HEAT AND MASS TRANSFER IN TEXTILES:

Theory and Applications

PART ONE: THEORY

CONTENTS- PART ONE

Nomenclature

A	area
a,b,c	constants
c_p	constant pressure specific heat
C_A	moisture content of air in fabric pores
C_a	water-vapor concentration in the air filling the inter-fiber void space
C_e	moisture content of extent air
C_F	moisture content of fibers in a fabric
C_f	water-vapor concentration in the fibers of the fabric (kg m^{-3})
C_p	specific heat
D	diffusion coefficient
D_b	bound water conductivity
D_{eff}	effective diffusivity
E_d	activation energy of movement of bound water
h	enthalpy (J/kg)
h_e	heat transfer coefficient
h_m	mass transfer coefficient
Δh_v	enthalpy of vaporization (J/kg)
Δh_{vap}	latent heat of evaporation
J	species diffusion flux
J_L	free water flux
K	permeability
K_0	single phase permeability of porous material
K_r	relative permeability
k	thermal conductivity
k_{eff}	effective thermal conductivity
m	ratio of diffusion coefficients of air and water vapour
m'	mass source per unit volume
$\dot{m}$	evaporation rate, mass transfer rate

M	molecular weight
p	pressure
P_c	capillary pressure
P_s	saturation pressure
q	convective heat transfer rate
Q	entholpy of desorption from solid phase
r	radius
R	gas constant, Fiber regain
S	pore saturation
t	Time
T	Temperature
T_e	external air temperature
U	moisture content

Greek symbols

γ	pore volume density function
λ	latent heat of evaporation
λ_{eff}	effective thermal conductivity
μ	Viscosity
v	fluid velocity
ρ	Density
σ	surface tension
τ	tortuosity factor of capillary paths
ψ	relative humidity
ω	averaging volume
ε	volume fraction (m^3 of quantity $/m^3$)

Subscripts

0	Initial
c	capillary, critical
eq	Equilibrium
g	Gas
ir	Irreducible
ms	maximum sorptive
v	Vapour
w	Water
β	Liquid phase
γ	Gas phase

σ	Solid phase
bl	Bound liquid
ds	Dry solid
lv	Liquid-to-vapor
ls	Liquid-to-solid
sat	Saturation
sv	Solid-to-vapor
v	Vapor

Superscripts

g	intrinsic average over the gaseous phase
l	intrinsic average over the liquid phase
*	vapour saturated
-	average value

Chapter 1

Basic concepts of heat transfer through fabrics

1.1. Introduction

Philosophers tell us that man is an “unfinished being”. This is certainly true in the man (Homo sapiens) has had to devise a ‘second skin’ called clothing, a product made from a material called fabric. Properly engineered (designed) fabrics and clothing permit people to (a) live in most of the locations on planet earth from Sahara Desert to Polar region environmental conditions, (b) explore lake and ocean depths as well as the earth’s moon, and (c) travel in interplanetary space. Clothing also functions to protect people from hazardous substances in their environment. 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.

For millenniums, textile fabrics have been improved to assist in thermal and moisture regulation to and from human body through engineering of fibers, yarns and fabric construction, and developing fabric finishes. Fabric can thus be designed to (a) offer a specific rate of loss of insensible perspiration thus assisting the skin in conserving essential levels of body fluids or to cool the body, (b) offer specific rates of heat loss to keep the body in a cold environment at its critical internal temperature, (c) keep cold water from reaching the skin and causing the body to become too cold, (d) absorb solar ultraviolet radiation and toxic gases, (e) and completely block the transport of harmful fluids such as blood-containing pathogens through it. Now, new technologies are permitting the production of ‘intelligent’ textiles; textiles capable of sensing changes in environmental conditions or body functioning and responding to those changes. Fabrics may now contain a chemical that senses a change in environmental temperature and respond by releasing heat when the temperature decreases.

It should be noted that, 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. Meanwhile, fabrics today may have integrated sensors to detect heart arrhythmia and respond by alerting the wearer of this physiological event. Other fabrics may contain carrier molecules that absorb substances from the skin, detect changes in levels of those substances, and respond by releasing a therapeutic or cosmetic compound to the skin.

