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EXPERIMENTAL INVESTIGATION OF MASS TRANSFER FROM THE SURFACE OF A SPHERE UNDER CONDITIONS OF LARGE REYNOLDS NUMBERS AND CAVITATION ON THE SURFACE

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UDC 66.015.23

The article studies mass transfer from the surface of a sphere when a liquid flows around it under conditions of Reynolds numbers 10^3 - $5 \cdot 10^5$, and also when a cavitation cavern forms behind the sphere.

Article [1] contains the theoretical and experimental investigation of the process of mass transfer from the surface of a sphere under conditions of small Reynolds numbers. By proceeding from the concept of the laminar boundary layer, it was possible to calculate theoretically the mass transport from the frontal part of the surface of a sphere, and eventually the averaged mass transfer coefficient. It was determined by the equation

$$\mathrm{Nu} = A\,\mathrm{Pr}^{0.33}\,\mathrm{Re}^{0.5},\ A = 0.8\text{–}0.95. \tag{1}$$

Equation (1) satisfactorily sheds light on the experimental data in the range Re = 10^2 - 10^4 [2].

Later investigations of the hydrodynamics behind a sphere [3] established that there exists a boundary layer similar to the laminar layer with Re = 60 - 410, thereby confirming the correctness of Eq. (1). The subsequent investigations [4] revealed that with increasing Reynolds number the role of the stern part of the sphere in the process of mass transfer assumes greater importance, and when $R > 10^4$, it becomes dominant. It is assumed that the cause of this is the transition to turbulence of the boundary layer behind the sphere, whereas on the frontal part the flow in the boundary layer is laminar. This led to the construction of binomial equations of the type

$$\mathrm{Nu} = \mathrm{Pr}^{0.33}\,(0.51\,\mathrm{Re}^{0.5} + 0.0244\,\mathrm{Re}^{0.78}). \tag{2}$$

This equation is correct for Re = 200 - 200,000 [4]. The present work represents an attempt at establishing the regularities if mass transfer from the surface of a sphere when the Reynolds numbers are larger than the investigated range.

The experiments were carried out with an installation whose diagram is shown in Fig. 1. Water from reservoir 1 is supplied by pump 2 to the glass pipe 5 with 0.1 m diameter in which were placed spherical particles of 0.025 m diameter made of powdery benzoic acid pressed under pressure of 10 MPa. The water in the reservoir was thermostatted. The temperature was 292±0.5°K.

The installation ensured the possibility of arranging for a lengthy flow around a spherical specimen lasting 60 - 900 sec at speeds of the liquid 0.1–20 m/sec. The mass transfer coefficient was determined from the loss weight of the specimen before and after the experiment. The flow of liquid through pipe 5 was checked by the induction flow meter 4.

To provide uniform turbulence in the flow around the sphere, screens were placed in front of the sphere. The first screen 6 with wire diameter $1.5 \cdot 10^{-3}$ m and mesh size $4 \cdot 10^{-3} \times 4 \cdot 10^{-3}$ m was mounted at a distance of 0.44 m from the sphere, and the second screen 7 with wire diameter $5 \cdot 10^{-4}$ m and mesh size $8 \cdot 10^{-3} \times 8 \cdot 10^{-3}$ m was mounted at a distance of 0.25 m from the sphere.

The results of the experiments are presented in Fig. 2. It can be seen from the figure

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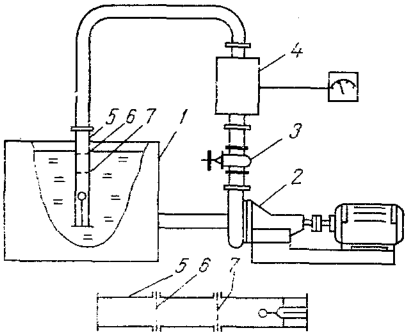

Fig. 1

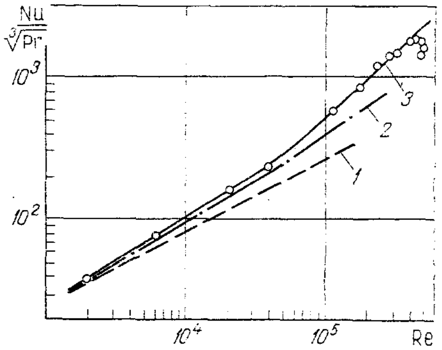

Fig. 2

Fig. 1. Diagram of the experimental installation: 1) reservoir; 2) pump; 3) valve; 4) induction flow meter; 5) glass pipe; 6, 7) screens.

Fig. 2. Data on the kinetics of dissolution of a single sphere: 1) according to Eq. (1); 2) according to (2); 3) experimental data.

