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HYDRODYNAMICS AND HEAT TRANSFER IN THE VOLUME OF A UNIFORM LIQUID WITH INDUCED TURBULENCE

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UDC 532.517.4+536.242

Many processes in chemical engineering are based on mass transfer between solid particles and a fluid. Mass transfer can be intensified by producing an organized average motion of the fluid or by agitating the latter. An increase in the level of turbulence in the fluid is an effective means of increasing the mass-transfer coefficient. The problem of determining the flow of a highly turbulent flow about a particle is extremely complex, and the literature presently contains very little information on the mechanism of turbulent transport and, in general, the effect of turbulence on transport processes.

One of the simplest methods of developing a high turbulence intensity is agitating the fluid in a vessel with an oscillating grid. Several studies have examined the fluid dynamics of such a flow. In these investigations, the frequency of oscillation of the grid ranged within f = 1-6 Hz. It was shown in [1] that after the grid is induced to move in the measurement volume — located a certain distance from the grid — the RMS fluctuations of fluid velocity

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 78-84, March-April, 1987. Original article submitted January 20, 1986.

 0021-8944/87/2802-0236$12.50

initially increase sharply and then slowly decrease in a steady value. The dimensionless time until establishment of the steady-state regime

$$\tau = ft \simeq 5000. \quad (1)$$

Measurements made in [2, 3] under steady-state conditions for the same frequency range showed that the RMS fluctuation velocity u depends on the distance to the oscillating grid z and the frequency and amplitude S of the grid vibrations. However, this dependence is disturbed with an increase in grid vibration frequency to 10 Hz, and the value of u becomes constant [4]. It is therefore of definite interest to study the behavior of u with a further increase in grid vibration frequency.

It can be concluded from the data in [3, 5] that the agitated fluid is isotropic at a distance of ony 50-60 mm from the grid. It should be noted that no previous studies have been made of the laws of mass transfer between a solid spherical particle and an agitated fluid by the above-described method. Units with mixers [6] are most often used for mass-transfer processes, while grids and porous plates [7] placed in channels containing the flowing fluid are sometimes used to agitate the flow.

Experimental Unit and Method of Measurement. The experimental unit 8 (Fig. 1) was an organic glass vessel measuring 230 × 230 × 500 mm. The vessel was filled with the working fluid (electrolyte) to a fixed level of 430 mm. A grid made of nickel pipes 3.6 mm in diameter was placed in the top part of the vessel 70 mm from the surface of the fluid. The size of the cells in the grid was 35 × 45 mm. The experimental unit was described in greater detail in [8]. Turbulent pulsations were created in the liquid by subjecting the grid to sinusoidal vibrations. The frequency and amplitude of these vibrations ranged within f = 6-20 Hz and S = 1.5-11 mm, respectively. By the amplitude, we mean the distance between the two extreme positions of the grid. The rate of mass transfer was measured by the electrochemical method with the use of a spherical transducer [9] 0.55 mm in diameter. The mass-transfer coefficient β is determined from the formula

$$\beta = I/(FAc), \quad (2)$$

where I is the diffusion current; F is the Faraday constant; A is the area of the transducer – a sphere; c is the concentration of ions of potassium ferricyanide.

The RMS fluctuations of the horizontal component of velocity u were measured with a Doppler–laser velocity meter (DLVM) constructed by a differential scheme with backscattering (Fig. 1). The power of the argon laser 1 was varied in the tests from 70 to 130 mW. The optical–acoustic shift cell 4 installed in one arm of the beam splitter 3 shifted one of the beams 40 MHz, which made it possible to determine the velocity and to work with large angles between the velocity vector and its horizontal component. The collimator 2 was used to compensate for the divergence between the laser beam and its focusing in the measurement volume. The module containing the detecting optical system 7, with field stops for spatial filtration of the scattered radiation, was installed between the shift cell and the beam widener 5. A measurement volume 35 μm in diameter and 8 mm long was formed in the focal plane of the focusing lens 6, with an angle of beam intersection $\alpha \simeq 3.2°$. As the scattering particles we used the natural turbidity of the working fluid – the electrolyte.

The Doppler signal obtained from the output of the photomultiplier was analyzed simultaneously tracking and counting blocks. The analog signal from the tracking demodulator – a spectrum analyzer [10] developed by the ITF SO AN SSSR (Institute of Thermophysics, Siberian Branch of the Soviet Academy of Sciences) – was recorded on a "Shlyumburzhe" magnetic recorder in the frequency modulation regime with a realization length of 100 sec and was analyzed on an "Elektronika-60" computer. In the counting method of analysis, the Doppler signal travelled from the output of the photomultiplier (40 MHz = f_d) to a mixer and was converted to an intermediate frequency of 20-50 kHz. It then proceeded to a model-1980 TSI electronic counting block, where it was filtered in the 1-100 kHz band and analyzed in 8 or 16 cycles. The signal was then sent from the output of the counting block to an Apple II computer. The computer stored 256 or 512 Doppler signals received in succession over about 100 sec, computed the RMS fluctuations, and constructed histograms of the process (Fig. 2).

