A METHOD OF ESTIMATION OF THE THICKNESS OF THE "LAMINAR" LAYER ABOVE AN EVAPORATING WATER SURFACE

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1. INTRODUCTION

WHEN a current of air flows horizontally over a surface of water there are, as is well-known, (i) a " laminar " or " boundary " layer adjacent to the water surface, in which the air movement is stream-lined in character and (ii) a turbulent or eddying layer above the laminar layer in which there is a considerable amount of mixing. The thickness of the laminary layer ***decreases*** rapidly with increase in the mean velocity of air current.

In the laminar layer AB to CD (Fig. 1) the variation with height of factors like temperature, vapour pressure and wind velocity may be assumed to be linear ; the transfer of momentum, water vapour or heat in the laminar

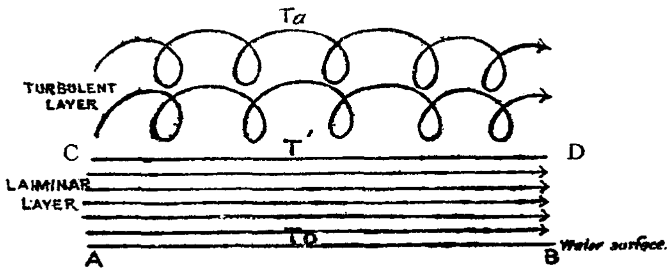

FIG. 1

layer will be due to molecules, whereas in the turbulent layer the eddies take a major part in such transfer. It is significant that the heat transfer between the air and the water surface will be $k \times \frac{dT}{dZ}$ where k is the molecular heat conductivity of air ($5 \cdot 77 \times 10^{-5}$) and $\frac{dT}{dZ}$ is the thermal gradient in the laminar layer. With the above assumptions and from a knowledge of (*a*) the rate of evaporaton, (*b*) the vertical temperature gradient between the water surface and a series of points above the surface, and (*c*) the temperatures of the water surface and the surrounding room it is possible to estimate, under certain favourable conditions (when the heat of evaporation is supplied entirely by the air and by radiative exchange), the thickness δ of the laminar layer and its dependence on the mean wind velocity. The present paper discusses the results obtained in a preliminary investigation on the above lines.

2. The Vertical Change of Temperature Inside and Above a Layer of Water

If a vessel containing water is kept exposed to the air, the variation of water temperature with depth and of the air temperature with height above the water surface will depend upon the mean temperature of the water layer, the difference of temperature between the water and the air above, the wind velocity and the rate of evaporation. Fig. 2 shows the variation of temperature when measurements were made with water at different mean temperatures. The general air temperature in the room was sensibly constant during these experiments. The measurements of the water temperature at various depths and of the temperature of the air just above the water surface at various heights above the surface were repeated in quick succession for various values of the mean temperature of the water layer.

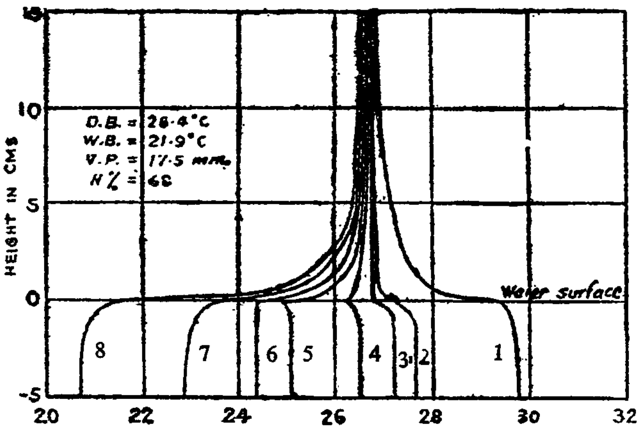

Fig. 2.

A water reservoir 24 cm. in diameter and 10 cm. deep was filled with water at the required tempereture. The water was stirred well and then allowed to come to rest. After the water column had come to rest and the conditions above and below the water surface had become steady, the temperature measurements were made. The temperatures were measured by using a series of fine copper-constantan (50 S.W.G.) junctions connected to a suitable switchboard and a common junction at a standard temperature.

