

MASS TRANSFER IN A MOVING DROP WHEN
IT PERIODICALLY COLLIDES WITH A
HARD SURFACE

A. M. Landau and A. S. Zheleznyak

UDC 66.015.23

The article describes an experimental study of mass transfer in a moving drop which periodically collides with a hard surface. An empirical formula for calculating the coefficients of mass exchange within the drop is obtained.

It is known that when a column is filled with disordered packing, the rate of mass transfer between the continuous liquid phase and the motionless dispersed phase increases substantially in the case in which the limiting resistance is concentrated in the dispersed phase [1-4].

In [5] we stated the hypothesis that the increase in the rate of mass transfer is due primarily to an increase in the average value of the true coefficient of mass transfer to the drop as the result of its collisions with the surface of the packing.

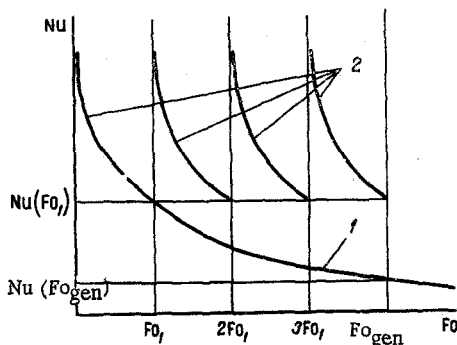


Fig. 1

Fig. 1. Variation of the criterion Nu as a function of the criterion Fo : 1) drop moving with no collisions, $Nu(Fo_{gen})$; 2) drop moving with periodic collisions, with complete mixing of the volume of the drop, $Nu(Fo_1)$.

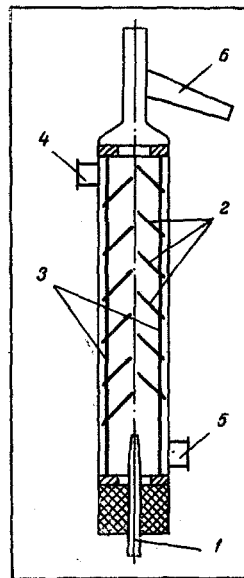


Fig. 2

Fig. 2. Column for investigating mass transfer to drops which move with periodic collisions: 1) nozzle for injection of the dispersed phase; 2) plates; 3) rods holding the plates; 4, 5) inlet and outlet of the continuous phase; 6) outlet of the dispersed phase.

All-Union Scientific Research Institute of Petrochemical Processes, Leningrad. Translated from *Inzhenerno-Fizicheskii Zhurnal*, Vol. 26, No. 5, pp. 908-913, May, 1974. Original article submitted August 22, 1973.

© 1975 Plenum Publishing Corporation, 227 West 17th Street, New York, N.Y. 10011. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, microfilming, recording or otherwise, without written permission of the publisher. A copy of this article is available from the publisher for \$15.00.

