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# PROPAGATION OF TEMPERATURE AND MOISTURE CHANGES DURING FORCED CONVECTIVE FLOW OF AIR THROUGH A MASS OF HYGROSCOPIC FIBRES

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**Abstract**—A solution is presented for the propagation of temperature and moisture changes through a mass of fibres when the condition of the air flowing through the mass is changed. The theory takes into account the finite rate of uptake or loss of moisture by the fibres; in previous treatments this rate has been assumed as infinitely fast. Calculations based on the present theory and assuming rates of air flow typical of industrial practice indicate that the moisture profile within the mass will be greatly extended in comparison with predictions from earlier theories. Experimentally determined profiles for desorption of fibres are in good agreement with the present theory.

## NOTATION

$A(C)$, function $\dfrac{\rho\omega l}{v}$;
$C$, concentration of water-vapour in air;
$C_\alpha$, value of $C$ at $x = \infty$;
$C_\beta$, value at $C$ at $x = -\infty$;
$C_0$, value of $C$ when $l = l_{\max}$;
$c_a$, specific heat of air at constant pressure;
$l$ difference between ordinates on a $C$–$M'$ plot;
$l_{\max}$, maximum value of $l$;
$M$, instantaneous regain*;
$M'$, equilibrium value of regain corresponding to the temperature ($T$) and humidity of the surrounding air;
$M'_\alpha$, value of $M'$ at $x = \infty$;
$M'_\beta$, value of $M'$ at $x = -\infty$;
$q$, differential heat of sorption of water by the fibre;
$S$, heat required to raise 1 cm$^3$ of air–fibre mixture through 1°C, assuming no moisture exchange;
$T$, temperature;
$t$, time;
$u$, velocity of wave propagation;
$v$, air velocity;
$x$, distance co-ordinate;
$\rho$, mass per unit volume of dry air–fibre mixture;
$\rho_a$, density of air;
$\omega$, rate constant of water sorption by a fibre.

* Regain is the moisture content of a fibre expressed as a fraction of its dry weight.

## INTRODUCTION

WHEN a change is made in the temperature or moisture content of air flowing through a mass of hygroscopic fibres, changes in the temperature and moisture content of the mass are propagated through it. Cassie and Baxter have investigated the process [1, 2], and Cassie has developed a theory for the propagation of the changes. The theory predicts that the propagation takes place by two "fronts", fast and slow, moving at constant velocities through the mass; the fronts are sharp, the fast front being characterized by a change in temperature and the slow by a change in moisture content of the fibres.

Experiment [2] shows that the fronts, and in particular the slow front, are not usually sharp. Possible reasons for this have been given by Cassie and Baxter [2], who pointed out that non-uniformity of air flow would cause a "broadening" of the front, and by Daniels [3], who examined the effect of diffusion of temperature and water-vapour at the front, and concluded that it could account for the broadening to the extent observed experimentally by Cassie and Baxter.

The authors have recently carried out experiments on the flow of air through beds of wool fibres, observing the passage of the fronts by measurement of the associated temperature changes with thermocouples inserted at suitable points in the bed. The air velocity used was 50–100 cm/s, i.e. much greater than the value of 1·4 cm/s used by Cassie and Baxter [2]. (The higher speeds are comparable with those used in industrial drying processes.) The slow front* was found to be very broad (see Fig. 1, curve A). Since care was taken to make the bed very uniform in density of packing by the use of short fibres, it appeared unlikely that non-uniform air flow could account for the broadening. Also, calculations based on Daniels' theory of the effect of diffusion showed that the observed broad fronts were not explicable on this basis, the effect of diffusion being usually negligible at the relatively high air velocities used. Curve B in Fig. 1 shows the profile of the front allowing for diffusion, calculated for the conditions of the experiment; it is seen to be very much sharper than the experimental curve.

From the consideration of alternative explanations for the broadness of the fronts it appeared that the assumption made by Cassie, that the fibres come instantaneously into equilibrium temperature and moisture content with the air around them, may not always be justified, particularly at higher values of air flow. Support for this idea comes from recent measurements [4, 5] of the rate of approach of the moisture content of single wool fibres to equilibrium with the air around them. Under some conditions, the time to reach equilibrium is not negligibly small in comparison with the time of passage of the front past a point, as assumed by existing theories.