Each junction could be connected in turn to a Moll galvanometer and the deflections recorded in quick succession. The values of temperature were read off from the calibration curve of each junction (previously determined). All the junctions were kept horizontal, except the one in contact with the water surface which was vertical with the sensitive point approaching the surface from *below* the water surface. In Fig. 2 the dry bulb and wet bulb temperature of the air in the room (well away from the water resorvoir) recorded with an Assmann Psychrometer together with the vapour tension and the relative humidity are also indicated. Curves 1 to 8 refer to the different mean temperatures of the water column. As is to be expected, all the curves tend to meet at a sufficient height above the water surface. In Curves 1 and 2 the temperature *decreases* gradually as one approaches the water surface from below. The most rapid fall occurs in the first few mm. *above* the water surface ; thereafter the fall of temperature is more gradual. Under these conditions the water column supplies heat to the water surface for the evaporation process as well as for warming the air layers above it.

Curve 3 refers to the case when the surface of the water is at the same temperature as the air above. Here there is no gradient of temperature *above* the water surface, so that the heat required for evaporation is supplied entirely by the water column. In Curve 4 the mean temperatures of the air is the same as that of the water column. Here there is a fall of temperature as we approach the water surface both from above as well as below, so that the heat required for evaporation is arriving by conduction both from the air as well as the water column. Curve 6 is the most interesting, as the whole water column tends to remain at a uniform temperature. The air temperature increases with height above the surface and the heat required for evaporation is obtained entirely by conduction from the air *above* the water surface (and by the heat gained by radiative exchange between the surface and the surroundings).

With further decrease of the mean water temperature (Curves 7 and 8) the temperature increases as one approaches the water surface from below and continues to increase with height above the water surface. Here the heat conducted from the air is used partly for evaporation and partly for warming the water layer as well. When the mean temperature of the water column is at or below the dew point water vapour begins to condense on the water surface adding a further contribution of heat.

In the rest of this paper we deal only with evaporation under the simple conditions defined by Curve 6 in Fig. 2. It must be remembered that no hea is then lost by the water ; the heat required for evaporation is supplied entirely by (*a*) conduction from the air and (*b*) radiative exchange* with the surroundings. Under these simple conditions we have

$$Lw = k\frac{dT}{dZ} + \sigma(T^4_a - T^4_0)$$

where L is the latent heat of evaporation,

w is the evaporation in grammes per second,

k is the molecular thermal conductivity,

T_0 and T_a are the temperatures of the water surface and of the walls of the room (the same as the temperature of the room air),

σ is the Stefan Boltzman constant.

In the above expression, L is known, w, T_0 and T_a can be measured directly, σ is known, so that the factor $k\frac{dT}{dZ}$ can be computed. This has been done for a number of wind velocities. These data have been used for estimating the thickness δ of the laminar layer, as will be clear from the next section.

3. Estimation of the Thickness of the Laminar Layer

The experimental arrangements are the same as in Section 2. The water reservoir is protected at the sides by a layer of heat insulating material. *In all the experiments the water layer is brought to the isothermal* condition *as defined by Curve* 6 *of Fig. 2.* The rate of evaporation is measured by keeping a small circular dish 26·42 sq.cm. in area at the centre of the water surface with a layer of water inside adjusted so as to be at the same level as that of the water surface outside. This vessel is weighed before and after each experiment, care being taken to dry the outside and keep the vessel covered during weighing. The wind velocity is regulated by means of an adjustable electric fan with a wire-gauze shield in front to reduce major fluctuations. After starting the fan and verifying that the water in the reservoir is isothermal, the surface temperature and the air temperature at 1, 2, 3, 5 mm. above the water surface as well as the temperature of the air in the room were measured. Table I gives the results of a series of experiments at different wind velocities. The first column gives the mean rate of evaporation during the period of half to one hour usually taken to complete each experiment. The total

* Both the water surface and the walls of the room act like "black" bodies in the infra-red.

