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Research Paper

Experimental study of the energy and exergy performance of a plastic mesh evaporative pad used in air conditioning applications

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HIGHLIGHTS

- 250-mm thick pad exhibits a maximum saturation efficiency of 80.5%.
- Maximum pressure drop is less than 17 Pa at air velocity of 1.95 m/s.
- Saturation efficiency decreases with increasing air velocity and decreasing pad thickness.
- Exergy efficiency evidences an opposite behaviour compared to saturation efficiency.
- Overall exergy efficiency could be used to optimize operating conditions of the pad.

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ABSTRACT

This paper experimentally studies the thermal and fluid-dynamic behaviour of a new type of evaporative pad made from a high-density polyethylene mesh. Three different pad sizes with dimensions of 492 × 712 mm and thicknesses of 80, 160, and 250 mm are tested. The experiments are conducted in a subsonic wind tunnel adapted to recirculate water on the pads by a pump-driven circuit. A complete set of tests are carried out in which the cooling pad operating parameters such as air flow velocity, water flow rate and pad thickness are varied. As a result, the values of the following characteristic variables of the cooling pad are obtained: saturation efficiency, energy efficiency, exergy efficiency, pressure drop, humidity ratio variation, air temperature variation and amount of evaporated water. The results show that the maximum saturation efficiency of this type of pad is 80.5% and the maximum pressure drop in the air flow is less than 17 Pa. In addition, it is established that the behaviour of exergy efficiency is opposite to the expected function of the evaporative pad and varies from 70% to 94% with decrease in pad thickness. Finally, a new overall exergy efficiency is proposed in this study to optimize the operating conditions of the evaporative pad in air conditioning applications.

1. Introduction

According to the International Energy Agency, the energy consumption in the building sector represents 32% of the total world energy consumption, which makes this sector the largest consumer of energy at present. Directive 2010/31/EU on energy performance of buildings and directive 2012/27/EU on energy efficiency state that 40% of the total energy consumption in the European Union corresponds to buildings and that this sector is expanding; it is therefore necessary to establish energy-saving measures to achieve the energy efficiency goal of 20% by 2020.

The energy consumption of air conditioning systems and their environmental impact in terms of CO_2 emissions are largely the result of the condensation system of their refrigeration cycle. A reduction of the condensing temperature implies a reduction of the condensing pressure, which has a beneficial effect on the power consumption of the compressor by reducing its compression ratio and improving its performance. In addition, a decrease in the condensing pressure produces a higher amount of refrigerant in the liquid phase at the end of the expansion system and enables the evaporator to operate with a higher cooling capability.

A method for improving the performance of air conditioning systems that use air condensation encompasses reducing the temperature of the ambient air that enters the condenser by passing it through an evaporative cooling module. There are two techniques commonly used to achieve this effect: direct evaporative cooling and indirect

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Nomenclature

a,b,c	constants in Eq. (14)
A_s	total exposed surface area of the pad module, $A_s \equiv \xi$ (m^2)
A_V	wetted media surface area per unit volume of the evaporative pad (m^2/m^3)
$c_{p,a}$	specific heat at constant pressure of moist air (J/kg K)
d_1,e_1,f_1	constants in Eq. (28)
d_2,e_2,f_2	constants in Eq. (29)
ex	specific exergy (J/kg)
$\dot{E}x_{dest}$	rate of exergy destruction (W)
g	standard gravity (m/s^2)
$g°_f$	Gibbs function of formation (J/kg)
h	enthalpy (J/kg)
h_C	convective heat transfer coefficient of air (W/m^2 K)
h_D	convective mass transfer coefficient (kg/m^2 s)
$h_{f,w}$	specific enthalpy of water evaluated at T_w (J/kg$_w$)
$h_{fg,w}$	change of phase enthalpy: $h_{fg,w} = h_{g,w} - h_{f,w}$ (J/kg$_w$)
$h_{g,T}$	specific enthalpy of saturated water vapor at T (J/kg$_w$)
$h_{g,w}$	specific enthalpy of saturated water vapor at T_w (J/kg$_w$)
k	thermal conductivity (W/m K)
Le	Lewis number ($Le = h_C/h_D c_{p,a}$)
l	thickness of the evaporative pad, $l \equiv \delta$ (m)
l_e	characteristic dimension of the pad module, $l_e = V/A_s = 1/\xi$ (m)
m,n	constants in Eq. (15)
$\dot{m}_a$	mass flow rate of dry air (kg$_a$/s)
$\dot{m}_w$	mass flow rate of water (kg$_w$/s)
$\dot{m}_{rw}$	mass flow rate of recirculated water (kg$_w$/s)
NTU	number of transfer units ($UA/C_{\min}$)
Pr	Prandtl number ($\rho \nu c_{pa}/k$)
Q	water flow rate per exposed pad surface area (l/min m^2)
q_a	volumetric air flow rate (m^3/s)
q_{rw}	volumetric flow rate of recirculated water (m^3/s)
R_i	Specific gas constant (J/kg K)
Re	Reynolds number ($Re = v_a l_e/\nu$)
s	constant in Eq. (13), specific entropy (J/kg K)
$\dot{S}_{gen}$	rate of entropy production (W/K)
T	temperature (K)
T_{wb}	wet bulb temperature of moist air (K)
V	volume of the pad module (m^3)
v_a	airflow mean velocity (m/s)
ω	humidity ratio of moist air (kg$_w$/kg$_a$)
$\omega_{s,w}$	humidity ratio of saturated moist air evaluated at T$_w$ (kg$_w$/kg$_a$)
ω_s^*	humidity ratio of saturated moist air evaluated at T$_{wb}$ (kg$_w$/kg$_a$)
y_i	mole fraction of component i of the gas phase
z	elevation (m)

