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MASS TRANSFER IN WAKE-INTERFERENCE FLOWS

by

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SUMMARY

This paper is concerned with gas absorption into thin films flowing in wake-interference flow over rough surfaces. The velocity fluctuations and the turbulence patterns are examined in relation to the movements of particles and fundamental turbulence theory. The presence of traces of surface-active agents is also discussed.

One interest of wake-interference flow is in the absorption of oxygen into, or the desorption of CO_2 or other gases from, water flowing over surfaces of controlled macroscopic roughness.

Another interest is in the high lateral dispersion which can be achieved with such flows.

The optimum geometry of packings for mass-transfer columns is also discussed.

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Glossary of Terms

B_f	mean thickness of falling liquid film(m. or mm)
D	diffusion coefficient (m^2. $sec.^{-1}$)
D_E	eddy diffusion coefficient (m^2. sec^{-1})
k_L	mass transfer coefficient on the liquid side (m. sec^{-1})
Re	Reynold number ($= v_m B_f/\nu = V_b/\nu$)
V_b	volumetric flow rate per unit breadth ($m.^2 sec.^{-1}$)
v_m	mean velocity of flow (m. sec^{-1})
v_s	surface velocity (m. sec^{-1}.)
v_{str}	velocity of stream of liquid (m. $sec.^{-1}$)
v'_x	fluctuation velocity in x direction (m. $sec.^{-1}$)
x	direction of flow
y	direction normal to free surface
z	direction across plate, perpendicular to x and tangential to the surface
$\tilde{\Delta} z$	root mean square, spreading in z direction (m.)
ν	kinematic viscosity (m^2. $sec.^{-1}$).
ρ	density of liquid (kg. $m.^{-3}$)
σ	surface tension (kg. sec^{-2})
τ_o	tangential stress exerted on surface (kg. m^{-1}. $sec.^{-2}$)

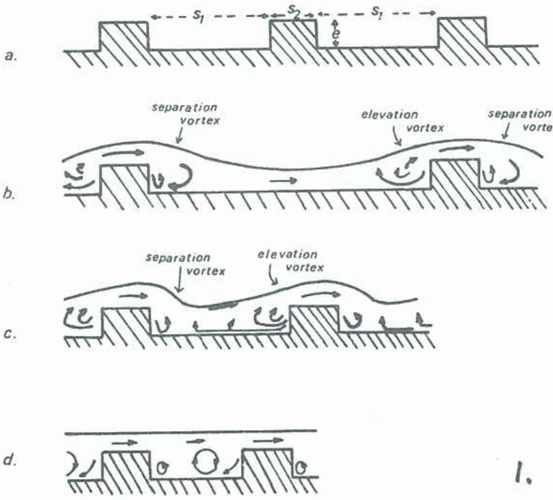

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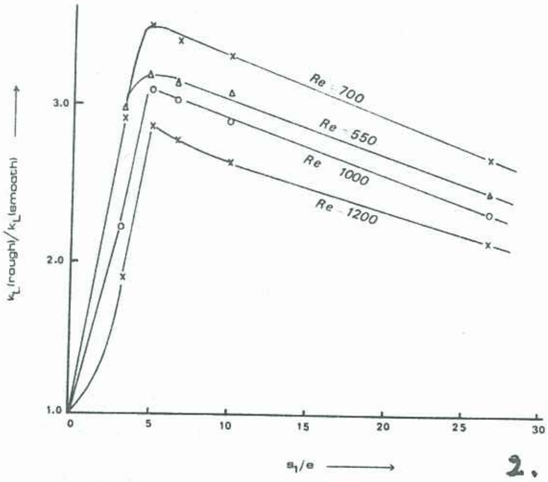
Fig. 1 (a) The definitions of s_1, s_2 and e.
(b) "isolated roughness" flow.
(c) Wake-interference flow.
(d) Quasi-smooth flow.



2.

