International Journal of Heat and Mass Transfer 127 (2018) 1147–1160

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

A new method for prediction and analysis of heat and mass transfer in the counter-flow dew point evaporative cooler under diverse climatic, operating and geometric conditions

Yangda Wan [a,b], Jie Lin [b], Kian Jon Chua [b,*], Chengqin Ren [a,*]

[a] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, College of Mechanical and Vehicle Engineering, Hunan University, Changsha 410082, China
[b] Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117575, Singapore

ARTICLE INFO

Article history:
Received 17 May 2018
Received in revised form 23 July 2018
Accepted 27 July 2018

Keywords:
Counter-flow
Dew point evaporative cooler
Air-conditioning
Modeling
Heat and mass transfer coefficients
Experiments

ABSTRACT

Dew point evaporative cooler, regarded as a zero polluting and energy efficient cooling device, has evolved to be a key technology in air-conditioning systems. The water evaporating process in the cooler is a key performing factor as it leads to the heat sink phenomenon. The cooling effectiveness is dictated by its heat and mass transfer coefficients. The conventional methods (mean temperature difference and integration methods) of obtaining these coefficients have limitations. In this work, a new method to determine these coefficients is proposed. Firstly, a $NTU-Le-R$ model is installed to detect these coefficients. It is based on the outlet data of the dew point evaporative cooler. Next, a two-dimensional computational fluid dynamic model is developed to simulate the evaporative cooling process within the cooler and compute the outlet data for the $NTU-Le-R$ model. Upon validation, results from the computational fluid dynamic model demonstrate close agreement to within ±6.0% with results acquired from experiments. Finally, the effects of the various conditions on the heat and mass transfer coefficients, including climatic, operating and geometric conditions, are judiciously investigated. The new proposed method has the capability to capture the essential boundary conditions to precisely obtain the transfer coefficients. In contrast to existing practices that combine the assumption of the Nusselt number under constant surface heat flux or temperature conditions with the Chilton-Colburn analogy. This new method simplifies computation while providing accurate data to realize optimum design of the dew point evaporative cooler.

1. Introduction

Heating, Ventilation and Air Conditioning (HVAC) constitutes the major energy consumption in a building and accounts for up to 50% of the total supplied energy [1]. Many factories, houses and commercial buildings are still adopting conventional vapor compression refrigeration systems to cool and, as a result, incur extensive electricity consumption. Moreover, the extensive utilization of chlorofluorocarbon and hydro-chlorofluorocarbon refrigerants in conventional vapor compression refrigeration systems has resulted in severe environmental concerns, such as ozone depletion and global warming. The widely used for air conditioning have drawn considerable attention to seek new cooling approaches to provide indoor air conditions for human comfort. Evaporative cooling technology has therefore been proposed as an alternative without the use of chemical refrigerants and mechanical compressors [2]. As water is the only cooling agent that drives the cooling process, the evaporative cooling technology is deemed to be both environmentally friendly and energy efficient [3]. Moreover, the electricity utilization of the evaporative cooling process is considered low and energy is consumed to maintain the supply of air and water. Thus, the coefficient of performance (COP) of the evaporative cooling is markedly higher than conventional vapor compression systems [4].

Evaporative coolers are categorized into direct evaporative cooler (DEC) and indirect evaporative cooler (IEC), which have been widely developed and used in dry climatic conditions [5]. Recently, dew point evaporative cooler (DPEC) is proposed as the new generation of evaporative cooling technology as it is able to provide cooler input air temperatures that are below its wet bulb temperature while approaching the inlet air dew point temperature [6,7].

* Corresponding authors.
E-mail addresses: mpeckje@nus.edu.sg (K.J. Chua), renchengqin@163.com (C. Ren).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.07.142
0017-9310/

Nomenclature

a	thermal diffusivity [$m^2\ s^{-1}$]
A	area [m^2]
c	mass fraction of water vapor
c_p	specific heat capacity [$kJ\ kg^{-1}\ °C^{-1}$]
C_w^*	water to dry air heat capacity rate ratio
D	half width of channel [m]
D_s	diffusion coefficient of water vapor in air [$m^2\ s^{-1}$]
h_c	heat transfer coefficient [$W\ m^{-2}\ °C^{-1}$]
h_D	working air side mass transfer coefficient [$kg\ m^{-2}\ s^{-1}$]
h_{fg}	evaporation heat of water [$kJ\ kg^{-1}$]
h_{fg}^0	evaporation heat of water at reference temperature condition (0 °C) [$kJ\ kg^{-1}$]
$\overline{h_{fg}}$	normalized heat of evaporation at reference temperature condition (0 °C)
i_w	specific enthalpy of the working air [$kJ\ kg^{-1}$]
i_{v,T_I}	specific enthalpy of the water vapor at water temperature [$kJ\ kg^{-1}$]
L	channel length [m]
Le	Lewis factor
m	mass flow rate [$kg\ m^{-1}s^{-1}$]
$\dot{m}_I$	mass flux of water evaporation [$kg\ m^{-2}\ s^{-1}$]
NTU	number of heat transfer units
Nu	Nusselt number
p	mixture pressure [Pa]
r	working air to input air mass flow rate ratio
R	input air to working air heat transfer coefficient ratio
T	temperature [°C]
u,v	velocity components in x, y coordinate directions, respectively [m/s]
ω	humidity ratio [$kg\ kg^{-1}$]
x, y	space coordinate

