Energy 113 (2016) 172–185

Contents lists available at ScienceDirect

Energy

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

Unsteady-state analysis of a counter-flow dew point evaporative cooling system

J. Lin [a], K. Thu [a, b], T.D. Bui [a], R.Z. Wang [c], K.C. Ng [a, d], M. Kumja [a], K.J. Chua [a, *]

[a] Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore, 117575, Singapore
[b] Interdisciplinary Graduate Schools of Engineering Science, Kyushu University, Kasuga-koen 6-1, Kasuga-shi, Fukuoka, 816-8580, Japan
[c] Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai, 200240, China
[d] Water Desalination and Reuse Center, 4700 King Abdullah University of Science and Technology, Thuwal, 23955-6900, Saudi Arabia

ARTICLE INFO

Article history:
Received 17 November 2015
Received in revised form
11 June 2016
Accepted 7 July 2016
Available online 18 July 2016

Keywords:
Dew point evaporative cooling
Transient response
Settling time
Dynamic performance

ABSTRACT

Understanding the dynamic behavior of the dew point evaporative cooler is crucial in achieving efficient cooling for real applications. This paper details the development of a transient model for a counter-flow dew point evaporative cooling system. The transient model approaching steady conditions agreed well with the steady state model. Additionally, it is able to accurately predict the experimental data within 4.3% discrepancy. The transient responses of the cooling system were investigated under different inlet air conditions. Temporal temperature and humidity profiles were analyzed for different transient and step responses. The key findings from this study include: (1) the response trend and settling time is markedly dependent on the inlet air temperature, humidity and velocity; (2) the settling time of the transient response ranges from 50 s to 300 s when the system operates under different inlet conditions; and (3) the average transient wet bulb effectiveness (1.00–1.06) of the system is observed to be higher than the steady state wet bulb effectiveness (1.01) for our range of study.

1. Introduction

Cooling is a necessity for houses, factories and commercial buildings [1]. Conventional vapor compression systems continue to be a dominant technology that occupies a significant market share in the past several decades. However, consequent environmental concerns, such as global warming and ozone depletion, have drawn great attention to new cooling approaches. These alternatives include evaporative cooling systems (direct and indirect) [2,3], and thermally activated cooling systems (absorption and adsorption) [4–6]. Among them, dew point evaporative cooling is a potential game-changing air conditioning technology [7,8]. The advent of dew point evaporative cooling provides a methodology for cooling the supply air to below its wet bulb temperature while dispensing with the use of compressor and refrigerant. A driving force for water evaporation is created when a working air stream is intentionally separated from the dry channel and supplied to the wet channel. The method utilizes the latent heat of evaporation to absorb sensible heat from the adjacent dry channel. As a consequence, the supply air stream is gradually conditioned and the process is repeated in a stack of channels to achieve an overall cooling effect. At the end of the channels, the saturated working air is discharged while a portion of supply air is redirected into the wet channel to continue evaporative cooling. The thermally conditioned air is delivered as the product air supplied to the room space. The only electric power consumed by the cooling process is due to maintaining the air flow regime in the channels. Accordingly, the COP of dew point evaporative cooling is much higher than conventional vapor compression systems [2,3,8].

In practice, there are two types of dew point evaporative cooling systems, namely, counter-flow and cross-flow, as shown in Fig. 1. The cross-flow configuration has been well adopted by some commercial cooling systems, such as the Coolerado air conditioner [9]. However, counter-flow configuration is thought to have greater cooling potential. Presently, it is still under lab development due to several challenges related to manufacturing technology and the difficulty in maintaining its flow regime [10–12].

Research has been carried out to develop the detailed design and prototype for counter-flow cooling system. Hsu et al. [13] studied three different configurations in wet-surface heat exchanger for indirect evaporative cooling. As the preliminary idea of dew point evaporative cooling, both experiment and simulation

---

* Corresponding author.
E-mail address: mpeckje@nus.edu.sg (K.J. Chua).

