Energy Conversion and Management 102 (2015) 140–150

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Performance evaluation of an indirect pre-cooling evaporative heat exchanger operating in hot and humid climate ☆

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A R T I C L E I N F O

Article history:
Available online 24 February 2015

Keywords:
Air conditioning
Mathematical model
Heat and mass transfer
Condensation
Indirect evaporative cooling

A B S T R A C T

A hybrid system, that combines an indirect evaporative heat exchanger (IEHX) and a vapor compression system, is introduced for humid tropical climate application. The chief purpose of the IEHX is to pre-cool the incoming air for vapor compression system. In the IEHX unit, the outdoor humid air in the product channel may potentially condense when heat is exchanged with the room exhaust air. A computational model has been developed to theoretically investigate the performance of an IEHX with condensation from the product air by employing the room exhaust air as the working air. We validated the model by comparing its temperature distribution and predicted heat flux against experimental data acquired from literature sources. The numerical model showed good agreement with the experimental findings with maximum average discrepancy of 9.7%. The validated model was employed to investigate the performance of two types of IEHX in terms of the air treatment process, temperature and humidity distribution, cooling effectiveness, cooling capacity, and energy consumption. Simulation results have indicated that the IEHX unit is able to fulfill 47% of the cooling load for the outdoor humid air while incurring a small amount of fan power. Consequently, the hybrid system is able to realize significant energy savings.

1. Introduction

Indirect evaporative cooling (IEC) is an effective and sustainable method for cooling application. Compared with conventional vapor compression cooling system, the IEC is gaining global interest due to its lower energy consumption coupled with low initial cost and simplicity of operation. [1,2]. Indirect evaporative heat exchanger (IEHX) usually employs a plate type wet surface heat exchanger. In a typical IEHX, the dry stream (or product air) flows in alternative passages and utilize the cooled wet stream (working air) as its heat sink. As it takes advantage of water evaporation to reduce the air temperature, indirect evaporative cooling is best suited for hot-arid regions.

Research works have been conducted to fundamentally understand the heat and mass transfer process in the IEHX. Kettleborough and Hsieh [3] developed a mathematical model for a counter-flow wet surface plate heat exchanger cooling unit. The theoretical minimum temperature in this heat exchange was the initial wet-bulb temperature of the ambient air. Erens and Dreyer [4] illustrated and compared three analytical models for the IEHX. Maclaine-cross and Banks [5] introduced a linear mathematical model for wet surface heat exchangers. Halasz [6] similarly proposed a general model for evaporative cooling devices by the introduction of a straight air saturation line. Based on the previous study [5], Stoitchkov and Dimitrov [7] presented a correction for the effectiveness of a cross-flow plate type IEHX. Ren and Yang [8] developed an analytical model considering the effects of Lewis factor, surface wetting condition, and spray water evaporation.

To further improve the cooling performance of the conventional IEHX, several studies investigated a novel regenerative IEHX that is capable of cooling air below its wet-bulb temperature [9]. In this type of IEHX, the air flow arrangement is termed as the M-cycle since it was proposed by Maisotsenko [10–13]. An analytical model based on the modification of the original effectiveness-NTU method was developed to study the performance of a regenerative IEHX [14,15]. In addition, numerical models have been developed in order to investigate the influence of key parameters on a counter-flow regenerative IEHX [16–19]. Recently, Anisimov et al. [20] developed a numerical model and studied five different flow arrangements based on the M-cycle for evaporative cooling.

☆ This article is based on a four-page proceedings paper in Energy Procedia Volume 61 (2015). It has been substantially modified and extended, and has been subject to the normal peer review and revision process of the journal.

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http://dx.doi.org/10.1016/j.enconman.2015.02.025
0196-8904/

Nomenclature

A	area (m^2)	V	volume flow rate (m^3/s)
α	thermal diffusivity (m^2/s)	ω	humidity ratio (g moisture/kg dry air)
c	molar concentration (mol/m^3)	W	mass transfer rate (kg/s)
c_{pa}	specific heat of moist air (kJ/(kg °C))	W_f	fan power (kW)
D	diffusivity (m^2/s)	X	percentage of cooling load
h	specific enthalpy (kJ/kg)	ε	efficiency
h_{fg}	specific latent heat of water evaporation (kJ/kg)	δ	thickness (m)
H	height of the channel (m)	Z	width of the channel (m)
k	thermal conductivity (kW/(m °C))		
L	length of the channel (m)	*Subscript*	
m	mass flow rate of air (kg/s)	1	product air (primary air)
M	molar mass (kg/mol)	2	working air (secondary air)
n	number of channel pairs	in	inlet
Nu	Nusselt number	out	outlet
P	pressure (kPa)	l	latent
q	heat flux (kW/m^2)	s	sensible
Q	heat transfer rate (kW)	w	water
R	ideal gas constant (J/(K mol))	j	condensation
T	temperature (°C)	dew	dew-point temperature
u	velocity in x direction (m/s)	wb	wet-bulb temperature
v	velocity in y direction (m/s)	pl	plate

