CHAPTER 17

THE INFLUENCE OF WIND ON OPEN CHANNEL FLOW

by

Erich J. Plate* and Carl R. Goodwin**

ABSTRACT

The effect of wind shear stress on the flow in an open channel is investigated for the case where wind and water move in the same direction. The investigation is based on experimental data obtained with a unique wind water tunnel. A method is developed by which it is possible to separate water surface shear stress and bottom shear stress. The difference between bottom shear stress calculated by this technique and water surface shear stress agrees well with the shear stress predicted from the velocity distribution in the water. A method is given by which the water surface shear stress may be calculated. The shear stress coefficient of the water surface is significantly lower than that for the case of initially standing water. The experimentally determined surface stress agrees with that calculated from the air velocity distribution.

INTRODUCTION

Wind blowing along a straight reach of a river causes significant changes in the flow characteristics of the water flow in the river. The most obvious effect is the generation of waves by the wind on the water surface. These waves initially do not affect the water flow in any important way, but if the wind is blowing long enough with sufficient intensity over a sufficiently long fetch, then the waves may grow to appreciable height and length. They become shallow water waves and can cause significant changes in the shear on the river bed and in the water velocity distributions.

The second effect of wind blowing along a river concerns the change in water depth which is caused by the shear stress exerted by the wind on the water. The depth change reaches its maximum if the wind blows long enough to set up a new regime of steady flow in the river. It results in a different mean velocity which influences the erosion or deposition of sediment caused by mean shear stress. No information exists on this effect, except for references on wind shear on standing water reported by Hellström (1941).

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A clear understanding and quantitative description of wind effects on river flow are still outstanding. The generation and growth of wind waves are difficult matters even on standing water (for a discussion see Ch. 12 in Kinsman (1965)). They are further complicated on a river by the flow of the water and by the presence of the banks and the bed. Therefore, this initial study shall be concerned only with the mean properties of the flow in an open channel with wind blowing parallel to the water surface and in the direction of channel flow. We shall investigate how the bottom shear stress, the velocity distributions in the water and in the air, and the water surface shear stress are affected by the wind as a new regime of flow at normal depth with wind blowing, becomes established.

The study is based on experimental data which were taken in a special laboratory wind water facility. The data and their analysis is taken in part from Goodwin (1965). The facility and the procedures which were used to obtain the experimental data will be described briefly. Then we shall present a procedure for determining the shear force on the water surface and the shear force on the channel bottom from the directly measured total drag. The shear stresses which are obtained by this procedure shall be called measured shear stresses and are identified by the subscript $m$.

The remainder of the paper consists of an attempt to design a method by which the shear stresses on the channel floor and on the water surface can be predicted from known characteristics of the air and water flows. Calculated shear stresses are compared with measured shear stresses and with shear stresses which are obtained from the velocity distributions in air and water.

EXPERIMENTAL EQUIPMENT AND PROCEDURES

The laboratory channel used for the experimental program is shown in Fig. 1. It consists of a truss supported plexiglas channel which has a 44 ft. long test section. The trusses can be rotated around a pivot by means of a screw driven support at the end of the facility. Slopes can thus be adjusted from +0.03 to -0.01.

Water enters the facility from the inlet section which consists of honeycomb screens. The screens serve as an effective diffusor for the incoming water, and at the same time act as wave dissipating beaches. The water flow is controlled by a pinch valve located in the supply pipe. The water leaves the test section through a honeycomb beach and returns to the sump through a metering orifice which has been calibrated in place. The pinch valve in the return pipe serves as a tail gate to control the depth of water in the test section. From the sump, the water is conveyed back into the channel by means of a three speed pump. The pump is kept at stable operating loads by means of a by-pass, controlled with a butterfly valve. At the discharge end of the pump, there is a five foot long piece of
Figure 1. General view of wind water facility
dredge hose which is capable of taking up the rotation of the system and of damping vibrations which are transmitted from the pump.

The air flow is drawn through a fiberglass inlet bell and a set of screens into a contraction section and smoothly enters the test section through a honeycomb screen. The pressure drop across the honeycomb screen was calibrated against the discharge of air obtained by integrating velocity profiles over the cross section of the wind duct. At the end of the test section, the air flow is guided through a rubber joint into the fan section which is supported independent of the test section. Inlet bell and fan section can be exchanged, if it is desirable, to reverse the air flow direction.