http://dx.doi.org/10.1016/j.energy.2016.07.036

Nomenclatures

A	surface area of water film, m^2
c_f	specific heat of water, kJ/(kg·K)
c_p	specific heat at constant pressure, kJ/(kg·K)
c_v	specific heat at constant volume, kJ/(kg·K)
D_h	hydraulic diameter, m
D_{AB}	mass diffusivity, m^2/s
$\dot{E}$	energy transfer rate, W
Gz	Graetz number
h	specific enthalpy, kJ/kg
$\bar{h}$	convective heat transfer coefficient, $W/(m^2 \cdot K)$
$\bar{h}_m$	convective mass transfer coefficient, m/s
H	channel height, m
j	diffusive mass flux, $kg/(m^2 \cdot s)$
k	thermal conductivity, W/(m·K)
l	channel length, m
l_e	characteristic length, m
Le	Lewis number
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
$\dot{M}$	mass transfer rate for species, kg/s
n	mass transfer rate, kg/s
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
q	heat transfer rate, W
r	working air ratio
Re	Reynolds number
t	temperature, °C
T	thermodynamic temperature, K
u	specific internal energy, kJ/kg
$\dot{U}$	internal energy transfer rate, W
v	velocity, m/s
V	volume of water film, m^3
W	channel width, m

Greek symbols

α	thermal diffusivity, m^2/s
δ	plate thickness, mm
ε	cooling effectiveness
μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3
τ	time, s
ω	humidity ratio, g/kg dry air
Φ	relative humidity, %

Subscripts

0	reference point
a	air
CV	control volume
d	dry channel
D	diameter
f	water film
in	inlet
out	outlet
s	saturation
th	thermal
v	water vapor
w	wet channel
wb	wet bulb
x	x-direction
y	y-direction

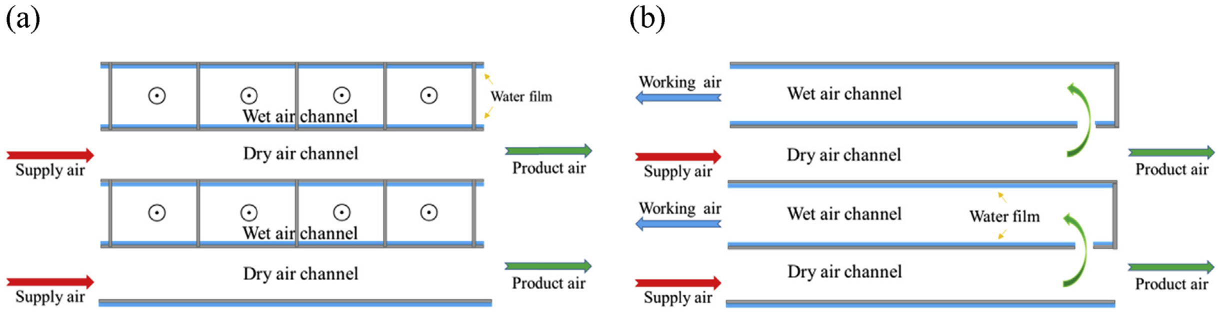

Fig. 1. System configuration of dew point evaporative cooling: (a) cross-flow; and (b) counter-flow.

were conducted on a counter-flow, closed-loop configuration. The results showed that the maximum wet bulb effectiveness was 1.30, higher than the unidirectional or counter-flow configuration. Riangvilaikul and Kumar [11] carried out an experimental study on a counter-flow dew point evaporative cooler having 4 dry channels and 5 wet channels. The system performed well under different inlet air temperatures, humidity and velocities with wet bulb effectiveness ranging from 0.92 to 1.14. Zhao et al. [14] proposed a counter-flow heat and mass exchanger with triangular channels, and his simulation work demonstrated a maximum wet bulb effectiveness of 1.30 under typical UK weather condition. Experiments were later conducted on their design by Duan [12]. His results showed that the product air temperature spanned 19–29 °C with wet bulb effectiveness ranging from 0.55 to 1.10. In addition, Lee and Lee [10] investigated a counter-flow regenerative evaporative cooler with finned channels. The effects of inlet air conditions, water and air flow rates, and extraction ratio on product air temperature and effectiveness were studied experimentally. Woods et al. [15] proposed a desiccant-enhanced evaporative (DEVAP) air conditioner, which combines air dehumidification and evaporative cooling to improve the capability of handling humid air. Individual tests were carried out for their hybrid liquid desiccant dehumidifier and indirect evaporative cooler. The results showed that the dehumidification process almost reached its