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Transport Phenomena in a Laboratory Wind Wave
Channel: II. Evaporation and Energy Transfer

by

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SUMMARY

The energy and water vapor flux through a wavy air-water interface was measured using the integral form of the conservation principles. The normalized profiles of water vapor concentration and temperature (and therefore enthalpy) were measured above the interface and were found to be similar. The processes governing energy and mass transfer would therefore appear to be almost identical for the experimental conditions. The water temperature near the interface was significantly reduced below bulk water temperature as energy transfer through the interface increased. Typical boundary layer thickness development and integral parameter growth along the channel test section is presented. Energy and mass transfer computed from the integral conservation equations for a variety of wind speeds and for heated and unheated water are also presented.

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NomenclatureEnglish letter symbols

B	Mass transfer driving force, $B = (q_0 - q_\infty)/(1 - q_0)$
$C_{p,a}$	Specific heat of air at constant pressure
$C_{p,wv}$	Specific heat of water vapor at constant pressure
E	Evaporation rate or water vapor flux
F	Mass flowrate ratio, $F = \rho_0 v_0 / \rho_\infty u_\infty$
i	Air-water vapor mixture enthalpy, $i = (1 - q) C_{p,a} (T - T_0) + q [L_{T_0} + C_{p,wv} (T - T_0)]$
K	Pressure gradient parameter, $K = (v/u_\infty^2)(du_\infty/dx)$
L_{T_0}	Latent heat of vaporization for water at temperature T_0
q	Water vapor concentration (specific humidity)
Q	Total energy (latent plus sensible) flux through the air water interface
Re_x	Reynolds number based on x, $Re_x = u_\infty x / \nu$
Re_θ	Reynolds number based on θ , $Re_\theta = u_\infty \theta / \nu$
Re_Ω	Reynolds number based on Ω , $Re_\Omega = u_\infty \Omega / \nu$
St	Normalized energy transfer Stanton Number, $St = Q / \rho_\infty u_\infty (i_0 - i_\infty)$
St_m	Normalized water vapor flux or mass transfer Stanton Number, $St_m = E / \rho_\infty u_\infty (q_0 - q_\infty)$
T	Temperature
u	Velocity of air-water vapor mixture along the channel
v_0	Evaporation induced vertical velocity through the air water interface
x	Horizontal coordinate
z	Vertical coordinate
Z	A height above the boundary layers

Greek letter symbols

θ	Enthalpy thickness defined by Eq. (4)
ν	Kinematic viscosity of air water vapor mixture
ρ	Mixture density
Ω	Concentration thickness defined by Eq. (2)

Subscripts

o	Evaluated at the interface
∞	Evaluated in the free stream

Introduction. Energy and mass transfer through a wavy air-water interface is of multidisciplinary interest. Meteorologists and oceanographers study the ocean-air interface transport processes as these serve as boundary conditions to the atmospheric boundary layer and govern to a large extent thermal and other gradients below the ocean air interface. Engineers are likewise interested in the flux of energy and mass across the interface of inland waters as these affect the quality and quantity of the water resource.

A variety of experimental techniques are available to determine the mass (water vapor) and energy flux through an air-water interface. Some techniques are eddy correlation [1], equilibrium spectrum [2], and profile gradients [3] in the inner constant flux region of the boundary layer. However, particularly in the laboratory, the integral conservation technique is a useful method of flux determination utilizing simple instrumentation and straightforward data reduction procedures.

The mass transfer integral conservation equation for steady, two dimensional flow (cf., Kays [4]) is

$$St_m + F = d\Omega/dx + (\Omega/u_\infty)(du_\infty/dx) \quad (1)$$

where St_m is a normalized evaporation rate and Ω is the water vapor concentration thickness

$$\Omega = \int_0^Z \frac{\rho u}{\rho_\infty u_\infty} \left(1 - \frac{q - q_0}{q_\infty - q_0}\right) dz \quad (2)$$

