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Performance comparison of the advanced indirect evaporative air coolers

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This paper numerically investigates the performance of the three highly efficient, advanced indirect evaporative air coolers: the “classical” cross-flow Maisotsenko cycle (M-Cycle) heat and mass exchangers and two novel combined M-Cycle air coolers proposed by authors. The novel heat and mass exchangers are based on a combination of parallel and counter-flow and cross and counter-flow schemes. An original mathematical models were developed and validated against experimental data.

Analysis of the results allowed establishing appropriate operational parameters (i.e. airflow ratios and initial sections relative length) for the new heat exchangers. The novel units were compared with cross-flow M-Cycle heat and mass exchanger. The main conclusion is that proposed solutions are characterized by higher cooling efficiency than the cross-flow M-Cycle unit. Combined cross-regenerative counter flow heat and mass exchanger obtained highest overall performance.

1. Introduction

During the last 20 years primary energy consumption has grown by 49% with an average annual increase of 2%. The predictions show that this growing trend will continue. Final energy consumption is usually divided into three main sectors: industry, transport and “other”, including agriculture, service and residential sector [1]. The application of environmentally friendly cooling technologies has raised attention of researchers and consumers [2], due to the large amount of electrical energy consumed by traditional air-conditionings. The air-conditioning can be applied in any climate, however, it is expensive and it is not environment-friendly. The higher working and living standards correlated with the reduced prices of air-conditioning systems caused significant increase in demand for air-conditioning in buildings. In European Union (EU) energy demand for space cooling applications has grown 14.6% per annum between 1990 and 2000 and it is expected an annual growth of 3.4% in the 2000–2030 period. The number of room air-conditioners in use in EU has grown from a value of 1.2 million in 1990 to 7.4 million in 1996, and should be close to 33 million in 2020, with an estimated electricity consumption of 43,928 GW h/year, four times greater than the 1996 value [3]. One of the methods considered as an alternative to the traditional air conditioning systems is indirect evaporative cooling.

Over the last few decades, many numerical [4–10] and experimental [11–17] studies have been performed for predicting performance of indirect evaporative coolers under various climatic conditions and analyzing the impact of different operating and geometrical parameters on the cooling effectiveness. Moshari and Heidarinejad [6] presented the numerical simulations of cross- and counter-flow regenerative evaporative coolers (REC) and a cross-flow indirect evaporative cooler (IEC) using Finite Difference Method and solved by an iterative method in Matlab. The influence of pre-cooling the working air of REC was conducted and compared to a four-stage IEC, which showed that the counter-flow REC can produce the lowest temperature of the inlet air in comparing to both cross-flow REC and four-stage IEC with the same air and exchanger parameters of this study. The numerical results showed the applicability of regenerative evaporative cooler in sub-wet bulb cooling for air conditioning systems. Maclaine-Cross and Banks [18] proposed a simplified mathematical model for heat and mass transfer process in the indirect evaporative cooling. Their model had some assumptions such as water film is stationary and constantly refilled with water at the same temperature. Zhan et al. [19] numerically analyzed the thermal performance of a cross-flow regenerative HMXs and

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evaluated the effect of operational parameters on the exchanger performance. A numerical simulation of a counter-flow regenerative heat and mass exchangers with separated working and product channels was also investigated by Cui et al. [20]. Riangvilaikul and Kumar [21] conducted an experimental study of a regenerative HMX to examine the exchanger effectiveness under various inlet air conditions. Zube and Gillan [22] carried out an experimental study of cross-flow M-Cycle heat exchanger to achieve the internal parameters for product and exhaust channels. Bruno [23] tested the performance of a novel dew-point evaporative cooler with counter-flow RHMX and noted a wet bulb effectiveness of 100–113%. It was indicated that the dew-point cooler could reduce the energy use by 54%. Lin et al. [24] presented the development of a transient model for a counter-flow dew-point evaporative cooling system. The transient results of the dew-point evaporative cooling system were investigated under various operating conditions. It was shown that the developed transient model is able to calculate the supply air temperature with at most discrepancy of 4.3%. Fakhrabadi and Kowsary [25] investigated a regenerative evaporative exchanger for indirect evaporative cooling. This article presented the optimal design of the proposed air cooler. The cooling capacity was studied as a main factor to achieve the optimal performance of the heat and mass exchanger. It was summarized that the working-to-primary air flow ratio is around 0.4 and the recommended geometrical characteristics is between 0.4 and 0.6 m for channel length and 0.004–0.006 m for channel height. Jradi and Riffat [26] conducted the experimental and numerical study of a dew-point cross-flow unit for air-conditioning comfort in buildings. A complex numerical model was developed for the indirect evaporative cooler in Matlab environment. Using the mathematical model, the simulations were performed to investigate the effect of different operating conditions on the overall cooler's performance. Moshari et al. [27] proposed three configuration (type A, type B and type C) for two-stage indirect/indirect evaporative cooling systems to determine configuration with better wet-bulb effectiveness in various climatic conditions. Numerical results showed that under these three configuration, the average wet-bulb effectiveness of Type A, Type B and Type C were around 8%, 21.5% and 31% higher than that of the one stage IEC respectively. Heidarinejad and Moshari [28] conducted the numerical study of an indirect evaporative cooling system (IEC) with consideration of wall longitudinal heat conduction and effect of spray water temperature variation along the exchanger surface. Comparing the numerical results of the presented simulation against experimental data revealed excellent agreement with them and showed around 3% discrepancy in the calculation. The numerical results showed applicability of the presented model for both sub-and above-wet bulb cooling applications. Xu et al. [29] investigated the energy performance of a novel irregular heat and mass exchanger for dew point cooling. CFD simulation was carried out to determine the flow resistance factors inside the heat and mass exchanger's channels. The optimum height of the channel was 5 mm while its length was in the range 1–2 m. The COP of the dew point cooler with irregular exchanger was 29.7%–33.3% higher in comparison with the flat-plate exchanger.

