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Comparative study of the conventional types of heat and mass exchangers to achieve the best design of dew point evaporative coolers at diverse climatic conditions

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ABSTRACT

The objective of this research is a comparative analysis of various kinds of heat and mass exchangers of dew point indirect evaporative cooler. Considering three key performance parameters of an evaporative cooler, namely life-cycle cost, annual water consumption and the annual average of the coefficient of performance as objective functions, the best design of two popular types of the dew-point evaporative cooler (counter-regenerative and cross configurations) for employing in small-scale residential buildings was found through a multi-objective optimization approach. Both operational and geometric characteristics of the coolers were selected as the design (decision) variables while proper constraints such as thermal comfort were imposed. Afterward, between the optimized counter-regenerative and cross configurations, the foremost one was selected for representative cities of four diverse groups within the Köppen-Geiger climate classification system. It was found that in very hot and dry areas, the counter-regenerative configuration was the ideal choice while in other investigated climates, using cross configuration was a better alternative. Moreover, the results showed that in comparison to the base case conditions by using the best-optimized configurations, 64.4, 86.4, and 1039.0% improvements in life-cycle cost, the annual water consumption, and the annual average of the coefficient of performance were achieved, respectively.

1. Introduction

During recent years, dew point indirect evaporative cooling system (DPIEC) has occupied an important role in air-conditioning system technologies. The system was originally patented and developed by Valery Maisotsenko [1–3]. Therefore, the system is also known as the Maisotsenko (M-cycle) indirect evaporative cooling system [4,5]. Maisotsenko (M-cycle) indirect evaporative coolers (MCIECs) not only provide the supply air temperature below the wet-bulb close to dew point temperature by the highest efficiency but also consume much lower electricity than the similar vapor compression systems [6]. Additionally, MCIECs are an environmental option for the conventional vapor compression system [7]. Providing cooled air without adding moisture and wet-bulb effectiveness of higher than 100% could be counted as the main advantages of MCIECs compared to direct evaporative cooling systems (DECs) and other indirect evaporative cooling systems (IECs) [8]. There are different versions of the air flow arrangement in the M-cycle heat and mass exchangers [9]. Fig. 1a represents a counter-flow regenerative heat and mass exchanger with partial extraction of air (also known as regenerative heat and mass exchanger). Moreover, Fig. 1b shows a cross-flow heat and mass exchanger. Each of these illustrated figures is one of the different types of air flow arrangement. Counter-flow regenerative and cross-flow M-cycles (CoFRMC and CrFMC) are the major popular developed kinds of heat and mass exchangers of MCIECs [10].

There have been two main approaches by which the performance of MCIECs has been analyzed: conducting experiments and developing analytical or numerical models. Conducting experiments is a method in which the researchers have performed a number of experiments and then they have reported and interpreted the results [11–14]. For instance, Xu et al. [11] investigated the performance of an innovative CoFRMC, in which high-quality wet material layer and intermittent water distribution system were employed. In another study, Kashif Shahzad et al. [12] tested an integrated cooling system which composed of solid desiccant and CrFMC. Moreover, Duan et al. [13] found the potential of electrical energy saving of a CoFRMC at diverse climatic conditions of China using an experiment-based evaluation. Khalid et al. [14] also studied the performance of a CrFMC under low inlet air

