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Comparative analysis of the cross-flow indirect evaporative air coolers

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ABSTRACT

This paper presents a comparative study of two selected types of cross-flow indirect evaporative units: typical air cooler and regenerative air cooler. The key target of presented analysis is to establish which of the considered units is more favorable for air-conditioning application. The analysis was performed on the base of numerical methods. An original mathematical model was developed and validated against existing experimental data. A comparison was performed for two basic operating conditions: constant airflow velocity in dry and wet channels and variable inlet airflow parameters (temperature and moisture content) and variable airflow velocity under constant inlet airflow parameters. Additionally, a sensitive analysis of heat and mass transfer process was performed on the base of the ε–NTU method to establish preferable operating conditions.

1. Introduction

Indirect evaporative air coolers (IECs) are one of the most effective solutions of new environmentally friendly air-conditioning units [1–5]. Unlike direct evaporative air coolers (DECs), where water is evaporated directly into the air stream, such devices operate on the basis of evaporation of the water film which occurs on one side of the heat exchanger's plate [5–7]. The plate is impenetrable, therefore water covers only one of side of the plate The working air stream is directed to the wet side, while the supply air moves along over the dry side. Evaporation of the water film results in decreasing temperature of the plate, which causes the sensible heat transfer flow from the supply air. On the other side of the channel plate, the vaporized water is taken away by the working air stream. This results in cooling the primary airflow without adding any moisture. The usage of evaporative air coolers in practice was investigated by many researchers. All of the obtained data showed that such devices can provide comfort conditions at minimal costs. Navon and Arkin [8] investigated the economic benefit and thermal comfort relating to utilization of a combined IEC/DEC system in a residential building in Israel. The results indicated that the economic benefit relating to use of the IEC/DEC is very promising owing to its significant electricity cost saving over the conventional air coolers. Jaber and Ajib [9] designed an indirect evaporative air-conditioning for the typical Mediterranean residential buildings and studied the economic benefit relating to utilization of such a system. The results indicated that most of the cooling load of the buildings could be matched by using an IEC unit with the airflow rate of 1100 l/s. Rogdakis et al. [10] presented experimental and numerical study of the M-cycle heat and mass exchanger. The obtained results indicated that the M-cycle HMXes can operate with high efficiency in the hot and dry Mediterranean climate, thus they can satisfy the necessary cooling power required for air conditioning. Pandelidis et al. [11] presented the numerical study of IECs in various air-conditioning applications. Their results showed that evaporative air coolers can obtain high efficiency during operation with the desiccant wheels, heat recovery units and traditional R410a air coolers.

Many existing studies are focusing on searching a new methods of increasing the effectiveness of IEC units. Such methods can be divided into four main groups:

1. Using multistage combination of IECs or IEC/DEC units.
2. Appling specially designed porous materials for channel construction. Such plates allow for very even water film distribution, keeping the water consumption at minimal value at the same time.
3. Using combined airflow schemes to achieve higher effectiveness of indirect evaporative air coolers.
4. Searching for the optimal HMX operating modes on the base of multi-objective Pareto optimization and determining the climatic regions where IECs are suitable to provide thermal comfort conditions.

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Nomenclature

A	surface, m^2
$c_{a,f}$	specific heat capacity of airflow, J/(kg K)
COP	coefficient of performance, –
d	channel characteristic dimension (height) , m
f	friction factor, –
h	heat transfer coefficient W/(m^2 K)
h_m	mass transfer coefficient referred to moisture content difference, kg/(m^2 s)
i_{fg}	latent heat of evaporation, J/kg
L	length, m
Le	Lewis factor, –
m	air mass flow rate, kg/s
$\dot{m}$	air mass flow rate referred to differential control volumes in air passage channel, kg/s
N	fan power demand, W
Nu	Nusselt number, –
p	pressure, Pa
q	heat flux, W/m^2
Q	rate of heat transfer, W
Q_c	cooling capacity, kW
Re	Reynolds number, –
RH	relative humidity, %
T	temperature, °C
v	airflow velocity, m/s
V	air volumetric flow rate, m^3/s
w	moisture content, kg/kg
W	heat capacity of fluid, W/K
WU	water usage, kg/h
WUQ	water used per 1 kWh of cooling power, kg/kWh

Greek symbols

ε_{wb}	wet-bulb effectiveness, –
λ	thermal conductivity, W/(m K)
ρ	air density, kg/m^3

