Exergy analysis of evaporative cooling to select the optimum system in diverse climates

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A R T I C L E   I N F O

Article history:
Received 17 August 2011
Received in revised form 28 January 2012
Accepted 31 January 2012
Available online 29 February 2012

Keywords:
Exergy analysis
Evaporative cooling
Exergy efficiency
Irreversibility
Diverse climates

A B S T R A C T

In this paper, an exergy analysis is applied to indicate the exergy efficiency and irreversibility of common models of evaporative cooling. Exergy analysis of conditioned air are based on the results of experimental investigations on the direct, indirect, and two-stage indirect/direct evaporative cooling for six cities in Iran, each having various weather conditions. For this purpose, exergy balances of three cooling methods are derived. The results obtained reveal that for a comprehensive efficiency analysis, both the first and second law of thermodynamics should be considered. Furthermore, the direct evaporative coolers work best in temperate and dry climate with estimated exergy efficiency of 20%. The indirect evaporative coolers are more efficient in hot and dry climate with approximate exergy efficiency of 55%. The indirect/direct evaporative coolers are better choice for hot and semi-humid climate with exergy efficiency of about 62%.

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1. Introduction

Exergy analysis exploits the conservation of mass and energy principles as well as the second law of thermodynamics for the analysis and enhancement of energy. The exergy method is a functional mean for promoting effectiveness of the energy-resource use. The method enables immensity of losses to be identified and meaningful efficiencies to be determined [1]. Exergy is another name for the available energy in thermodynamic terms. Since the introduction of exergy concept, it has been burgeoned in diverse engineering fields, including air-conditioning systems [2,3]. A considerable fraction of the energy is consumed in air-conditioning. In order to appraise available alternatives or to select the suitable kind of air-conditioning systems, defining the efficient cooling techniques are important. Although the efficiency of air-conditioning systems has been evaluated by the first law of thermodynamics, the second law of thermodynamics is another opposite method. Also an energy analysis alone is not adequately able to show some important viewpoints [4,5]. The exergy analysis can calculate the necessary reversible work (minimum work) of a process. Knowledge of the minimum work assists both producers and customers. It helps the air-conditioning producers to improve systems by comparing the energy consumption of their designs with the calculated minimum energy. And it helps customers and contractors to choose appropriate air conditioners for their buildings. Furthermore, in a broad point of view, calculations of the irreversibility of air-conditioning processes help decision makers to outline the energy demands.

Forty percent of energy is consumed in buildings in Iran in a way that a considerable portion of it is used for heating and air-conditioning. Because of high energy consumption in buildings, the demand to design energy-efficient building heating, ventilation, and air-conditioning (HVAC) systems is growing. In addition, evaporative cooling systems can be an economical alternative, or can be used as a pre-cooler in the conventional systems. Also, they are popular due to zero pollution, easy maintenance, and low electrical energy consumption [6,7].

Direct evaporative cooling (DEC) is the oldest and most widespread form of air-conditioning in Iran. The underlying principle of DEC is the conversion of sensible heat to latent heat. Through a DEC system, hot outdoor air passes through a porous wetted medium. Heat is absorbed by water as it evaporates from the porous wetting medium, so the air leaves the system at a lower dry-bulb temperature. In fact, this is an adiabatic saturation process in which dry-bulb temperature (DBT) of the air reduces as its humidity
increases. Some of the sensible heat of the air is transferred to the water and become latent heat by evaporating the water. The latent heat follows the water vapor and diffuses into the air. The minimum temperature that can be obtained is the wet-bulb temperature (WBT) of the air entering [8].

Another alternative of evaporative cooling is indirect evaporative cooling (IEC) which has high potential for providing air-conditioning demand at a low energy cost. An IEC system consists of two types of impervious separate air passages, primary and secondary, which are dry and wet, respectively. In the primary passages, outdoor air is sensibly cooled without adding water, while the secondary air and water flow in the secondary passages. The surfaces of the secondary passages are wetted by spray water, so that the water film evaporates into the secondary air, and it decreases the temperature of the walls. As a result, the cold walls remove the heat from the outdoor air which passes through the primary passages. Consequently, the air leaving from the primary passages has lower WBT and DBT than the air entering [9,10].