The experimental method was as follows. The oscillating grid was brought into motion and measurements were begun in the steady-state regime. The time to establish this regime was calculated from Eq. (1) and was checked against the constancy of the diffusion current in the

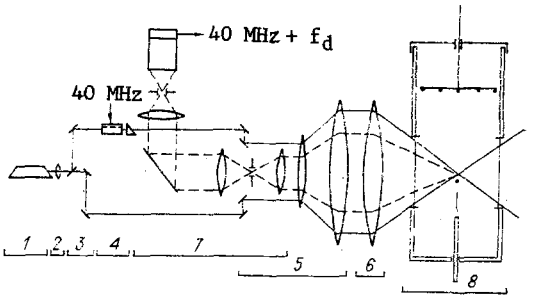

Fig. 1

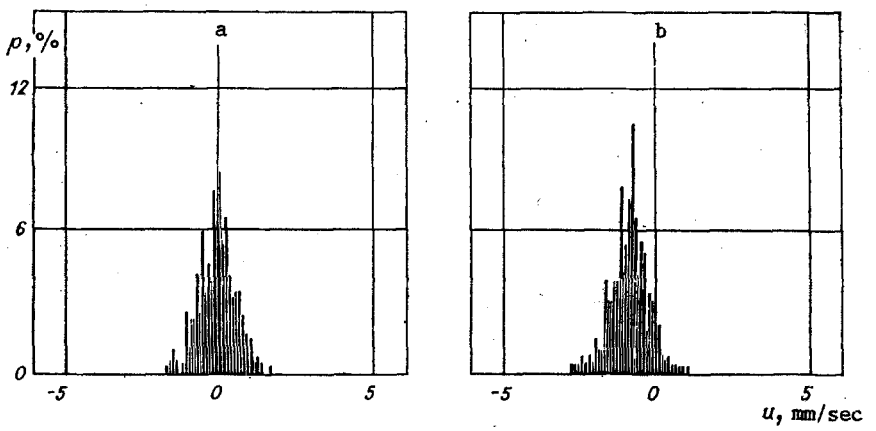

Fig. 2

transducer. We simultaneously measured the rate of mass transfer between the solid spherical particle and the agitated liquid and the RMS fluctuations of the horizontal velocity component u at a distance of 200 mm from the grid in the center of the vessel. The electrochemical mass-transfer sensor and the measurement volume of the DLVM were located 3 mm from each other, which allowed us to assume that the value found for the mass-transfer coefficient β corresponded to the RMS fluctuation velocity. In each regime we recorded an average of at least 10 100-sec realizations for both the mass-transfer rate and for the RMS fluctuation velocity. The mean was then calculated. Thus, the minimum total averaging time was 15 min.

This minimum total time was chosen on the basis of the following considerations. The measured quantities were subjected to an intermediate averaging every 1000 sec in the experiments with a measurement duration of 3000-4000 sec, and the values obtained at the end of the experiment were compared with the mean value calculated for the total time of measurement. It turned out that the deviation of the intermediate means from the total mean was ±5% for the first and second levels and ±3% for the third level. It can be assumed with the same error that the 1000-sec duration of the averaging interval was sufficient.

After this, the grid was stopped and the liquid was allowed to come to rest. The time required for stilling of the liquid at the maximum agitating capacities reached 1.5 h. The process was monitored via the amplitude of the diffusion current I. We then changed either the frequency or the amplitude of the grid vibrations and again brought the grid into motion.

Discussion of Results. An analysis of the histograms of the process obtained from the analysis permits certain conclusions to be made regarding the structure of the fluid being agitated. Thus, Fig. 2a shows the histogram for the regime with a frequency f = 8 Hz and amplitude S = 3 mm. It is evident that a velocity close to zero is most probable. This pattern is characteristic of low mixing intensities, i.e., at low values of f from the investigated range of grid-vibration frequencies. The perturbations are evidently propagated from the grid in the absence of so-called secondary flows. A visualization of the flow [4] done for low mixing intensities confirms this fact. Under such conditions, the RMS fluctuations of the horizontal component of fluid velocity are determined, for example, by the formula [2]

$$u = 1.4fS^{2,5}z^{-1,5}. \quad (3)$$

With an increase in the power used for mixing of the fluid (or with an increase in the frequency of the oscillating grid), circulating flows comparable in magnitude to the dimensions

