Numerical Simulation of Heat and Moisture Transfer of Wall with Insulation

Ming Wei*, Bo Wang, Shunbo Liu
School of Rocket Force University of Engineering, Xian, China

*Corresponding author e-mail: 2621113272@qq.com

Abstract. This paper improves the heat-moisture coupling transfer model with temperature and relative humidity as the driving force, and regards the effective thermal conductivity and vapor permeability of the wall material as a function of temperature and relative humidity. The latent heat generated by steam diffusion was introduced into the model and the model was numerically calculated using the finite element software COMSOL Multiphysics. The calculation results show that as the thickness of the insulation increases, the heat transfer and moisture transfer inside the wall slow down. When the temperature gradient or the water vapor concentration gradient on both sides of the wall increases, the heat transfer rate will also increase. But they will gradually stabilize. After reaching a steady state, there will still be moisture and temperature transfer due to the existence of the gradient.

1. Introduction
Most of the building materials can be regarded as porous media with different porosity. The thermal and moisture migration inside the building wall will affect the heat and moisture characteristics of the wall, building energy consumption, indoor air quality and construction and it’s service life. Since the thermal conductivity of water is about 25 times that of air and the thermal conductivity of ice is about 4 times that of liquid water, excessive moisture in the wall will not only significantly enhance the thermal conductivity of the wall, but also increase the number of microorganisms in the wall. As the wall deteriorates and the service life of the building is reduced, the outer wall of the modern building is covered with thermal insulation to reduce the heat and humidity sensitivity of the wall.

Many scholars have done lots of research on the mechanism of heat and moisture transfer in walls (porous media). Many mathematical models have been proposed around Fick's law and Darcy's law. Zhang Hualing et al[1], proposed a mathematical model for the coupled heat and moisture transfer of porous walls driven by temperature and relative humidity. The model not only considers the transfer of water vapor and liquid water in capillary pores, but diffuses water vapor. The coefficient and material thermal conductivity are considered constants that are not consistent with the actual. Due to the transfer of moisture, the effective thermal conductivity and effective diffusion coefficient of the material changes greatly. Literatures [2-6] proposed some new research methods for the measuring of moisture content in the wall and the determination of the heat transfer coefficient on the wall surface. The influence of moisture distribution of porous wall on indoor heat and humidity environment is analyzed,too. Literature [7-12] focus on various influencing factors of heat and moisture coupling transfer between porous media and free fluids, as well as the scope of application of various models. Based on the previous studies, this
paper adds the dependence of effective thermal conductivity and vapor permeability on temperature and humidity. Using cellulose batt as insulation material, the heat transfer and moisture transfer process of the wall is simulated. The relationship of the heat flux between the wall and the indoor air as a function of temperature, relative humidity and thickness of the insulation layer is obtained.

2. Establishment of heat and moisture coupling transfer model

2.1 Wall geometry.
In this paper, a double-layer wall is taken as an example. The thickness of the concrete layer on the indoor side is $L_1=40$ cm, and the outdoor side is the insulation layer. The geometric structure is shown in Figure 1.

Figure 1. Two-layer wall

Figure 2. Heat and moisture transfer process

2.2 Mathematical model

2.2.1 Physical mechanism of heat and moisture coupling transfer. The heat and moisture transfer in the wall are coupled to each other. The conduction of heat causes evaporation or condensation of water. Similarly, the moisture also causes changes by latent heat when the phase change occurs. As shown in Fig 2, due to the existence of water vapor concentration gradient and gas pressure gradient, the flow of water vapor occurs inside the porous medium; the capillary medium has a capillary pressure gradient due to the difference in water content; the capillary pressure gradient and the gas pressure gradient; The water inside the porous medium flows under the action of the capillary pressure gradient and the gas pressure gradient. The flow of water vapor and the flow of liquid water are also accompanied by the transfer of heat.

The theory of heat-moisture coupling transfer model established by researchers is based on the principle of energy conservation, mass conservation, Fourier's law, Fick's law and Darcy's law. According to these laws, many models have been established by the predecessors. Because they are different in the field, they are not universal. The results obtained by using these models will have errors in comparison with the experimental results.

2.2.2 Model Assumptions. As mentioned above, the heat and moisture transfer in the building wall is a complex coupling process. In order to eliminate some unnecessary factors and make the research content more specific, the following assumptions are made:

1) The wall is a continuous and uniform porous medium, and isotropic. The wall would not undergo compression deformation and some other deformation during heat and moisture transfer. So the porosity of the wall do not changes;

2) The effect of radiation and capillary hysteresis during moisture absorption and desorption on heat transfer is not considered;

3) The thermal properties of the wall matrix such as density and heat capacity do not change when temperature and moisture content change;
4) There is no dissolution of chemical substances during the process of moisture transfer; 
5) Since the thickness of the wall is smaller than height and weight of the wall, the model of the heat and moist transfer is simplified to the one-dimensional problem;

2.2.3 Governing equations. Based on the above assumptions, the heat transfer equation in the heat transfer coupling process of the wall is:

\[
\left(\rho C_p\right)_{\text{eff}} \frac{\partial T}{\partial t} + \nabla q = Q_0
\]  