The analogous energy conservation equation (which requires the additional assumption that the Lewis number, the ratio of mass to energy diffusion coefficients, is unity) is

$$St + F = d\theta/dx + (\theta/u_\infty)(du_\infty/dx) \quad (3)$$

where θ the enthalpy thickness is

$$\theta = \int_0^Z \frac{\rho u}{\rho_\infty u_\infty} \left(1 - \frac{i - i_0}{i_\infty - i_0}\right) dz \quad (4)$$

The Lewis number unity assumption has been shown by Hogstrom [5] to be valid for the neutrally stable conditions under which these experiments were run. The mass flowrate ratio term F in Eq. (1) arises from the small evaporation induced vertical velocity just above the interface. Consequently F can be related to the evaporation or mass transfer Stanton number (cf., Kays [4]) as $F = B St_m$ where B the mass transfer driving force is dependent solely on interface and free stream values of the water vapor concentration, i.e.

$$B = (q_0 - q_\infty)/(1 - q_0)$$

Using the relationship for F and expressing the gradient terms in the form of Reynolds numbers, Eq. (1) becomes

$$St_m = (1 + KRe_x)(dRe_\Omega/dRe_x)/(1 + B) \tag{5}$$

Similarly, the Reynolds number form of Eq. (3) is

$$St = (1 + KRe_x)(dRe_\theta/dRe_x) - F \tag{6}$$

The Stanton numbers were determined by computing those terms on the right-hand-sides of Eqs. (5) and (6) from the measured data.

Experimental apparatus, equipment, and procedure. The experimental configuration has already been described by Chambers, et al. [6]. Briefly the wind wave channel was 35 m long, 1.93 m high, and 0.91 m wide. The channel was approximately half filled with water. Air was drawn through the upper half of the channel which caused wind wave growth with fetch or distance along the channel. Four cases were examined in which the water was heated to approximately 10 - 20°C above ambient temperature with wind speeds of approximately 3.5, 6.6, 11.0 and 14.5 m sec⁻¹. The three lower wind speed cases were repeated with unheated water.

Average velocity u , specific humidity q , and temperature T above the mean water level were taken at eight stations along the channel. Standard pitot static tubes, electric hygrometers (Hydrodynamics, Inc.) and thermistors were used for the measurements. The water temperature near the interface was determined with an infrared radiometer (Model PRT-5, Barnes Eng. Co.) courtesy of the Remote Sensing Lab., Dept. of Geophysics, Stanford University. A considerable reduction of interface temperature below bulk water temperature was observed as shown in Fig. 1. The bulk-interface temperature difference was approximately proportional to total energy as discussed by Saunders [7].

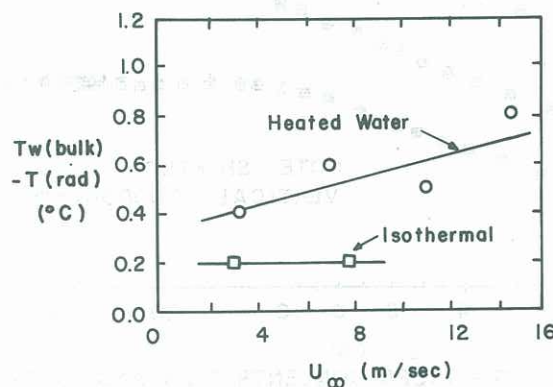


FIGURE 1. BULK WATER - INTERFACE TEMPERATURE DIFFERENCE VS. WIND SPEED

Experimental results. Fig. 2 shows typical measured normalized water vapor concentration and temperature profiles. Enthalpy was computed using the equation

$$i = (1 - q)[C_{p,a} (T - T_0)] + q[L_{T_0} + C_{p,wv} (T - T_0)] \tag{7}$$

where the first and second terms in the square brackets correspond to the enthalpies of the air and water vapor components respectively. The terms $(1 - q)$ and q are the concentrations of the air and water vapor. The enthalpy datum were chosen such that the enthalpy of the components evaluated at the interface was the latent heat of vaporization of water L_{T_0} in accordance with

meteorological practice of describing the energy transfer associated with mass diffusion as $L_{T0}E$. Normalized enthalpy profiles were computed using Eq. (7) and were found to be similar to the profiles shown in Fig. 2. It would appear from the similarity between the enthalpy and concentration profiles that the mechanisms governing energy and mass transfer are the same for these experimental conditions.