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Nomenclature

AACOP	the annual average of coefficient of performance
AACC	the annual average of cooling capacity (kW)
AADP	the annual average of dew-point efficiency
ANN	artificial neural network
AWC	annual water consumption ($m^3\,year^{-1}$)
C	cost ($)
c_p	constant pressure specific heat ($J\,kg^{-1}\,K^{-1}$)
CC	cooling capacity (W)
CoFRMC	counter-flow regenerative Maisotsenko (M-cycle) indirect evaporative cooler
COP	the coefficient of performance
CrFMC	cross-flow regenerative Maisotsenko (M-cycle) indirect evaporative cooler
d	discount rate
D_H	hydraulic diameter (m)
DEC	direct evaporative cooler
DPIEC	dew point indirect evaporative cooling system
EPC	electrical power consumption (W)
EW	external work ($W\,m^{-2}$)
f_{on}	the fraction of time in an hour in which CoFRMC or CrFMC is on
f_{cl}	clothing surface area factor
f_{resale}	the fraction of resale income at the end of system life span to the initial cost
gap	the height of dry channel (m)
GMDH	group method of data handling type neural network
H	cooler height (m)
h_c	convective heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
i	inflation rate
I_{cl}	insulation ($m^2\,K\,W^{-1}$)
I_R	resale income ($)
k	conductive heat transfer coefficient ($W\,m^{-1}\,K^{-1}$)
L	channel length (m)
L^*	dimensionless length of the channel
LCC	life-cycle cost ($)
$\dot{m}$	the mass flow rate ($kg\,s^{-1}$)
M	metabolic rate ($W\,m^{-2}$)
MCIEC	Maisotsenko (M-cycle) indirect evaporative cooler
NSGA-II	non-dominated sorted genetic algorithm 2
Q	volumetric flow rate ($m^3\,h^{-1}$)
Q_a	volumetric flow rate of required fresh air ($m^3\,h^{-1}$)
P	pressure (Pa)
P_a	water vapor partial pressure (Pa)
PMV	predicted mean vote
POF	Pareto optimal frontier
PPD	predicted percentage dissatisfied (%)
PW_C	present worth of the cash flow of C ($)
PWF	present worth factor
RFMP	retailer's profit
RLSHS	the ratio of low speed to the high speed of the fan
T	temperature (°C)
TOPSIS	technique for order preference by similarity to ideal solution
$\overline{T}_r$	mean radiant temperature (°C)
SCST	soft computing and statistical techniques
SH	fan static head (Pa)
SRM	the stepwise regression method
V	velocity ($m\,s^{-1}$)
W	cooler width (m)
WAR	working air to total inlet air ratio
WC	water consumption
X	the size of a component of the system whose cost is determined based on that
years	the system's life span (years)

Scripts

air	air
base	base condition
board	board
db	dry bulb
dp	dew point
I	initial
in	inlet air
fan	fan
fr	friction
O	operating
O1	operating in the first year
out	outlet (product) air
PE	purchase of equipment
rel	relative
sa	supply air
sensible	sensible
thermostat	thermostat
w	water
wa	working air

Greek symbols

Δ	difference
ζ	minor loss coefficient
η	efficiency
ν	kinematics viscosity ($m^2\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
ϕ	relative humidity (%)
ω	absolute humidity ($kg_{moisture}\cdot kg_{dry\ air}{}^{-1}$)

velocity conditions experimentally. Although experimental measurements provide accurate results, they suffer from the cost of experiments. Developing a model is an alternative approach; however, a developed model must be validated with experimental data. If numerical or analytical models are validated using experimental data, they can be employed in the cases in which there is a lack of experimental data. The models have been obtained either by numerical methods or soft computing and statistical techniques (SCSTs). In the numerical modeling [15–19], different analytical methods such as the effectiveness-NTU method (ε-NTU) [16,18], the Eulerian-Lagrangian computational fluid dynamics (CFD) [15] and the finite difference method (FDM) [17,19] have been applied and the obtained numerical results have been validated against existing experimental data. Moreover, in the statistical modeling [5,7,20,21], the effective parameters have been determined and after extraction of enough data from experiments or numerical models, the modeling process has been conducted to transfer the data into analytical models [22]. Artificial neural networks (ANN) [20], group method of data handling (GMDH) [5,7,20], genetic programming (GP) [20], response surface methodology (RSM) [21], multiple linear regression (MLR) [20] and stepwise regression method (SRM) [6,20] are the statistical techniques by which MCIECs have been modeled so far. In Fig. 2, a graphical summary of the mentioned classification was presented.

From the point of view of the subject, the conducted studies about MCIECs were categorized into some groups. The largest group of studies is those research that the performances of the system are investigated under a variety of effective parameters such as inlet air conditions, the air flow velocity, the dimensions of the air flow passages, and working