EXPERIMENTAL STUDY OF MASS EXCHANGE IN AXISYMMETRIC CAVITIES

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Results are presented from a study of mass exchange in axisymmetric cavities of different configuration. Measurements were made by the electrodiffusion method. The test results are generalized using an empirical relation.

Vortex flows in cavities are of considerable interest for various areas of technology: heat-and-power engineering, water engineering, chemical engineering, and mining. Studies have also been made in recent years of hydrodynamics and mass exchange in the flow of blood in vessels with local dilations (aneurysms) [1]. The flow in the pore space of fillings is also vortical in character.

The flow mechanism in cavities is fairly complex. A mixing layer is formed on the boundary between the boundary-layer flow (boundary layer) and external flow. This mixing layer is governed by the same laws as ordinary streams. When a stream formed in the mixing zone impacts against the rear wall of the cavity, a boundary stream is formed. This boundary stream propagates over all of the walls of the cavity. A vortex core is formed in the center of the cavity. Flow in cavities is usually three-dimensional [2-4]. Naturally, it is still not possible to account for all of these flow features simultaneously in analyses. In connection with this, experimental study of vortex flows remains important.

The present work studies the average mass exchange between the walls of a cavity and a fluid flow within the cavity. The measurements were made by the electrodiffusion method [5]. The essence of this method is measurement of the rate of the diffusional redox reaction on the measurement electrode (cathode), which served as the internal surface of the cavity. The working fluid was a 0.01 N solution of potassium ferrocyanide and potassium ferricyanide in a 0.5 N solution of NaOH in distilled water. The solution temperature was held constant to within ±0.1°C.

The first tests to determine mass exchange were conducted on a cylindrical section $1.36\cdot 10^{-2}$ m in diameter and $3.425\cdot 10^{-2}$ m in length located beyond the hydrodynamic stabilizer ($1.36\cdot 10^{-2}$-m diameter and 0.5-m length). The test results were analyzed in the form of the relation $Nu/Pr^{1/3} = f(Re)$ and compared with Leveque's solution for a mean mass-transfer coefficient on an initial mass-exchange section [6]

$$Nu = 1.55\,Re^{1/3}Pr^{1/3}(d/l)^{1/3}. \tag{1}$$

The results of these experiments are shown in Fig. 1. The test and theoretical results agree up to Reynold numbers of about 2000.

Leveque's formula is valid at values $(1/Pe)(l/d) < 5\cdot 10^{-4}$. In our case, $10^{-6} < (1/Pe)(l/d) < 10^{-5}$. The Pr number was of the order of 1800.

The main test results from the mass-exchange study were obtained on axisymmetric cavities of different configuration (shown in Fig. 2). The cavities were installed after a hydrodynamic stabilization section. The main form of cavity was No. 1 (Fig. 2). This geometry was chosen to realize flow without secondary angular vortices. The results of measurement of mass exchange on this cavity are shown in Fig. 3a (designated by the number 1). The figure clearly shows different sections of laminar and turbulent flow and a broad transitional zone between these regimes.

In chemical engineering, one often encounters mass-exchange processes with gas or liquid flowing through several successive constrictions and expansions (several cavities). Ap-

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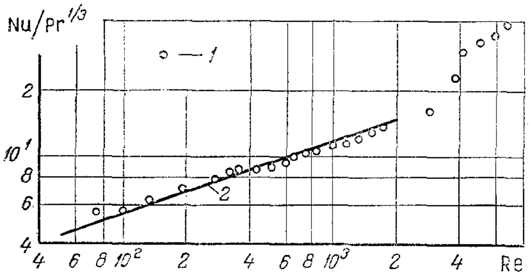

Fig. 1. Comparison of experimental (1) and theoretical (2) — from Eq. (1) — relation Nu = f(Re) for a cylindrical tube.

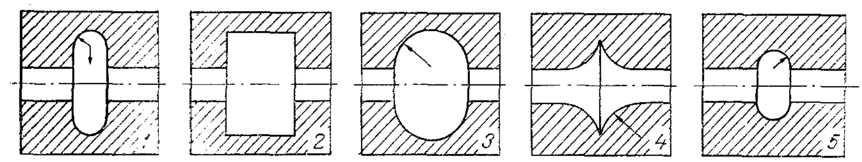

Fig. 2. Cavity configurations: 1-5) numbers of cavities.

