Applied Thermal Engineering 84 (2015) 211–224

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research paper

Comparison study of the counter-flow regenerative evaporative heat exchangers with numerical methods

Demis Pandelidis [a, *], Sergey Anisimov [a], William M. Worek [b]

[a] *Department of Environmental Engineering, Wroclaw University of Technology, 27 Wyspiański st., 50-370 Wroclaw, Republic of Poland*
[b] *Stony Brook University, College of Engineering and Applied Sciences, Department of Mechanical Engineering, 127 Engineering Bldg., Stony Brook, NY 11794, USA*

HIGHLIGHTS

- A numerical study of regenerative heat exchangers is presented.
- The developed ε-NTU model is verified against existing experimental data.
- Numerical simulations show unique features of the considered exchangers.
- The optimum ranges of the working to main air-flow ratio are determined.

ARTICLE INFO

Article history:
Received 26 October 2014
Accepted 26 March 2015
Available online 4 April 2015

Keywords:
Indirect evaporative cooling
Mathematical model
Regenerative heat and mass exchanger
Channel perforations

ABSTRACT

This paper numerically investigates the performance and heat and mass transfer processes that occur in regenerative heat and mass exchangers (HMXs) used for indirect evaporative air cooling. Two basic types of regenerative air coolers were compared: an exchanger with typical airflows arrangement and an exchanger with perforations along the whole length of the dry channel. The numerical model is based on one-dimensional heat and mass transfer assumptions and was validated against existing experimental data. The results obtained from the simulation reveal high effectiveness of the presented unit. The results allow defining optimal geometric and operational parameters for the typical regenerative exchanger and regenerative exchanger with perforations. It was determined that the value of working to main air-flow ratio has a significant impact on the cooling performance of considered air coolers.

1. Introduction

Energy conservation and environmental preservation has become an important issue worldwide and many systems are designed to minimize energy use and environmental impact. Air-conditioning is used to provide comfort as well as an efficient working environment. On the other hand, typical air handling units consume large amounts of energy. In the context of global scale energy issues, it is necessary to reduce fossil fuel-consumption as well as to find new solutions to replace conventional systems. One of the most promising opportunities is the use of evaporative cooling. Evaporative air coolers utilize the latent heat of water evaporation to provide cooling and are less dependent on fossil fuels [1–4]. Currently available units include direct and indirect exchangers.

Indirect evaporative air coolers can reduce the airflow temperature without adding moisture to it. Thermodynamically, an indirect evaporative air cooler passes primary (main) air over the dry side of the plate of heat exchanger, and the secondary (working) air over the opposite wet side of the exchanger. The wet side absorbs heat from the dry side and cools the dry side, while the latent heat of vaporizing water is given to the wet-side air stream. This feature makes indirect evaporative coolers more attractive than direct evaporative coolers for air-conditioning applications. However, in practice such systems are far from ideal performance. Under typical European and American summer climate conditions the wet bulb cooling effectiveness of indirect evaporative air coolers can reach only 50–60% [3]. Currently, new designs of indirect evaporative units are analyzed in many studies. These units involve structures based on modified indirect evaporative heat exchangers, realizing a new thermodynamic cycle called sub-wet bulb temperature evaporative cooling or dew point cooling [1–7]. These heat exchangers can cool the product air to a temperature below the wet-bulb temperature approaching the dew point temperature of

* Corresponding author.
E-mail address: demis.pandelidis@pwr.wroc.pl (D. Pandelidis).

http://dx.doi.org/10.1016/j.applthermaleng.2015.03.058
1359-4311/

the incoming working air stream. Evaporative cooling below the wet-bulb temperature is a limitation for many typical indirect evaporative air coolers. However, several investigations have been reported on achieving air temperatures lower than the wet-bulb temperature using a new generation of heat exchangers. These are discussed next.