(1)

\(Q_0\) is the source item; \(T\) is the thermodynamic temperature of the wall, \(K\); \(t\) is the time, \(s\); \((\rho C_p)_{\text{eff}}\) is the equivalent heat capacity associated with moisture content, \(J/K\);

\[q = k_{\text{eff}} \nabla T + L_v \delta_p \nabla (\phi p_{\text{sat}})
\]  

(2)

\(k_{\text{eff}}\) is the equivalent thermal conductivity associated with moisture content, \(W/(m \cdot K)\); \(L_v\) is the latent heat for evaporation, \(J/Kg\); \(\delta_p\) is vapor permeability coefficient of material, \(s\); \(\phi\) is relative humidity; \(p_{\text{sat}}\) is partial pressure of saturated vaporization, \(Pa\);

\[\delta_p = \frac{M_w}{R_w T_{\text{ref}}} \cdot 2.61 \times 10^{-6} \cdot \frac{1 - \frac{w}{146}}{0.503 \left(1 - \frac{w}{146}\right)^2 + 0.497}
\]  

(3)

\[(\rho C_p)_{\text{eff}} = \rho_s C_{p,s} + w C_{p,w}
\]  

(4)

\[k_{\text{eff}} = 1.5 + \frac{15.8}{1000} w
\]  

(5)

\(\rho_s\) is porous matrix density, \(Kg/m^3\); \(C_{p,s}, C_{p,w}\) is the heat capacity of the porous substrate and water, respectively, \(J/(Kg \cdot K)\); \(w\) is the water content in the wall, \(Kg/m^3\);

The governing equation for wet transfer is:

\[\zeta \frac{\partial \phi}{\partial t} + \nabla g = G_0
\]  

(6)

\[g = \zeta D_w \nabla \phi + \delta_p \nabla (\phi p_{\text{sat}})
\]  

(7)

\[\zeta = \frac{\partial w}{\partial \phi}
\]  

(8)

among them, \(G_0\) is mass source item; \(D_w\) is water diffusivity, represents liquid water flux, \(m^3/s\); \(\zeta\) is the slope of the wet balance curve of the porous material;

\[D_w = -K \frac{\partial s}{\partial w}
\]  

(9)

\(K\) is the permeability of liquid water, \(Kg/(m \cdot s \cdot Pa)\);
As the liquid water content in the wall changes, the vapor permeability and the effective thermal conductivity of the wall are also constantly changing. The effective permeability coefficient of the vapor in material 2 is:

$$\delta_p = 6 \times 10^{-11} \times e^{1.8 \phi}$$

(10)

The effective thermal conductivity for material 2 is:

$$k_{\text{eff}} = 0.0382 + \frac{0.0415 - 0.0382}{30} \times (T - 263.15) (T > 263.15)$$

(11)

2.2.4 Boundary and initial conditions. The uniqueness of the heat transfer and moisture transfer equation is determined by the initial conditions and boundary conditions. The air temperature inside the wall is set to 25 degrees Celsius and the relative humidity is 0.6. The air temperature and relative humidity outside the wall are set to a number of different values in order to study the relationship between heat transfer with ambient temperature and relative humidity. Heat and mass transfer between air and wall on the wall’s both sides through natural convection, so the heat transfer coefficient of the wall’s inside surface is set to be 0.34 W/(m·K) and the outside heat transfer coefficient is 0.05 W/(m·K). The mass transfer coefficient is determined by the formula 12 according to the heat-wet transfer analogy law:

$$h_m = \frac{D}{k} \left( \frac{k}{\rho C_p D} \right)^{1/3} h, n = 1/3$$

(12)

k is thermal conductivity; D is the vapor-air diffusion coefficient;

3. Model solving

3.1 Software Settings

The multi-physics simulation software COMSOL is used to solve the heat and moisture transfer governing equation. In order to study the relationship between the amount of heat transfer with the outdoor temperature and humidity and the thickness of the insulation layer, using the parametric scanning method, three research contents will be set. The temperature and humidity and the thickness of the insulation layer are set to several different values in turn, and the solver’s time step size of the software is set to 1 day. The heat transfer amount change within 30 days is continuously solved.

The three research contents are:

Study 1: The outside air of the wall is 303.15K, the relative humidity is 0.95, and the thickness of the insulation layer is 0.40cm, 0.41cm, 0.42cm, 0.43cm, 0.44cm, 0.45cm, respectively;

Study 2: The thickness of the insulation layer is 0.45 cm, the relative humidity outside the wall is 0.95, the temperature is changed from 398.15K to 312.15K, and the step length is 2K;

Study 3: The outside air of the wall is 303.15K, the thickness of the insulation layer is 0.45cm, and the relative humidity is increased from 0.6 to 0.9, and the step length is 0.1;

3.2 Solution results and analysis

When the external temperature and humidity remain unchanged, the heat flux, water vapor concentration and water content at the inner side of the wall are shown in Figure 3, Figure 4, and Figure 5:
It can be seen from the figure that as the thickness of the insulation layer increases, the rate of change of heat flux and water content decreases significantly. On the 30th day, the change of heat flux tends to be stable due to the rise of temperature and the transfer of outdoor water vapor. The transfer causes the water vapor concentration and the relative moisture content in the wall to rise continuously, and the phase change of the water changes from evaporation to condensation, so the water content also starts to rise after a certain period of time.