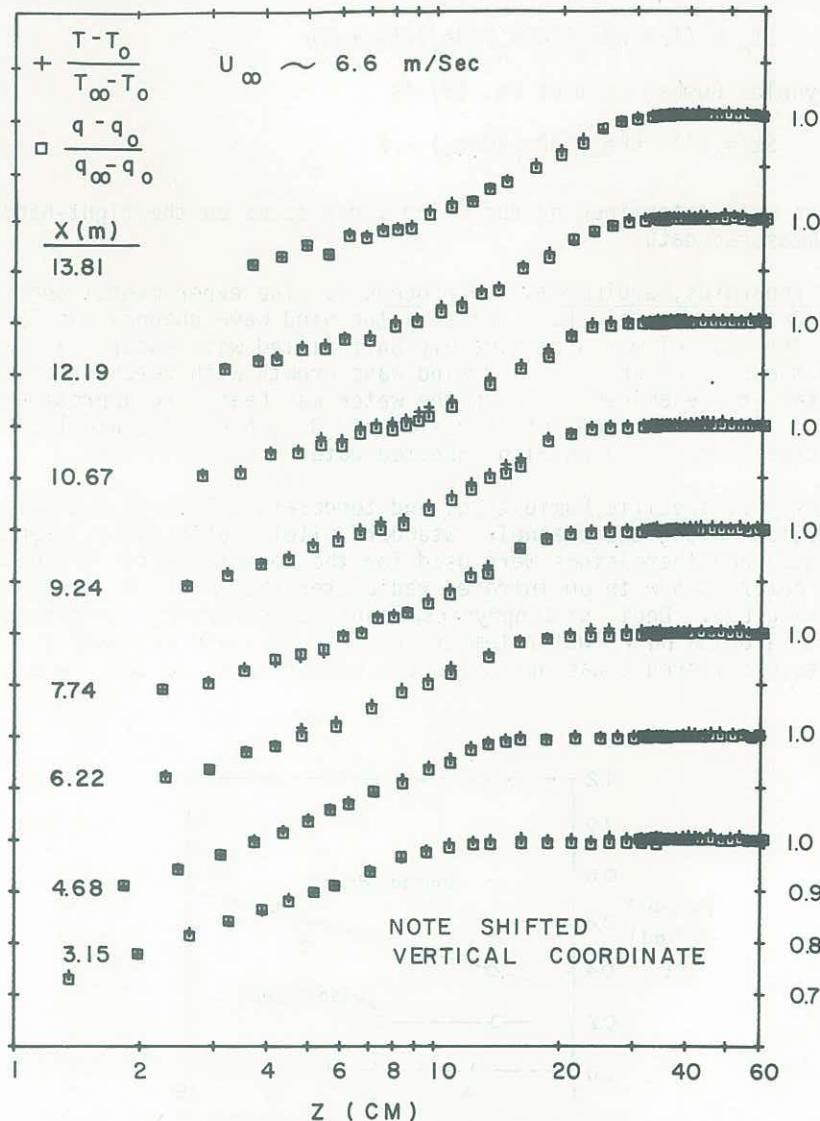


FIGURE 2. NORMALIZED CONCENTRATION AND TEMPERATURE PROFILES ABOVE THE MEAN WATER LEVEL

Boundary layer thicknesses were determined where the normalized temperature, concentration, and velocity were approximately 0.99. Typical boundary layer thickness growth is shown in Fig. 3. The thermal and concentration boundary layer thicknesses grew faster and exceeded the momentum boundary layer thickness, a phenomenon which has been observed by Thielbahr et al. [8] under somewhat different experimental conditions.