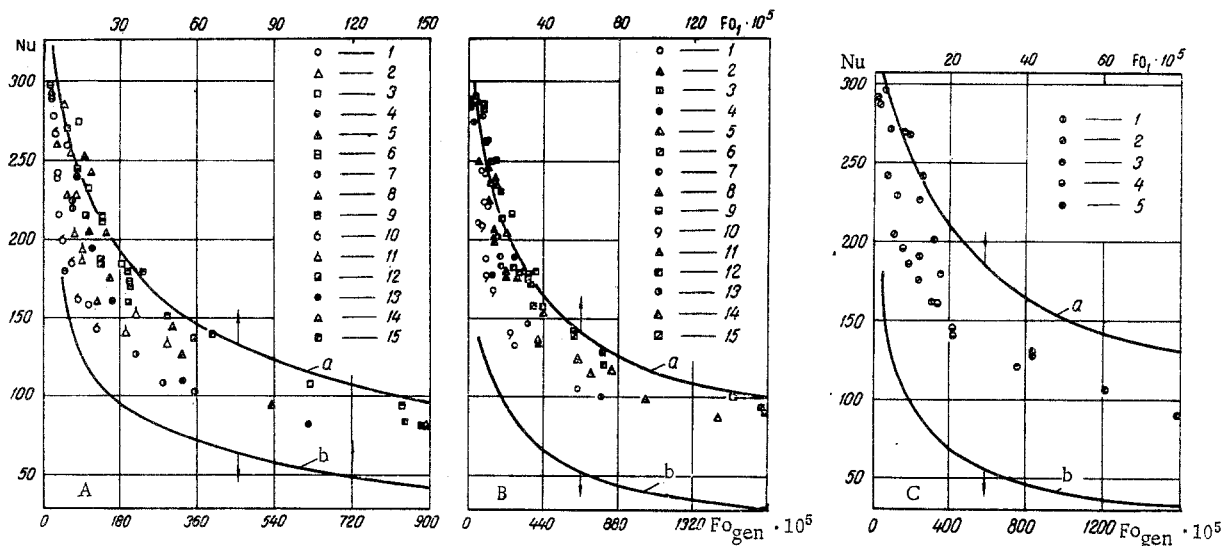


Fig. 3. Comparison of experimental data on mass transfer to drops moving with collisions and the theoretical curves: a) $Nu = f(Fo_1)$; b) $Nu = f(Fo_{gen})$; A) 5 collisions; B) 10 collisions. In the case of A and B: for system I: 1) distance between plates 26 mm; 2) 40 mm; 3) 65 mm; II: 4) 26 mm; 5) 40 mm; 6) 65 mm; III: 7) 26 mm; 8) 40 mm; 9) 65 mm; IV: 10) 26 mm; 11) 40 mm; 12) 65 mm; V: 13) 26 mm; 14) 40 mm; 15) 65 mm; C: 19 collisions; distance between plates 26 mm: 1) system I; 2) system II; 3) system III; 4) system IV; 5) system V.

Experimental investigation of mass transfer to individual colliding drops, carried out on a system containing water, organic acids, and benzene [6], showed that when the time of free motion of the drop is long, there is a substantial intensification of the mass-transfer process. However, because the amount of experimental material in [6] was small, it was not possible to obtain sufficient information on the mechanism of this process.

We attempted to study in greater detail the effect of collisions between the drop and the hard surface on the rate of mass transfer within the moving drop.

Studies of mass transfer to a moving drop have led the great majority of researchers to the conclusion that the process is a nonstationary one [7-11]. This means that the average value of the coefficient of mass exchange decreases as the contact time increases; this has been confirmed in a number of experimental studies [9, 12-26].

The nonstationary nature of the mass transfer within the drop is due to the gradient of concentration of the transferring material within the volume of the drop. Therefore, if the collision of the drop with a hard surface leads to complete mixing of the volume of the drop, then the process of mass transfer may be regarded as beginning again after the collision. The variation of the number Nu as a function of the dimensionless contact time Fo in this case will have the shape shown in curve 2 of Fig. 1. For purposes of comparison, this figure also includes curve 1, which shows the variation of Nu as a function of Fo for the case in which the drop moves without collisions. The criterion $Nu(Fo_1)$, corresponding to the time the drop moves between one collision and the next, is greater in comparison with the value of the criterion $Nu(Fo_{gen})$ for greater values of the time of free movement of the drop.

The experimental apparatus is shown in Fig. 2. The drops of the dispersed phase, leaving the nozzle 1, move upward, colliding with the plates 2, which are held at an angle of 45° to the supports 3. The construction of the column made it possible to change the number of plates and the distance between them. In the case when the density of the dispersed phase was higher than the density of the continuous phase (system 4), the column was overturned, so that the tests could be carried with drops moving downward. The method and the scheme of the apparatus used in carrying out this experiment did not differ from those described earlier in connection with single drops [24].

Tests were carried out on five systems: I) heptyl alcohol, HCl , and water (continuous phase); II) octyl alcohol, HNO_3 , and water (continuous phase); III) isobutanol and isobutanol-saturated water (continuous phase); IV) propylene carbonate, benzene, and heptane (continuous phase); V) ethyl acetate and ethyl-acetate-saturated water (continuous phase).

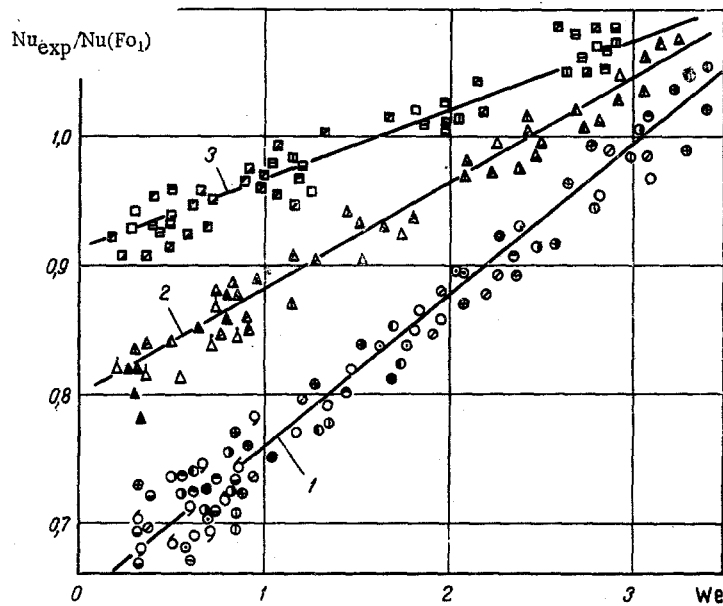


Fig. 4. Variation of $Nu_{exp}/Nu(Fo_1)$ as a function of the criterion We : 1) distance between plates = 26 mm; 2) 40 mm; 3) 65 mm.

