Energy 165 (2018) 958–971

Contents lists available at ScienceDirect

Energy

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

On the exergy analysis of the counter-flow dew point evaporative cooler

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ARTICLE INFO

Article history:
Received 18 June 2018
Received in revised form
2 September 2018
Accepted 7 October 2018

Keywords:
Dew point evaporative cooling
Second law of thermodynamics
CFD simulation
Exergy analysis
Exergy efficiency

ABSTRACT

The dew point evaporative cooler has been proposed to replace the mechanical vapor compression chiller in air sensible cooling, for its significantly larger energy efficiency and simpler system layout. Many of the existing studies focused on applying a first-law thermodynamic analysis to the dew point evaporative cooler, however, its performance involving the second-law thermodynamic assessment remains unclear. Therefore, in this paper, an exergy analysis of the counter-flow dew point evaporative cooler is conducted. The exergy performance of the dew point evaporative cooling process is examined by incorporating the first law of thermodynamics for energy and mass balances. A counter-flow dew point evaporative cooler prototype has been designed, fabricated and tested to investigate its cooling performance. A 2-D computational fluid dynamics (CFD) model is then formulated to simulate the flow, temperature and humidity fields of the cooler. The model agrees well with the acquired experimental data with the maximum discrepancy of ±5.6%. The exergy flow, efficiency and efficiency ratio of the cooler are discussed under various simulation conditions. Key findings that emerged from this study reveal that the saturated air state at ambient temperature is the rational dead state to properly describe the physical mechanisms involved in the dew point evaporative cooling process. The exergy efficiency ratio of the dew point evaporative cooler is greater than 1.0, highlighting a remarkable second-law efficiency for air conditioning applications.

1. Introduction

Ever since 1902, the modern air conditioning market has been dominated by the mechanical vapor compression chillers, due to its excellent cooling effectiveness and capacity. However, the continuous utilization of the vapor compression cycle, on the other hand, has led to extensive electricity consumption, accounting for up to 50% of building energy supply [1–3]. Global environmental issues, such as ozone depletion and greenhouse effect, have also emerged and are attributed to the primary use of CFCs and HCFCs as refrigerants [4].

To reduce the power consumption of the conventional vapor compression chillers, the second-law thermodynamic analysis has been conducted to identify major losses in the refrigeration cycles [5]. It has been reported that the compressor is chiefly responsible for the largest portion of exergy destruction, followed by the condenser, expansion valve and evaporator [6,7]. Although this finding motivated researchers to develop more efficient compressors and condensers, no significant breakthrough has been made to improve the average energy efficiency of the mechanical chillers in the past few decades [8]. Furthermore, the high energy efficiency of heat pumps with the COP of more than 1.0 does not represent a better utilization of energy, when compared with an electric heater based on the second law efficiency [9]. Thus, all these issues have driven researchers to consider other approaches to facilitating air conditioning, namely, to find potential alternatives to vapor compression chillers.

Recently, dew point evaporative cooling has been proposed as an improved substitute for the mechanical chiller, especially under dry and moderate humidity [10]. By eliminating the use of compressor, the energy efficiency of the dew point evaporative cooler is expected to be several times to one order of magnitude larger than a mechanical chiller [11–14]. Several studies have specifically focused on the development and investigation of dew point evaporative coolers. Elberling [15] carried out an experimental study on the cross-flow dew point evaporative cooler,

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https://doi.org/10.1016/j.energy.2018.10.042

Nomenclatures

c_p	specific heat at constant pressure, J/(kg·K)
D	diffusion coefficient, m^2/s
ex	specific exergy, J/kg of dry air
Ex	exergy, J
h	specific enthalpy, J/kg of dry air
h_{fg}	latent heat evaporation, J/kg
H	nominal channel height, m
H_t	total channel height, m
k	thermal conductivity, W/(m·K)
L	channel length, m
N	number of channel pairs
P	pressure, Pa
R	specific gas constant, J/(kg·K)
r	working air ratio
s	specific entropy, J/(kg·K)
T	temperature, °C
u	velocity, m/s
$\dot{V}$	volumetric flow rate, m^3/s
W	channel width, m

