Performance evaluation of a direct evaporative cooling system with hollow fiber-based heat exchanger

Weichao Yan, Xin Cui*, Xiaohu Yang, Liwen Jin*, Xiangzhao Meng

Institute of Building Environment and Sustainable Technology, School of Human Settlements and Civil Engineering, Xi’an Jiaotong University, Xi’an, Shaanxi 710049, China

*Email: cuixin@xjtu.edu.cn (Xin Cui); lwjin@xjtu.edu.cn (Liwen Jin)

Abstract. Direct evaporative cooling systems usually involve the process of spraying water, which may form the drift of water droplets. In addition, the use of circulating water can also lead to the growth of bacteria and molding on the surface of the packing material, affecting the indoor air quality. To address these issues, this paper intends to propose an evaporative cooling method incorporated with hollow fiber membranes. The selective permeation membrane technology allows the membrane module to isolate air from water, which selectively allows only water vapor to pass through, preventing the droplets from entraining bacteria into the air. A mathematical model has been developed to theoretically investigate the heat and moisture transfer between water and air in a hollow fiber membrane-based evaporative cooling module. The governing equations for the pre-cooling IEHX were established and then solved by employing the COMSOL Multiphysics platform. This study validated the model by comparing its outlet air dry bulb temperature and relative humidity against experimental data acquired from literature sources. The numerical model showed good agreement with the experimental findings with maximum discrepancy of 7.0%. The validated model was employed to investigate the influences of the inlet air velocity, inlet air dry-bulb temperature, inlet air relative humidity and geometric parameters on the cooling effect of the evaporative cooling module. Simulation results indicated that the outlet air temperature is greatly affected by the relative humidity of the inlet air under constant inlet air temperature conditions. A higher inlet air relative humidity will result in a higher outlet air dry bulb temperature. In addition, the cooling effectiveness was reduced for a higher inlet air velocity. The design of the hollow fiber membrane-based evaporative cooling module was optimized based on the simulation study.

1. Introduction

In the past few decades, the global demand for building energy consumption has increased dramatically, and the proportion of building air-conditioning energy consumption in total building energy consumption is very large, which has caused people's concerns about global warming and resource depletion [1]. Instead of the current widely-used mechanical vapor compression refrigeration system (MVC), the evaporative cooling, thermoelectric cooling, absorption and adsorption cooling systems attract widespread attention from researchers. Among them, the evaporative cooling system is particularly important in hot and dry climates since it consumes less primary energy, requires less initial investment, and has higher cooling efficiency [2]. Evaporative cooling systems are generally divided into two types, namely, the indirect evaporative cooling (IEC) and the direct evaporative...
cooling (DEC). DEC refers to a process in which the air and water get direct contact in a large area. During this process, the air temperature is reduced due to the evaporation of water while the moisture content of air is increased. Khalid et al. [3] pointed out that DEC system was most effective in terms of energy savings in hot and dry climate zones on account of the negligible pump power consumption compared to other cooling systems in the data center industry. K. Panchabikesan et al.[4] proposed a novel system combining evaporative cooling with phase change material (PCM) based free cooling, which indicates DEC contributes to the storage of useful energy in PCM even in summer, regardless of local ambient temperature.

DEC systems usually involve the process of spraying water, which may form the drift of water droplets. In addition, the use of circulating water can also lead to the growth of bacteria and molding on the surface of the packing material, affecting the indoor air quality. In order to solve these problems, this study intends to propose an evaporative cooling method incorporated with hollow fiber membranes. The selective permeation membrane technology allows the membrane module to isolate air from water, which selectively allows only water vapor to pass through, preventing the droplets from entraining bacteria into the air.

Chen et al. [5] introduced a membrane-based system integrating the liquid desiccant with the evaporative cooling. The proposed system was able to handle the latent load and simultaneously to remove the sensible load for the conditioned spaces. Maiya and Tiwari [6] conducted a theoretical analysis on a membrane-based dehumidifier. The numerical model was employed to study the influences of operating parameters in the dehumidifier with flat-plate arrangement. Zhang [7] studied the evaporative cooling system using hollow fiber membranes by experimental and numerical methods. The fractal model was used to establish the relationship between the Sherwood number obtained by experiments and the Reynolds number. Chen et al. [2] proposed a hollow fiber membrane-based DEC system using a spindle configuration. For the aim of avoiding the shielding effect of adjacent fibers on the airflow, the hollow fiber tubes in each bundle were fabricated into a spindle conformation. In their work, the outlet air temperature, dew-point efficiency, wet-bulb efficiency and cooling capacity under various inlet air temperatures were investigated through simulation and experiments.

The literature review indicates that few attempts have been made to conduct an in-depth analysis on a counter-flow hollow fiber-based module by evaluating the influence of key parameters on the cooling performance. The present work establishes a numerical model to theoretically investigate the heat and mass transfer process of the hollow fiber-based evaporative cooling module with a countercurrent arrangement. The design of this evaporative cooling module can be optimized based on the simulation results.

