# Mechanism of Drying Thick Porous Bodies During the Falling Rate Period

## I. The Pseudo-Wet-Bulb Temperature

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**The drying of two highly porous thick textiles is studied and compared. Extremes are chosen in that one package is composed of a Terylene (British form of a polyester fiber) net fabric of open structure and the other of a woolen flannel of close structure. The cloths are wound as bobbins and dried by hot air streaming in a wind tunnel, the air flowing parallel to the axis of the cylinder of material. The weight of water as drying progresses is measured by a balance, and thermocouples within the bobbin provide a temperature record.**

**On investigation of the thermal conductivity of the dry structure, it is found that whereas the coefficient for the wool-air mixture is constant throughout, the coefficient for the Terylene-air mixture applies only in the depths, the apparent thermal conductivity growing larger toward the surface and with increasing air speed, as if the heat transfer through the open structure is assisted by some form of air penetration.**

**As the thick textiles dry, the rate of evaporation falls off, since heat and water vapor have to pass through an increasing layer of dry material. While this is occurring, a constant temperature, the "pseudo-wet-bulb temperature," is established throughout the wet cloth. This state of equilibrium may be expressed as an equation between the rate of heat conduction inward and that required to produce the vapor diffusion outward. From this equation the pseudo-wet-bulb temperature can be calculated.**

The rate of drying of any particular material depends upon the relative magnitudes and modes of variation of two processes, heat and mass transfer. For evaporation to take place heat must be supplied to the evaporating fluid from some heat source. In air drying the heat is contained in the air and must be conveyed through the stagnant surface-air layer to the solid surface and thence must pass to the zone of evaporation. In the later stages of drying this often has to occur through a thick layer of dry material. A knowledge of the thermal conductivity of the dry material is thus important in an investigation of the drying process.

In this paper the heat transfer in the dry material is considered first and then the complete drying sequence. Results are reported for two packages, both of high porosity, one consisting of Terylene (British form of a polyester fiber corresponding to the American Dacron) net fabric of open structure and the other of a woolen flannel of close structure.

### THE APPARATUS

The materials were wound as bobbins and supported in hot air streaming through a wind tunnel. Thermocouples throughout the bobbins and in the wind tunnel indicated temperatures. As drying took place, the weight of water leaving the bobbin was determined directly by a continuous weighing with an analytical balance.

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#### The Wind Tunnel

The wind tunnel and ancillary components are shown diagrammatically in Figure 1. The main structure was of ⅜-in. asbestos cement sheeting with inside section 8¾ in. square. The upper working section was made hexagonal, and flow straighteners were inserted at the bends ($C_{1,2,3}$) to reduce transverse flow. Flow mixers ($B_1$ and $B_2$) ensured a uniform distribution of air velocity across the tunnel section. The tunnel was usable with continuous recirculation, direct flow through, or proportions of the two by means of the shutters ($a$ to $g$). The air was blown by a fan ($F$) through the heating section ($A$) containing four 1¼-kw. spiral heating elements. Temperature was controlled with a thermostat ($J$) and vacuum relay to two of the spiral heater elements. The air temperature was measured immediately after this by probe thermocouples at positions $L$ or $L'$. The air flow was indicated by an inclined alcohol manometer connected to the corner tappings of an orifice plate ($K$).

#### The Specimen Bobbins

Figure 2 shows the Terylene bobbin in position in the wind tunnel. The cloth, 6 in. wide, was wound on a spool between Bakelite disks on a Bakelite tube of outer diameter ½ in. and inner diameter ¼ in. The fabric package had an outer diameter of just under 3 in., and there was thus over 1-in. depth of material. Thermocouples were situated between layers of the cloth at various depths, and the wires from the junctions passed to sockets attached behind the rear Bakelite disk. Corresponding plugs were attached to arm $R$ in the tunnel (Figure 1). A streamlined aluminum nose formed the leading edge, and the streamlines were continued in the aluminum cover over the plug-socket connection.

The tube $R$ (Figure 1) passed through the end of the tunnel and was attached to a knife edge ($P$) from which the counterbalance arm supported weight $S$ and, for fine adjustment, weight $T$. The thermocouple leads within $R$ being led out at the pivot and clamped to the support ($V$) exerted no moment on the system. Thus the dry weight of the bobbin could be supported by the lever and the weight of the added water measured by means of the analytical balance ($M$).

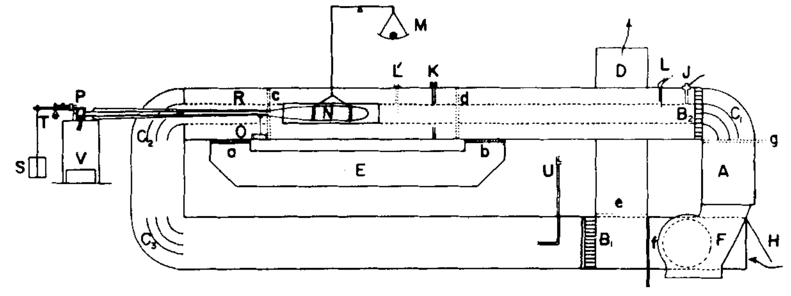



**Fig. 1. Sketch of wind tunnel.**

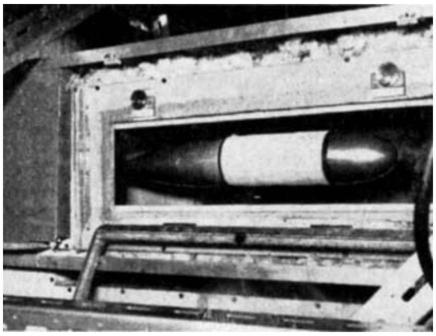
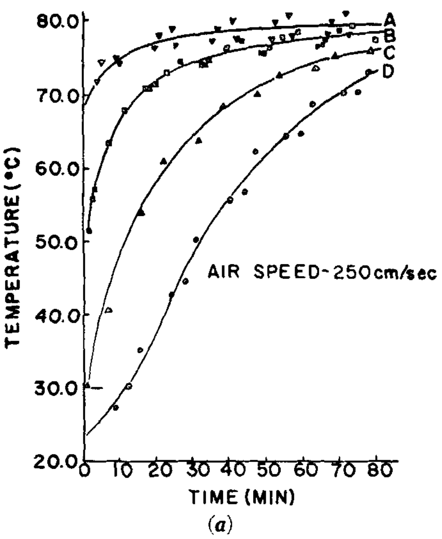


