Reports

On Evaporation from Wind-Swept Surfaccs

Abstract. Evaporation is analyzed in terms of resistances and driving forces for the coupled flows of vapor and heat. The conditions and assumptions under which all resistances can be determined independently are discussed, and preliminary experiments are reported. The effect of a monomolecular layer upon the transport of vapor is thus measured on a wind-swept surface, and its effect upon heat transport in the water is indicated.

The use of monolayers in evaporation control of reservoirs is assuming considerable importance (*1*), yet it seems to be based primarily on fundamental studies of film resistance on quiescent surfaces (*2*). The present report has been written to point out that the rate of evaporation can depend on a number of factors in addition to the film resistance, and that these can either be measured directly or estimated on the basis of reasonable assumptions with respect to a wind-swept surface.

Figure 1 illustrates schematically the specific resistances and specific driving forces involved during evaporation. The driving force for the transport of water is the difference between the pressure of the vapor in equilibrium with the water surface (P_s) and in the air above it (P_h). This vapor encounters the resistance of the air (R_a) and of the surface film, if any (R_f). Its flow per unit surface (W_t) is therefore given by

$$W_t = (P_s - P_h)/(R_a + R_f) \qquad (1)$$

The process of evaporation is highly endothermic (about 585 cal/g); hence the flow of vapor must be coupled to an equivalent flow of heat, and this can be conveniently expressed in the same units (W_t). This heat can flow only from the air (W_a) or from the bulk of the water (W_w). Hence:

$$W_t = W_a + W_w \qquad (2)$$

The flow of heat from the air encounters an air resistance r_a but is certainly not impeded by a monomolecular layer. The difference between the air temperature (T_a) and the temperature of the surface (T_s) provides the driving force:

$$W_a = (T_a - T_s)/r_a \qquad (3)$$

Similarly, the flow of heat from the bulk of the liquid is caused by the difference between the temperature of the bulk of the water (T_w) and that of the surface (T_s) against a resistance r_w:

$$W_w = (T_w - T_s)/r_w \qquad (4)$$

Experimentally it is possible to determine directly T_a, T_w, W_t, and W_w and the relative humidity of the air. Tables then give P_h and P_w (the equilibrium vapor pressure of the bulk water), and W_a is obtained from Eq. 2. The surface quantities T_s and P_s and the resistances cannot in general be measured directly.

The situation is simplified if no heat is supplied to the bulk of the water—by keeping it in a well-insulated vessel—so that $W_w = 0$ when a steady state is reached. Under these "acaloric" conditions there can be no difference between bulk and surface temperature as shown by Eq. 4, and therefore surface temperature and vapor pressure become directly measurable: $T_s = T_w$, $P_s = P_w$. This gives directly, then, the thermal resistance of air and the total resistance to vapor, from Eqs. 2 and 1:

$$r_a = (T_a - T_w)/W_t \qquad (5)$$

$$R_a + R_f = (P_w - P_h)/W_t \qquad (6)$$

When, in addition, no film is present —that is, when the surface is clean— $R_f = 0$, and Eq. 6 gives directly the vapor resistance of the air (R_a). These are psychrometric conditions determining the "wet bulb" temperature. The wet bulb temperature is constant for a given relative humidity and temperature over a wide range of wind velocities although the rate of evaporation changes. This shows that R_a/r_a is substantially constant, so that $R_a = Kr_a$. The value of the constant K can be determined experimentally for any given conditions, or it can be calculated from psychrometric tables which give $K \cong 0.50$ mm-Hg per degree centigrade. Introducing this into Eq. 5 and 6 gives directly the film resistance:

$$R_f = [P_w - P_h - K(T_a - T_w)]/W_t \qquad (7)$$

in terms of experimental quantities.

It may be noted that the effect of a film resistance is to raise the acaloric temperature above the psychrometric one, and this effect increases with increasing wind velocity—that is, decreasing $r_a/(R_a + R_f)$.

If conditions are not acaloric but heat is supplied to the water at a constant rate, the air and film resistance should not be affected. Knowledge of these resistances permits two independent estimates of the surface temperature, one directly by Eq. 3, the other through P_s from Eq. 1. Agreement of the two values is an indication of the correctness of the assumption of the constancy of the resistances. Once surface temperature has been estimated, Eq. 4 gives directly the resistance encountered by heat within the water.

