10 mm for clusters Nos. 13, 14, and 15, and 5 mm for clusters Nos. 30 and 31.

The character of the dependence $\xi = \xi(\mathrm{Re})$ and of the value of coefficients at the same Reynolds numbers for blocks Nos. 6, 8, 13, 14, and 15 coincide within the experimental accuracy with the corresponding dependences and values for the packets that were composed of integral rods (Fig. 1a and b). The data on clusters Nos. 6 and 8 are not given, because they do not differ from the results obtained for clusters Nos. 13, 14, and 15.

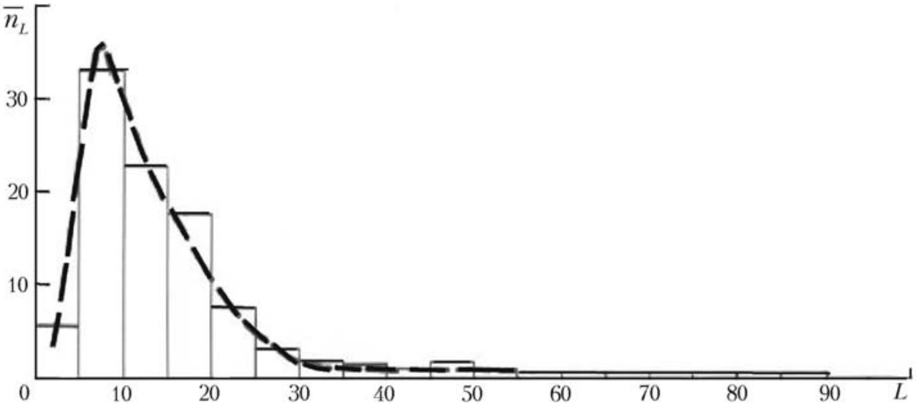

Fig. 2. Distribution of the fragments of rods in the cluster "П". L, mm; $\overline{n}_L$, %.

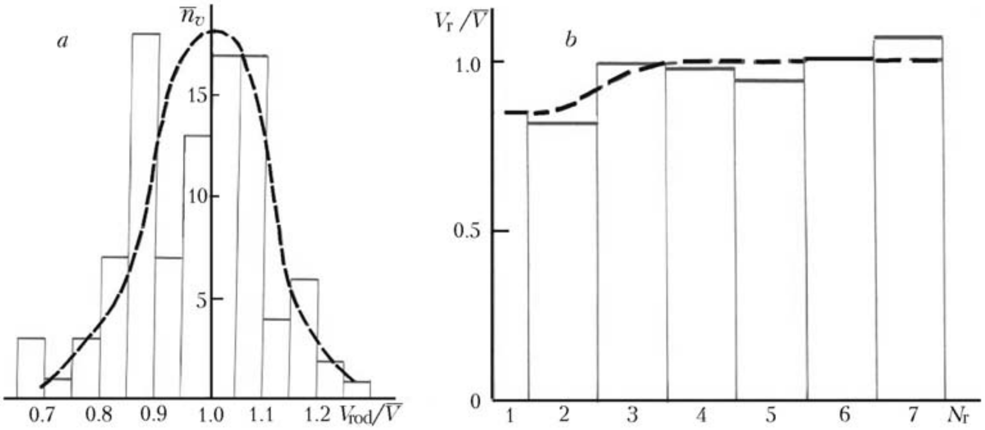

Fig. 3. Distribution of air velocities (a) and the field of the averaged values of velocities for each row of rods over the radius (b) in the outlet section of the cluster "0". $\overline{n}_v$, %.

The reduction of the size of the rod fragment to 5 mm (clusters Nos. 30 and 31, Fig. 1a) leads to a noticeable increase in the coefficient ξ (at $\text{Re} = 2 \cdot 10^4$ by about 20% higher as compared to the cluster of defectless rods). This seems to be attributed to the fact that fragments of small length commensurable with the rod diameter and longitudinal twist pitch may move more freely in a cluster. This may be accompanied by heavy destructions of the hydraulic circuit and, correspondingly, by appreciable disturbances of changes in ξ. The data given show that the average coefficient of hydraulic resistance of a cluster at considerable defects of the group of 19 rods (the fragments are 10–20 mm in length) changes insignificantly. It should be noted that the repetition of the experimental data for different packets of rods with identical defects is rather satisfactory (Fig. 1a and b) and in this sense the experimental results can be considered reliable.