Figure 6, Figure 7, and Figure 8 show the changes in heat flux, water vapor concentration, and water storage at the interface of the wall when the thickness of the insulation layer is constant.

It can be seen from the figures that as the temperature increases, the amount of heat transfer between the wall and the air increases, and the greater the temperature difference between the two sides of the wall, the steeper the change in the amount of heat transfer. It can be seen from Fig. 7 and Fig. 8 that as the concentration of vapor increases, the amount of water stored in the wall decreases continuously. We can speculate that the evaporation of water causes the concentration of water vapor to rise. However, when the time is close to thirty days, the water storage capacity is not changing, and the heat flux and water vapor concentration are slightly increased, which also indicates the transfer of water vapor and heat between the wall and the air, but since the saturation temperature is not reached, there is no condensation of water vapor, so the water storage capacity is no longer increased.
The changes in heat flux, water vapor concentration, and water storage capacity inside the wall due to the difference in relative humidity are shown in Figures 9, 10 and 11:

The three graphs show that changes in heat flux, water vapor concentration, and water storage are similar to changes in temperature as the ambient humidity increases. Figure 10 shows that the water vapor concentration rises sharply at the beginning and then remains stable. Due to the concentration difference, the water vapor concentration rises again after the 25th day and begins to approach saturation, but the amount of condensation of water vapor is not very large because of the slow rise of temperature.
4. Conclusion
The heat and moisture transfer process between the wall and the air has a great influence on the comfort of the indoor air, the energy consumption of the ventilation and air conditioning system. Through the above simulation analysis, we can summarize as follows:

(1) When the outside temperature and humidity change, the changes in the internal temperature and moisture of the wall caused by the two are similar. The change is severe at the beginning, and the degree of change is continuously weakened.

(2) The speed of conduction of temperature in the wall is faster than the water conduction speed, because when the outside temperature is greater than the internal temperature, the moisture in the wall always evaporates firstly, so the liquid water decreases. When the temperature is basically no longer changed, moisture transfer causes the water vapor concentration to increase continuously, and then condensation occurs to increase the water storage amount.

(3) With the increase of the thickness of the insulation layer, the heat and moisture transfer intensity between the wall and the air are continuously reduced, but since the existence of the temperature gradient and the water vapor concentration gradient, there will still be an equilibrium state of moisture and heat transfer.

References
[1] Hualing Z, Liu C, Liu F, et al. Numerical Simulation of Heat and Moisture Transfer in Porous Wall. HVAC, 2006, 36(12): 9-13.
[2] Guojie C, Xiangwei L, Youming C, et al. Experimental Method for Coupled Heat and Moisture Transfer in Porous Building Envelope. Journal of University of South China, 2013(4): 90-95.
[3] Hualing Z, Chao L, Xiangyu F. Study on moisture transfer in porous building components and indoor environment. HVAC, 2006, 36(10): 29-34.
[4] Wei Z, Guangfa T, Youming C, et al. System identification of wall surface heat transfer coefficient. HVAC, 2002, 32(2): 89-91.
[5] Ninghua D, Youming C, Zaikang C, et al. Research on Identification Methods of Determining Heat Transfer Coefficient of Wall Surface. Journal of Hunan University(Natural Sciences Edition), 2001, 28(4): 83-87.
[6] Peng Mengxi, Huang Jingyuan, Ding Lixing, et al. Dynamic Computation of Coupled Heat Transfer Process of Rock Wall in Deeply Buried Building. BUILDING SCIENCE, 2007, 23(6): 37-40.
[7] Hussain M M, Dincer I. Two-dimensional heat and moisture transfer analysis of a cylindrical moist object subjected to drying: A finite-difference approach. International Journal of Heat & Mass Transfer, 2003, 46(21): 4033-4039.
[8] Chandramohan,V. P. Numerical Prediction and Analysis of Surface Transfer Coefficients on Moist Object During Heat and Mass Transfer Application. Heat Transfer Engineering, 2015, 37(1): 1-11.
[9] Yu S, Zhang X. The Analysis of Coupled Heat and Moisture Transfer in Building Envelope Based on Numerical Simulation. Advanced Materials Research, 2012, 450-451.
[10] Mohan V P C, Talukdar P. Three dimensional numerical modeling of simultaneous heat and moisture transfer in a moist object subjected to convective drying. International Journal of Heat & Mass Transfer, 2010, 53(21): 4638-4650.
[11] A.K. Datta. Porous media approaches to studying simultaneous heat and mass transfer in food processes. I: Problem formulations. Journal of Food Engineering, 2007,80:80-95.
[12] A.K. Datta. Porous media approaches to studying simultaneous heat and mass transfer in food processes. II: Property data and representative results. Journal of Food Engineering, 2007, 80:96-110.