The air and water flows are both essentially three dimensional. However, the data analysis had to be performed, in order to avoid excessive complications, using two-dimensional fluid mechanics. In order to maintain the flow in the water as two-dimensional as possible, the ratio of the channel depth to the channel width was kept small (to a maximum of 0.25), and the bottom of the channel was roughened. Roughening of the channel bottom has two advantages: first it permits the use of comparatively steep slopes (0.003 to 0.0014) with normal depths of flow which were not too shallow (up to 6 inches) and thus making possible to obtain deep water waves at least in the early stages of wave development. Second, a roughened bottom makes it possible to ignore the effect of the channel side walls on the total shear stress acting on the body of water. The roughening elements consisted of 0.25" gravel which was glued to aluminum plates and placed on the channel floor. Calculations of the side wall roughness effect on the total drag based on the method of Einstein (1942), showed that the side wall effect was negligible for all depths of flow used, i.e., the hydraulic radius pertaining to the bottom is equal to the depth of flow.

The following data were taken. For the water: the discharge, the normal depth of flow before and after the wind started blowing, and for some cases also the mean water velocity distributions. For the air: the mean velocity and the velocity in the center of the air duct at a distance of 34 ft. from the entrance honeycomb, the pressure gradient along the test section, and for some cases the velocity distributions in the air above the water surface waves.

Water velocities were measured with a pitot static tube and an inductive (Pace type 7d) pressure transducer. Individual data points were difficult to obtain because of low frequency fluctuations which were set up by waves. Therefore, the output of the pressure transducer was recorded as a function of time and the average dynamic pressure obtained by graphic integration. Furthermore, 5 vertical profiles were taken for each station at distances of 0, 3 in. and 6 in. from the center line of the tunnel, and an average profile was formed from these 5 profiles. Water velocity profiles were taken only at a distance of 34 ft. from the test section entrance and at a mean water surface slope of 0.0014.
Water surface velocities were measured by following the motion of buoyant particles floating on the surface. For the purpose of this paper, only the mean value of the water surface elevation is of importance. It is measured by connecting bottom taps in the channel and ceiling taps to the two open-ends of water manometers mounted on a board.

Air velocity profiles were measured with a pitot static tube connected to a capacitative differential pressure transducer (Transonics Equibar Type 120) which had a voltage output proportional to the differential pressure. Profiles were plotted directly on an x-y-recorder against a signal across a potentiometer on the carriage proportional to the distance from the water surface. The pressure transducer was also used for determining the air pressure gradients from pressure taps in the ceiling of the channel.

The equipment is described more fully in a forthcoming note by Plate (1965).

THE EXPERIMENTAL RESULTS

In this section, the experimental results which were directly measured in the laboratory are presented. From these, the shear stresses for both the water surface and the bottom of the channel will be calculated.

WATER FLOW DATA

Mean water depths - When the wind does not blow, the normal depth of the water flow is related to the discharge of the water through Chezy's equation:

\[ Q = y_n \cdot b \cdot C \sqrt{y_n S}, \]

where \( S \) is the channel slope and \( C \) is the Chezy roughness coefficient. \( C \) has been found to depend on the depth and on the roughness geometry. Sayre and Albertson (1963) have expressed the dependency on the depth by the formula:

\[ \frac{C}{\sqrt{y_n}} = 6.06 \log y_n + B, \]

where \( B \) is the coefficient containing the effect of the geometry of the roughness in the channel. Values of \( B \) calculated from the experimental data varied widely. An average trend for \( B \) as function of slope shown in Fig. 2 was found. A plot of \( Q \) calculated by means of Eqs. 1 and 2 and Fig. 2 generally agrees well with the experimental data (Fig. 3). There seems, however, to be some systematic deviation of the data points from the calculated curves for large values of \( y_n \), but the calculated...
Figure 2. Average B-values as function of $S_c$
Figure 3. Depth $y_n$ before wind blows as function of $Q$, calculated from $\frac{c}{V_g} = 6.06 \log y_n + B$. The dashed curves are calculated using the given equation.
curves give a good fit to the experimental points over most of the range of measurement. The data are indicative of the fact, which renders all further analysis difficult, that large scatter in the data must be expected. This is a result of the comparatively short test section length which required utmost care in setting up and maintaining normal depth of flow.

When the wind blows over the water surface in the direction of the channel flow, the depth is decreased by an amount depending on the slope and on the wind velocity. Qualitatively, these results confirm estimates made by Hellström (1941), namely that the depth decrease is, for a constant wind, larger if the slope is flatter, and smaller if the water velocity is increased. Quantitatively, however, agreement cannot be expected because a velocity profile based on a constant eddy viscosity in the water which was used by Hellström is not found, as will be discussed below. The experimental data for the case of open channel flow with concurrent wind flow are summarized in Table 1.