Figure 1c presents the dependences $\xi = \xi(\text{Re})$ for "П" blocks, No. 29 having a random number and shape of fractures in the rods. The distribution of the lengths of rod fragments for the packet "П" is presented in Fig. 2. The relative fraction of fragments $\overline{n}_L = n_L/N_{\text{fr}}$ with the same length L relative to the total number of fragments N_{fr} is plotted along the ordinate, and the size of fragments along the abscissa axis; each range of length of the fragments of 5–10 mm, 10–15 mm, and so on has its own value of $\overline{n}_L$. Packet No. 29 was composed of 600 fragments of 151 rods with an average length of a fragment of about 26 mm. For these clusters the value of the coefficient ξ is much higher (approximately 2 times) that the corresponding values of ξ for clusters made from integral rods (for comparison the figure contains data for a packet of integral rods).

Figure 3 presents the distribution of air velocities in the outlet section of the lattice over the radius of the cluster of integral rods, as well as average values of velocity for each row of rods over the radius of cluster "0." The

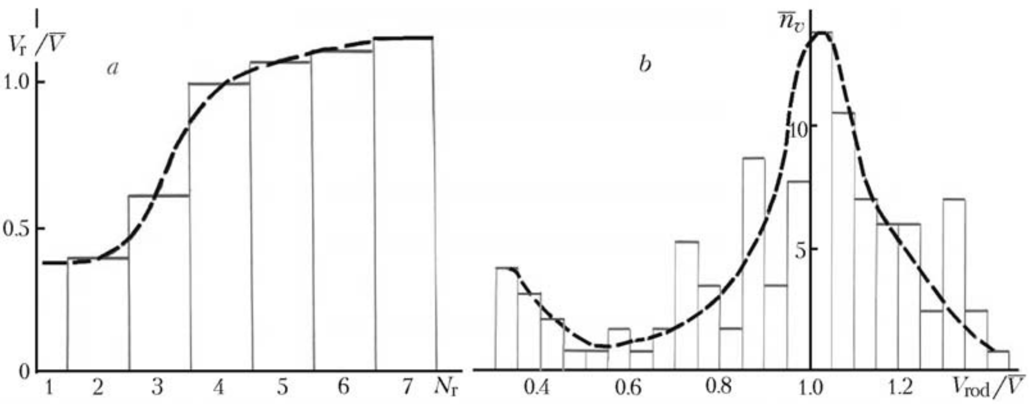

Fig. 4. Field of averaged values of velocities for each row of rods over the radius (a) and distribution of gas velocities (b) in the outlet section of cluster No. 14. $\overline{n}_v$, %.

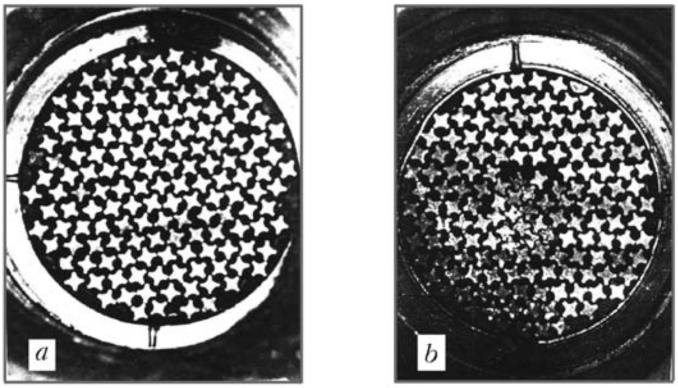

Fig. 5. Outlet sections of the cluster "0" (integral rods) (a) and of cluster No. 31 (19 central fractured rods with fragments of 5 mm) (b).

considerable scatter of the velocity values in the cross section of the cluster obeys a law close to the normal law of distributions of random quantities (Fig. 3a). This feature seems natural in the sense that the hydraulic properties in the volume of the packet can be inhomogeneous (due to the deviations in the geometric parameters of rods, shape of a lobe, curvature of the rod axis; specific features of flow past groups of neighboring rods with different mutual position of lobes, etc.) and for a large number of rods it obeys the normal law of distribution. In Fig. 3a and in other similar figures the ordinate axis gives the relative number of rods $\overline{n}_v$ for which the velocity of flow around them V_r is the same ($\overline{n}_v = n_v/N$, for each range of change in the relative velocity V_r/V: 1–1.05, 1.05–1.1, etc. there corresponds its own value of $\overline{n}_v$).

