EFFECT OF THE SHAPE OF A SOLID ON THE KINETICS OF EXTERNAL MASS TRANSFER

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A procedure is proposed for calculating local and average mass-transfer coefficients, and results are presented for the interaction of solids of various shapes with a stream of liquid.

On the basis of our previous experimental investigations [1] of mass transfer of solids of various shapes to a stream of viscous incompressible liquid (water), the following dimensionless equations were obtained: for a cone

$$\mathrm{Nu} = 0.487\,\mathrm{Re}^{0.585}\,\mathrm{Pr}^{0.33}, \tag{1}$$

for a sphere

$$\mathrm{Nu} = 0.328\,\mathrm{Re}^{0.620}\,\mathrm{Pr}^{0.33}, \tag{2}$$

and for a cylinder

$$\mathrm{Nu} = 0.183\,\mathrm{Re}^{0.693}\,\mathrm{Pr}^{0.33}, \tag{3}$$

which are valid for Reynolds numbers from $2 \cdot 10^3$ to $2 \cdot 10^4$.

These data show that the shape of a solid has an appreciable effect on mass transfer to a stream of liquid. It turns out that the frequently used assumption that a body whose dimensions along the three coordinate axes differ only slightly behaves like a sphere in diffusion and thermal respects [2, 3] is incorrect. The significant differences in the equations obtained are due largely to the nature of the detached flow and vortex formation behind a bluff body. The effect of these factors on mass transfer can be characterized by the exponent of the Reynolds number, which has its largest value for longitudinal flow past a cylinder.

Values of the mass-transfer coefficient averaged over the whole surface of the body can be found from Eqs. (1)-(3). In this case, however, the activity of various parts of the surface of the body in the transfer process remains unexplained. This question is of great interest from the point of view of finding the optimum type of hydrodynamic interaction.

We set ourselves the problem of finding local and average mass-transfer coefficients for individual portions of the surface of the body.

The samples interacting with the stream of liquid were made by compressing powdered benzoic acid C_6H_5COOH under a pressure of 10^8 N/m^2 and then shaping the samples on a lathe into spheres, cylinders, and cones. The diameters and heights of the samples were all chosen equal to 20 mm. The samples were washed by a stream of constant-temperature water on the arrangement shown schematically in Fig. 1. The plastic working tube permitted visual observation during the experiment. The temperature of the liquid was kept constant to within ±0.5° by a supply of hot or cold water in a heat exchanger. These small variations of temperature had practically no effect on the value of c_s. The velocity of the liquid could be varied from 0.10 to 1.20 m/sec. The temperature of the liquid and the readings of the electromagnetic flowmeter were observed during the experiment. The interaction time was recorded with a timer.

Local mass-transfer coefficients at an arbitrary point of the surface of a body were determined by photographing the sample before and after its interaction with the stream of liquid and then accurately superposing the photographs. To avoid distorting the shape of the body by photographing it from a short distance, the apparatus was placed 1 m from the sample and a telescopic objective was employed to achieve a large scale. As an example, Fig. 2 shows the superposition of photographs of a cylindrical sample which was washed for

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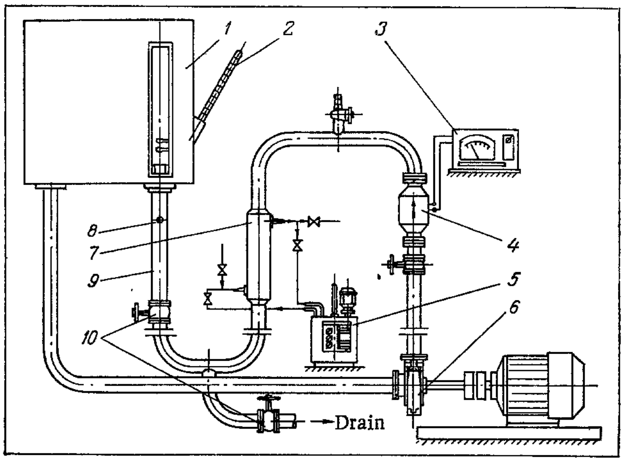

Fig. 1. Schematic diagram of experimental arrangement for investigating kinetics of external mass transfer: 1) make-up tank; 2) thermometer; 3, 4) type IR-11 electromagnetic flowmeters; 5) type TS-16 thermostat; 6) centrifugal pump; 7) concentric-tube heat exchanger; 8) test sample; 9) working tube; 10) control equipment.