Fig. 2. Mass transfer coefficient for carbon dioxide gas absorping into a film of pure water on a rough plate, at various values of s_1/e.

Introduction

The flow of a liquid film down a smooth inclined plane ceases to be laminar when Re exceeds about 500. Here Re is defined as the ratio of the volumetric flow rate per unit breadth (V_b) to the kinematic viscosity, ν .

With roughness elements on the surface, however, eddying can be induced at quite low values of Re, and at all flow rates the rate of gas absorption into a liquid film flowing over suitable roughness elements is enhanced (1, 2). This can have important consequences for the aeration of water, the design of packings for absorption columns, and the optimum roughness of the walls of heat exchangers (3).

The particular type of flow which gives most turbulence in the surface is that called "wake-interference" flow (4). Here the roughness elements are spaced in such a manner that the separation or wake vortex behind each roughness element interferes with the approach vortex to the next element (Fig. 1).

The optimum form of geometry is apparently that of rectangular transverse roughness elements: the sharp edges of these elements are particularly important in promoting eddying. The optimum spacing ratio is $6.7 \geq (s_1/e) \geq 5$ for both water (2) and white spirit (5), and the wake-interference flow that results from this arrangement is for Re values up to 1200. Uniform wake-interference flow was established at Re = 225 for white spirit, and at 350 for distilled water. This greater tendency to wake-interference flow for white spirit may well be related to its lower surface tension (26 mN. m^{-1}.), as against 72 mN. m^{-1}. for water.

The periods of the pulsations of the flickering of the interference pattern of the vortices in our work are about 0.1 sec. for water at Re = 350, reducing to 0.06 sec. at Re = 1000 (2). But from the mass transfer results it can be deduced (1) that eddying to the surface (i. e. "surface renewal") occurs rather faster than this observed flickering.

Theory of Mass Transfer

A quantitative theory of gas absorption into turbulent liquids was put forward by Levich (6). This supposes that it is the Prandtl eddies which are responsible for most of the mass-transfer. Indeed, the visualization experiments of Prandtl and of later workers, placing particles of talc or other material on the interface of a turbulent liquid, were taken as confirmation of Prandtl's original idea of "lumps" of liquid being transposed. In a recent paper, Bradshaw (7) points out that the mixing length concept is a good model where vertical motion is suppressed, i. e. in the "local equilibrium" in wall layers and in the flow patterns at free surfaces. Thus it is not unreasonable to use the Prandtl eddy mixing length concept as a basis for a theory of gas absorption.

In quantitative terms, if the eddy fluctuation velocities in the free surface in the direction of flow are independent of the depth y below the surface, the equation of continuity gives

$$\tilde{v}_y{}' = y\, v_o/\lambda \tag{i}$$

where $\tilde{v}_y{}'$ is the root mean square of the velocity fluctuations in the y direction, v_o is the shear stress velocity in the falling film and λ is the thickness of a zone near the surface within which turbulence is damped. The velocity v_o is the velocity fluctuation in the bulk phase, near the surface. As they move towards the surface, the eddies are restrained by the surface tension σ, and

$$\rho v_o^2 = 2 \sigma/R \qquad \text{(ii)}$$

where R is the radius of curvature of the local deformation. We have shown experimentally (1) that $R = 2\lambda$, and that, following Levich (1, 6)

$$k_L = 0.32\, D^{\frac{1}{2}}\, v_o^{3/2}\, \rho^{\frac{1}{2}}\, \sigma^{-\frac{1}{2}} \qquad \text{(iii)}$$

Here k_L is the mass-transfer coefficient on the liquid side, D is the molecular diffusivity and ρ is the density of the liquid.

Application of eq. (iii) has shown (1, 2, 5) that the k_L values predicted are rather smaller than calculated on the assumption that (calculated from τ_o) v_o is the fluctuation velocity in the general region of the free surface. Agreement between theory and experiment is achieved for white spirit if v_o is replaced in eq (iii) by $4\, v_o$, i.e. if it is assumed that v' can be as great as 40% of v_m. The physical justification for this assumption is explained below. For water, the agreement is good only if v_o is replaced by $5\, v_o$.