In addition, the lower wet-bulb temperature of the air leaving can be used in combining indirect and direct evaporative coolers to boost the cooling capacity. By adding an indirect stage to a direct stage, a two-stage indirect/direct cooler is capable of cooling the outdoor air more than a stand-alone unit. The outdoor air is cooled through the IEC without an increase in its humidity ratio, and then it is further cooled through DEC [11].

Several research papers have been dedicated to explore the issue of evaporative cooling, Dai and Sumathy (2002) [12], Liao and Chiu (2002) [13], Al-Sulaiman (2002) [14], Camargo et al. (2005) [7], Chengjin and Hongxing (2006) [15] and Hettiarachchi et al. (2007) [16] propose mathematical modeling and do experimental tests in order to analyze the efficiency of simulate direct and indirect evaporative cooling. El-Dessouky et al. (2004) [17] and Heidarinejad et al. (2009) [11] study two-stage evaporative cooling to examine its effectiveness and cooling capacity of this air-conditioning system. However, none of them has investigated the second law of thermodynamics nor has analyzed exergy in their research.

In the field of exergy analyses, Ren Chengqin et al. (2002) [3] analyze exergy changes in the HVAC systems. They presume an unusual dead state to eliminate the exergy calculation of water. Also, they break down the exergy of moist air to three components: thermal, mechanical, and chemical components. By assuming efficiency for each scheme of evaporative cooling, the results have shown that the regenerative scheme has the best performance. Alhamzy (2005) [6] calculates the minimum work of dehumidification in an air-conditioning process based on the second law of thermodynamics. In his research, the state of environment was chosen as the dead state. Taufiq et al. (2007) [18] study the exergy analysis of the direct evaporative cooling in a Malaysian building. The average temperature and relative humidity were considered as the dead state. The results obtained have shown that increase in relative humidity increases exergy efficiency. Muangnoi et al. (2007) [19] use an exergy analysis to demonstrate exergy and exergy destruction of water and air flowing through the cooling tower. They show thermodynamics irreversibility is higher at bottom of a cooling tower. Chen et al. (2011) [20] analyzed and optimized several practical evaporative cooling systems based on the newly introduced moisture entransy theory. They realized that the most efficient evaporative cooling performance requires a minimum thermal resistance. Aforementioned research papers on exergy analysis have not examined exergetic efficiency on various climates. Indeed, multi-climate countries such as Iran necessitate an abrad consideration of exergy analysis on diverse environmental conditions.

To the best of our knowledge, few amounts of investigation on exergy efficiency of evaporative cooling are available in the literature. In addition, different points of view and approaches are held about exergy analyses that lead to consideration of different dead states. Also, information about the second law efficiency in different atmospheric conditions is insufficient. Hence, we provide analyses of exergy efficiency of evaporative cooling in various climatic conditions.

In this study, the temperature and specific humidity of air leaving direct, indirect, and two-stage indirect/direct evaporative cooling (IDEC) systems are first measured through several experimental tests for different climates of some cities in Iran. Then changes in exergy of cooled air in each system for various climatic conditions have been investigated. Moreover, exergy efficiency and exergy destruction by irreversibilities are calculated by means of exergy balance.

2. Test setup

A schematic diagram of the experimental setup is shown in Fig. 1. The main parts of the setup are described below.

- Air simulator: Electrical heaters are installed inside the simulator body to heat the income air up to setting value. These heaters totally can provide a wide range of power to control air temperature. In the lower part of the simulator body, an electrical humidifier is located to control air humidity by injecting water vapor. Using two described parts together, air temperature and humidity can be controlled separately. A straighter is provided to achieve air flow uniformity. Also, a free rotational mixer downstream of the simulator is used to obtain temperature and relative humidity homogeneity.

![Fig. 1. A schematic diagram of the experimental setup.](image)
Secondary air simulator: this unit is similar to the primary air simulator in the secondary air stream.

Indirect evaporative cooler: Including a plate-type plastic wet surface heat exchanger, a water-circulating pump, a flow meter, and a valve to control water flow rate. Specifications of this heat exchanger have been presented in Table 1.

Direct evaporative cooler: Including a 15 cm thick cellulose pad, a water-circulating pump, a flow meter and a valve to control water flow rate of this unit. Water is distributed over indirect and direct systems using proper spray pattern nozzles.