The physicochemical properties of the systems varied over the following ranges: density of the continuous phase, $\rho_c = 0.717-0.999 \text{ g/cm}^3$; density of the dispersed phase, $\rho_d = 0.798-1.202 \text{ g/cm}^3$; difference in density between the phases, $\Delta\rho = 0.096-0.485 \text{ g/cm}^3$; dynamic viscosity of the continuous phase, $\mu_c = 0.467-1.23 \text{ cP}$; dynamic viscosity of dispersed phase, $\mu_d = 0.46-7.72 \text{ cP}$; relative viscosity $\mu_d/\mu_c = 0.45-7.7$; interphase tension, $\sigma = 2.1-27.7 \text{ dyn/cm}$; coefficient of diffusion in the dispersed phase, $D_d = (0.096-0.89) \cdot 10^{-5} \text{ cm}^2/\text{sec}$.

During the first stage we investigated mass transfer to single drops moving without collisions. The experimental data were found to be in satisfactory agreement with the Kronig-Brink model [8]; the difference between the experimental and the theoretical values for the criterion Nu did not exceed 30% as the Reynolds criterion varied over a range of $Re = 60-250$ and the Fourier criterion varied over a range of $Fo = (30-1700) \cdot 10^{-5}$.

During the second stage of the investigation we conducted tests in which the drop collided with 5, 10, and 19 plates. In the first two cases the distance between the plates was 26, 40, or 65 mm; in the third case the distance was 26 mm.

During the tests the experimental values varied over the following ranges: diameter of drop, $d = 0.11-0.36 \text{ cm}$; velocity of motion of the drop, $u = 3.5-13.6 \text{ cm/sec}$; time of motion of the drop between collisions, $t_1 = 0.22-1.85 \text{ sec}$; Fourier criterion corresponding to the time the drop moved between collisions, $Fo_1 = (1.2-160) \cdot 10^{-5}$; Weber criterion, $We = 0.25-3.4$.

The experimental values, Nu_{exp} , were compared with the theoretical $Nu(Fo_1)$ and $Nu(Fogen)$ curves according to Kronig and Brink [8] (Fig. 3). The data indicated show that collisions of the drop with a hard surface lead to a considerable increase in the rate of mass transfer, and that as the number of plates increases, so does the ratio $Nu_{exp}/Nu(Fogen)$. This fact may be regarded as an indirect confirmation of the nonstationary nature of the mass transfer taking place within the drop.

At the same time, in addition to the cases corresponding to the representation of complete mixing of the volume of the drop whenever it collides with a plate, it should be noted that there are systematic deviations of the experimental data from the theoretical curve.

In the first place, as the drop diameter decreases and the Fo criterion consequently increases, each series of tests shows an increasing deviation between the theoretical curve and the experimental data.

In the second place, as the distance between the plates is reduced, the amount of deviation between the theoretical curve and the experimental data increases.

This may be explained as follows: as the diameter of the drop decreases its resistance to deformation is increased because it has a greater specific surface, and there is a decrease in the kinetic energy that causes mixing of the volume of the drop when there is a collision.

The increase in the deviation between the calculated and the experimental values as the distance between the plates (and hence the time of free travel of the drop) is reduced can be explained from the point of view of present-day ideas about mass transfer to a drop. As was shown by Johns and Beckmann [11], during the initial period of drop motion, corresponding to the boundary-layer relaxation time, the mass transfer to the drop is determined only by the mechanism of molecular diffusion. In addition, account should be taken of the fact that after the volume of the drop is disturbed by a deformation, a certain amount of time is required to restore the toroidal circulation in it. As the distance between the plates is reduced, these initial effects make a larger contribution, which can explain the greater deviation of the calculated values for small values of Fo .