The wearing of a ‘second skin’ is, unfortunately, not without problems. Potential health risks are introduced. Most fabrics that people wear every day are flammable materials and thus can burn the skin if accidentally ignited. Fabrics that are meant to protect from hazardous substance may not permit the necessary amounts of heat and moisture transfer from the skin to the external environment under all wearing conditions. The amount of water retained in a fabric is traditionally expressed as some function of the fabric weight. This is valid, useful, and convenient method for many purposes. 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.

Heat and mass transfer in wet porous media are coupled in a complicated way. The structure of the solid matrix varies widely in shape. There is, in general, a distribution of void sizes, and the structures may also be locally irregular. Energy transport in such a medium occurs by conduction in all of the phases. Mass transport occurs within voids of the medium. In an unsaturated state these voids are partially filled with a liquid, whereas the rest of the voids contain some gas. It is a common misapprehension that nonhygroscopic 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.

For thermal analysis of wet fabrics, the liquid is water and the gas is air. Evaporation or condensation occurs at the interface between the water and air so that the air is mixed with water vapor. A flow of the mixture of air and vapor may be caused by external forces, for instance, by an imposed pressure difference. The vapor will also move relative to the gas by diffusion from regions where the partial pressure of the vapor is higher to those where it is lower.

Again, 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.

Meanwhile, Textile manufacturing involves a crucial energy-intensive drying stage at the end of the process to remove moisture left from dye setting. Determining drying characteristics for textiles, such as temperature levels, transition times, total drying times and evaporation rates, etc is vitally important so as to optimize the drying stage. In general, drying means to make free or relatively free from a liquid. We define it more narrowly as the vaporization and removal of water from textiles.

In this book, two types of heat source is considered:

- dryers (chapters 2-4) and
- skin (chapter 5).

1.2. Heat

When a wet fabric is subjected to thermal drying two processes occur simultaneously, namely:

a) Transfer of heat to raise the wet fabric temperature and to evaporate the moisture content.
b) Transfer of mass in the form of internal moisture to the surface of the fabric and its subsequent evaporation.

The rate at which drying is accomplished is governed by the rate at which these two processes proceed. Heat is a form of energy that can across the boundary of a system. Heat can, therefore, be defined as "the form of energy that is transferred between a system and its surroundings as a result of a temperature difference". There can only be a transfer of energy across the boundary in the form of heat if there is a temperature difference between the system and its surroundings. Conversely, if the system and surroundings are at the same temperature there is no heat transfer across the boundary.

Strictly speaking, the term *"heat"* is a name given to the particular form of energy crossing the boundary. However, heat is more usually referred to in thermodynamics through the term "heat transfer", which is consistent with the ability of heat to raise or lower the energy within a system.

There are three modes of heat transfer:

- convection
- conduction
- radiation

All three are different. Convection relies on movement of a fluid. Conduction relies on transfer of energy between molecules within a solid or fluid. Radiation is a form of electromagnetic energy transmission and is independent of any substance between the emitter and receiver of such energy. However, all three modes of heat transfer rely on a temperature difference for the transfer of energy to take place.

The greater the temperature difference the more rapidly will the heat be transferred. Conversely, the lower the temperature difference, the slower will be the rate at which heat is transferred. When discussing the modes of heat transfer it is the rate of heat transfer Q that defines the characteristics rather than the quantity of heat.

As it was mentioned earlier, there are three modes of heat transfer, convection, conduction and radiation. Although two, or even all three, modes of heat transfer may be combined in any particular thermodynamic situation, the three are quite different and will be introduced separately.

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.

Mass transfer in the drying of a wet fabric will depend on two mechanisms: movement of moisture within the fabric which will be a function of the internal physical nature of the solid and its moisture content; and the movement of water vapour from the material surface as a result of water vapour from the material surface as a result of external conditions of temperature, air humidity and flow, area of exposed surface and supernatant pressure.

1.3. Convection heat transfer

A very common method of removing water from textiles is convective drying. Concevtion is a mode of heat transfer that takes place as a result of motion within a fluid. If the fluid, starts at a constant temperature and the surface is suddenly increased in temperature to above that of the fluid, there will be convective heat transfer from the surface to the fluid as a result of the temperature difference. Under these conditions the temperature difference causing the heat transfer can be defined as:

$$\Delta T = \text{surface temperature-mean fluid temperature}$$

Using this definition of the temperature difference, the rate of heat transfer due to convection can be evaluated using Newton's law of cooling:

$$Q = h_c A \Delta T \tag{1.1}$$

where A is the heat transfer surface area and h_c is the coefficient of heat transfer from the surface to the fluid, referred to as the "convective heat transfer coefficient".