Water surface velocities - With wind blowing along the water surface, the layer nearest to the surface is strongly affected. A change in water surface velocity results. For water standing in the channel, Keulegan (1951) found a curve which related the ratio \( \frac{V_{ws}}{U_{av}} \), where \( V_{ws} \) is the water surface velocity and \( U_{av} \) the average air velocity in the channel, to a Reynolds number \( \frac{V_{ws} \cdot y}{v_w} \). The curve was confirmed by Masch (1963). Hidy and Plate (9) observed ratios in the laboratory channel used for the present study which were about 20% lower. They were unable to explain the difference, except perhaps by the fact that in comparison to the air flows in the channel of Keulegan (which was 4 in. wide and 60 ft. long) and the channel of Masch (which was 4 ft. wide and 100 ft. long), the air flow in the channel used by Hidy and Plate could never become fully developed. An average velocity over the whole air duct has thus no clear meaning. The results of the experiments for standing water of Hidy and Plate are reproduced in Fig. 4.

For moving water, the water surface velocity will also depend on the flow in the channel. It is found that reasonable agreement between standing and moving water data is obtained if the ratio \( \alpha \) for moving water is defined by \( \frac{V_{ws} - V_{av}}{U_{av}} \), where \( V_{av} \) is the average velocity of the water. These results have also been plotted in Fig. 4. A significant deviation of the data points from the general trend in Fig. 4 occurs for the two points corresponding to the largest depths of water (4.4 in.), but a reason for this cannot be given at present.

Velocity distributions in the water - When the wind blows over the surface of a laminar flow of water, then a situation is set up which resembles plane Couette flow with a pressure gradient. Consequently, the velocity distribution consists of a superposition of a linear
Standing water (from Hidy and Plate (1965))

Moving water (S = 0.0014 only)

Test results of Keulegan (1951)

\[ \alpha = \frac{V_{WS} - V_{av}}{U_{av}} \]

\[ \frac{V_{WS} \cdot y}{v_w} \cdot 10^{-3} \quad \text{or} \quad \frac{(V_{WS} - V_{av}) \cdot y}{v_w} \cdot 10^{-3} \]

Figure 4. Water surface velocity as function of Reynolds number
Table I (continued)

Summary of experimental data for concurrent air and water flow (Series II).

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<th>( \theta_{0} )</th>
<th>( \rho_{a} )</th>
<th>( \rho_{w} )</th>
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The experimental data shown in Fig. 5 have been plotted by subtracting the coefficient \( A \) from the ratio \( \frac{u}{u_{0}} \). In this manner, the linear trend of the data in the semi-logarithmic presentation is better recognized. The coefficients \( A \) depend on the roughness of the channel floor, they are also tabulated in Table 2. However, no attempt was made to relate \( A \) to the roughness; this task shall be postponed until more extensive measurements have become available.
Figure 5. Velocity distribution in the channel with wind
Figure 6. The air pressure gradient for standing water
The velocity distributions should extrapolate to reach the water surface drift velocity at \( z/y_n = 1 \). This would require a more rapid increase of the velocities near the water surface than can be obtained from an extension of the logarithmic distribution law. However, this increase is not evident in the data. Therefore, the effect of the wind stress leads to a rapid increase of the velocities only within a thin layer close to the surface, unless, of course, the trend is hidden in the scatter of the experimental data.

AIR FLOW RESULTS

Air pressure data - The air pressure gradients which are measured with standing water in the channel are reproduced in Fig. 6. The pressure gradient does not only depend on the air velocity, but also on the depth of flow. An empirical relationship

\[
\frac{1}{\rho g} \frac{dp}{dx} = \beta y_n^{1/4}
\] 

was found, in which \( \beta \) depends only on the air velocity.

For moving water, the relationship between pressure gradient and depth becomes more complicated since a dependency on the flow conditions in the water was found. In order to account for this effect, the coefficient \( \beta \) was plotted against the average water velocity \( V_{aw} \), with air velocity \( U_{av} \) as third variable. The results are reproduced in Fig. 7. Some scatter is again found, but the trends indicated by the straight lines appear to be real. The decrease in pressure associated with concurrent air and water flow indicates a change in water surface shear stress which must be attributed to the change in wave pattern. The wave pattern, and its effect on the water surface drag, will be discussed elsewhere. For use in the calculations of this paper, the pressure gradient in the air duct is determined from Fig. 7 and Eq. 4.

Mean velocity distributions in the air - It is commonly assumed that the wind velocity distribution over the wavy water surface obeys the logarithmic velocity distribution law. This conclusion is based on experimental data, especially those of Roll (1948) for wind over a
Figure 7. Pressure coefficient $\beta$ as function of $V_{av}$
shallow part of the ocean, and those of Sibul and Johnson (1957) for wind in laboratory channels. The validity of the logarithmic law down to the water surface has as yet not been confirmed; for the upper portion of the wind velocity distribution there is some recent evidence for it by Fitzgerald (1963) and others. Near the water surface, the profile of the wind is not known, except for some soap bubble experiments which were made by Schooley (1963). The data of Schooley showed an unusual feature. There appeared to exist a high velocity current near the water surface. If this current is real, then most analytical work on the generation of wind waves needs a quantitative revision. However, more extensive experiments are required to verify Schooley's findings. The high velocity current appeared, at a different elevation, also in earlier data by Francis (1951) and data by Fitzgerald (1963). There exists the distinct possibility that these data reflect also inlet conditions at the air intake rather than only a real physical phenomenon associated with wind flow over waves. For the present study, care was therefore taken to have a uniform inlet velocity distribution in the air stream. The wind profiles, over moving water, were taken at a distance of 34 ft. from the entrance. Three parallel profiles were determined and the average was used in the calculations. The parameters of the velocity profiles are summarized in Table 3. The experimental data are represented, in non-dimensional form, in Fig. 8. It was assumed that the distributions follow a logarithmic distribution law of the form:

