

Numerical model of heat and moisture transfer in membrane material used for protective clothing against steam hazard

Yun Su^{1,2}, Rui Li², Guowen Song², Chunhui Xiang², Huanjiao Dong² and Jun Li¹
¹Donghua University, China
²Iowa State University, USA

Keywords: Waterproof and breathable fabric, thermal protective performance, hot water, steam

1. Introduction

Membrane material, while possessing resistance to the transmission of liquid water, allows the penetration of water vapor through fabric structure [1]. The waterproof and breathable membrane can be used to improve thermal protective performance and thermal comfort of clothing, which is determined by heat and moisture transfer in it. The membrane material due to the unique structure can change the modes of heat and moisture transfer in commonly used textile materials. However, there are few studies investigating the mechanism associated with heat and moisture transfer in membrane material. Thus, this study aimed to develop and validate a numerical model to simulate heat and moisture transfer in membrane material under steam hazard. The parameters in this study, such as fabric thickness, density, porosity and moisture content, was carried out to improve thermal protective performance in steam hazard.

2. Model formulation

Waterproof and breathable fabric consists of waterproof membrane and substrate material. Moisture can penetrate through absorptive membrane by absorption-diffusion-desorption process, depending on concentration difference. Moisture transfer in porous membrane is determined by pressure and concentration difference, since the porous structure allows the transmission of water vapor. For substrate fabric, there presents phase change and absorption/desorption of water in all phases. The moisture transfer in substrate fabric is driven by diffusion and Darcy flow [2]. The mass conservation equations of solid water, liquid water and water vapor are written as, respectively,

$$\frac{\partial(\varepsilon_b \rho_b)}{\partial t} = m_{vs} + m_{ls} \quad (1)$$

$$\frac{\partial(\varepsilon_l \rho_l)}{\partial t} = m_{vl} - m_{ls} \quad (2)$$

$$\frac{\partial(\varepsilon_g \rho_v)}{\partial t} = \frac{\partial}{\partial x} \left(D_{eff} \frac{\partial \rho_v}{\partial x} \right) - \frac{\partial(\varepsilon_g \rho_v)}{\partial x} V_g - m_{vs} - m_{vl} \quad (3)$$

Heat transfer in waterproof and breathable fabric is coupled with moisture transfer, such as phase change and absorption/desorption. Conductive and convective heat transfer is also the key mode of heat transfer in waterproof and breathable fabric. The energy conservation equations for all phases is given by,

$$(\rho c_p)_{eff} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k_{eff} \frac{\partial T}{\partial x} \right) - (\rho c_p)_g V_g \frac{\partial T}{\partial x} + \Delta h_{vap} (m_{vl} + m_{vs}) + \Delta h_{abs} (m_{vs} + m_{ls}) \quad (4)$$

3. Results and discussion

Figure 1 shows the comparison of skin temperature from experimental test and model prediction. Overall agreement can be observed from these comparisons of model predictions and experimental results. However, the temperature decrease predicted by the model during the cooling phase is relatively lower than the experimental data. It might be attributed to the fact that the ambient temperature subjected to fabric and skin system during the cooling phase is high, since the high-temperature objects surrounding fabric continue to transmit thermal energy to fabric and skin system. The developed model can be used to analyze the heat and moisture transfer behavior in waterproof and breathable fabric. Figure 2 presents the temperature histories in fabric and skin during the exposure and cooling phase in one experimental condition. For heat exposure, the steam temperature is 104.34 °C. The fabric temperature shows a rapid decrease with the increase of distance from the steam nozzle. The maximum skin temperature is lower than steam temperature. It indicates that the membrane material can provide high resistance to steam heat transfer. After the heat exposure, the skin temperature begins to decrease, depending on the ambient temperature and fabric properties.

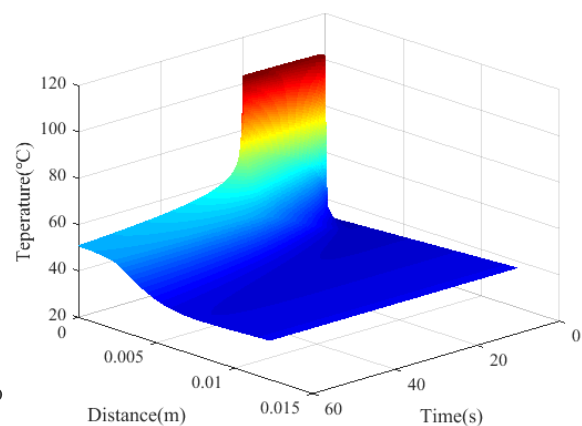
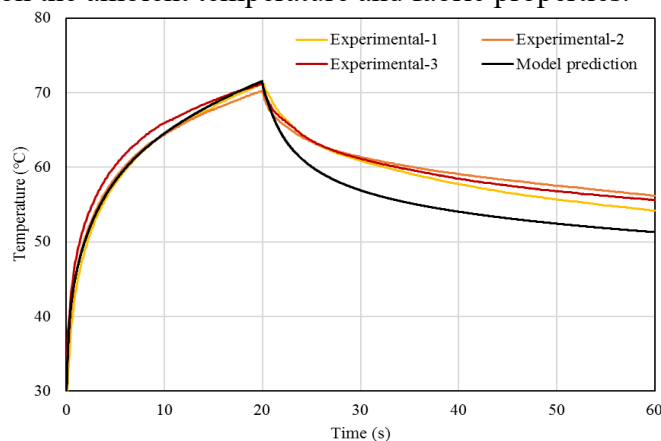


Fig. 1 Comparison of experimental and model predictive results Fig. 2 Temperature histories in fabric and skin

4. Conclusion

A numerical model of heat and moisture transport in membrane material under steam hazard was developed and agreed well with experimental results. This model was employed to explore the mechanism of heat and moisture transfer in membrane material. Additionally, the effect of membrane material properties and exposure conditions on thermal protective performance of protective clothing was analyzed based on the developed model.

References

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