Greek symbols

β_1,β_2	constants depending on pad material and configuration
δ	thickness of the evaporative pad (m)
η	saturation efficiency
η_{en}	energy efficiency
η_{ex}	exergy efficiency
γ	constant in Nusselt equation
ν	kinetic viscosity of air (m^2/s)
ρ	density (kg/m^3)
ξ	compactness of the evaporative pad (m^2/m^3)

Subscripts

0	dead state conditions
1	inlet airflow
2	outlet airflow
a	air
v	water vapor
rw	recirculated water
f	saturated liquid water
g	saturated water vapor
w	water, evaporated water

Abbreviations

COP	coefficient of performance

evaporative cooling. In systems with direct evaporative cooling, air comes into contact with water in a cross-flow heat exchanger. The air blown by a fan goes through a pad consisting of a mesh made of a porous or plastic material whose surface is constantly moistened by the spray or vertical drip of the water driven by a hydraulic pump. In the process of evaporative cooling, the sensible heat of the air turns into latent heat of the water vapour that forms and ultimately joins the air stream. In this process, the enthalpy and wet bulb temperature of the air stream remain essentially constant, and there is almost no heat exchange with the outside environment; hence, this process is also called adiabatic cooling.

Evaporative cooling systems work extremely well in hot, dry climates, where their maximum cooling capacity can be experienced. There are numerous studies that have demonstrated how the performance of air conditioning systems benefits from the use of evaporative cooling processes. Evaporative pre-cooling units or pads are used in aero-condensers to reduce the air inlet temperature and use less than 15% of the water required by cooling towers for their operation [1]. Hajidavalloo and Eghtedari [2] connected an evaporative cooler to the condenser of a split-type air conditioner and proved that in a hot and dry climate, the system could reduce power consumption by up to 20% and increase its coefficient of performance (COP) by up to 50%. Wang et al. [3] compared a conventional air conditioning system for residential use with a system with pre-adiabatic cooling and demonstrated that refrigerant flow in the evaporator increased, and the COP increased by more than 10%. The authors of this paper studied the efficiency improvement of a conventional air conditioning system with evaporative pre-cooling pads of different thicknesses and noted that the consumption of the compressor decreased by 11.4% and the COP increased by 10.6%.

The efficiency of evaporative cooling pads depends on several factors: air-water surface contact, pad thickness, type of pad material (metal, plastic, cellulose, plant fibres, etc.), geometric structure of the mesh of the pad, air flow and its psychrometric conditions, water flow, etc. Several experimental, analytical, and numerical studies have been conducted to determine the performance and efficiency of these pads. Koca et al. [4] designed a test methodology for evaporative pads and proved that both the pressure drop caused by the pad and their efficiency depends on air velocity and its thickness. Liao and Chiu [5] developed a compact wind tunnel to determine the efficiency of two types of evaporative pads made of coarse and fine fabric PVC sponge mesh with pinhole diameters of 2.5 and 7.5 mm, respectively. The authors investigated the effects of water flow, air velocity, and pad thickness on efficiency and found that the pad made with coarse fabric PVC sponge was more efficient. Gunhan et al. [6] experimentally tested different porous materials, such as volcanic tuff, and determined that these materials are a good options for low air velocities of 0.6 m/s. In addition, the authors demonstrated that increasing the thickness of the pads and the water flow increases efficiency; however, in this case, the pressure drop also increased. Beshkani and Hosseini [7] performed a