AN ELECTROCHEMICAL STUDY OF HEAT AND MASS TRANSFER IN THE VIBRATIONAL MOTION OF A MEDIUM AND A BODY

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An experimental test is reported for the effects of low-frequency oscillations on the mass transfer between a sphere and a medium at large Prandtl numbers.

Transfer processes are substantially accelerated in pulsating and oscillating flows. Fundamental investigations have been conducted on heat and mass transfer in vibrational processes and empirical relationships have been derived [3-6, 8, 9]. In [1] a solution was given for transport from bodies of simple shape in a sonic field under conditions of free convection and the mass transfer from a cylinder in a sonic field at high Prandtl numbers has been solved by Grafov [2].

In the present work some theoretical relationships for heat and mass transfer in vibrational motion were subjected to experimental test. The tests were conducted at 0.50 Hz and at large Prandtl numbers for mass exchange between a sphere and a medium at large and small s/R. To allow measurement of the mass flux when the diffusion Prandtl numbers were some thousands, we used an electrochemical method of examining the mass transfer, which has considerable advantages: it provides good reproducibility and adequate accuracy, while substantially reducing the time and labor needed [7].

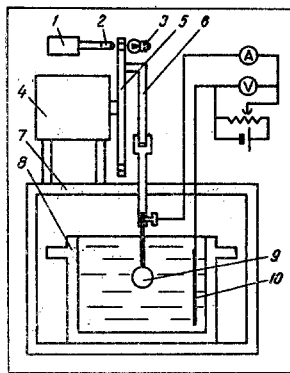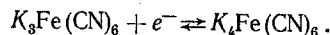The method is based on the rate of the redox reaction

$$K_3Fe(CN)_6 + e^- \rightleftarrows K_4Fe(CN)_6.$$

Fig. 1

Fig. 2

Fig. 1. Apparatus: 1) frequency meter, 2) photodiode, 3) light source, 4) metric motor, 5) disc, 6) crank mechanism, 7) frame, 8) thermostatic vessel, 9) cathode, 10) anode.
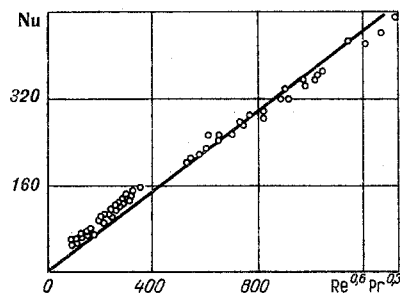
Fig. 2. Transducer calibration for steady flow around a sphere. The points are experimental values while the line represents Eckert's formula.
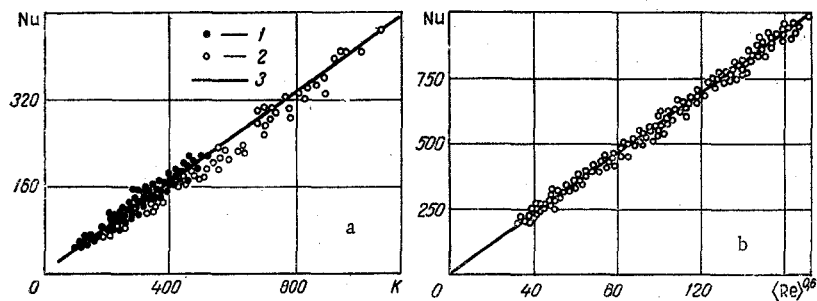
Fig. 3. Mass transfer for a sphere in the presence of vibrations; a) $s/R < 1$: 1) our results, 2) for benzoic acid [1], 3) theory; b) $s/R > 1$: the points are experimental values, the line corresponds to the points $Nu = 2 + 0.53\ Pr^{0.3} < Re^{0.6})$.

The area of the anode is 100-1000 times that of the cathode, so that the anode does not become polarized. The rate can be monitored from the current between the electrodes; it increases exponentially with the potential difference at first and then tends to a limit set by molecular and convective diffusion.

An exterior flow produces $I_2 > I_1$ if $Re_2 > Re_1$, so the limiting current allows one to judge the flow character. The cathode rate in the limiting condition is controlled by the mass-transfer rate, which is related to the limiting current by

$$q = \frac{IM}{F}.$$

The mass-transfer coefficient is

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

The ion concentration at the cathode is zero in the limiting condition, therefore for the dimensionless mass-transfer coefficient

$$Nu = \frac{Id}{FSc_\infty D}.$$

Then the average transport coefficient for a sphere is found via the limiting current for a given mode of flow.

We used 0.001-0.01 M $K_3Fe(CN)_6$ and $K_4Fe(CN)_6$. Effects of ion migration on the result were prevented by adding 0.5-2 N NaOH, choosing the exact concentration to adjust the Prandtl diffusion number as required. The composition and reaction scheme prevented deposition on the electrodes.

Figure 1 shows a line diagram of the apparatus on which the experimental data were obtained.

The electrolyte temperature was kept constant at 25°C. As $K_3Fe(CN)_6$ may decompose, and atmospheric oxidation is possible, we prepared a fresh solution each time and measured its concentration at the start and end. The current was measured with an M1104 milliammeter (class 0.2), while the potential difference was measured with a vacuum-tube voltmeter having a high internal resistance. The anode area was 2000 times that of the cathode. The cathode was a steel sphere welded to a mount attached to the crank vibrator mechanism. The spheres had been nickel-plated and the anode was also of nickel.

The calibration was checked in steady-state flow, which also served to check the purity of the plating and the presence of parasitic emfs. The calibration curve (Fig. 2) fitted closely to Eckert's formula.

$$Nu = 2 + 0.37\,Pr^{0.3}\,Re^{0.6}$$

so the method is reliable and can be used in research on transport phenomena. We used spheres with R 1.6-3.6 mm, which gave s/R 0.2 to 8.0, while Pr was 2200. The results for $s/R < 1$ were compared with the theoretical result [1]

$$Nu = 0.416 \left(\frac{B^2R}{\sqrt{\omega \nu} \, D} \right)^{1/3} , \qquad (1)$$

and the results for $s/R > 1$ with

$$Nu = 2 + APr^{0.3} \left(\frac{<B>d}{\nu} \right)^{0.6} , \qquad (2)$$

which corresponds to steady-state flow.

The observations for $s/R < 1$ (Fig. 3a) agree well with (1), while those for $s/R > 1$ (Fig. 3b) agree satisfactorily with (2) for $A = 0.53$.

The results can be used to evaluate the effects of low-frequency oscillations on transport in liquids.

NOTATION

Nu	Nusselt number;
Re	Reynolds number;
Pr	Prandtl number;
B	amplitude of oscillation velocity;
s	displacement amplitude;
ω	circular frequency;
R	radius of sphere;
d	diameter of sphere;
ν	kinematic viscosity;
D	diffusion coefficient;
c	concentration;
F	Faraday number;
S	area;
M	molecular weight;
q	mass flux;
β	mass-transfer coefficient;
$\langle B \rangle$	average oscillation velocity.

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