Subscripts

1	supply airflow
2	working airflow
a,f	airflow
in	inlet
l	latent heat
out	outlet
plate	platet
s	sensible heat
w	water film
wb	wet-bulb

There are many studies connected with this four points. The example analysis connected with the first group are presented as follows. El-Dessouky et al. [12] performed an experimental research on two-stage IEC/DEC unit. The obtained data showed that the wet-bulb effectiveness of this device was varying in range (0.9–1.2). Heidarinejad et al. [13] presented a hybrid system of nocturnal radiative cooling, cooling coil, and direct evaporative cooling in Tehran. The results obtained demonstrate that overall effectiveness of hybrid system is more than 100%. Hsu et al. [14] studied theoretically and experimentally, two configurations of closed-loop wet surface heat exchangers to generate sub-wet bulb temperature cooling by a counter-flow and cross-flow arrangement. As for the second group, detail study of the plate materials was presented by Zhao et al. [15]. The materials analyzed were fibers, metals, zeolite, ceramics, and carbon. It was established that obtained results indicated that shape holding ability, durability and cost, are more important than thermal conductivity. Metals such as aluminum and cooper were considered to be the most appropriate material for IEC units. There were many studies connected with the third methods group: Anisimov et al. [16] presented a combined parallel-counter flow indirect evaporative cooler. This device connected the effectiveness of parallel air flow scheme in its initial phase and counter flow in its final phase. Riangvilaikul and Kumar [17,18] analyzed the regenerative air cooler. This unit operates on initial pre-cooling the working air flow in the dry channel. Another interesting complex thermodynamic cycle used for indirect evaporative air cooling is the Maisotsenko cycle (M-cycle). This unique cycle allows to achieve very low outlet airflow temperatures. Zhan et al. [19] presented the analysis of a M-cycle cross-flow air cooler. This unit was also analyzed in detail by Pandelidis et al. [19–23]. The obtained results allowed establishing the preferable design pattern. Zhao et al. [24] presented a numerical study of the counter-flow M-cycle air cooler. Obtained wet-bulb effectiveness was up to 1.3. As for the fourth group the researches were performed by many authors. Stoitchkov and Dimitrov [3] proposed a method of calculating the cooling effectiveness of the cross-flow flat-plate heat exchanger by analyzing the characteristics of the pre-set flowing water film, determining the mean water temperature on the wet surface and developing an equation to calculate the ratio of the total to sensible heat, by taking into account the barometric pressure. Chen [25] analyzed the wet porous evaporative plate in term of cooling performance. Chen developed a mathematical model to study the influences of different ambient conditions and the porous plate parameters on the obtained cooling efficiency. Anisimov et al. [26,27] presented numerical model of five different exchangers with the M-cycle. The obtained data indicated that each exchanger can show more effective performance, depending on consider efficiency factor (i.e. cooling capacity, outlet air temperature, wet-bulb effectiveness). Alonso et al. [28] presented a numerical model for thermal analysis of indirect evaporative air cooler. The model was simplified to make it use-friendly. Cui et al. [29] developed an analytical model for indirect evaporative heat exchangers via a modified log mean temperature difference (LMTD) method designed for sensible heat exchangers. The model has been demonstrated to be a practical method to provide an accurate result with a short computational time. Kanzari et al. [30] analyzed the sub-wet bulb temperature air cooling unit with a numerical methods. The exchanger used the ceramic porous material for the plate construction. The wet-bulb effectiveness obtained by this unit was 1.17. Gao et al. [31] analyzed an integrated liquid-desiccant indirect evaporative air-cooling system with the M–cycle. The results showed that the dehumidification process in the first stage of the cycle has direct impact on the cooling capacity in the second stage. The energy balances obtained were in the range of ± 20% for all conditions. Zeng et al. [32] analyzed a solar-hybrid one-rotor two-stage desiccant cooling and heating system with mathematical model. The simulation results showed that about 60% of the humidity load can be totally handled by the one-rotor two-stage desiccant cooling unit, and about 40% of the heating load can be met using solar energy. Farmahini-Farahani and Heidarinejad [33] presented a system which based on a combination of nocturnal radiative cooling and two-stage evaporative cooling. The results obtained showed that the novel system should be considered as a new alternative for typical cooling systems in some hot regions.