MASS TRANSFER IN POROUS INJECTION OF AN INERT GAS INTO A LIQUID

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Measurements are reported on mass-transfer coefficients for a liquid containing a porous body through which an inert gas is injected. The data are compared with measurements on heat transfer on porous injection and on boiling.

There are fairly detailed studies [1-4] on heat transfer in porous injection of an inert gas into a liquid, but there are virtually no studies where the mass-transfer coefficients have been derived for analogous systems. Such data are required to elucidate the trends in reactions accompanied by the production of a gas phase and also in establishing similarity relations between convective transfer coefficients.

1. Methods. We used an electrochemical method of determining the mass-transfer coefficient in the redox reaction between potassium ferricyanide and ferrocyanide occurring at a sensing electrode under diffusion-limited conditions [5]. The sensor was a porous sphere of diameter 6 mm pressed from nickel wire of diameter 0.1 mm and of porosity 0.4. Within the sphere there was a stainless-steel capillary of internal diameter 1.8 mm electrically insulated from the outer surface, which at the same time was a holder, the current lead, and the gas supply. The sensor was placed at the axis of a vertical hydrodynamic tube of diameter 100 mm at the point where the velocity profile was uniform. The reference electrode was the end of an electrically insulated nickel wire of diameter 0.1 mm placed at about 0.3 mm from the surface of the sphere. The constant voltage between the sensor and the reference electrode of 0.4 V was maintained by means of a special fast electronic circuit. The anode was a cylindrical nickel strip at the perimeter of the tube whose surface exceeded the surface of the sphere by several orders of magnitude.

The criterion for diffusion-limited operation was that the current was independent of the potential difference between the comparison electrode and the sensor.

The solution has the following properties: density $\rho_2 = 1050$ kg/m^3, viscosity $\nu_2 = 1.16 \cdot 10^{-6}$ m^2/sec, ionic diffusion coefficient $D_2 = 5.6 \cdot 10^{-10}$ m^2/sec. The gas flow speed (nitrogen or helium) varied over the range 0-2 m/sec at the outer surface of the sensor, while the speed of the incident liquid flow was $u_2 = 0$-0.4 m/sec; the pressure in the system varied over the range 0.1-1 MPa.

The analog signal was processed with a GVS-100 hybrid computer. A sufficiently representative realization (about 300 sec) was used with an interrogation frequency of 100 Hz to determine the instantaneous and mean transfer coefficients, as well as the standard deviation and variance.

2. Results. In the first stage, the method was tested by determining the mass-transfer coefficients between the flowing liquid and the surfaces of nonporous and porous particles. The relationship of [6] was obeyed satisfactorily for liquid speeds up to 0.02 m/sec ($Re_2 = 100$):

$$Sh_2 = 0{,}68 Re_2^{0{,}5} Sc^{0{,}33}. \tag{1}$$

At higher speeds, the data tended to separate into groups (Fig. 1), with increase in the flow speed causing a more pronounced increase in the mass-transfer coefficient for the porous particles. This may be due to some of the liquid passing directly through the porous sphere and thus disrupting the boundary layer.

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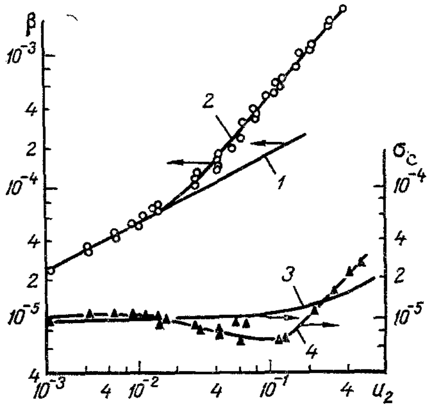

Fig. 1

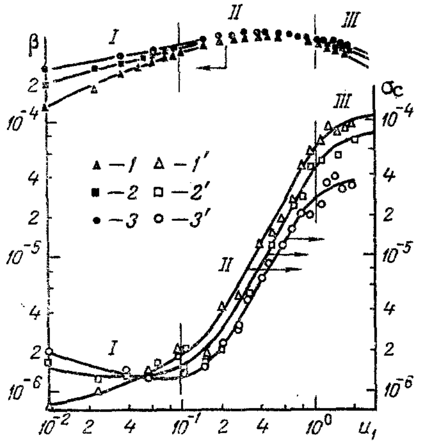

Fig. 2

Fig. 1. Effects of liquid flow speed on the time-averaged mass-transfer coefficient (1 and 2) and on the standard deviation (3 and 4) for porous particles (2 and 4) and nonporous ones (1 and 3); β, σ_c, and u_2 in m/sec.

