

PULSATION CHARACTERISTICS OF THE PROCESS OF MASS EXCHANGE BETWEEN A
SOLID SPHERICAL PARTICLE AND A TURBULIZED LIQUID

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To intensify the process of mass exchange at an interface between liquid and solid phases, as a rule, one creates conditions such that the liquid is in a turbulent regime. Revealing the laws of mass transfer under these conditions makes it possible to choose the optimum regime of operation of a chemical apparatus, i.e., obtain the maximum coefficients of mass transfer for small energy costs. Vessels in which the liquid is mixed with agitators of the turbine or vane type are used as the working apparatus in industry. For this reason, many investigators occupied in studying mass-exchange processes in a liquid-solid system have fully modeled the actual conditions [1-4]. Another group includes papers in which mass exchange was studied in the flow of a liquid stream over a single spherical solid particle in channels of different configurations [5-10]. Two main methods used to study mass-exchange processes can be distinguished: dissolving solids in liquids [1-5, 9] and the electrochemical method [6-8, 10]. The first method is used only to obtain average values of the mass-exchange coefficient, and it is also characterized by variation of the shape and size of the investigated particles, which considerably lowers the accuracy of the results obtained. The electrochemical method has now become very popular; it provides a high measurement accuracy and also makes it possible to investigate both the integral and the pulsation characteristics of a process, which is important for systems in which the liquid is in a turbulent regime. In [11] the problem of mass exchange of a turbulent liquid with a plane wall was considered and the question of correlations between pulsations of the liquid velocity and the mass-transfer coefficient on the basis of a spectral analysis was discussed. It was shown that in a turbulent regime of flow over the wall, the shape of the power spectrum of pulsations of the mass-transfer coefficient does not depend on the Reynolds number, whereas a strong influence of the Schmidt number on the frequency of pulsations of the mass-transfer coefficient was noted. No noticeable influence of a change in the size of the electrode on the form of the spectral energy density of pulsations of the mass-transfer coefficient was found. Thus, the application of spectral analysis to the interpretation of results obtained using the electrochemical method to study mass-exchange processes allows one to estimate sufficiently precisely the influence of one or another factor on the process being studied. In the present paper a similar approach is used to study mass exchange between a fixed spherical solid particle and a turbulized liquid.

Experimental Setup and Measurement Procedure

The measurements were made on an experimental setup, the general form of which is presented in Fig. 1. The working section consists of a plastic vessel 1 with dimensions of 230 × 230 × 500 mm, filled with liquid to a fixed mark. The source of the disturbances is an oscillating grid 2, located in the upper part of the vessel and set into motion with a special device 3 consisting of two dynamic heads of type 25GD-26. The signal from a sinusoidal voltage generator 5 was fed to the device 3 through a power amplifier 4. A frequency meter 6 and an oscillograph 7 served to measure the frequency f and monitor the form of oscillations of the oscillating grid. The amplitude and frequency of the oscillations were varied in the ranges $a = 2-11$ mm and $f = 5-20$ Hz, respectively. The spherical electrochemical electrode - the cathode 8 with a diameter $d = 0.57$ mm - was made of platinum and simultaneously was the investigated particle. An aqueous solution of potassium ferri- and ferrocyanide with the addition of a neutral electrolyte to reduce the migration (under the action of the electric field) of diffusing ions was used as the working liquid. The current of the electrochemical sensor was amplified with a direct-current amplifier 9, which also provided a supply of bias voltage to the sensor for operation in the regime of a limiting diffusional current. The output voltage of the amplifier, proportional to the instantaneous value of the diffusional

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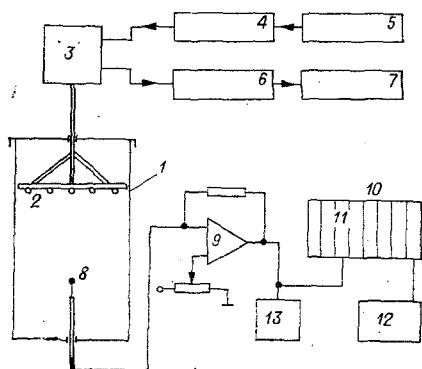


