MOISTURE PERMEATION OF CLOTHING
A factor governing thermal equilibrium and comfort

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Abstract

The manner in which the wetting and drying behavior of a textile fabric depends upon the properties of the fibers comprising it is of both practical and theoretical significance. The consumer is justifiably interested in the relationship of fiber content to such serviceability criteria as wicking, solubility, wettability, and speed of drying. At the same time, the extent to which the drying of textiles conforms with or departs from theory is of scientific interest, particularly if noteworthy distinctions in behavior among fabrics can be related to intrinsic fiber properties or geometry of the textile structure. This work was undertaken to answer some practical questions about fiber-fabric-water relationships. Especially of interest was the extent to which rate of fabric drying might depend upon (a) fiber moisture regain, and (b) speed of capillary migration. These and other aspects of the general problem were examined in the light of pertinent theory in connection with appropriate practical findings.

Introduction

For thermal equilibrium of man in his environment, it is convenient for the parameters related to the ambiance (air and radiant temperatures, air velocity and humidity) and for those concerning man (activity and clothing) to compensate their effects. In temperate climates this is possible, whereas in hot or cold climates constraints on lifestyle necessarily exist.

The total heat loss from skin is made up of two parts, the heat loss by evaporation and the heat loss by conduction, convection and radiation. Under normal conditions the loss of heat by evaporation takes place in the form of insensible perspiration which accounts for approximately 15% of the heat loss through the skin. In cases of hard physical exertion or in tropical conditions the heat loss by evaporation is enhanced by sweating, when the skin becomes covered with a film of water.

The amount of water retained in a fabric is traditionally expressed as some function of the fabric mass. This is valid, useful, and convenient method for many pur-

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poses. It is quite obvious that any water beyond that actually sorbed in the fibers must be retained as liquid water within the voids of the fabric structure. Generally, such free volumes are considerably greater than the volume of fibers which provide the space matrix of the fabric. For the liquid water held in a fabric, the fiber network constitutes an elaborately shaped vessel with peculiar and specific wall properties.

It is a common misapprehension that non-hygroscopic fibers (i.e., those of low intrinsic for moisture vapor) will automatically produce a hydrophobic fabric. The major significance of the fine geometry of a textile structure in contributing to resistance to water penetration can be stated in the following manner:

The requirements of a water repellent fabric are (a) that the fibers shall be spaced uniformly and as far apart as possible and (b) that they should be held so as to prevent their ends drawing together. In the meantime, wetting takes place more readily on surfaces of high fiber density and in a fabric where there are regions of high fiber density such as yarns, the peripheries of the yarns will be the first areas to wet out and when the peripheries are wetted, water can pass unhindered through the fabric. The ease of penetration, which controls both the extent of liquid uptake and dependent upon the spatial disposition of the fiber surfaces.

Some of the issues of clothing comfort that are most readily involve the mechanisms by which clothing materials influence heat and moisture transfer from skin to the environment. Heat transfer by conduction, convection, and radiation and moisture transfer by vapor diffusion are the most important mechanisms in very cool or warm environments from the skin.

It has been recognized that the moisture-transport process in clothing under a humidity transient is one of the most important factors influencing the dynamic comfort of a wearer in practical wear situations. However, the moisture transport process is hardly a single process since it is coupled with the heat-transfer process under dynamic conditions.

Trying to stay warm and dry while active outdoors in winter has always been a challenge. In the worst case, an individual exercises strenuously, sweats profusely, then rests. During exercise, liquid water accumulates on the skin and starts to wet the clothing layers above skin. Some of the sweat evaporates from both the skin and the clothing. Depending on the temperature and humidity gradient across the clothing, the water vapor either leaves the clothing or condenses and freezes somewhere in its outer layers.

When one stops exercising and begins to rest, active sweating soon ceases, allowing the skin and clothing layers eventually dry. During this time, however, the heat loss from body can be considerable. Heat is taken from the body to evaporate the sweat, both that on the skin and that in the clothing. The heat flow from the skin through the clothing can be considerably greater when the clothing is very wet, since water decreases clothing's thermal insulation. This post-exercise chill can be exceedingly comfortable and can lead to dangerous hypothermia.

A dry layer next to the skin is more comfortable than a wet one. If one can wear clothing next to the skin that does not pick up any moisture, but rather passes it through to a layer away from the skin, heat loss at rest will be reduced.

In cold climates clothing to worn to restrict heat loss from the body. The fabric used in apparel differ in moisture sorption and thermal properties, and it is important to consider these properties when choosing garments. One way of expressing in the insulating performance of a textile is to quote its 'effective thermal conductivity'. Here the term 'effective' refers to the fact that conductivity is calculated from the rate of heat flow per unit area of the fabric divided by the temperature gradient between opposite faces. It is not true conduction, because heat transfer takes place by a combination of conduction through fibers and air and infrared radiation. If moisture is present, other mechanisms may be also involved.

Research on thermal resistance of apparel textiles has established that thermal resistance of dry fabric or one containing very small amounts of water depends on its thickness, and to a lesser extent on fabric construction and fiber conductivity. Indeed, measurements of effective thermal conductivity by standard steady-state methods show that differences between fabrics are mainly attributable to thickness. Despite these findings, consumers continue to regard wool as 'warmer' than other fibers, and show preference for wearing wool garments in cold weather, particularly when light rain or sea spray is involved.

Background

One factor influencing the suitability of fabrics for clothing is their resistance to the passage of water vapor. This factor is important for both hot- and cold-climate clothing.

Clothing is often exclusively considered by its insulating aspect. However, another function, called the pumping effect, can be utilized to help man keep comfortable. With it, an air layer is confined between skin and fabric, or between two fabric layers. Its hygro-thermal conditions are different from the outside air and mainly depend on the renewal rate. At rest, or in low activity, the pumping effect does not work; so the air layer behaves as an insulating layer, as does the fabric. On the other hand, in a hot humid climate, the pumping effect becomes a fan effect by air agitation near the skin; moreover, a wick effect is sought for decreasing wetness and increasing the evaporating area. The ability to absorb the smallest quantities of moisture, to diffuse it and to let it evaporate easily must be a high quality of the fabric.

High contact angles of wetting of fiber surfaces will impede wetting if the fabric geometry takes advantage of this effect. However, there is no categorical necessity that a non-hygroscopic fiber be hydrophobic. Indeed, wool, one of the most hygroscopic fibers, has been described as hydrophobic gives the receding angle of contact for most of the fibers employed in this work.