The units of the convective heat transfer coefficient can be determined from the units of other variables:

$$\begin{gathered} Q = h_c A \Delta T \\ W = (h_c) m^2 K \end{gathered} \tag{1.1a}$$

so the units of h_c are $W / m^2 K$.

The relationship given in equation (1.1) is also true for the situation where a surface is being heated due to the fluid having higher temperature than the surface. However, in this case the direction of heat transfer is from the fluid to the surface and the temperature difference will now be

$$\Delta T = \text{mean fluid temperature-surface temperature}$$

The relative temperatures of the surface and fluid determine the direction of heat transfer and the rate at which heat transfer take place.

As given in equation (1.1), the rate of heat transfer is not only determined by the temperature difference but also by the convective heat transfer coefficient h_c. This is not a constant but varies quite widely depending on the properties of the fluid and the behaviour of the flow. The value of h_c must depend on the thermal capacity of the fluid particle considered, i.e. mC_p for the particle. In other words the higher the density and C_p of the fluid the better the convective heat transfer.

Two common heat transfer fluids are air and water, due to their widespread availability. Water is approximately 800 times more dense than air and also has a higher value of C_p. If the argument given above is valid then water has a higher thermal capacity than air and should have a better convective heat transfer performance. This is borne out in practice because typical values of convective heat transfer coefficients are as follows:

Fluid	$h_c\left(W/m^2K\right)$
water	500-10000
air	5-100

The variation in the values reflects the variation in the behaviour of the flow, particularly the flow velocity, with the higher values of h_c resulting from higher flow velocities over the surface.

Polyester fiber-containing fabrics are mostly heat-set on a pin-stenter. Hot air is usually employed and is directed from above and below by jets onto the material. A controlled lengthwise and widthwise shrinkage is possible on this machine; the width of the frame and the overfeed can be adapted to the shrinkage to be expected. To ensure a good flow of hot air between the selvedge and the pin chain, and to avoid an impression of the pin-bed on the edge of the material, it is recommended that use be made of hook shaped pins or pins with a thickened base or the like. "Quenching" of material is a cooling zone by blowing on cold air.

1.4. Conduction heat transfer

If a fluid could be kept stationary there would be no convection taking place. However, it would still be possible to transfer heat by means of conduction. Conduction depends on the transfer of energy from one molecule to another within the heat transfer medium and , in this sense, thermal conduction is analogous to electrical conduction.

Conduction can occur within both solids and fluids. The rate of heat transfer depends on a physical property of the particular solid of fluid, termed its thermal conductivity k, and the temperature gradient across the medium. The thermal conductivity is defined as the measure of the rate of heat transfer across a unit width of material, for a unit cross-sectional area and for a unit difference in temperature.
From the definition of thermal conductivity k it can be shown that the rate of heat transfer is given by the relationship:

$$Q = \frac{kA\Delta T}{x} \tag{1.2}$$

where ΔT is the temperature difference $T_1 - T_2$, defined by the temperature on the either side of the fabric. The units of thermal conductivity can be determined from the units of the other variables:

$$\begin{aligned} Q &= kA\Delta T / x \\ W &= (k) m^2 K / m \end{aligned} \tag{1.3}$$

so the unit of k are $W / m^2 K / m$, expressed as W/mK.

1.5. Radiation heat transfer

The third mode of heat transfer, radiation, does not depend on any medium for its transmission. In fact, it takes place most freely when there is a perfect vacuum between the emitter and the receiver of such energy. This is proved daily by the transfer of energy from the sun to the earth across the intervening space.

Radiation is a form of electromagnetic energy transmission and takes place between all matters providing that it is at a temperature above absolute zero. Infra-red radiation form just part of the overall electromagnetic spectrum. Radiation is energy emitted by the electrons vibrating in the molecules at the surface of a body. The amount of energy that can be transferred depends on the absolute temperature of the body and the radiant properties of the surface.

A body that has a surface that will absorb all the radiant energy it receives is an ideal radiator, termed a "black body". Such a body will not only absorb radiation at a maximum level but will also emit radiation at a maximum level. However, in practice, bodies do not have the surface characteristics of a black body and will always absorb, or emit, radiant energy at a lower level than a black body.