$$\frac{u}{u_{\infty}} = 6.06 \log \left(\frac{z-y_n}{\delta}\right) + D. \tag{5}$$

The shear velocity $u_{\infty}$ was determined from the slope of the lower portion of the velocity distribution. In order to obtain a clear presentation of the data, the quantity $\frac{u}{u_{\infty}} - D$ was plotted against $\log \frac{(z-y_n)}{\delta}$ in Fig. 8a. The boundary layer thickness is defined as that distance from the water surface at which the local velocity has reached 99% of the value in the potential core $U_a$. As can be seen from the tabulated values of $\delta$, the boundary layer thickness appears to be increasing with increase in $U_a$, which is in contrast to boundary layer flows over smooth flat plates.

Table 3: Air velocity profile data

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<thead>
<tr>
<th>$U_a$ (fps)</th>
<th>$U_{av}$ (fps)</th>
<th>$y_n$ (in.)</th>
<th>$S_o$ (-)</th>
<th>$Q$ (cfs)</th>
<th>$V_{av}$ (fps)</th>
<th>$\delta$ (in.)</th>
<th>$u_{\infty}$ (fps)</th>
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<td>1.9</td>
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</table>
Figure 8. Velocity distribution in the air flow

8a Non-dimensional velocity distribution

8b D as function of $y_n$

Figure 8. Velocity distribution in the air flow
The quantity $D$ should be a measure of the water surface roughness, i.e., it should depend on the wave configuration. Empirically, it is seen in Fig. 8b that $D$ decreases with increase in depth, but the significance of this result has not yet been established.

The data in Fig. 8 show that the air velocity distributions in the lower forty to fifty percent of the boundary layer over the water are well described by a logarithmic "law of the wall". It is possible that a correction for a zero plane displacement would fit the logarithmic law over a larger portion of the data. However, no consistent zero plane displacement could be defined, and further, the shear velocities calculated from modified distributions do not agree with the directly determined shear velocities which are described below. The air velocity profiles certainly warrant further investigation. Nevertheless, two preliminary conclusions are: a.) the lower part of the profiles can be represented by a logarithmic distribution law, and b.) the high velocity jet near the water surface cannot be found in the laboratory equipment used for this study.

**CALCULATIONS OF SHEAR STRESSES**

The quantities of greatest importance for the study of the wind effect on open channel flow are the water surface shear stress exerted by the wind on the water surface, and the bottom shear stress which is caused by the flowing water with wind blowing over its surface. Connected with these, there arise two problems: the determination of the shear stresses from the experimental data, and the use of the results for the prediction of shear stresses in other than the experimentally chosen cases. Both problems are of equal importance, and shall be investigated in some detail.

**DATA REDUCTION TECHNIQUE**

For two dimensional flow down an incline, the momentum equation for channel flow at normal depth $y_n$ is:

$$\tau_b - \tau_{ws} = \gamma y_n S_o - \frac{1}{\rho g} \frac{dp}{dx}$$

in which $S_o$ is the water surface slope. The right side of Eq. 6 consists of quantities which can be measured directly. But no simple method exists which permits the separation of the bottom shear stress $\tau_b$ and of the water surface shear stress $\tau_{ws}$. A separate equation for the determination of the water surface shear stress must be obtained by considering the momentum balance of the air flow in the duct above the water. This flow consists of flow in a duct with three smooth walls, and a rough floor with unknown roughness characteristics, namely the water surface.

The difficulty of this analysis lies in the fact that the wind tunnel portion is not long enough for fully established duct flow in the air passage.
Thus, the air flow consists of a potential core which is narrowed with increasing distance downstream from the wind tunnel entrance by the growing boundary layers on the four surfaces. For such a situation, the shear stress coefficients are not known, even for smooth surfaces.

In order to overcome this problem, the assumption was made that the shear stresses on the sidewalls and on the ceiling of the air duct above the water depend only on the depth of flow and on the air velocity, i.e. they are independent of the velocity of the water. With this assumption, the shear stresses on the duct walls can be obtained from experiments on standing water, where the water surface shear stress is reasonably well known. The shear stresses on walls and ceiling obtained for the standing water case can then be used for determining the water surface shear stress in the moving water situation. Once the water surface shear stress is known, the bottom shear stress $\tau_b = \tau_{bm}$ can be calculated from Eq. 6. In this manner the shear stresses on the water surface and on the channel bottom can be determined from the experimental data.