Greek symbols

δ	thickness, mm
η	exergy efficiency
ε	exergy efficiency ratio
μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3
φ	relative humidity
ω	humidity ratio, kg/kg of dry air
$\tilde{\omega}$	mole fraction ratio
υ	specific volume, m^3/kg

Subscripts

0	dead state
a	air
ch	chemical
d	dry channel
de	destruction
dp	dew point
e	evaporation
ex	exergy
f	water film
fan	electric fan
i	inlet
me	mechanical
o	outlet
p	product
pl	plate
s	supply
sa	saturation
sp	supply to product
sw	supply to working
th	thermal
v	water vapor
w	wet channel/working
x	x-direction
y	y-direction

Abbreviations

CFD	computational fluid dynamics
COP	coefficient of performance
RH	relative humidity

which was known as the M-cycle cooler and commercialized by Coolerado™ [16]. The test facility was established according to ASHRAE standard [17], and ten major conditions were selected to rate the cooling performance. It was found that the average wet bulb effectiveness of the cooler was 0.86 with a COP of 9.6. Jradi et al. [18] developed a cross-flow dew point evaporative cooler with the channel dimensions of 850 × 750 × 600 (L×W×H) mm. Their test results showed that the cooler was able to cool the supply air from 41.1 °C (14.5% RH) to 17.3 °C with wet bulb effectiveness and cooling capacity of 1.17 and 1054 W, respectively. Concurrently, Riangvilaikul et al. [19] designed and tested a counter-flow dew point evaporative cooler prototype. The cooler was comprised of 4 dry channels and 5 wet channels with rectangular shape. They reported that the wet bulb and dew point effectiveness spanned 0.92–1.14 and 0.58–0.84, respectively under different operating conditions. Xu et al. [20] proposed a counter-flow dew point evaporative cooler with corrugated surface. A remarkable COP value of 52.5 was achieved at the supply air conditions of 37.8 °C dry bulb and 21.1 °C wet bulb.

In addition to the experimental investigation of the dew point evaporative cooling, theoretical analyses have been conducted. Zhan et al. [21] numerically compared the thermodynamic performance of cross-flow and counter-flow dew point evaporative coolers with identical channel size. They reported that the counter-flow configuration demonstrated higher cooling effectiveness and cooling capacity, while the cross-flow cooler incurred less pressure drop and achieved larger COP. Anisimov et al. [22,23] formulated a modified ε-NTU model to investigate the heat and mass transfer phenomena in a cross-flow dew point evaporative cooler. The finned surface and the channel entrance and exit, as well as the air mixing process, were judiciously considered. Jafarian et al. [24] developed a group method of data handling (GMDH) neural network model for the counter-flow dew point evaporative coolers. The model was employed for a multi-objective optimization. The average specific area and COP were optimized by varying the design parameters of the cooler using a non-dominated sorting genetic algorithm II (NSGA-II), according to the specific ambient conditions. Fakhrabadi et al. [25] used the simplified conjugate gradient method to optimize the counter-flow dew point evaporative cooler. The optimal supply air velocity and working air ratio were investigated to achieve the maximum room cooling capacity. Additionally, Lin et al. [26–28] conducted scaling, dimensional and heat and mass transfer analyses on the counter-flow dew point evaporative cooler. Key correlations for the dimensionless time constant and product air temperature, as well as Nusselt number and Sherwood number, were proposed.

It can be inferred from the literature review that the cooling performance of the dew point evaporative cooler, such as cooling effectiveness, cooling capacity and energy efficiency, has been extensively explored. Also, the improved energy efficiency of the dew point evaporative cooler compared to the mechanical chiller has been demonstrated. However, the basic approach of these existing studies on the dew point evaporative cooling is currently confined to the first law of thermodynamics. The related mathematical modeling, thermodynamic analysis and heat and mass transfer investigation are based on conventional energy and mass balance equations. In contrast, there are limited research performed on the second-law thermodynamic analysis of the dew