Control unit: Each part of experimental setup in both circuits (primary and secondary) including heaters, fans and pump are controlled using this unit.

The states of both primary and secondary air are the same in our experiments. However, two separate simulators are required for other simulations such as regenerative and/or recover cycles. Fig. 2 shows a view of the experimental setup.

As it can be seen from Fig. 1, temperature and relative humidity are measured in appropriate locations. The accuracy and resolution of the temperature sensors were ±0.3 °C and 0.01 °C, respectively. The relative humidity ratio measured by the sensors ranged from 10% to 95% and the accuracy and resolution were ±3% and 0.01%.

<table>
<thead>
<tr>
<th>Heat exchanger specification</th>
<th>Unit Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height × Width × Length</td>
<td>cm × cm × cm</td>
</tr>
<tr>
<td>Plates spacing</td>
<td>mm</td>
</tr>
<tr>
<td>Plates thickness</td>
<td>mm</td>
</tr>
<tr>
<td>Height of projections</td>
<td>mm</td>
</tr>
<tr>
<td>Spacing between projections</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>50 × 50 × 40</td>
</tr>
<tr>
<td></td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>20</td>
</tr>
</tbody>
</table>

Fig. 2. A view of the experimental IEC/DEC setup. Inset is close view of IEC and DEC units.

Fig. 3. Comparison between energy change in the primary air and the secondary air. Respectively. The pressure measured by pitot tubes with 1.0% accuracy and 0.03 kPa resolution according to ANSI/ASHRAE 143 [21].

Also, average air velocity is measured in proper positions in primary and secondary flows using thermal anemometers (accuracy ±4% of reading and resolution of 0.01 m/s) according to ASTM D3464 [22].

Moreover, the measurement error is also affected by the property of the sensor installation. Specifically, the accuracy of the air...
flow evaluation from air velocity measurement largely depends on uniformity of the velocity field. Energy balance between the primary and secondary air streams in the IEC were carefully examined to verify the accuracy of flow rate and position of sensors. In a series of operating conditionings, Fig. 3 describes the experimental results in terms of energy change in primary air side and the corresponding results in secondary air side. It is shown that the results agree well and the inconsistency between the results is less than 5%.

3. Exergy analysis

Exergy reveals the capability of energy to work. Exergy transfer happens in three ways, exergy transfer related to work, heat transfer, and matter entering and exiting a control volume. All processes in nature are irreversible. Irreversibilities within the system or the control volume destroy exergy [21]. Air-conditioning processes are basically steady-flow processes. So, the exergy balance can be written as shown below [1].

\[ \sum_{in} \dot{E}_{x, in} + \sum_{in} \bar{m}(\psi) - \sum_{out} \dot{E}_{x, out} - \dot{E}_{x, \text{dest}} = 0 \]  

(1)

In Equation (1), kinetic and potential energies and work are assumed to be negligible. \( \dot{E}_{x, in} \) is the exergy transfer associated with heat transfer, \( \dot{E}_{x, \text{dest}} \) is the exergy destruction which is a positive quantity for any actual process and zero for a reversible process, and \( \psi \) represents specific exergy that is written as the following equation:

\[ \psi = (i - h_0) - T_0(s - s_0). \]

(2)

where \( h_0 \) and \( s_0 \) are specific enthalpy and entropy at the dead state, respectively.

Humid air can be considered as an ideal gas containing dry air and water vapor mixture. Wepfer et al. (1979) [23] introduced the total flow exergy of humid air per kg dry air by the following equation:

\[ \psi = (C_p + \omega C_v) T_0 \left( \frac{T}{T_0} - 1 - \ln \frac{T}{T_0} \right) + (1 + 1.608 \omega) R_a T_0 \ln \frac{P}{P_0} + R_a T_0 \left[ (1 + 1.608 \omega) \ln \left( \frac{1 + 1.608 \omega \phi_0}{1 + \omega \phi_0} \right) + 1.608 \omega \ln \frac{\phi_0}{\omega} \right] \]

(3)

where \( C_p \) is water vapor specific heat at a constant pressure, \( R_a \) is the air specific gas constant, and the constant 1.608 is the ratio of molar mass of air to molar mass of water vapor. Chengqin et al. [3] divided exergy of humid into three components: thermal, mechanical and chemical which are present as the first, second, and third terms in Equation (3). This division simplifies exergy analysis in air-conditioning systems.