Water surface shear stress for standing water - The momentum equation for standing water, as applied to a body of fluid contained between two vertical sections, a distance $dx$ apart, becomes

$$\tau_{ws} - \tau_b = \gamma y \left( S_0 + \frac{1}{\rho g} \frac{dp}{dx} \right).$$

In this equation, $y$ is the depth at the point considered, which is assumed to be essentially constant along the channel (i.e. it is assumed that $S_0$ is very small). Then the difference $\tau_{ws} - \tau_b$ can be calculated from measured values of the depth, the water surface slope and the pressure gradient. The problem again arises of separating $\tau_b$ and $\tau_{ws}$ in this case, however, the bottom shear stress is a small portion of water surface shear stress. Keulegan (1951) found for laminar flow $\tau_b = 0.5 \tau_{ws}$, but it has been argued (notably by Francis (1951)) that for turbulent flow the bottom shear stress is considerably smaller. Keulegan (1951) assumed $\tau_b = 0.25 \tau_{ws}$, Francis (1951) $\tau_b = 0$, and recently Baines and Knapp (1965) have shown some evidence that $\tau_b = 0.1 \tau_{ws}$. The true ratio of $\tau_b$ to $\tau_{ws}$ is probably not constant but depends on the depth of flow and on the roughness of the bottom of the channel. The effect can be quite pronounced as was shown by Sibul and Johnson (1967). However, the standing water data were taken in the channel with smooth floor and for the calculations of this paper, the water surface shear stress was determined from Eq. 7 with the assumption $\tau_b = 0$.

In order to obtain an average $\tau_{ws}$ from the experimental data, the adjusted slope $S_0 + \frac{1}{\rho g} \frac{dp}{dx} = S_c$ was plotted first against the depth of flow in Fig. 9 and a straight line was drawn through the data with slope of minus 1. The intercepts of these lines for the depth of 12 in divided by $\rho_a U_{av}^2 / \gamma$ yield the shear stress coefficients $c_{ws}$ for...
Figure 9. Standing water slope as function of $y$
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water surface shear stress shown in Fig. 10. It is evident that the experimental data of this study agree well with the data of both Keulegan (1951) and Fitzgerald (1963).

Sidewall and ceiling shear stress for standing water - With the water surface stress known, the shear stress on the side walls and the ceiling of the air duct can be calculated from the momentum equation as applied to the air duct above the water. This equation is given by:

\[ \tau_s \left[ b + 2(h-y) \right] + \tau_{ws} b = \frac{dp}{dx} \cdot b (h-y) + M \cdot b (h-y), \]  

where \( h \) is the height and \( b \) the width of the wind water tunnel, \( \tau_s \) is the shear stress along walls and ceilings, and \( M \) is the momentum change averaged over the cross sectional area. \( M \) is difficult to determine experimentally because it involves measuring velocity distributions across the whole cross sectional area at different distances \( x \). Instead of measuring the quantity \( M \), we prefer to write Eq. 8 as follows:

\[ \tau_s \left[ b + 2(h-y) \right] (1- \alpha_s) + \tau_{ws} b = \frac{dp}{dx} \cdot b (h-y), \]  

where \( \alpha_s = \frac{b (h-y)}{b + 2(h-y)} \frac{M}{\tau_s} = \frac{2}{3} \frac{M}{\tau_s}, \)

and define further \( \tau_s (1- \alpha_s) = \lambda \cdot \frac{1}{2} \rho U_{av}^2 \),

where \( \lambda \) is a coefficient embodying both the effect of friction and of momentum change. It therefore depends on the air velocity and on the depth of flow, as is shown in Fig. 11. The figure is based on actual water surface shear stress data and not on the smooth curves of Fig. 9. The trends of the curve are purely hypothetical, and it is inevitable that the use of the curves introduces some error into the calculations.

The quantity \( \lambda \) is related to the conventional friction coefficient \( c_f \) through the equation

\[ c_f = \frac{\lambda}{1- \alpha_s}, \]

which could serve as a means of obtaining the quantity \( \alpha_s \) from measured pressure drops in rectangular conduits. However, for the calculations of the bottom shear stress in moving water, we assume that the quantity \( \tau_s (1- \alpha_s) \) depends only on the depth of flow and the air velocity has the same value for the moving water and for the standing water. This means that we assume \( \lambda \) to be the same for both cases.