The other characteristic feature of the results obtained is the decrease in the air velocity near the central rod in comparison with the neighboring ones (Fig. 3b). This effect was observed for rods of different sizes and for different shapes of the lattice. It might be that this decrease is attributable to the fact that in the heating sections, because of the spiral character of flow around each coiled rod, a collective centrifugal motion of the scale of the heating sections is formed manifesting itself, in particular, in the flowoff of gas from the flow axis.

Figure 4a presents the distribution of average velocity of gas for each row of rods over the radius of a cluster with defects in the rods. Packets Nos. 8, 13, 14, and 30 include the core of 19 central rods consisting of fragments of the same length, but different for each packet. The profiles of the axial velocities have an expressed trough at the center of the cross section of the cluster. The average air velocity at the center is nearly 50% of the normal (average) value and depends slightly on the size of the rod fragments. The dimensions of the fragments changed from 5 to 20 mm at the rod twisting pitch of 100 mm. Since the pictures obtained for different kinds of destructions are practically identical, only the data on cluster No. 14 are given.

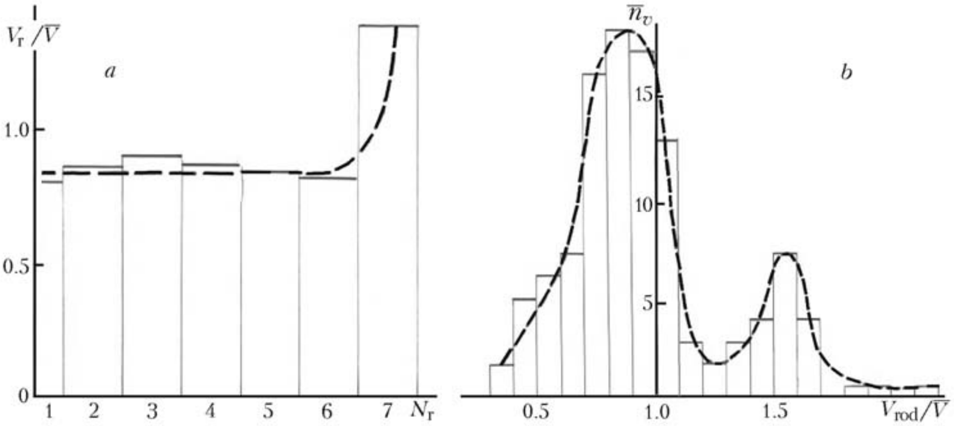

Fig. 6. Field of averaged values of velocities for each row of rods over the radius (a) and distribution of the gas velocities (b) in the outlet section of the cluster "Π". $\overline{n}_v$, %.

The fact that the change in the velocity depends slightly on the size of the investigated lumps of a rod can be explained as follows: either the size of the disturbed region — 19 rods ($\sim 10d_h$) — is insufficiently large and the different disturbances of air velocity for different sizes of lumps are smoothed by the interaction with the main flow in the nonperturbed region of the packet (a sharp discontinuity in the field of average velocities at the boundary of the disturbed flow is of low probability), or simultaneously with the increase in disturbances in the central zone the effective coefficients of transfer in the gas increase.

Figure 4b presents a characteristic velocity distribution for packets with the central core composed of fractured rods. These distributions display the second peak with the amplitude and position on the axis for velocity which are almost independent of the magnitude of the rod lumps adopted (this feature is associated with the central region of the fractured rods; in clusters of integral rods there is one maximum). The data are given for cluster No. 14; the pictures of distributions for other clusters of this type do not differ (clusters Nos. 8, 13, and 30).

Figure 5 presents photographs of the outlet faces of clusters "0" and No. 31 (integral and fractured rods, respectively). In the latter, the regularity of the disposition of rods at its center is disturbed.

The packet "Π", for which the profile of the velocity averaged over the rows of rods is given in Fig. 6a and the distribution of the velocity field in Fig. 6b, consists of chaotically fractured rods and the peripheral row of integral rods. In the velocity profile there is correspondingly a spike on the radius of the last row. The characteristic feature is the absence of the second maxima on the left branch of velocity distribution in the transverse section of the packet in contrast to the clusters with other types of defects (Fig. 4b) (this means that groups of rods of large scale with hydraulic properties markedly different from average ones are not formed in the packet; the properties of the packet are homogeneous enough). The values of the velocity averaged for every row of the rods for the cluster Π fluctuate over the radius within ±10%. These nonuniformities are comparable with the scatter in the velocity for the packets composed of integral rods.

