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Thermal comfort based resources consumption and economic analysis of a two-stage direct-indirect evaporative cooler with diverse water to electricity tariff conditions

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A B S T R A C T

For many years, investigation of impacts of variation of effective parameters on the evaporative cooling systems performance has been limited to the thermodynamic or hydraulic analyses, while economic issues, consumption of all resources together and capability of the cooler to provide thermal comfort in the ranges of variation have not been considered. In order to cover all the three above-mentioned shortcomings and provide an applicable realistic point of view from the system operation, this research is done. For a two-stage direct-indirect evaporative cooler, the impacts of variation of effective parameters on different performance criteria of the system, including each stage outlet air conditions, cooling capacity, resource consumption and their ratios, operating and initial costs are investigated while for smart selection of the variation range of the effective parameters, a novel approach based on employing thermal comfort indices is proposed. In addition, the economic analysis is done for diverse existing water to electricity tariff conditions all around the world. It is found that there is a trade-off between performance criteria when the working to inlet air ratio of the second-stage increases, so it has an optimum value. In addition, using pads with higher specific contact areas is recommended as one of the most economical strategies to enhance the system. The results also show that the best values for inlet air velocity and pad thickness area are minimum possible magnitudes. These values for this study are 0.4 m s^{-1} and 5 cm, respectively.

1. Introduction

As an ancient but still popular way to provide thermal comfort, evaporative cooling systems have made a huge contribution to the market of air-conditioning system technologies [1]. Advantages such as fewer emissions [2], lower electrical power consumption [3] and initial costs as well as higher values of the coefficient of performance compared to the main rival, i.e. vapor compression systems [4–6] make evaporative coolers as the most favorite option in each place they are able to provide thermal comfort during the cooling season [7].

Direct and indirect types are two major kinds of evaporative coolers. During the years, each type has experienced different changes to achieve better performance. For example, in the case of direct evaporative cooler (DEC) straw (wood-wool) has been replaced with more efficient heat and mass transfer media like cellulose pads [8,9]. Using a part of the product cooled air as the working air has been also one of the best modifications to the field of indirect evaporative coolers (IECs) [10], which improves the cooling effectiveness significantly [11]. The indirect coolers employ the above-mentioned improvement are known as the dew-point (Maisotsenko or M-cycle [12]) evaporative cooling systems [13,14].

In addition to using individually, these two types can work together and make a direct-indirect evaporative cooler (DIEC). DIEC has the major benefits of both DEC and IEC simultaneously [15] while it is applicable to the very hot and dry climates in which single-stage evaporating cooling does not bring thermal comfort [16]. Like other engineering systems [17–21], enhancing the performance of DIEC has great importance.

Investigation of impacts of effective parameters on the system performance has been one of the major topics in the field of evaporative coolers. It provides an extensive insight into not only the behavior but also the level of importance of studied parameters. In addition, it usually brings beneficial points to run the system more efficiently. The investigations have been done by employing experiments or modelling

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Nomenclature

A_{spec}	the specific contact area of the pad ($m^2\,m^{-3}$)
C	cost ($)
c_p	constant pressure specific heat ($J\,kg^{-1}\,K^{-1}$)
CC	cooling capacity (W)
D	cooler depth (m)
D_H	hydraulic diameter (m)
$EPCR$	electricity power consumption ratio
EPC	electrical power consumption (W)
EPU	electricity price unit
EW	effective mechanical power ($W\,m^{-2}$)
f_{cl}	clothing surface area factor
gap	the height of dry channel (m)
h	enthalpy ($kJ\,kg^{-1}$)
h_c	convective heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
H	cooler height (m)
I_{cl}	insulation ($m^2\,K\,W^{-1}$)
ICD	initial cost difference ($)
IPP	initial purchase price ($)
k	conductive heat transfer coefficient ($W\,m^{-1}\,K^{-1}$)
L	channel length (m)
L^*	dimensionless length of the channel
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
M	metabolic rate ($W\,m^{-2}$)
num	number
Q	volumetric flow rate ($m^3\,hr^{-1}$)
P	pressure (Pa)
P_a	the partial pressure of the vapor (Pa)
PMV	predicted mean vote
pow	power (W)
PPD	predicted percentage dissatisfied (%)
$RFMP$	retailer's profit for CoFRMC initial cost
RCC	resorce consumption cost (electricity price unit)
T	temperature (°C)
$\overline{T_r}$	mean radiant temperature (°C)
$S.F.$	safety factor for the initial cost of the direct evaporative cooler
SH	static head of the fan (Pa)
$specrc$	the specific charge of resource consumption (electricity price unit per kW)
V	velocity ($m\,s^{-1}$)
vol	volume (m^3)
WCR	water consumption ratio
WAR	working air to total inlet air ratio
W	cooler width (m)

Abbreviations

ANN	artificial neural network
CoFRMC	counter-flow regenerative Maisotsenko (M-cycle) indirect evaporative cooler
DEC	direct evaporative cooler
DIEC	direct-indirect evaporative cooler
GP	genetic programming
IEC	indirect evaporative cooler
MLR	multiple linear regression
WTETR	water to electricity tariff
WTETRC	water to electricity tariff conditions

Greek symbols

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

Scripts

0	base case
air	air
base	base condition
board	board
da	dry air
dry channels	dry channels
cl	clothing
elec	electricity
episa	effective parameters investigated in sensitivity analyses
I	initial
in	Inlet
fan	fan
fr	friction
L	a layer of artificial neural network structure
out	outlet
PE	purchase of equipment
rel	relative
thermostat	thermostat
w	water
wa	working air

approaches. Modelling approaches consist of numerical and statistical methods themselves.

During recent years, several studies have been conducted on the above-mentioned topic. However, as Table 1 suggests, to our best of knowledge, they have been limited to the investigation of effects of parameters on the thermodynamic and hydraulic parameters and rarely only one of the water or electricity consumptions has been considered. It means resources (water and electricity) consumptions and their trend of variation have not been studied, simultaneously. In addition, despite the valuable works, in that type of studies, other important performance parameters like the corresponding initial and operating costs have not been taken into account yet. In other words, all the studies have neglected the economic issues of variation of effective parameters. Moreover, in the case of hybrid evaporative coolers, only the performance criteria of the integrated system have been reported and there have not been any details from the operation of each stage. Another point is that in those investigations, the range of variation of effective parameters has been selected by Authors' decision and in whole or some parts of the range, the thermal comfort condition has not been met.

A correct judgment about the evaporative cooling system is made only when its functionality i.e. bringing thermal comfort and other major criteria like resource consumption and economic performance are taken into account, simultaneously. Therefore, in this study, to bring an extensive and realistic insight from the DIEC, we investigate the impacts of variation of effective parameters including each stage's product air temperature and relative humidity, cooling capacity, resource consumption and economic performance criteria thoroughly. Both water and electricity consumptions, as well as the ratios of water and electricity consumptions of two stages, are analyzed in details while initial and operating costs are other parameters whose variations are studied. Moreover, the specific charge of resource consumption, which is defined as the ratio of charge of resource consumption to the cooling capacity, is investigated. Inlet air velocity, pad thickness, and specific contact area, as well as working air ratio of dew-point