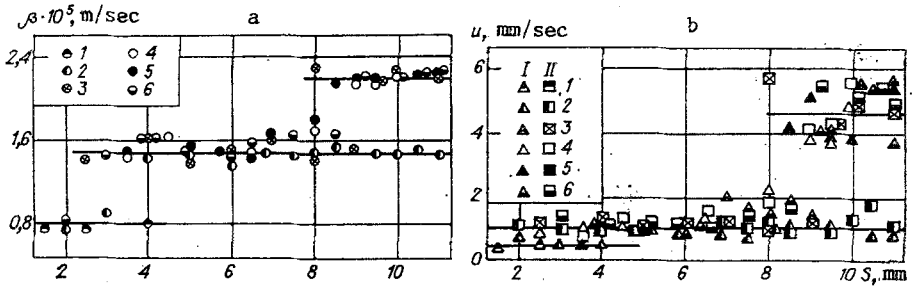

Fig. 3

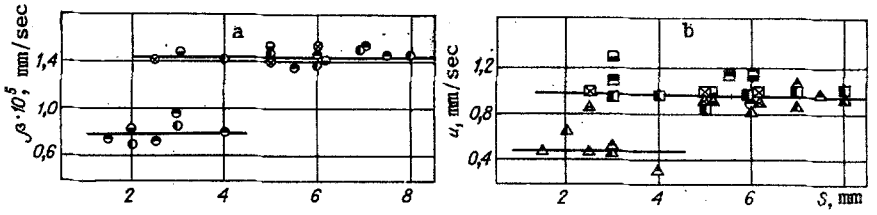

Fig. 4

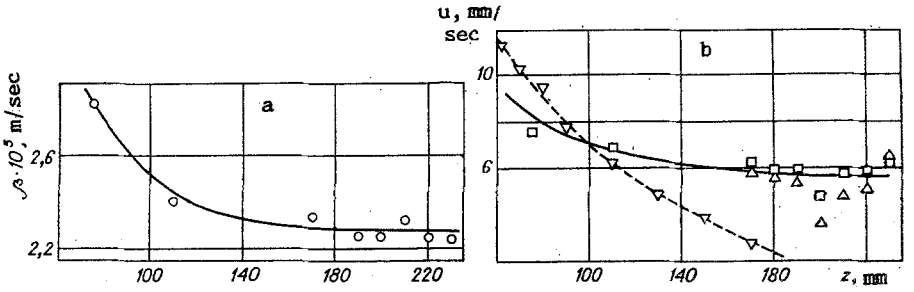

Fig. 5

TABLE 1

№	I, μA		u, mm/sec		U, mm/sec	
	*	†	*	†	*	†
1	10.7	7.0	3.45	0.73	1,88	1,01
2	9.4	6.2	2.91	1.02	—1,7	—1,25
3	9.25	6,3	3.04	0.61	—1,14	—0,16
4	9.35	6.2	3,25	0,92	5,25	1,3
5	10.3	6.95	2.19	1.11	0,51	—0,3
6	9.1	6.35	6,28	0,81	3,35	1,24
7	10.55	6.4	2.71	0,99	—3,5	—0,08
8	9.3	6.85	3.89	1,1	2,4	—1,67
9		7.2	2.19		2.79	
10		6.75	5.55		1.4	
11			4,38		—1.52	
Mean valves						
	9,74	6,62	3,83	0,93	0,88	0,09

*f = 15 Hz, S - 9.5 mm;
†f = 10 Hz, S = 10.5 mm.

of the vessel appear at distances z > 100 mm. The appearance of such flows — which have a vortical structure — violates Eq. (3). This is expressed on the graph by a section on which the RMS values of fluctuation do not depend on the power consumed in mixing the entire volume of fluid. In [4], where this phenomenon was first observed, the value of u remained constant with an increase in grid vibration frequency from 6 to 10 Hz at a fixed amplitude, and large-scale eddies were observed by visualization.

Figure 2b shows the histogram for the regime with the parameters f = 10 Hz and S = 10.5 mm; the power consumed in mixing the liquid was much greater than in Fig. 2a. The measurement results for this case are shown in Table 1 (line 3). There was a nonvanishing mean velocity for the relatively short time interval (~100 sec) for which velocity was measured. This may also be evidence of the presence of large-scale eddies (along with the flow visualization in [4]).

It is evident from the table that the mean velocity U often changes sign. This is apparently an indication of the slow movement of eddies in the liquid undergoing mixing, except for the region directly adjacent to the grid and occupying roughly one-third of the entire volume. As regards the visualization [2-4], it was done by photographing with short exposures. Thus, it is difficult to make a judgement concerning the slow mixing of eddies in space. This can be evaluated only through observations over long time intervals.