TABLE I

Evaporation in gr./cm.^{2} per sec. $\times 10^7$ (w)	Wind velocity in metres per sec. (v)	H%	Isothermal temperature of water column in °C. T_0	Room temperature in °C. T_a	Temperature gradient in °C. per cm. between				$Lw - \rho (T_a^4 - T_0^4)$ $\left(= k\frac{dT}{dZ}\right) \times 10^5$	$10^5 \times$				$\frac{dT}{dZ}$ in laminar layer °C. per cm.	Estimated thickness of laminar layer δ	Fall of temperature $\Delta T°$ C. in laminar layer $\delta \times \frac{dT}{dZ}$	Fall of temperature in laminar layer ΔT / Total fall
					0–1 mm.	0–2 mm.	0–3 mm.	0–5 mm.		k_1	k_2	k_3	k_5				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(3)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
31·76	0·2	44	21·6	27·6	26·2	17·0	12·4	8·3	107·3	4·07	6·28	8·66	13·01	18·6	0·170	3·16	0·5
43·91	0·35	61	22·3	26·9	31·4	17·1	12·0	7·8	195·4	6·25	11·39	16·21	24·94	33·9	0·087	2·95	0·6
44·79	0·72	64	22·5	26·7	26·5	14·2	9·9	6·1	206·2	7·82	14·60	20·98	33·65	35·7	0·068	2·43	0·6
53·30	1·00	70	23·2	26·9	1·5	16·0	10·5	6·6	269·9	8·58	16·90	24·97	40·84	46·8	0·056	2·62	0·7
62·39	1·80	70	23·6	26·9	28·2	14·8	10·1	6·1	321·9	11·45	21·83	32·02	52·65	55·8	0·038	2·12	0·6

evaporation divided by the time in seconds and by the area of cross-section of the floating vessel is of the order of 30×10^{-7} to 65×10^{-7} gr./cm.^{2} sec. for the range of velocities which are indicated in column (2) in metres per second. The relative humidity of the air as measured with the Assmann Psychrometer is given in column (3). Column (4) gives the isothermal temperature of the water column (also temperature of water surface). The room temperature well away from the evaporimeter is given in the next column. Columns (6) to (9) give the temperature gradients between 0 (surface) to 1 mm. (above surface), 0 to 2 mm. 0 to 3 mm. and 0 to 5 mm. in °C. per cm. Column (10) gives the values of the difference between the heat L*w* used up for evaporation and the heat gained by the surface by radiative exchange with the surroundings. This difference $[Lw - \sigma (T^4_a - T^4_o)]$ is equal to the heat kdT/dZ transported to the water surface by molecular conduction across the laminar layer. The evaporation and temperature measurements thus give us an estimate of the heat gained by conduction. We do not know the value of dT/dZ in the laminar layer directly, but the values of column (10) divided by the molecular heat conductivity of air ($5{\cdot}77 \times 10^{-5}$) give us estimates of this gradient; these are given in column (15).

It is well known that the gradient of temperature dT/dZ in the laminar layer will be much higher than that above it. If the mean temperature gradients between 0 to 1 mm., 0–2 mm., 0–3 mm. and 0–5 mm. are computed it will be found that as we gradually increase the distance between the water surface and the point of reference above it, the values of mean temperature gradient will *decrease*. If the figures given in column (10) are divided by the apparent mean temperature gradients given in columns (6) to (9) we ge estimates of the apparent heat conductivities given in columns (11) to (14). In Fig. 3 these values of apparent conductivity are plotted against the distance between the surface and the point of reference used for computing the