The effect of the surface geometry on k_L is shown in Fig. 2.

Flow Patterns

For the flow of films of liquid over smooth plates, the waves which form spontaneously (below Re = 500) can increase the rate of gas absorption by 2 to 3.5 times. When turbulent flow is approached (above Re = 500) there is a confused pattern of capillary waves, and the surface velocity approaches that of the mean linear flow rate.

For turbulent flow over single cavities, it has been shown (8) by the photolysis method that the local eddy velocities within the liquid film can indeed by as great as 40% of v_m, and this has subsequently been confirmed (9) for flow of thin liquid films over an array of rectangular roughness elements.

Dr. R. W. Makepeace and I have recently made a high-speed photographic study of the flow patterns within water flowing over ridged plates. For a plate of e = 1.9 mm, $s_1/e = 6.7$ with flow at Re = 1650 the mean velocity v_m of flow of the water in the x-direction (along the plate) was 0.33 m. sec^{-1}. The inclination of the plate was 17^o to the horizontal. The movements of magnesium particles in the body of the liquid showed clearly the great fluctuations in the wake-interference flow characteristic of this roughness geometry. Reverse velocities in the x-direction were observed to be up to 50% of v_m. Fig. 3 shows the regions of observed recirculation, which are in accord with the general picture of Fig. 1.

However, for the surface velocities v_s in wake-interference flow, Orridge (5) showed from high-speed photography of small particles of expanded silica ("Permarock") that these velocities do not reverse: they fluctuate, however, by up to 30% about the mean (Fig. 4).

The highest of these surface velocities corresponded to the regions of separation vortices, while the lowest surface velocities correspond to the regions of the elevation vortices.

Eddy Diffusivities

Lateral mixing might be expected to be much higher than otherwise in wake-interference flow and this is indeed found (Figs 5 and 6). Quantitatively, one applies

$$D_E = \frac{(\widetilde{\Delta} z)^2 \, v_{str.}}{2\,x}$$

As a first approximation, Dr. Orridge and I (5) took v_{str} to be the measured mean v_s values for these highly turbulent liquids. In these studies, the inclination of the plates was 24^o to the horizontal. For water, D_E is 2×10^{-4} m^2. sec^{-1}. for the flow over the rough plate at Re = 1100, varying approximately as $Re^{1.0}$, and about 5 times greater than for turbulent flow (at the same Re) over a smooth plate. Since D_E is typically about $10^5 D$, transport within the bulk liquid will be entirely by the turbulence eddies. The implication of the fact that D is controlling for absorption of a gas at the free surface is therefore that the eddies must be very severely damped as they approach the free surface ($y = o$) as implied by eq. (i).

For white spirit D_E is 2×10^{-4} m^2. sec^{-1}. at Re = 780, i.e. the values for a given Re are about twice as high as for water, perhaps because of the lower surface tension of the white spirit.

For the dispersion of sediment, it is clear that one requires D_E to be as high as possible. From the results of Dr. Orridge and Dr. Makepeace, it is therefore clear that the particles should not fall near the bottom of the stream if they are to be dispersed to the maximum. They should be dispersed (e.g. by flotation) to have at least neutral buoyancy, otherwise the eddies may not disperse them. The dispersion will clearly be much greater if turbulence levels approaching that of wake-interference flow can be attained. Waves are clearly (Fig. 5) much less effective than is the turbulence of wake-interference flow (Fig. 6).

