WIND-INDUCED STRESSES ON WATER SURFACES
A WIND-TUNNEL STUDY

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[*Manuscript received May* 28, 1963]

Summary

A laboratory wind tunnel has been used to study the effect of wind on a water surface. The surface shearing stress τ_0 and the slope of the surface induced by wind have been measured. Values of the surface stress, in good agreement with each other, have been obtained from: (*a*) the velocity profile of the wind above the water surface, (*b*) the measured values of surface slope or set-up, and (*c*) the spreading characteristics of surface films. The drag coefficient, $C_h = \tau_0/\rho u_h^2$, was found to be constant for wind speeds up to about 412 cm/s and then to rise gradually for higher wind speeds.

When the surface waves are damped out by the addition of small amounts of surface-active material to the water, the shearing effect of the wind on the surface is somewhat modified. If detergent solution is used for this purpose, there is a critical concentration at which conditions in the boundary layer near the water surface appear to undergo a marked change in character.

I. Introduction

In experiments on the reduction of evaporation from water storages, monomolecular films of long-chain alcohols are spread on the water surface. It has been pointed out by a number of workers, including Mansfield (1962), Timblin, Florey, and Gartska (1962), Vines (1962), and others, that a recurring problem in this work is the removal of the films from the surface by wind. Thus it is necessary that as much information as possible should be obtained about the effect of wind both on the surface of the water and on the surface films themselves.

In order to be able to study this effect more closely than is possible on an open water storage, a small laboratory wind tunnel was constructed in which wind speeds up to about 7 m/s could be obtained over a water surface. With the aid of such a tunnel the following phenomena can be investigated:

(*a*) the nature of wind-induced surface stresses,

(*b*) the relation between surface velocity and wind velocity,

(*c*) flow characteristics in and below the water surface,

(*d*) the effect of surface films on the rate of evaporation of water under windy conditions, and

(*e*) the effect of wind on the spreading characteristics of surface films.

This paper will deal with the first of these investigations and it is intended to present the results of the others in subsequent papers.

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Other workers who have studied the surface stresses due to wind on confined water surfaces include Keulegan (1951), Francis (1954), and Vines (1959), using wind tunnels, and Van Dorn (1953), using an open pond. There appears to be much disparity between the experimental conditions prevailing and the conclusions drawn from these various studies, and a closer look at the problem seems to be warranted.

II. Wind-Tunnel Design

To obtain a maximum wind velocity of about 700 cm/s (15 m.p.h.), a tunnel was designed having a rectangular cross section of 15 in. by 12 in. and a length of about 9 ft. A 15-in. diameter, duct-axial fan giving 1425 r.p.m. was specified and the wind speed was varied by means of a baffle plate on the down-wind side of the fan. Figure 1 shows the main features of the tunnel design.

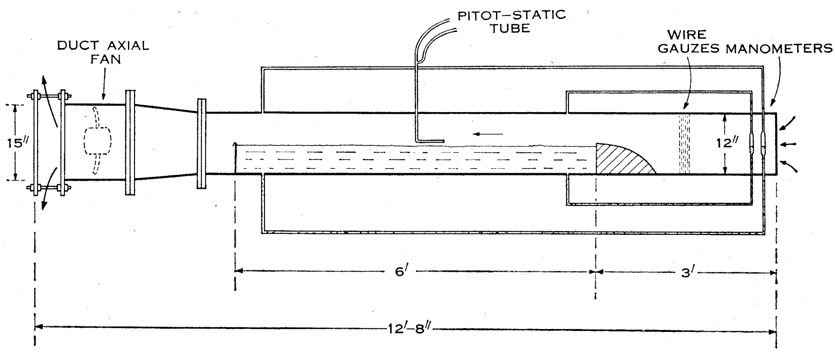

Fig. 1.—Wind-tunnel design.

The water channel for use in the wind tunnel was constructed with an end-section of 6 in. by 6 in. and a length of 6 ft. All inside surfaces and the top edges of the brass channel were spray-coated with Fluon (PTFE) to enable a clean water surface to be readily obtained. A piece of fine wire gauze was placed in the water at the leeward end of the channel to damp out the surface waves at that point.

Measurements of wind speed were made with a pitot-static tube and inclined micromanometer. Undesirable fluctuations in the wind speed were reduced by placing wire gauzes at the entrance to the tunnel. According to Taylor and Batchelor (1949) and Townsend (1951), a grid at the entrance to the tunnel will produce turbulence whereas a wire gauze will reduce turbulence. Several screens of relatively coarse gauze will have greater effect than one very fine gauze. Screens of wire gauze (10 wires to the inch) were therefore built up at the open end of the tunnel. Fluctuations in wind speed and pressure difference over the length of the water channel were reduced satisfactorily with six such screens installed.

