

## Heat–moisture interactions and phase change in fibrous material

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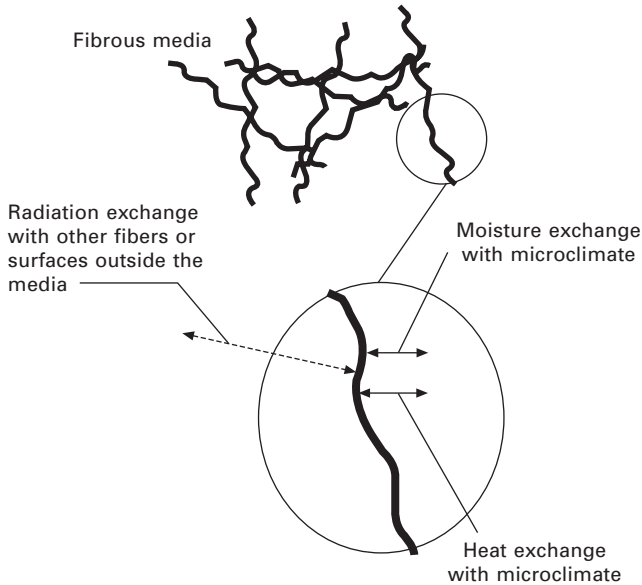
B. JONES, Kansas State University, USA  
K. GHALI, Beirut Arab University, Lebanon  
N. GHADDAR, American University of Beirut, Lebanon

This chapter focuses on phase-change phenomena associated with the adsorption of moisture into fibers, the condensation of moisture onto fibers, and the release or absorption of heat associated with this change of phase. First, a set of mathematical relationships is developed that describes these interactions. These relationships may be somewhat simplified compared to the relationships developed in other chapters so that it is easier to focus on the heat and moisture interactions. However, every effort is made to point out any limitations associated with this simplification. The equations are also developed so that they are based on variables, properties, and other parameters that are readily measured or readily obtained. These equations are then presented in a finite difference form that has been proven effective in modeling heat and moisture interactions in clothing systems.

### 12.1 Introduction

Each fiber in a fibrous media continually exchanges heat and moisture with the air in the microclimate immediately surrounding it, as shown in Fig. 12.1. In addition, there will be radiation heat exchanges with other fibers and other surfaces. These radiation exchanges are not addressed in the present chapter but may be important in certain situations, especially in fibrous media with a low fiber density or with high temperature gradients. The heat and moisture exchanges between the fiber and the surrounding environment are the focus of this chapter.

When there is a temperature difference between a fiber and the air in the surrounding microclimate, a net heat flow results; this exchange is generally well understood, at least in principle. Similarly, if there is difference between the water vapor pressure at the fiber surface and the water vapor pressure in the air in the surrounding microclimate, there will be a net exchange of moisture. For a given fibrous material, the vapor pressure at the surface depends upon the amount of moisture adsorbed onto that surface and the



12.1 Heat and moisture between a fiber and its microclimate.

temperature of the fiber. The amount of moisture on the fiber is not limited by adsorption, however. When the fiber becomes saturated with respect to the adsorption state, i.e. it has adsorbed as much moisture as it can, additional moisture may condense as a liquid onto the surface of the fiber. Depending on the nature of the fibrous media, large amounts of water condensate may be held on the surface of the fiber.

The liquid on the surface may be relatively immobile and trapped in place, or may be transported within the fibrous media by capillary pressure. This capillary pressure transport is not addressed in the present chapter but is addressed in other chapters. Generally, the moisture adsorbed onto a fiber is considered to be immobile and can only move by exchange with the air in the surrounding microclimate. While not well understood or documented, it is possible that the adsorbed moisture becomes mobile when the fiber is nearly saturated with adsorbed moisture. There could then be some transport along the fiber in this situation.

There is sometimes confusion with respect to the use of the term 'saturated' with regard to moisture in a fibrous media. When a fiber has all of the moisture adsorbed that it can hold in the adsorbed state, it is said to be saturated. Similarly, when a fibrous media is fully wetted with liquid, it is said to be saturated. In the present chapter, both forms may be used with the context making it clear what which form is intended.