Greek letters

δ	water film thickness [m]
λ	thermal conductivity [$W\ m^{-1}\ °C^{-1}$]
μ	dynamic viscosity [Pa s]
ρ	density [$kg\ m^{-3}$]

Subscripts

dg	dry air
i	inlet
I	condition at the air–water interface
pl	plate wall
qb	saturation vapor pressure
l	water
o	outlet
p	output air (product air)
s	input air (supply air)
w	working air

The DPEC has the capability to achieve 20–70% higher cooling effectiveness compared to its counterparts, conventional IEC and DEC. This has motivated many researchers to study its capability, cooling performance and practical applications under varying climatic conditions. Hsu et al. [8] studied four types of heat exchangers, including unidirectional flow, counter-flow and counter-flow/cross-flow closed-loop flow configurations. Their results indicated that the counter-flow closed-loop flow configuration is able to achieve the highest wet bulb effectiveness of up to 1.3. Cui et al. [9] proposed an analytical model to evaluate the performance of dew point evaporative coolers based on a Log Mean Temperature Difference (LMTD) method. Their study was specifically carried out to demonstrate the potential of the LMTD method to provide accurate results while realizing short computational durations. Alklaibi [10] experimentally studied the performance of a two-stage evaporative cooler in contrast to a direct evaporative cooler. Results from this study indicated that the efficiency of the two-stage evaporative cooler was less sensitive to air velocity than that of the direct evaporative cooler. Zhao et al. [11] carried out a numerical study on a counter-flow indirect evaporative cooler. Their investigation findings indicated that the effectiveness of the cooler was less dependent on its supply water temperature, and was largely dependent on the working air to input air mass flow rate ratio, air velocity and airflow passages. Riangvilaikul and Kumar experimentally [12] and numerically [13] investigated another counter-flow dew point evaporative cooling system. Their numerical model demonstrated good agreement with experimental results in terms of the quantitative values of the output air temperature and the effectiveness of the cooler. They also studied the cooler performance under different air conditions such as dry, humid and moderate climate and investigated the effect of key operation parameters such as input air velocity, working air to input air mass flow rate ratio and dimension. Their experimental results showed that the cooler is capable of obtaining wet bulb effectiveness and dew point effectiveness spanning 0.92 to 1.14 and 0.58 to 0.84, respectively. Bruno [14] experimentally studied a dew point evaporative cooling system in both residential and commercial buildings. The dew point evaporative cooler was capable of achieving wet bulb effectiveness of up to 1.29. Additionally, the annual energy saving obtained was between 52% and 56%. Lee et al. [15] studied and compared the performance of three different dew point evaporative cooler configurations, namely, flat plate type, corrugated plate type and finned channel type. Comparatively, the finned channel type was observed to have the smallest volume. In addition, Lee et al. [16] conducted an experimental study on the counter-flow dew point evaporative cooler with finned channel. Their results indicated that the achievable wet bulb effectiveness was 1.2 when the respective input air temperature and relative humidity were 32 °C and 50%. Kabeel and Abdelgaied [17] proposed five configurations for a novel indirect evaporative cooler with internal baffles in the dry channel to determine a better configuration to enhance the performance of indirect evaporative coolers. The results showed for the five configurations, the output air temperature decreases with increases the number of baffles. Duan et al. [18] experimentally determined the performance of a counter-flow dew point evaporative cooler under various operational conditions. It was shown that the effectiveness of the cooler was markedly affected by the input air velocity, working air to input air mass flow rate ratio and inlet wet bulb depression. The corresponding wet bulb effectiveness ranged between 0.55 and 1.06. Hasan [19,20] compared the predictions from an analytical model using the ε-NTU method and a numerical method using the finite difference method to study the counter-flow dew point evaporative cooler. It was found that the results of the two methods were close, and agreed well with experimental data. Anisimov and Pandelidis [21] also developed a modified ε-NTU model to analyze the heat and mass transfer characteristics of the dew point evaporative cooler. The modified ε-NTU model was employed to assess the cooling performance of the cooler under various operational conditions. Pandelidis et al. [22] compared how different