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§ Introduction.

The rate of evaporation in still air is larger than that calculated by molecular diffusion theory. It will be mainly by natural convection due to cooling of water surface by evaporation. If the problem of natural convection is solved in the case of a heated flat plate, one can by analogy between heat transfer and evaporation obtain the solution for the rate of evaporation from a flat evaporating surface. Actually on heat transfer the solution is only obtained at present in the two-dimensional case of a vertical plate and so the corresponding solution for evaporation would be of little practical use in itself. But it is known experimentally that the heat transfer from a horizontal plate is expressed by the same law except with some different numerical coefficient, so that the theoretical formula for the case of evaporation will also have some physical meaning.

§ Calculation of the Rate of Evaporation by Natural Convection from a Vertical Evaporating Surface.

We take \( x \)-axis vertically, \( y \)-axis horizontally and the evaporating surface on \( x \)-axis as shown in Fig. 1. Then the differential equations for the two-dimensional case will be as follows. The equation of motion will be

\[
\frac{\partial \Phi}{\partial y} \frac{\partial^2 \Phi}{\partial x \partial y} - \frac{\partial \Phi}{\partial x} \frac{\partial^2 \Phi}{\partial y^2} = \nu \frac{\partial^4 \Phi}{\partial y^4} + \frac{\partial^2 \Phi}{\partial y^2} + g \beta \Theta, \tag{1}
\]

and the equation of heat transfer from the evaporating surface will be

\[
\frac{\partial \Phi}{\partial y} \frac{\partial T}{\partial x} - \frac{\partial \Phi}{\partial x} \frac{\partial T}{\partial y} = a \frac{\partial^2 T}{\partial y^2}, \tag{2}
\]

and the equation of diffusion will be

\[
\frac{\partial \Phi}{\partial y} \frac{\partial C}{\partial x} - \frac{\partial \Phi}{\partial x} \frac{\partial C}{\partial y} = \frac{\partial^2 C}{\partial y^2}, \tag{3}
\]

where \( \Phi \) = stream function, \( \nu \) = kinematic viscosity, \( \beta \) = expansion coefficient of air, \( g \) = acceleration of gravity, \( \Theta = \theta - \theta_\infty \), \( T = \frac{T}{T_0} = \theta - \theta_\infty \), \( \theta = \) temperature of water surface, \( \theta_\infty = \) air temperature near the surface and at infinity respectively, \( C = C - C_\infty = C_0 \), \( C_0 \), \( C_\infty \) = respectively vapour concentrations at the surface, near the surface and at infinity, \( a = \) coefficient of heat transfer, \( \alpha = \) diffusivity. The boundary conditions are:

\( u = \frac{\partial \Phi}{\partial y} = 0, v = -\frac{\partial \Phi}{\partial x} = 0, T = 1, C = 1 \) at \( y = 0, u = 0, v = \) const., \( T = 0, C = 0 \) at \( y = \infty \).

Now we introduce the new variable \( \xi \) defined by

\[
\xi = \left( \frac{g \beta \Theta}{4 \nu^2} \right)^{1/4} \frac{y}{x^{1/4}} = \frac{y}{x} \left( \frac{Gr}{4} \right)^{1/4},
\]

where \( Gr = \frac{x^3 g \beta \Theta}{\nu^2} \) (GRASHOF number), then

\[
\Phi (x,y) = 4 \nu A x^{3/4} \xi (\xi),
\]

\[
T (x,y) = t (\xi),
\]

\[
C (x,y) = \eta (\xi),
\]

where \( \xi, t \) and \( \eta \) satisfy following differential equations,

\[
\xi'''' + 3 \xi''' - 2 \xi'' + t = 0, \tag{4}
\]
EVAPORATION BY NATURAL CONVECTION

vertical evaporating surface. According to M. ten Bosch the rate of heat transfer from a horizontal disk or plate is given by the formula which has the same form as for the heat transfer from the vertical plate, but in which the radius or half of the length of the plate is taken as \( x \) instead of the total length in the case of the vertical plate. Therefore by analogy in the case of evaporation from a horizontal disk or plate (9) will be available in which the radius or half of the length of the plate must be taken as \( x \).

§ Experiment and Discussion.

Measurement of the rate of evaporation was carried out by employing a glass vessel whose radius is 1.83 cm and depth 2 cm. A nichrome wire was inserted in the vessel as shown in Fig. 2, and by heating it experiment was carried out in the range of \( \theta_s - \theta_m \) between 0.1 and 50°C. The rate of evaporation was measured by weighing the water loss by chemical balance whose sensitivity is 1 mg. The vessel was covered by a glass lid to prevent evaporation during weighing. The vessel was also surrounded by cork to protect heat exchange to the surroundings. The temperature of water surface was measured by a thermocouple of copper-constantan, and the vapour pressure and air temperature were measured by ASSMANN's psychrometer before and after the weighing. Experiment was
carried out in a closed chamber at night to avoid the variation of air temperature and vapour pressure as far as possible.

The result of measurement was shown in Fig. 3, in which abscissa expresses \( \theta_0 - \theta_\infty \) and ordinate \( \frac{E}{C_0 - C_\infty} \), each in logarithmic scale. The unit of \( E \) is g cm\(^{-2}\) sec\(^{-1}\), and that of \( C_0 \) or \( C_\infty \) g cm\(^{-3}\). The full line in the figure shows

\[
\frac{E}{C_0 - C_\infty} = 0.298 (\theta_0 - \theta_\infty)^{\frac{1}{4}}
\]

which expresses the mean value of the measurement, and the dotted line shows the theoretical value for vertical surface, i.e.,

\[
\frac{E}{C_0 - C_\infty} = 0.359 (\theta_0 - \theta_\infty)^{\frac{1}{4}}
\]

which is obtained from (9) by inserting following numerical data corresponding to \( \theta_\infty = 20^\circ \mathrm{C} \);

\( \nu = 0.153, \ d = 0.257, \ \beta = 0.367 \times 10^{-2} \) and \( x = 1.83 \mathrm{~cm} \).

It will be shown from the result that the measured rate of evaporation from the horizontal disk by natural convection is about 21% smaller than that predicted by the above theory.

In the case of heat transfer from a horizontal surface by natural convection, HENCKY's experimental result\(^{(2)}\) agrees with the theoretical calculation by M. ten BOSCH, whereas WEISE's experimental result\(^{(3)}\) shows about 20% smaller rate of heat transfer than BOSCH's calculation.

Our experimental result on evaporation resembles with WEISE's result on heat transfer.

References.

(1) M. ten Bosch, "Wärmeübertragung".
(2) K. HENCKY, Oldenburg (1921).
(3) R. WEISE, Forschung, 6, 281 (1935).