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Numerical investigation of wet-bulb effectiveness and water consumption in one-and two-stage indirect evaporative coolers

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ABSTRACT

In this study, three configuration for two-stage indirect/indirect evaporative cooling systems (IEC/IEC) were proposed (Type A, Type B and Type C) to determine what configuration produces a better wet-bulb effectiveness (or better energy-saving). For this purpose, six cities with a variety of hot weather conditions with the dry-bulb in range of 31.9–46.66 °C were selected. Results show that under these three configuration, the wet-bulb effectiveness of Type A, Type B and Type C varies over ranges of 62–68%, 76–81% and 85–91% respectively, whereas the effectiveness of a one stage IEC varies over a range of 54–60%. There is a common misconceive belief in the concept of water evaporation rate of an evaporative cooling system, which were fueled by many articles; this belief is, if a cooler consumes less water it is an environmentally friendly cooler for dry areas. A more accurate and practical definition is proposed in this article named Dimensionless Water Evaporation Rate (DWER). The numerical results showed that Type B is the optimum configuration, because of a range of 4–24% DWER saving could be obtained by Type B in comparison with Type C whereas Type B increases the product air up to 32%. As well as IEC, in a counter-flow regenerative evaporative cooler the DWER decreases as the primary airflow rate increases whereas water consumption increases. Moreover, using Type B the index of thermal comfort was investigated which showed that Type B could meet thermal comfort condition in two climatic zones of temperate-dry and hot-dry.

1. Introduction

Direct Evaporative Cooling system (DEC) and Indirect Evaporative Cooling system (IEC) are two main groups in evaporative cooling systems. In hot and humid or temperate and humid regions where the DEC and IEC systems do not provide comfort condition, mechanical vapor compression cooling systems are used. some advantages of evaporative cooling systems in comparison with mechanical vapor compression systems are as following:

(a) Reduction in electrical input power and input current.
(b) Using environmentally friendly liquid as the working fluid.
(c) Elimination of ozone-depleting fluid from refrigeration cycle.
(d) Ability to induce fresh air into the room.
(e) low base price.

Also, some disadvantages of evaporative cooling systems are as following:

(a) Water supply restrictions in an area where water is very scarce.
(b) Evaporative cooling systems will have little or no cooling effect in a moist environment.
(c) Due to supplied humid air in the room, the air of room will get saturated.
(d) Evaporative cooling systems need more frequent maintenance.
(e) Evaporative cooling systems need ductwork.

The simplest and oldest form of the evaporative cooler is DEC. In a DEC a fan is used in order to propel outdoor air through a porous wetted pad. In a DEC the pads are wetted using the gravity-driven water which are supplied from the water sump using water pump. In a direct evaporative cooler, sensible heat changes into the latent heat therefore, the dry bulb temperature of the air decreases. In a DEC, the heat and mass transferred between air and water, decreases the dry bulb temperature of the inlet air while increases the inlet air relative humidity. This process can be considered as an

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Nomenclature

c_p	specific heat capacity (kJ/kg °C)
C_w, C_F	water to air and fluid to air heat capacity rate ratios, respectively
D_H	hydraulic diameter of channel (m)
DBT	dry bulb temperature (°C)
$DWER$	dimensionless water evaporation rate $\left(\frac{kg}{kg\ Primary\ air}\right)$
h	heat transfer coefficient (W/m^2°C)
h_c	convective heat transfer coefficient (kW/m^2 °C)
h_{fg}^0	evaporation heat of water at reference temperature (0 °C) (kJ/kg)
h_v	specific enthalpy of water vapor at water film temperature (kJ/kg)
k	thermal conductivity (W/mK)
K_m	convective mass transfer coefficient (kg/m^{2}s)
L	length of channel (m)
Le	Lewis factor
m	mass flow rate (kg/s)
NTU	number of heat transfer units
Nu	Nusselt Number
p	pressure (Pa)
Q	secondary airflow rate (m^3/h)
R_{va}, R_{wa}	water vapor and liquid water to dry air specific heat capacity ratios, respectively
RH	Relative Humidity (%)
Re	Reynolds Number
s_p	spacing between palate (m)
t	thickness of the wall (m)
T	temperature (°C)
U	overall heat transfer coefficient (kW/m^2°C)
V	velocity (m/s)
W	width of channel (m)
WBT	wet bulb temperature (°C)
WER	water evaporation rate (l/h)
x	coordinate along length of channel (m)
y	coordinate along width of channel (m)