The comfort of a garment is linked to several factors: lightness, heat and vapor transport, sweat absorption and drying. A garment's comfort depends on the properties of each fabric layer and the combination of all the layers worn. The coupled heat and liquid moisture transport of porous material has wide industrial applications in textile engineering and functional design of apparel products. Heat transfer mechanisms in porous textiles include conduction by the solid material of fibers, conduction by intervening air, radiation, and convection. Meanwhile, liquid and moisture

transfer mechanisms include vapor diffusion in the void space and moisture sorption by the fiber, evaporation, and capillary effects. Water vapor moves through textiles as a result of water vapor concentration differences. Fibers absorb water vapor due to their internal chemical compositions and structures. The flow of liquid moisture through the textiles is caused by fiber-liquid molecular attraction at the surface of fiber materials, which is determined mainly by surface tension and effective capillary pore distribution and pathways. Evaporation and/or condensation take place, depending on the temperature and moisture distributions. The heat transfer process is coupled with the moisture transfer processes with phase changes such as moisture sorption/desorption and evaporation/condensation.

The influence of relative humidity on fabric permeability has previously studied and it was found that there can be large changes in convective gas flow transport properties of woven and non-woven textile materials due to changes in fabric structure caused by fiber swelling.

King and Cassie [1] conducted an experimental study on the rate of absorption of water vapor by wool fibers. They observed that, if a textile is immersed in a humid atmosphere, the time required for the fibers to come to equilibrium with this atmosphere is negligible compared with the time required for the dissipation of heat generated or absorbed when the regain changes. McMahon and Watt [2] investigated the effects of heat of sorption in the wool-water sorption system. They observed that the equilibrium value of the water content was directly determined by the humidity but that the rate of absorption and desorption decreased as the heat-transfer efficiency decreased. Heat transfer was influenced by the mass of the sample, the packing density of the fiber assembly, and the geometry of the constituent fibers. Crank [3] pointed out that the water-vapor-uptake rate of wool is reduced by a rise in temperature that is due to the heat of sorption. The dynamic-water-vapor-sorption behavior of fabrics in the transient state will therefore not be the same as that of single fibers owing to the heat of sorption and the process to dissipate the heat released or absorbed.

Henry [4, 5] was who the first started theoretical investigation of this phenomenon. He proposed a system of differential equations to describe the coupled heat and moisture diffusion into bales of cotton. Two of the equations involve the conservation of mass and energy, and the third relates fiber moisture content with the moisture in the adjacent air. Since these equations are non-linear, Henry made a number of simplifying assumptions to derive an analytical solution.

In order to model the two-stage sorption process of wool fibers, David and Nordon [6] proposed three empirical expressions for a description of the dynamic relationship between fiber moisture content and the surrounding relative humidity. By incorporating several features omitted by Henry into the three equations, David and Nordon were able to solve the model numerically. Since their sorption mechanisms (i.e. sorption kinetics) of fibers were neglected, the constants in their sorption-rate equations had to be determined by comparing theoretical predictions with experimental results. Based on conservation equations, this global model consists of two differential coupled equations with variables for temperature and water concentration in air (C_a) and in the fibers of the textile (C_f), which is generally the water ad-

sorbed by hygroscopic fibers. C_a is not in equilibrium with C_f, but an empirical relation between the adjustable parameters is assumed: the rate of sorption is a linear function of the difference between the actual C_f and the equilibrium value. The introduced coefficients are not directly linked to the physical properties of the clothes.

Farnworth [7] reported a numerical model describing the combined heat and water-vapor transport through clothing. The assumptions in the model did not allow for the complexity of the moisture-sorption isotherm and the sorption kinetics of fibers. Wehner *et al*. [8] presented two mechanical models to simulate the interaction between moisture sorption by fibers and moisture flux through the void spaces of a fabric. In the first model, diffusion within the fiber was considered to be so rapid that the fiber moisture content was always in equilibrium with the adjacent air. In the second model, the sorption kinetics of the fiber were assumed to follow Fickian diffusion. In these models, the effect of heat of sorption and the complicated sorption behavior of the fibers were neglected.

Li and Holcombe [9] developed a two-stage model, which takes into account water-vapor-sorption kinetics of wool fibers and can be used to describe the coupled heat and moisture transfer in wool fabrics. The predictions from the model showed good agreement with experimental observations obtained from a sorption-cell experiment. More recently, Li and Luo [10] further improved the method of mathematical simulation of the coupled diffusion of the moisture and heat in wool fabric by using a direct numerical solution of the moisture-diffusion equation in the fibers with two sets of variable diffusion coefficients. These research publications were focused on fabrics made from one type of fiber. The features and differences in the physical mechanisms of coupled moisture and heat diffusion into fabrics made from different fibers have not been systematically investigated.

In this paper, the physical mechanisms of moisture diffusion into fabrics made from different fibers are studied.

Formulation of the problem

The course of evaporative drying

Intuitively, one might expect an open yarn to be more penetrable; but consider that the capillary migration depends for its function upon continuous, long, narrow pores. Yarns spun from smooth-surfaced, more regular fibers are inclined to present localized dense regions for easier initial wetting by queues films. Secondly, the same fiber characteristics will regulate fabric fine geometry in the direction of long and continuous, albeit twisted, capillary pores necessary for thorough and rapid penetration. The speed of capillary migration, or wicking, is a behavior characteristic of apparel fabrics of some note itself. Stains and liquid-dispersed soils are probably more thoroughly and rapidly carried into finer recesses and over wider areas in fabrics of high capillarity. Similarly, simple water-wetting, such as in a rain shower, will be more thorough and will carry through a fabric as well as along it, at perhaps an uncomfortable rate to the wearer. Increasing the fiber-to-water contact angle by suitable surface treatments may be effective in reducing the effects of close and regular fiber packing, however.

Most theories for the evaporation of liquid water from saturated, porous substrate provide three periods. It is generally found that evaporation during the course of drying from saturation in a constant atmosphere proceeds first at an essentially constant rate. After the total moisture content has been reduced below a particular threshold, the rate begins to decrease first linearly and eventually in some non-linear manner with the residual moisture content. A number of possible mechanisms which may control the overall process are:

Constant-rate period

During this period the substrate presumably starts out entirely saturated with moisture, and evaporation occurs from a continuous water-air interface at the periphery of the substrate. Energy for evaporation and the water mass are exchanged across this interface as evaporation transpires. Conditions are analogous to water evaporating in a beaker, and the phenomena are governed by relatively simple thermodynamic principles. With external conditions such as air flow velocity and temperature constant, the grams of water departing per unit of time will remain constant and proportional to the actual area of liquid interface.