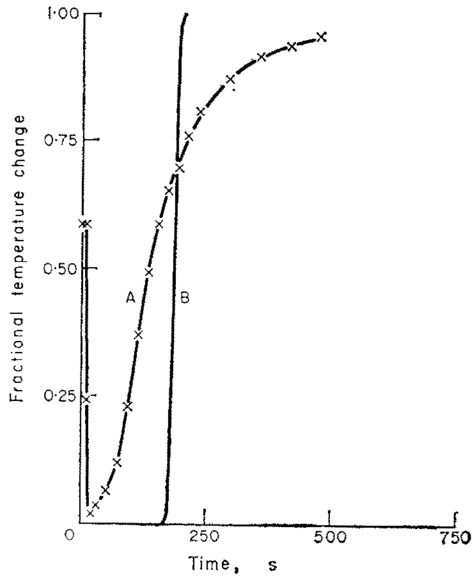


FIG. 1. Experimental determination of temperature front at a point 6·5 cm from the upstream face of a uniform bed of wool. Curve B is a calculated front taking into account the effect of diffusion according to Daniel's theory [3].

The mathematical treatment given below may be applied to systems other than beds of textile fibres, provided that the same basic conditions apply: (a) mass transfer takes place from the air stream to the material and (b) this transfer is not instantaneous.

This paper presents an analysis of the effect which a finite rate of approach to moisture equilibrium between a fibre and its surroundings has on the mode of propagation of changes through the mass of fibres. The assumption that a fibre is always in *temperature* equilibrium with the surrounding air appears justifiable in most practical cases and will be adopted here.

## MATHEMATICAL ANALYSIS

### *The finite rate of approach to moisture equilibrium*

To take account of the finite rate of approach to moisture equilibrium between a fibre and its surrounding air we assume the relationship

* The form of the fronts propagated depends on the temperature and humidity changes which are imposed. If the temperature is changed at constant vapour-pressure, the temperature changes associated with the fast and slow fronts are in the same direction; this was the case in the experiments of Cassie *et al.* [1–3]. In the present experiments, the fronts were established by alteration of the proportions of different air streams, the effect of which was to change both the temperature and the vapour-pressure of the air entering the wool mass. Under these conditions the fast front is represented by a fall of temperature, and the slow front by a subsequent rise.

$$\frac{\partial M}{\partial t} = \omega(M' - M) \tag{1}$$

where $M$ is the instantaneous regain,
$M'$ is the equilibrium value of regain corresponding to the temperature, $T$, and humidity of the surrounding air, and
$\omega$ is a rate constant.

The exponential relation (1) is only an approximation to the observed behaviour. For example, in wool fibres when small changes in $M'$ are involved, the sorption process is known to be two-stage in character [4, 5], the first stage occupying times of the order of a minute and the second stage typically some hours. However, in practice, the second-stage contribution can frequently be neglected and the observed behaviour sufficiently described by the relation (1). As a guide to the magnitude of $\omega$, its value for Merino wool at room temperature ranges between 0·1 $s^{-1}$ (at high regains) and 0·0013 $s^{-1}$ (at low regains).

*Solution of the equation of moisture balance*

Following Cassie [1] we write the equation of moisture balance between air and fibres as

$$\frac{\partial C}{\partial t} + v\frac{\partial C}{\partial x} + \rho\frac{\partial M}{\partial t} = 0 \tag{2}$$

where $C$ is the concentration of water-vapour in the air,
$v$ is the air velocity, and
$\rho$ is the mass per unit volume of dry air–fibre mixture.

Substituting (1) in (2) gives

$$M = M' + \frac{1}{\rho\omega}\left(\frac{\partial C}{\partial t} + v\frac{\partial C}{\partial x}\right). \tag{3}$$

Eliminating $M$ between (2) and (3) gives

$$\frac{1}{\omega}\frac{\partial}{\partial t}\left(\frac{\partial C}{\partial t} + v\frac{\partial C}{\partial x}\right) + \frac{\partial C}{\partial t} + v\frac{\partial C}{\partial x} + \rho\frac{\partial M'}{\partial t} = 0. \tag{4}$$

The quantity $M'$ is a function of $C$ and the temperature $T$.