It is possible to define how much of the radiant energy will be absorbed, or emitted, by a particular surface by the use of a correction factor, known as the "emissivity" and given the symbol ε. The emmisivity of a surface is the measure of the actual amount of radiant energy that can be absorbed, compared to a black body. Similarly, the emissivity defines the radiant energy emitted from a surface compared to a black body. A black body would , therefore, by definition, has an emissivity ε of 1. It should be noted that the value of emissivity is influenced more by the nature of texture of clothes, than its colour. The practice of wearing white clothes in preference to dark clothes in order to keep cool on a hot summer's day is not necessarily valid. The amount of radiant energy absorbed is more a function of the texture of the clothes rather than the colour.

Since World War II, there have been major developments in the use of microwaves for heating applications. After this time it was realized that microwaves had the potential to provide rapid, energy-efficient heating of materials. These main applications of microwave heating today include food processing, wood drying, plastic and rubber treating as well as curing and preheating of ceramics. Broadly speaking, microwave radiation is the term associated with any electromagnetic radiation in the microwave frequency range of 300 MHz-300 Ghz. Domestic and industrial microwave ovens generally operate at a frequency of 2.45 Ghz corresponding to a wavelength of 12.2 cm. However, not all materials can be heated rapidly by microwaves. Materials may be classified into three groups, *i.e.* conductors insulators and absorbers. Materials that absorb microwave radiation are called dielectrics, thus, microwave heating is also referred to as dielectric heating. Dielectrics have two important properties:

-They have very few charge carriers. When an external electric field is applied there is very little change carried through the material matrix.

- The molecules or atoms comprising the dielectric exhibit a dipole movement distance.

An example of this is the stereochemistry of covalent bonds in a water molecule, giving the water molecule a dipole movement. Water is the typical case of non-symmetric molecule. Dipoles may be a natural feature of the dielectric or they may be induced. Distortion of the electron cloud around non-polar molecules or atoms through the presence of an external electric field can induce a temporary dipole movement. This movement generates friction inside the dielectric and the energy is dissipated subsequently as heat.

The interaction of dielectric materials with electromagnetic radiation in the microwave range results in energy absorbance. The ability of a material to absorb energy while in a microwave cavity is related to the loss tangent of the material.

This depends on the relaxation times of the molecules in the material, which, in turn, depends on the nature of the functional groups and the volume of the molecule. Generally, the dielectric properties of a material are related to temperature, moisture content, density and material geometry.

An important characteristic of microwave heating is the phenomenon of “hot spot” formation, whereby regions of very high temperature form due to non-uniform heating. This thermal instability arises because of the non-linear dependence of the electromagnetic and thermal properties of material on temperature. The formation of standing waves within the microwave cavity results in some regions being exposed to higher energy than others. This result in an increased rate of heating in these higher energy areas due to the non-linear dependence. Cavity design is an important factor in the control, or the utilization of this “hot spots” phenomenon.

Microwave energy is extremely efficient in the selective heating of materials as no energy is wasted in “bulk heating” the sample. This is a clear advantage that microwave heating has over conventional methods. Microwave heating processes are currently undergoing investigation for application in a number of fields where the advantages of microwave energy may lead to significant savings in energy consumption, process time and environmental remediation.

Compared with conventional heating techniques, microwave heating has the following additional advantages:
-higher heating rates;
-no direct contact between the heating source and the heated material;
-selective heating may be achieved;
-greater control of the heating or drying process;
-reduced equipment size and waste.

1.6. Combined heat transfer coefficient

For most practical situations, heat transfer relies on two, or even all three modes occurring together. For such situations, it is inconvenient to analyze each mode separately. Therefore, it is useful to derive an overall heat transfer coefficient that will combine the effect of each mode within a general situation. The heat transfer in moist fabrics takes place through three modes, conduction, radiation, and the process of distillation. With a dry fabric, only conduction and radiation are present.

