INVESTIGATION OF THE EFFECT OF ULTRASONIC VIBRATIONS ON MASS TRANSFER FROM A SPHERE, WITH LARGE PRANDTL NUMBERS

A. M. Boldarev, A. P. Burdukov,
V. E. Nakoryakov, and V. I. Sosunov

The article presents the results of an experimental investigation of the effect of ultrasonic vibrations on mass transfer from a sphere at large values of the Prandtl number. An electrochemical method was used to measure the mass-transfer coefficient.

The results of the experimental investigation are compared with a theoretical dependence obtained earlier in [1].

Transfer processes between a solid body and a liquid or gaseous medium are considerably accelerated with a relative vibrational motion of the body and the medium.

A number of experimental investigations by Soviet and foreign authors [1-4] have been devoted to the question of heat and mass transfer from solids of simple form in a field of acoustic vibrations. A detailed review of investigations carried out up to 1960 is given in [4].

The concepts with respect to the mechanism of the action of sonic vibrations on transfer processes, put forward by various authors, are rather contradictory.

In [1] a theoretical dependence of the mass-transfer coefficient on the parameters of the sonic field was derived. In the solution of this problem, the following assumptions were made:

1) The wave lengths of the sonic vibrations, λ, are much greater than the radius of the sphere, $\lambda \gg R$;

2) the ratio of the amplitude of the displacement, s, to the radius of the sphere, R, is either much less than unity, $s/R \ll 1$, or much greater than unity, $s/R \gg 1$;

3) the Grashof number approaches zero, $G \to 0$.

With the limitations adopted, for mass transfer from a sphere, in [1], for the averaged mass-transfer coefficient (the Nusselt number, constructed with respect to the diameter of the sphere, d, the following formula was obtained

$$N = 0.832 \left(\frac{B^2 R}{\sqrt{\omega\nu}\, D}\right)^{1/3} \qquad \left(\frac{s}{R} \ll 1\right) \tag{1}$$

Here B is the amplitude of the vibrational velocity; ω is the cyclic frequency; ν is the kinematic viscosity coefficient; D is the diffusion coefficient.

The purpose of the present investigation was an experimental verification of the theoretical dependence describing heat- and mass-transfer processes with a vibrational motion.

The investigation of the effect of ultrasonic vibrations on mass transfer from a sphere at large Prandtl numbers was carried out in a unit, a schematic diagram of which is shown in Fig. 1. In this schematic diagram, 1 is a high-voltage rectifier; 2 is an ultrasonic generator; 3 is a source of sound; 4 is a USh-2

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 133-135, March-April, 1971. Original article submitted January 4, 1970.

© 1973 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for $15.00.

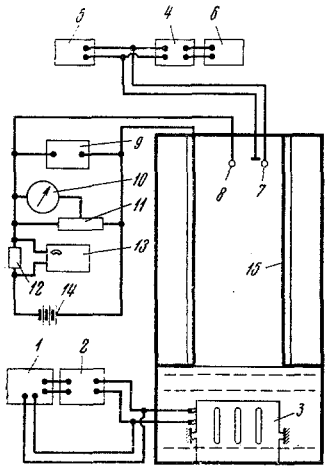

Fig. 1

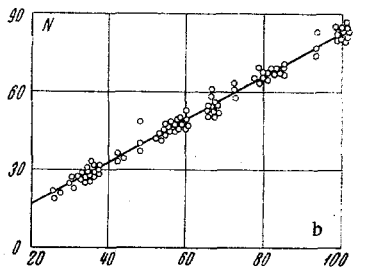

Fig. 2

broad-band amplifier; 5 is a vacuum voltmeter; 6 is an SI-7 oscillograph; 7 is a piezoelectric pickup; 8 is a nickel sphere (the cathode); 9 is a VLU-2 vacuum voltmeter; 10 is an M1104 milliammeter; 11 is a variable resistance; 12 is a standard resistance; 13 is an R2/1 potentiometer; 14 is a source of direct current; 15 is the anode.

An electrochemical method was used to measure the dimensionless mass-transfer coefficient. The electrochemical method, described in a number of articles, is based on the following electrochemical reaction, controlled by diffusion [5]

$$Fe(CN)_6^{3} + e^{-} \rightleftarrows Fe(CN)_6^{4}$$

The oxidation-reduction system $K_3Fe(CN)_6/K_4Fe(CN)_6$ is convenient because of the fact that the electrochemical reaction takes place in the diffusion region over a wide range of parameters, because no deposits are formed on the electrodes, and, finally, because none of the components of the system are consumed; consequently, the composition of the system can remain constant over the course of a long period of time.