## 12.2 Moisture regain and equilibrium relationships

It is customary to refer to the adsorbed moisture content of fibrous material as 'moisture regain'. The moisture regain is defined as the mass of moisture adsorbed by a fiber divided by the dry mass of the fiber. The dry mass of the fiber is the mass of fiber when it is in equilibrium with completely dry air, even though some fibers may contain a residual amount of moisture in this state. The mass of moisture adsorbed does not include this residual moisture in the dry state (Morton and Hearle, 1993). Mathematically, the regain ( $R$ ) is defined as

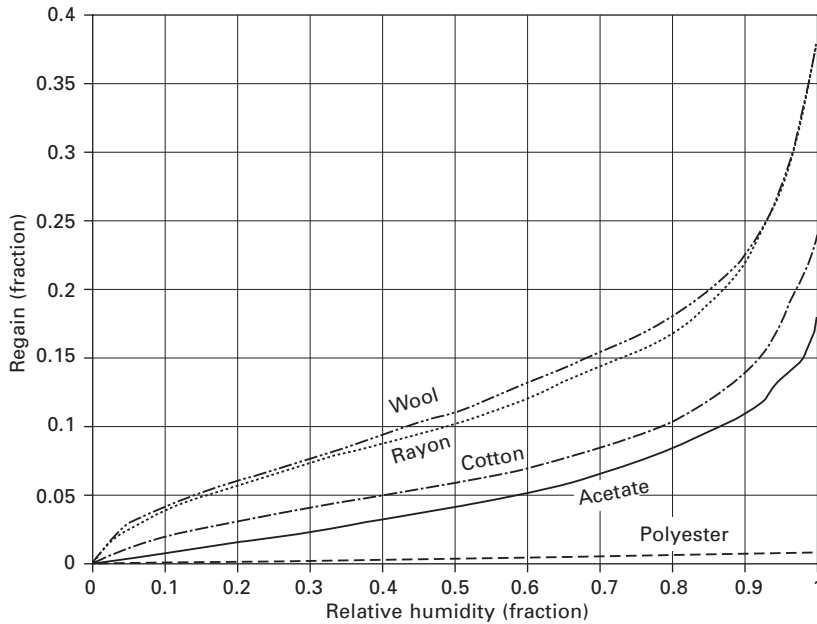
$$R = \frac{\text{Mass at given condition} - \text{Mass at dry condition}}{\text{Mass dry condition}}$$

It is customary to express regain as a percentage.

The equilibrium moisture regain of most fibrous material depends primarily on the relative humidity of the air in the ambient microclimate surrounding a fiber. That is, the equilibrium regain will be nearly the same at different temperatures if the ambient relative humidity is the same. Ambient temperature and atmospheric pressure can have a small impact independent of relative humidity. However, relative humidity is clearly the dominant variable for most terrestrial applications at common indoor and outdoor environmental temperatures. At more extreme conditions, such as might occur in manufacturing processes, the relationship between relative humidity and regain may not hold.

Figure 12.2 presents standardized relationships for moisture regain for a number of common fibers (Morton and Hearle, 1993). In general, natural fibers tend to have higher regains than manufactured fibers, with some of the latter fibers having nearly negligible regain. The regains shown in Fig. 12.2 are for raw fibers. A variety of surface finishes and other treatments are often applied to raw fibers to impart desired properties. While generally not applied for the purpose of changing moisture regain characteristics, some treatments can impact the moisture regain curve and care must be used in applying the equilibrium relationships in Fig. 12.2, especially for fibers that have very low regains in the raw state.

The curves in Fig. 12.2 stop at 100% relative humidity, as the regain is defined in terms of adsorbed moisture. Once the ambient microclimate relative humidity reaches 100%, liquid water may condense on the fiber. In terms of actual moisture present on a real fiber, the curves do not terminate at the values shown in Fig. 12.2. Rather, the curves actually become vertical and can extend to very large values, depending on the nature of the fibrous media. For individual fibers, it is difficult to define an upper limit. For fibers in a fibrous media, the upper limit is controlled by a number of factors including the porosity of the media and its structure.