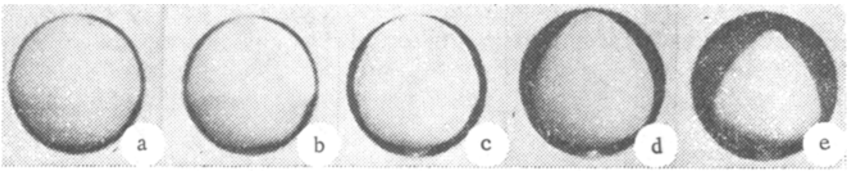

Fig. 3. Change of shape and dimensions of spheres made of benzoic acid when water flows around them for 15 min: a) Re = $0.85 \cdot 10^5$; b) $1.2 \cdot 10^5$; c) $2.8 \cdot 10^5$; d) $3.6 \cdot 10^5$; e) $4.2 \cdot 10^5$.

that with increasing Reynolds numbers the obtained results are not described by the presented equations. The deviations are particularly large in the range Re > 10^5. It may be assumed then that new effects originate in the process of flow around the sphere. To reveal these effects, the spheres were photographed after water had flown around them for 15 min with different Reynolds numbers. The photographs of these spheres are shown in Fig. 3 (before dissolution, the diameter of the sphere was the same as the gauge diameter).

It is known [5] that with moving to the stern part of the sphere, the thickness of the boundary layer on it increases up to the line of detachment, which at Re > 1000 lies approximately on the line corresponding to the angular distance $\varphi = 90°$. What has been said is well confirmed by the data on the dissolution of spheres under conditions of small Reynolds numbers presented in [1]. With increasing Reynolds numbers, the boundary layer behind the line of detachment becomes turbulent, but the position of the line of detachment does not change (see Figs. 3a, b). When Re = Re_{cr}, the boundary layer becomes turbulent, and on the front part of the sphere the line of detachment shifts toward the stern, corresponding to an angular distance $\varphi = 110°$ [5]. Figures 3c, d, e show the pattern of mass transfer from the surface of the sphere under these conditions. Thus, the increase of the mass transfer coefficient with Re = $1.2 \cdot 10^5$ - $1.5 \cdot 10^5$ is due to the transition to turbulence of the boundary layer on the front part of the sphere and the corresponding thinning of the diffusion layer. Curve 3 in Fig. 2 in the range Re = $0.6 \cdot 10^5$ - $4 \cdot 10^5$ can be described by the equation

$$Nu = 0.00165\, Pr^{0.33}\, Re^{0.9}. \qquad (3)$$

During the experiments it was noted that with Re = $3 \cdot 10^5$ a small unsteady cavern formed in the wake behind the sphere; with increasing Reynolds number this cavern became gradually filled with a vapor—air mixture, and at Re = $4.7.10^5$ it became steady; this was accompanied by an abrupt decrease of mass transfer as a result of the loss of contact between the stern part of the sphere and the liquid. The last four points of curve 3 in Fig. 2 correspond to the process of dissolution of the sphere under conditions of cavitation. Unfortunately, it proved impossible to photograph the sphere dissolving under conditions of developed cavitation with the formation of a steady cavern similar to Fig. 3, because under these conditions the sphere is subject to strong vibrations and is destroyed within 1.5—2 min, a time that is too short for visible changes of its shape to be observed.

NOTATION

Re = wd/ν, Reynolds number; Pr = ν/D, diffusion Prandtl number; φ, angle between the frontal critical point and the point of detachment of the boundary layer; w, speed of the incoming flow; d, diameter of the sphere; ν, kinematic viscosity of the liquid; D, diffusion coefficient.

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PORE MOTION AND CHANGE OF SHAPE IN A TEMPERATURE FIELD BECAUSE OF EVAPORATION AND CONDENSATION PROCESSES

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UDC 536.422

Mass transfer in a vacuum spherical and cylindrical pore due to evaporation and condensation of the wall material in a temperature gradient field is examined on the basis of a molecular—kinetic analysis.

The temperature gradient over a pore section causes transport of the wall material and results in the origination of directional pore motion. A number of mass transport mechanisms exist that cause such motion. An analysis of different motion mechanisms and conditions under which some one is dominant can be found in [1]. The governing mass transfer mechanism for large-scale vacuum pores at high temperatures is transport through the pore volume, i.e., recondensation; hence, mass transfer occurs in the free-molecule regime in a solid with low saturated vapor pressure. This regime was investigated in a vacuum pore in a number of papers [1-3], in which, however, a macroscopic description of the mass transport is used, and only the case of small temperature gradients over the pore section is examined. The kinetic approach used in this paper has a number of advantages as compared to the macroscopic description, since it permits refinement of the velocity of pore motion, the consideration of the mass transport for an arbitrarily given wall-temperature distribution (usually the case when a constant temperature gradient exists far from the pore is considered), and also nonlinear problems, and the clarification of the nature of the change in its shape.

Let us examine the mass transfer in a spherical pore and a cylindrical channel whose wall temperature is constant along the channel axis z. We shall assume that both the evaporating and the reflected molecules have a Maxwell velocity distribution, a condensation factor β independent of the temperature, and isotropic pore-surface characteristics. Under these assumptions, the expression for the mass flux density incident on the pore surface at the point r is written analogously to what is done for free-molecular flow around bodies with concavities [4]:

$$q(\mathrm{r}) = \sqrt{\frac{m}{2\pi k}}\,\beta \iint_S \frac{P(\mathrm{r}_1)}{\sqrt{T(\mathrm{r}_1)}}\,G(\mathrm{r}\;\mathrm{r}_1)\,d\mathrm{r}_1 + (1-\beta)\iint_S q(\mathrm{r}_1)\,G(\mathrm{r}\mathrm{r}_1)\,d\mathrm{r}_1, \tag{1}$$

where P(r) is the saturated vapor pressure of the pore wall material at the temperature T(r).

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