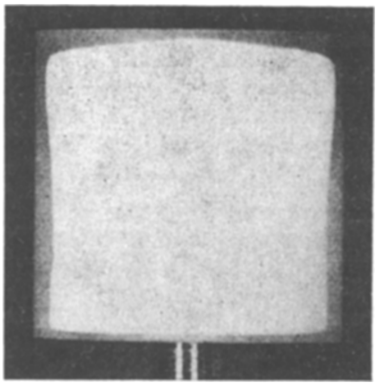

Fig. 2. Superposed photographs of a cylindrical sample before and after interaction with a stream of liquid; τ = 3600 sec, u = 1.18 m/sec, and Re = $2.36 \cdot 10^4$.

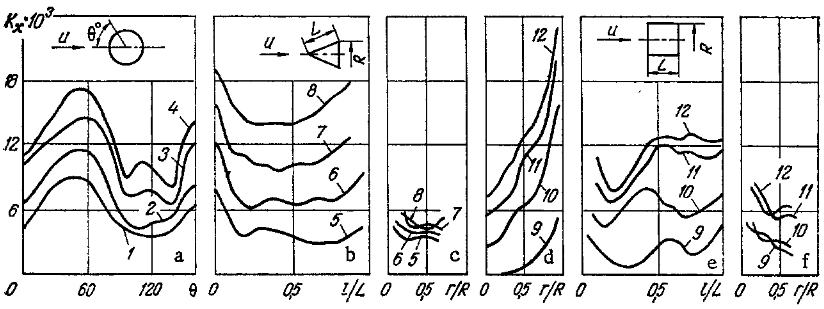

Fig. 3. Distribution of local mass-transfer coefficients k_x (m/sec) over the surfaces of bodies: a) sphere: 1) Re = $3.6 \cdot 10^3$; 2) Re = $7.8 \cdot 10^3$; 3) Re = $1.18 \cdot 10^4$; 4) Re = $1.36 \cdot 10^4$; lateral (b) and rear (c) surfaces of cone: 5) Re = $3.2 \cdot 10^3$; 6) Re = $9.4 \cdot 10^3$; 7) Re = $1.58 \cdot 10^4$; 8) Re = $2.34 \cdot 10^4$; front (d), lateral (e), and rear (f) surfaces of cylinder: 9) Re = $2.8 \cdot 10^3$; 10) Re = $9.0 \cdot 10^3$; 11) Re = $1.6 \cdot 10^4$; 12) Re = $2.36 \cdot 10^4$.

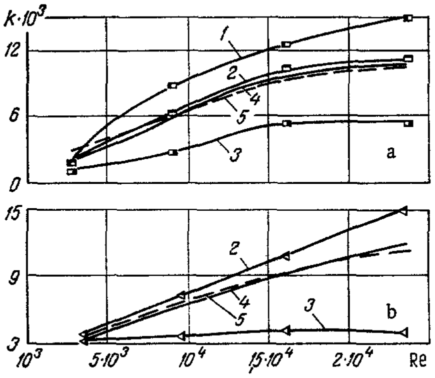

Fig. 4. Dependence of average mass-transfer coefficients k (m/sec) of the surface of a cylinder (a) and a cone (b) on Reynolds number: 1) front surface of cylinder; 2) lateral surface of bodies; 3) rear surface of bodies; 4) total surfaces of bodies (from local coefficients); 5) total surfaces of bodies (from change in mass).

3600 sec by a stream of water flowing at 1.18 m/sec ($Re = 2.36 \cdot 10^4$). The photograph clearly shows the change in configuration of the body as a result of its interaction with the stream. Using a twenty-power measuring microscope the change in linear dimensions of the sample Δh_x at various points of the surface was determined to within 3%.

Local mass-transfer coefficients were calculated from the equation

$$k_x = \Delta h_x \rho / c_s \tau, \tag{4}$$

derived from the equation of mass transfer for an arbitrarily small portion of the surface. Figure 3 shows the distribution of local mass-transfer coefficients over the surfaces of a sphere, cylinder, and cone for various Reynolds numbers. The graphs show that in the interaction of a solid sphere with a stream the mass-transfer coefficient is maximum at an angular distance $\theta \approx 45-60°$ from the front critical point. This type of pattern was observed under all the experimental conditions investigated. After the maximum, k_x decreases to a minimum in the region where the laminar boundary layer separates from the surface of the body ($\theta \approx 100-135°$). On the rear part there is again observed an increase in the intensity of the transfer process, indicating the presence in this region of active vortex flows which have an appreciable effect on mass transfer. For flow past a cone the values of the local mass-transfer coefficient decrease sharply over the initial part of the lateral surface and increase close to the rear edge. A certain increase in activity is observed with increasing Reynolds number on the second half of the lateral surface. After a certain decrease close to the edge of the cone the values of k_x in the rear part vary slowly and the transfer process is nearly independent of the Reynolds number. There is a sharp increase in the local mass-transfer coefficients on the front surface of a cylinder from the front critical point to the edge where they reach their largest values. The lateral surface of a cylinder is characterized by a decrease of mass-transfer activity on the initial part. The distribution of local transfer coefficients is strongly dependent on the Reynolds number: For small Reynolds numbers the middle part of the lateral surface and the rear edge are relatively active; for large Reynolds numbers all the second half of the surface is active. In the rear zone of a cylinder the situation is basically similar to that on the rear of a cone.