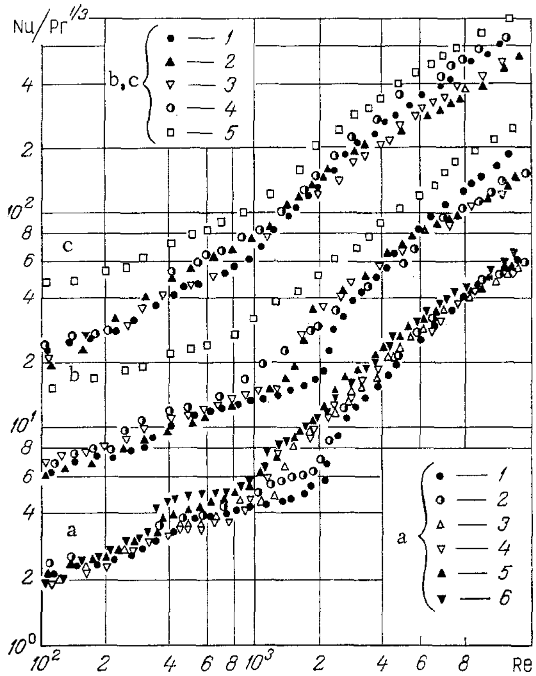

Fig. 3. Curve of the function $Nu/Pr^{1/3} = f(Re)$: a] 1) cavity No. 1 without agitator; 2) with superposed cavities; 3, 4, 5, 6) with agitators $1.16 \cdot 10^{-2}$ m, $0.96 \cdot 10^{-2}$ m, $0.86 \cdot 10^{-2}$ m, and $0.76 \cdot 10^{-2}$ m in diameter, respectively; b] 1) cavity No. 1; 2) cavity No. 2; 3) No. 3; 4) No. 4; 5) No. 5; c] 1) cavity No. 1 with agitator, ϕ $0.86 \cdot 10^{-2}$ m; 2) No. 2, ϕ $0.86 \cdot 10^{-2}$ m; 3) No. 3, ϕ $0.86 \cdot 10^{-2}$ m; 4) No. 4, ϕ $0.86 \cdot 10^{-2}$ m; 5) No. 5, ϕ $0.86 \cdot 10^{-2}$ m.

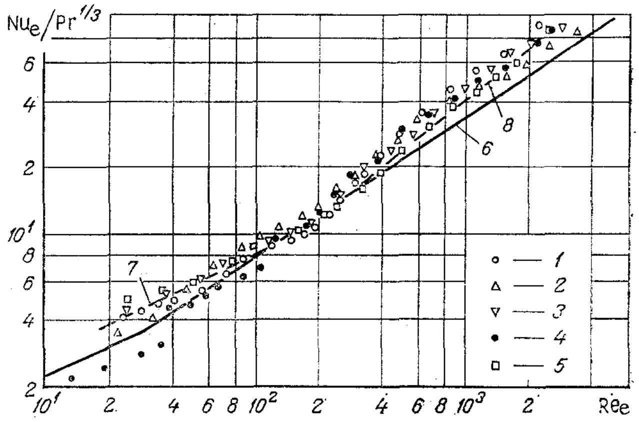

Fig. 4. The function $Nu_e/Pr^{1/3} = f(Re_e)$: 1) cavity No. 1; 2) No. 2; 3) No. 3; 4) No. 4; 5) No. 5; 6) the function in [7]; 7) Eq.(2); 8) Eq.(3).

proximately the same type of flow is seen in the pore space in a cubical packing of spheres. The presence of superposed cavities may have an effect on the flow in the main cavity. To shed light on this question, we conducted tests on cavity No. 1 in the presence of superposed cavities of the same configuration, made of organic glass. Figure 3a shows the case with three superposed cavities (2). It is apparent that the presence of the superposed cavities makes the transitional zone smaller, leaving mass exchange in the turbulent and laminar regions practically unchanged.