Calculation of bottom shear stress for moving water - If the value of \( \lambda \) is the same for corresponding cases with standing water and with
0.010
0.008
0.006
0.004
0.002
0.000
0.010
0.008
0.006
0.004
0.002
0.000
0.010
0.008
0.006
0.004
0.002
0.000

\[ C_{WS} = \frac{T_{WS} - T_b}{\rho_a U_{av}^2} \]

Keulegan (1951)
Fitzgerald (1963)

Figure 10. Water surface friction coefficient for standing water

Experimental averages based on FIG. 9.
Figure 11. $\lambda$ as function of $U_{av}$ and $y_n$ for standing water
moving water, then the bottom shear stress $\tau_{bm}$ can be calculated as follows. First, with the known water depth and air velocity, we determine $\lambda$ from Fig. 11. Then, by using $y_n$ instead of $y$ and the pressure gradient $\frac{dp}{dx}$ for the moving water case, the water surface shear stress is calculated from Eq. 9. Finally, the bottom shear stresses $\tau_{bm}$ are determined from Eq. 6 and tabulated in Table 1.

For the calculations, the pressure gradient was found from Eq. 4 by using the $\beta$ - values of Fig. 7.

**SHEAR STRESS CORRELATIONS**

The data reduction technique used in the previous section cannot be used for predicting the shear stresses on the channel bottom and on the water surface. For this purpose, relationships must be found between the flow conditions without wind and flow conditions with wind blowing concurrently with the water flow.

**Shear stress on channel bottom -** For the flow in an open channel without wind blowing, Chezy's equation Eq. 1 holds

$$Q = V_{av} \cdot y_n \cdot b = C \sqrt[4]{y_n} S$$

with $C$ given by the equation of Sayre and Albertson (1963):

$$C \sqrt[4]{g} = 6.06 \log y_n + B ,$$

where $B$ for our laboratory channel is obtained from Fig. 2. In order to apply these equations to the case of open channel flow with concurrent wind, a number of assumptions were made.

In attempting to define an appropriate value of $B$ for the case of moving water with wind blowing over the surface of the water, it was assumed that the factor $B$ does not depend on the water surface shear stress but only on the conditions of the flow in the absence of water surface drag. Thus, $B$ is known from experiments without wind. It is therefore given also for wind cases by the curve in Fig. 2. However, instead of using the slope $S_o$, $B$ has to be found corresponding to the corrected slope $S_C$.

A further assumption that must be made is that the Karman constant $k$ is independent of wind conditions. Implied in Eq. 2 is a value of $k = 0.38$, as was assumed by Sayre and Albertson (1963). However, in the discussion of Sayre's and Albertson's paper, it was brought out that the coefficient $k$ depends also on the roughness pattern and the depth of flow, thus, the assumption $k = 0.38$ is a simplification which needs verification.
A third assumption is that the bottom shear stress depends on the flow velocity and on $C$ in the same way as for no-wind conditions where

$$\tau_b = \gamma y_n S$$

and from Eq. 1 follows:

$$\tau_b = \frac{\gamma}{C^2} V_{av}^2.$$  \hfill (12)

Eq. 12 is assumed to be valid also for the case with wind blowing over the surface if the $C$-values are given by Eq. 2 with $y_n$ = the normal depth with wind. Then, the depth of flow $y_n$ can be determined from the calculated water surface shear stress $\tau_{ws}$, by use of Eq. 12, Eq. 6 and Eq. 2, by trial and error.

The bottom shear stresses $\tau_b$ can also be calculated by this method. The measured depth $y_n$ must be used, and the $\tau_{ws}$ must be found from the experiments, and from Eqs. 9 and 10 in the manner outlined above. The calculated $\tau_b$-values are compared in Fig. 12 with $\tau_{bm}$-values obtained from the data reduction technique. Generally, the agreement is only fair. The scatter lies within a $\pm 20\%$ fractional error, but there is some evidence that the calculated water surface shear stresses $\tau_{ws}$ are too small. This might be caused by neglecting the bottom shear stress for standing water in calculating $\lambda$. Water surface shear stresses corrected for bottom shear stresses would result in smaller $\lambda$-values and thus the water surface shear stress calculated from Eq. 8 is larger.

The calculated bottom shear stress should compare with the shear stress calculated from the water velocity distribution. However, it is found that the slope of the water velocity distribution is dependent on the shear stress difference through the relation:

$$u_{sww}^1 = \sqrt{\frac{\tau_b - \tau_{ws}}{\rho_w}}.$$  \hfill (13)

The shear velocity $u_{sww}^1$ is compared with $u_{sw}$ in Table 3, and the agreement is good. This means that the shear stress on the water surface is transmitted to the channel bottom without any apparent effect on the velocity distribution.