Fig. 2. Effects of air injection speed on measn mass-transfer coefficients (1, 2, and 3) and on the standard deviations (1', 2', and 3') at the following incident flow speeds: $u_2 = 0$ (1 and 1'); $u_2 = 0.17$ m/sec (2 and 2'); $u_2 = 0.4$ m/sec (3 and 3'); I-III) characteristic ranges in β and σ_c.

For $Re_2 \leqq 100$, the values of σ_c and β were the same for the porous and nonporous sensors, whereas the values tended to separate at higher speeds, so the velocity distributions in the boundary layers are different for these two cases with $Re_2 > 100$. While the nonporous sensor showed a smooth increase in σ_c, which is evidently due to vortex pulsations around the rear part of the sphere, there was a fall in σ_c for the porous case up to 0.1 m/sec ($Re_2 = 1000$) and then a rise. These effects and the changes in the mean mass-transfer coefficient may be due to some of the liquid passing through the porous particles.

Gas injection increased the mass-transfer coefficient and the standard deviation of it. Figure 2 shows the results for one series. The effects of gas speed on β and σ_c caused there to be three characteristic ranges. In the first ($u_1 \leqq 0.1$ m/sec), there is a marked effect from the liquid flow speed. This is seen as gas bubbles growing to a fairly small size and detaching without merging. As the detachment frequency was high and the lag in the sensor was fairly substantial, increasing u_1 did not affect the mean fluctuation in the mass transfer over the surface but increased the mean mass-transfer coefficient.

In the range 0.1-1 m/sec (second range), the liquid speed had hardly any effect on the mean mass-transfer coefficient but reduced σ_c; σ_c however increased with the gas speed, which implies an increase in the scale of the pulsations.

It could be seen that the bubbles were beginning to merge at these gas and liquid speeds, with the detaching bubble sizes becoming comparable with the size of the sensor. The detachment frequency was reduced, and the effects of the liquid pulsations in the formation, growth, and detachment of the bubbles extended to much of the surface.

This range has the maximum gas-transfer coefficient (at $u_1 = 0.4$-0.5 m/sec), while at higher values, increased gas speed reduced β but increased σ_c further. These effects may due to reduction in the fraction of wetted surface because the liquid is partly displaced by the gas. Approximately the same gas speeds have given [4] the maximum heat-transfer coefficient for a liquid with a porous plate. The velocity at which one gets the maximum transport coefficients is less than that calculated as necessary for the first boiling crisis [1] by about a factor 2-3.

The third range ($u_1 > 1$ m/sec) has the mass-transfer coefficient further reduced and less rapid increase in σ_c. In that range, the liquid speed begins to influence β.

Some of the experiments also dealt with the effects of the injected gas density ρ_1 on the conditions. The density was varied by means of the moelcular weight of the gas (air or helium) and also via the pressure in the system (P = 0.1, 0.6, and 1.0 MPa). Throughout this range in ρ_1, there was virtually no effect on the transfer coefficients. Figure 3 shows some

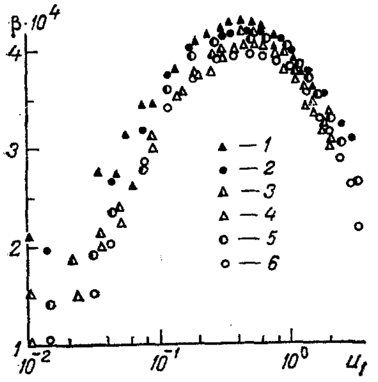

Fig. 3

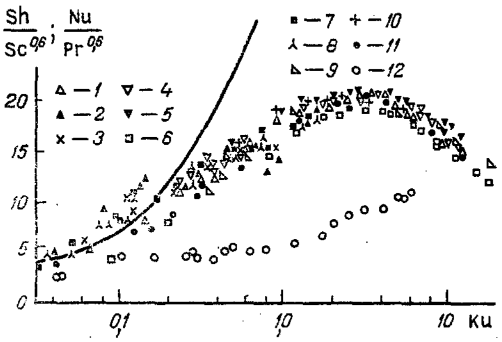

Fig. 4

Fig. 3. Effects of gas injection speed for air (1, 3, 4) and helium (2, 5, 6) on the mean mass-transfer coefficients for incident liquid flow speeds $u_2 = 0$ (4 and 6); $u_2 = 0.17$ (3 and 5); and $u_2 = 0.4$ m/sec (1 and 2); $P = 0.1$ MPa, β in m/sec.