**Fig. 2. Bobbin in tunnel.**



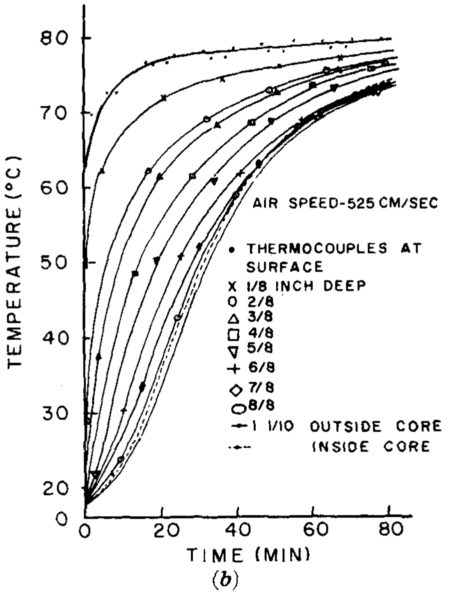




**Fig. 3*a*. Temperature vs. time at various depths in the Terylene bobbin (dry).**

**Fig. 3*b*. Temperature vs. time at various depths in the wool bobbin (dry).**

#### The Bobbin Materials and Thermocouple Arrangements

From the weight of cloth wound, the density, and the volume the bulk density of the Terylene was 0.366 g./cc. and the porosity (void fraction) 0.735. For the similar wool bobbin the figures were 0.283 g./cc. and 0.762, representing conditions when the wool was in equilibrium with air of tunnel temperature and relative humidity.

Fourteen thermocouples were used in each bobbin. In the Terylene bobbin the couples were placed in the vertical axial plane, a few at each of four levels, for example (a) under the first layer, (b) ⅛ in. deep, (c) ⅜ in. deep, and (d) ⅞ in. deep. They were spread along the length of the bobbin but showed no evidence of any axial flow of heat. Consequently in the wool bobbin the couples were mostly placed in the central plane of the bobbin, a spiral arrangement of placings being used, with one available for each succeeding ⅛ in. in depth and for the inside and outside of the central core.

The thermocouples were connected in random order to a sixteen-point potentiometer recorder which selected each in turn and printed the temperature on a chart with a number to identify the particular thermocouple.

### HEAT CONDUCTION

The apparent thermal conductivity of a dry porous material represents heat transfer by a number of methods. There is conduction in solid and void, and convection and radiation in the voids. For small temperature differences the effect of radiation will be small, and convection will be important only in very open structures. The summation of the conduction in solid and void is complex, being sometimes in series and sometimes in parallel, depending on the particular structure.

The temperature distribution while a dry bobbin is heating gives a means by which a good estimate of the apparent thermal-conductivity coefficient of the dry material may be made, provided sufficient values are calculated to allow of reasonable averaging. A method of dividing the cylinder into small finite elements and using step-by-step calculations was used, as it was suspected that the conductivity might not be constant throughout. Other workers (*1, 2, 3, 4*) have used similar methods to determine the temperature distributions within a body of a given shape, starting with a knowledge of the conductivity and stated external conditions. The theoretical relationships given graphically by Gurney and Lurie (*5*) for a long cylinder and their adaptation by Newman (*6*) for a finite cylinder would not hold for a body of variable conductivity.

#### Method of Calculating $k$ and $h$ from the Temperature

The bobbin is divided from the surface into annular elements ⅛ in. thick, and it is assumed that for a short period of time (5 min.) conditions remain sufficiently constant for the steady state Fourier (7) relationship to hold across the annulus considered; that is,

$$q = -kA\frac{d\theta}{dx} \qquad (1)$$

$q$ is given by the rate at which sensible heat is taken up by the layers enclosed by the annulus considered, the increases in temperature in the 5 min. considered being taken from the graphs showing the temperature distribution (Figures 3 and 4). Little error is introduced by using the average annular area in lieu of the logarithmic mean area, and the temperature gradient is taken from the temperature record. The value of $k$ obtained will be the mean value obtaining for the particular annulus at the particular time.

Outside the cylinder a boundary layer of air occurs before the main air stream, and this is assumed to have an over-all heat transfer coefficient $h$ defined by

$$h = \frac{q}{A(\theta_a - \theta_s)} \qquad (2)$$

$q$ being the rate of supply of sensible heat to the whole bobbin at a particular time, with the heat passing through the perimeter area of the bobbin.

#### Experimental Results

*Procedure*

For an investigation of the thermal conductivity of the dry bobbin the balance system was unnecessary, and therefore the experiments were carried out with the suspension wire clamped as it left the tunnel. The bobbin was allowed to stand in uniform air conditions until it attained the same temperature throughout; it was then quickly inserted into the heated tunnel and the recorder switched on.

As a preliminary with the woolen bobbin it was necessary to heat it for some time while the water of absorption was driven off and equilibrium was reached at tunnel temperature and humidity. The bobbin was then inserted in a polythene bag to prevent water from reentering it as it acquired room temperature before being inserted into the tunnel.

*Variation of Temperature with Time*

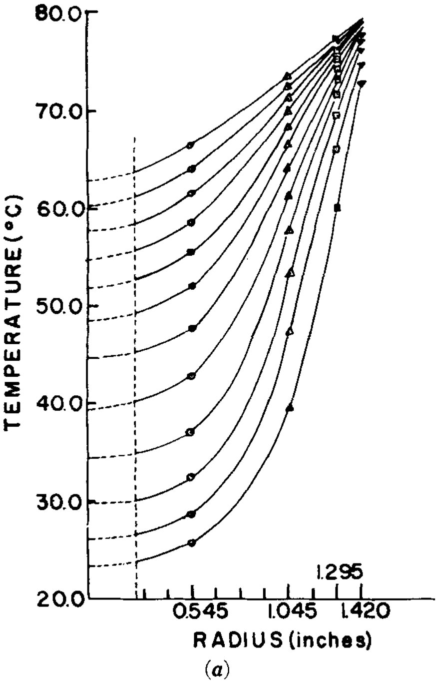
The bobbin starts at a uniform temperature, and when it is subjected to the hot air flowing over the surface, heat begins to flow in. The surface layers rapidly reach the air temperature, but layers at greater depths take longer. The curves for this temperature change as the heating proceeds are shown for the various depths in the bobbins in Figure 3.

*Variation of Temperature with Depth*

The variation of temperature with distance from the center can be found at any particular instant by reading the temperature from the curves given in Figure 3 at that particular instant. From these values of temperature the changes of temperature with distance from the center of the bobbin can be shown for different times. Such curves of temperature against radius for both bobbins are shown in Figure 4.