First falling-rate period

By virtue of the evaporative loss of liquid water, it is inevitable that the previously continuons liquid surface will eventually begin to retreat below the highest protuberances of the porous medium. A so-called 'critical moisture content' is eventually achieved, at which time the original steady-state heat and mass transfer conditions no longer prevail. From this point until a second so-called 'falling-rate period' sets in, the evaporation rate of substrate periphery falls in direct proportion to the total residual held within the body of the porous substrate.

The critical moisture content is considered, by this argument, to be the minimum concentration of water at which capillary rise to the air-liquid interface remains sufficiently rapid to maintain the original maximum peripheral surface of evaporation. At the critical moisture content the exposed liquid surface decreases in area, and, consequently, the rate at which water departs of exposed area of substrate decreases proportionately as the wetted fraction of the total exposed area decreases.

Second falling-rate period

The transition from the first to the second falling-rate period is rarely clear-cut. Moreover, the second falling-rate period is not characterized by a linear dependence of rate upon moisture content.

The mathematical model

The mathematical model describing the coupled heat and moisture diffusion in textiles was first proposed by Henry [4, 5] and then further developed by Nordon and David [11] and Li and Holcombe [9]. The conservation of heat and moisture can be expressed by the following equations:

$$\varepsilon\frac{\partial C_a}{\partial t}+(1+\varepsilon)\frac{\partial C_t}{\partial t}=\frac{D_a\varepsilon}{\tau}\frac{\partial^2 C_a}{\partial x^2}$$ (1)

$$C_v\frac{\partial T}{\partial t}-\lambda\frac{\partial C_t}{\partial t}=K\frac{\partial^2 T}{\partial x^2}$$ (2)

In the equations, both C_v and λ are functions of the concentration of moisture absorbed by the fibers. Most textile fibers are of very small diameter and have a very large surface/volume ratio. The assumption in the second equation of instantaneous thermal equilibrium between the fibers and the inter-fiber space does not therefore lead to appreciable error. The two equations in the model are not linear and contain the three unknowns, C_p, T and C_a. A third equation is needed to solve the equations.

Henry [4, 5] derived a third equation to obtain an analytical solution by assuming that C_f is linearly dependent on T and C_s and that fibers reach moisture equilibrium with the adjacent air instantaneously. Downes and Mackay [12] found experimentally that the sorption of water vapor by wool is a two-stage process, the first stage obeys Fick's law of diffusion with a concentration-dependent diffusion coefficient. The second stage, which involves structural changes within fibers, is much slower than the first. To simulate the two-stage sorption process, Nordon and David [11] proposed an exponential function to describe the rate of change of fiber water content, which needed to be adjusted according to the measured fabric moisture content. Li and Holcombe [9] developed a two-stage sorption-rate equation to describe the moisture sorption of wool. The first stage is represented by a Fickian diffusion with a constant coefficient. The diffusion equation was solved by using Crank's truncated solution [3]. The second stage is described by an exponential relationship, which also needs to be adjusted according to the experimental measurements. The relative contributions of the two stages to the total moisture sorption are function of the sorption time and the initial regain of the fibers.

Li and Luo [10] improved the sorption rate equation by assuming that the moisture sorption of wool fiber can be generally described by a uniform-diffusion equation for both stages of sorption:

$$\frac{\partial C_t}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left\{rD_t(x,t)\frac{\partial C_f}{\partial r}\right\}$$ (3)

where $D_f(x,t)$ are the diffusion coefficients that have different values at different stages of moisture sorption. In a wool fabric, $D_f(x,t)$ is a function of water content of the fibers, which is dependent on the time of sorption and the location of the fiber.

In the first stage, the diffusion coefficient is concentration-dependent and is assumed to be quadratic function of water content when the sorption is less than 540 s, as given in Eq. (4a). In the second stage, in which the moisture sorption is much slower than in the first, the diffusion coefficient of moisture in a wool fiber is attenuated along with the time of sorption when $t \geq 540$ s as shown in Eq. (4b).

$$D_t\{W_c(t)\}=\{1.04+68.204W_c(t)-1342.5924W_c(t)^2\}10^{14}, \; t \leq 540 \text{ s}$$ (4a)

$$D_t\{W_c(t)\}=1.616405[1-\exp\{-18.16323\exp(-28.0W_c(t))\}]10^{-14}, \; t \geq 540 \text{ s}$$ (4b)

The second formula for D_f in Eq. (4b) shows that the rate of moisture diffusion into a wool fiber (when $t \geq 540$ s) attenuates in the form of double-exponential function, which may indicate that the attenuating feature of the moisture sorption of wool is due to its microstructural changes and the decreasing number of available polar groups.

Now, we assume that the sorption process for all the fabrics can be described by a uniform diffusion equation from Eq. (3), with diffusion-coefficient functions to describe the moisture-sorption kinetics. Through a large number of computational experiments in comparison with the measured water-content changes and temperature changes of various fabrics, we try to identify whether the moisture-sorption process needs to be described by a two-stage process or a single Fickian-diffusion process. The diffusion-coefficient functions identified for fabrics made from wool, cotton, porous acrylic fiber, and polypropylene fiber which is reported by Li *et al.* [13] are summarized in the appendix.

Initial and boundary conditions

To generate a solution to the above-mentioned equations, we need to specify an initial condition and boundary conditions at the fabric surfaces of the humidity, moisture content, and temperature. Initially, a fabric is equilibrated to a given atmosphere of temperature T_{a0} and humidity (C_{a0} and H_{a0}), the temperature and moisture content being uniform throughout the fabric at known values:

$$T_a(x,0) = T_{a0} \tag{5}$$

$$C_a(x,0) = C_{a0} \tag{6}$$

$$C_f(x,r,0) = f(H_{a0}, T_0) \tag{7}$$

The fabric then undergoes a step change to a different atmosphere. Its boundaries are exposed to an air stream of a new moisture concentration C_{ab} and temperature T_{ab}. Considering the convective nature of the boundary air layers, the boundary conditions can be described by the following equations:

$$D_a \varepsilon \frac{\partial C_a}{\partial x}\bigg|_{x=0} = h_c(C_a - C_{ab}) \tag{8}$$

$$D_a \varepsilon \frac{\partial C_a}{\partial x}\bigg|_{x=L} = -h_c(C_a - C_{ab}) \tag{9}$$

$$K \varepsilon \frac{\partial T}{\partial x}\bigg|_{x=0} = h_t(T - T_{ab}) \tag{10}$$

$$K \varepsilon \frac{\partial T}{\partial x}\bigg|_{x=L} = -h_t(T - T_{ab}) \tag{11}$$

These conditions show that the thermal and moisture fluxes across the boundaries are proportional to the differences in the temperature and moisture concentration between the surrounding medium and the fabric surface, respectively.

