



Research Paper

A novel evaporative cooling system with a polymer hollow fibre spindle

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HIGHLIGHTS

- A novel micro porous hollow fibre module is utilized as the humidifier in an evaporative cooling system.
- The fibres were made into a novel spindle shape in order to allow maximum contact between the air and water.
- The working performance with respect to various incoming air dry bulb temperature were experimentally studied.
- The hollow fiber module proves to offer superior heat and mass transfer performance.
- Experimentally derived heat and mass transfer correlations were summarized and compared with results from literature.

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ABSTRACT

A polymer hollow fibre evaporative cooling system with a novel configuration of fibre bundle is proposed. With the aim to avoid the flow channelling or shielding of adjacent fibres the fibres inside each bundle were made into a spindle shape to maximize contact between the air stream and the fibres. For the porous wall of hollow fibre, the vapour of evaporated water can permeate through it effectively, while the liquid water droplets can be prevented from mixing with the processed air. For various dry bulb temperatures (27 °C, 30 °C, 33 °C, 36 °C and 39 °C) and relative humidity (23%, 32% and 40%) of the inlet air, the cooling performances of the proposed novel evaporative cooling system were experimentally investigated. The variations of outlet air dry bulb temperature, wet bulb effectiveness, dew point effectiveness and cooling capacity with respect to different incoming air dry bulb temperature were studied. The effects of various incoming air Reynolds number on the heat and mass transfer coefficients, heat flux and mass flux across the polymer hollow fibre module were analysed. Experimentally derived non-dimensional heat and mass transfer correlations were compared with other correlations from literature. Due to the proposed spindle shape of hollow fibre bundle, the shielding between adjacent fibres could be mitigated greatly, therefore the heat and mass transfer performance of the proposed system demonstrated significant improvement compared with other designs reported in literature.

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1. Introduction

Global energy demand is soaring during past few decades due to the rapid worldwide economy development and urban sprawl. According to the research report produced by International Institute of Refrigeration, air conditioning system accounts for 45% of the total energy consumption for domestic and commercial build-

ings [1]. Overall, air-conditioning system takes up approximately 15% of the total energy consumption around the world [1]. In the Middle East, where the climatic condition is dry and humid, air conditioning system consumes as high as 70% of energy required for buildings and around 30% of the total energy [2]. With the impact of global warming, the demands of effective air-conditioning system which consumes less energy and provide higher cooling performance is massive.

The current widely-used vapour compression system plays dominant role in the market. However, vapour compression system has the disadvantages of intensive energy consumption and low performance in hot and humid climate. Moreover, the possible

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Nomenclature

A	heat transfer area (m^2)
C_p	specific heat (kJ/kg K)
d	fiber diameter (m)
h	heat transfer coefficient ($\text{W/m}^2 \text{K}$)
h_v	enthalpy of saturated water vapour (kJ/kg)
L	characteristic length of hollow fibre bundle (m)
m	mass flow rate (kg/s)
n	number of fibres inside the heat exchanger
N	mass flux ($\text{mg/m}^2 \text{s}$)
Nu	Nusselt number
Pr	Prandtl number
q	heat flux (W/m^2)
Re	Reynolds number
Sh	Sherwood number
Sc	Schmidt number
T	temperature ($^\circ\text{C}$)
U	overall heat transfer coefficient ($\text{W/m}^2\text{K}$)
V	volumetric flow rate of the incoming air, m^3/h ;
Q	sensible cooling capacity or rate of heat transfer (W)

Greek letters/subscripts

a	air
dew	dew point
dry	dry bulb
e	evaporated water
ϕ	packing fraction of the module
ε	effectiveness
H	heat transfer
λ	thermal conductivity (W/mK)
M	mass transfer
ρ	density of the fluid (kg/m^3)
u	incoming air velocity, m/s
ν	kinematic viscosity of air (m^2/s)
ω	humidity ratio of the air (kg/kg)
wb	wet bulb

leakage of high GWP refrigerants will lead to the depletion of Ozone Layer, which further contributes to the global warming and other associated environmental and social changes. Hence, the development of more energy efficient and environmental benign cooling systems remains to be the research topics for scientific researches.

In the past few decades, evaporative cooling system arouses great attentions among the researchers due to the fact that it is more environmentally friendly (use of the water as working fluids), simple in structure configuration, and less consumption in primary energy. Direct evaporative cooling system works under the following principle: the incoming hot and humid air gets direct contact with the circulating water, causing the evaporation of the water and the air temperature will be reduced accordingly. Consequently, the evaporated water, in the form of vapour will be absorbed by the air, which leads to the humidity increase of the outlet air.

Recently, the research interests of this topic are focused 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 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 may 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. 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 [16]; (2) provide large surface area per unit volume [17], which is favourable for enhanced heat and mass transfer. Detailed descriptions about hollow fibre materials and their applications are summarized in the literature [18]. According to Chen et al. [19], the overall heat

transfer coefficients could reach 1675 $\text{W/m}^2\text{K}$ with a fibre diameter of 550 μm . Kachhwaha and Preahhakar [20] 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 $^\circ\text{C}$ and 23 $^\circ\text{C}$, at the inlet dry bulb temperature of 24.8–28.4 $^\circ\text{C}$, 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 [21] 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 $^\circ\text{C}$ when the inlet dry bulb temperature was 30 $^\circ\text{C}$. 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 0.35–1.13 m^2 , and around 0.4 $^\circ\text{C}$ 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 large number of fibres inside one module.

A summary of the recent experimental and modelling works on evaporative cooling system is presented in Table 1. Literature review indicates that the previous published papers were mainly concentrated on the theoretically modelling of evaporative cooling system. For the limited experimental investigations reported in the literature, the evaporative coolers were mainly made from porous paper materials. This paper presents a novel evaporative cooling system with a hollow fibre evaporative cooler. Instead of previously reported cross flow configurations [13,15,21], 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. 2. 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. As a subsequent work of previous research [22], this research work extends the previous experimental testing conditions to a wider range, with the incoming air temperature up to 39 $^\circ\text{C}$ and relative humidity up to 40%. The variations of outlet air dry bulb temperature, wet bulb effectiveness, dew point effectiveness and cooling

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