Ray [8] proposed a combined indirect and direct evaporative cooling unit where the temperature of a cooled air flow can be reduced below the wet-bulb temperature. Crum et al. [9] showed that temperatures below the wet-bulb temperature are also achievable with a cooling tower-heat exchanger combination. Riangvilaikul et al. [2,3] carried out experiments to analyze a dew point air cooler performance at various operating conditions. The results indicated that dew point effectiveness varied between 58 and 84% depending on the inlet air conditions. Boxem et al. [10] numerically analyzed a counter-flow heat exchanger with fins on both surfaces. He developed a model that predicts the outlet temperature of a small scale evaporative cooler (400 m^3/h) for different environmental conditions. Discrepancies of up to 20% were reported for inlet airflow temperatures below 24 °C and less than 10% discrepancies for higher inlet air temperatures. Hasan [1,11] numerically simulated multistage heat and mass exchangers under various airflow arrangements. The highest efficiency was obtained by pre-cooling of the working air flow. Lee [12,13] studied different configurations of three indirect evaporative air cooler designs (flat channel plate type, corrugated channel plate type and finned channel type) and compared them to select the most efficient configuration. Zhao et al. [4–6] analyzed a counter-flow heat and mass exchanger. The simulations allowed obtaining the optimal conditions for the exchanger. According to their results, the optimal average air velocities in the dry and wet channels should be in the range of 0.3–0.5 m/s, the recommended channel height is 6 mm or below and the working-to-intake air ratio should be around 0.4. Gillan [14] described cross-flow heat and mass exchanger with the Maisotsenko cycle (M-cycle). This novel thermodynamic cycle allowed achieving outlet air temperatures close to the dew point temperature. As the review shows, previous researchers have indicated the attractiveness of obtaining temperatures below the wet-bulb temperature in evaporative cooling systems. Gao et al. [15] experimentally 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, when the inlet parameters of the airflow or desiccant are changed. The energy balances obtained were in the range of ±20% for all experimental conditions. Montazeri et al. [16] simulated the impact of selected parameters on evaporative cooling efficiency with computational fluid dynamics methods. The selected parameters were: air temperature, air humidity ratio, airflow velocity, water temperature and droplet size distribution. The results showed that the sensible cooling capacity of the system can be improve by more than 40% if, for the given inlet water temperature (35.2 °C), the temperature difference between the inlet air and the inlet water droplets increases from 0 °C to 8 °C. Farmahini-Farahani and Heidarinejad [17] presented a novel system which is a combination of nocturnal radiative cooling and two-stage evaporative cooling. The effectiveness of the system was investigated for four different cities having different climatic conditions. The results obtained indicated that the proposed system can become a new alternative for typical cooling systems in some hot regions. Zeng et al. [18] numerically studied a solar-hybrid one-rotor two-stage desiccant cooling and heating system. 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.

The objective of this paper is to numerically study a method to improve the effectiveness of regenerative air coolers. The two main different types of exchangers will be analyzed and their performance will be compared. First a typical regenerative heat and mass exchanger and regenerative HMX with perforations (Fig. 1) will be considered. Three types of perforation densities will be considered: 5; 10 and 20 holes along dry channel. Additionally, the influence of the channel shape on efficiency of considered exchangers will be examined. A computational model based on mathematical analysis of the heat and mass transfer processes inside a cooler is developed for this purpose.

2. Methods

The mathematical models developed to analyze the performance of indirect evaporative coolers are based on the modified ε-NTU method. In this method, the air stream in the matrix passages is considered as a gaseous fluid flow with constant temperature, velocity and mass transfer potential (humidity ratio of the air) in the direction normal to the plate surfaces. It is assumed the bulk average values can be used for all variables (the details of the evaporative air coolers analysis with the ε-NTU method are presented in Refs. [1,7,19–21]). The basis of the method, including main heat transfer and flow characteristics assumptions, are presented in Ref. [22]. The main assumptions used in the model are listed below for completeness.

In the perforated regenerative exchanger, the perforations are regularly distributed in the plate along the X–axis in each cross-section (e.g. for exchanger with 5 holes, they are placed in sections $\overline{X} = X/L_X = 0.2$; 0.4… etc. – Fig. 2(b)). In each cross-section of the X–axis, 1/5 1/10 or 1/20 (depending on the assumed number of holes) of the total working air flow gets to the wet channel (regardless of the number of holes along the Y– axis). The basic explanation of the assumptions connected with analysis of the perforated air coolers was presented by Anisimov and Pandelidis in Ref. [7,21]. A small number of perforations was adopted for a detail analysis of the impact of air streams mixing phenomenon on the heat and mass transfer processes in the wet channel of the indirect evaporative HMX.

The balance equations used in the mathematical models are the same for the typical regenerative exchanger and regenerative exchanger with perforations, the only difference is the value of NTU number which is constant for regenerative HMX and variable for perforated HMX. The main difference between the two models lies

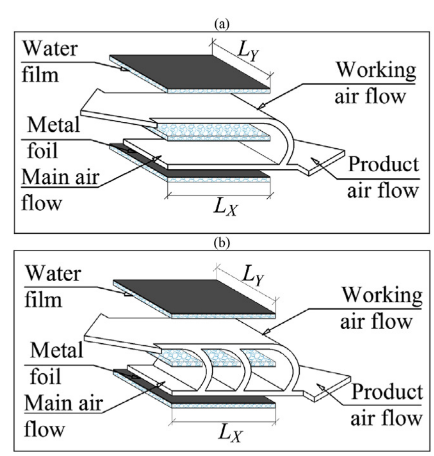

Fig. 1. Analyzed exchangers: (a) typical regenerative HMX, (b) perforated regenerative HMX.