Numerical solution

Equations (1) and (2) are solved by a finite-difference method by using the Crank–Nicolson scheme, and Eq. (3) is solved by using an implicit-difference scheme, together with specification of the initial condition of Eqs (5) – (7), the boundary conditions of Eqs (8) – (11), and the fiber and fabric properties. Details of the solution method have been reported previously by Li and Luo [10].

Experimental

The discrepancy between laboratory tests and consumer preferences may be partly due to the fact that existing methods for measuring conductivity normally involve fabrics pre-conditioned to standard atmosphere. Fibers such as wool are hygroscopic, and therefore it is common practice in the textile industry to equilibrate specimens to an atmosphere of 20°C and 65% relative humidity before testing. The state of a specimen obtained by such method does not necessarily represent typical wear conditions. Clothing may be contain moisture levels in excess of those present during these tests as a result of perspiration, or as mentioned above from rain or spray.

Current methods cannot be used to measure the thermal properties of fabrics containing water. Typical methods such as the guarded hot plate and ratio-metric devices use a temperature gradient across the specimen, and measurements are made when equilibrium heat flow is reached. This can take a long time, especially with specimens of large heat capacity such as those containing higher amounts of water, and is of questionable accuracy owing to the possibility of moisture in the fabric redistributing itself. Measuring the thermal properties of moist fabrics requires a rapid technique. In this study a transient technique have been applied to textiles containing moisture. The apparatus consists of a heat source of constant temperature higher than ambient and passive guarded heat sink that is initially at ambient temperature. The distance between the sink and source plates is adjusted to suit the specimen thickness, and the fabric is placed between the two plates. From that moment the temperature of the heat sink rises, and the effective thermal conductivity of the fabric can be determined from this rise during the first 100 s of heat flow.

We have measured the effective thermal conductivities of different knitted fabrics (Table 1) for varying regains. Regain is the mass of water present expressed as a percentage of dry mass of the material. We believe that the effective thermal conductivity of moist fabrics may be influenced by the fiber sorption properties, so the fiber types we tested had different properties namely:

• Wool (non-wicking and absorbent).
• Polypropylene (non-wicking and almost non-absorbent).
• Cotton (wicking and absorbent).
• Porous acrylic (wicking and almost non-absorbent).

To measure the absorption of liquid water in fabrics, circular samples were uniformly wetted in water and left overnight sandwiched between two wet sponges. The next day, the mass of water freely absorbed by each sample was recorded. We obtained

the desired regains by drying wetted samples; approximately 10 min was allowed after drying for the specimen to reach uniform moisture distribution. Regain was determined shortly before the test by massing the sample. Fabric thickness was measured after conditioning to standard textile test conditions (65% RH, temperature 20°C), and the distance between the heat source and the sink was adjusted to this figure. While it was noticed that the thickness of a fabric changes slightly with regain, we chose this approach for simplicity. After each test, we determined the amount of water condensed on the heat sink by blotting it with a paper tissue, which we then weighed.

Results

Figures 1–4 present the results of conductivity measured using transient technique as a function of regain over the range of 0 to 300% on porous acrylic, polypropylene, wool, and cotton fabrics. The conductivity of four fabrics is approximately the same at the zero regain, which is consistent with known thermal behavior of dry or normally conditioned fabrics. At 300% regain, the materials can be considered 'dripping wet'. There are differences in the behavior of each fabric between dry and wet, which can be explained in terms of the amount of water present in the material and the way it is held,

Table 1 Pertinent properties of and results for fabrics used in water absorption and drying experiments

Fabric	Mass/g m^{-2}	Thickness/mm	Mass of water in fabric/g	Time to dry/h
Wool plain weave	122	0.48	0.60	3
Wool singel knit	214	0.83	1.66	7
Polypropylene plain weave	168	0.66	0.82	3
Polypropylene knit	223	1.26	2.28	9
Cotton duck	364	0.68	1.27	5
Cotton sheeting	157	0.43	0.98	5
Acrylic plain weave	143	0.40	0.52	2
Acrylic knit	123	0.73	1.47	5

e.g., absorbed into the fiber in the case of absorbent material, retained in pores within the fiber structure within the porous acrylic, or as free water between fibers and yarns.

According to Table 1, we have also found no relationship between regain and the amount of water picked up by the fabric (r=0.074). Initially, we had plotted the percent water in the sample, based on its mass, *vs.* thickness and found poor correlation (r=0.48). However, after plotting actual water content *vs.* various properties, we found the best correlation (r=0.92) to be between the actual amount of water in the samples and their thickness (Fig. 5).

When we converted the results of others (Maejima [14], Dolhan [15], Fourt *et al*. [16], Bertioniere [17]) from liquid content to actual liquid content and

plotted these values *vs.* thickness, we again found a very good correlation. The results of Fourt *et al.*, whose experiment included a very wide range of materials. It was concluded that expressing the amount of water in a fabric as a percent of its mass is simply an extension of the percent regain calculation for water vapor to that for liquid water. The amount of water vapor a fiber pick up, expressed as a percent of its mass, is valid because it is directly related to the number of hydrophilic sites the fiber has to which water vapor can bond: this is proportional to fiber mass. Like
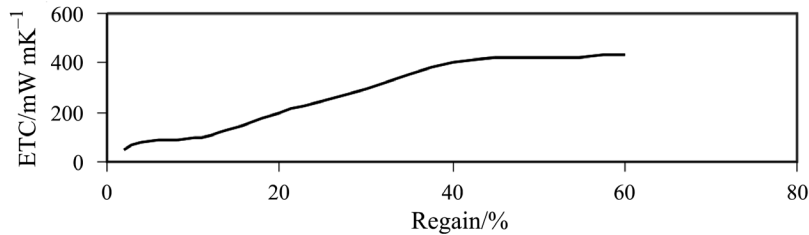
Fig. 1 Effective thermal conductivity (ETC) of a porous acrylic fabric as a function of regain
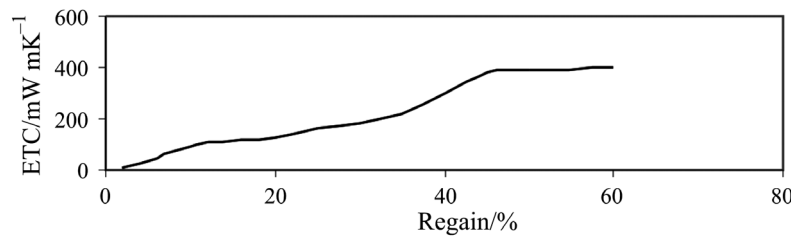