The specific flow exergy of liquid water can be approximated by the following equation:

\[ \psi_w = -R_a T_0 \ln \phi_0 \]

(4)

In the equation above, \( R_a \) is vapor specific gas constant, and \( \phi_0 \) is the proportion of the water vapor pressure of the unsaturated atmospheric air to the saturated water vapor pressure at the dead state temperature. Equation (4) is a simplified form for exergy of liquid water. The complete form has been suggested by Wepfer et al. [23]. According to Equation (4), the relative humidity predominates the exergy of water.

\[ \eta_{\text{ex}} = 1 - \frac{\text{exergy destroyed}}{\text{exergy supplied}} \]

(5)

In Equation (5), exergy supplied is the input exergy in the process, the exergy destroyed represents the lost work potential and is also called the irreversibility or lost exergy. In addition, it is proportional to the entropy generated. Irreversibility is expressed as:

\[ T_0 S_{\text{gen}} = l = W^{\text{rev}} - W_{c.v.} \]

(6)

where \( S_{\text{gen}} \) is the entropy generated in the process, \( l \) is irreversibility, \( W^{\text{rev}} \) is reversible work, and \( W_{c.v.} \) is axial work.

Reversible work presents the minimum amount of work necessary to perform a process. In the direct and indirect evaporative cooling, no axial work is done on the control volume. So, Irreversibility or exergy destroyed shows the amount of reversible work. Fig. 4 shows direct and indirect evaporative cooling processes on a psychrometric chart.

In Fig. 4, the direct, indirect and indirect/direct evaporative cooling process on the psychrometric chart.

The exergy efficiency of an overall air-conditioning process may be formulated as [1]:

The direct evaporative cooling is an adiabatic process, no axial work is done on the control volume. In the direct and indirect evaporative cooling, no axial work is done on the control volume. So, Irreversibility or exergy destroyed shows the amount of reversible work. Fig. 4 shows direct and indirect evaporative cooling processes on a psychrometric chart.

As shown in Fig. 4, direct evaporative cooling is an adiabatic humidification in which dry-bulb temperature decreases while moisture increases. In other words, few amounts of water on the pad evaporate into the air. Dry-bulb temperature decreases during an indirect cooling process, and only a change occurs in the sensible heat. Based on the descriptions above and by employing Equation (1), the exergy balance for each process can be written as follows:

Direct evaporative cooling:
In direct evaporative cooling, added moisture to air is considered as an input quantity.

Indirect evaporative cooling:

\[
\dot{m}_w = \dot{m}_a \left( \psi_2 - \psi_1 \right) (8)
\]

Exergy transfer associated with heat transfer can be derived by integration over input and output points.

\[
\dot{E}_{xQ_{1-2}} = - \int_{1}^{2} \left(1 - \frac{T_2}{T_1} \right) \frac{dQ}{T_2} (10)
\]

Two-stage indirect/direct evaporative cooling:

\[
\dot{m}_a \psi_1 + \dot{m}_w \psi_w - \dot{m}_a \psi_{a2} - I = 0 \quad (11)
\]

Equations (8) and (10) can be used for water mass flow rate and the exergy transfer associated with heat transfer, respectively.

By means of Equations (7), (9) and (11), the irreversibility as well as the reversible work and the entropy generation can be calculated.

4. Results and discussion

Exergy analyses for three models of evaporative cooling have been investigated for six cities in Iran. Iran is a multi-climate country in which evaporative cooling is the most popular method of air-conditioning. Thus, examination of efficiency from the second law of thermodynamics point of view complements demand for energy saving. A list of cities and their climatic characteristics are tabulated in Table 2. Psychrometric specifications of outdoor conditions for each city are based on 1% design condition according to the ASHRAE standard [24,25].

Based on summer design conditions, there are five different climatic conditions in Iran. Each city in Table 2 can be categorized as one of these conditions.

