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# SHORTER COMMUNICATIONS

## MASS TRANSFER BETWEEN A FALLING LIQUID FILM AND A PLANE VERTICAL SURFACE

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### NOMENCLATURE

$a_{g,x}, g$, component of gravitational acceleration in the direction of flow [cm/s$^2$];
$D$, diffusion coefficient [cm$^2$/s];
$\bar{g}$, average mass-transfer coefficient [g/cm$^2$s];
$K_L$, coefficient of mass transfer between solid surface and flowing film [cm/s];
$L, X$, length of mass-transfer surface [cm];
$L^+$, dimensionless length;
$N_{Re}$, Reynolds number defined as $N_{Re} = \Gamma/\mu$;
$N_{Sc}$, laminar Schmidt number, $= \mu/\rho D$;
$N_{Sc,T}$, turbulent Schmidt number, $= 0{\cdot}9$;
$\bar{S}$, dimensionless average conductance.

Greek symbols

$\Gamma$, mass flow rate of liquid per unit width of film [g/cm·s];
$\delta$, average film thickness [cm];
$\delta^+$, dimensionless mean film thickness, $= \delta^{\frac{1}{3}} a_{g,x}^{\frac{1}{3}} \rho/\mu$;
$\mu$, viscosity of liquid [g/cm·s];
$\rho$, density of liquid [g/cm$^3$].

### INTRODUCTION

A RECENT paper by Iribarne, Gosman and Spalding [1] has presented a theoretical and experimental treatment of mass transfer between a falling liquid film and a wall. The purpose of the present communication is to report results of a similar research undertaken contemporarily and in a different experimental arrangement so that a comparison of the two sources of data is permitted. The present work was motivated by the general lack of mass-transfer data in this type of system, and more particularly by the need to provide a sounder basis against which data for a recently published electrochemical investigation of the hydrodynamics of liquid films on serrated grid packings might be evaluated [2]. In this latter study assumptions were made concerning the nature of the flow on packings based on theoretical expressions for which there had been no experimental confirmation in well defined geometric and hydrodynamic conditions.

### EXPERIMENTAL

In the present work therefore the apparatus was so designed as to be similar to the grid packing experiments whilst also being more regular and controlled. Short nickel electrodes to act as cathodes of lengths 0·15, 0·30, 0·47 and 0·96 cm and 4 cm in width were fixed in the surface of individual vertical plane perspex plates along with a larger downstream nickel anode. Feed of the electrolyte liquid to the plate was effected by means of overflow from a trough controlled by an adjustable distribution plate parallel to the experimental plate. The cathodes were positioned 6 cm downstream from the end of the distribution plate. Limiting electrolysis currents for the reduction of ferricyanide ions from an equimolar solution of potassium ferricyanide and ferrocyanide with 2 M sodium hydroxide were measured at 21°C over a Reynolds number ($\Gamma/\mu$) range of 15–550 and in two concentrations of ferricyanide, 0·01 and 0·1 M. Some 120 experimental points were determined.

### RESULTS AND DISCUSSION

In order that comparison might be made with the grid packing experiments the mass-transfer coefficients, $K_L$(cm/s), were calculated and plotted for constant Schmidt numbers and single electrode lengths against Reynolds number. A very similar behaviour to that of the [2] results was observed, the data conforming closely to the $\frac{1}{3}$ slope throughout the Reynolds number range and lying an average of 6·5 per cent below the Lévêque line.

In comparing the present data with those of Iribarne *et al.* it must first be pointed out that equation (8) of [2], i.e.

$$\frac{K_L X}{D} = 0{\cdot}784 \left(\frac{\mu D}{\rho}\right)^{\frac{1}{3}} \left(\frac{X^2 g \rho^3}{\mu^2}\right)^{\frac{1}{6}} \left(\frac{4\Gamma}{\mu}\right)^{\frac{1}{9}}$$

may be shown to be equivalent to equation (2.3.2) of [1], i.e.

$$\bar{S} = 0{\cdot}807\ L^+/(N_{Sc}/N_{Sc,t})^{\frac{1}{3}}$$

where in the notation of that paper

$$\bar{S} = \frac{\bar{g}\, N_{Sc}}{(\mu\rho^2 a_{g,x})^{\frac{1}{3}}\delta^{+\frac{1}{3}}} \quad \text{and} \quad L^+ = \frac{L}{N_{Sc,t}}\left[\frac{a_{g,x}\rho^2}{\mu^2}\right]^{\frac{1}{3}}\delta^{+\frac{1}{3}}.$$

We have plotted our data in the $\bar{S} - L^+$ form for the two values of Schmidt number employed in Figs. 1 and 2. Diffusivity values were taken from the data of **Bazan** and Arvia [3]. The data are seen to lie consistently below the theoretical Lévêque line falling an average of 8 per cent lower. The points are generally rather lower than those of Iribarne *et al.* and exhibit a little more scatter, and this probably reflects the greater instability of the film on the flat plate with the distribution method employed, and also the slightly greater difficulty in obtaining strictly reproducible results with short mass-transfer sections and the very thin mass-