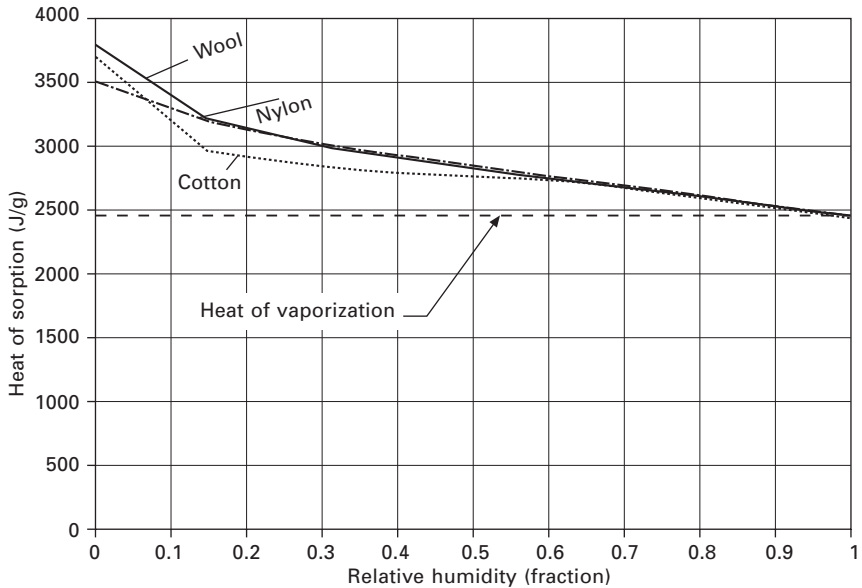


12.2 Equilibrium regain for typical fibers (based on data from Morton and Hearle, 1993).

### 12.3 Sorption and condensation

The heat of adsorption describes the amount of energy that is released when water vapor in the air is adsorbed onto the fiber surface. Similarly, this same amount of energy must be added when moisture is desorbed from the fiber. The heat of adsorption is not a constant, even for a given fiber, but depends on the environmental conditions under which the adsorption or desorption occurs. The primary factor affecting the heat of adsorption is the microclimate relative humidity and, for most applications at normal environmental temperatures and pressures, heat of adsorption can be treated as a function of humidity alone.

Figure 12.3 shows the heat of adsorption for several fibers. It is seen that, as the microclimate relative humidity becomes high, the heat of adsorption becomes equal to the heat of vaporization. The heat of sorption is often divided into two components: the heat of vaporization and the 'heat of wetting'. The heat of wetting is the added heat that is released above and beyond the heat release that would occur if the vapor simply condensed. Or viewed differently, it is the heat that is released if liquid water is added to a fiber. In Fig. 12.3, it is the distance between the heat of adsorption curve and the heat of vaporization line. It is often more convenient to present data in terms of the heat of wetting as it allows the large heat of vaporization, which is the same for all fibers, to be subtracted.



12.3 Heat of adsorption for typical fibers (based on data from Morton and Hearle, 1993).

As can be seen from Fig. 12.3, the heat of sorption for a given relative humidity does not vary greatly from fiber to fiber, especially when one considers the large heat of vaporization component that is common. Given the inaccuracies associated with many fibrous media heat and mass transport calculations, it is often adequate to simply use a common heat of sorption curve for all fibers.

## 12.4 Mass and heat transport processes

For steady-state conditions where any moisture on the fiber is immobile, there will be no net moisture exchange between the fiber and the air in the surrounding void space in the media. In this steady-state condition, there is no need to address heat–moisture interactions associated with moisture phase change. However, there are many situations where there is a net exchange of moisture between the fiber and the void space and it is necessary to develop mathematical descriptions of these processes. While relationships describing the heat and moisture transport between the fiber and the immediate void space can be developed, these processes are generally not the limiting factors in the transport phenomena. The high surface area associated with the fiber–microclimate interface results in minimal restriction to moisture and heat transport, and local equilibrium between the fiber and the surrounding microclimate is achieved over the time-scale of most applications for fibrous

media; or it is at least an acceptable approximation. The factors limiting the heat and moisture interchanges are the restrictions of heat and vapor transport in the bulk fibrous media.

A transient, one-dimensional moisture balance gives the following relationship at any location in the media:

$$\frac{\partial R}{\partial t} \rho = -\frac{\partial m}{\partial x} \quad [12.1]$$

where  $R$  is the regain (kg H<sub>2</sub>O per kg of dry fabric),  $\rho$  is the bulk density of the dry porous media (kg/m<sup>3</sup>),  $m$  is the vapor moisture flux through the media (kg/s m<sup>2</sup>),  $t$  is time (s), and  $x$  is distance along the dimension of interest (m).