III. Velocity Profile of Wind above Surface of Water

Velocity profiles were obtained by measuring the wind speed as a function of height, h cm, above the water surface for various fan speeds. These measurements were made at a number of points along the length of the channel, both in the presence of and in the absence of surface waves. Surface waves could be damped out completely by the addition of a small amount of detergent. Figure 2 shows the velocity profiles measured in the centre of the channel for a wave-free water surface and at two different fan speeds (corresponding to wind speeds of about $4\frac{1}{2}$ and 7 m/s respectively). Profiles measured at other points along the channel and also those measured with surface waves present had, essentially, the same features as those shown in Figure 2. These velocity profiles are characteristic of a turbulent flow of air through the wind tunnel. It can be seen that there is little change in the magnitude of u for most values of h.

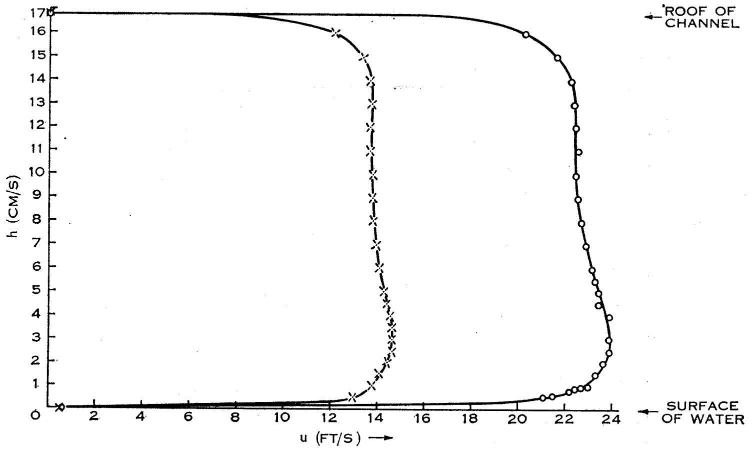

Fig. 2.—Velocity profiles for two different fan speeds and a wave-free water surface.

IV. Methods of Measuring the Surface Stress

(a) *From Velocity Profiles*

The wind profile expression for turbulent flow over an "aerodynamically rough" surface, i.e. when the boundary layer is turbulent right down to the surface, is given by Sutton (1949) as

$$\bar{u} = \frac{1}{k}\left(\frac{\tau_0}{\rho}\right)^{\frac{1}{2}} \ln\left(\frac{z}{z_0}\right) = 5\cdot 757\left(\frac{\tau_0}{\rho}\right)^{\frac{1}{2}} \log\left(\frac{z}{z_0}\right), \qquad z \geqslant z_0, \tag{1}$$

where $\bar{u}$ is the mean wind speed at height z,

k is a non-dimensional constant known as Karman's constant (taken as $0\cdot 4$ in aerodynamic work),

ρ is the density of water,

τ_0 is the shearing stress at the surface, and

z_0 is the "roughness length" and is related to the size of roughness elements on the surface.

Hence, experimental values of the shearing stress at the surface may be obtained from the slope of the plot of wind speed $\bar{u}$ against log z. Figure 3 shows the two velocity profiles of Figure 2 with the z values plotted on a logarithmic scale. It can be seen that a linear relationship between $\bar{u}$ and log z holds only for values of z between $0 \cdot 5$ and $2 \cdot 0$ cm. For heights above the surface of the water greater than $2 \cdot 0$ cm the wind speed is apparently affected by the drag of the roof of the tunnel. Measurements of wind speed in all the work to be described in this paper were made at a height of $z = 2 \cdot 0$ cm above the surface of the water.

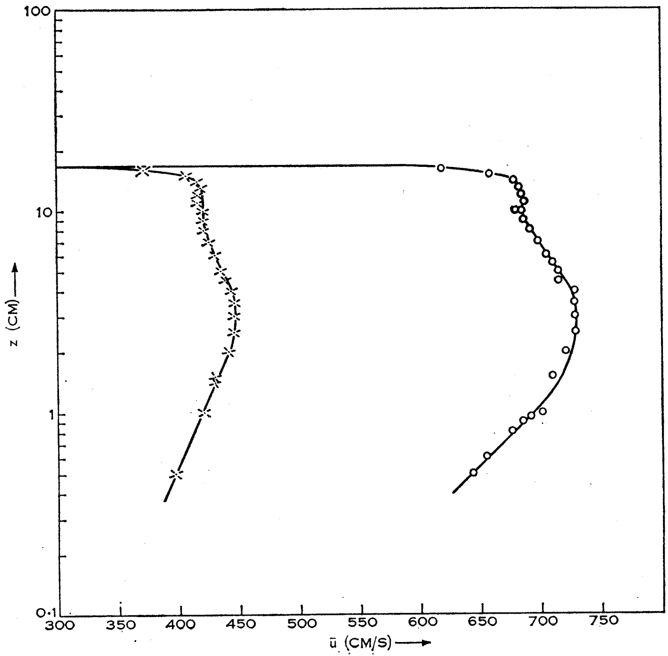

Fig. 3.—Velocity profiles of Figure 2 with z plotted on a logarithmic scale.

