THE EFFECT OF WAVE-DAMPING ON THE SURFACE VELOCITY OF WATER IN A WIND TUNNEL

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Summary

A laboratory wind tunnel has been used to study the movement of the surface of a body of water over which a wind is blowing. The ratio of the surface velocity u_S to the wind velocity V has been measured for both smooth and wavy surfaces at wind speeds between 350 and 750 cm/s. It has been found that this ratio is markedly affected by the damping-out of surface waves. For a wavy surface, as obtained with clean water, u_S/V has a constant value of about $0 \cdot 03$. The damping of the surface waves is achieved by the addition of detergent solution to the water. There is a particular concentration of detergent, and a corresponding surface pressure, at which u_S/V ceases to have this constant value and begins to rise to values around $0 \cdot 045$. For a fully damped surface u_S/V rises linearly with V for low wind speeds and tends to a constant value of $0 \cdot 045$ for wind speeds greater than 550 cm/s. These findings are, to some extent, in conflict with the observations and theories of previous workers.

I. INTRODUCTION

A number of workers, both in the laboratory and on natural water surfaces, have observed and studied the surface drift caused by wind. Keulegan (1951), using a 60 ft wind tunnel, and Van Dorn (1953), on an 800 ft model-yacht pond, both concluded that, for turbulent conditions (namely, for Reynolds numbers greater than 30 000),† the surface moves with a velocity about 1/30 that of the wind velocity. Both found that this value of the ratio u_S/V was the same for all wind speeds and was independent of the presence or absence of waves on the water surface. Vines (1962) and McArthur (1962), separately, measured the ratio u_S/V by observing the drift of monomolecular films spread on the exposed surfaces of lakes, yet they obtained differing results. Vines obtained a value in close agreement with that of Keulegan and Van Dorn whilst McArthur obtained values between $0 \cdot 04$ and $0 \cdot 07$ and claimed to have detected an *acceleration* of the film slicks on the surface. Davies (1962) has suggested an explanation of this acceleration in terms of a transfer of energy, where slicks are present, from the wind to laminar layers of water just below the surface.

It will be shown in this paper that, contrary to the observations of Keulegan and Van Dorn, there is a marked difference in the behaviour of the surface velocity according to whether there are surface waves present or not. It is known from Vines (1960) that monomolecular surface films produce very effective damping of surface waves and so it should be expected that measurements of u_S/V derived from observing

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† In Keulegan's and Van Dorn's work the Reynolds number R is taken as $u_S H/\nu$, where u_S is the surface velocity, H is the liquid depth, and ν is the kinematic viscosity of the liquid.

the movement of film slicks will be affected by this variation in behaviour between wavy and smooth surfaces. The findings of McArthur and Davies will be discussed from this point of view.

II. Experimental

In a previous paper, Fitzgerald (1963) described a laboratory wind tunnel which was used to study the effect of the shearing stress of the wind on the surface of a water channel 6 ft long, 6 in. wide, and 6 in. deep. The same wind-tunnel arrangement was used for the present investigation of the relation between surface velocity and wind velocity. Measurements of wind speeds were made with a pitot-static tube and inclined micromanometer. All wind speeds were measured at a height of $z = 2 \cdot 0$ cm above the surface of the water and at a point midway down the length of the channel.

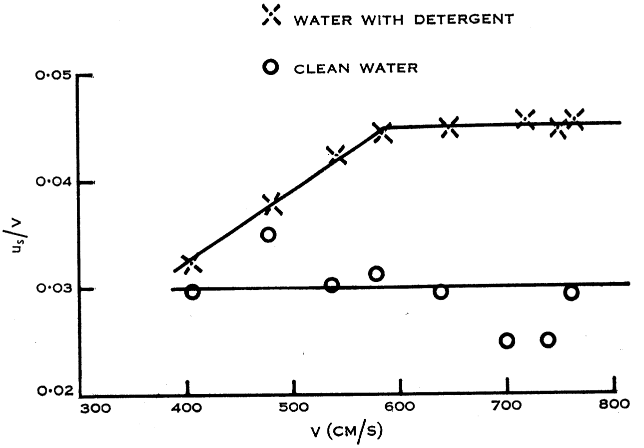

Fig. 1.—Variation of u_S/V with wind speed.