In view of the above, many researchers have focused on the reduction of primary energy consumption. The researchers showed the high potential of indirect evaporative cooling systems to become the new, cheap and environmentally friendly source of cooling energy. According to the literature there are many methods to obtain high cooling efficiency with indirect evaporative cooling. One of such opportunities is the Maisotsenko cycle, the unique thermodynamic process, where air flow can be cooled to the very low temperature levels with indirect evaporative air cooling (Fig. 1 (a)). Another method is the combination of direct and indirect evaporative air cooling [30,31]. Such method allows achieving high efficiency, but it is connected with using multiple devices which is

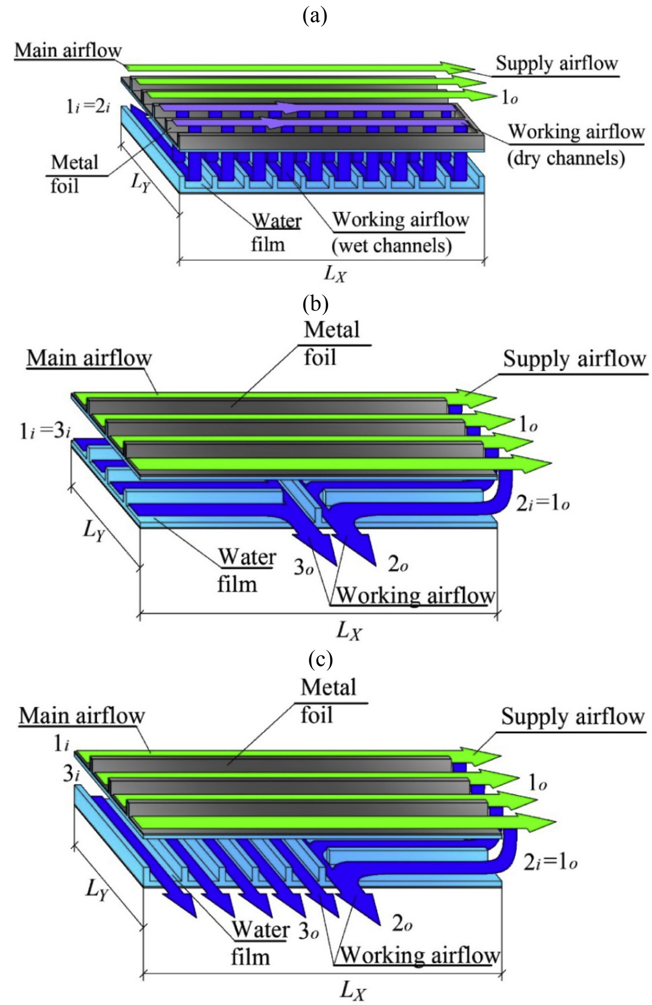

Fig. 1. Indirect evaporative air coolers studied in this paper. (a) Cross-flow Maisotsenko-cycle air cooler. (b) Combined parallel-regenerative counter flow exchanger. (c) Combined cross-regenerative counter flow exchanger.

more expensive and covers more space than one simple unit. In many cases investors and producers give preference to simple unit, which may be less effective but it is easier to apply in air conditioning units than combination of few different exchangers. High efficiency within a simple device can be achieved through Maisotsenko cycle especially in advanced indirect evaporative air coolers, with combined air flow schemes. That is why presented paper focuses on three units with advanced indirect evaporative cooling cycles, which can achieve high effectiveness and have very high potential to become a partial replacement for traditional air conditioning systems. First unit is a cross-flow M-Cycle heat and mass exchanger (Fig. 1(a)), two other units are novel devices proposed by authors (Fig. 1 (b) and (c)). Due to the fact that these units were never compared in the previous studies, therefore the purpose of the paper is analyze and compare presented devices in terms of cooling effectiveness.

The two novel solutions proposed by authors are presented in Fig. 1 (b) and (c). The first unit is a combination of parallel and counter flow indirect evaporative air cooler. Its operating principle lays in the fact of high efficiency of the parallel-flow scheme at the beginning of the exchanger and high efficiency of the counter-flow at the terminal parts of the exchanger. The second unit is the combination of cross-flow and counter-flow exchanger. The cross-flow is not as effective as parallel-flow at the entrance part of the