The obtained experimental data on the coefficients of hydraulic resistance and air velocity fields allow some general comments to be made.

For clusters made from integral twisted rods the distributions of velocities in the transverse sections of the packet obey a law close to the normal law of distribution of random quantities. The velocities differ very strongly in value, and in this sense one may speak of a local Reynolds number based on the velocity at each point of the cross section and, correspondingly, a local coefficient of hydraulic resistance corresponding to this Re number. This characteristic feature may lead to the appearance of zones with different conditions of flow around rods and heat transfer in a cluster. It is natural to assume that the nonuniformities in the velocity are formed along the rod length (discontinuities in the velocity distribution are of low probability). Then, from the velocity profile in the outlet section one can determine the average value of the coefficient of hydraulic resistance for some conventional "streamline" (along the rod). With the aid of such a type of resistance coefficient it seems possible to predict the distribution of the working body velocities and the temperature field in the transverse section of the cluster in the presence of some probable defects of clusters of fuel elements.

For the motion of a liquid there exists the notion of the critical Reynolds number at which the flow loses its stability (transition from a laminar character of motion to a turbulent one). If we consider two types of characteristic flows for packets of rods, then because of the above-described characteristic features of flow, the change in the coefficient of hydraulic resistance in the transient region should be smooth. The notion of the critical Re number for a cluster of rods is less defined than for channels, since substantial nonuniformities of the velocity field in the transverse section of the cluster is possible.

The average coefficient of hydraulic resistance of a cluster of rods ξ does not adequately characterize the state of the flow part. As the results of experiments show, in the case of appreciable defects in the cluster the value of ξ changes insignificantly, whereas the velocity field changes appreciably. At the same time, the nonuniformity of the velocity field will determine the temperature field in a cluster of fuel elements and correspondingly the efficiency of the cluster. In this sense, in the thermophysical calculations of a cluster of fuel elements account should be taken of the possible nonuniformities of the velocity field associated with the characteristic features of gas flow in a system of twisted rods and the effects which may result from possible disturbances of the integrity of rods. For the analyzed packets of rods the uniformity of the velocity field can be improved by making more strong the clearances of the cluster parameters.

CONCLUSIONS

1. For the considered packets composed of integral rods the scatter in the values of the axial gas velocity over the section of the cluster is observed. The distribution of the velocities averaged in the scale of one rod obeys a law close in form to the normal law of distribution of random quantities.

2. The average coefficient of hydraulic resistance of a cluster does not adequately characterize the properties of the flow portion of integral packets. At the same values of the Reynolds number-based resistance coefficients the distribution of the velocities of the working body in the cross section of a cluster can be different for different clusters of rods of the same batch.

3. Destruction of a group of 19 neighboring rods (for example, one of the concentration zones in the case where the profiling of loading is made over the radius of a cluster of fuel elements) leads to substantial redistribution of the working body velocities with a slight change in the coefficient ξ of the packet (for rod lumps of length 10–20 mm).

4. In the case of chaotic fractures of the rods of a whole packet the resistance coefficient of the cluster changes substantially and the distribution of the gas velocities in the cross section of the packet differs slightly from the corresponding distribution for a cluster consisting of rods free of fractures.

NOTATION

d_{cir}, circumscribed diameter of a rod, mm; d_{h}, hydraulic diameter of a cluster, mm; L, size of fragments, mm; N, total number of rods in a cluster; N_{fr}, total number of rod fragments in a cluster; N_{r}, number of the row of rods over the radius of a cluster; n_L, number of fragments of the same length; $\overline{n}_L$, relative fraction of fragments of the same length, %; n_v, number of rods for which the velocities of flow around them are identical; $\overline{n}_v$, relative number of rods for which the velocities of flow around them are identical, %; Re, Reynolds number; V_{r}, average gas velocity for a row of rods; $\overline{V}$, average gas velocity for a cluster of rods; V_{rod}, velocity of flow around a single rod; z, number of fractured rods; ε_{gas}, porosity ratio of the gas flow area to the cross-sectional area of a cluster; ξ, coefficient of hydraulic resistance; ψ, ratio of the cross-sectional perimeter of a rod to its circumscribed diameter. Subscripts: h, hydraulic; cir, circumscribed; r, row; rod, rod; fr, fragment; v, velocity.

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