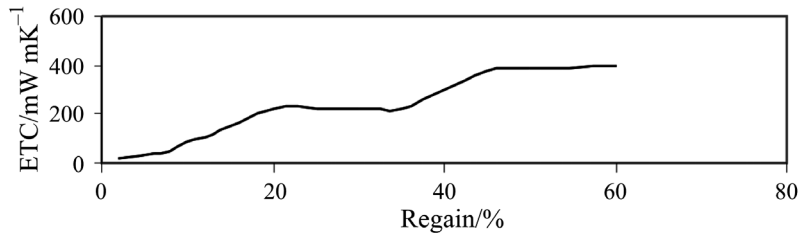**Fig. 2** Effective thermal conductivity (ETC) of a polypropylene fabric as a function or regain

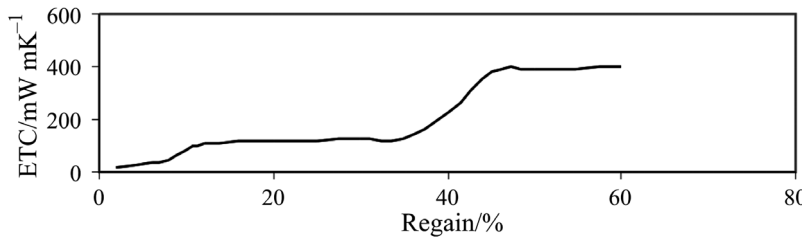**Fig. 3** Effective thermal conductivity (ETC) of a wool fabric as a function of regain

Fig. 4 Effective thermal conductivity (ETC) of a cotton fabric as a function of regain
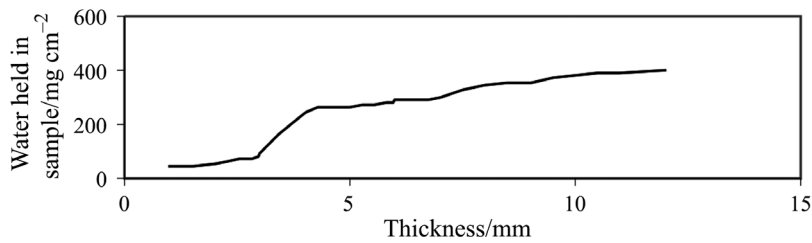
Fig. 5 A plot of Fourt *et al.* results for thickness *vs.* the amount of water held

Fourt *et al*. [16], we found a very good correlation (r=0.98) between the amount of water initially in these fabrics and the time for them to dry; this correlation was independent of fiber type (Fig. 6). Note that Fourt *et al*. found this relationship did not hold for some of their napped fabrics, explaining that the napped surface retarded heat flow to the water in the fabric and thus limited the evaporation rate.

It is noted that after an initial equilibrium period at 0% *r.h*., the humidity in the cell was raised to 99% in a single step, the mean air velocity at the fabric surface being 1.7 m s^{-1}. The results show that wool fabric has a significantly greater total moisture uptake than other fabrics. Meanwhile we can note the temperature changes at the surface of fabric during the dynamic-moisture-diffusion process. Obviously, the
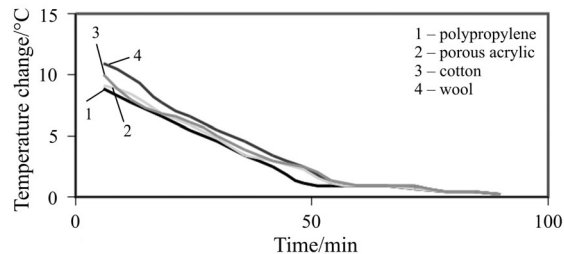

Fig. 6 Temperature changes at surface of fabrics during humidity transient

wool fabric had the highest temperature rise during the humidity transients and was closely followed by the cotton, acrylic and polypropylene fiber fabrics.

Application of results

Finally, the question arises – Can our results be applied to the person exercising strenuously and sweating? Several researchers have examined the effect of clothing made from various fibers of constructions on the physiological responses of subjects during work followed by rest.

Holmer [18] compared the heat exchange and thermal insulation of two ensembles, one made from wool, the other from nylon, worn by subjects who exercised either lightly (dry condition) or strenuously (wet condition) for 60 min, then rested 60 min. He found that there was a significant difference in physiological and subjective responses between

dry and wet conditions, but not between the two fiber types. Further, there was no significant difference between the ratings of temperature and humidity sensations for the wool and nylon garments. The wool garment picked up more water than the nylon garment (245 g *vs*. 198 g) for the wet condition.

However, the wool fabric may have been slightly thicker than the nylon fabric, since it was reported to have a slightly greater thermal resistance and therefore hold more water.

Nielsen and Edrusick [19] evaluated the effect of five kinds of knit structures, all made from 100% polypropylene. On subjects exercising for 40 min at 5°C followed by 20 min at rest, and then repeated. The thickest knit, a fleece, caused the greatest total sweat production, retained the most moisture, and wetted skin the most. They stated that the hydrophobic polypropylene prevented extensive sweat accumulation in the underwear (10 to 22%) causing the sweat to accumulate in the outer garments.