The curves in Figure 4 show consecutive 5-min. intervals after the start of heating. The lowest curve is at 5 min. and the highest at 60. The temperature at zero time would be represented by a straight line of constant temperature.

The dotted portion of the Terylene



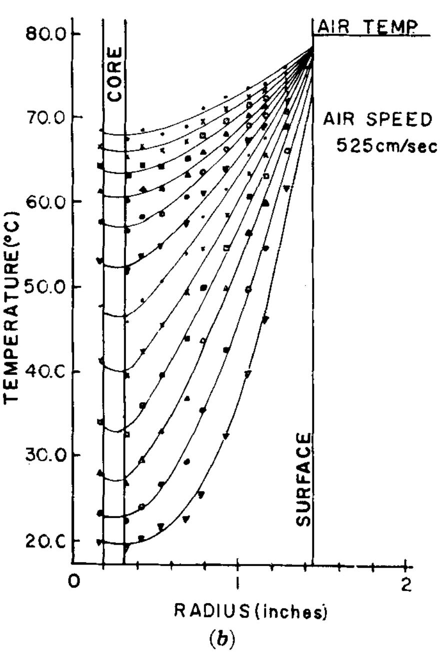




**Fig. 4*a*. Temperature vs. radius at various times: Terylene bobbin (dry).**

**Fig. 4*b*. Temperature vs. radius at various times: wool bobbin (dry).**

curve represents uncertainty as to what is happening in the region of the core. As a result, in the wool bobbin thermocouples were inserted on the inside and outside of the solid core; these indicate that in that bobbin there is a very small flow of heat outward through the core, a heat balance being achieved in the region of the outer surface of the core.

A major difference between the two sets of curves is that the Terylene ones show a small but distinct tendency to flatten out near the surface, whereas within the limits of graphical interpretation there is no such effect in the case of wool. This indicates that the Terylene layers near the surface are reaching the air temperature sooner than theoretical curves which assume constant thermal conductivity would indicate.

### *Values of Thermal Conductivity Obtained for the Bobbins*

The method given above was applied to different annuli of the bobbins. The values of thermal-conductivity coefficients derived during the various experiments are given in Table 1. Each value is the mean of a number of determinations involving the heat passing through an annulus in various 5-min. intervals.

Values beyond the fourth innermost layer in the case of the Terylene were rejected because the dotted portion of Figure 4*a* was assumed to hold, and a doubtful quantity of heat was thus attributed to the core. If one allows a 50% error in the value of the heat to the core, all results are rejected where the error due to this cause in the final result could be more than 10%. As far as the wool was concerned, it was assumed that the temperature minima in Figure 4*b* occurred at the core outer surface and that no heat entered the core via the wool. On this account the values of $k$ for annuli 7 and 8 were lower and have been omitted.

It is clear from Table 1 that in the case of the open structure given by the Terylene there is an increase in the coefficient of thermal conductivity as the surface is approached. In the case of the close structure of the wool the thermal conductivity is constant throughout. The actual value agrees reasonably with that given by Baxter (*8*) for wool of this bulk density.

### *Analysis of the Terylene Results*

As the temperature of the bobbin increases with increasing radius, the variation in $k$ could be due either to temperature increase or to change of position, the air velocity remaining constant. A statistical analysis showed that the significant variation of $k$ was with increasing radius and not with temperature. The possibility of the temperature effect being thus eliminated, the variation of thermal conductivity with radius can be investigated by the usual graphical methods.

The mean values of the apparent coefficient of thermal conductivity for each ⅛-in.-thick annulus were plotted as ordinates against the mean radii of the annuli, and the two curves which were obtained, one for each air speed, are shown in Figure 5. These indicated that the thermal conductivity increased in the surface layers but that for the main body of the material a value $k_o$ of 1.0 × $10^{-4}$ cal (cm.$^{-1}$)(sec.$^{-1}$)(°C.$^{-1}$) held. Logarithmic plots then indicated the relationship

$$(k - k_o) \propto V^{0.89} \times e^{(5/3)r} \quad (3)$$

The graph of $(k - k_o)$ against $V^{0.89} \times e^{(5/3)r}$ is shown in Figure 6, and all the experimental points lie well on this line. The constant of proportionality is $1.94 \times 10^{-9}$.

### *Experimental Values for the Boundary-Layer Heat Transfer Coefficient*

This quantity was calculated from Equation (2). Detailed results are given in Table 2 because they illustrate the amount of variation which exists owing to the difficulty in obtaining the small temperature dfference across the boundary layer with any degree of accuracy.

The values obtained for the rough textile cylindrical surfaces might be expected to compare with those quoted for the heat-transfer coefficient in flow in a rough cylindrical pipe. Lander (*9*) gives the equation

$$h = 0.76 \frac{V_o^{0.56}}{D^{0.44}} \quad (4)$$

B.t.u. (ft.$^{-2}$)(hr.$^{-1}$)(°F.$^{-1}$)

Values calculated from this equation are of the same order as those in Table 2.

#### Discussion on Heat Transfer

Terylene. This material, made with hard twisted yarn and very open weave, gave an open structure with relatively large holes in it. The increase in $k$ values toward the surface has been shown to depend on the external air speed. The power-law index of 0.89 is similar to that quoted for heat transfer to a body by by a fluid flowing over its surface. This suggests that the effect is due to the actual flow of air through the outermost layers of the material. The speed of flow would decrease with increasing depth, and thus the heat transferred by this means would decrease. However it is difficult to visualize the air flowing into the material to a depth of possibly ½ in. and yet revealing no axial flow of heat. It is possible that the slight transverse vibrations of the bobbin in the air stream contribute to the convection effects observed. A different explanation, and one which seems more acceptable, is that the rough surface of the material causes turbulence over the surface which penetrates some way into the material and causes an increase in heat flow.

The still-air value of $k$ in the depths is the mean of the solid and air conductivities, each weighted in proportion to the space it occupies, that is for the Terylene bobbin

$$k = k_o + 1.94 \times 10^{-9} V^{0.89} e^{(5/3)r} \quad (5)$$

and

$$k_o = [k_s(1 - \epsilon) + k_a\epsilon] \qquad (6)$$

Wool. This material, composed of a bulked yarn in a hairy and felted cloth, has a close structure. There was no evidence of any but uniform still-air conductivity applying throughout, unless there was an effect in the extreme layer of the cloth which is outside the range of experimental measurements. The value of $k$ obtained for this structure is not that given by the simple volume relationship as with the Terylene, expressed in Equation (6).

