The Parametric Study of Counter-flow Regenerative Evaporative Cooler With Energy and Exergy Analysis

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Abstract. For further understanding of the heat and mass transfer occurred in a counter-flow REC, a novel mathematical model is developed based on the principle of the thermodynamic theory. The parametric study is performed to investigate the performance of the REC under different operating and geometrical conditions. It is found that the exergy destruction and exergy efficiency ratio of the REC are strongly influenced by the working to intake air ratio and channel gap, followed by the channel length. The working to intake air ratio choosing from 0.3 to 0.4 is appropriate in order to achieve better thermal performance with permissible level of thermodynamic cost. Moreover, the results obtained in this paper reveal that the best thermal performance does not correspond to the best thermodynamic performance. Thus, both the first and second law of thermodynamics should be considered for a comprehensive analysis.

Introduction

Recently, the regenerative evaporative cooler (REC), as an advanced evaporative cooling configuration, has attracted great attention for providing the air below the wet bulb temperature of inlet air without moisture content increase [1,2]. However, the previous research mainly focused on energy analysis [3,4] and few researchers consider the applicability of exergy analysis for the counter-flow REC investigation. Therefore, to overcome the shortfall in the theoretical study of the REC, the paper has presented an energy and exergy analysis using both the first and second laws of thermodynamics for the counter-flow REC. A parametric study is conducted based on the performance parameters of the REC including cooling capacity, exergy destruction, dew point effectiveness and exergy efficiency ratio under different operational and geometrical conditions. The work of the study is expected to help researchers better understand the thermal and thermodynamic characteristics of the REC and provides some original information for the improving design.

Calculation method of exergy

Fig. 1 shows the schematic of counter flow REC. To conduct a parametric study of the cooler, the prior determination of air and water conditions at the cooler’s output is required. To obtain these conditions, the analytical solution developed in [5,6] was applied. The moist air and water are the only two kinds of fluids involving in the REC. The moist air can be considered to be a mixture of ideal gases composed of dry air and water vapor. The exergy of moist air and water can be written as

\[ e_a = (c_{da} + dc_v)[T - T_0 - \ln(T/T_0)] + (1 + 1.608d)R_aT_0\ln(p/p_0) + \]

\[ R_aT_0[(1 + 1.608d)\ln((1 + 1.608d)/(1 + 1.608d)) + 1.608\ln(d/d_0)]. \]  \hspace{1cm} (1)

\[ e_w = [i_w(T) - i_w(T_0)] - T_0[s_w(T) - s_w(T_0)] + R_aT_0\ln\varphi_0 \]  \hspace{1cm} (2)
Where $c_{da}$ is the specific heat capacity of dry air, $c_v$ is the specific heat capacity of water vapor, $R_a$ is the specific ideal gas constant of dry air, $R_v$ is the specific ideal gas constant of water vapor, $T_0$ is temperature of reference state and the saturated condition of ambient air is defined as the reference state, $T$ is the temperature of certain state, $d_0$ is humidity ratio of reference state, $d$ is the humidity ratio of certain state, $p_0$ is the pressure of reference state, $p$ is the pressure of certain state, $i_w(T)$ is the enthalpy of saturated water at certain state, $i_w(T_0)$ is the enthalpy of saturated water at reference state, $s_w(T)$ is the entropy of saturated water at certain state, $s_w(T_0)$ is the entropy of saturated water at reference state, $\phi_0$ is the relative humidity at reference state.

Fig. 1. Schematic of counter flow REC

The process is adiabatic with no work delivered, so the exergy balance for the REC is calculated as follows,

$$(m_{p,i}e_{i,p} + m_{w,i}e_{i,w}) = (m_{p,o}e_{o,p} + m_{s,o}e_{o,s}) + I$$

(3)

Where $m_{p,i}$ is mass flow rate of primary air inlet, $m_{w,i}$ is added moisture to air, $m_{p,o}$ is mass flow rate of primary air outlet, $m_{s,o}$ is mass flow rate of secondary air outlet, $e_{i,p}$ is the specific exergy of primary air inlet, $e_{i,w}$ is the specific exergy of water inlet, $e_{o,p}$ is the specific exergy of primary air outlet, $e_{o,s}$ is the specific exergy of secondary air outlet, $I$ is the exergy destruction.

For free energy involving in the service system, the exergy efficiency ratio is defined as an important index to evaluate the effective use of the purchased available energy. The exergy efficiency ratio is defined as

$$EER_{ex} = m_{p,o}e_{o,p,th}/(m_{p,i}e_{i,p,me} + m_{s,i}e_{i,s,me})$$

(4)

Where $e_{i,p,me}$ is the specific mechanical exergy of primary air inlet, $e_{o,p,th}$ is the specific thermal exergy of primary air outlet, $e_{o,s,me}$ is the specific mechanical exergy of secondary air outlet.

Simulation results and analyses

According to the above model, the numerical simulations have been undertaken to investigate the impact of the selected operational and geometrical parameters on the thermal performance and thermodynamic performance obtained by the counter-flow REC. The dimensions of the counter-flow REC are set initially to $1.0 \times 1.0 \times 0.1$ m$^3$. The experiment study was performed for inlet air velocity of 2.4 m/s and working to intake air ratio of 0.33. The inlet air temperature and humidity ratio were $33.5 \, ^\circ C$ and 8.244 g/kg.