1.7. Porosity and pore size distribution in fabric

The amount of porosity*, i.e.*, the volume fraction of voids within the fabric, determines the capacity of a fabric to hold water; the greater the porosity, the more water the fabric can hold. Porosity is obtained by dividing the total volume of water extruded from fabric sample by the volume of the sample:

Porosity = volume of water/volume of fabric
= (volume of water per gram sample)(density of sample)

It should be noted that most of water is stored between the yarns rather than within them. In the other words, all the water can be accommodated by the pores within the yarns, and it seems likely that the water is chiefly located there. It should be noted that pores of different sizes are distributed within a fabric (Figure 1.1). By a porous medium we mean a material consisting a solid matrix with an interconnected void. The interconnectedness of the pores allows the flow of fluid through the fabric. In the simple situation ("single phase flow") the pores is saturated by a single fluid. In "two-phase flow" a liquid and a gas share the pore space. As it is shown clearly in Figure 1, in fabrics the distribution of pores with respect to shape and size is irregular. On the pore scale (the microscopic scale) the flow quantities (velocity, pressure, etc.) will clearly be irregular.

The usual way of driving the laws governing the macroscopic variables are to begin with standard equations obeyed by the fluid and to obtain the macroscopic equations by averaging over volumes or areas containing many pores.

In defining porosity we may assume that all the pore space is connected. If in fact we have to deal with a fabric in which some of the pore space is disconnected from the reminder, then we have to introduce an "effective porosity", defined as the ratio of the connected pore to total volume.

A further complication arises in forced convection in fabric which is a porous medium. There may be significant thermal dispersion, i.e., heat transfer due to hydrodynamic mixing of the fluid at the pore scale. In addition to the molecular diffusion of heat, there is mixing due to the nature of the fabric.