### DRYING

Generally most substances first give a region in which drying occurs at a steady rate, and the laws applying during this constant rate period are well established (*10* to *16*). At a particular moisture content, the critical moisture content, the rate of evaporation begins to fall as drying continues. The falling-rate period is usually divided into two sections, the rate in the first portion varying linearly with moisture content. The variety of shapes in drying-rate curves have been described by Sherwood (*17*). McCready and McCabe (*29*) have discussed the question of drying hygroscopic materials, like the wool in this work.

The accepted chief mechanism, to which water movement in porous solids is attributed, is that of capillarity (*18*), and in a recent investigation where beds of glass spheres were used Newitt et al. (*19*) discuss the forces involved and the state of water distribution. With special reference to textiles Coplan (*20*) visualizes internal evaporation at all depths into the pervading vapor atmosphere in the pores and thence by vapor diffusion across the boundary layer. In this study the temperature distribution in the thick textiles is considered in conjunction with the drying rates, particular reference being made to the second falling-rate period.

### Experimental Results

*Procedure*

Preliminary tests were carried out so that the counterpoise weights on the external end of the bobbin arm supported the weight of the dry bobbin and a suitable weight was ready on the analytical balance to cover the weight of water in the wet bobbin. The bobbin was soaked by immersion in water and, after a suitable drainage time, weighed and inserted into the heated tunnel. The recorder was switched on, the analytical balance was released, and the weights were adjusted to give balance. The weight was reduced 5 g. at a time as the water evaporated. The times at which balance occurred were noted and a further decrement of weight was effected. In the later stages of drying, the amount removed from the pan was reduced as the rate of evaporation decreased. Finally, when the bobbin was dry, the balancing weight representing zero water content was noted. The bobbin was

TABLE 1.

| | Terylene | | | | | | | | Wool | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Air speed = 250 cm./sec. | | | | Air speed = 525 cm./sec. | | | | Air speed = 525 cm./sec. | |
| Annulus | $\theta_a$ 80°C. | 65°C. | 65°C. | Mean | $\theta_a$ 80°C. | 65°C. | 65°C. | Mean | $\theta_a$ 80°C. | |
| | Values of $k \times 10^4$, c.g.s. centigrade units | | | | | | | | | |
| 1 (outer) | 1.75 | 1.82 | 1.85 | 1.81 | 2.57 | 2.23 | 3.01 | 2.60 | 0.97 | 1.07 |
| 2 | 1.48 | 1.56 | 1.46 | 1.50 | 1.88 | 1.80 | 2.19 | 1.96 | 1.05 | |
| 3 | 1.35 | 1.25 | 1.27 | 1.29 | 1.64 | 1.66 | 1.66 | 1.65 | 1.10 | |
| 4 | 1.17 | 1.33 | 1.08 | 1.22 | 1.28 | 1.40 | 1.47 | 1.38 | 1.14 | |
| 5 | | | | | | | | | 1.11 | |
| 6 | | | | | | | | | 1.04 | |

TABLE 2. VALUES OF $h \times 10^3$, C.G.S. CENTIGRADE UNITS

| $\bar{t}$ | Terylene | | | | | | Wool |
|---|---|---|---|---|---|---|---|
| Mean time (min.) in the 5-min. intervals in which heat transfer was considered | 525 cm./sec. $\theta_a$ | | | 250 cm./sec. $\theta_a$ | | | 525 cm./sec. $\theta_a$ |
| | 65°C. | 65°C. | 80°C. | 65°C. | 65°C. | 80°C. | 80°C. |
| 12.5 | 1.57 | 1.25 | 1.08 | 0.76 | 0.72 | 0.63 | 0.89 |
| 22.5 | 1.54 | 1.19 | 1.35 | 0.97 | 0.85 | 1.09 | 0.82 |
| 32.5 | 1.86 | 1.14 | — | 1.04 | 1.02 | 0.98 | 0.64 |
| 42.5 | 1.95 | 1.13 | — | 1.12 | 0.99 | 0.87 | 0.53 |
| 52.5 | 2.85 | 1.05 | 0.77 | 1.03 | 0.88 | 0.96 | 0.52 |
| Mean value | 1.95 | 1.15 | 1.07 | 0.98 | 0.89 | 0.91 | 0.68 |
| Over-all mean | | 1.39 | | | 0.93 | | 0.68 |

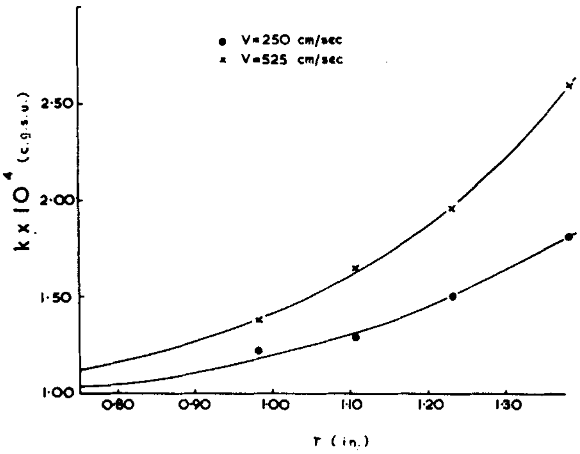



Fig. 5. $k$ vs. radius for Terylene.

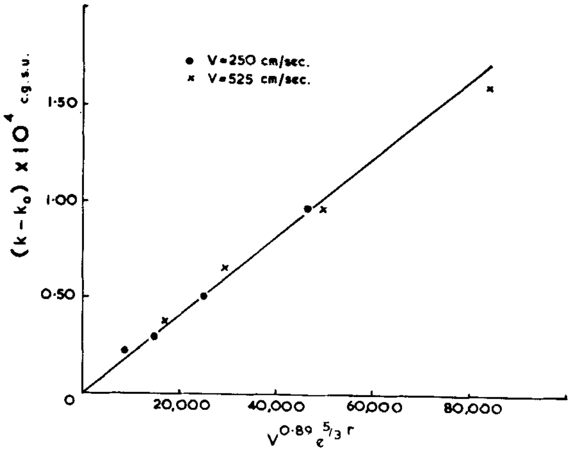



Fig. 6. $k - k_o$ vs. $V^{0.89} \times e^{(5/3)r}$ for Terylene.

removed and weighed to give the dry weight.