2. Numerical model

The hollow fiber membrane-based evaporative cooling module has a structure similar to that of a shell-and-tube heat exchanger in which the air flows across the tube and the circulating water flows inside the tube, and the water vapor is able to be transferred through the membrane material. Figure 1 indicates the schematic diagram of computational domain in the established numerical model.

![Figure 1. Explanatory diagram of computational domain in the numerical model.](image)

In this proposed module, assuming that the moist air is steady and incompressible, thus the general governing equations of the moist air can be given as follows[8]:

```latex
\text{Continuity equation:} \nabla \cdot \mathbf{v} = 0
\text{Momentum equation:} \nabla \cdot \left( \mathbf{v} \mathbf{v} \right) = -\nabla p + \mathbf{u} \cdot \nabla \mathbf{v} + \mathbf{f}
\text{Energy equation:} \nabla \cdot \left( \mathbf{v} \mathbf{T} \right) = -\nabla \cdot \mathbf{k} \nabla T + \mathbf{Q}
\text{Species equation:} \nabla \cdot \left( \mathbf{v} C \right) = \mathbf{R}
```

Where 
- \( \mathbf{v} \) is the velocity vector,
- \( p \) is the pressure,
- \( \mathbf{f} \) is the body force vector,
- \( \mathbf{k} \) is the thermal conductivity tensor,
- \( T \) is the temperature,
- \( \mathbf{Q} \) is the heat source vector,
- \( C \) is the concentration vector,
\[
\frac{\partial u_a}{\partial x} + \frac{\partial v_a}{\partial y} = 0
\]

(1)

\[
u_a \frac{\partial u_a}{\partial x} + v_a \frac{\partial u_a}{\partial y} = -\frac{1}{\rho_a} \frac{dp}{dx} + v_a \frac{\partial^2 u_a}{\partial y^2}
\]

(2)

\[
\frac{\partial}{\partial x} (u_a T_a) + \frac{\partial}{\partial y} (v_a T_a) = \alpha_a \frac{\partial^2 T_a}{\partial y^2}
\]

(3)

\[
u_a \frac{\partial c_a}{\partial x} + v_a \frac{\partial c_a}{\partial y} = D_a \frac{\partial^2 c_a}{\partial y^2}
\]

(4)

The basic heat and mass transfer equations:

\[
q = m_a C_{pa}(T_1 - T_2) + m_a[\omega_1(h_{v1} - h_{wb}) - \omega_2(h_{v2} - h_{wb})] \times 10^{-3}
\]

(5)

\[
m_e = m_a(\omega_2 - \omega_1) \times 10^{-3}
\]

(6)

where \(q\) is the total amount of heat transfer (W), \(m_a\) is the inlet air mass flow rate (kg/h), \(C_{pa}\) is the specific heat of moist air [kJ/(kg·°C)], \(T\) is the air temperature (°C), \(h\) is the specific enthalpy of saturated water vapour (kJ/kg), \(\omega\) is the humidity ratio of moist air (g moisture/kg dry air), and \(m_e\) is the mass flow rate of evaporated water (kg/h).

The cooling efficiency of the evaporative cooler can be evaluated by the expression of wet bulb effectiveness (WBE or \(\varepsilon_{wb}\)), which is defined as the value of reduction of temperature \((T_1 - T_2)\) in the process of air passing through the cooler divided by the largest reduction of temperature when the air is fully saturated \((T_1 - T_{wb})\):

\[
\varepsilon_{wb} = \frac{T_1 - T_2}{T_1 - T_{wb}}
\]

(7)

### 3. Results and discussion

#### 3.1. Model validation

The numerical model is validated with experimental data obtained from existing literature [9]. In this simulation, the main parameters were consistent with the experimental conditions. Figure 2 compares the simulated outlet air temperature and relative humidity with the experimental data. From the information in this figure, it is clear to conclude that the established numerical model is able to accurately predict the performance of evaporative cooling module, with maximum discrepancy of outlet air temperature and relative humidity being about 2.7% and 7.0%, respectively.

![Figure 2. Comparison between simulation results and experimental data.](image)

(a) Temperature of outlet air

(b) Relative humidity of outlet air

#### 3.2. Effect of inlet air temperature and relative humidity

Figure 3 shows the variation of the outlet air dry-bulb temperature under various simulated circumstances. It can be inferred that under the uniform inlet air temperature condition, the outlet air temperature is significantly affected by the relative humidity of the inlet air. The figure shows that the
lower the inlet air relative humidity, the lower the outlet air temperature. The reason is that the inlet air with a low relative humidity has a lower partial pressure of water vapor, which results in a large partial pressure difference of water vapor. Therefore, the evaporation of more water causes a larger drop in air temperature. It is worth mentioning that this figure also demonstrates that the outlet air temperature is approximately linear with the inlet air temperature while keeping the inlet air relative humidity constant. The outlet air temperature reduces by 8.2-9.2 °C while decreasing the inlet air temperature by 10 °C.