These tests led us to the conclusion that the effect of superposed cavities can be simulated by artificial agitation of the flow before the cavity. The agitator used in the test had the form of a diaphragm and was installed $7 \cdot 10^{-2}$ m in front of the cavity. The degree of agitation of the flow was varied by using diaphragms with different-size holes. Figure 3a shows the results of 3-6 tests with different agitators. It is apparent that both a decrease in the through cross section of the diaphragm and the presence of superposed cavities is accompanied by a change in the Nu = f(Re) relation only in the transitional zone. With an optimum size of diaphragm, there is a smooth transition in the mass-transfer relation from Re numbers for the laminar region ($Nu \sim Re^{0.5}$) to the relationship for turbulent flow ($Nu \sim Re^{0.8}$). These tests are denoted by the number 5 in Fig. 3a. A jump is seen in the curve of Nu = f(Re) (6, Fig. 3a) with a further increase in the degree of agitation.

Thus, it is apparent on this graph that the method of agitation is not particularly important. There is some change in mass exchange in the transitional region with either superposed cavities or an artificial agitator.

The following series of experiments was conducted on cavities with the forms shown in Fig. 2 (Nos. 2, 3, 4, 5)). (No. 2 had a square cross section, and secondary angular vortices were always present; No. 4 roughly corresponded in shape to the core space in a cubical packing of spheres; cavities 3 and 5 were geometrically similar, but cavity 5 had a smaller expansion dimension than the other cavities). The results of these tests are shown in Fig. 3b. The test data were shifted along the y axis by multiplying the actual values of the Nusselt number by the coefficient K. Meanwhile, K = 1, 3, and 10, respectively, for Fig. 3a, b, and c. It is apparent that for all cavities with a constant ratio of inside diameter to channel diameter, the mass-transfer coefficient, referred to the inside surface of the cavity, is nearly independent of the form of the latter in both the turbulent and laminar cases. The transitional zone is most extensive for cavity No. 1. The presence of secondary eddies in the cavity leads to additional agitation of the flow and accelerates the transition from laminar to turbulent conditions. The experiments curve of Nu = f(Re) for cavity No. 5 is considerably higher than the curves for the other cavities. The following series of tests was conducted on the same cavities with an agitator at the inlet. We used the optimum agitator design chosen earlier for cavity No. 1. The results of these experiments are shown in Fig. 3c. Mass transfer in the cavities of different configuration (same values of d/d_c) is nearly the same in all of the flow regions. The effect of the agitator is most pronounced for cavity No. 4. Here, agitation of the flow evidently leads to a certain decrease in size of the stagnation zones and to an increase in the percentage of the inside surface of the cavity occupied by the turbulent boundary layer. The slight effect of the agitator on the flow in cavity No. 5 is also evident from the figure. The character of Nu = f(Re) turns out to be the same for cavities of different dimensions in the presence of an agitator, the only difference being in the numerical values of the mass-transfer coefficients. These values are determined by the characteristic rotational velocity in the cavity.

The results of the above tests were generalized using the analogy of analysis of tests of mass transfer from an element of a filling in random packings. To this end, the test results were analyzed in the form of the criteria $Nu_e = \beta d_e/D$ and $Re_e = u_c d_e/\nu$, where $d_e = 4V/S_c$. As the characteristic velocity u_c, we used the mean velocity in the broad cross section of the cavity $u_c = \bar{u}S_{in}/S_b$.

The results of this analysis are shown in Fig. 4. It is apparent that the data for cavities with different ratios d/d_c, which stratified in the previous analysis (in relation to the values of d/d_c), now nearly coincide. The solid line on the graph shows the relation obtained from generalizing test data on mass transfer from a filling element in a random packing [7]. Our test data agree adequately with the data obtained for porous media. There is an element of conditionality to our determination of the characteristic velocity. The characteristic velocity $u_c = u/\varepsilon$ is used in analyzing tests in fillings. In our case, u_c is the mean-flow-rate velocity in the broad cross section of the cavity. The resulting agreement indicates that, with additional agitation of the flow, the character of flow in a single cavity and in a pore space in a filling is the same.