Greek letters

η	wet-bulb effectiveness
λ	ratio of thermal conductivity $\frac{k_y}{k_x}$
ρ	density (kg/m^3)
μ	dynamic viscosity coefficient (Pa s)
σ	surface wettability
ω	Humidity ratio of moist air (kg/kg(a))

Subscripts

a	secondary air or working air (wet channel)
asw	moist air in equilibrium with water surface
db	dry bulb
f	primary air or air (dry channel)
i	inlet
o	outlet
pl	wall
$Rmax$	maximum living room
$Rmin$	minimum living room
v	water vapor
vs	saturation vapor
w	water film
wb	wet bulb

adiabatic cooling process, so, the enthalpy of the inlet air remains constant. Therefore, in a DEC, the wet bulb temperature of the inlet and outlet air has the same value. By adiabatic saturation process in a DEC, minimum temperature of the product air will be limited by the wet-bulb temperature of the ambient air. Parameters that can affect the wet bulb effectiveness of a DEC are: air velocity through the pad, pad thickness, inlet air temperature and wetted surface area per unit volume of the material.

When the increase in the air moisture content is not desired, the indirect evaporative cooling system shall be used. In an indirect evaporative cooling system there are two air streams, primary and secondary air. In the wet channel, secondary air is directly cooled by evaporation of the water. In fact, water film absorbs sensible heat of the secondary air and converts it into the latent heat by water evaporation, therefore the secondary air will be humidified. In the dry channel, due to the heat conduction through the separating wall between wet and dry channels, primary air stream will be cooled without any increase in the humidity ratio of the primary air. The product air (primary air) leaves the dry channel at a lower wet bulb temperature.

Indirect evaporative cooling systems can be classified into the two main groups: above-wet bulb cooling and sub-wet bulb cooling. Using pre-cooling the secondary air (working air, before it enters the wet channel) indirect evaporative cooling systems can be used for sub-wet bulb cooling. This sub-wet bulb cooler is called as Regenerative Evaporative Cooler (REC). In a regenerative evaporative cooler, a portion of inlet air stream is extracted for product air at the end of the dry channel (turning point) and the remaining air stream is being diverted into the wet channel. Fig. 1(a) and (b) shows the schematic of working principle for an indirect evaporative cooling system and a regenerative evaporative cooling system respectively. Fig. 1(c) shows the element that was used in mathematical model of an indirect evaporative cooling system. This element consists of the dry channel, the plate wall, the water layer and the wet channel. In addition, the origin of the used *x*-*y*-coordinate and exchanger dimensions are shown in the Fig. 1(c).

An early study on characteristics of an IEC was done by Pescod [1]. With respect to low thermal conductivity of the plastic plates, Pescod [1] showed that in an exchanger the heat transfer resistance of thin plastic plates would be less than the thermal resistance between the air and plate in dry channel. His model showed discrepancy with experimental data in numerical study of efficiency for an IEC. Maclaine-cross and Banks [2] based on analogy to dry surface heat exchangers proposed a simplified model for heat and mass transfer process in the exchanger. They assumed stationary water layer, whereas water continuously replenished with water at the same temperature. Chen et al. [3] proposed a heat and mass transfer model for calculations of thermal and hydraulic performance of an indirect evaporative cooler. They have presented a universal model, which could be used in simulation of tube- and plate-types of indirect evaporative cooling systems. Their numerical results were presented for water evaporation rate, air pressure drops, cooling capacity, COP, effectiveness, and power demand of the unit. In order to calculate the performance of an indirect evaporative cooler, a user-friendly model were proposed by Alonso et al. [4]. Their model was universal and could be used in order to analyze different indirect evaporative coolers and energy analysis as well as for system or product optimization. Joudi and Mehdi [5] evaluated two arrangements of an indirect/direct evaporative cooling system. They considered four