Bakkevig and Nielsen [20] repeated the protocol above, but used low and high work rates with three kinds of underwear (a polypropylene 1×1 knit, a wool 1×1 knit, and a fishnet polypropylene) worn under wool fleece covered by polyester/cotton outer garments. Total sweat production and evaporated sweat were the same for all three underwear fabrics, but where the sweat accumulated differed significantly. More sweat accumulated in the wool underwear than either polypropylene at both work rates. At the higher work rate, more sweat moved into the fleece layer from both kinds of polypropylene underwear than for the wool. Most likely for the 1×1 knits, the thicker wool underwear (1.95 mm) simply holds more water than the polypropylene underwear (1.41 mm) and based on outer layer-to-layer wicking results, needs a greater volume of sweat to fill it pores before it starts to donate the excess to the layer above it.

Galbraith *et al*. [21] compared cotton, water repellent cotton, and acrylic garments through wearing tests and concluded that the major factor causing discomfort was the excess amount of sweat remaining on the skin surface. Niwa [22] stated that the ability of fabrics to absorb liquid water (sweat) is more important than water vapor permeability in determining the comfort factor of fabrics.

Morooka and Niwa [23] postulated physiological factors related to the wearing comfort of fabrics as follows: sweating occurs whenever there is tendency for the body temperature to risk, such as high temperature in the surrounding air and physical exercise, etc. If liquid water (sweat) cannot be dissipated quickly, the humidity of the air in the space in between the skin and the fabric that contacts with the skin rises. This increased humidity prevents rapid evaporation of liquid water on the skin and gives the body the sensation of 'heat' that triggered the sweating in the first place. Consequently, the body responds with increased sweating to dissipate excess thermal energy. Thus a fabric's inability to remove liquid water seems to be the major factor causing uncomfortable feeling for the wearer.

Hollies *et al*. [24] conducted wear trails for shirts made of various fibers. They concluded that the largest factor that influenced wearing comfort was the ability of fibers to absorb water, regardless of whether fibers were synthetic or natural.

All of these studies indicates that the transient state phenomenon responding to the physiological demand to cause sweating is most relevant to comfort or discomfort

associated with this general principle. It is important to point out that a highly water absorbing fabric placed in the first layer keeps the partial pressure of water vapor near the skin low, which helps dissipate water at the skin surface, although the water vapor transport rate is smaller than for non-absorbing fabrics.

In the other words, the dissipation of water by means of absorption by fabrics appears to be much more efficient way to keep the water vapor pressure near the skin low than dissipation by permeation through fabrics. Highly water absorbing fabrics raise the temperature of the air space near the skin. The temperature rise will further decrease relative humidity; however, the higher temperature may or may not desirable depending on environmental conditions.

In the literature, the emphasis has been placed on the correlation between sweating and discomfort associated with wearing fabrics. However, there is relatively less emphasis placed on the influence of changes in the surrounding conditions, that is, the influence of the seasons. Many comfort studies are conducted with a single layer of fabric at relatively warm and moderately humid conditions. Severe winter conditions, which mandate the use of layered fabrics, would necessitate totally different kinds of testing procedures. Consequently, it is necessary to distinguish the comfort factor and the survival factor, and to investigate these factors with different perspective.

Discussion

The evaporation process is also influenced by the liquid transport process. When liquid water cannot diffuse into the fabric, it can only evaporate at the lower surface of the fabric. As the liquid diffuses into the fabric due to capillary action, evaporation can take place throughout the fabric.

Moreover, the heat transfer process has significant impact on the evaporation process in cotton fabrics but not in polyester fabrics. The process of moisture sorption is largely affected by water vapor diffusion and liquid water diffusion, but not by heat transfer. When there is liquid diffusion in the fabric, the moisture sorption of fibers is mainly determined by the liquid transport process, because the fiber surfaces are covered by liquid water quickly. Meanwhile, the water content distributions in the fibers are not significantly related to temperature distributions.

All moisture transport processes, on the other hand, affect heat transfer significantly. Evaporation and moisture sorption have a direct impact on heat transfer, which in turn is influenced by water vapor diffusion and liquid diffusion. The temperature rise during the transient period is caused by the balance of heat released during fiber moisture sorption and the heat absorbed during the evaporation process.

As a whole, a dry fabric exhibits three stages of transport behavior in responding to external humidity transients. The first stage is dominated by two fast processes: water vapor diffusion and liquid water diffusion in the air filling the interfiber void spaces, which can reach new steady states within fractions of seconds [25]. During this period, water vapor diffuses into the fabric due to the concentration gradient across the two surfaces. Meanwhile, liquid water starts to flow out of the regions of higher liquid content to the dryer regions due to surface tension force.

The second stage features the moisture sorption of fibers, which is relatively slow and takes a few minutes to a few hours to complete. In this period, water sorption into the fibers takes place as the water vapor diffuses into the fabric, which increases the relative humidity at the surfaces of fibers [26]. After liquid water diffuses into the fabric, the surfaces of the fibers are saturated due to the film of water on them, which again will enhance the sorption process. During these two transient stages, heat transfer is coupled with the four different forms of liquid transfer due to the heat released or absorbed during sorption/desorption and evaporation/condensation. Sorption/desorption and evaporation/condensation, in turn, are affected by the efficiency of the heat transfer. For instance, sorption and evaporation in thick cotton fabric take a longer time to reach steady states than in thin cotton fabrics.

Finally, the third stage is reached as a steady state, in which all four forms of moisture transport and the heat transfer process become steady, and the coupling effects among them become less significant. The distributions of temperature, water vapor concentration, fiber water content, and liquid volume fraction and evaporation rate become invariant in time. With the evaporation of liquid water at the upper surface of the fabrics, liquid water is drawn from capillaries to the upper surface.

Conclusions

In summary, the physical mechanisms of moisture diffusion into fabrics vary with fabrics made from different degree of hygroscopicity. For highly hygroscopic fibers such as wool and cotton, the moisture diffusion can be described by two-stage process: a fast Fickian diffusion with a concentration-dependent diffusion coefficient and a slow diffusion with a time-dependent diffusion coefficient. For weakly hygroscopic fibers such as polypropylene fiber, the moisture-sorption process can be described by a single Fickian diffusion with a constant diffusion coefficient.

For the range of fabrics studied, we found no correlation whatsoever between fiber regain and the amount of liquid water a fabric absorbed or freely picked up. We have shown that the effective thermal conductivity of moist materials is substantially higher than that for dry materials. Fiber sorption properties mainly determine the evaporation process and therefore the heat and mass transfer by evaporation of water, diffusion of water vapor, and condensation. Fiber sorption properties influence the heat and mass transfer up to the point when the rate of increased conductivity with regain is low in the curves, and then all fiber types behave similarly. Generally heat transfer increases with increasing regain, but in this initial region the rise is most pronounced for the non-absorbent polypropylene. The fiber with the lowest effective conductivity over the region 0–200% regain is wool, an effect that is especially pronounced in the region of low regains from zero to saturation. Cotton fabric had the highest effective thermal conductivity for almost the whole region of regains tested.