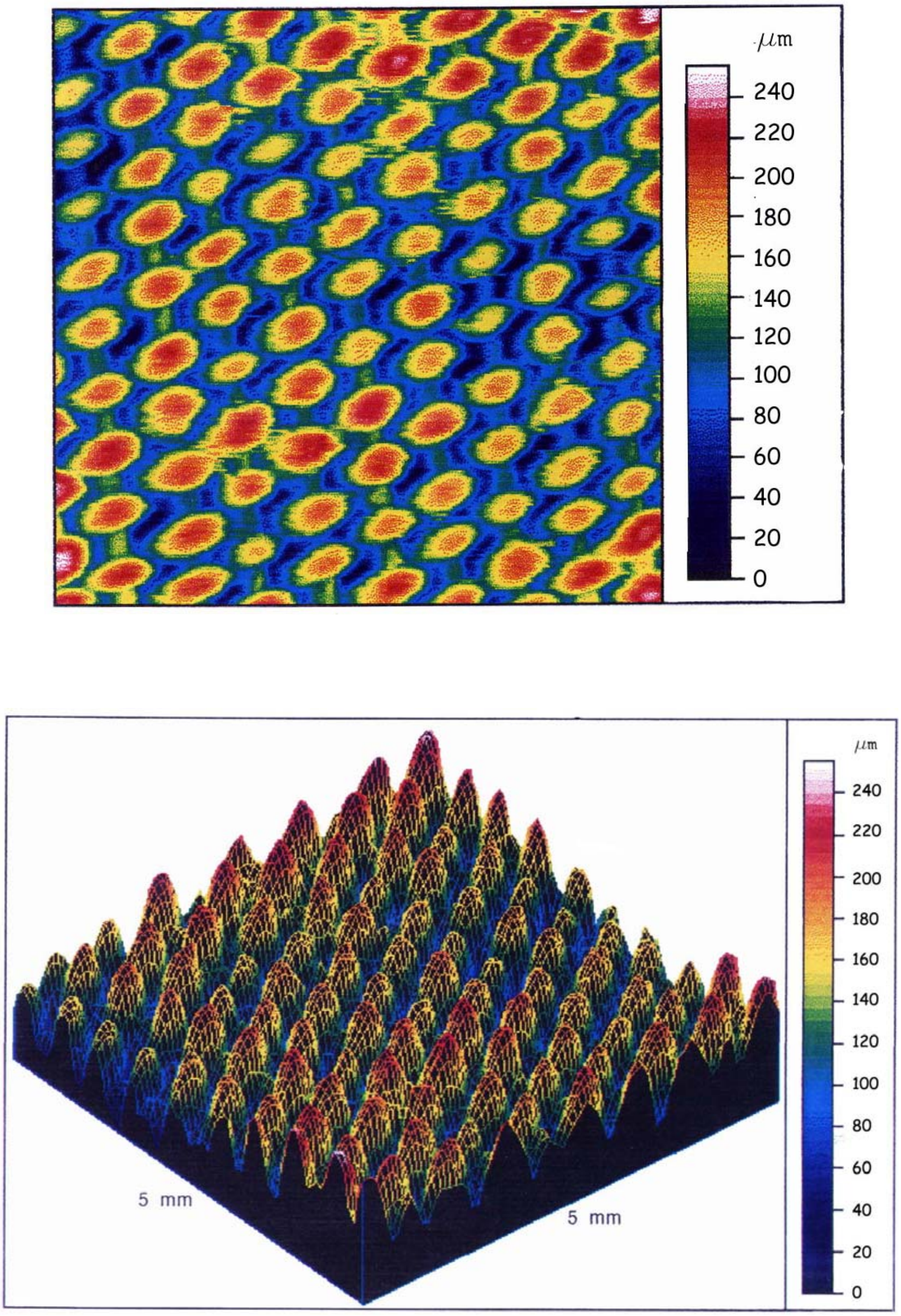

Figure 1.1. Pore size distribution within a fabric

1.8. Moisture permeation of clothing: A factor governing thermal equilibrium and comfort

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. Some materials will posses properties promoting rapid capillary and diffusion movement of moisture to the surface and the controlling factor will be the rate at which surface evaporation can be secured. In the initial stages of drying materials of high moisture content, also it is important to obtain the highest possible rate of surface evaporation. This surface evaporation is essentially the diffusion of vapour from the surface of the fabric to the surrounding atmosphere through a relatively stationary film of air in contact with its surface. This air film, in addition to presenting a resistance to the vapour flow, is itself a heat insulant. The thickness of this film rapidly decreases with increase in the velocity of the air in contact with it whilst never actually disappearing. The inner film of air in contact with the wet fabric remains saturated with vapour so long as the fabric surface has free moisture present.

These results in a vapor pressure gradient through the film from the wetted solid surface to the outer air and, with large air movements, the rate of moisture diffusion through the air film will be considerable. The rate of diffusion, and hence evaporation of the moisture will be directly proportional to the exposed area of the fabric, inversely proportional to the film thickness and directly proportional to the inner film surface and the partial pressure of the water vapour in the surrounding air. It is of importance to note at this point that, since the layer of air film in contact with the wetted fabric undergoing drying remains saturated at the temperature of the area of contact, the temperature of the fabric surface whilst still possessing free moisture will lie very close to wet-bulb temperature of the air.

1.9. Moisture in fibers

The amount of moisture that a fiber can take up varies markedly, as Table 1.1 shows. At low relative humidities, below 0.35, water is adsorbed monomolecularly by many natural fibers.. From thermodynamic reasoning, we expect the movement of water through a single fiber to occur at a rate that depends on the chemical potential gradient. Meanwhile, moisture has a profound effect on the physical properties of many fibers.

Hygroscopic fibers will swell as moisture is sorbed and shrink as it is driven off. Very wet fabrics lose the moisture trapped between the threads first, and only when the threads themselves dry out will shrinkage begin. The change in volume on shrinkage is normally assumed to be linear with moisture content. With hydrophilic materials moisture is found to reduce stiffness and increase creep, probably as a result of plasticization.

Variations in moisture content can enhance creep. To describe movement of moisture at equilibrium relative humidities below unity, the idea of sorptive diffusion can be applied. Only those molecules with kinetic energies greater than the activation energy of the moisture-fiber bonds can migrate from one site to another. The driving force for sorptive diffusion is considered to be the spreading pressure, which acts over molecular surfaces in two-dimensional geometry and is similar to the vapour pressure, which acts over three dimensional spaces (Keey, 1993).

Table 1.1. Smoothed values of dry-basis moisture content (kg/kg) for the adsorption of water vapour at 30˚C onto textile fibers (Keey, 1993).

Fiber	Mc=0.2	Mc=0.5	Mc=1.0
Cotton	0.0305	0.0565	0.23
Cotton, mercerized	0.042	0.0775	0.335
Nylon 6.6, drawn	0.0127	0.0287	0.05
Orlon (50˚C)	0.0031	0.0088	0.05
Cupro	0.0515	0.0935	0.36
Polyester	0.0014	0.0037	0.03
Viscose	0.034	0.062	0.25
Wool	0.062	0.09	0.38