Fig. 1

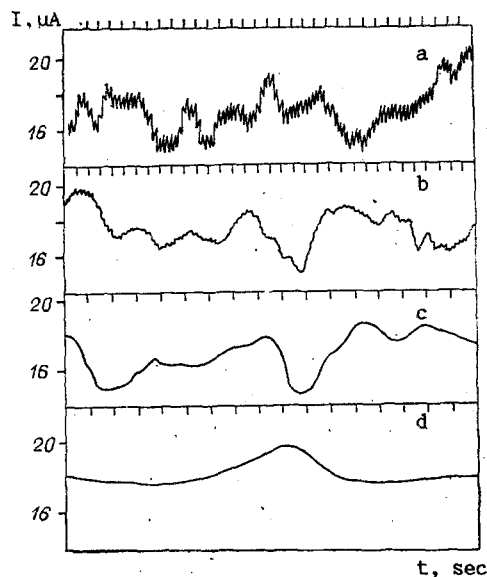


Fig. 2

current of the sensor, was fed to an ATsP-118 analog-to-digital converter 11 mounted in a KAMAK crate 10. The signal converted to digital form was processed in an Elektronika-60 M computer 12. The output signal of the amplifier was monitored visually with an S1-70 oscillograph 13. The frequency of quantization of the signal was varied in the range of 100-1000 Hz, depending on the regime and the position of the sensor. The spectral density was calculated by the method of a fast Fourier transform of the original realization [12]. The package of FFT programs developed at the Institute of Automation and Electrometry, Siberian Branch of the Academy of Sciences of the USSR, was used. The length of one realization was 512 points. The calculated spectral density was averaged over an ensemble of realizations numbering 20-50. Such averaging assured good reproduction of the measurement results in all the investigated regimes. The results of the calculations were put out on a color graphic display and plotted in logarithmic coordinates with an N-306 graph plotter. The integral coefficient of mass exchange between the spherical electrode and the liquid is determined from the equation

$$\beta = I/(FAc)_s$$

where I is the diffusion current; F is the Faraday constant; A is the area of the electrode; c is the concentration of potassium ferricyanide ions.

The measurements were made following a certain time after the grid was set into oscillation, required to establish a steady regime. In [13] it was shown that initially there is an increase in the intensity of the mean-square pulsations of velocity and then it decreases to a constant value. The dimensionless time of establishment of the steady regime is $\tau = ft = 5000$. In our experiments the establishment of a steady regime was monitored by measuring the average coefficient of mass transfer from the sensor.

In Fig. 2 we give recordings on a loop oscillograph of the diffusion current of the electrochemical sensor for the regime with $f = 15$ Hz and $a = 7.5$ mm at distances $h = 5, 10, 100,$ and 200 mm from the lower edge of the oscillating grid (a-d, respectively). It is seen that the variation of β has a pulsating character. With an increase in the distance from the oscillating grid, the amplitude of the pulsations of β varies little, whereas the frequency of the pulsations decreases by an order of magnitude. The time marks in Fig. 2a and b are 0.2 sec while those in Fig. 2c and d are 2 sec. In the immediate vicinity of the oscillating grid one observes a wide range of pulsation frequencies, from the highest, equal to the frequency of the oscillating grid, to the lowest, with characteristic frequencies of several hertz. The frequency of the oscillating grid can be distinguished clearly. In the lower part of the vessel, occupying two-thirds of the entire liquid volume, the characteristic frequency of pulsations of the mass-transfer coefficient is less than one hertz. Therefore, an analysis of the energy of turbulent pulsations of the coefficient β in the part of its distribution over different frequencies observed in the pulsations is of great interest.