Figure 3a, b shows data from an experiment in which we simultaneously measured the rate of mass transfer between a solid spherical particle and the agitated fluid on the one hand and the RMS fluctuations u of the horizontal velocity component of the fluid on the other hand. Points 1-6 show regimes for which the grid vibration frequency had values of 8, 10, 13, 15, 16, and 17 Hz, respectively. The mass-transfer coefficient was calculated from Eq. (2). Calibration of the sensor before and after each test showed that the physical properties of the fluid and the concentration of potassium ferricyanide ions remained constant during the experiment.

There are three distinct levels of mass-transfer rate, each of these rates depending on the power consumed in mixing. For example, in the regimes with f = 13 Hz, the experimental point with S = 2.5 mm is located at the second level. A further increase in grid vibration amplitude with an increment of 1 mm (and, thus, an increase in the power for mixing) to the value 9 mm does not change the rate of mass transfer between the particle and the liquid. This rate remains constant. At the next amplitude, equal to 9.5 mm, the mass-transfer rate changes suddenly and the mass-transfer coefficient corresponds to level three. A further increase in the amplitude to 11.0 mm also fails to increase mass-transfer rate.

We then repeated the regime with f = 17 Hz and S = 8 mm, but the coefficient β corresponded to level three. This can be interpreted as a peculiar form of hysteresis. However, no special studies were conducted to explain the detailed pattern of the transition from a higher level to a lower level, although this phenomenon was observed in the other regimes. A similar pattern occurs, for example, in the transition to turbulent flow in a circular pipe and in the reverse transition with a reduction in the Reynolds number.

The data obtained for the regimes with f = 17 Hz is distinguished by the fact that all three levels of mass-transfer rate were observed with a change in amplitude from 2 to 11 mm.

It should be noted that the first level of mass-transfer rate in the investigated range of f and S was observed very rarely — only at low values of frequency and amplitude. As a rule, the sensor recorded the presence of the second level of mass-transfer rate, and when a certain critical amplitude was reached there was an abrupt change in the coefficient with the transition to the third level.

The quantity u behaves similarly, i.e., there are three levels of RMS fluid velocity fluctuation. Meanwhile, there is also a correspondence between the changes in u and β expressed in a coincidence of the intervals within which these quantities are independent of a change in the governing parameters. The transitions of the RMS fluctuations and mass-transfer rate to another level occur simultaneously.

Figure 3b shows two types of points: I) points obtained by means of the DLVM with the counting block; II) points obtained with the tracking filter—analyzer.

It is evident that both methods of analyzing the Doppler-laser signal give satisfactory results, the scatter of the experimental data being minimal for the first and second levels. The scatter increases for the third level, which is attributable to features of the hydrodynamics of the fluid at high mixing powers. It is also evident that the intensity of the secondary flows is high in these regimes. It can be concluded from analysis of the graph that the results obtained by one method do not deviate systematically from the results obtained by the other method. The first level of RMS fluctuations could be obtained only by means of the counting block. The presence of hysteresis in the transition between levels was also noted for u.

Figure 4 shows values of u and β for low mixing intensities. The stratification of these values into two levels can be clearly seen. The notation used here is the same as in Fig. 3.

Thus, the rate of mass transfer between the solid spherical particle and the agitated fluid depends on the RMS fluctuations of fluid velocity. This conclusion can be reached on the basis of the correlation between the mass-transfer coefficient and the RMS fluctuation velocity. Another important hydrodynamic characteristic — the mean flow velocity — evidently

cannot determine transport processes in the fluid because it changes sign and because the range of its absolute value is much greater than the corresponding range for the mass-transfer coefficient β (see Table 1).

Figure 5 shows experimental results from measurement of mass-transfer rate and u at different distances from the bottom edge of the oscillating grid. The entire volume can be tentatively divided into two regions with respect to the character of the change in these quantities. The first is the volume directly adjacent to the grid and occupying roughly one-third of the total volume. There is a significant change in the measured quantities in the first volume. The second region occupies the remaining part of the total volume of fluid mixed in the experiment and is characterized by a nearly constant mass-transfer rate and RMS fluctuations of fluid velocity. The test data obtained in this region is shown in Figs. 3 and 4.

Comparison (Fig. 5b) of our data with the available experimental data [2], obtained with f = 2-5 Hz and S = 10-14 mm, shows that in the absence of circulating flows, the law of change in RMS velocity fluctuations with increasing distance from the oscillating grid is different from the law obtained in the present study. In this case, throughout the volume of agitated fluid there is a sharp reduction in u to its minimum near the free surface (in the experiment in [2], the oscillating grid was located near the bottom of the vessel).

In conclusion, we thank V. I. Titkov for his help in performing the experiments.

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