*Assumption of wave solution*

Owing to the form of equation (4) and the fact that the relationship between $M'$ and $C$ and $T$ is empirical (the sorption isotherm), general analytical solution presents serious difficulties. We therefore attempt to find if a solution exists in the form of one or more fronts propagated with constant velocity through the mass, in the manner found in Cassie's analysis. We shall show later that if a wave solution is accepted for equation (4), then $C$ and $T$ are connected by a single-valued relation. This means that $T$ can be expressed in terms of $C$, and hence $M'$ is a function of $C$ alone, and we may write

$$\frac{\partial M'}{\partial t} = \frac{\partial C}{\partial t}\cdot\frac{\mathrm{d}M'}{\mathrm{d}C}. \tag{5}$$

Substituting (5) in (4) we get

$$\frac{1}{\omega}\frac{\partial}{\partial t}\left(\frac{\partial C}{\partial t} + v\frac{\partial C}{\partial x}\right) + \frac{\partial C}{\partial t} + v\frac{\partial C}{\partial x} + \rho\frac{\mathrm{d}M'}{\mathrm{d}C}\cdot\frac{\partial C}{\partial t} = 0. \tag{6}$$

The assumption of a wave solution may be put into the form

$$C = C(x - ut) \tag{7}$$

so that $$\frac{\partial C}{\partial t} = -u\frac{\partial C}{\partial x}, \text{ etc.,}$$

and $u$ is the velocity of propagation.

Substituting (7) in (6) we get

$$\frac{\partial^2 C}{\partial x^2} + \left(\frac{\omega}{v-u}\frac{\mathrm{d}M'}{\mathrm{d}C} - \frac{\omega}{u}\right)\frac{\partial C}{\partial x} = 0. \tag{8}$$

Equation (8) is simplified somewhat by finding a relation between the air velocity $v$ and the front velocity $u$, as follows: we assume the mass of fibres to be of infinite thickness. Let $C_\alpha$, $M'_\alpha$ be values of $C$, $M'$ respectively at $x = \infty$, and $C_\beta$ and $M'_\beta$ be corresponding values at $x = -\infty$. The exchange of moisture takes place at a front moving in the $x$-direction with velocity $u$. The velocity of the air relative to the front is $(v - u)$. The change in concentration across the front is $(C_\alpha - C_\beta)$. The amount of water picked up by the air per second in unit cross section of the mass normal to the $x$-axis may then be expressed as

$$(v - u)(C_\alpha - C_\beta) \tag{9}$$

and also as $\rho u(M'_\alpha - M'_\beta)$. (10)

By equating (9) and (10) we find

$$u = \frac{v-u}{\rho}\,\frac{C_\alpha - C_\beta}{M'_\alpha - M'_\beta} \tag{11}$$

and substituting (11) in (8) we get

$$\frac{\partial^2 C}{\partial x^2} + \frac{\rho\omega}{v-u}\left(\frac{\mathrm{d}M'}{\mathrm{d}C} - \frac{M'_\alpha - M'_\beta}{C_\alpha - C_\beta}\right)\frac{\partial C}{\partial x} = 0. \tag{12}$$

Now

$$\frac{\partial}{\partial C}\left(\frac{\partial C}{\partial x}\right) = \left(\frac{\partial^2 C}{\partial x^2}\right)\Big/\left(\frac{\partial C}{\partial x}\right)$$

which, from (12),

$$= -\frac{\rho\omega}{v-u}\left(\frac{\mathrm{d}M'}{\mathrm{d}C} - \frac{M'_\alpha - M'_\beta}{C_\alpha - C_\beta}\right) \tag{13}$$

so that

$$\frac{\partial C}{\partial x} = -\frac{\rho\omega}{v-u}\left(M' - \frac{M'_\alpha - M_\beta}{C_\alpha - C_\beta}\,C\right) + \text{const.} \tag{14}$$

The arbitrary constant is evaluated by introduction of the boundary condition that, [at $x = -\infty$], $\partial C/\partial x = 0$, $C = C_\beta$ and $M' = M'_\beta$.