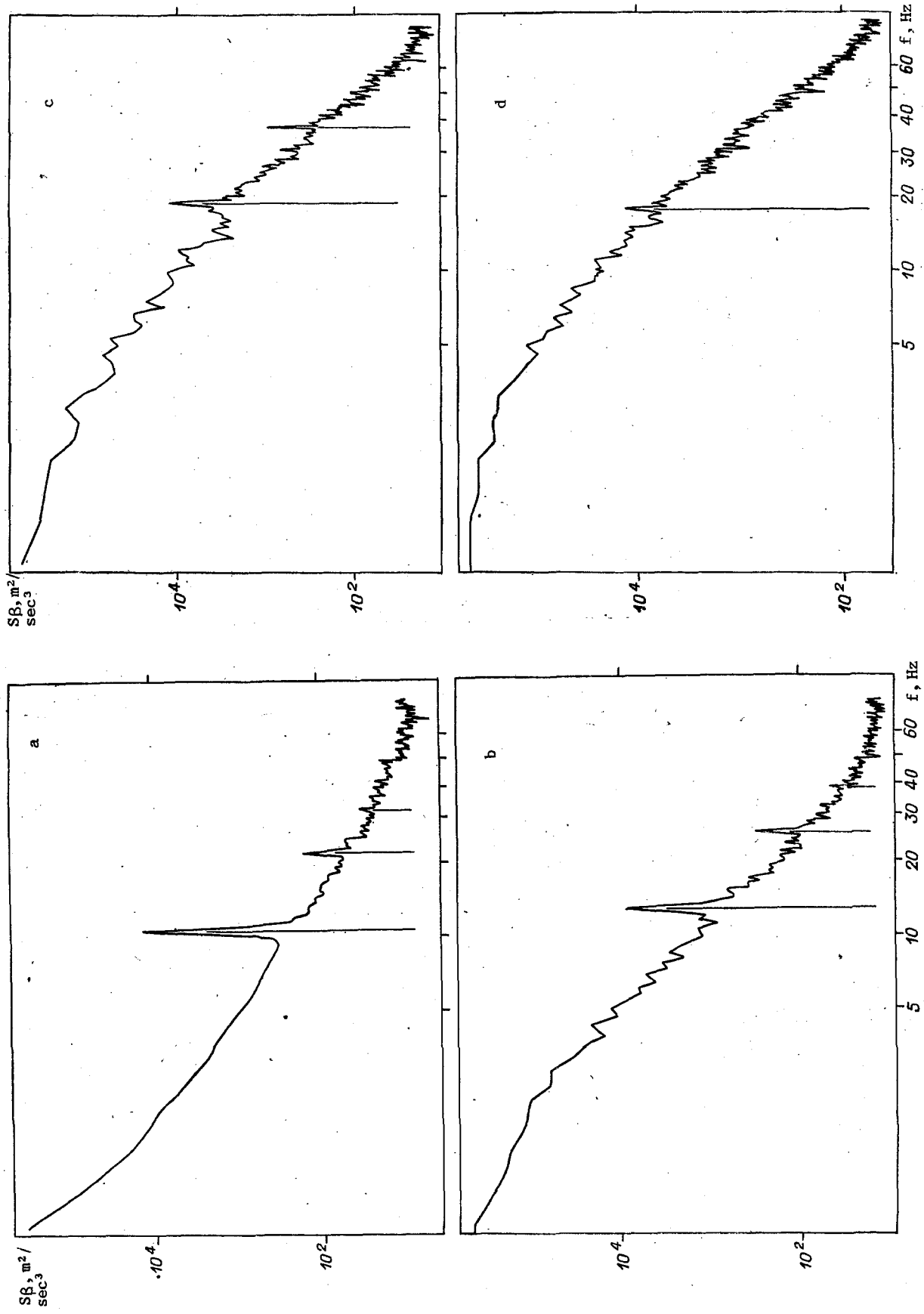


Fig. 3

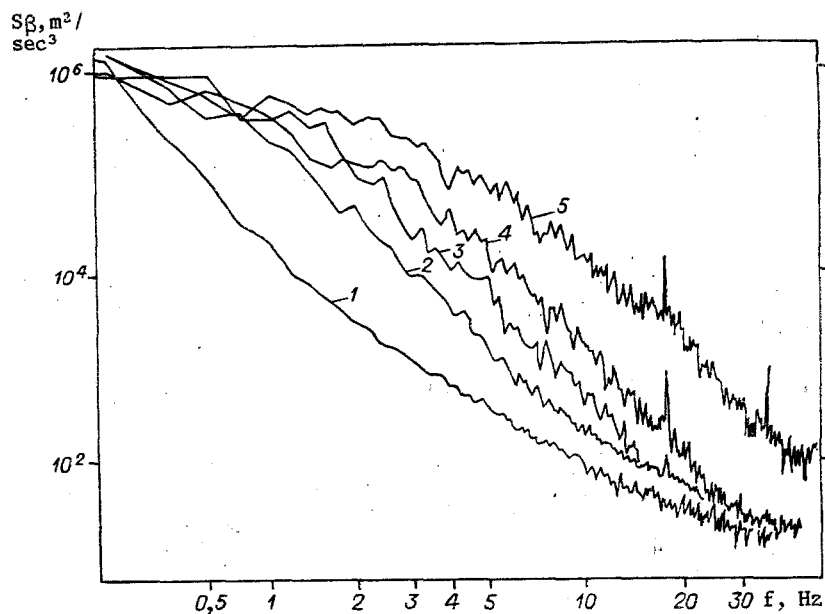


Fig. 4

Discussion of Results

The spherical electrochemical sensor used in the work is insensitive to the direction of flow. The mass-transfer coefficient measured by such a sensor is not connected with any one component of pulsations of the liquid velocity. Nevertheless, there is no doubt that fluctuations of this quantity are due to the movement of vortex structures in the liquid and correctly characterize the structure of the liquid turbulence as a whole. With an increase in the size of the electrode, the ratio of the intensity of the pulsations to the average value decreases owing to effects of averaging of the mass transfer over the surface of the sphere. The measurement of pulsations of the coefficient β by a small sensor, the size of which is much less than the characteristic sizes of the structural formations in the liquid, yields quantitative information about the pulsation structure of the liquid flow; this method is one of the simplest and most convenient in investigations of highly turbulized flows with a zero or a low average velocity in comparison with the pulsations. Despite the relatively large size, the frequency characteristic of the sensor is sufficient to record the highest frequencies in the spectrum, equal in order of magnitude to the frequency of the oscillating grid.

In Fig. 3a-d we present graphs of the spectral power density S_β of pulsations of the coefficient of mass exchange between a solid spherical particle and a turbulized liquid, measured at a distance of 3 mm from the lower edge of the oscillating grid, for