Surface Active Additives

Fig. 7 shows that, for a water film in wake-interference flow, the mass transfer coefficient of absorbing gas is reduced by "Aerosol OT". The effect is largely due to the tangential stresses in the surface reducing eddy movements in the plane of the surface, i.e. reducing the surface renewal. (This is confirmed by the dependence of k_L on D: if $k_L \propto D^{\gamma}$, it is found from studies of different gases that $\gamma = 0.5$ for clean surfaces, but $\gamma = 0.64$ in the presence of 10 ppm of "Aerosol OT". For solid surfaces $\gamma = 0.67$).

But that the fractional reduction in k_L is greater in wake-interference flow than in turbulent flow over smooth plates (1) shows that the surface tangential stresses do reduce somewhat the wake-interference movements near the surface. Dr. Orridge (5) confirmed this by close-up high-speed photography: the surface of the liquid in wake-interference flow was seen to be much smoother with the higher concentrations of surface-active agent, there being fewer small disturbances on the surface.

For laminar films, the effect of surface-active agents is to reduce the natural wave formation and so reduce still further the lateral mixing (Fig. 8).

Eddy-promoting packings

The flow of water over a suitable array of roughness elements can lead to considerably enhanced efficiency. The turbulent fluctuations not only cause good surface renewal and so enhance heat and mass transfer at the free surface, but the lateral fluctuations also lead to excellent distribution characteristics. The small-scale roughness elements produce the liquid turbulence and assist water distribution. The air turbulence is promoted by the larger roughness elements of the larger scale steps on the packing. (Fig. 9)

With such packing, a cooling tower with 17 feet of wood grid can be operated instead with 8 feet of a suitable plastic packing with roughened surfaces, with double the water flow rate. Such packings, developed by Mr. R. Priestley in the Department of Chemical Engineering at Birmingham, are now available commercially under the trade names of "Coolstak" (Mass Transfer Ltd.) and "Flocool" (I.C.I. Ltd.).

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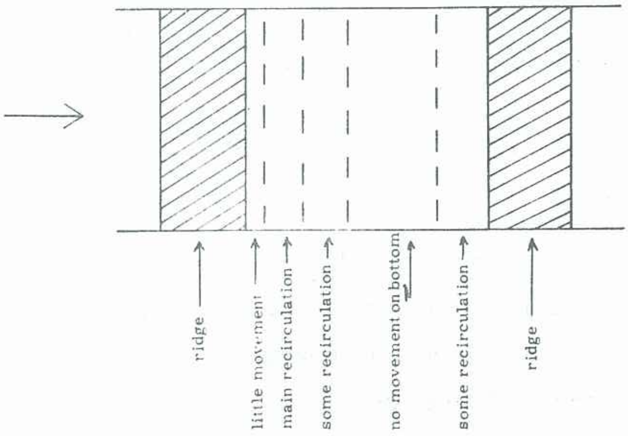