Values of τ_0 calculated from velocity profiles, in the manner described above, are given in Figure 4. The shearing stress is plotted here as a function of the wind speed, $\bar{u}$, and was measured at three different fan speeds for both wavy and wave-free surfaces. It can be seen that the values of τ_0 obtained in the absence of waves are lower than those obtained on a wavy surface at the corresponding wind speeds. This modification of the shearing effect of wind when detergent is present in the water will be discussed at greater length in this paper.

(b) *From the Measurement of Set-up*

The surface slope produced by the action of a uniform and steady wind is known as the "set-up". The set-up is defined here as the difference in the displacements of the water levels at the windward and the leeward ends of the channel. These displacements must be corrected for the difference in the air pressure along the length of the channel. The equation relating the set-up S to the surface stress τ_0 has been given by Keulegan (1951) as

$$S/L = n\tau_0/\rho g H, \tag{2}$$

where L is the distance in the channel between measuring points, and H is the depth of water in the channel. n is defined by

$$n-1 = \tau_b/\tau_0, \tag{3}$$

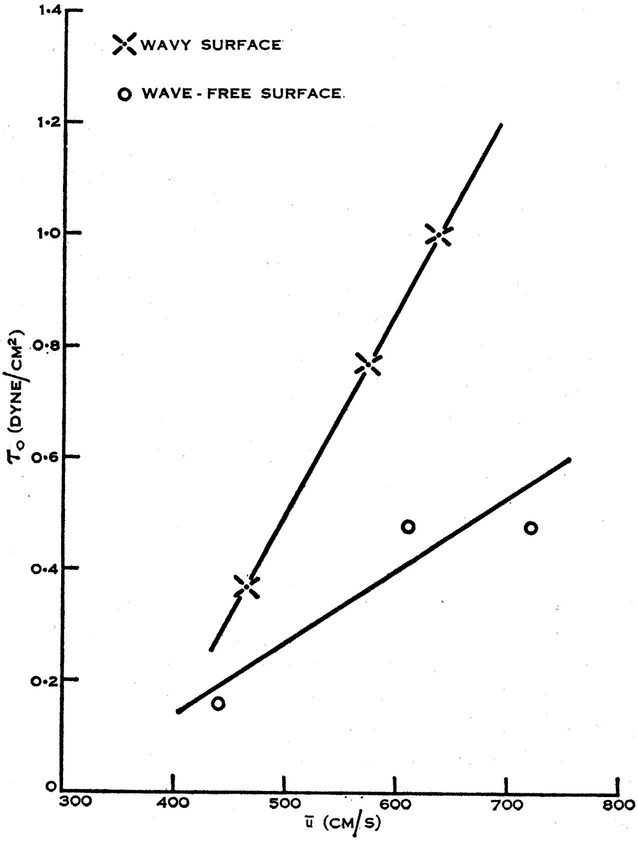

Fig. 4.—Values of shearing stress obtained from wind velocity profiles.

where τ_b is the stress on the bottom of the water channel. If we assume that $n = 1 \cdot 0$ for turbulent flow (Van Dorn), we then have the simple relation

$$S/L = \tau_0/\rho g H. \tag{4}$$

Thus, if we know the surface stress τ_0, we may calculate an expected value of the set-up for a given wind speed and, conversely, if we measure the set-up S, we can then obtain values for the surface stress.

The measurement of the changes in water level due to the wind stress on the surface over a length of about 5 ft involves the measurement of a very small difference in height. An inclined micromanometer was used in the first instance but was found to be not sensitive enough, owing to surface tension effects at the meniscus and the difficulty of calibration. Vertical manometer tubes with diameters of about 2 cm were used subsequently and the changes in level observed with a micro-cathetometer reading to 1 μ. The pressure difference of the air over the length of the channel was measured initially by connecting openings in the top wall of the tunnel to an inclined manometer, the pressure difference being read in heads of water. When the larger manometer tubes were introduced this pressure difference was automatically compensated for by connecting the openings in the roof of the tunnel to the manometers in the manner shown in Figure 1.