Figure 3. Effect of inlet air temperature and relative humidity.

3.3. Effect of inlet air velocity

Figure 4 displays the variations of temperature and WBE of outlet air with the change of inlet air velocities (1-3 m/s). The overall trend from the figure shows that the inlet air velocity is a critical factor influencing the outlet air temperature and WBE. As can be observed from Figure 4(a), a larger inlet air velocity will result in a higher outlet air dry bulb temperature, while keeping other simulation parameters constant. The reason is that the air and hollow fibers get less contact time by increasing the inlet air velocity. In addition, a similar variation trend can be found from Figure 4(b), the WBE of the hollow fiber membrane module decreases as the air velocity increases, which is also caused by a decrease in the contact time between the two streams. Therefore, in practical applications, on the basis of being able to ensure sufficient air volume, the inlet air velocity should not be set too high to achieve a higher cooling efficiency.

Figure 4. Effect of inlet air velocity on (a) outlet air temperature, and (b) wet-bulb effectiveness.
3.4. Effect of length of hollow fiber tube

The variation of the outlet air temperature with the length of hollow fiber tube (300-1800 mm) is shown in Figure 5. It can be observed from this figure that as the length of the hollow fiber tube increases, the outlet air temperature gradually decreases. It can be attributed to the fact that the contact area and time between the water and air flow increase by increasing the length of hollow fiber tube. The heat and mass transfer process is carried out more fully, thereby enhancing the cooling effect. It can be seen from the trend that the outlet air temperature does not vary much when the length of fiber tube increases to a certain value. Therefore, in the geometric design of the hollow fiber membrane module, a comprehensively analysis on the cooling effect and the economic factors is required to select an optimal hollow fiber tube length for different working conditions.

![Figure 5. Effect of length of hollow fiber tube.](image)

4. Conclusions

A numerical model has been established to theoretically study the cooling effect of the hollow fiber membrane-based evaporative cooling module with a countercurrent arrangement. The validated model was employed to study the influences of the temperature, relative humidity and velocity of the inlet air, and geometric parameters on the cooling performance. The simulation results indicated that the temperature of outlet air was greatly affected by the relative humidity of inlet air under constant inlet air temperature. In addition, the cooling efficiency of the proposed module was reduced for a higher inlet air velocity. To achieve a higher cooling effectiveness, the intake air velocity was suggested to be less than 1.5 m/s.

Acknowledgement

The research was supported by National Key R&D Program for the 13th-Five-Year Plan of China (2018YFF0300304 in 2018YFF0300300)

References

[1] Wang N, Phelan P E, Harris C, Langevin J, Nelson B and Sawyer K 2018 Past visions, current trends, and future context: A review of building energy, carbon, and sustainability Renewable and Sustainable Energy Reviews 82 976–93

[2] Chen X, Su Y, Aydin D, Ding Y, Zhang S, Reay D and Riffat S 2018 A novel evaporative cooling system with a polymer hollow fibre spindle Applied Thermal Engineering 132 665–75
[3] Khalid R, Wemhoff A P and Joshi Y 2017 Energy and Exergy Analysis of Modular Data Centers *IEEE Transactions on Components, Packaging and Manufacturing Technology* **7** 1440–52

[4] Panchabikesan K, Antony Aroul Raj V, Abaranji S, Vellaichamy P and Ramalingam V 2017 Effect of direct evaporative cooling during the charging process of phase change material based storage system for building free cooling application—A real time experimental investigation *Energy and Buildings* **152** 250–63

[5] Chen Z, Zhu J, Bai H, Yan Y and Zhang L 2017 Experimental study of a membrane-based dehumidification cooling system *Applied Thermal Engineering* **115** 1315–21

[6] Gurubalan A, Maiya M P and Tiwari S 2017 Performance characterization of membrane dehumidifier with desiccants in flat-plate arrangement *Energy and Buildings* **156** 151–62

[7] Zhang L Z 2011 Heat and mass transfer in a randomly packed hollow fiber membrane module: A fractal model approach *International Journal of Heat and Mass Transfer* **54** 2921–31

[8] Cui X, Chua K J, Islam M R and Ng K C 2015 Performance evaluation of an indirect pre-cooling evaporative heat exchanger operating in hot and humid climate *Energy Conversion and Management* **102** 140–50

[9] Chen X, Su Y, Aydin D, Zhang X, Ding Y, Reay D, Law R and Riffat S 2017 Experimental investigations of polymer hollow fibre integrated evaporative cooling system with the fibre bundles in a spindle shape *Energy and Buildings* **154** 166–74