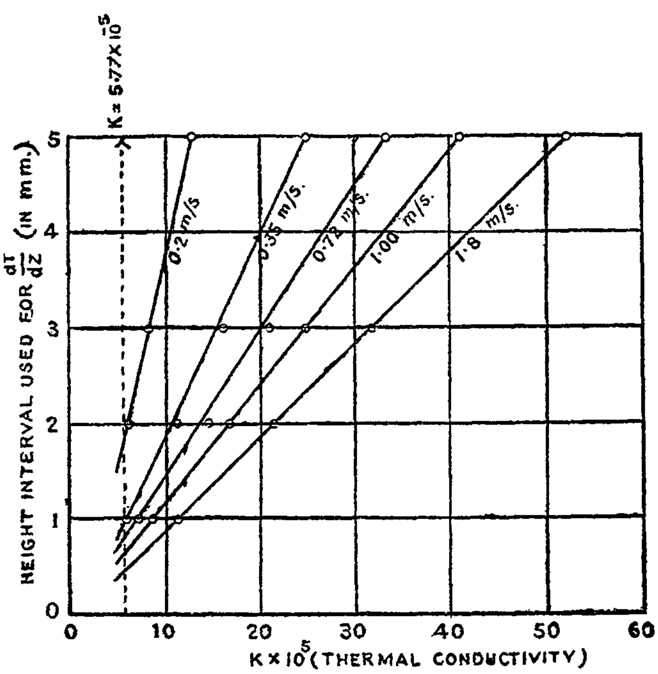

FIG. 3

apparent temperature gradients. The values for each wind velocity lie along a straight line, which can be produced to cut the vertical line at $5 \cdot 77 \times 10^{-5}$, the molecular heat conductivity. These points of intersection give estimates of the thickness δ of the lamina layer within which molecular heat conductivity must prevail. The values of δ are given in column (16). The values of $dT/dZ \times \delta$ representing the total fall of temperature in the laminar layer are given in column (17). In the last column the values of the ratio of the fall of temperature in the laminar layer to the total fall of temperature from the air to the water surface are given. It will be seen that on an average about 6/10 of the total fall occurs in the laminar layer. The effect of increasing wind velocity is to increase the temperature gradient in the laminar layer in which about 6/10 of the temperature variation with height occurs.

Fig. 4 shows how δ, the thickness of the laminar layer, varies with the wind velocity v. δ decreases with v rapidly at first and more gradually thereafter. It was difficult to carry out measurements for $v > 2 \cdot 0$ metres per second,

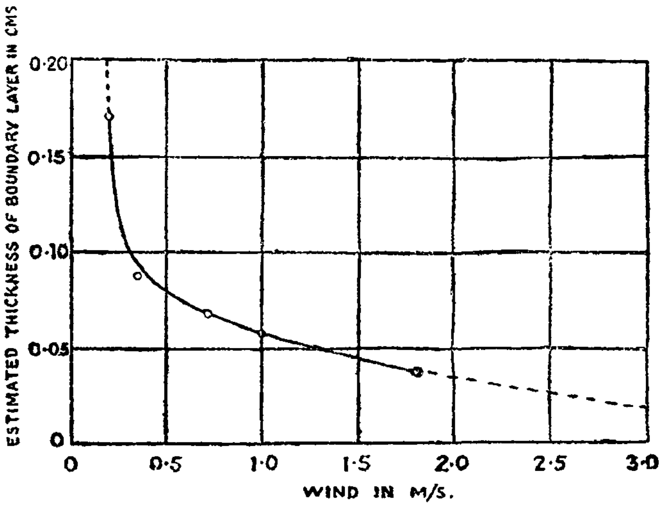

FIG. 4

as the water surface began to get agitated at higher wind velocities ; by extrapolation it is easy to see from Fig. 3 (dotted portion) that δ may decrease to 0·025 cm. at a wind velocity of 3 metres per second. The rapid increase of δ with decrease of v towards zero is also obvious.

4. SUMMARY AND CONCLUSION

The present paper indicates a simple experimental method of estimating the thickness δ of the laminar layer of an evaporating water surface at different wind velocities. When the water layer is adjusted to be isothermal (*vide* Curve 6 of Fig. 2) the heat Lw required for evaporation comes entirely by molecular conduction across the laminar layer $k\ dT/dZ$ and by exchange of radiation $(\sigma T_a^4 - \sigma T_o^4)$ with the surroundings. From estimates of dT/dZ using increasing height intervals between the surface and the next level of reference, it is possible to calculate a series of k's which fall on straight lines, when plotted against the corresponding values of ΔZ. The values of ΔZ given by the points of intersection of the above lines with the vertical line at $k=$ molecular conductivity, give estimates of δ, the thickness of the laminar layer.

Further work on these lines is in progress.