Thus, the following empirical relations (generalizing the results of our measurements) for the flow regions can be proposed to calculate mass exchange in axisymmetric cavities of different form:

laminar

$$Nu_e = 0.8\,Re_e^{0.5}Pr^{0.33},\quad 20 < Re_e < 180, \tag{2}$$

turbulent

$$Nu_e = 0.166\,Re_e^{0.8}Pr^{0.33},\quad 180 < Re_e < 3000. \tag{3}$$

It should be noted that, with superposed cavities, agitating rings, and agitating grates, the transitional zone is nearly absent and the above relations embrace the entire range of Re numbers from 20 to 3000. If there are no agitating elements, then the above formulas will give exaggerated values in the transitional zone (at $Re_e \sim 100$-300).

For approximate engineering calculations of mass-transfer coefficients in cavities of different configuration in the laminar and turbulent regions and with agitation of the flow throughout the Re range from 20 to 3000, the following relation, derived to calculate mass transfer from an element of a filling [7], can also be used:

$$Nu_e = 0.395\,Re_e^{0.64}Pr^{0.33}.$$

NOTATION

Nu, Nusselt number; Pr, diffusional Prandtl number; Re, Reynolds number calculated from the tube diameter; Pe, Péclet number; l, length of section; d, tube diameter; d_c, inside diameter of cavity; β, mean mass-transfer coefficient; V, volume of cavity; S_c, area of inside surface of cavity; u_c, characteristic velocity in cavity; $\bar{u}$, mean-flow-rate velocity in the inlet channel; S_{in}, cross-sectional area of channel; S_b, cross-sectional area in broad cross section of cavity; u, velocity calculated for the total cross section of a packed bed; ε, percentage of free volume of the packed bed; D, diffusion coefficient; ν, kinematic viscosity; Nu_e, equivalent Nusselt number; Re_e, equivalent Reynolds number.

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STUDY OF THE DRAG OF A THROTTLE IN THE FILM BOILING OF A CRYOGENIC LIQUID FLOWING IN A HORIZONTAL PIPE

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A one-dimensional model is used to calculate the parameters of a two-phase flow and generalize test data on discharge coefficients.

The flow rate of a coolant and its efficiency are determined in large part by the drag of throttling devices (rings, chokes, valves, etc.) installed at the outlet of a cryogenic system. It has been shown in cooling such systems, for example [1], that the rate of flow of the cryogen changes significantly over time. This is attributable to a change in the parameters of the two-phase flow — especially the volume and mass vapor contents — and a change in the discharge coefficient of the throttling devices during cooling. The parameters of the two-phase flow during the cooling of the pipelines of a cryogenic system can be calculated using a unidimensional mathematical model describable by the equations of hydrodynamics and closing relations on heat transfer and slip obtained for vertical pipes in [2, 3].

In the absence of control of coolant flow rate, a solution of the system of equations requires a closing relation to connect the change in the discharge coefficient with the change in the parameters of the two-phase flow. An attempt was made in [4] to obtain a relation to calculate the drag of throttling rings. However, in calculating the parameters of the flow at the ring inlet, the authors used a unidimensional flow model which did not allow for phase slip. It was shown in [2] that this model cannot be used to calculate cooling. Thus, test data on the discharge coefficients of throttling devices should be generalized using direct measurements of parameters of the two-phase flow at the device inlet or the results of calculations which take into account actual values of phase slip and heating of the liquid phase (when the temperature of the liquid is below the saturation temperature).

The present article describes results of a study of the discharge coefficients of throttles during the unsteady cooling of a horizontal pipe with hydrogen. The pipe was 70 mm in diameter and 3500 mm in length and had a wall 3 mm thick. The following parameters were recorded during cooling: the second-by-second flow rate of the liquid at the pipe inlet; the temperature of the liquid phase at four stations; the temperature of the wall of the pipe at five stations, using copper–constantin thermocouples (five thermocouples per station). We also measured the temperature at five other stations of the pipe wall on the top generatrix, using single thermocouples. Pressure in the pipe and the pressure drop at the throttle was measured with potentiometric pickups. The volume vapor content was measured by the radioisotope method at two stations 1650 and 2650 mm from the inlet. The measurement technique was described in [2].

Figure 1 shows the change in the basic parameters determined during cooling. It is apparent that the mass flow rate of the coolant changes significantly over time and depends on the pressure gradient at the throttle and the parameters of the two-phase flow.

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