Fig. 3. Findings of Dr. R. W. Makepeace

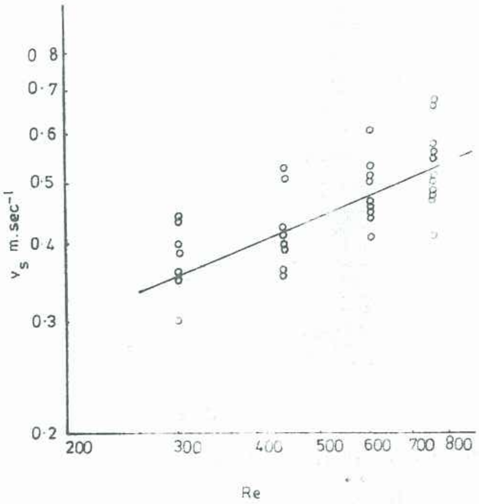
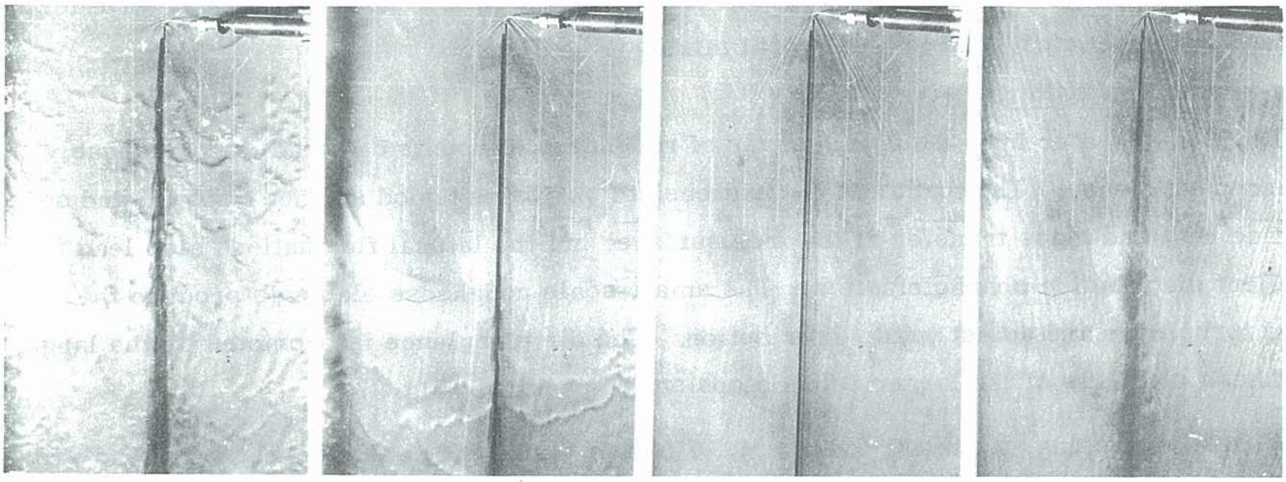


Fig. 4. Surface velocities of white spirit film on rough plate inclined at 24°
(Dr. M. A. Orridge)



Re 285 Re 380 Re 730 Re 1354

Fig. 5. Dispersion of dye streak for flow of water over smooth plate incline at 24°. Gravity waves (e.g. at Re = 285) and turbulence (e.g. at Re = 1354) clearly cause only slight dispersion (5).

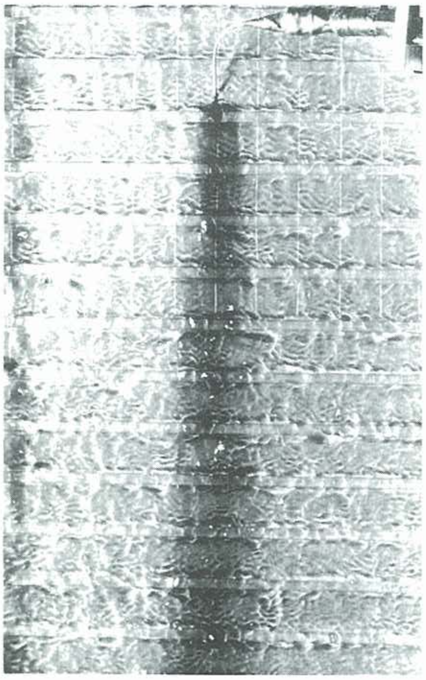


Fig. 6. Flow of water over rough plate at Re = 435. Inclination 24°(5)