1- Temperate and dry climate with DBT less than 40 °C and WBT less than 23 °C, such as Tabriz and Tehran;
2- Hot and dry climate with DBT more than 40 °C and WBT less than 23 °C, such as Yazd;
3- Hot and semi-humid climate with DBT more than 40 °C and WBT between 23 °C and 27 °C, such as Bam;
4- Hot and humid climate with DBT more than 40 °C and WBT more than 27 °C, such as BandarAbass;
5- Temperate and humid climate with DBT less than 40 °C and WBT more than 23 °C, such as Babolsar.

Based on the experimental investigations, the output temperature and humid ratio of cooled air for each city are shown in Fig. 5.

<table>
<thead>
<tr>
<th>City</th>
<th>Longitude (°E)</th>
<th>Latitude (°N)</th>
<th>DBT (°C)</th>
<th>RH (%)</th>
<th>Altitude (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 Tehran</td>
<td>51.4</td>
<td>35.7</td>
<td>38.5</td>
<td>27</td>
<td>1190</td>
</tr>
<tr>
<td>C2 Yazd</td>
<td>55</td>
<td>32</td>
<td>41.3</td>
<td>19.5</td>
<td>1327</td>
</tr>
<tr>
<td>C3 Bam</td>
<td>58.21</td>
<td>29.6</td>
<td>42.4</td>
<td>24</td>
<td>1067</td>
</tr>
<tr>
<td>C4 BandarAbass</td>
<td>56.2</td>
<td>37.1</td>
<td>41.8</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>C5 Tabriz</td>
<td>46.2</td>
<td>38.5</td>
<td>36</td>
<td>25.5</td>
<td>1361</td>
</tr>
<tr>
<td>C6 Babolsar</td>
<td>52.4</td>
<td>36.4</td>
<td>32</td>
<td>67</td>
<td>-21</td>
</tr>
</tbody>
</table>

Table 2
Specifications and summer design conditions of the cities evaluated for exergy analyses.

Fig. 5. Direct, indirect, and indirect-direct evaporative cooling processes for each city on the psychrometric chart.
The pressure drop through the direct evaporative cooler is 25 Pa and that of the indirect evaporative cooler is 250 Pa. When the air entering is unsaturated and has higher pressure to overcome pressure drop through both of a cooler and ducts, it possesses available energy. So, dead state for each cooling process is the ambient temperature, the saturation state of the process, and the pressure after the process. For instance, the ambient condition of Tehran is $T = 38.5^\circ C$, $\omega = 1.357$ g/kg(a), $P = 86131$ Pa, for DEC cooler the dead state is $T_0 = 38.5^\circ C$, $\omega_0 = 2.059$ g/kg(a), $P_0 = 86101$ Pa, and for the two-stage IDEC the dead state is $T_0 = 38.5^\circ C$, $\omega_0 = 1.550$ g/kg(a), $P_0 = 85851$ Pa.

The most common form of evaporative cooling in Iran is the direct evaporative cooling system. Table 3 shows the amount of drop in the dry-bulb temperature, increase in the humidity ratio, increase in the thermal exergy, and decrease in the chemical exergy after passing through the direct evaporative pad.

Variations in the temperature and the humidity ratio cause changes in exergy of the air. Exergy of humid air can be divided into three components (See Equation (3)). Monitoring changes of the thermal and the chemical exergy of air simplifies the exergy analysis of evaporative cooling. During the direct evaporative cooling, the temperature drops but the humidity ratio increases. So, the thermal exergy increases but the chemical exergy decreases and converts to the thermal exergy. Due to the same amount of the pressure drop, the mechanical term of exergy equally lessens in all cities.

Fig. 6 shows exergy efficiency of the direct evaporative cooling process in different cities or different weather conditions in Iran.

Based on Equations (5) and (7), exergy efficiency of DEC is derived in Equation (12):

$$\eta_{ex} = \frac{\psi_{a2}}{\psi_{a1} + (\omega_2 - \omega_1)\psi_w} \quad (12)$$

The first term of the denominator in Equation (12) is specific exergy of input air and the second term is specific exergy of input water multiply by humidity difference. Amount of the second term is almost four times bigger than the first term. As a result, both the second term in denominator and specific exergy of leaving air (numerator) dominate the amount of exergy efficiency. Since the amount of specific exergy of input water is a function of weather conditions, irrespective of the cooler, the exergy efficiency of DEC is roughly the ratio of exergy of leaving air to the humidity ratio difference. Increase in the humidity ratio of BandarAbass and Babolsar is higher than other cities. In the same way, increase in the humidity ratio of Yazd is high, so the exergy efficiency of DEC is lower in this climate. However, as shown in Fig. 6, like the effectiveness of DEC, the exergy efficiency of DEC is almost the same value for all weather conditions.