The tunnel was run without recirculation of the air and the humidity and temperature of the air were measured by an Assman wet- and dry-bulb hygrometer. Temperatures in the working section were measured both with thermocouples and mercury in glass thermometers.

*Variation of Water Content with Time*

The initial conditions for the two bobbins differed; water drained more freely from the Terylene, leaving only some 60% of the pore space occupied by water as compared with 90% in the case of wool. The water content vs. time curves were similar for the two materials, differing only insofar as the proportions were concerned. These curves were differentiated graphically to produce drying-rate curves for the two structures which may be compared.

being between 1/4 and 1/5 that of the corresponding Terylene curve. Moreover the second falling-rate period commences much sooner, at a moisture content of 210 g., when some 40% of the pore space is occupied by water, as compared with 45 g., or 10% of pore space occupied, in the case of the Terylene.

In the over-all picture the Terylene curve is similar to that given by Pearce et al. (*21*) for the drying of beds of glass spheres of radius $6 \times 10^{-3}$ cm. The proportions of the wool curve are much more like those associated with fine particles of silica flour.

*Constant Rates of Evaporation*

Values for the Terylene bobbin range from $5.1 \times 10^{-6}$ to $11.8 \times 10^{-6}$ g. (cm.$^{-2}$)(sec.$^{-1}$)(mm. Hg)$^{-1}$, and for the case given of the wool bobbin the value is $5.4 \times 10^{-6}$ g. (cm.$^{-2}$)(sec.$^{-1}$)(mm. Hg)$^{-1}$.

all layers, amply confirming the generalized picture. The lettering in Figure 8*a* will be used in the following explanation of the temperature record contrasting it with the drying-rate curve, which is also given.

Region $AB$ represents the heating of the wet bobbin from room temperature to the wet-bulb temperature, the temperature distribution being similar to that in Figure 3. The constant-rate period $ST$ agrees with this phase. A period of transition follows. The surface dries, as is indicated by the temperature rise of the surface thermocouples. The water surface recedes, evaporation being no longer directly into the air stream, and gradually evaporation has to depend on diffusion of water vapor outward through

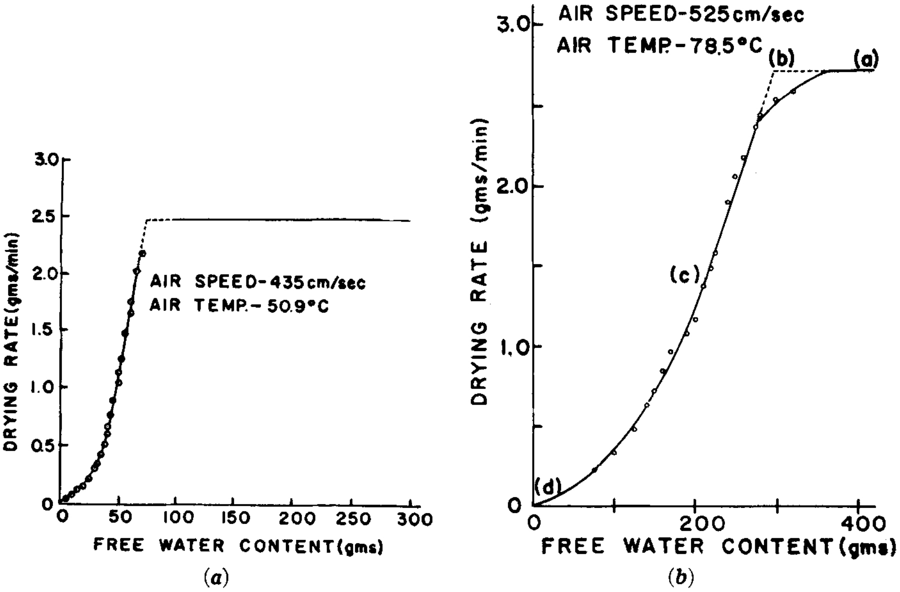



**Fig. 7*a*. Drying rate vs. free water content for Terylene bobbin.**
**Fig. 7*b*. Drying rate vs. free water content for wool bobbin.**

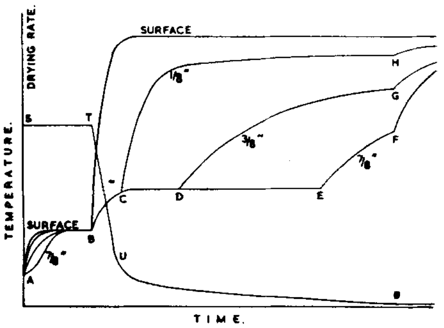



**Fig. 8*a*. The ideal variation of temperature during drying.**

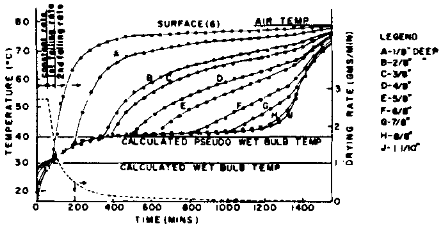



**Fig. 8*b*. The actual variation of temperature during drying: wool bobbin.**

*Drying Rates and Critical Points*

Figure 7 compares the drying-rate curves. In each case *ab* is the constant rate, *bc* the first falling rate, and *cd* the second falling-rate periods. The zero on the water-content scale for the wool represents the equilibrium moisture content at tunnel temperature and hnmidity.

In the case of the Terylene the very long constant-rate period ends at a moderate content of 73 g. (a water-to-solid ratio of 0.33), but for the wool a much shorter constant-rate period terminates at a critical moisture content (b) of 296 g. (a water-to-solid ratio of 1.68). A series of experiments does not appear to indicate that the critical moisture content is influenced by the external conditions.

In the linear first falling-rate period the rate falls off much more slowly in the case of the wool, the slope of the line

These values are all higher than those given by other workers, the figures for the Terylene more so than for the wool. The discrepancy may be due to the penetration of the surface layers by the air which produced the increased heat transfer and also to increased turbulence caused by the presence of the orifice plate just before the working section. As the principal aim was the study of the falling-rate period, this latter point was not pursued.

*Temperature Changes within the Bobbin*

Figure 8 gives a general picture of the variation of the temperature at the various radii as the drying proceeds. Figure 8*a* is based on the temperature records for the Terylene experiments and shows what happens in the layers considered in those experiments. Figure 8*b* for the wool fills in the gaps and shows

a layer of dry cloth. Also the temperature of the wet cloth rises to a new level. This new temperature equilibrium is established throughout, somewhere between $C$ and $D$, and represents the balance between heat passing inward and water vapor diffusing outward as the water surface recedes into the depths of the material. Possibly this whole transitional region would provide a more natural phase of the falling-rate period than that dicated by the linear $TU$.

