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Modeling and experimental study of an indirect evaporative cooler

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ABSTRACT

The use of indirect evaporative cooling technologies is an effective way to reach high energy efficiency systems and to reduce primary energy consumption. At present, interest in such systems is strongly increasing, with particular attention to data centers facilities. In fact, in these applications the indoor air temperature can be higher than the one of residential and commercial buildings, leading to a greater number of yearly operating hours of the system.

In this paper an indirect evaporative cooler, based on a cross flow heat exchanger, has been tested and modelled. Many experiments have been carried out in typical data centers operating conditions, varying both water flow rate and inlet air conditions. A phenomenological model of the indirect evaporative cooler has been developed: the model takes into account the effects of the adiabatic cooling of the secondary air stream in the inlet plenum and the actual wettability of the heat exchanger surface. The model has been extensively validated and it is shown that simulation results are in very good agreement with experimental data. Therefore, it can be a suitable tool to design and to predict performance of indirect evaporative cooling systems.

1. Introduction

In recent years, demand of ICT services raised fast, leading to a significant increase in the number and size of data centers [1]. It has been estimated that in 2010 the worldwide electricity used by data centers was 1.3% of the total consumption [2] and that in 2012 it was around 270 TWh [3]. It is well known that in such facilities high heat fluxes should be dissipated: they can reach even 10 kW m^{-2}, leading to an electricity consumption for cooling up to 50% of the total consumption of the data center [1,2]. As a consequence, there is great interest from executive, technical and research personnel in improving both cooling system design and operation.

At present, buildings containing servers are mainly cooled through conventional vapour compression chillers. Recently, thermal ASHRAE guidelines for data centers [4], reporting appropriate temperature and humidity range for operation of ICT equipment, have been updated. The maximum allowable temperature, which should be properly selected in order to achieve energy savings and ICT equipment reliability, has been raised up even to 45 °C. Therefore, interest in application of free cooling technologies in data centers is rapidly increasing.

In the air to air indirect evaporative cooling systems, which are one of the most promising technologies, the primary air stream, which is supplied to the building, is cooled in a heat exchanger through a secondary air stream, which is humidified with liquid water. In case of data centers facilities, the system is generally arranged in recirculation mode: the primary air stream is extracted from the building while the secondary air stream is at outdoor conditions. An additional cooling system of the primary air stream is installed, in order to provide backup and peak load cooling capacity.

Currently, many research groups are working on indirect evaporative cooling systems [5], dealing with new thermodynamic cycles, heat exchanger materials and geometries, humidification systems and with the evaluation of energy savings compared to conventional devices. As summarized by Lin et al. [6], several models of indirect evaporate coolers based on cross-flow heat exchangers, which are widely used components, have been proposed in literature. Guo and Zhao [7] developed a one dimensional model, investigating the effects of many input parameters on system performance. Stoitchkov and Dimitrov [8] developed a short-cut method for calculating the effectiveness of a cross-flow IEC, introducing a correction to the Maclaine-cross and Banks' model [9]. Bolotin et al. [10] presented an ε-NTU analysis of two different

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Nomenclature

A–C	Experimental setup configuration
$A_{HE,net}$	Net heat exchanger cross area $[\mathrm{m^2}]$
cp	Specific heat $[\mathrm{J\,kg^{-1}\,K^{-1}}]$
c_1–c_4	Correlation parameters
Cw	Wettability coefficient
D_1–D_3	Setup geometric distances [m]
h	Net channel height [m]
H_{HE}	Heat exchanger height [m]
k	Thermal conductivity $[\mathrm{W\,m^{-1}\,K^{-1}}]$
h_M	Convective mass transfer coefficient $[\mathrm{kg\,s^{-1}\,m^{-2}}]$
h_T	Convective heat transfer coefficient $[\mathrm{W\,m^{-2}\,K^{-1}}]$
k_1–k_3	Correlation parameters
$L_{HE}{}^*$	Net plates length and width [m]
$\dot{m}$	Specific flow rate $[\mathrm{kg\,s^{-1}\,m^{-2}}]$
$\dot{M}$	Flow rate $[\mathrm{kg\,s^{-1}}]$
N_{HE}	Number of heat exchanger plates [–]
pt	Plates pitch [m]
$\dot{Q}$	Volumetric flow rate $[\mathrm{m^3\,h^{-1}}]$
S1–S4	Numerical simulation conditions
T	Temperature [°C]
U_T	Overall heat transfer coefficient $[\mathrm{W\,m^{-2}\,k^{-1}}]$
T0–T12	Experimental test conditions
v	Velocity $[\mathrm{m\,s^{-1}}]$
x	Primary air flow direction [m]
x_i	Measured quantity [–]
X	Humidity ratio $[\mathrm{kg\,kg^{-1}}]$
y	Secondary air flow direction [m]
y_i	Calculated quantity [–]