The values of the surface velocities were obtained by timing the travel of particles of talc dropped on to the surface of the water at the upwind end of the channel. Very small particles of foam-styrene could be used for this purpose but care must be taken to see that they do not become water-logged. If this happens their movement does not truly represent the movement of the surface for they become partially submerged.

III. The Ratio u_S/V

The dependence of the surface velocity u_S, as measured in the manner described above, on the wind velocity V has been studied for the various conditions of the surface from that of clean water to a fully damped condition. The damping of the surface waves was produced by the addition of detergent solution to the water.* It has been found, in this work, that the presence of detergent in the water considerably affects the relationship between u_S and V, and that, in fact, the magnitude of the surface current is dependent on the concentration of detergent in the water.

* The detergent used in obtaining the results given here was the commercial detergent Comprox. However, similar results were obtained using other available detergent solutions.

In Figure 1, u_s/V is plotted as a function of V for both clean water and water to which excess detergent was added. (The depth of water in the channel was constant at $H = 13 \cdot 3$ cm for all these measurements.)

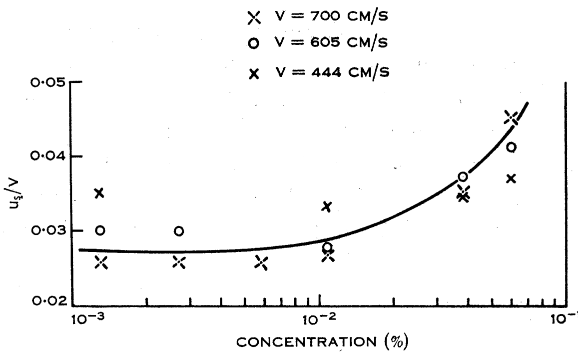

Fig. 2.—The ratio u_s/V as a function of the concentration of detergent in the water.

For the clean water case, values of around $0 \cdot 03$ were obtained for u_s/V for all wind speeds. In the case of the fully damped surface, the ratio u_s/V rose linearly with wind speed, reaching a maximum value of $0 \cdot 045$ for wind speeds greater than about 550 cm/s. This gradual increase in u_s/V for wind speeds up to 550 cm/s is most likely due to its dependence on the Reynolds number until a certain value of R is reached (Schiller 1925). Experimental difficulties involved in measuring the velocity of a wavy surface, particularly at low wind speeds, account for the scatter in the results obtained with clean water. However, each point shown in Figure 1 represents

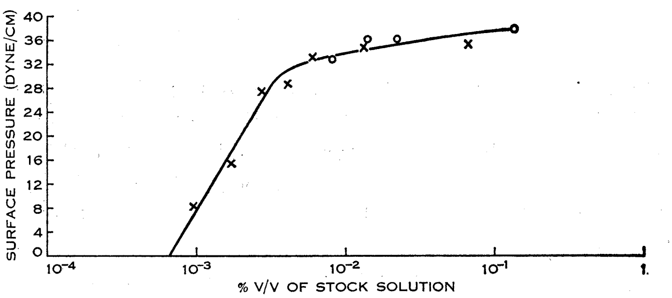

Fig. 3.—Relation between concentration of detergent and surface pressure (after Fitzgerald 1963).

the mean of at least 10 individual measurements of the surface velocity. For clean water, the error involved in each determination was of the order of $\pm 10\%$, whilst the points for the fully damped surface were highly reproducible and were obtained with an accuracy of better than $\pm 1\%$.