Preliminary measurements along these lines have been made with a simple apparatus based on a 15-cm crystallizing dish fitted with a side arm and set in foamed plastic insulation above a bare-wire electric heater also surrounded by the insulation. An adjustable air stream was provided by a blower, and the rate of evaporation was measured by the amount of water required to restore the level, as indicated by a sharp point located just below the surface. The whole was operated in an air-conditioned room

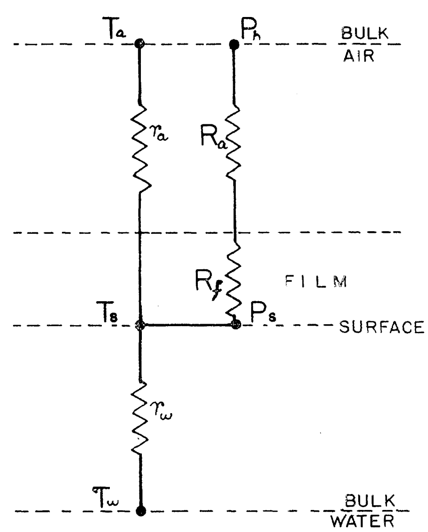

Fig. 1. The resistances and driving forces in the coupled flows of heat (left) and water vapor (right) during evaporation.

Instructions for preparing reports. Begin the report with an abstract of from 45 to 55 words. The abstract should *not* repeat phrases employed in the title. It should work with the title to give the reader a summary of the results presented in the report proper. (Since this requirement has only recently gone into effect, not all reports that are now being published as yet observe it.)

Type manuscripts double-spaced and submit one ribbon copy and one carbon copy.

Limit the report proper to the equivalent of 1200 words. This space includes that occupied by illustrative material as well as by the references and notes.

Limit illustrative material to *one* 2-column figure (that is, a figure whose width equals two columns of text) or to *one* 2-column table or to *two* 1-column illustrations, which may consist of two figures or two tables or one of each.

For further details see "Suggestions to Contributors" [*Science* 125, 16 (1957)].

to reduce fluctuations in temperature and relative humidity. A few bits of commercial cetyl alcohol sprinkled by hand on the surface of the water provided the resisting film. Imperfectness of the insulation seems to have been the limiting factor on the accuracy and range of the measurements. Reproducibility of the film was also somewhat haphazard.

At a high wind velocity of about 18 mi/hr the acaloric steady-state temperature was raised by 4.4°C as a result of the film, while at a lower wind velocity of about 6 mi/hr, the effect was 3.8°C. The corresponding resistances were $r_a = 4.2$ and 7.5×10^5°C sec cm²/g; $R_f = 20$ and 22×10^5 mm-Hg sec cm²/g, or, in centimeter-gram-second units, $R_f = 2.1$ sec/cm within experimental error. When the water was heated, the experimental uncertainty in W_a was too large to make it useful in determining the surface temperature through Eq. 3. Equations 1 and 4 were therefore used to estimate the thermal resistance of water (r_w). The values found did not seem to depend appreciably on wind velocity but increased markedly in the presence of film, especially when heat input was small and bulk temperature was close to surface temperature. They ranged from $0.4 \pm 0.15 \times 10^5$°C sec cm²/g for a clean surface to 1.4×10^5 in the presence of a film when $T_w - T_s \cong 3$°C and 2.6×10^5 when $T_w - T_s \cong 0.8$°C. These effects suggest that convection currents are the main factor determining r_w.

Rather surprisingly, the film had no perceptible effect upon the thermal resistance of air (r_a). Thus, the quieting effect of a monolayer (*3*)—the calming of troubled waters—which is so prominent in field tests of evaporation control (*4*) seems not to affect the rate of evaporation under the conditions of these small-scale experiments (*5*).

KAROL J. MYSELS
Chemistry Department, University of Southern California, Los Angeles

References and Notes

1. Proceedings of First International Conference on Reservoir Evaporation Control, San Antonio, Texas, 1956, Southwest Research Institute; *Proc. Intern. Congr. Surface Activity, 2nd Congr.* (Butterworths, London, 1957), vol. I, pp. 259–280.
2. I. Langmuir and V. J. Schaefer, *J. Franklin Inst.* 235, 119 (1943); R. Archer and V. K. LaMer, *Ann. N.Y. Acad. Sci.* 58, 807 (1954); ——, *J. Phys. Chem.* 59, 200 (1955); H. L. Rosano and V. K. LaMer, *ibid.* 60, 348 (1954).
3. J. W. Rayleigh, *Proc. Roy Soc. (London)* 68, 127 (1890); *Phil. Mag.* 30, 386 (1890); *Collected Papers*, vol. III, pp. 363, 386; J. Samashima and T. Sasaki, *Bull. Chem. Soc. Japan* 11, 539, 547 (1936).
4. See, for example, *Chem. Eng. News* 36, No. 26, 44 (30 June 1958).
5. I am indebted to the research staff of Continental Oil Co., Ponca City, Okla., for introducing me to this subject; to Miss Jeanne Hotchkiss for her careful measurements; and to P. Scholten for his many sceptical remarks. This study was sponsored by the Office of Ordnance Research, U.S. Army.