With the presence of an electrical potential between the anode and the cathode, the area of the anode is taken many times greater than the area of the cathode, to avoid polarization of the anode; the electrochemical reaction proceeds on their surface in accordance with the above scheme. The current in the cathode circuit is proportional to the number of ions reacting in the circuit in unit time; this, in turn, is determined by the rate of supply of the reacting ions to the surface of the sphere and by the rate of removal of the reaction products from the sphere as the result of convective and molecular diffusion.

Thus, the current in the cathode circuit is a quantitative measure of the rate of the mass-transfer process on the surface of the body under investigation.

Under the conditions of a limiting diffusional current, the rate of the reaction at the cathode is determined by the rate of mass transfer between the surface of the cathode and the flow of electrolyte; under these circumstances, the flow of mass, q, is connected with the value of the limiting current, I, by the relationship

$$q = IM / F$$

Here M is the molecular weight; F is the Faraday number. For the mass-transfer coefficient we thus have

$$\beta = \frac{I}{FS(c_\infty - c)}$$

Here S is the area of the cathode (the sphere); c is the concentration of the electrolyte. Under conditions of a limiting diffusional current, as the result of polarization the concentration of ions at the cathode is equal to zero; therefore, for the dimensionless mass-transfer coefficient we have

$$N = \frac{Id}{FSc_\infty D}$$

Consequently, the problem of determining the dimensionless mass-transfer coefficient from a sphere has been reduced to measurement of the value of the current in the cathode circuit under the given flow conditions. The electrolyte was a solution of the salts of ferri-and ferrocyanide, $K_3Fe(CN)_6$ and $K_4Fe(CN)_6$, with a 0.001-0.01 N concentration. To eliminate the effect of the migration of ions on the value of the electric current, foreign ions in the form of caustic soda with a concentration of 0.5-2N were added to the electrolyte. By varying the concentration of caustic soda it is possible to obtain liquids with different values of the diffusion Prandtl number; in the present investigation, the Prandtl number P = 2200.

In view of the possibility of oxidation in air and of decomposition of the $K_3Fe(CN)_6$ salt, a new solution of electrolyte was prepared each time, and its concentration was measured before and after an experiment. By thermostatting of the working volume of the liquid during the experiments the temperature of the electrolyte was maintained constant and equal to t = 25°C.

The experimental method consisted in the following. The sonic emitter was installed in the vessel with the liquid at a determined distance; on a special base, parallel to the plane of the emitter, there was installed a flask with the electrolyte into which, using a positioning device, there were inserted the sphere being investigated (the cathode) and a piezoelectric pickup for measuring the intensity of the ultrasonic vibrations.

The current in the cathode circuit was measured with an M1104 milliammeter, class 0.2. The voltage between the cathode and the anode was measured using a vacuum voltmeter with a large internal resistance.

The frequency of the ultrasonic vibrations was measured and monitored in a SI-7 double-beam electronic oscillograph.

The sources of ultrasonic vibrations were magnitostrictive and quartz emitters, making it possible to obtain a sound of sufficiently high intensity, from 5 to 30 W/cm^2, respectively.

The main parameters of the experiment were varied within the following limits: the frequency of the ultrasonic vibrations from 20 kHz to 1 MHz; the diameter of the sphere from 1.5 to 6 mm; the Prandtl number from 2000 to 2300.

The results of the experimental investigation of mass transfer from a sphere are presented in Fig. 2, where $b = B^{2/3} R^{1/3} (\omega \nu)^{1/6} D^{1/3}$; the theoretical dependence (1) satisfactorily correlates the experimental results.

From the results of the present work it follows that the mechanism proposed earlier [1] for mass transfer, with large values of the Prandtl number and a small value of the ratio of the amplitude of the displacement of the medium to the radius of the sphere, is determined by the laws governing the internal region of secondary flows.

The data obtained can be used for evaluation of the effect of vibrations on mass-transfer processes in liquid media.

LITERATURE CITED

1. A. P. Burdukov and V. E. Nakoryakov, "The effect of vibrations on mass transfer from a sphere at large Prandtl numbers," Zh. Prikl. Mekhan. i Tekh. Fiz., No. 3 (1967).
2. B. M. Grafov, "Calculation of diffusional flow to a vibrating electrode," Élektrokhimiya, 3, No. 8 (1967).
3. F. K. Deaver, W. R. Penney, and T. B. Jefferson, "Heat transfer from an oscillating horizontal wire to water," Trans. ASME, Ser. C. J. Heat Trans., 84, No. 3 (1962).
4. R. M. Fand and J. Kaye, "The influence of sound on free convection from a horizontal cylinder," Trans. ASME, Ser. C., J. Heat Trans., 83, No. 2 (1961).
5. B. M. Smol'skii, V. I. Popov, and N. A. Pokryavailo, "Experimental investigation of the unsteady-state mass transfer of a flat plate, around which flows an incompressible liquid at different angles of attack," in: Heat and Mass Transfer Vol. 1 [in Russian], Izd. Énergiya, Moscow (1968).