Table 1

MEASURED VALUES OF SET-UP COMPARED WITH VALUES OBTAINED FROM VELOCITY PROFILES

$\bar{u}$ (cm/s)	H (cm)	$S=\dfrac{\tau_0 L}{\rho g H}$ (from velocity profiles) (cm)	S (measured) (cm)	Condition of Surface
466	14·2	$3\cdot9\times10^{-3}$	$3\cdot8\times10^{-3}$	Waves
574	12·7	8·2	13·0	Waves
636	12·5	12·0	20·3	Waves
441	13·3	1·7	2·4	No waves
611	13·3	5·5	4·4	No waves
721	13·3	5·5	7·8	No waves

Values of set-up measured in this way are compared, in Table 1, with values estimated from the wind stress data obtained from velocity profiles (cf. Fig. 4). It can be seen that there is fairly good agreement between these two independently obtained sets of values. The agreement is closer for data obtained with wave-free surfaces. The likelihood of error will be larger when measuring set-up with rough surfaces. Indeed, in view of the very small order of magnitude of the set-up for both smooth and rough surfaces, the correlation between the measured and estimated values is surprisingly good. In Figure 5 values of the wind stress τ_0, obtained from the set-up measurements, are plotted as a function of the wind speed $\bar{u}$, in the same way as was done in Figure 4 for the velocity profile results. Once again it can be seen that the shearing effect of the wind is modified by damping out the waves on the surface.

(c) *From the Spreading Characteristics of Surface Films*

A third method of determining the shearing stress due to wind is by studying the spreading of a surface film on water. When a monolayer is spread on the surface of water in the presence of wind, retraction of the film occurs and a surface pressure gradient is established which opposes the wind stress. At equilibrium conditions these opposing stresses will be exactly balanced. Thus we will have

$$\tau_0 = \mathrm{d}\pi/\mathrm{d}x, \tag{5}$$

where π (dyne/cm) is the surface pressure at a distance x cm down wind.

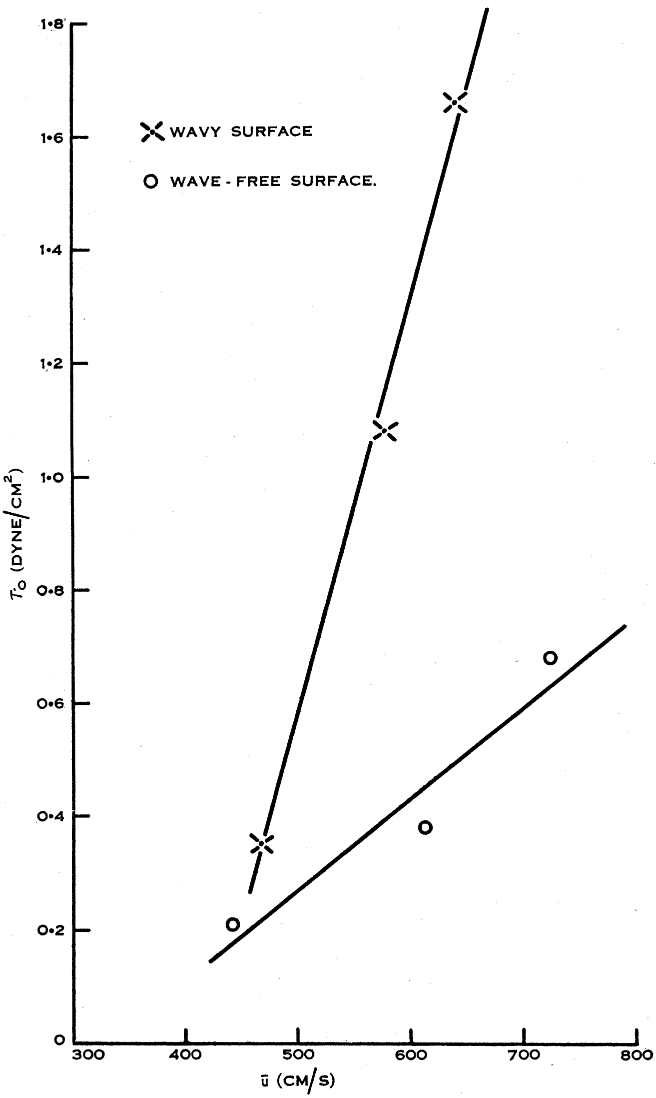

Fig. 5.—Values of shearing stress obtained from set-up measurements.

In this experiment solid cetyl alcohol was added to the surface of the water in the wind tunnel. The surface pressure for a monolayer in equilibrium with solid cetyl alcohol is 40 dyne/cm (Mansfield 1959) and we may write, therefore,

$$\tau_0 = 40/l, \tag{6}$$

where l cm is the equilibrium distance of film spread for a given wind speed. The distance l will decrease as the wind speed is increased.

Experimental values of τ_0, calculated from measurements of l, are shown in Figure 6. The determination of wind stresses for speeds above 500 cm/s was not possible by this method. At such speeds the surface became so rough over most of the length of the channel that the retraction of the film could not be observed. Vines (1959), also using the retraction of a monolayer, determined wind stresses for *low* wind speeds and his results are included in Figure 6.