Because of the similarity between this second temperature equilibrium between heat and mass transfer and the earlier one, the wet-bulb temperature, the temperature established within the bobbin will be called the *pseudo wet-bulb temperature* (*22*). The wet portion of the bobbin remains at this temperature as the second falling-rate period continues ($CDE$), and as the receding water surface passes each thermocouple in turn, the temperature rises. Finally, when the water surface reaches the core, more heat is made available to heat the dry material, and the final upward surge of temperature occurs from $H$, $G$, $F$, etc., in Figure 8, toward air temperature.

*Drying of the Bobbin Surface*

The fact that $B$ approximately coincides with $T$ in the Terylene experiments means that the surface of the Terylene bobbin was completely dry at the outset of the linear falling-rate section. In fact the outer $\frac{1}{8}$-in. depth of cloth is almost all dry by the end of it, as $C$ represents the time of drying at the $\frac{1}{8}$-in. depth. Thus the theory that the drying of the surface is responsible for the linear first falling-rate period does not fit in the case of the Terylene. A possible alternative is that the transition from wet-bulb to pseudo-wet-bulb temperature conditions fortuitously produces linearity between $(dX/dt)$ and $X$ as a balance between the increase in the rate of drying due to the rising surface temperature of the water and the decrease in this rate as the surface recedes to the interior. To compare conditions in the wool at this point Figure 9 represents a magnified picture. It must be stressed that all the so-called "surface" thermocouples are beneath one layer of cloth and therefore do not quite mirror true surface conditions. Four such couples are shown here, and it can be observed that whereas two of them rise directly to air temperature, the other two acquire the pseudo-wet-bulb temperature before doing so. It is suggested that the former are actually nearer the surface and that the water recedes past them before the new equilibrium conditions are established; the latter, being deeper, reflect the changed conditions. This means that the transition occurs through one layer of the woolen cloth, that is in less than 1/16 in. Apparently both the drying out of the surface and the establishment of the pseudo-wet-bulb temperature conditions occur during the linear section of the falling-rate period.

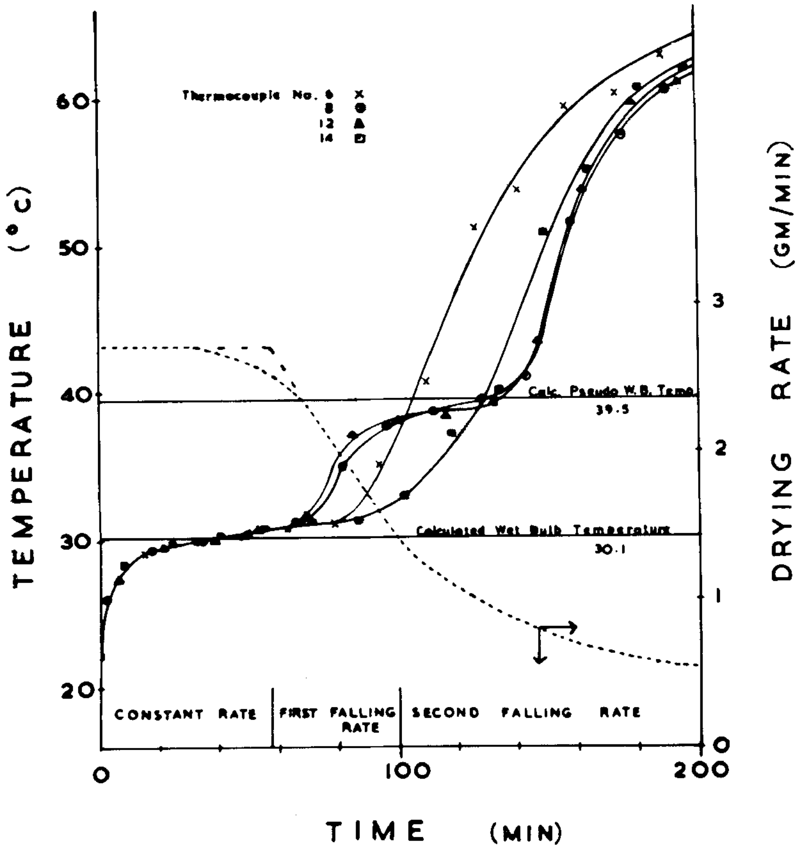



**Fig. 9. Surface conditions in the wool at the beginning of the falling rate period.**

*Moisture Contents within the Terylene Bobbin*

Although the concept of a retreating water surface arose from the temperature records, at a later date a simple experiment was performed to obtain a measure of the various moisture contents. A section 1 in. wide and 1 in. deep was cut transversely in the Terylene bobbin and the unwrapped cloth made up into eight pads 1 in. wide and $\frac{1}{8}$ in. thick which could be replaced as the consecutive $\frac{1}{8}$-in. thick layers to reform the complete bobbin. Experimental conditions were reproduced as nearly as possible to those in the experiment for which the drying-rate curve is given in Figure 7*a*. When one started with the wet bobbin each time and allowed the necessary drying time, points $T$, $U$, $C$, $D$, and $E$ (Figure 8*a*) were reached in turn. At each point the bobbin was taken out of the tunnel and the pads were quickly unwrapped, placed in polythene bags, and weighed. The results are given in Table 3.

Table 3 shows that within the limits of the experiment it is confirmed that there is a retreating water surface as deduced from the temperature record. It is of course extremely difficult to reproduce conditions exactly, and there are the usual errors of any redeployment of water or losses while the cylinders are being unwrapped. Other points of interest are the reduced values in the outermost three layers, possibly due to air penetration; the constant value in the depths; and the fact that the saturation in the depths is slowly reducing as the water surface retreats. This last mentioned point means that there is still some some mechanism by which moisture moves to the water boundary.

Table 3. Percentage of Moisture Contents (Dry Basis) to Nearest 1%, in Consecutive $\frac{1}{8}$-in. Layers From the Surface

| Layer | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
|---|---|---|---|---|---|---|---|---|---|
| At point $T$ | 27 | 27 | 29 | 38 | 37 | 38 | 38 | 39 | |
| $U$ | 8 | 17 | 19 | 23 | 23 | 22 | 22 | 23 | Wet |
| $C$ | 1 | 13 | 16 | 19 | 18 | 18 | 18 | 18 | region |
| $D$ | 0 | 0 | 0 | 5 | 14 | 15 | 15 | 14 | |
| $E$ | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 8 | |
| | | | | Dry region | | | | | |

**Pseudo-wet-bulb Temperature**

*A Theoretical Explanation*

The limiting water surface of the wet material is considered to have receded well within the bobbin and, with a cylindrically symmetrical distribution of water assumed, the water surface is at a radius $r$ from the center. The heat transfer through the narrow dry layer, thickness $\delta r$, adjoining the water surface must be allowed to cause evaporation and to produce the mass transfer outward through the layer.