This formulation ignores the water vapor in the air in the void space in the media. Normally, the amount of moisture stored in this phase is small compared with the regain. Additionally, it does not play an important role in the heat and moisture interactions and thus is ignored in the equations developed in this chapter.

The vapor moisture flux is proportional to the vapor partial pressure flux for most fibrous media and the relationship can be written as

$$m = -\phi \frac{\partial P}{\partial x} \quad [12.2]$$

where  $P$  is the vapor pressure (kPa), and  $\phi$  is the vapor permeability of the media (kg/s m kPa)

While it is customary to use concentration gradients rather than vapor pressure gradients as the driving force for vapor diffusion, the vapor pressure gradients are equally valid and are more convenient for this application (Fu, 1995). The vapor permeability,  $\phi$ , is an empirical parameter that describes the overall ability of vapor phase moisture to be transported through the media and is equal to the inverse of the vapor resistance per unit thickness (ASTM, 2005a).

Equations [12.1] and [12.2] combine to give a moisture balance in terms of partial pressure:

$$\frac{\partial R}{\partial t} \rho = \phi \frac{\partial^2 P}{\partial x^2} \quad [12.3]$$

The right-hand term expands directly to three dimensions, but the one-dimensional form is retained here for simplicity.

A one-dimension, transient energy balance can be written in similar fashion

$$\frac{\partial T}{\partial t} c \rho = -\frac{\partial q}{\partial x} - Q_s \frac{\partial m}{\partial x} \quad [12.4]$$

where  $T$  is the temperature ( $^{\circ}\text{C}$ ),  $c$  is the heat capacitance of the bulk fibrous media ( $\text{kJ/kg } ^{\circ}\text{C}$ ),  $q$  is the heat flux through the media ( $\text{kW/m}^2$ ), and  $Q_s$  is the heat of adsorption ( $\text{kJ/kg}$ ).

Several terms in the transient energy balance that are normally negligible have been omitted in Equation [12.4] to yield a relatively simple expression. Equation [12.4] should be acceptably accurate as long as there are no extreme temperature gradients in the porous media.

The heat flux through the fibrous media is proportional to the temperature gradient and the relationship can be written as

$$q = -k \frac{\partial T}{\partial x} \quad [12.5]$$

where  $k$  is the thermal conductivity of the fibrous media ( $\text{W/mK}$ ).

It should be noted that the thermal conductivity, above, is for the air–fiber combination that makes up the fibrous media and can be determined experimentally (ASTM, 2005b). Equations [12.5] and [12.2] combined with Equation [12.4] allow the energy balance to be expressed in terms of the temperature gradient and the vapor pressure gradient:

$$\frac{\partial T}{\partial t} c \rho = k \frac{\partial^2 T}{\partial x^2} + Q_s \phi \frac{\partial^2 P}{\partial x^2} \quad [12.6]$$

Equations [12.3] and [12.6] then describe the transient energy and mass balances at a location within a fibrous media. These equations also describe the transport of heat and vapor through the media. These equations are coupled in that there is a relationship between  $P$ ,  $T$ , and  $R$ . Using the approximation that fiber is in moisture and thermal equilibrium with the immediately surrounding void space, this relationship is defined by the curve for the particular fiber in question in Fig. 12.2. Note that relative humidity is a unique function of  $P$  and  $T$ . Similarly, there is also a relationship between  $Q_s$  and  $P$  and  $T$ , with that relationship being defined by the appropriate heat of adsorption curve such as is shown in Fig. 12.3.

In order to solve Equations [12.3] and [12.6], appropriate boundary conditions, empirical relationships for equilibrium regain, and empirical relationships for heat of adsorption are required. In addition, the values of the bulk density, heat capacitance, thermal conductivity, and vapor permeability must be known. The thermal conductivity and the vapor permeability generally must be determined experimentally for the fibrous media of interest. One way to measure these parameters is to use a sweating hotplate (ASTM, 2005a; ISO, 1995). The bulk density can be measured experimentally (ASTM, 2005b). Thermal capacitance of the media can be estimated with reasonable accuracy if the fiber content is known:

$$c = c_F + R c_L \quad [12.7]$$

where  $c_F$  is the thermal capacitance of the fiber (kJ/kg K), and  $c_L$  is the thermal capacitance of liquid water (kJ/kg K).