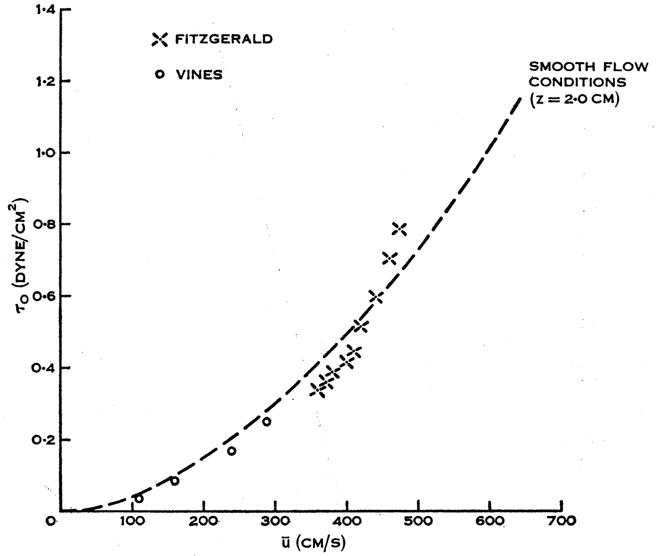

Fig. 6.—Values of shearing stress obtained from measurements of film retraction.

It is of interest to compare these results of shearing stress determinations with those which would be obtained under aerodynamically smooth conditions. The expression for the universal logarithmic velocity profile for smooth flow, as given by Sutton (1949), is

$$\bar{u}/v_* \simeq 2 \cdot 5 \ln(9v_* z/\nu), \tag{7}$$

where $\bar{u}$ is the mean wind speed at height z,

ν is the kinematic viscosity of water, and

v_* is the "friction velocity", defined as

$$v_* = (\tau_0/\rho)^{\frac{1}{2}}. \tag{8}$$

Here, τ_0 and ρ have the same meanings as in equation (1) for fully rough flow. Thus, we may calculate values of τ_0 which should be expected when conditions of aerodynamically smooth flow obtain. These values are represented in Figure 6 by the dashed line. It is seen that there is good agreement between the measured values and values calculated for smooth flow conditions, for most wind speeds. There is a tendency, at the higher wind speeds, for the measured values of τ_0 to be larger than the corresponding smooth flow values. This is most likely due to the fact that, at these wind speeds, the extent of film retraction is so great that we have, essentially, rough flow conditions prevailing.

TABLE 2

VALUES OF WIND STRESS OBTAINED FROM RETRACTION OF SURFACE FILMS

$u_{0 \cdot 02}$ (cm/s)	l (cm)	$\tau_0 = 40/l$ (dyne/cm²)	$C_{0 \cdot 02} = \tau_0/\rho u^2_{0 \cdot 02}$
360	118	0·34	$2 \cdot 24 \times 10^{-3}$
371	111	0·36	2·24
381	102	0·38	2·26
401	96	0·42	2·22
411	90	0·44	2·25
421	78	0·51	2·48
443	67	0·60	2·60
461	57	0·70	2·82
476	51	0·78	2·94

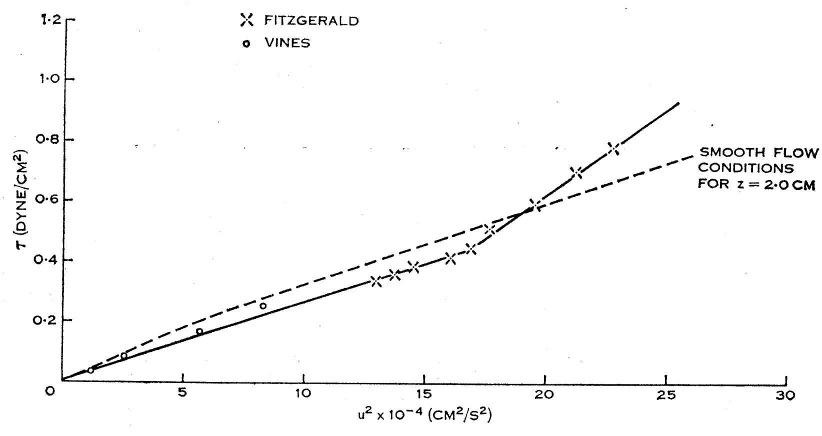

Fig. 7.—Surface stress as a function of the square of the wind speed.

The shearing stress τ_0 (dyne/cm²) may be expressed as

$$\tau_0 = \rho C_h u_h^2, \tag{9}$$

where ρ is the density of air ($1 \cdot 169 \times 10^{-3}$ g/cm³),

C_h is the *drag coefficient*, and

u_h is the wind velocity measured at a height h metres above the surface.

Since the wind speeds were measured at a height of 2·0 cm above the water, we can obtain values for the drag coefficient $C_{0 \cdot 02}$ from (9). These are given in Table 2.