Mass-transfer coefficients averaged over the front, lateral, and rear surfaces were determined for the cylindrical and conical samples. To this end the mean integral values of the mass-transfer coefficients for parts of the surface were determined graphically (Fig. 4). The graphs show that the front part of the surface of a cylinder and the lateral surface of a cone are the most active in the mass-transfer process, and the rear parts of the surfaces of both bodies are the least active. The effect of the flow velocity on the intensity of the mass-transfer process is greatest on the lateral surface of a cone. Here the average mass-transfer coefficient varies almost linearly with the Reynolds number. For all the remaining parts of the surfaces the curves become less steep with increasing Reynolds number, and in the rear zones beginning with $Re = 1.6 \cdot 10^4$ the mass-transfer activity remains practically unchanged. The average mass-transfer coefficients for total surfaces of bodies calculated with local values (curve 4) agree rather well with the values found from the change in mass of the bodies as a result of the interaction with the stream (curve 5). The measured values of the average mass-transfer coefficients of the total surfaces of a cone and cylinder agree with the values calculated with Eqs. (1) and (3) to within ~10% on the average. This difference is due largely to the differences in the experimental conditions and the assumption, in deriving Eqs. (1) and (3), that the interaction time does not exceed 10 min and the shapes and sizes of the bodies experience negligible change. In the experimental determination of local mass-transfer coefficients the samples are washed for an hour, and the shapes and sizes of the bodies are changed appreciably.

NOTATION

u, flow velocity; τ, interaction time; k_x, local mass-transfer coefficient; Δh_x, decrease in linear dimension of sample; ρ, density of test sample; c_s, saturation concentration; θ, angular distance from front critical point; r, distance from axis of sample to a point on front and rear surfaces; l, distance to a point from beginning of lateral surface; R, radius of sample; L, length of lateral surface; $Nu = kd/D$, Nusselt number; $Pr = \nu/D$, Prandtl number; $Re = ud/\nu$, Reynolds number.

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TRANSFER EQUATION IN THERMODIFFUSION COLUMN WITH SPIRAL WINDING

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The derivation of the transfer equation for a thermodiffusion column with spiral winding is outlined. It is shown that, in contrast to the classical case, this is a two-dimensional equation.

In 1962, Washal and Melpolder suggested that the separation of liquid mixtures could be intensified by winding onto the internal cylinder of the thermodiffusion column a wire spiral of diameter equal to the gap between the hot and cold surfaces of the column [1]. In their experiments with a mixture of cis and trans isomers of decahydronaphthalene, they found that for some winding angles of the spiral the degree of separation was higher by a factor of 10 than in the column without a spiral.

This result aroused the interest of researchers, and a number of papers [2-6] were devoted to the verification of the "spiral effect," since it is simple to utilize from a constructional viewpoint and allows significantly better enrichment of the mixture components to be obtained for the same energy consumption. Note, however, that the verification offered in some works [2, 5] was based not on a comparison of the results obtained with a single column with and without a spiral, but only on data obtained upon introducing into the gap a spiral with an arbitrary winding angle. In these cases, good fractionation of petroleum products and a reduction in the time of the transient process were observed. A more thorough investigation was made in [3] for binary mixtures, with different winding angles of the spiral. Only withdrawal conditions were considered; no experiments were conducted under static conditions.

The column geometry was chosen so as to satisfy the condition $c(1-c) \approx \text{const}$. It was established that there is an optimum winding angle of the spiral (depending on the rate of withdrawal and the properties of the mixture) at which the degree of separation has a clearly expressed maximum.

On the other hand, in [4-6] the introduction of a spiral winding in the working gap was not found to have any pronounced effect on the separation of the mixture. For the separation of bromium isotopes in butyl bromide [4], an increase in the time of the transient process was noted, with no increase in the degree of separation. (The experiments were conducted in the absence of withdrawal.)

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