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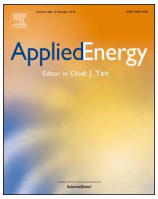

On the fundamental heat and mass transfer analysis of the counter-flow dew point evaporative cooler

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HIGHLIGHTS

- A counter-flow dew point evaporative cooler is developed and investigated.
- A mathematical model is derived to study the heat and mass transfer performance.
- The dimensionless product air temperature is investigated.
- The convective heat and mass transfer coefficients are measured and analyzed.
- The local and average Nusselt number and Sherwood number are investigated.

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ABSTRACT

The performance of the dew point evaporative cooling (DPEC) is dominated by its convective heat and mass transfer mechanism. Existing mathematical models are mainly developed for the thermodynamic analysis of DPEC under various operating and geometric conditions. The convective heat and mass transfer coefficients are estimated using the Nusselt number and Sherwood number at constant surface conditions. However, as the channel surface is subjected to a naturally-formed boundary condition, the cooler's actual heat and mass transfer performance remains unclear and has never been investigated. Therefore, we propose an experimental and numerical study, to examine at the fundamental level, the convective heat and mass transfer process of the DPEC. The temperature and humidity distributions of a counter-flow dew point evaporative cooler are measured under different test conditions. The magnitude of the convective heat and mass transfer coefficients are determined using the log mean temperature/humidity difference method. Concurrently, a 2-D mathematical model has been formulated to simulate the heat and mass transfer performance of the cooler. The model agrees well with the acquired experimental data with a maximum discrepancy of ± 7.0%. The product air temperature, convective heat and mass transfer coefficients and the Nusselt number and Sherwood number, are further examined under different conditions. Key findings emerged from this study reveal that Re_D, r, $\frac{H}{L}$, $\frac{\delta}{H}$ and π are the dominant factors related to the heat and mass transfer performance. The average convective heat and mass transfer coefficients are found to be 26.8–29.9 W/(m^2·K) and 0.025–0.027 m/s. The corresponding $\overline{Nu}_{D,d}$, $\overline{Nu}_{D,w}$ and $\overline{Sh}_{D,w}$ span 8.67–9.95, 8.68–9.21 and 8.17–8.67, respectively, under varying dimensionless numbers/groups.

1. Introduction

With the advent of the vapor compression cycle, the modern air conditioning system has been dominated by the mechanical vapor compression (MVC) chiller over the past century [1]. Although the best available efficiency of the MVC has improved from 0.9 kW/Rton in the 1970 s to 0.47 kW/Rton in the 2000 s, the chiller still accounts for about 50% of the total energy consumption in buildings [2,3]. In the past decade, no significant progress has been made towards the design of the MVC, and the energy efficiency of the MVC is approaching its limit. Thus, to achieve a further reduction in the energy consumption of air conditioning systems, it is vital to find potential substitutes for the mechanical chiller. Among the available technologies [4–7], evaporative cooling has a few salient features, including: (1) low capital and operational costs; (2) high energy efficiency (normal COP 10–20 or 0.18–0.35 kW/Rton); (3) easy installation and maintenance; and (4) no emission of harmful liquids/gases. As a result, direct and indirect evaporative cooling (IEC and DEC) are widely used in industrial and

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Nomenclature

A	area, m^2
c_p	specific heat at constant pressure, J/(kg·K)
D	diameter, m
D_{va}	diffusion coefficient, m^2/s
Fo	Fourier number
h	heat transfer coefficient, $W/(m^2{\cdot}K)$
h_{fg}	latent heat evaporation, J/kg
h_m	mass transfer coefficient, m/s
H	height, m
H_t	channel height, m
i	enthalpy, J/kg
k	thermal conductivity, W/(m·K)
L	channel length, m
Le	Lewis number
$\dot{m}$	mass flow rate, kg/s
n	mass transfer rate, kg/s
n''	mass flux, $kg/(m^2{\cdot}s)$
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
q	heat transfer rate, W
q''	heat flux, $W/(m^2{\cdot}s)$
r	working air ratio
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
T	temperature, °C
u	velocity, m/s
$\dot{V}$	volumetric flow rate, m^3/s
W	channel width, m
x	x-coordinate, m