When the surface velocities were measured at various wind speeds for a range of concentrations of detergent in the water, it was found that the surface velocity for a given wind speed remained constant until a particular concentration of detergent was reached, when there was a sharp increase in u_s. Figure 2 shows u_s/V, for three different values of V, plotted against the concentration of detergent. (The conditions obtaining with the lowest concentration of detergent, namely, about $10^{-3}\%$, are virtually the same as those for clean water; hence the scatter in the experimental points, especially for low wind speed.) We see, therefore, that the ratio u_s/V is dependent on the concentration of detergent present. The surface pressures, corresponding to the concentrations of detergent used, are shown in Figure 3 (after Fitzgerald 1963). By comparing Figures 2 and 3, it can be seen that the marked change in the slope of each curve occurs at a concentration of the solution (about $10^{-2}\%$) which gives rise to a surface pressure of about 33 dyne/cm. This can be seen more clearly by replotting the points of Figure 2, using the surface pressure π as the abscissa instead of the concentration. This is shown in Figure 4. The surface pressure

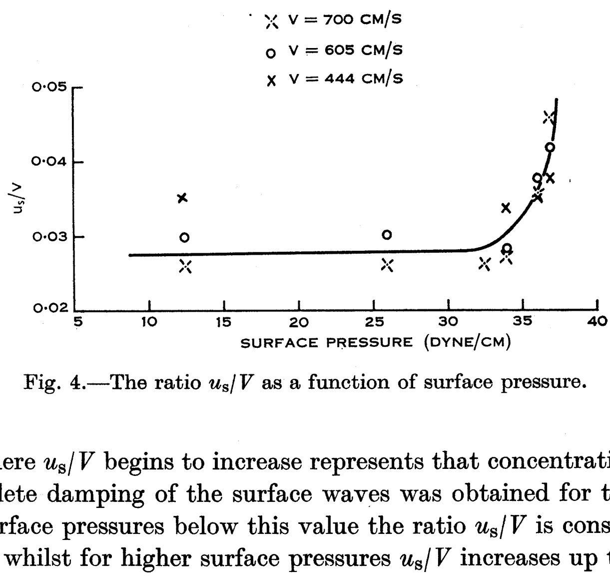

Fig. 4.—The ratio u_s/V as a function of surface pressure.

at the point where u_s/V begins to increase represents that concentration of detergent at which complete damping of the surface waves was obtained for the fastest wind speeds. For surface pressures below this value the ratio u_s/V is constant and in the region of $0 \cdot 03$, whilst for higher surface pressures u_s/V increases up to values of the order of $0 \cdot 045$.

IV. Discussion

From these results, it would appear that, in both Keulegan's and Van Dorn's work, the amount of detergent added to the water must have been only just sufficient to produce damping of the waves and so must have corresponded to our surface pressure of about 33 dyne/cm. Thus they did not observe the increase in u_s/V for concentrations in excess of this critical value. The value of about $0 \cdot 03$ for u_s/V found here for clean, wavy water is in agreement with Keulegan's results. Furthermore, these results were obtained for Reynolds numbers of the order of 30 000, where $R = u_s H/\nu$, as was the case in Keulegan's and Van Dorn's experiments. By lowering the value of H, Reynolds numbers of the order of 3000 were obtained. However, even for depths of $H = 1 \cdot 5$ cm, no significant changes could be detected in the results of Figure 1.

Vines, in his measurements on the drift of surface films on the surface of a lake, also obtained values of u_s/V of the order of 0·03. McArthur, on the other hand, has suggested that, where surface films are present, u_s/V increases with time or, in other words, that the surface undergoes an acceleration for a given wind speed. In explaining McArthur's observations, Davies (1962) suggests that when the waves are damped by the surface-active agent, conditions of laminar flow exist at the surface and in the underlying water layers and that the flow of water under the surface leads to an increase in momentum and so to an acceleration of the surface. Although, as has been seen in Fitzgerald (1963), it is clear that conditions near the surface are considerably affected by the presence of surface-active material, it will be shown in a subsequent paper that laminar flow conditions near the surface do not extend right down into the body of the water when the surface is smoothed, as proposed by Davies.

Whereas Vines' measurements of the drift of film slicks were made on the trailing edge of such slicks and so were probably unaffected by the damping of the surface, McArthur's observations were made on the leading edge of the slicks. Apart from introducing errors due to the spreading rate of the cetyl alcohol film itself, it would seem that the varying values of u_s/V obtained by McArthur, using this method of observation, are very likely to be due to differing conditions at the points of measurement.

V. Acknowledgments

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