The air in the void space in the media is again ignored in Equation [12.7] and the equation is valid as long as the bulk density of the media is much greater than the density of air, which is true for nearly all applications. It should also be noted that the liquid term is based on the approximation that the thermal capacitance of a fiber increases with adsorbed moisture as if the adsorbed moisture is in the liquid state. This approximation is sufficiently accurate for all but the most precise calculations.

## 12.5 Modeling of coupled heat and moisture transport

Modeling the coupled heat flow requires appropriate boundary conditions to be established and Equations [12.3] and [12.6] to be solved. Fortunately, the equations are generally well bounded and well behaved, and the simplest of numerical methods may be used to solve the equations with acceptable accuracy. For modeling purposes, these equations can be written in finite difference form:

$$\Delta R_i \rho = \phi \frac{P(\phi_{i-1}, T_{i-1}) + P(\phi_{i+1}, T_{i+1}) - 2P(\phi_i, T_i)}{\Delta x^2} \Delta t \quad [12.8]$$

$$\Delta T_i c_i \rho = Q_s(\phi_i) \Delta R_i \rho + k \frac{T_{i-1} + T_{i+1} - 2T_i}{\Delta x^2} \Delta t \quad [12.9]$$

where  $\Delta t$  is the integration time step (s),  $\Delta x$  is the distance step in the  $x$ -direction (m),  $\phi_i$  is the local relative humidity (fraction),  $i$  refers to a specific discrete location in the  $x$  direction,  $P(\phi, T)$  is the equilibrium vapor pressure for the fibrous media at the local relative humidity and temperature (kPa), and  $Q_s(\phi)$  is the heat of sorption for the fibrous media at the local relative humidity, (kJ/kg).

The local relative humidity,  $\phi_i$  is determined from the adsorption equilibrium curve for the media, such as in Fig. 12.2, corresponding to the local regain. This relative humidity value is then used to determine the equilibrium pressure from

$$P(\phi, T) = \phi(R) P_s(T) \quad [12.10]$$

where  $\phi(R)$  is the relative humidity corresponding to the local regain  $R$  from the equilibrium relationship (fraction) and  $P_s(T)$  is the saturation pressure of water at local temperature  $T$  (kPa).

This same value of relative humidity is also used to determine the heat of sorption from the heat of sorption curve for the media, such as in Fig. 12.3.

Given initial conditions of temperature and regain,  $T$  and  $R$ , throughout



the media, appropriate boundary conditions, the equilibrium relationships such as in Fig. 12.2, and the heat of sorption information such as in Fig. 12.3, Equations [12.8]–[12.10] can be used to step through time and model the media response fully representing the interactions between heat and moisture. Time steps as small as 0.1 second or less may be required for clothing applications when boundary conditions change rapidly. However, the simplicity of the time-based solution puts little demand on computational capability, and transient solutions for complex systems can be readily solved. For thin fabric layers, it is often sufficient to use only a single increment in the  $x$ -direction. For thick fabric layers or fiber fillings, only a small number of increments in the  $x$ -direction is generally quite sufficient to obtain solutions of acceptable accuracy; generally, less than ten increments is adequate.

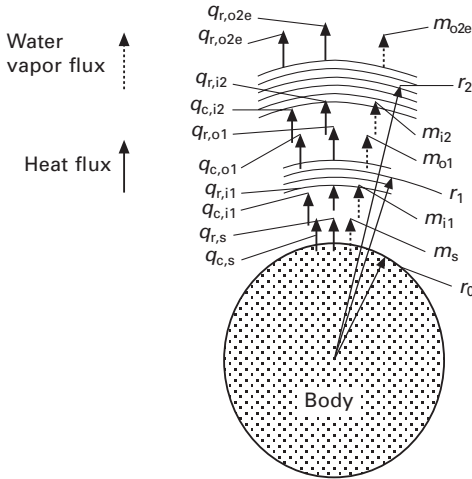
Equations [12.8] and [12.9] can be readily expanded to three dimensions. The single dimension form is presented here for simplicity. For many clothing applications, the radial direction from the body is usually the dominant direction for heat and moisture fluxes and local, one-dimensional representations are usually acceptable as long as the local variations in clothing and boundary conditions are addressed.