Greek symbols

α	thermal diffusivity, m^2/s
δ	thickness, mm
π	dimensionless number
μ	dynamic viscosity, Pa·s
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
ω	humidity ratio, kg/kg dry air

Subscripts

a	air
d	dry channel
D	diameter
dp	dew point
e	evaporation
f	water film
h	hydraulic
i	inlet
lm	log mean
m	mean
p	product
pl	plate
s	surface
v	water vapor
w	wet channel
wo	working air outlet
x	x-direction
y	y-direction

Abbreviations

COP	coefficient of performance
DB	dry bulb
DEC	direct evaporative cooling
DP	dew point
DPEC	dew point evaporative cooling
IEC	indirect evaporative cooling
MVC	mechanical vapor compression
WB	wet bulb

residential cooling systems, especially in arid climatic conditions [8,9].

Recently, dew point evaporative cooling (DPEC) has been proposed as an advanced evaporative cooling technology [10,11]. Through precooling of the working air, the theoretical limit of evaporative cooling has been extended from the wet bulb (WB) temperature to the dew point (DP) temperature of the supply air. In contrast with the conventional IEC and DEC, the DPEC is able to achieve 20–70% higher cooling effectiveness while maintaining constant supply air humidity [12,13]. This remarkable improvement motivated researchers to further explore its potential in terms of cooling performance and related applications. For instance, Riangvilaikul et al. [13] investigated a counter-flow dew point evaporative cooler that operated based on a flat-sheet heat and mass exchanger. The cooler was tested under different supply air temperatures, humidity and velocities, and achieved 0.92–1.14 WB effectiveness. Bruno [14] developed a large-scale counter-flow dew point evaporative cooler for commercial and residential applications. The cooler was able to deliver an average product air temperature of below 18.0 °C with the WB effectiveness of up to 1.29, over an extended test period of 44 days. Jradi et al. [15] proposed a cross-flow dew point evaporative cooler, and a 2-D numerical model was formulated to simulate its performance. With the dimensions of 0.85 m × 0.75 m × 0.6 m (L × W × H), the cooler achieved the WB effectiveness of 0.70–1.17 at the supply air flow rate of 300–1500 CMH. Lee et al. [16] presented a counter-flow dew point evaporative cooler with finned channels. The product air temperature of the cooler was around 22.0 °C under the supply air conditions of 32.0 °C and 50% RH. Xu et al. [17] conducted an experimental study on a corrugated counter-flow dew point evaporative cooler. The channel support guides were removed to reduce 50–56% of flow resistance and increase 40% of the heat transfer area. Under the supply air conditions of 37.8 °C dry bulb (DB) and 21.1 °C WB temperatures, the COP of the cooler was 52.5 at the optimal working air ratio of 0.364.

Concurrently, some mathematical models were developed to predict and optimize the performance of the dew point evaporative cooler. Anisimov et al. [18,19] proposed a modified ε-NTU model to investigate the heat and mass transfer process of the dew point evaporative cooler. Different flow arrangements of the heat and mass exchanger were simulated and compared in terms of their cooling effectiveness and specific cooling capacity. Cui et al. [20] numerically studied a counter-flow closed-loop dew point evaporative cooler. A CFD model was established using the ANSYS FLUENT platform. The limits of the channel height, supply air velocity and working air ratio were examined to ensure the WB effectiveness of more than 1.00. Jafarian et al. [21] presented a multi-objective optimization of the counter-flow dew point evaporative cooler, based on the group method of data handling (GMDH) neural network model. The model was employed to design the operating and geometric conditions that simultaneously maximized the average COP and minimized the specific area of the cooler, according to different climatic conditions. Zhu et al. [22] developed a data-driven model for the counter-flow dew point evaporative cooler using the