The drag coefficient $C_{0\cdot02}$ is approximately constant for wind speeds up to about 412 cm/s and then rises gradually for higher wind speeds. This deviation from a constant value for $C_{0\cdot02}$ is seen clearly in Figure 7, where the wind stress τ_0 is plotted as a function of u^2. For wind speeds below 412 cm/s the drag coefficient is given by the slope of the experimental curve. Vines's results for $C_{0\cdot05}$, at low wind speeds, are seen to agree well with the approximately constant value of drag coefficient obtained here for all wind speeds up to 412 cm/s.

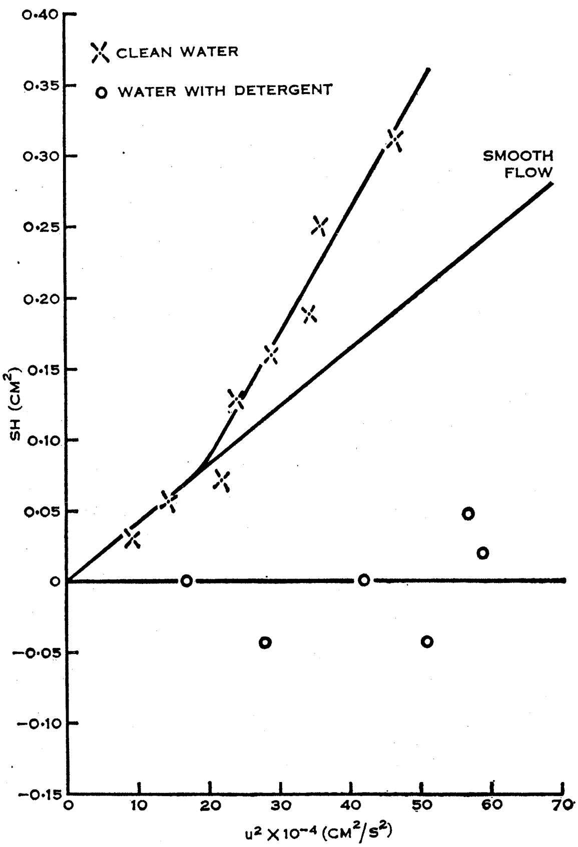

Fig. 8.—Relation between SH and u^2 for rough, smooth, and overdamped flow.

We also see, from the dashed curve of Figure 7, that equation (7) yields a nearly linear relationship between τ_0 and u^2 for aerodynamically smooth flow.

V. The Shearing Effect of Wind in the Presence of Surface-active Agents

It was seen in Section IV that the values of τ_0 obtained for a surface on which all waves were damped out were lower than those obtained for a clean, wavy surface (see Figs. 4 and 5). The wave-free condition of the water surface was obtained by the addition of detergent solution to the water. Since the wind stress τ_0 is directly related to the surface slope S (cf. equation (4)) it was decided to measure the set-up in the presence of varying amounts of detergent solution. The relationship between set-up S, depth of water H, and wind velocity u has been studied under these conditions. A linear relation between SH and u^2 was found for most wind speeds for both wavy water and wave-free water, but the amount of set-up produced at any particular wind speed was dependent on the concentration of detergent solution present in the water. In general, as the concentration was increased the set-up was decreased. Graphical representation of these results is shown in Figures 8 and 9.

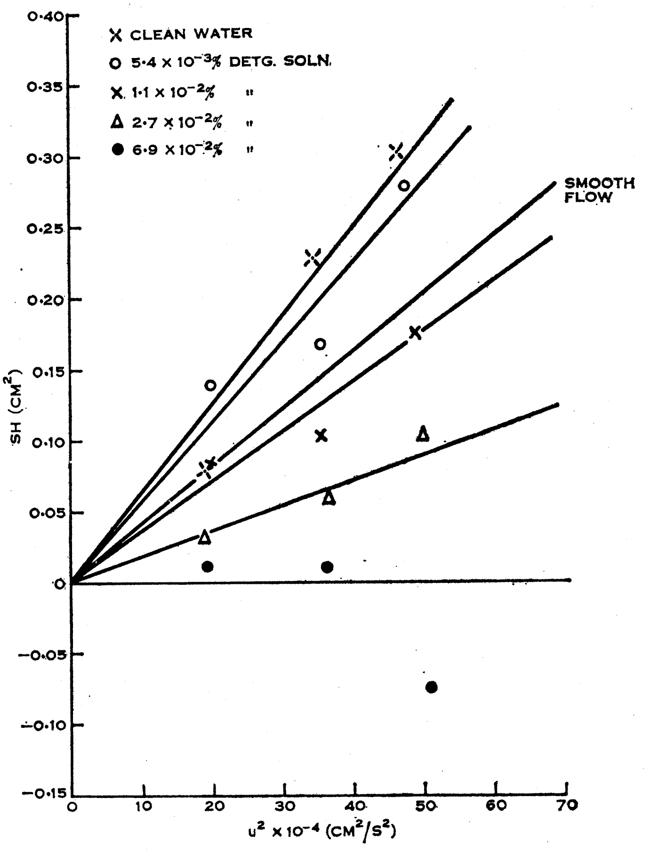

Fig. 9.—Relation between SH and u^2 for different concentrations of detergent solution in the water