Influence of working to intake air ratio on cooling capacity, exergy destruction, dew point effectiveness and exergy efficiency ratio is analyzed under different working to intake air ratio spanning 0.1 to 0.9 and the results are shown in Fig. 2 (a) and Fig. 2 (b). As shown in Fig. 2, when the working to intake air ratio is varied from 0.1 to 0.9, the variation trend of cooling capacity is similar with that of exergy efficiency ratio. The cooling capacity and exergy efficiency ratio are almost direct proportional to the working to intake air ratio firstly till 0.3. After this, the cooling capacity and exergy efficiency ratio are inversely proportional to the working to intake air ratio. That is because both the mass flow rate of supply air and the temperature drop between inlet air and supply air have a coupled impact on the cooling capacity and exergy efficiency ratio. Increasing in working to intake air ratio can lead to the reduction of supply air to the cooling space. The exergy destruction and dew point effectiveness increase at the same time with working to intake air ratio rising. It is due to the fact that
an increase in working to intake air ratio results in the enhancement of heat and mass transfer in the wet channel. Therefore, the temperature drop between inlet air and supply air and exergy destruction both increase, as the amount of pressure drop is almost same. As the working to intake air ratio rises, the exergy destruction is increased by 1.7 times from 47.9 W to 130 W, and the exergy efficiency ratio is decreased by 85% from 21.3 to 3.2. Moreover, the working to intake air ratio choosing from 0.3 to 0.4 is reasonable enable the cooler to reach a compromise between thermal performance and thermodynamic performance.

Fig. 2. Influence of working to intake air ratio: (a) cooling capacity and exergy destruction (b) dew point effectiveness and exergy efficiency ratio

Simulations are performed to investigate the effect of channel length on cooling capacity, exergy destruction, dew point effectiveness and exergy efficiency ratio, and the results are illustrated in Fig. 3(a) and Fig. 3(b). It can be seen from Fig. 3(a) that the cooling capacity and exergy destruction increase with varying the channel length from 0.25 to 3.5 m. The rates of cooling capacity and exergy destruction increase slow down when channel length exceeds 1.5 m. The Fig. 3(b) presents the dew point effectiveness and exergy efficiency ratio depending on the channel length. By comparison, the changing trend of dew point effectiveness is similar with that of cooling capacity but is opposite with that of exergy efficiency ratio. That is because the increase of the length can increase the residence time and contact area, which is conducive to heat and mass transfer process. However, the increased channel length means increased pressure loss and mechanical exergy. Consequently, the exergy destruction increases from 85 W to 100.4 W, increased by about 0.18 times, as the value of channel length rises. Meanwhile, the exergy efficiency ratio decreases from 33.2 to 9.3, decreased by about 0.72 times. Therefore, the effect of channel length is smaller than the working to intake air ratio on the performance of exergy destruction and exergy efficiency ratio. It is also concluded that that the best thermal performance does not correspond to the best thermodynamic performance.

Fig. 3. Effect of channel length: (a) cooling capacity and exergy destruction (b) dew point effectiveness and exergy efficiency ratio

To investigate the impact of channel gap on the thermal performance and thermodynamic performance of the REC through changing the channel gap from 2mm to 12mm while other parameters keep unchanged under the pre-set conditions and the results are presented in Fig. 4(a) and Fig. 4(b). As shown in Fig. 4(a), the cooling capacity and exergy destruction quickly decreases with increasing the channel gap. Fig. 4(b) indicates that the exergy efficiency ratio increases but the dew point effectiveness decreases almost linearly with channel gap rising. This can be attributed to a high channel gap resulting in decreased flow resistance. The mechanical exergy is smaller in both channels
while the thermal exergy of the primary air outlet is bigger. The decrease of mechanical exergy is relatively small comparing to the increase of the primary air outlet temperature. It should be noted that the small channel gap can provide good thermal performance but bad thermodynamic performance. As the channel gap decreases, the exergy destruction is increased by about 27% from 80.8 W to 102.9 W, while the exergy efficiency ratio is decreased by about 81% from 31.6 to 5.9. Results come out that the effect of channel gap is smaller than the working to intake air ratio on the exergy destruction and exergy efficiency ratio, yet it is greater than the effect of the value of channel length.

Fig. 4. Effect of channel gap: (a) cooling capacity and exergy destruction (b) dew point effectiveness and exergy efficiency ratio

Conclusions

An exergy balance is derived in order to determine the exergy destruction associated with heat and mass transfer for the counter-flow REC. The performance of the considered REC is parametrically evaluated under various operating and geometrical conditions in terms of cooling capacity, exergy destruction, dew point effectiveness and exergy efficiency ratio. The results show the working to intake air ratio choosing from 0.3 to 0.4 is appropriate in order to achieve a compromise between thermal performance and thermodynamic performance. Furthermore, it is found that the influence of operational and structural parameters on the exergy destruction and exergy efficiency ratio from large to small are listed as follows: working to intake air ratio, channel gap, channel length.

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References