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Experimental investigations of polymer hollow fibre integrated evaporative cooling system with the fibre bundles in a spindle shape

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ABSTRACT

Due to the advantages of light weight, corrosion resistant and low cost, hollow fibres have been studied as the substitute for metallic materials. A novel hollow fibre integrated evaporative cooling system, in which the hollow fibre module constitutes as the humidifier and the evaporative cooler, is proposed. This novel hollow fibre integrated evaporative cooling system will provide a comfortable indoor environment for hot and dry area. Moreover, the water vapour can permeate through the hollow fibre effectively, and the liquid water droplets will be prevented from mixing with the processed air. In order to avoid the flow channelling or shielding of adjacent fibres, the fibres inside each bundle were made into a spindle shape to allow maximum contact between the air stream and the fibre. The cooling performances of the proposed novel polymer hollow fibre integrated evaporative cooling system were experimentally investigated under the incoming air temperature in the range of 26 °C to 32 °C and relative humidity of 25%–35%. The effects of air velocities on the cooling effectiveness, heat and mass transfer coefficients, specific water consumption and pressure drop across the polymer hollow fibre module were analysed. Two sets of experimentally derived non-dimensional heat and mass transfer correlations were summarized, which could be favourable for the future design of polymer hollow fibre integrated evaporative cooling system.

1. Introduction

With the rapid development of urbanization and urban sprawl, the world metropolitan areas are becoming significantly hotter due to intensive human activities. Together with the consequences of global warming, the energy demand for air conditioning in the world has soared dramatically during the past few decades. A recent literature review by Frontczak and Wargocki [1] indicated that thermal comfort had been regarded as the most important indoor environmental factor compared with acoustic and visual comfort. According to [2], in Europe, 6% of office, commercial and industry buildings are air-conditioned, with a total volume of 20 million cubic meters.

In the global market, the conventionally-used air conditioning system is based upon the mechanical vapour compression cycle. The electricity required to power the vapour compression system is most commonly generated by the combustion of primary energy (coals and fossil fuels), which is associated with the emission of global warming gases (carbon dioxide, nitrogen oxide, sulphur oxides, etc). Moreover, conventional vapour compression systems currently use HFC refrigerants, which potentially lead to the global warming and depletion of the Earth's ozone layer.

With the advantage of reduced energy consumption and the utilization of environmental friendly fluids, evaporative cooling system has been studied extensively by researchers, with focus on pad incorporated evaporative cooling system [3–6], desiccant based evaporative cooling system [7,8], and dew point based evaporative cooling system [9–12]. Due to the large contact surface area, porous pad incorporated evaporative cooling systems have attracted more attentions. Wu et al. [13] presented a simplified mathematical model to describe the heat and moisture transfer between water and air in a direct evaporative cooler, with pad thickness of 125 mm and 260 mm, the cooling efficiency reached 58% and 90% respectively. Franco et al. [14] studied the influence of water and air flows on the performance of cellulose media. The

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Nomenclature

A	Heat transfer area (m^2)
c_p	Specific heat (J/kg K)
d	fibre diameter (m)
h	Enthalpy (kJ/kg)
k	Thermal conductivity (W/mK)
L	Length of hollow fibre bundle (m)
m	Mass flow rate (kg/s)
N	Number of fibres inside the heat exchanger
NTU	Number of heat transfer unit
Nu	Nusselt number
ΔP	Pressure drop (Pa)
Pr	Prandtl number
q	Heat transfer rate (W)
Re	Reynolds number
Sc	Schmidt number
T	Temperature (°C)
U	Overall heat transfer coefficient (W/m^2K)
v	Air velocity (m/s)

Greek Letters/Subscripts

a	Air
e	Evaporated water
ε	Cooling effectiveness
i	Inside
λ	Packing fraction of a PHFHE
H	Heat transfer
M	Mass transfer
ρ	Density of the fluid (kg/m^3)
o	Outside
s	Surface
μ	Dynamic viscosity of the fluid (kg/ms)
ω	Absolute humidity (kg/kg)
w	Water
wb	Wet bulb
v1	Saturated water vapour at the entrance of the hollow fibre manifold
v2	Saturated water vapour at the exit of the hollow fibre manifold
v	Incoming air velocity (m/s)

results showed that with a thickness of 85 mm, a plastic grid pad could offer a cooling efficiency of 65% at wind speed of 1.5 m/s. However, since water is directly in contact with the incoming air in the closed system, there is the potential for microbial growth due to the supply of stagnant water. This will provide an opportunity for the spread of liquid phase-born bacterial diseases for occupants [15].