Equation [12.3] and [12.6] and, consequently, Equations [12.8] and [12.9] apply only when the moisture adsorbed or condensed onto the fiber is immobile. This limitation prevents these equations from being considered general representations of mass transport in fibrous media. Once the media contains sufficient moisture for this condensed moisture to become mobile and be transported in significant amounts by capillary pressure gradients, the air in the microclimate surrounding the fiber is saturated,  $\phi = 1$ , and the heat and moisture interaction phenomenon becomes one of condensation or evaporation.

Establishing the necessary boundary conditions is often the most difficult aspect of modeling heat and moisture interactions with fibrous media. Without proper boundary conditions, the equations described previously are of limited value. Each application is unique and it is not feasible to address all boundary condition situations that might be encountered with fibrous media. The following discussion addresses boundary conditions in a layered, cylindrical system which is typical of clothing applications and is depicted in Fig. 12.4.

The nomenclature for Fig. 12.4 follows:

$q_c$  is the conduction or convection heat transfer to/from a surface ( $\text{W}/\text{m}^2$ ),  
 $q_r$  is the radiation between two surfaces or between a surface and the surrounding environment ( $\text{W}/\text{m}^2$ ),  
 $m$  is the vapor flux to/from a surface ( $\text{kg}/\text{s m}^2$ ),  
 $r$  is the characteristic radius of the respective layer (m),  
the  $i$  subscript refers to the inner surface of a layer,  
the  $o$  subscript refers to the outer surface of a layer,  
the  $s$  subscript refers to the body surface, and  
the  $e$  subscript refers to the surrounding environment.



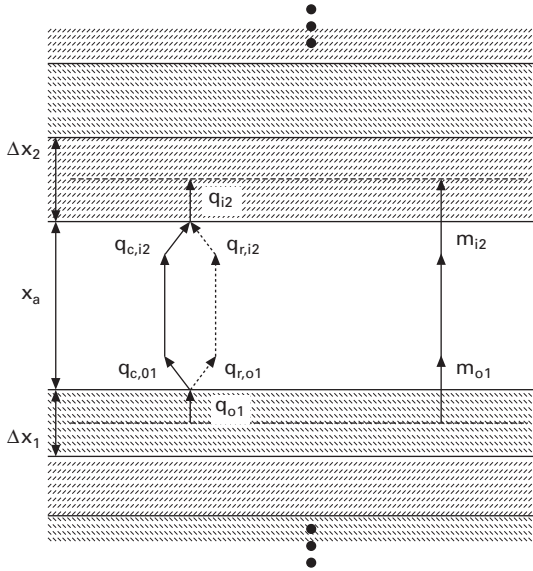
12.4 Depiction of boundary conditions for a two-layer radial system.

Each layer of porous media (e.g. fabric) is shown divided into a number of sub-layers that could correspond to  $\Delta x$  in the finite difference solution. The radius of each layer is characterized by a single value. This simplification is acceptable as long as the layer thickness is less than about one-fourth of the radius. The intervening air layers may present substantial resistance to heat and moisture transport and, consequently, are important in the overall modeling of the system. They do not normally contribute appreciably to the storage of heat or moisture and, thus, simplified modeling is usually acceptable even for transient applications. Figure 12.4 shows all of the boundary conditions for heat and mass transport in a two-layer system. These boundaries can be represented in several ways for finite difference solutions. Figure 12.5 shows one form that is compatible with Equations [12.8] and [12.9].

In the simplest representation, the air can be treated as a single lumped resistance to heat or water vapor transport. For this situation, the boundary conditions shown in Fig. 12.5 take the following form:

$$q_{o1} \frac{r_1}{r_0} = q_{i2} \frac{r_2}{r_0} = \frac{T_{1,n} - T_{2,1}}{\frac{r_0}{h_{c,1-2} \frac{r_1 + r_2}{2}} + \frac{r_0}{h_{r,1-2} \frac{r_1 + r_2}{2}} + \frac{\Delta x_1 r_0}{2k_1 r_1} + \frac{\Delta x_2 r_0}{2k_2 r_2}} \quad [12.11]$$

$$m_{o1} \frac{r_1}{r_0} = m_{i2} \frac{r_2}{r_0} = \frac{P_{1,n} - P_{2,1}}{\frac{r_0}{h_{m,1-2} \frac{r_1 + r_2}{2}} + \frac{\Delta x_1 r_0}{2\phi_1 r_1} + \frac{\Delta x_2 r_0}{2\phi_2 r_2}} \quad [12.12]$$