**Determination of the water surface shear stress** - The total drag on the water surface will consist of two parts: the skin friction drag due to the condition of equal velocity of both air and water at the water surface, and the form drag imposed by pressure differences between wind-ward and lee side of the waves. For very low velocities, the water surface in the channel remained unruffled and the skin friction is the only portion of the drag which is effective. Under these circumstances, the water
Figure 12. Comparison of measured and calculated bottom shear stresses
surface behaves like a smooth flat plate. Consequently, the drag decreases with fetch. With increase in velocity, or with increase of fetch, a wave pattern is generated on the water surface which produces a sudden increase in friction, as was observed in a laboratory channel by Keulegan (1951). For very high winds, and short fetches, the wind flows may separate from the crest of the waves. The drag becomes almost exclusively form drag. For these conditions, the drag on the water surface is approximately described by the sheltering hypotheses of Jeffreys (1925), according to which

\[ \tau_{ws} = s \rho_a U_a^2 \frac{da}{dx} \]  

(14)

where \( s \) is Jeffreys sheltering coefficient (about 0.01) "a" is the wave height, and \( \frac{da}{dx} \) is the slope of the waves. By showing that \( \frac{da}{dx} \) increases approximately linearly with \( U_a \), Munk (1955) was able to demonstrate that \( \tau_{ws} \sim U_a^3 \) and therefore also:

\[ \tau_{ws} \sim U_{av}^3 \]  

(15)

This relation had been found for channels earlier by Hellström (1941) and was confirmed by Francis (1951), Fitzgerald (1963), Hidy and Plate (1965) and others. Field data indicating the validity of the third power relation between water surface stress and \( U_a \) have been collected for example by Van Dorn (1953). None of the data have been taken at sufficiently low velocities to confirm that the water surface behaves like a smooth flat plate; since there exists a water surface drift, this is not self-evident. There exists some experimental evidence, by Kunishi (1963), of the smooth surface behavior in agreement with smooth flat plate findings. Kunishi also showed that the break between smooth flat plate behavior and rough plate behavior occurred with the beginning of the first small water surface ripples. He gave for the beginning of ripple formation the criterion

\[ \frac{u_s a}{\nu} \cdot a = 0.3 \]  

(16)

where \( a \) again is the wave height. This relation has not yet been confirmed by other experimenters.

The data reproduced in Fig. 10 show that, over the range studied by Keulegan and Fitzgerald, the relation Eq. 15 is also verified for the experimental data of this study which were performed with standing water. Only at the highest velocity does a marked deviation from Eq. 15 occur, and it is not certain whether this deviation is significant. The results for moving water are reproduced in the same manner in Fig. 13. Generally,
Figure 13. Water surface friction coefficient for moving water
the data fall below the curve for standing water indicating that friction of concurrent air and water flow is lower than that of standing water. We are at present unable to explain the large scatter of the data. Perhaps the water depth or velocity must enter as an independent variable, or the wave pattern must be considered. On the other hand, the water surface shear stress was determined from the λ curves for standing water, and these are far from satisfactory. The momentum term M in Eq. 8 must be measured directly and the assumptions leading to the application of Eq. 10 to the moving water data must be verified.

We have calculated the water surface shear stresses for the cases corresponding to those at which the air velocity data were obtained, by using an average value of \( c_{ws} = 0.0036 \) for the experimental data of Fig. 13. From the shear stress values \( \tau_{ws} \), the shear velocity \( u_{*a} \) was calculated from the relation

\[
u_{*a} = \sqrt{\frac{\tau_{ws}}{\rho_a}}.
\]

The values of \( u_{*a} \) and \( u_{*a} \) are compared in Table 3, and reasonable agreement is found. The agreement could perhaps be improved by using a \( c_{ws} \)-value which increases with velocity.

**SUMMARY AND CONCLUSIONS**

An experimental study was performed for the purpose of determining the drag which is exerted by the wind on open channel flow, and its effect on the bottom shear stress and the velocity distributions in the air and the water. The study was performed at shallow depths of water and in a channel of limited length. The following conclusions can be drawn from the results.

1. The air velocity profiles over moving water in the laboratory channel can be represented by a logarithmic distribution law. The slope of the logarithmic law is given to 6.06 \( u_{*a} \) when \( u_{*a} \) agrees well with shear velocities which are calculated directly from the pressure gradient in the air.

2. The water velocity distribution can be expressed by a logarithmic velocity distribution law, the slope of which is given to 6.06 \( u_{*w} \). The shear velocity \( u_{*w} \) does not agree with the shear velocity calculated from the bottom shear stress, but agrees with a shear velocity based on the difference between bottom shear stress and water surface shear stress.

3. The water surface velocity obeys essentially the same law for moving water as it does for standing water, provided that instead of the water surface velocity \( V_{ws} \) one uses the difference \( V_{ws} - V_{av} \) between the water surface velocity and the mean water velocity.
4. The shear stress on the bottom of the channel can be calculated by using momentum balances for both the air and the water. The calculated bottom shear stress is in reasonable agreement with a bottom shear stress predicted by making the following assumptions:

a. Chezy's $C$ can be expressed by the equation

$$ C = 6.06 \log y_n + B $$

where $y_n$ is the depth of flow with wind blowing and $B$ is a coefficient which depends only on the slope $S_o$, but not on the wind conditions.

b. The shear stress is given by

$$ \tau_b = \frac{y}{C^2} v_{av}^2 $$

where $v_{av}$ is the mean velocity of the channel flow with wind blowing.