The overall dissipation rate of water vapor depends on both the vapor transport rate and the vapor absorption by fibers, which are mutually interrelated. Water vapor transport is governed by the vapor pressure gradient that develops across a fabric layer. When a fabric is subjected to given environmental conditions, the actual water

vapor transport rate greatly differs depending on the nature of the fibers, even when other parameters are nearly identical, such as density, porosity, and thickness.

It is believed, first, that the constant rates observed cannot depend upon the existence of a single liquid-air interface maintained by capillary migration from the core to the surface of a fabric. Rather, the liquid-vapor interfaces throughout the entire wetted lattice of fibers are considered to maintain a constant reservoir of saturated vapor on one side of a boundary film of stagnant air which exists at the external surfaces of the fabrics. Diffusion of water vapor from the continuously near-saturated internal atmosphere of the fabric to the ambient environment proceeds at a constant rate consistent with the energy gradient across the film. This gradient is determined by the temperature differential between the fabric and the external atmosphere. The fabric temperature, in turn, is regulated by the ease with which the internal atmosphere can be maintained saturated (or nearly so) by the internal evaporation from liquid films on fibers into the fabric voids. During the constant-rate period a steady-state balance is achieved between internal evaporation rate, internal vapor pressure, and fabric temperature.

Second, the final falling-rate period is not felt to be initiated at the instant of total depletion of liquid water and the onset of fabric substance desorption. Actually, the fall in over-all rate starts while there are still significant amounts of liquid water present in interfiber capillaries, and while the internal atmosphere is still at a concentration of 99+% R.H. However, further evaporation of liquid water from trapped capillaries or from concave liquid surfaces into the fabric void atmosphere requires the fabric temperature to rise. In the shifting dynamic equilibrium, the increased difficulty of internal evaporation reduces the thermal gradient across the fabric surface boundary film. The internal vapor phase remains substantially saturated but only at the expense of a lower rate of energy transmission through the boundary film, and hence a reduced over-all evaporation rate.

Third, until the final falling-rate period sets in, internal evaporation occurs essentially from liquid surface. When the residual liquid, however, is eventually held mainly in trapped capillaries, or beneath concave liquid surfaces, saturated fiber surfaces may become sites for internal evaporation. Intrafiber diffusion of water from surfaces wetted by trapped or capillary water to non-wetted surfaces exposed to the void atmosphere can be expected. If this diffusion-evaporation can occur rapidly enough, the downward shift in over-all mass-energy transfer rates may be slowed up or even arrested at a new dynamic equilibrium level before all the liquid water is dissipated. Fabric temperature will not rise as rapidly since the internal atmosphere of the fabric can be maintained at near-saturation more easily in spite of reduced evaporation from liquid water surfaces. Such intrafiber diffusion is believed to account for a double inflection in the wool fabric drying rate curves just prior to final fiber desorption.

In the meantime, it should be noted that certain fiber characteristics promote rapid capillary migration during the wetting of a fabric. It might be supposed, in the light of classical drying theories, that such marked differences in capillarity as were observed would produce some detectable differences in drying behavior during the period when considerable amount of liquid water are present.

The drying mechanism is believed to depend upon vapor diffusion from the atmospheric 'well' within the fabric to its periphery, and thence through a boundary film, where mass-energy transfer occurs. Towards the end of drying, the water retained in interfiber capillaries is believed to be replenishing the atmospheric 'well' by evaporation from both concave liquid films and from saturated fiber surfaces. The total rate of dissipation of this capillary-retained water into the atmospheric 'well' may be greater for fibers of high moisture permeability. The fall in over-all evaporation rate begins at about 10–20% water content above 100% R.H. equilibrium moisture regain for all fabrics. This drop in rate is momentarily checked in the case of wool fabrics before the entire supply of liquid water has evaporated. For other fibers, the fall in rate occurs smoothly without any indication of arrestation.The volume uptake of water at saturation is approximately equal to the void volume of all of the wet fabrics, except in the case of wool. Fiber crimp and surface roughness are believed to impede capillary penetration into all pores of a wool yarn, and thus account for only about 75% void occupation. The rate of capillary migration is shown to be high for the smooth-surfaced fibers and low for wool, with the rate increasing with increasing non-wool content in a series of tropical suiting fabrics.

Notations

C_a — Water-vapor concentration in the air filling the inter-fiber void space ($kg\ m^{-3}$)
C_f — Water-vapor concentration in the fibers of the fabric ($kg\ m^{-3}$)
C_v — Volumetric heat capacity of the fabric ($kJ\ m^{-3}\ {}^{\circ}C^{-1}$)
D_a — Diffusion coefficient of water vapor in the air ($m^2\ s^{-1}$)
D_f — Diffusion coefficient of water vapor in the fibers of the fabric ($m^2\ s^{-1}$)
h_c — Convective-mass-transfer coefficient ($m\ s^{-1}$)
h_t — Convective-heat-transfer coefficient ($kJ\ m^{-2}\ {}^{\circ}C^{-1}$)
K — Thermal conductivity of the fabric ($kJ\ m^{-1}\ {}^{\circ}C^{-1}$)
L — Thickness of the fabric (m)
r — Radial co-ordinate of fiber (m)
t — Real time from change in conditions (s)
T_{ab} — Temperature of the ambient air (°C)
T — Temperature of the fabric (°C)
W_c — Water content of the fibers in the fabric, $W_c=C_f/\rho$
x — Distance (m)
λ — Heat of sorption or desorption of water vapor by the fibers ($kJ\ kg^{-1}$)
ρ — Density of the fibers ($kg\ m^{-3}$)
τ — Effective porosity of the fabric

Appendix -A (physical characteristics)

Wool

Diffusion coefficient of water vapor – 1st stage:

$$D_f = (1.04+68.20W_c-1342.59W_c^2)\ 10^{-14},\ t<540\ s \qquad (A1)$$

Diffusion coefficient of water vapor – 2nd stage:

$$D_f = 1.6164\{1 - \exp[-18.163\exp(-28.0W_c)]\} \cdot 10^{-14}, \, t \geq 540 \text{ s} \tag{A2}$$