$$\frac{\partial C}{\partial x} = \frac{\rho\omega}{v-u} \times\left\{\frac{M'_\alpha - M'_\beta}{C_\alpha - C_\beta}(C - C_\beta) - (M' - M'_\beta)\right\}. \tag{15}$$

*Relationship between concentration and temperature*

If wave solutions to (4) exist, that is if a change in concentration can be propagated through the mass in accordance with equation (7), then the shape of the front is given by (15). However, the relationship between $M'$ and $C$ cannot in general be expressed analytically, and is determined by experiment. The solution of (15) is therefore best carried through numerically. Before proceeding with this solution one must recall that in the derivation of equation (5) it was stated that $C$ and the temperature $T$ are uniquely related. It is now necessary to show this and to find the relation.

Following Cassie, we write the equation of heat balance between air and fibres as

$$S\frac{\partial T}{\partial t} + \rho_a c_a v\frac{\partial T}{\partial x} - q\rho\frac{\partial M}{\partial t} = 0 \tag{16}$$

where $S$ = heat required to raise 1 cm³ of the air–fibre mixture through 1 degC, assuming no moisture exchange;
$\rho_a$ = density of air;
$c_a$ = specific heat of air at constant pressure; and
$q$ = differential heat of sorption of water by the fibre.

Eliminating $\partial M/\partial t$ between (16) and the equation of moisture balance (2), we find

$$\frac{\partial C}{\partial t} + v\frac{\partial C}{\partial x} + \frac{S}{q}\frac{\partial T}{\partial t} + \frac{\rho_a c_a v}{q}\frac{\partial T}{\partial x} = 0. \tag{17}$$

Making the previous assumption (7) that a change in concentration is propagated with uniform velocity $u$, and the further assumption that the temperature change caused by the mass transfer is propagated with the same velocity, i.e. that

$$T = T(x - ut), \tag{18}$$

equation (17) becomes

$$(v-u)\frac{\partial C}{\partial x} + \frac{S}{q}\left(\frac{\rho_a c_a v}{S} - u\right)\frac{\partial T}{\partial x} = 0 \tag{19}$$

or $$C + \frac{S}{q}\left[\frac{(\rho_a c_a v/S) - u}{v-u}\right]T = \text{const.} \tag{20}$$

Equation (20) gives us the required relationship between $C$ and $T$. However, it is not a particularly convenient form, involving both $v$ and $u$. It may be simplified either by making the assumption

$$\frac{\rho_a c_a}{S} \simeq 1 \tag{21}$$

or the assumptions

$$u \ll v \tag{22}$$

$$u \ll \frac{\rho_a c_a}{S} v. \tag{23}$$

In either case, (20) then becomes

$$C + \frac{\rho_a c_a}{q} T = \text{const.} \tag{24}$$

The assumption (21) was made by Cassie [1] in order to simplify the interpretation of his mathematical solution, but under usual conditions is hardly justifiable. In practice (22) is easily satisfied and (23) is usually justifiable for the slow second front. Equation (24) is interesting in being closely related to August's wet-bulb hypothesis [6]. It is consistent with the idea that the heat required to evaporate water from the fibre is derived from the volume of air into which it evaporates.

With assumption (22), equation (15) may be written

$$\frac{\partial C}{\partial x} = \frac{\rho\omega}{v} \times \left\{\frac{M'_\alpha - M'_\beta}{C_\alpha - C_\beta}(C - C_\beta) - (M' - M'_\beta)\right\} \tag{25}$$

and, by means of (24) in conjunction with experimentally determined isotherms, the relationship between $M'$ and $C$ necessary for the solution of (25) may be evaluated.

*Graphical representation of the wave solution*

The right-hand side of (25) is readily represented on a $C - M'$ plot; see Fig. 2. The first term within the outer brackets is the ordinate (less $M'_\beta$) of the straight line through the points $(C_\alpha, M'_\alpha)$, $C_\beta M'_\beta)$, while the second term is the ordinate (again less $M'_\beta$) of the $C$–$M'$ curve through the same points. Thus we may write

$$\frac{\partial C}{\partial x} = \frac{\rho\omega l}{v} \tag{26}$$

$$= A(C), \tag{27}$$

say, where $l$ is the difference between the two ordinates at any given value of $C$.