The IEHX can be integrated into new or existing air-conditioning systems as pre-cooling unit. This integrated system is able to provide energy and cost saving in various climate conditions [21,22]. Heidarinejad et al. [23] investigated the feasibility of five types of cooling systems in a multi-climates country. They studied the potential of the direct evaporative cooling (DEC) systems, indirect evaporative cooling systems, desiccant wheel with DEC systems, mechanical cooling systems, and combination of these methods for air cooling application. Delfani et al. [24] evaluated the performance of indirect evaporative cooling system to pre-cool air for a mechanical cooling system in Iran. The experimental data and analytical results indicated that the system can achieve about 55% saving in electrical energy consumption. Delfani et al. [25] investigated cooling system combined with air-to-air sensible heat recovery system. The estimated energy consumption can be reduced by 11–32% when using the heat recovery system for building air conditioning. Zhong and Kang [26] studied the potential application of air-to-air heat exchangers for heat recovery system in China by evaluating the energy consumption and the investment specific cost.

In hot and humid climate, however, a stand-alone IEHX is often inadequate to produce comfort conditions for cooling buildings because of the high wet bulb temperature of the ambient air [27]. The exhaust air of a conditioned room generally has a lower temperature and humidity ratio compared with the outdoor humid air. If an IEHX employs the room exhaust air as the working air to pre-cool the outdoor humid air, the humid air in product channel may condense when the plate temperature is lower than the dew-point temperature. As a result, the IEHX presents a more complicated air treatment process with a possibility of condensation in the dry product air flow passages.

It is observed from previous works that the theoretical analysis of an IEHX has been extensively investigated through analytical and numerical models. In many previous studies, the product air and working air have the same inlet conditions so that no condensation occurs in the product air stream since the temperature is always higher than its dew point temperature. However, work related to utilizing room exhaust air as working air to pre-cool the outdoor air in humid tropical climate is scarce. In addition, to the best of our knowledge, few works have studied the complicated air treatment process with condensation from the product air since the temperature may be lower than its dew point temperature when the room exhaust air is used as the working air under humid tropical climate.

The present study develops a computational model to theoretically investigate the performance of an IEHX with condensation from the product air by employing the room exhaust air as the working air under humid conditions. Table 1 indicates the differences between the present study and selected representative studies from recent literature. In this article, we first introduce the hybrid IEHX and vapor compression cooling system, followed by the mathematical description of the IEHX with condensation in product channel. The validated computational model is then employed to examine the performance of two types of IEHX in terms of their air treatment processes, temperature and humidity ratio distributions, cooling effectiveness, cooling capacities, and energy consumptions. The IEHX is theoretically investigated under hot and humid climate. The inlet dry bulb temperature of the product air spanned 30 to 37.5 °C while the relative humidity ranged from 70% to 90%. The working air adopted the room exhaust air at a dry bulb temperature of 25 °C and a relative humidity of 50%.

2. Description of the hybrid IEHX and vapor compression cooling system

A schematic of the hybrid system for cooling application is presented in Fig. 1. The IEHX is employed as a pre-cooling unit before a mechanical vapor compression system.

Two types of IEHX are investigated in this study. The first type of IEHX is a conventional counter flow unit and the second type is a regenerative IEHX unit based on the M-cycle. A schematic of a one-unit channel pair of these two types of IEHX is shown in Fig. 2. The IEHX consists of numerous stacked channel pairs. For Type-1, a one-unit channel pair comprises a product channel and a working channel. In the wet channel, the inner surface is maintained under wet condition by spraying water. The working air directly contacts with the water film, and absorbs heat due to water evaporation. The product air can be cooled along the dry channel by transferring heat to the adjacent working channel. The advantages of Type-1 IEHX include: (1) extensive savings on energy and cost; (2) production of cool air without absolute humidity increase; and (3) reduc-