In order to solve this problem, a hollow fibre integrated evaporative cooling system has been proposed. Detailed review on the polymer fiber heat exchanger and its application were summarized in the review paper by X. Chen et al. [16] and Huang et al. [17]. Compared with porous pad media, hollow fibre materials provide several advantages as follows: 1) allow selective permeation of moisture: with pore sizes less than 0.1 μm, hollow fibre material will allow the water vapour transfer but eliminate the bacteria and fungi penetration [18]; 2) provide large surface area per unit volume [19], which is favourable for enhanced heat and mass transfer. According to Chen et al. [20], the overall heat transfer coefficients could reach 1675 W/m^2K with a fibre diameter of 550 μm. Kachhwaha and Preahhakar [21] analysed heat and mass transfer performance for a direct evaporative cooler using a thin plastic plate. The experimental testing results indicated that the outlet air temperatures were between 21 °C and 23 °C, at the inlet dry bulb temperature of 24.8–28.4 °C, the air humidity ratio of 2.3–5.8 g/kg and air mass flow rate of 0.13, 0.2, 0.3 and 0.4 g/s. Zhang [22] proposed the theoretical investigations on a rectangular cross-flow hollow fibre membrane module for air humidification. With 2600 fibres (fibre outside diameter 1.5 mm) inside the module, the outlet air temperature could reach 21.5 °C when the inlet dry bulb temperature was 30 °C. Another analytical solution to heat and mass transfer in hollow fiber membrane contactors for liquid desiccant air dehumidification was proposed by Zhang [23] using effectiveness-NTU method. The hollow fiber contactor was made into a shell and tube shape and about 200 fibers with outside diameter of 1.5 mm were inserted into the contactor. Johnson et al. [15] studied the heat and mass transfer of a hollow fibre membrane evaporative cooling system. With a different range of fibre bundles (9, 19, 29 fibre bundles), the heat transfer area was in the range of 0.35 m^2–1.13 m^2, and around 0.4 °C temperature drop could be observed from the experiments. The above publications are mainly concentrated on the theoretical analysis on the polymer hollow fibre integrated evaporative cooling system. The available experimental results were limited to the variation of outlet air temperatures with respect to different air flow rates. In addition, as stated by Johnson et al. [15], due to the shielding from adjacent fibres, the heat and mass transfer performance will decrease when using a higher number of fibres inside one module. Furthermore, inserting a large numbers of fibre into one module will lead to the uniform packing of the fibre inside the module. This will lead to the shell side flow channelling or mal-distribution, which is consequently associated with reduced heat and mass transfer performance for evaporative cooling system.

This paper presents a novel polymer hollow fibre integrated evaporative cooling system, with the incoming air temperature in the range of 26 °C to 32 °C and relative humidity of 25%–35%. Instead of previously reported cross flow configurations [13,15,22], five fibre bundles (each contains 100 fibres) with the distance of 5 cm were placed normal to the air stream, with detailed configuration shown in Fig. 1. In order to avoid the flow channelling or shielding of adjacent fibres, the fibres inside each bundle were made into a spindle shape to allow maximum contact between the air stream and the fibre. The cooling performances of the proposed novel polymer hollow fibre integrated evaporative cooling system were experimentally investigated. The variations of saturation effectiveness and NTU were studied by varying the incoming air velocity from 0.1 m/s to 4.5 m/s. The effects of air velocities on the cooling effectiveness, heat and mass transfer coefficients, specific water consumption and pressure drop across the polymer hollow fibre module were analysed. Two sets of experimentally derived non-dimensional heat and mass transfer correlations were summarized and compared with the results obtained from the literature. These sets heat and mass transfer correlations could be favourable for the future design of polymer hollow fibre integrated evaporative cooling system.

2. Theory

Considering the polymer hollow fibre material as a porous medium through which flows of air and water pass, the following expressions [5]. were used to characterize their functioning based on heat and mass balance between the air flow and the porous fibre medium. The schematic diagram of the system is shown in Fig. 1.

The basic heat and mass transfer equation:

$$q = m_a C_{pa} (T_1 - T_2) + m_a [\omega_1 (h_{v1} - h_{wb}) - \omega_2 (h_{v2} - h_{wb})] \quad (1)$$

$$m_e = m_a(\omega_2 - \omega_1) \quad (2)$$

Where q is the flow of transferred heat (W);