From this representation it can be seen that $l$ and therefore $\partial C/\partial x$ must always be positive if

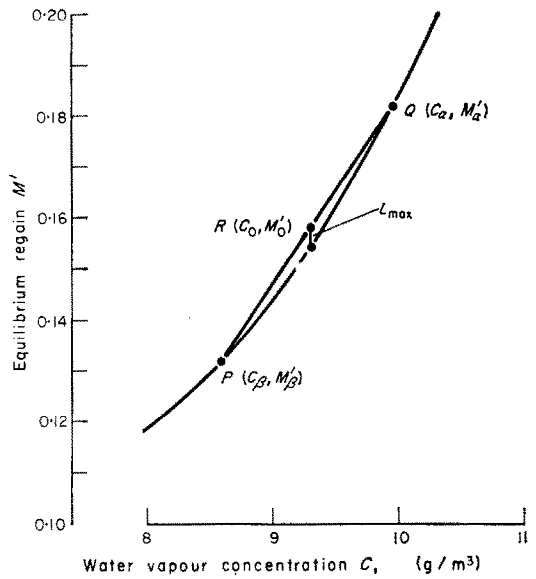


FIG. 2. $C$–$M'$ plot for wool fibres representing the terms $(M'_\alpha - M'_\beta)(C - C_\beta)/(C_\alpha - C_\beta)$ and $(M' - M'_\beta)$ of equation (25), and showing graphical determination of $l_{max}$ for particular boundary conditions.

the $C$–$M'$ curve is concave upward. If it is remembered that a sorption front implies a negative value of $\partial C/\partial x$, while a desorption front implies a positive value, it can be seen that if the $C$–$M'$ curve is concave upward a stable wave solution exists for only the desorption case. A *sorption* change is not propagated as a stable wave of constant velocity.

Conversely, if the $C$–$M'$ curve is concave downward, $\partial C/\partial x$ is negative, and a stable wave solution exists only for a sorption change. The $C$–$M'$ curve in the case of textile fibres has this form only at very low values of regain. Equation (26) may be solved, by numerical methods, to give $C$. In general, experiments show the existence of fast and slow waves, such as were found in Cassie's analysis. However, the assumptions (22) and (23) which have been made in deriving (26) will usually be justified only for the slow wave, and the solution is therefore confined to this wave, in which nearly all the moisture transfer occurs.

$C$ having been determined, $M$ may be found from (3), remembering that $\partial C/\partial t = -u\, \partial C/\partial x$. $T$ may be found from (24).

*Approximate analytical solution*

An analytical solution of (26) may be made for the case where the change in concentration is not large.

Let $C = C_0$ when $l = l_{\max}$ (see Fig. 2), and assume that $l$ may be adequately represented between $C_0$ and $C_\alpha$ by a parabolic function of $C$. Then from (26) and (27) we may write

$$\frac{\partial C}{\partial x} = A(C_0)\left\{1 - \left(\frac{C - C_0}{C_\alpha - C_0}\right)^2\right\}. \qquad (28)$$

Combining this equation with the assumption that $C = C(x - ut)$ (equation 7), we obtain

$$\frac{C - C_0}{C_\alpha - C_0} = \tanh \frac{A(C_0)}{C_\alpha - C_0}(x - ut),\ x \geqslant ut \qquad (29)$$

if we choose that $x - ut = 0$ when $C = C_0$. By assuming a second parabolic function for $l$ between $C_\beta$ and $C_0$, we find

$$\frac{C - C_0}{C_\beta - C_0} = \tanh \frac{A(C_0)}{C_\beta - C_0}(x - ut),\ x \leqslant ut. \qquad (30)$$

Hence in the case where the $C - M'$ curve can be adequately represented between $C_\alpha$ and $C_\beta$ by a quadratic form, a profile of the front at any time, $C(x, 0)$ say, is in the form of two tanh functions (29) and (30), joining with a common maximum slope $A(C_0)$ at $C = C_0$ which is therefore an inflexion point.

*The width of the front*

To obtain an estimate of the width of the front, we note that tanh 1 = 0·762, and examine the front at fixed time $t = 0$.