Thus

$$q = -\frac{dX}{dt}\lambda_w \tag{7}$$

Therefore if one assumes the rate of evaporation to be governed by diffusion,

$$kA_m\left(\frac{\delta\theta}{\delta r}\right)_{\text{layer}} = -(\epsilon\, D_v)A_m\left(\frac{\delta c}{\delta r}\right)_{\text{layer}} \lambda_w \qquad (8)$$

For this layer $k$ will be $k_o$, representing the value applying for the solid-air mixture.

The temperature gradient across the layer and the concentration gradient are unknown, but, because of the analogy in heat, momentum, and mass transfer, it will be assumed that

$$\frac{(\delta\theta)/\delta r)_{\text{layer}}}{(\theta_a - \theta_w)/(R - r)} = \frac{(\delta c/\delta r)_{\text{layer}}}{(c_a - c_w)/(R - r)} \qquad (9)$$

The maximum radius of the bobbin should strictly include the outer boundary layer. The concentration boundary layer is not exactly equal to the thermal boundary layer under all conditions, but to a first approximation they will be assumed to be equal. $(R - r)$ cancels, and

$$k(\theta_a - \theta_w) = (\epsilon\, D_v)\lambda_w(c_w - c_a) \qquad (10)$$

From the ideal gas equation $c = a$ constant $\times\, p/T$.

Therefore

$$k(\theta_a - \theta_w) = 2.886 \times 10^{-4}(\epsilon\, D_v)\lambda_w\left(\frac{p_w}{T_w} - \frac{p_a}{T_a}\right) \qquad (11)$$

where the constant is appropriate for c.g.s. centigrade units.

Thus when heat and mass transfer balance within the bobbin, with vapor diffusion controlling the evaporation, a temperature $\theta_w$ will be established at the water surface which has been called the *pseudo-wet-bulb temperature*. As the radius does not come into the equation, the temperature will be the same with the water surface at any level, provided the ratio $D_v/k$ remains constant.

Equation (11) shows a constant differences between $\theta_a$ and $\theta_w$. Examination of Figure 8*b* shows strictly that there is a constant difference between the bobbin surface temperature and the pseudo-wet-bulb temperature. Indeed this equation could have been as readily, and with fewer assumptions, derived for $(\theta_s - \theta_w)$, where $\theta_s$ is the bobbin surface temperature. Unfortunately such a derivation requires knowledge, which is not available, of the vapor concentration at the surface. Accordingly Equation (11) has to be accepted as an approximation.

Sherwood and Pigford (*23*) report a similar equation given by Maxwell (*24*) to account for the ordinary wet-bulb temperature but point out that it is at fault in making no allowance for eddy diffusion. Here in the depth of the cloth the eddy diffusion is eliminated, and so Maxwell's original concepts apply more particularly in the body of a porous material than in a free air stream.

*Calculations of the Pseudo-wet-bulb Temperature by use of the Theoretical Equation*

Equation (11) was used to calculate the pseudo-wet-bulb temperature by successive approximations from a first reasonable guess of $\theta_w$. Values are given in Table 4 for a set of experiments with the Terylene bobbin along with a value for the wool bobbin. The latter value is marked in Figure 8*b*.

The values of $D_v$ used in the calculations were taken from Figure 10. In Figure 10 curve *A* represents earlier experimental values given by Dorsey (*25*) and Gilliland (*26*), and curve *B* represents values based on a recent correlation of Fair and Lerner (*27*) depending on the Hirschfelder, Bird, and Spotz (*28*) equation. Values from curve *B*, being considered the best available, were used.

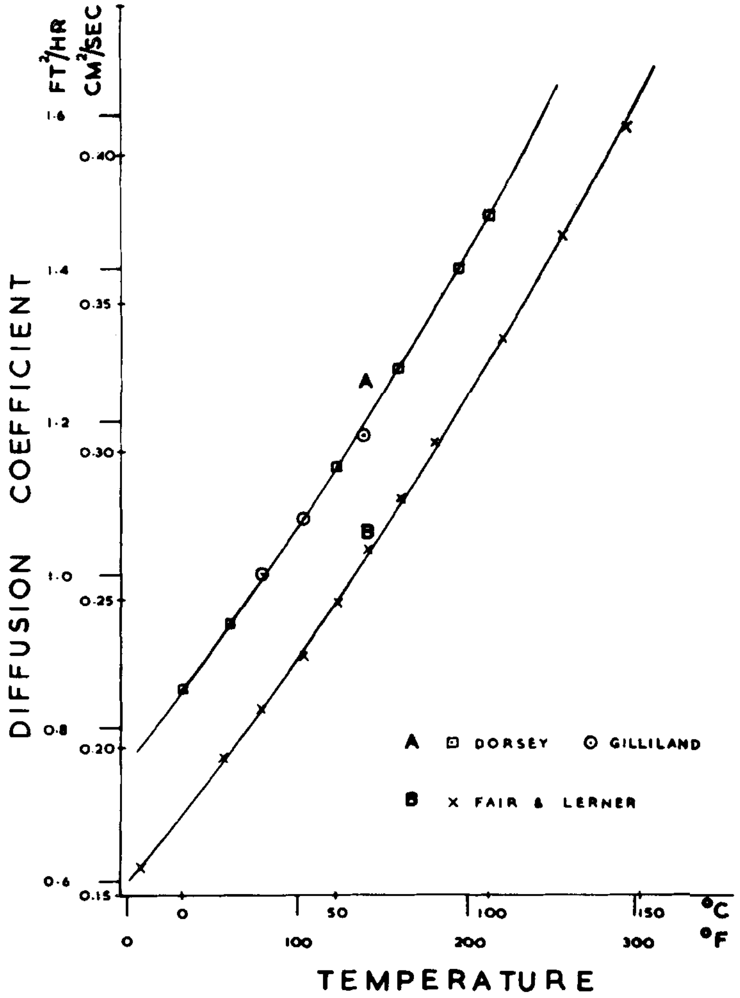



**Fig. 10. Diffusion coefficient for water vapor vs. temperature.**

TABLE 4.