different values of the power expended on mixing the liquid, with $a = 3, 7, 8,$ and 9 mm and $f = 11, 13, 19,$ and 18 Hz, respectively. It is seen that with an increase in power there is a continuous change in the shape of the spectrum: It becomes ever fuller and at the highest frequencies of the oscillating grid it acquires a form characteristic for flows with developed turbulence. The fundamental frequencies defined by the oscillating grid are clearly distinguished in the spectrum in the entire investigated range of variation of the determining parameters. In addition, multiple harmonics of the fundamental frequency can be distinguished. The multiple harmonics disappear with an increase in the mixing intensity, and this process is accompanied by a relative decrease in the power of the multiple harmonics against the background of the main spectrum. With an increase in the frequency of the oscillating grid, and hence in the energy applied to the liquid volume, an ever greater number of intermediate frequencies are excited, and there is a redistribution of energy from low-frequency to high-frequency disturbances. This agrees well with the time recordings of the diffusion current in Fig. 2.

In Fig. 4 we show graphs of S_β for $h = 300, 70, 30, 15,$ and 5 mm (lines 1-5) and data for one regime with $f = 18$ Hz and $a = 9.2$ mm. It is seen that with an increase in the distance from the oscillating grid, the spectrum becomes narrower, i.e., the contribution of high-frequency pulsations of the coefficient β to the process of mass exchange between the solid spherical particle and the liquid becomes ever smaller. This is evidently a consequence