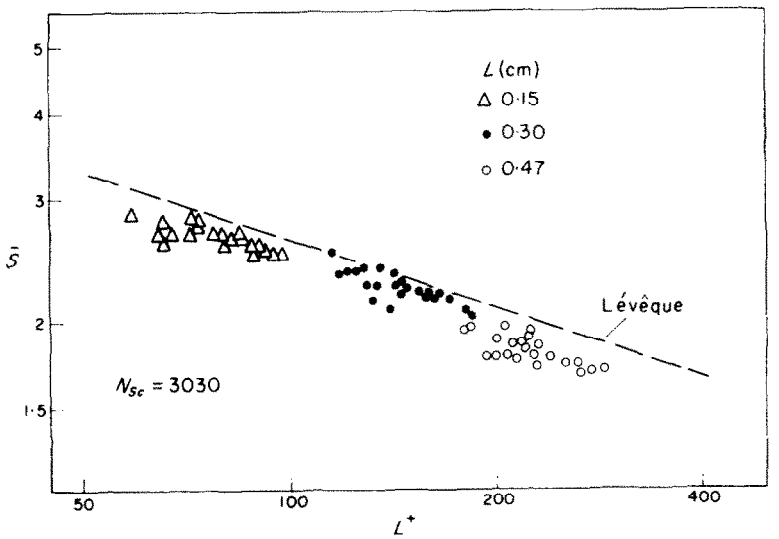


FIG. 1. Mass-transfer data in the $\bar{S} - L^+$ form, $N_{Sc} = 3030$.

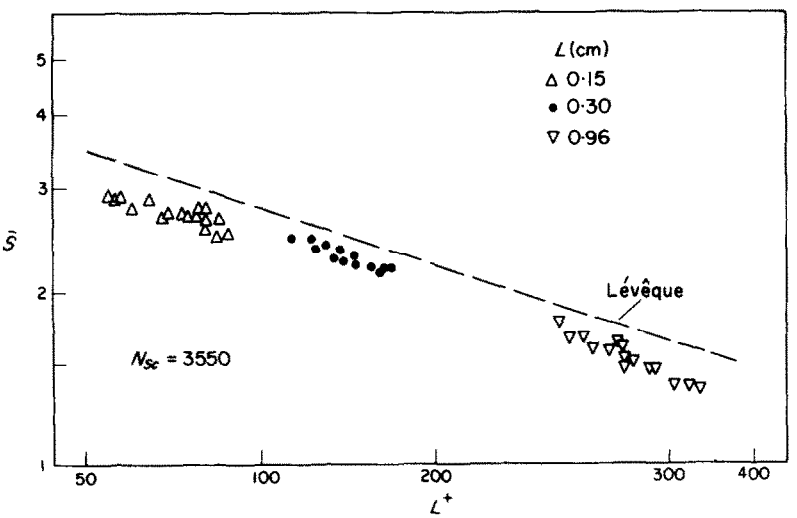


FIG. 2. Mass-transfer data in the $\bar{S} - L^+$ form, $N_{Sc} = 3550$.

transfer boundary-layer conditions prevailing. When compared with the dissolution data of Kramers and Kreyger [4] plotted in $\bar{S} - L^+$ form, the present data are less scattered and approximate more closely to the Lévêque line over the range studied.

As Fulford [5] makes clear many values of $(\Gamma/\mu)$ have been suggested at which turbulence may commence, the lower limit generally lying between 250 and 400. Iribarne *et al.* state that their data are well described by the laminar Lévêque solution up to $\Gamma/\mu = 700$ and in the present work no effect of turbulence is noted up to 550. Dukler [6] has criticised the concept of a film being in either purely laminar or turbulent motion and urges that a combined mechanism must always be considered. The fact that only laminar mechanisms have been observed up to $Re = 550$ and 700 does not necessarily conflict with reports of turbulence being detected as low as 250, since the ionic mass transfer is controlled by the region of flow close to the wall.

A number of further experiments were carried out with the leading edge of the electrode at varying distances from the end of the distributor and as close as 2·4 cm from it. As with the Series 2 data of the grid packing work [2] no difference was observed within the limits of experimental error between the performance of these electrodes and those placed further down the plate and this indicates development of the hydrodynamic conditions. The provision of 38·5 cm as entry length by Iribarne *et al.* was therefore over cautious, but did cause their experiments to be performed in the region where ripples had developed, whereas our work was carried out in the pre-rippling section, this fact constituting another fundamental difference between the two researches.

In conclusion we observe an essentially similar liquid–solid falling film mass-transfer behaviour to that of Iribarne *et al.*, using a flat plate system, shorter electrodes, and mass-transfer sections positioned closer to the point of liquid distribution.

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# THE INFLUENCE OF STRONG ADVERSE PRESSURE GRADIENTS ON THE EFFECTIVENESS OF FILM COOLING

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## NOMENCLATURE

$c$, mass concentration of helium in secondary air;
$c_f/2$, wall shear stress coefficient, $\tau_S/\rho u_1^2$;
$c_P$, surface pressure coefficient, $(p_S - p_1)/\frac{1}{2}\rho u_1^2$;
$p_S$, wall static pressure;
$p_1$, value of $p_S$ at station 1;
$Re_C$, injection Reynolds number, $\rho v_S x_C/\mu$;
$m$, injection ratio, $v_S/u_1$;
$u_G$, free-stream velocity;
$u_1$, value of $u_G$ at station 1;
$v_S$, average injection velocity;
$x$, distance measured along the plate;