Diffusion coefficient in the air:

$$D_a = 2.5e^{-5} \tag{A3}$$

Volumetric heat capacity of fabric:

$$C_p = 373.3 + 4661.0W_c + 4.221T \tag{A4}$$

Thermal conductivity of fabric:

$$K = (38.49 - 0.720W_c + 0.113W_c^2 - 0.002W_c^3)10^{-3} \tag{A5}$$

Heat of sorption:

$$\lambda = 1602.5\exp(-11.72W_c) + 2522.0 \tag{A6}$$

Cotton

Diffusion coefficient of water vapor – 1st stage:

$$D_f = (0.8481 + 50.6W_c - 1100W_c^2)10^{-14}, \, t < 540 \text{ s} \tag{A7}$$

Diffusion coefficient of water vapor – 2nd stage:

$$D_f = 2.5\{1 - \exp[-3.5385 \exp(-45W_c)]\}10^{-14}, \, t \geq 540 \text{ s} \tag{A8}$$

Diffusion coefficient in the air:

$$D_a = 2.5e^{-5} \tag{A9}$$

Volumetric heat capacity of fabric:

$$C_v = \frac{1663.0 + 4184.0W_c}{(1 + W_c)1610.9} \tag{A10}$$

Thermal conductivity of fabric:

$$K = (44.1 + 63.0W)10^{-3} \tag{A11}$$

Heat of sorption:

$$\lambda = 1030.9\exp(-22.39W_c) + 2522.0 \tag{A12}$$

Porous acrylic fiber

Diffusion coefficient of water vapor – 1st stage:

$$D_f = (1.12 - 410W_c - 8200W_c^2)10^{-13}, \, t < 540 \text{ s} \tag{A13}$$

Diffusion coefficient of water vapor – 2nd stage:

$$D_f = (6.23)10^{-13}, \ t \geq 540 \ \text{s} \qquad \text{(A14)}$$

Diffusion coefficient in the air:

$$D_a = 2.5e^{-5} \qquad \text{(A15)}$$

Volumetric heat capacity of fiber:

$$C_p = 1610.9 \qquad \text{(A16)}$$

Thermal conductivity of fiber:

$$K = 28.8 \cdot 10^{-3} \qquad \text{(A17)}$$

Heat of sorption:

$$\lambda = 2522 \ \text{kJ kg}^{-1} \qquad \text{(A18)}$$

Polypropylene fiber

Diffusion coefficient of water vapor – 1st stage:

$$D_f = 1.3e^{-13}, \ t < 540 \ \text{s} \qquad \text{(A19)}$$

Diffusion coefficient of water vapor – 2nd stage:

$$D_f = 1.3e^{-13}, \ t \geq 540 \ \text{s} \qquad \text{(A20)}$$

Diffusion coefficient in the air:

$$D_a = 2.5e^{-5} \qquad \text{(A21)}$$

Volumetric heat capacity of fiber:

$$C_v = 1715.0 \qquad \text{(A22)}$$

Thermal conductivity of fiber:

$$K = 51.80 \cdot 10^{-3} \qquad \text{(A23)}$$

Heat of sorption:

$$\lambda = 2522 \ \text{kJ kg}^{-1} \qquad \text{(A24)}$$

Appendix B

– the mass balance of water vapor:

$$\frac{\partial(C_a \varepsilon_a)}{\partial t} + \omega_1 \frac{\partial(C_f \varepsilon_f)}{\partial x} - \varepsilon_a h_{l \to g} S_v \ (C^*(T) - C_a) = \frac{1}{\tau_a} \frac{\partial}{\partial x}\left[D_a \frac{\partial(C_a \varepsilon_a)}{\partial x} \right] \quad \text{(B-1)}$$

– the energy balance:

$$c_v \frac{\partial T}{\partial t} - \omega_1 \lambda_v \frac{\partial (C_f \varepsilon_f)}{\partial t} + \varepsilon_a \lambda h_{1 \to g} S_v (C^*(T) - C_a) = \frac{\partial}{\partial x} \left[K_{mix} \frac{\partial T}{\partial x} \right] \qquad \text{(B-2)}$$

– the mass balance of liquid moisture:

$$\frac{\partial (\rho_1 \varepsilon_1)}{\partial t} + \omega_2 \frac{\partial (C_f \varepsilon_f)}{\partial t} + \varepsilon_a h_{1 \to g} S_v (C^*(T) - C_a) = \frac{1}{\tau_1} \frac{\partial}{\partial x} \left[D_1 \frac{\partial (\rho_1 \varepsilon_1)}{\partial x} \right] \qquad \text{(B-3)}$$

$$\varepsilon_1 + \varepsilon_a + \varepsilon_f = 1 \qquad \text{(B-4)}$$

Sorption and desorption of moisture by the fibers obey the fickian law:

$$\frac{\partial C_f (x,r,t)}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r D_f (x,t) \frac{\partial C_f (x,r,t)}{\partial t} \right) \qquad \text{(B-5)}$$

On the basis of the assumption of interconnected capillaries and pore distributions in a fabric, we can derive the diffusion coefficient of liquid water on the basis of Darcy's law and Hagen–Poiseuille's law as follows:

$$D_1 (\varepsilon_1) = \frac{\sigma \cos\phi \sin^2\beta d_c \varepsilon_1^{1/3}}{20 \eta \varepsilon^{1/3}} \qquad \text{(B-6)}$$

In order to generate a solution to the equations, we need to specify initial and boundary conditions in term of humidity, water content, liquid moisture content, and temperature, respectively. We assume that a textile porous material is initiallly equilibrated to a given atmosphere of temperature T_0 and vapor concentration C_0. The temperature and moisture content are uniform throughout the material at known values.

The boundaries of the material are then exposed to two different environment: one is an unsaturated vapor environment with temperature T_0 and vapor concentration C_0, and the other is a saturated liquid environment at temperature T_0^*.

At $x=0$, liquid moisture is exposed to saturated liquid moisture. We have $C_a(0,t)=C^*(T)$, $T(0,t)=T_0^*$, $\varepsilon_1(0,t)=$const.

At $x=L$, we have the following boundary conditions to take into account the convective nature of the boundary air layers:

$$D_a \frac{\partial (C_a \varepsilon_a)}{\partial x} \Big|_{x=L} = -K_L \qquad \text{(B-7)}$$

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