Since it is a complicated matter to find analytically the number and nature of the complexes determining how the collisions will affect the mass transfer to the drop, we decided to use as our first step a statistical processing of the experimental data. Using a standard correlation-analysis program [27], we found the coefficients of correlation between the quantity $Nu_{exp}/Nu(Fo_1)$ and the preselected complexes $h_{rel} = h/h_0$; $Re = du/\nu_C$; $We = \rho_C du^2/\sigma$; μ_d/μ_C , where $h_0 = 2.5$ cm is the dimension of the "standard" packing used by V. V. Kafarov [28] in complexes of a similar nature. The complexes h_{rel} and We were found to be significant. The physical meaning of the complexes found is the following: the criterion We is a measure of the resistance of the drop to deformation and mixing of its volume, and the relative distance h_{rel} is a measure of the influence of the initial effects. The final form of the relation, $Nu_{exp}/Nu(Fo_1) = f(h_{rel}, We)$, was determined by means of a standard program of regression analysis [28]:

$$Nu_{exp}/Nu(Fo_1) = 0.63h_{rel}^{0.46} + 0.115h_{rel}^{-0.53} We. \quad (1)$$

Figure 4 illustrates the relation (1). The data shown on this figure indicate that the ratio $Nu_{exp}/Nu(Fo_1)$ is independent of the number of collisions. This fact makes it possible to use the results obtained for the calculations of packing columns.

LITERATURE CITED

1. N. I. Ponikarov, A. M. Nikolaev, and N. M. Zhavoronkov, *Khim. Mash.*, No. 3, 11 (1962).
2. L. Leibson and R. Beckmann, *CEP*, 49, 405 (1953).
3. G. Smith and R. Beckmann, *AIChE Journ.*, 4, 185 (1958).
4. G. Laddha and I. Smith, *CEP*, 46, 195 (1950).
5. A. M. Landau and A. S. Zheleznyak, *Zh. Prikl. Khim.*, 43, 317 (1970).
6. A. S. Zheleznyak and É. M. Tarasova, *Zh. Prikl. Khim.*, 46, 451 (1973).
7. A. Newman, *Trans. Am. Inst. Ch. Engrs.*, 27, 203 (1931).
8. R. Kronig and I. Brink, *Appl. Sci. Res.*, A2, 142 (1950).
9. B. I. Brounshtein and A. S. Zheleznyak, *Physicochemical Foundations of Liquid Extraction [in Russian]*, "Khimiya" (1966).
10. B. I. Brounstein, A. S. Zheleznyak, and G. A. Fishbein, *Int. J. Heat Mass Transf.*, 13, 963 (1970).
11. L. Johns and R. Beckmann, *AIChE Journ.*, 12, 10 (1966).
12. R. McDowell and Y. Myers, *AIChE Journ.*, 2, 385 (1956).
13. P. H. Calderbank and I. S. O. Korchinski, *CES*, 6, 65 (1956).
14. L. Garvin and B. D. Smith, *CEP*, 49, 591 (1953).
15. A. Johnson and A. E. Hamueleck, *AIChE Journ.*, 6, 145 (1960).
16. Yu. I. Bytnerskii and A. N. Planovskii, *Teor. Osnovy Khim. Tekhnol.*, 5, 460 (1971).
17. Ya. G. Shmagin and É. K. Sirde, in: *Liquid Extraction [in Russian]*, Proceedings of the Third All-Union Meeting, "Khimiya" (1969).
18. W. S. Huang and R. C. Kinther, *AIChE Journ.*, 15, 735 (1969).
19. F. H. Garner and A. R. Hale, *Ch. Eng. Sci.*, 2, 157 (1953).
20. G. S. Constan and S. Calvert, *AIChE Journ.*, 9, 109 (1963).
21. F. H. Garner and I. I. Lane, *Trans. Inst. Chem. Engrs.*, 37, 162 (1959).
22. F. B. West, P. A. Robinson, A. C. Morgenthaler, T. R. Beck, and D. K. McGregor, *Ind. Eng. Chem.*, 43, 234 (1951).
23. I. G. Plitt, *Chemical Technology*, Republican Collection, No. 9, 113 (1967).
24. A. S. Zheleznyak and B. I. Brounshtein, *Zh. Prikl. Khim.*, 36, 2437 (1963).

25. A. S. Zheleznyak, Candidate's Dissertation, M. V. Lomonosov Institute of Fuel and Chemical Technology, Moscow [in Russian] (1965).
26. A. H. Skelland and R. M. Wellek, *AIChE Journ.*, 10, 491 (1961).
27. Mathematical Statistics Programs for the Minsk-22 Electronic Computer [in Russian], Izd. MGU, Moscow (1969).
28. V. V. Kafarov, *Fundamentals of Mass Transfer* [in Russian], "Vysshaya Shkola," Moscow (1972).