| Air speed c./sec. | Air temperature, $\theta_a$ °C. | Partial vapor pressure in air stream $p_a$, mm. Hg | $\theta_w$ °C. Experimental | $\theta_w$ °C. Calculated |
|---|---|---|---|---|
| | | Wool | | |
| 525 | 78.5 | 10.0 | 39 rising to 41 | 39.5 |
| | | Terylene | | |
| 200 | 96.1 | 18.5 | 48.0 | 44.9 |
| 287 | 81.2 | 14.9 | 42.5 | 40.7 |
| 320 | 78.9 | 13.6 | 43.0 | 39.9 |
| 435 | 50.9 | 14.5 | 31.2 | 31.8 |
| 535 | 49.6 | 15.4 | 31.0 | 31.6 |

#### Discussion on Drying

The establishment of a pseudo-wet-bulb temperature during the falling-rate period within the thick textiles considered appears to be accounted for by the simple *heat-transfer–mass-transfer* balance, and Equation (11) provides a means of calculating this temperature and the rate of evaporation. It must be remembered however that the sensible heat required for the dry material and for raising the temperature of the vapor formed to that of the air stream was omitted. Moreover it is impossible to insulate the depths of the bobbin perfectly, and in the case of the Terylene instances occurred when the recorded temperatures at a lower level crossed and came above the line representing the temperature further out. This would be due to a little heat flow from the core outward. In the case of the later wool bobbin this effect seemed to be almost eliminated by keeping the return thermocouple leads between layers of the cloth at the level of the couple; previously some of these wires had returned to the rear end of the bobbin packed fairly tightly in the center of the solid core and had apparently carried heat from the ends of the bobbin to the core. There will be some radiation from the surroundings, mainly absorbed by the surface layers. This is evidenced by the fact that the experimental wet-bulb temperature is a little higher than the calculated value (Figure 8*b*).

As far as the wool is concerned, no account has been taken of the heat required by the evaporation of the bound water held by the fibers in the air-dry region. As the vapor pressure in the various layers slowly decreases, this adsorbed water will be released, heat of adsorption and latent heat of vaporisation being necessary in the process. It would appear that for this particular highly porous structure such heat is of secondary importance in the general equilibrium established.

The transition period, including the first falling-rate section, requires further study. The drying out of the surface, as some factor limits the water supply, is accompanied by the change from one equilibrium condition of heat and mass transfer across the boundary layer to another through a layer of cloth. The exact relationships of these processes, to produce the rates obtaining and the linearity, need elucidation.


## SUMMARY

Highly porous thick textiles have at depth a thermal-conductivity coefficient which depends on the relative volumes and distribution of solid and air. Near the surface, if the structure be sufficiently open, a higher apparent thermal-conductivity coefficient can apply, being affected by the air speed at the surface and apparently due to some form of air penetration.

When such structures are drying, the rate of evaporation falls off as heat and water vapor have to pass through an increasing layer of dry material left by a receding water surface. While this is occurring, a temperature equilibrium is maintained within the wet portion, and this temperature has been called the *pseudo-wet-bulb temperature*. The formula giving the simple heat balance is

$$k(\theta_a - \theta_w) = 2.886 \times 10^{-4}(\epsilon\, D_v)\lambda_w\left(\frac{p_w}{T_w} - \frac{p_a}{T_a}\right)$$



## ACKNOWLEDGMENT

Thanks are due to Courtaulds' Scientific and Educational Trust Fund for providing funds and a scholarship for one of the authors (W. G. Kaye) and to the Wool Textile Research Council for providing funds and a fellowship to another of the authors (J. R. Bell). P. M. Harrison greatly assisted the research in helping to build the hot-air tunnel.


## NOTATION

$A$ = area, sq. cm.
$A_m$ = mean area of annular section, sq. cm.
$c$ = vapor concentration, g. cm.$^{-3}$
$c_a$ = vapor concentration in air stream, g. cm.$^{-3}$
$c_w$ = vapor concentration at water surface, g. cm.$^{-3}$
$D$ = pipe diameter, ft.
$D_v$ = coefficient of vapor diffusion, sq. cm. sec.$^{-1}$
$h$ = surface heat-transfer coefficient, cal. (cm.$^{-2}$)(sec.$^{-1}$)(°C.)$^{-1}$
$k$ = thermal-conductivity coefficient, cal. (cm.$^{-1}$)(sec.$^{-1}$)(°C.)$^{-1}$
$k_a$ = thermal-conductivity coefficient of air, cal. (cm.$^{-1}$)(sec.$^{-1}$)(°C.)$^{-1}$
$k_o$ = thermal-conductivity coefficent within depths of material, cal. cm.$^{-1}$ sec.$^{-1}$ (°C.)$^{-1}$
$k_s$ = thermal-conductivity coefficient of solid, cal. (cm.$^{-1}$)(sec.$^{-1}$)(°C.)$^{-1}$
$p$ = vapor pressure, mm. Hg
$p_a$ = partial pressure in air stream, mm. Hg
$p_w$ = vapor pressure at water surface, mm. Hg
$q$ = rate of flow of heat, cal. sec.$^{-1}$
$r$ = radius, cm.
$R$ = radius of bobbin, cm.
$t$ = time, sec.
$T$ = absolute temperature, $°_{absolute}$
$T_a$ = absolute temperature of air stream, $°_{absolute}$
$T_w$ = absolute temperature of water surface, $°_{absolute}$
$V$ = air speed, cm. sec.$^{-1}$
$V_o$ = air speed at normal temperature and pressure, ft. sec.$^{-1}$
$X$ = free water content of bobbin, g.

### Greek Letters

$\epsilon$ = void fraction or porosity
$\epsilon D_v$ = diffusion coefficient for layer next to water corrected for presence of solids (assumed to be of zero diffusion) and occupying $(1 - \epsilon)$ of total area
$\theta$ = temperature, °C.
$\left(\frac{\delta\theta}{\delta r}\right)_{layer}$ = temperature gradient across layer
$\theta_a$ = temperature of air stream, °C.
$\left(\frac{\delta c}{\delta r}\right)_{layer}$ = concentration gradient
$\theta_s$ = temperature of bobbin surface
$\theta_w$ = temperature of water surface, °C., pseudo-wet-bulb temperature, °C.
$\lambda_w$ = latent heat of evaporation at temperature of water surface, cal. g.$^{-1}$

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*Manuscript received December 3, 1957; revision received May 15, 1958; paper accepted May 27, 1958.*