15 September 1958

Effect of Interruption of the Visual Pathway on the Response to Geniculate Stimulation

Abstract. Optic nerve section or destruction of the lateral geniculate nucleus increased the amplitude and elevated the recovery cycle of the cortical response to lateral geniculate radiation stimulation in cats. The lesions may have acted by eliminating tonic inhibitory or occlusive volleys originating in the retina, or both.

Since publication of the initial descriptions of the cortical response to electrical stimulation of the geniculo-striate pathway (*1*) there have been a number of studies of the anatomical substrate (*2*) and recovery cycle (*3, 4*) of this response. Recent studies of this recovery cycle (carried out in unanesthetized cats with chronically implanted electrodes) showed that a stimulus to the lateral geniculate radiations was followed by subnormality lasting 1 second or more (*5*). In recent studies of the factors underlying this prolonged subnormality, it was found that optic nerve section or destruction of the lateral geniculate nucleus markedly altered the recovery cycle of the cortical response to lateral geniculate radiation stimulation. The present report describes these observations.

Adult cats were anesthetized with pentobarbital, ether, or urethane and placed in a stereotaxic instrument. Stimulating electrodes in the lateral geniculate radiations delivered a pair of shocks every 5 seconds. The first (conditioning) stimulus of the pair preceded the second (test) stimulus by 3.2 to 1600 msec. The evoked responses were recorded from the surface of the lateral gyrus with a pore electrode. Lesions of the lateral geniculate were produced electrolytically. The optic nerve was interrupted by freezing or by clamping.

Interruption of both optic nerves or destruction of the ipsilateral lateral geniculate caused a decrease in variability and an increase in amplitude of the postsynaptic components of the cortical response to geniculate radiation shock. Such lesions also caused a marked decrease in the degree of subnormality of the surface positive components, though not of the surface negative component, of the test response (Fig. 1). Figure 2 presents a graph of a recovery cycle before and after optic nerve section. These effects could be demonstrated in cats anesthetized with each of the three anesthetics employed.

Several experimental variables modified the degree to which recovery was enhanced following interruption of the visual pathway. One of these was stimulus intensity, recovery being enhanced more for the responses to supramaximal than for those to near-threshold stimuli. A second variable was the relative position of the stimulating and recording electrodes. The responses in cortical positions outside the maximal cortical focus of the stimulating electrodes showed marked increase in amplitude, but the enhancement of the recovery cycle was relatively slight. On the other hand, at the maximal focus, responses showed less increase in amplitude but more enhancement of the recovery cycle.

Several hypotheses may be offered as to the mechanism by which interruption of the visual pathway exerts these effects. The lesions might act by eliminating the

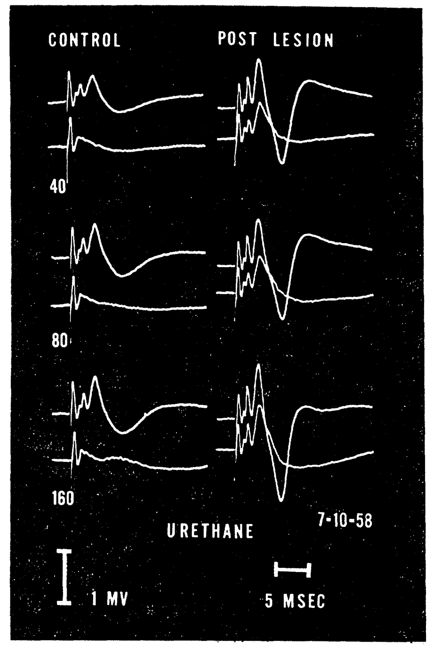

Fig. 1. Cortical responses to paired geniculate radiation shocks before (left) and after (right) optic nerve section under urethane anesthesia. Separations between the shocks of each pair are indicated at the left of each row. Following the lesion there is an increase in amplitude of all components of the response. Positive is up.

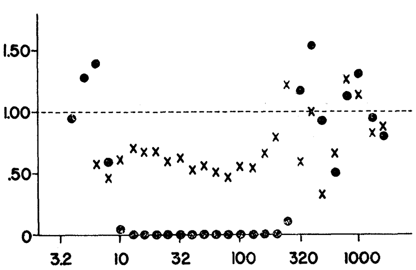

Fig. 2. The recovery cycle of the major positive component (C_4) of the cortical response to geniculate radiation stimulation before (dots) and after (crosses) optic nerve section. On the abscissa is plotted separation (in milliseconds) between paired shocks. On the ordinate is plotted the ratio of the amplitude of C_4 (the major positive component of the test response) to C_4 of the control. Following the lesion, depression of the test response between 10 and 250 msec was much less marked than it had been before the lesion.