In Figure 8 the set-up S is shown for the two cases of a clean, wavy surface and an overdamped surface, for wind speeds ranging from 300 to 700 cm/s. Figure 9 shows the behaviour of the set-up, as the concentration of detergent in the water is gradually increased, for three wind speeds within the above range. The values of set-up which should be expected under conditions of aerodynamically smooth flow, calculated from equation (7), are plotted in both Figures 8 and 9. These values yield a nearly linear relation between SH and u^2 and, for the purposes of comparison with experimental values, are drawn as straight lines in these two figures. It can be seen in

Figure 9 that the smooth flow values correspond to those obtained experimentally with a particular concentration of detergent solution in the water, namely, approximately 0·01%.

The surface pressures, corresponding to the concentrations of detergent used, are shown in Figure 10. (The surface pressure π is the amount by which the surface tension of the water is lowered due to the presence of surface-active material.) A solution of 0·01% concentration thus gives rise to a surface pressure of 33·4 dyne/cm. If SH is plotted against concentration or surface pressure there is found to be a discontinuity at about this value of 33·4 dyne/cm, with a sudden lowering of the amount of set-up obtained for higher concentrations. Figure 11 shows such curves for two different values of u^2. As can be seen from Figure 10, the surface pressure itself increases very little with increase in concentration above this value. Complete damping of the surface waves was obtained with a 0·02% solution (π = 35 dyne/cm). For large concentrations (much larger than that required to produce complete damping of the waves) and high values of wind speed, the suppression of the set-up may be seen to have progressed so far as to give apparent "negative" values of S (see Figs. 8 and 9).

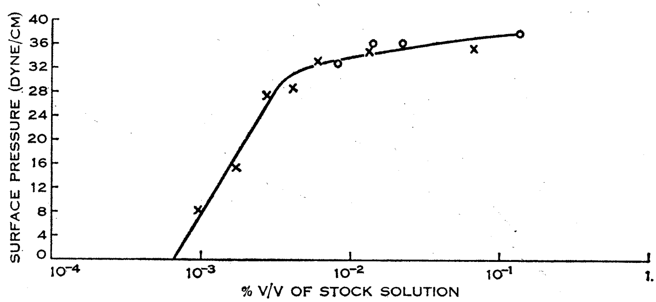

Fig. 10.—Relation between concentration of detergent and surface pressure.

The lower values of set-up, obtained with detergent present in the water, may be explained if we think of the wind stress, which gives rise to the set-up, being opposed by a surface pressure gradient along the length of the water surface. This surface pressure gradient is due to the presence of more molecules of detergent at the downwind end of the channel than at the upwind end. This hypothesis, however, is not helpful in explaining the zero and sub-zero values of set-up obtained with excess detergent present. In fact, as the concentration of detergent in the water increases above a critical value, the existence of a surface pressure gradient effect becomes less and less likely. There is, then, always an adequate supply of detergent molecules to replace those being blown down the channel surface. It seems, therefore, that at this critical concentration (approximately 0·02%) the conditions prevailing near the surface undergo a change. If this is the case, it is possible that the measurement of set-up S is subject to error under these changed conditions. Perhaps the pressures measured at the openings in the roof of the tunnel do not now truly represent the pressure of the air in the channel. It was seen in Section IV (b) that the difference in this pressure, Δp, over the length of the channel must be applied as a correction in the measurement of the set-up. Since the order of magnitude of S is so small, any error in Δp will produce a considerable error in S. It would be most useful to able to measure the pressure profile between the surface of the water and the roof of the tunnel at each end of the channel. However, no method of making this measurement was possible with the existing apparatus. The fact that the values of τ_0 obtained from velocity profile measurements in the case of overdamped surfaces (see Fig. 4) do not give rise to negative values of S (see Table 1) supports the view that the experimental