Integral parameters were evaluated from Eqs. (2) and (4) using the profile data. A typical variation of concentration thickness and free stream velocity is shown in Fig. 4. There was a slight increase in free stream velocity with fetch caused by constricting effects of momentum boundary layer growth and the configuration of the apparatus. Also indicated in the Figure is

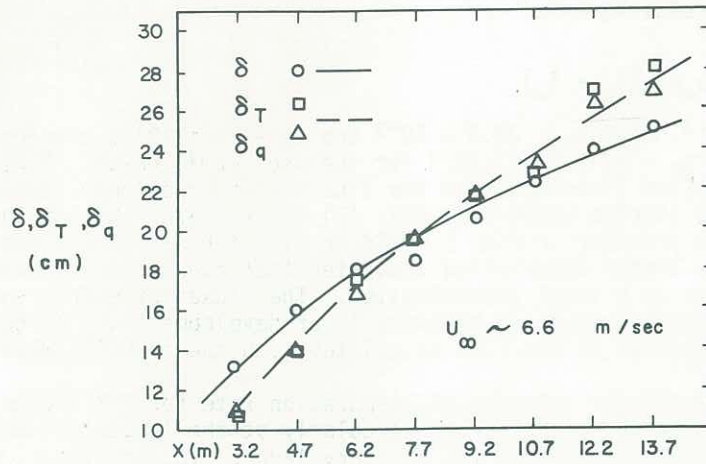


FIGURE 3.

MOMENTUM, THERMAL AND CONCENTRATION
BOUNDARY LAYER THICKNESS DEVELOPMENT

that portion of the integral parameter thickness which was computed by extrapolating below the lowest measuring height to the interface. The integral parameters were also plotted in Reynolds number form, e.g., Re_Ω vs. Re_x , on a doubly logarithmic scale, and fit with a least-squares-fit line of the form $Re_\Omega = aRe_x^b$. The gradient term dRe_Ω/dRe_x was then determined and used in Eq. (5) to compute the mass transfer Stanton numbers. An analogous procedure was used to compute the energy transfer Stanton numbers. In the fitting routine the variable x in Re_x was measured from the point where the integral parameter as in Fig. 4 was zero.

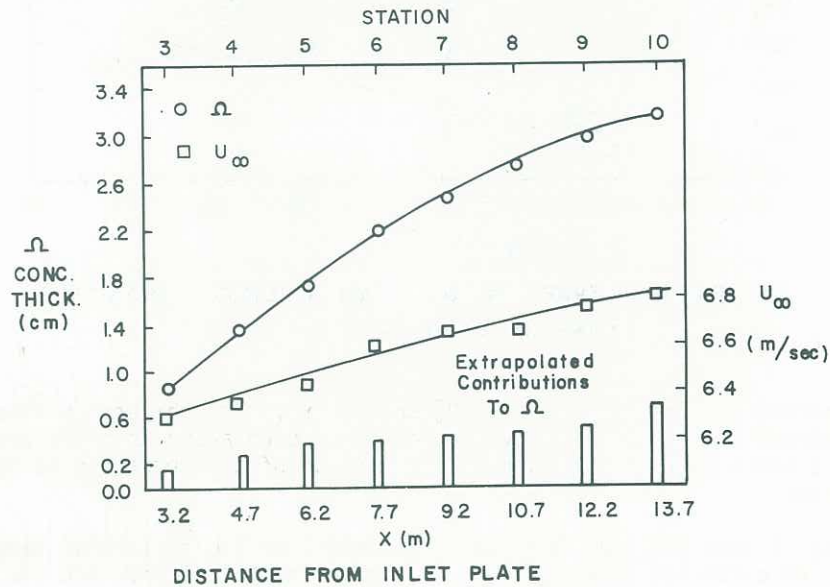


FIGURE 4. CONCENTRATION THICKNESS
AND FREE STREAM VELOCITY VS. FETCH

Evaporation and energy transfer were computed using the Stanton number defining equations