Fig. 4. Our results on transport coefficients and comparison with those of [3, 4, 7], with the numbers corresponding to the following: mass transfer on injecting air with $u_2 = 0$: 1) $P = 0.1$; 2) 0.6; 3) 1.0 MPa; $P = 0.1$ MPa: 4) $u_2 = 0.17$; 5) $u_2 = 0.4$ m/sec. Mass transfer on helium injection: $u_2 = 0$; 6) $P = 0.1$; 7) 0.6; 8) 1.0 MPa; $P = 0.1$ MPa: 9) $u_2 = 0.17$; 10) 0.4 m/sec. Heat transfer on gas injection: 11) [4]; 12) [3]. Solid line for heat transfer on liquid boiling from [7].

results for the effects of the molecular weight on β, which are qualitatively similar to those of [2], where measurements were made on the heat-transfer coefficients for gases bubbling into a liquid. However, β varies only slightly with the density when the pressure is varied, which does not agree with the heat-transfer measurements on bubbling made in [1], where it was found that the pressure had a considerable effect on the heat-transfer coefficient.

Several suggestions may be made on these discrepancies, but it is difficult to perform a detailed analysis because the working conditions in [1, 2] are only very briefly described.

3. Data Processing. The analysis of [1, 2] shows that porous gas injection into a layer of liquid produces a hydrodynamic state at the surface determined in the main by interaction between two effects: the dynamic head set up by one of the phases and the surface tension. Our experiments show that the gas density has only a small effect on the mass-transfer coefficient but that ther gas speed has a very large one. Therefore, one can use the following parameter [2] as a dimensionless one characterizing the liquid flow conditions at the surface in the absence of an external flow:

$$\mathrm{Ku} = u_1 \frac{\sqrt{\rho_2}}{\sqrt[4]{\sigma g(\rho_2 - \rho_1)}} . \tag{2}$$

In the case of forced liquid flow, (2) must be supplemented with a term characterizing the effects of this. By analogy with the crisis condition for moderate liquid speeds [1, 2], one can use the ratio of the dynamic heads set up by the injected gas and the incident liquid, i.e.,

$$\mathrm{Ku} = u_1 \frac{\sqrt{\rho_2}}{\sqrt[4]{\sigma g(\rho_2 - \rho_1)}} + \varkappa \frac{u_2}{u_1} \sqrt{\frac{\rho_2}{\rho_1}} , \tag{3}$$

where $\varkappa$ is a certain constant to be determined by experiment.

The dimensionless quantities characterizing the transport are $\mathrm{Sh} = \beta/D_2\sqrt{\sigma/g(\rho_2 - \rho_1)}$, $\mathrm{Sc} = \nu_2/D_2$ for the mass transfer and $\mathrm{Nu} = \alpha/\lambda_2\sqrt{\sigma/g(\rho_2 - \rho_1)}$, $\mathrm{Pr} = (\nu_2/\lambda_2)c_{p2}\rho_2$ for the heat transfer.

In the first stage, we compared the measurements on mass transfer with the results of [4] for heat transfer to refine the powers to Pr (Sc), which were close to 0.6. Subsequently, the entire data set on the mass transfer with free or forced convection was used to determine $\varkappa$. The best value was found to be $\varkappa = 0.41 \cdot 10^{-4}$. Then Fig. 4 shows the data for all our experiments, together with the heat-transfer coefficients of [3, 4]. The mass-transfer coefficients for the different gases, phase speeds, and pressures are in satisfactory agreement. The measurements of [4] are also close to our results. There is some tendency for the point to separate from those of [3].

These results on bubbling can be compared with heat-transfer coefficients in boiling.

The transfer coefficients on gas injection characterize mainly the convective component, whereas in boiling there may be an important additional contribution from evaporation, which means that the heat-transfer coefficients in boiling will usually be larger than those on bubbling. Figure 4 illustrates this, where the solid line gives the heat-transfer coefficients of [7] for boiling in water in the near-critical state.

The ordinates for a given Ku show that the dimensionless transfer coefficients in bubbling and boiling are similar only for $\mathrm{Ku} \leqq 0.15$. At higher Ku (for example, $\mathrm{Ku} = 1$), as much as 50% of the heat is transferred by evaporation. This may be important in elucidating transport processes in fast reactions involving gas production.

NOTATION

ρ, density, $\mathrm{kg/m^3}$; ν, kinematic viscosity, $\mathrm{m^2/sec}$; D, diffusion coefficient, $\mathrm{m^2/sec}$; β, mass-transfer coefficient, m/sec; α, heat-transfer coefficient, $\mathrm{W/m^2 \cdot K}$; σ_c, standard deviation in mass-transfer coefficient, m/sec; σ, surface tension, N/m; u, speed, m/sec; λ, thermal conductivity, $\mathrm{W/m \cdot K}$; c_p, specific heat, $\mathrm{J/kg \cdot K}$; g, acceleration due to gravity, $\mathrm{m/sec^2}$; $\mathrm{Re}_2 = u_2 d/\nu_2$; d, diameter of sphere, m; $\mathrm{Sh} = \beta d/D$. Subscripts: 1, gas; 2, liquid.

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