When $x = (C_\alpha - C_0)/A(C_0)$ and $t = 0$, $(C - C_0)/(C_\alpha - C_0) = 0{\cdot}762$ and similarly in the interval $C_0$ to $C_\beta$. Hence an interval of $(C_\alpha - C_\beta)/A(C_0)$ in $x$ contains 76 per cent of the total change in $C$ and is a good measure of the width of the front.

Remembering that $l = l_{\max}$ at $C = C_0$, we have from (26) and (27) that

$$\text{width of front} = \frac{v(C_\alpha - C_\beta)}{\rho\omega l_{\max}}. \qquad (31)$$

*Time for front to pass any point*

When examined as a function of time at a fixed point ($x = 0$), the front becomes, from (29),

$$\frac{C - C_0}{C_\alpha - C_0} = \tanh \frac{-u\,A(C_0)t}{C_\alpha - C_0},\ \text{for } t < 0.$$

With relations (27) and (11), this can be simplified to

$$\frac{C - C_0}{C_\alpha - C_0} = \tanh \frac{-\omega l_{\max}}{M'_\alpha - M'_0}t \qquad (32)$$

where $M'_0$ is such that

$$\frac{M_\alpha - M'_0}{M'_\alpha - M'_\beta} = \frac{C_\alpha - C_0}{C_\alpha - C_\beta}.$$

In Fig. 2, $M'_0$ is the regain at the point $R$ on chord $PQ$ which has the abscissa $C_0$. A similar relation to (32) holds for $t > 0$.

Equation (32) shows that the behaviour at a fixed point is independent of the air velocity $v$, and of the packing density given by $\rho$. The interpretation of this is that with increasing air velocity or decreasing density the front velocity increases, but the front width increases proportionately.

The time for the front to pass a point may be estimated in the same way as the width. This measure is

$$\frac{M'_\alpha - M'_\beta}{\omega l_{\max}}. \qquad (33)$$

*Numerical evaluation of a particular case*

Experimental data can most conveniently be obtained by measuring temperature at a fixed position in the bed. Owing to the linear relation between water-vapour concentration and temperature (20), the fractional temperature change should be always the same as the fractional change in $C$.

We now evaluate equation (33) for the time required for the slow front to pass a given point, inserting values corresponding to the conditions of one of the experiments mentioned in the first part of this paper.

The initial and final values of concentration for

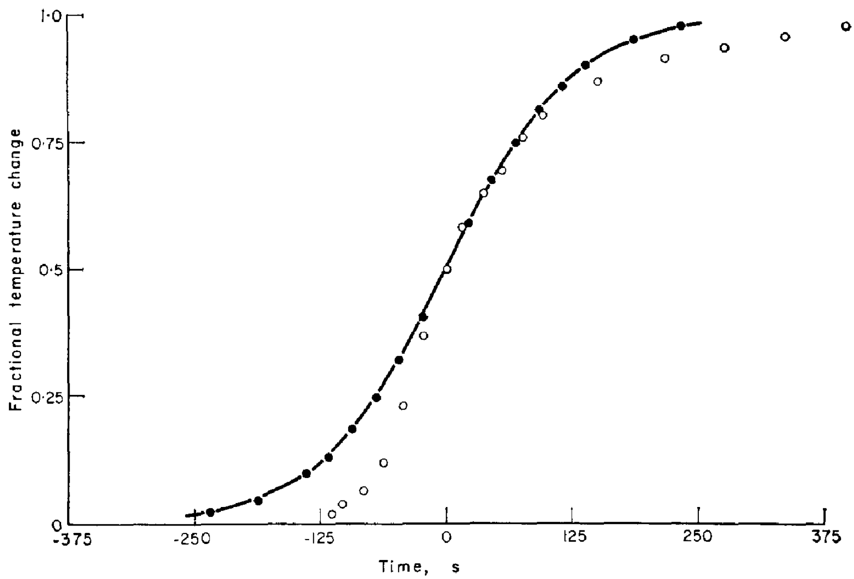


FIG. 3. A front (temperature vs. time at a fixed point) formed by two tanh functions, superimposed on experimentally obtained slow front. The zero of the time scale is arbitrary for the two curves, which have been made to coincide at the mid-point of the calculated front.