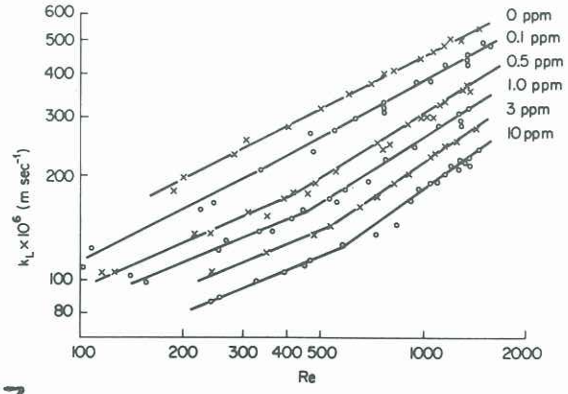


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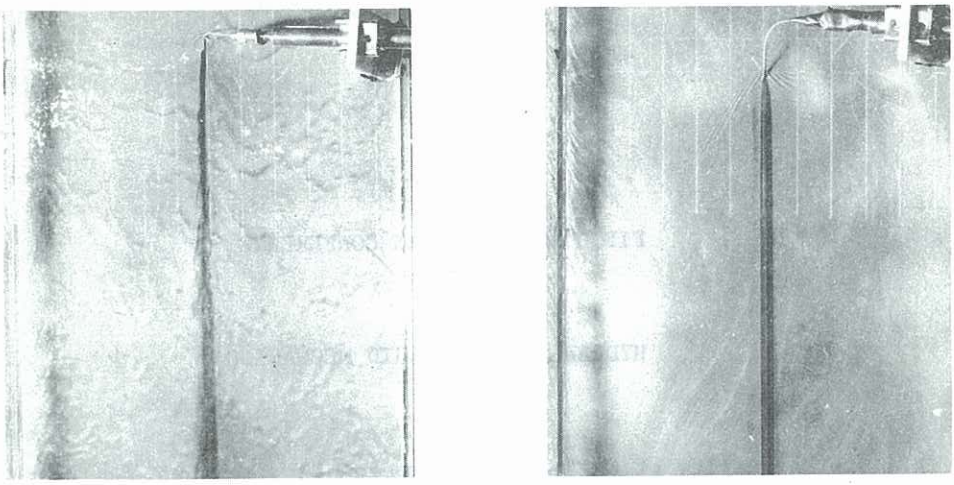
Fig. 7. Log-log plot of k_L versus Re for various concentrations of "Aerosol OT" in water flowing over rough plate at 24° (5).



a) Re 285. Clean.

b)Re 285. 3ppm surfactant.

Fig. 8. Effect of "Aerosol OT" on flow of water over a smooth plate inclined at 24°. The surface-active agent clearly reduces both the wave formation and the spreading of the dye trace (5).

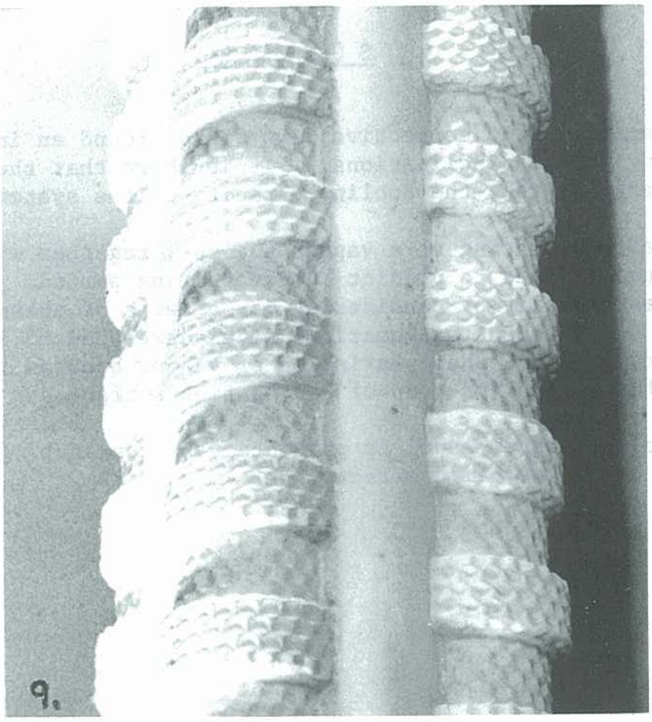


Fig. 9. Unit of packing of "Coolstak", which gives good liquid distribution and air turbulence, but without large pressure drops (R. Priestley).