12.5 Boundary condition detail between layers 1 and 2.

where  $q_{o1}$  is the total heat flux from the outer surface of layer 1 ( $\text{W/m}^2$ ),  $q_{i2}$  is the total heat flux to the inner surface of layer 2 ( $\text{W/m}^2$ ),  $h_{c,1-2}$  is the overall heat conduction/convection heat transfer coefficient for the air layer ( $\text{K/W m}^2$ ),  $h_{r,1-2}$  is the linearized radiation heat transfer coefficient for the air layer ( $\text{K/W m}^2$ ) (see ASHRAE, 2005),  $m_{o1}$  is the vapor mass flux from the outer surface of layer 1 ( $\text{kg/s m}^2$ ),  $m_{i2}$  is the vapor mass flux from the inner surface of layer 2 ( $\text{kg/s m}^2$ ), and  $h_{m,1-2}$  is the mass transfer coefficient for the air layer ( $\text{kPa m}^2 \text{ s/kg}$ ).

Note that the  $r/r_0$  terms are included to account for the increasing area at increasing distances in the radial direction. Equations [12.8]–[12.10] plus Equations [12.11] and [12.12] for each air layer along with time-dependent values for temperature and vapor pressure for the body surface and the environment allow calculation of the time-dependent heat and vapor flows in the porous media system, fully accounting for the heat and moisture phase change interactions.

## 12.6 Consequences of interactions between heat and moisture

Equations [12.8] and [12.9] show a clear coupling between moisture and heat in porous media. In particular, Equation [12.9] shows that any increase in regain results in an increase in temperature and vice versa. The heat of sorption is large and, consequently, only small changes in regain can result

in large temperature changes. Since heat flows are driven by the temperature gradients, the adsorption and desorption of moisture by the media has a large impact on the heat fluxes through the media as well.

It has been known for many years that moisture sorption and desorption can impact body heat loss and affect perceptions of the thermal environment (Rodwell *et al.* 1965). This effect has been modeled for clothing systems using the above equations and has been measured experimentally as well (deDear *et al.*, 1989; Jones and Ogawa, 1992). The effect is so large that a person dressed in clothing made of highly adsorptive fibers such as wool or cotton can experience a short-term change in heat loss from the body of the order of  $50 \text{ W/m}^2$  when going from a dry environment (e.g. 25% rh) to a humid environment (e.g. 75% rh), even when the temperatures of both environments are identical. This effect is relatively short-lived and may only last for 5–10 minutes but is sufficient to elicit a strong change in thermal sensation and plays a large role in the perceived effect of humidity on comfort in many situations. A lesser, but still important, effect can persist for 30 minutes to an hour for some moderately heavy indoor clothing made of highly adsorptive fibers.

This interaction is particularly important for the drying of porous media. The transport of adsorbed moisture from a porous media is driven by the vapor pressure gradient. A negative vapor pressure gradient from the media to the surroundings will result in transport of water vapor from the media to the surroundings. The source of this water vapor is moisture adsorbed on the fibers. As the moisture is released and the regain decreases, there is a cooling effect on the media, as quantified by Equations [12.8] and [12.9]. Only a very small decrease in regain results in a large cooling effect. This small decrease in regain has minimal impact on the local equilibrium relative humidity (refer to Fig. 12.2). However, the large change in temperature has a big impact on the saturation pressure. The net result is a big decrease in local vapor pressure (refer to Equation [12.10]). The end result is that the cooling effect nearly eliminates the partial pressure gradient that is driving the moisture removal and, in the absence of a heat source, drying proceeds at a very low rate. The drying of a porous media is almost always limited by heat transfer and this effect is why thick media can take hours of even days to dry.

For fibers such as polypropylene or polyethylene that adsorb very little moisture, the interaction of heat and moisture is very minimal unless the conditions are such that condensation occurs. In the case where condensed moisture is present, but still relatively immobile, the equations presented in this chapter still apply and the strong interaction between heat and moisture will be present.

## 12.7 References

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