$$E = St_{III} \rho_{\infty} u_{\infty} (q_0 - q_{\infty}) \tag{7}$$

and

$$Q = St \rho_{\infty} u_{\infty} (i_0 - i_{\infty}) \tag{8}$$

with $\rho_{\infty} = 1.21 \times 10^{-3} \text{ gm cm}^{-3}$, $q_0 - q_{\infty} = 22.5 \times 10^{-3}$ and $T_0 - T_{\infty} = 13^{\circ}\text{C}$, average conditions for the heated water cases, and $q_0 - q_{\infty} = 6.5 \times 10^{-3}$ for the isothermal cases. These results are shown in Fig. 5 where the dotted lines describe the flux variation between Stations 3 and 10. It is commonly assumed that the Stanton numbers in Eqs. (7) and (8) are constant in which case the experimental energy and mass transfer in Fig. 5 could be fit with straight lines as drawn. The departure of the data from a linear description indicates that the constant Stanton number assumption can only be viewed as a first approximation. The fluxes of energy and mass are significantly reduced with fetch because of boundary layer development and perhaps because of a change in the diffusive properties of the flow associated with the changing wave field.

Fig. 5 also shows a significant increase in evaporation rate for the highest wind speed case. It is felt that some portion of this increase (particularly at the larger fetches) was due to the evaporation of spray particles ejected into the boundary layer. The additional spray evaporation

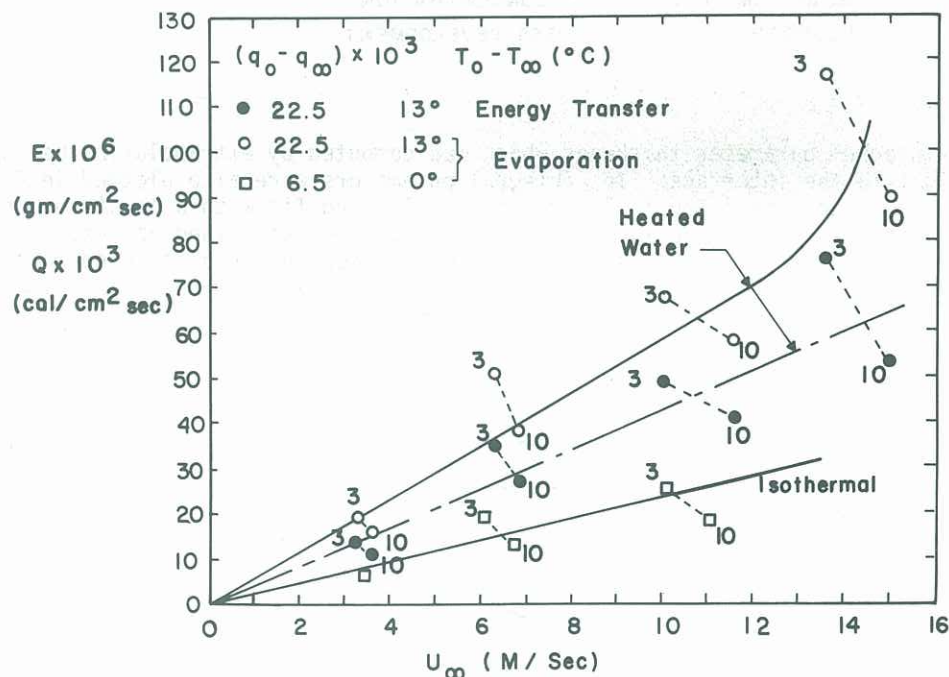


FIGURE 5. EVAPORATION AND ENERGY TRANSFER VS. FREE STREAM VELOCITY

mode has been observed by Okuda and Hayami [9] and others. The net energy flux however does not show a similar uptrend with wind velocity. It might also be added that the profile similarity as shown in Fig. 2 broke down for the spray case because of the reduction in temperature caused by spray evaporation.

Note that Fig. 5 does not show the energy transfer for the isothermal cases as these are simply $Q = L_{T_0} E$. An extensive discussion of this experimental program and its results can be found in [10].

Conclusions. Integral conservation equations have been shown to provide an experimental tool by which energy and mass flux through an air-water interface can be determined. Thermal and concentration boundary layer thicknesses grew faster and exceeded the momentum boundary layer thickness. The reason for this behavior is not clear. Evaporation and energy transfer cannot be predicted on the basis of constant Stanton number, rather such coefficients vary with fetch and perhaps can be significantly affected by spray droplets in the boundary layer.

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