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Similarity analysis and comparative study on the performance of counter-flow dew point evaporative coolers with experimental validation

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ABSTRACT

This paper entails a comparative study on the performance of counter-flow dew point evaporative coolers with two different configurations (type A and type B). Type A refers to the flow configuration where the supply air flows parallel to the water film, while type B refers to the flow configuration where the supply air flows counter to the water film. Both cooler types, when compared with a conventional indirect evaporative cooler, have better potential of lowering the product air temperature below its wet bulb temperature approaching the dew point temperature. A two-dimensional computational fluid dynamics model based on the continuity, momentum, energy and diffusion equations is firstly formulated and then employed to simulate the heat and mass transfer processes. The model, when validated with experimental date, shows a maximum discrepancy of 6.0%. A similarity analysis is then performed to structure the original governing equations of the model into dimensionless forms so as to evolve a fundamental platform that allows key dimensionless parameters to be determined. By regulating these key dimensionless parameters, distributions of the dew point and wet bulb effectiveness and the dimensionless product temperature are plotted via numerical simulation method. Additionally, key simulated data are regressed to obtain the empirical correlation of the dimensionless product air temperature. The key findings that emerged from the present study include: (1) the key dimensionless parameters that are essential to evaluate the performance of the counter-flow dew point evaporative cooler are supply air Reynolds number, water Reynolds number, working air to supply air mass flow rate ratio, water inlet dimensionless temperature, channel length to half width of dry channel ratio and half width of wet channel to half width of dry channel ratio; (2) comparatively, type B configuration has a higher cooling effectiveness and lower product temperature than type A configuration; and (3) the developed dimensionless product air temperature correlation for type B adhered closely to simulated results.

1. Introduction

Heating, Ventilation and Air Conditioning (HVAC) constitutes the major energy consumption in a building and comprises about 50% of the total supplied energy [1]. Many buildings are still adopting vapor compression refrigeration systems. During the hottest summer period when air conditioners are in full operation, many cities in the world, experienced surged electricity consumption, resulting in undesirable grid “cut-off” [2]. Moreover, the widely used chlorofluorocarbon (CFCs) and hydro chlorofluorocarbon (HCFCs) refrigerants in vapor compression refrigeration systems are responsible for ozone depletion and global warming. The extensive need for air conditioning and its growing pressure on the environment have exerted enormous pressure on mankind to seek urgently for a new approach to provide thermal comfort air conditioning. Evaporative cooling, a potential alternative without compressor and refrigerant, has, therefore, received considerable attention. A substantial reduction in energy consumption is known to possible to provide air conditioning when compared to vapor compression systems. The achievable COP can be as high as 15–20 [2], which is significantly higher than that for conventional vapor compression systems (COP in the range of 2–4) [3].

Thus far, evaporative cooler are classified into direct evaporative cooler (DEC) and indirect evaporative cooler (IEC) [4]. For conventional IEC [5], the temperature of the product air is reduced without the introduction of any moisture to the product air, making IEC more attractive than DEC [6]. However, the wet bulb effectiveness of a conventional IEC is only in the range of 55–75% [7]. Therefore, the conventional IEC cannot provide sufficient cooling capacity to meet the

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Nomenclature

a	thermal diffusivity [$m^2\ s^{-1}$]
c	mass fraction of water vapor
$c_{sw,i}$	mass fraction of water vapor for saturated air at inlet working air temperature
C	normalized mass fraction of water vapor
D_1	half width of dry channel
D_2	half width of wet channel
D_s	diffusion coefficient of water vapor in air [$m^2\ s^{-1}$]
g	gravitational acceleration [$m\ s^{-2}$]
h_{fg}	evaporation heat of water [$kJ\ kg^{-1}$]
L	channel length [m]
m	mass flow rate [$kg\ m^{-1}\ s^{-1}$]
$\dot{m}_I$	mass flux of water evaporation [$kg\ m^{-2}\ s^{-1}$]
p	mixture pressure [Pa]
P	dimensionless pressure defined as $p/(\rho_w v_{w,i}^2)$
Pr	Prandtl number
r	working air to supply air mass flow rate ratio
Re	Reynolds number
Sc	Schmidt number
T	temperature [°C]
u, v	velocity components in x, y coordinate directions, respectively [m/s]
U, V	dimensionless velocity components in X, Y coordinate directions, respectively
W	humidity ratio of air [$kg\ kg^{-1}$]
x, y	space coordinate
X, Y	dimensionless space coordinate