Greek letters

α, β	Correlation parameters
δ	Plates thickness [m]
δ_w	Water thickness [m]
ΔT	Temperature difference [°C]
ΔX	Humidity ratio difference $[\mathrm{kg\,kg^{-1}}]$
ε_{db}	Dry bulb effectiveness [–]
ε_h	Saturation efficiency [–]
ρ	Density $[\mathrm{kg\,m^{-3}}]$
σ	Wettability factor [–]
φ	Relative humidity [–]

Superscripts

N	Nominal condition ($\rho = 1.2\,\mathrm{kg\,m^{-3}}$)

Subscripts

a	Air
HE	Heat exchanger
in	Inlet
out	Outlet
p	Primary air
s	Secondary air
sat	Saturation condition
v	Water vapour
w	Liquid water
W	Wall heat exchanger plates
wb	Wet bulb condition

Acronyms

EXP	Experimental
IEC	Indirect evaporative cooling
ICT	Information and communication technologies
NUM	Numerical

configurations of cross flow IEC, based on experimental tests provided by Martinez et al. [11]. Ren and Yang [12] discussed an analytical model of a parallel/counter-flow configuration of IEC, evaluating the effect of the wettability factor on performance. Heidarinejad and Moshari [13] developed the model proposed by Ren and Yang [12] to describe a sub-wet bulb indirect evaporative cooler. Hasan [14] presented a model for a sub-wet bulb IEC based on the ε-NTU method, using experimental data provided by Hsu et al. [15]. Finally, several works focus on the M-cycle or regenerative configurations: Anisimov et al. [16] evaluated performance of a system based on a cross flow heat exchanger, Pandelidis et al. [17] discussed the effect of different indirect evaporative coolers in desiccant cooling systems and Moshari et Heidarinejad [18] numerically studied a system for sub-wet bulb cooling. Anyway, these systems are not suitable for data centers: in fact, as previously described, in these applications the primary air flow of the IEC system is recirculated and it is completely separated from the secondary air stream.

It is well known that the variation of water flow rate has a significant effect on system performance [19]. In particular, the IEC system cooling capacity decreases significantly when the water flow rate cannot provide a satisfactory wettability of the heat exchanger surface. Furthermore, depending on the equipment setup, part of the supplied water can evaporate in the inlet plenum, leading to a pre-cooling and humidification of the secondary air stream which should be properly considered. Such effects have not been analyzed in detail in the existing literature. Therefore, the aim of this work is to develop an indirect evaporative cooling system model taking into account:

- The effect of adiabatic humidification of the secondary air stream in the inlet plenum.
- The wettability factor of the heat exchanger surface, as a function of the operating conditions of the system.

The research has been carried out through a detailed experimental analysis of the system. The model has been widely validated within and outside the calibration range and simulations have been performed to investigate primary air cooling in different working conditions of data centers.

2. Description of the investigated indirect evaporative cooling system

As shown in Fig. 1, the analyzed indirect evaporative cooling system consists of a commercial cross-flow plate heat exchanger, of n° 8 water spray nozzles installed in the upper part of the component and of an equipment to increase water pressure.

According to Fig. 1, the primary air stream is cooled in the heat exchanger at constant humidity ratio: it enters the system in condition *p,in* (indoor data center air condition) and it leaves the component in condition *p,out*. The secondary air stream, whose inlet condition is denoted as *s,in* (outside air condition), is supplied to the upper plenum where spray nozzles are installed. Due to the evaporation of water droplets, the secondary air stream is humidified almost at constant enthalpy and it reaches the heat exchanger face in condition *s,in,HE*, with higher humidity ratio and lower dry bulb temperature compared to the inlet condition *s,in*. Afterward, the secondary air stream passes through the heat exchanger and most water droplets impact on plate's surface. The further water evaporation leads to a reduction of the temperature of the secondary air stream, of the heat exchanger plates and of the primary air stream, which is the useful effect of the system. The secondary air stream leaves the system from the lower plenum in condition *s,out*.