○ = experimental curve

—•—•— = calculated curve

the second front were:

$$C_\alpha = 10 \text{ g/m}^3$$
$$C_\beta = 8{\cdot}6 \text{ g/m}^3.$$

From Fig. 2, in which a curve of $M'$ vs. $C$ is given for wool under the conditions of the experiment, corresponding values of $M'$ can be determined as follows:

$$M'_\alpha = 0{\cdot}133$$
$$M'_\beta = 0{\cdot}183.$$

By the graphical construction described in the section "Graphical representation of the wave solution", we find (Fig. 2) a value

$$l_{\max} = 0{\cdot}004.$$

For completeness, it may be mentioned that the air velocity $v$ was 75 cm/s and the density $\rho$ was 0·11 g/cm$^3$.

From data on the rate of sorption of water by wool fibres [4, 5] we assign for the conditions of the experiment a value:

$$\omega = 0{\cdot}05 \text{ s}^{-1}.$$

The time for the front to pass a point is then estimated from (33) to be 230 s. This time is much greater than is predicted when the finite rate of sorption of the fibres is neglected, and agrees much more closely with the experimental results of Fig. 1. This may be seen from Fig. 3, in which the experimental curve is plotted together with the theoretical curve (equation 32) evaluated for the above conditions. It should be understood, however, that this comparison is merely illustrative, since the experimental results are obtained from a finite bed, in which transient effects, beyond the scope of this paper, can be expected.

## CONCLUSION

The analysis shows that, when account is taken of the finite rate of approach to moisture equilibrium between air and fibres, a constant-velocity-wave solution for the propagation of changes through the mass exists under certain conditions, which are satisfied in the cases of most textile fibres only when a *desorption* step is propagated. A general solution for the profile of the propagated front may be found by numerical methods. Provided the concentration change is not great, an analytical expression for the width of front may be obtained, and this, when evaluated for typical conditions, is found to be much greater than would be predicted when the finite rate of fibre sorption is neglected.

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**Résumé**—Cet article présente une solution pour la propagation des variations de température et d'humidité dans une masse de fibres, quand on fait varier les conditions d'écoulement de l'air dans la masse. La théorie tient compte de la vitesse finie d'absorption ou de désorption des fibres; dans les études précédentes cette vitesse avait été supposée infinie. Les calculs, basés sur la théorie actuelle et supposant des vitesses d'écoulement égales à celle que l'on utilise en pratique dans l'industrie, montrent que le profil d'humidité dans la masse doit être beaucoup plus grand que celui que prévoyait les théories précédentes. Les profils de désorption des fibres donnés par l'expérience sont en bon accord avec la théorie présentée.

**Zusammenfassung**—Es wird eine Lösung angegeben für die Ausbreitung von Temperatur- und Feuchtigkeitsänderungen durch einen Faserstoff, wenn der Zustand der durch den Faserstoff hindurchströmenden Luft geändert wird. Die Theorie stellt die endliche Geschwindigkeit der Feuchtigkeitsaufnahme oder -Abgabe durch die Fasern in Rechnung; in früheren Arbeiten war diese Geschwindigkeit als unendlich gross angenommen worden. Berechnungen nach der hier vorleigenden Theorie und mit für die industrielle Praxis kennzeichnenden Luftgeschwindigkeiten zeigen, dass das Feuchtigkeitsprofil im Faserstoff weit ausgedehnt sein wird im Vergleich zu Aussagen nach früheren Theorien (die Feuchtigkeitsänderungen erstrecken sich über einen grösseren Zeitraum). Durch Versuch ermittelte Profile für die Desorption der Fasern stimmen mit der vorliegenden Theorie gut überein.

**Аннотация**—В статье приводится аналитическое решение для нахождения полей температур и влажности в слое волокон шерсти при различной скорости протекания воздуха через слой. В отличие от ранее принимавшейся методики авторы учитывают, что состояние равновесия между влажным материалом и воздухом наступает не мгновенно, а с определенной конечной скоростью. Результаты численных расчётов показали, что профили влагосодержаний по толщине слоя, полученные исходя из указанных предпосылок, значительно отличаются от тех, которые вытекают из прежних теорий.