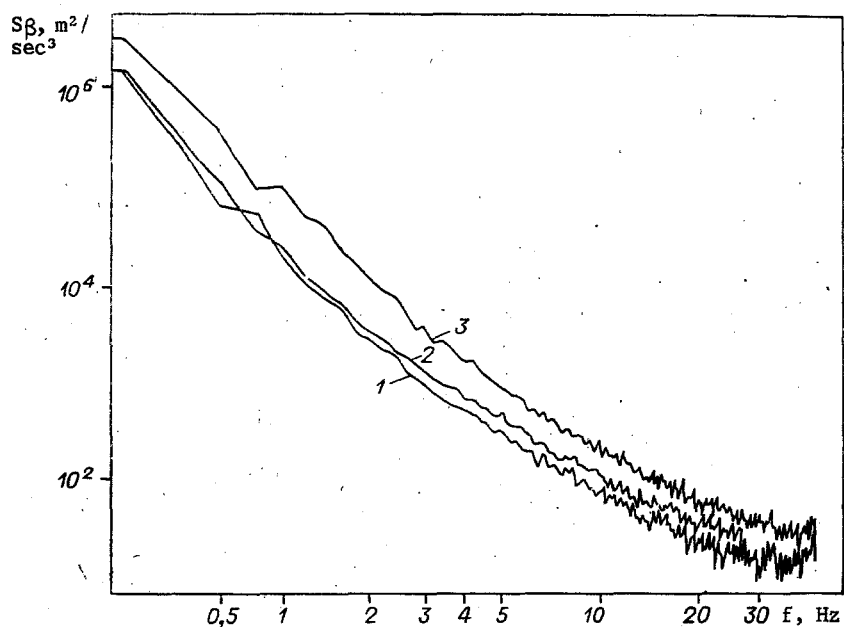


Fig. 5

of the fact that small-scale, high frequency disturbances generated in the liquid by the oscillating grid already dissipate in the immediate vicinity of the grid, since they propagate in a highly turbulized medium. The larger low-frequency disturbances, having the highest energy, propagate through the entire volume. Therefore, the spectrum measured at distances of more than 100 mm has high values of S_{β} only in the low-frequency part (Fig. 4).

Thus, the entire volume of the liquid mixed with the oscillating grid can be divided into two parts: a region where the form of the spectrum undergoes a sharp change and a region in which the form of the spectrum remains unchanged. The first region is located near the oscillating grid and occupies about a third of the entire volume. The second region occupies the remaining two-thirds. In Fig. 5 we give graphs of the spectral power density of pulsations of the coefficient β measured in the second region for $h = 300, 150,$ and 100 mm (lines 1-3). Despite the quantitative disparity, these spectra are similar, i.e., their form remains unchanged. It should be noted that the graphs differ little quantitatively. In [11] it is noted that quantitative agreement does not exist between the fluctuations of liquid velocity and the fluctuations of the mass-exchange coefficient, but there is qualitative similarity between the power spectra of the respective quantities. On this basis we can conclude that in the second region there are only low-frequency, large-scale vortex formations that vary little in size.

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DETERMINATION OF FLOW VELOCITIES CAUSING BLOWING AND MOVEMENT OF SOLID PARTICLES

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In pneumatic transport and also in air cleaning of various surfaces it is often necessary to move, blow off, wash off, different solid particles of granular materials, soils, sands, icicles, and other loose materials.

Under actual conditions solid particles at a surface with flow over it change their condition depending on the velocity of the running flow. There are numerous experimental data for determination of critical velocities, but there is no single procedure. Authors record the process of blowing away (washing off) in different ways on the basis of visual observation of the condition of particles under the action of a flow [1].

We call critical those values of velocity for undisturbed flow outside the boundary layer of a surface with flow around it under whose influence the condition of solid particles changes. We designate in terms of u_1^* the velocity when particles are in a limiting equilibrium condition, i.e., they may complete oscillatory-translational motion by a distance not more than their diameter without separating from the surface, m/sec; u_2^* when separating (washing away) of individual particles is observed, m/sec; u_3^* , when there is mass blowing way (washing away) of solid particles, i.e., erosion starts to develop. Corresponding to these velocities, values of Reynolds's number for average particle diameter are designated in terms of $Re_1^* = u_1^*d/\nu$, $Re_2^* = u_2^*d/\nu$, $Re_3^* = u_3^*d/\nu$.

Existing methods for determining these critical velocities reflect insufficiently the change in condition of solid particles under the action of flow. Also there has been little study of the intensity of the wear of solid particles under the action of a given (critical) flow velocity.

A semiempirical method is provided here for determining critical flow velocities under whose action these states set in for solid particles of a certain size and density. For this purpose experiments were carried out in aerodynamic units at the M. T. Urazbaev Institute of Mechanics and Seismic Stability of Structures, Academy of Sciences of the UzbSSR. An aerodynamic tube of the open type of rectangular cross section in the operating section at the outlet of the nozzle 0.2×0.3 m operated on a forced air stream. Use of a GM (generator-motor) electric circuit made it possible to control the running flow velocity from 0 to 40 m/sec. An experimental plate with sharp edges 0.6 m long was set up at a height of 0.07 m from the lower wall of the working section so that the wind stream flowed smoothly over the plane surface. A groove 0.06 m wide and 0.006 m deep was made at a distance of 0.3 m from

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