5. The water surface shear stress for standing water is proportional to the third power of the average velocity of the air, in agreement with previous findings by other authors. For moving water, the surface shear stress lies generally lower than for standing water. We are unable to give a complete account of the scatter in the data.

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### LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>a</td>
<td>water surface elevation above mean water surface level</td>
</tr>
<tr>
<td>A</td>
<td>constant in the velocity distribution law for the water</td>
</tr>
<tr>
<td>b</td>
<td>channel width</td>
</tr>
<tr>
<td>B</td>
<td>parameter in the equation relating Chezy's C to channel parameters</td>
</tr>
<tr>
<td>c_f</td>
<td>friction coefficient of sidewalls and ceiling of air duct</td>
</tr>
<tr>
<td>c_{ws}</td>
<td>water surface friction coefficient</td>
</tr>
<tr>
<td>C</td>
<td>Chezy discharge coefficient</td>
</tr>
<tr>
<td>D</td>
<td>constant in the velocity distribution law of the air</td>
</tr>
<tr>
<td>g</td>
<td>acceleration of gravity</td>
</tr>
<tr>
<td>h</td>
<td>height of wind water tunnel duct</td>
</tr>
<tr>
<td>M</td>
<td>momentum change in the air over standing water</td>
</tr>
<tr>
<td>dp</td>
<td>pressure gradient above the water</td>
</tr>
<tr>
<td>dx</td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>discharge</td>
</tr>
<tr>
<td>Re_{ws}</td>
<td>Reynolds number of water surface drift</td>
</tr>
<tr>
<td>s</td>
<td>Jeffreys' sheltering coefficient</td>
</tr>
<tr>
<td>S</td>
<td>slope of channel bottom</td>
</tr>
<tr>
<td>S_e</td>
<td>effective channel slope incorporating the pressure gradient</td>
</tr>
<tr>
<td>S'_o</td>
<td>water surface slope</td>
</tr>
<tr>
<td>u</td>
<td>local horizontal velocity in the air or water</td>
</tr>
<tr>
<td>u_{*a}</td>
<td>shear velocity for the air as calculated from the air velocity distribution</td>
</tr>
<tr>
<td>u'_{*a}</td>
<td>shear velocity for the air calculated from momentum balance</td>
</tr>
<tr>
<td>u_{*w}</td>
<td>shear velocity for the water calculated from velocity distributions</td>
</tr>
<tr>
<td>u'_{*w}</td>
<td>shear velocity for the water calculated from momentum balance</td>
</tr>
<tr>
<td>U_{av}</td>
<td>velocity of the air in the potential region outside the boundary layer</td>
</tr>
<tr>
<td>U_{av}</td>
<td>average air velocity in the duct above the water</td>
</tr>
<tr>
<td>V_{ws}</td>
<td>velocity of the water surface</td>
</tr>
<tr>
<td>V_{av}</td>
<td>average water velocity</td>
</tr>
<tr>
<td>x</td>
<td>co-ordinate parallel to the bottom of the laboratory channel</td>
</tr>
<tr>
<td>y</td>
<td>depth of water</td>
</tr>
<tr>
<td>y_n</td>
<td>normal depth in the channel</td>
</tr>
<tr>
<td>z</td>
<td>co-ordinate perpendicular to the channel bottom</td>
</tr>
<tr>
<td>a</td>
<td>velocity ratio V_{ws} / U_{av}</td>
</tr>
<tr>
<td>a_s</td>
<td>momentum change coefficient</td>
</tr>
<tr>
<td>a_p</td>
<td>pressure gradient coefficient</td>
</tr>
<tr>
<td>γ</td>
<td>specific weight of water</td>
</tr>
<tr>
<td>δ</td>
<td>boundary layer thickness</td>
</tr>
<tr>
<td>k</td>
<td>Karman's constant</td>
</tr>
<tr>
<td>λ</td>
<td>coefficient of momentum balance</td>
</tr>
<tr>
<td>ν_a</td>
<td>viscosity of the air</td>
</tr>
<tr>
<td>ν_w</td>
<td>viscosity of the water</td>
</tr>
<tr>
<td>ρ_a</td>
<td>air density</td>
</tr>
</tbody>
</table>
\( \rho_w \)  water density
\( \tau_b \)  calculated bottom shear stress
\( \tau_{bm} \)  measured bottom shear stress
\( \tau_s \)  shear stress on air duct side walls and ceiling
\( \tau_{ws} \)  water surface shear stress