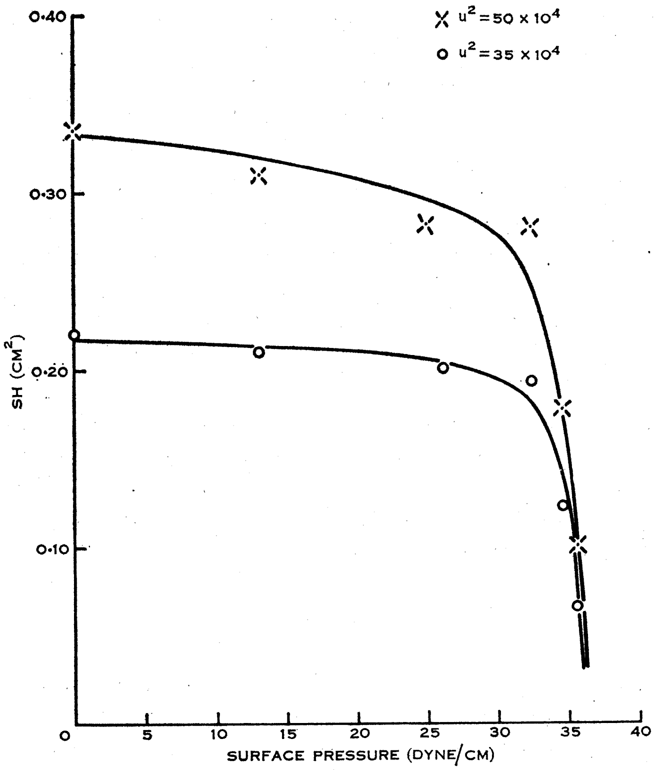

Fig. 11.—Relation between SH and surface pressure.

observations of set-up are in error under these conditions. (The experimental values of set-up quoted in Table 1 for the wave-free surface were obtained with a concentration of detergent nearly equal to the critical value of 0·02%, and so they do not correspond to the overdamped case. On the other hand, the wave-free surface referred to in Figure 4 does correspond to an overdamped condition.)

The experiments described above with different concentrations of detergent solution were done using the commercial detergent "Comprox". These experiments were repeated using another detergent solution, cetyl trimethyl ammonium bromide (Cetavlon). Similar results were obtained in both cases.

VI. Conclusions

Values of surface shearing stress and surface slope have been obtained for wind speeds up to about 700 cm/s. A good measure of agreement was found between the stress determinations obtained by three independent methods. For clean water, a square law relationship between τ_0 and $\bar{u}$, corresponding to that for aerodynamically smooth flow, was found to hold for wind speeds up to about 430 cm/s. At higher wind speeds the values of surface stress were greater than the smooth flow values (See Figs. 7 and 8). The magnitude of the shearing stress, at any particular wind speed, was lowered by the addition of surface-active materials to the water. Such materials have the effect of damping out surface waves. It was shown (see Fig. 9) that there was a certain concentration of detergent for which the relationship between τ_0 and $\bar{u}^2$ agreed with smooth flow conditions for all wind speeds. However, as the amount of detergent was increased beyond this concentration the values of stress fell below the smooth flow values.

In measuring the surface slope, there was found to be a critical concentration of detergent at which conditions in the boundary layer near the surface of the water appear to become quite different. This change in character of the boundary layer for overdamped surfaces has been suggested here because of the marked lowering of the measured values of set-up. It will be shown in later papers that the surface velocities and the flow characteristics in and below the surface also undergo sudden changes in behaviour at this critical concentration.

The approximate square law relationship between τ_0 and u_h implies a constant value for the drag coefficient C_h. As can be seen in Figure 7, the drag coefficient is constant for wind speeds up to between 4 and $4\frac{1}{2}$ m/s and then gradually increases for higher wind speeds. A similar variation in C_h was also observed by Deacon, Sheppard, and Webb (1956) for winds measured at a height of 10 m above the surface of the sea.

VII. Acknowledgments

The author wishes to thank Mr. W. W. Mansfield and Dr. R. G. Vines for much useful discussion throughout this work. The surface pressure determinations shown in Figure 10 were made by Mr. Mansfield using a surface balance employing the Wilhelmy plate method.

VIII. References

Deacon, E. L., Sheppard, P. A., and Webb, E. K. (1956).—*Aust. J. Phys.* **9**: 511.

Francis, J. R. D. (1954).—*Quart. J. R. Met. Soc.* **80**: 438.

Keulegan, G. H. (1951).—*J. Res. Nat. Bur. Stand.* **46**: 358.

Mansfield, W. W. (1959).—*Aust. J. Appl. Sci.* **10**: 73.

Mansfield, W. W. (1962)—"Retardation of Evaporation by Monolayers: Transport Processes." p. 133. (Academic Press: New York and London.)

Sutton, O. G. (1949).—"Atmospheric Turbulence." p. 22. (Methuen: London.)

Taylor, G. I., and Batchelor, G. K. (1949).—*Quart. J. Mech. Appl. Maths.* **2**: 1.

Timblin, L. O., Florey, Q. L., and Gartska, W. U. (1962).—"Retardation of Evaporation by Monolayers: Transport Processes." p. 186. (Academic Press: New York and London.)

Townsend, A. A. (1951).—*Quart. J. Mech. Appl. Maths.* **4**: 308.

Van Dorn, W. G. (1953).—*J. Mar. Res.* **12**: 249.
Vines, R. G. (1959).—*Quart. J. R. Met. Soc.* **85**: 159.
Vines, R. G. (1962)—"Retardation of Evaporation by Monolayers: Transport Processes." p. 137. (Academic Press: New York and London.)