Greek letters

α	channel length to half width of dry channel ratio
α_δ	water film thickness to half width of dry channel ratio
α_t	dimensionless water film thickness
β	half width of wet channel to half width of dry channel ratio
δ	water film thickness [m]
ε	effectiveness
θ	dimensionless temperature defined as $(T-T_{dp,i})/(T_{s,i}-T_{dp,i})$
λ	thermal conductivity [$W\ m^{-1}\ °C^{-1}$]
μ	dynamic viscosity [Pa s]
ρ	density [$kg\ m^{-3}$]

Subscripts

dp	dew point
i,	inlet
I	condition at the gas-liquid interface
l	water film
o	outlet
pl	plate
qb	saturation vapor pressure
s	supply air
w	working air
wb	wet bulb

increasing demand for air conditioning. Recently, the dew point evaporative cooler, a new class of IEC, has been demonstrated to achieve better cooling potential by lowering the product air temperature to below its wet bulb temperature and closer to its dew point temperature [8]. Accordingly, a wet bulb effectiveness of above 1.2 is possible [9].

The dew point evaporative cooler is a zero pollution, inexpensive and energy efficient cooling device [10], which has been numerically and experimentally investigated by numerous studies. Hsu et al. [11] investigated some types of wet-surface heat exchangers, including unidirectional flow, counter-flow and counter-flow/cross-flow closed-loop flow configurations. Their results have shown that the highest wet bulb effectiveness of the counter-flow closed-loop flow configuration is 1.3. Cui et al. [12] developed an analytical model for the dew point indirect evaporative coolers based on a modified Log Mean Temperature Difference (LMTD) method. Their investigation was carried out to demonstrate the method to provide accurate results with short computational time. Alklaibi [13] experimentally studied the performance of internal two-stage evaporative cooler in comparison with direct evaporative cooler. The results showed that the efficiency of the internal evaporative cooler was less sensitive to air speed than direct evaporative cooler. Jradi and Riffat [14] numerically and experimentally studied a modified dew point evaporative cooling system using a psychometric energy core (PEC) with a cross-flow heat and mass exchanger. The proposed dew point cooler presents an efficient and cost-effective alternative to conventional cooling units. Zhao et al. [15] numerically studied a novel counter-flow indirect evaporative cooler. Their simulation results indicated that the effectiveness of the cooler was largely dependent on the dimensions of the working air ratio, airflow passages, air velocity, and was less dependent on its feed water temperature. Riangvilaikul and Kumar numerically [16] and experimentally [17] investigated a counter-flow dew point evaporative cooling system. Their numerical model showed reasonable agreement with experimental data in terms of the product air temperature and the cooler's effectiveness. Additionally, they investigated the performance of the cooler under various inlet air conditions (dry, moderate and humid climate) and studied the influence of major operation parameters such as velocity, dimension and working air ratio. The experimental results showed that the heat exchanger can obtain dew point effectiveness and wet bulb effectiveness spanning 58–84% and 92–114%, respectively. Bruno [18] carried out an experimental investigation on an on-site study of a counter-flow dew point evaporative cooler for both commercial and residential applications. The annual energy saving obtained was between 52% and 56%. Lee et al. [19] investigated three different regenerative evaporative cooler configurations, including the corrugated plate type, the flat plate type and the finned channel type. Comparing the three different types, the finned channel type was found to have the smallest volume. In addition, Lee et al. [20] conducted an experimental investigation on the performance of a counter flow dew point evaporative cooler with finned channel. The results showed that the wet bulb effectiveness of the cooler was about 1.2 when the supply air temperature is 32 °C and relative humidity is 50%. Duan et al. [21] experimentally investigated the performance of a counter-flow regenerative evaporative cooler. The cooler was fabricated and tested under various operational conditions. It was observed that the cooler's effectiveness and efficiency were markedly affected by the inlet air velocity, inlet wet bulb depression and working air ratio. The corresponding wet bulb effectiveness was in the range of 0.55–1.06. Anisimov and Pandelidis [22] conducted a series of numerical studies on the heat and mass transfer processes of cross-flow dew point evaporative cooler. A modified ε-NTU model was proposed to investigate the cooling performance of the cooler under various inlet and operational conditions. Kabeel and Abdelgaied [23] proposed five configurations for a novel indirect evaporative cooler with internal baffles to determine a better configuration of indirect evaporative cooler. It was found that a novel with internal baffles is a better configuration to study the thermal comfort condition. Pandelidis et al. [24] compared the cross-flow and the counter-flow dew point evaporative coolers by developing a modified ε-NTU model and analyzed the effects of operational and geometric parameters on the cooling performance of units. Their model was judiciously validated using the numerical results