Although the chemical exergy converts to the thermal exergy, the sum of thermal and chemical exergy decreases due to the exergy destruction during the irreversible adiabatic process. The irreversibility of DEC for each city is shown in Fig. 7. As shown in Fig. 7, a region with lower relative humidity (RH) has higher irreversibility. In other words, increase in the humidity ratio adds to the irreversibility. So, the irreversibility is the highest value in Yazd and lowest in Babolsar. Also, the irreversibility is proportional to the entropy generated in a process. Thus, the entropy produced during DEC is low in BandarAbass and Babolsar. It is obviously higher for the conditions of Yazd than other cities.

It is worth mentioning, as far as the comfort conditions are concerned, a direct evaporative cooler is not able to meet the comfort conditions on the psychrometric chart (See Fig. 5) for some cities such as Bam, BandarAbass, and Babolsar. Consequently, to determine whether a direct evaporative cooler is suitable for a climate, besides exergy efficiency, we should consider both irreversibility and feasibility of meeting the comfort conditions on the psychrometric chart. In other words, three parameters of exergy

Table 3 Changes in the temperature, humidity ratio, thermal exergy, and chemical exergy after the direct evaporative cooling process.

<table>
<thead>
<tr>
<th>ID</th>
<th>City</th>
<th>Temperature (°C)</th>
<th>Humidity ratio (g/kg(a))</th>
<th>Thermal exergy (J/kg(a))</th>
<th>Chemical exergy (J/kg(a))</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Tehran</td>
<td>11.22</td>
<td>4.98</td>
<td>214.85</td>
<td>175.73</td>
</tr>
<tr>
<td>C2</td>
<td>Yazd</td>
<td>13.82</td>
<td>6.12</td>
<td>324.24</td>
<td>292.59</td>
</tr>
<tr>
<td>C3</td>
<td>Bam</td>
<td>12.79</td>
<td>5.73</td>
<td>277.60</td>
<td>207.28</td>
</tr>
<tr>
<td>C4</td>
<td>BandarAbass</td>
<td>7.41</td>
<td>3.47</td>
<td>94.62</td>
<td>44.78</td>
</tr>
<tr>
<td>C5</td>
<td>Tabriz</td>
<td>10.91</td>
<td>4.79</td>
<td>203.86</td>
<td>190.15</td>
</tr>
<tr>
<td>C6</td>
<td>Babolsar</td>
<td>3.74</td>
<td>1.69</td>
<td>24.27</td>
<td>14.13</td>
</tr>
</tbody>
</table>

Table 4 Changes in the temperature and thermal exergy after the indirect evaporative cooling process.

<table>
<thead>
<tr>
<th>ID</th>
<th>City</th>
<th>Temperature (°C)</th>
<th>Thermal exergy (J/kg(a))</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Tehran</td>
<td>8.86</td>
<td>132.14</td>
</tr>
<tr>
<td>C2</td>
<td>Yazd</td>
<td>10.94</td>
<td>199.52</td>
</tr>
<tr>
<td>C3</td>
<td>Bam</td>
<td>10.53</td>
<td>185.50</td>
</tr>
<tr>
<td>C4</td>
<td>BandarAbass</td>
<td>6.40</td>
<td>69.87</td>
</tr>
<tr>
<td>C5</td>
<td>Tabriz</td>
<td>8.61</td>
<td>125.21</td>
</tr>
<tr>
<td>C6</td>
<td>Babolsar</td>
<td>3.29</td>
<td>18.75</td>
</tr>
</tbody>
</table>
efficiency, irreversibility, and capability of meeting the comfort conditions are important for decision making.

According to Figs. 5–7, although the exergy efficiency in BandarAbass and Babolsar is highest, DEC cannot provide comfort conditions. In addition, for the conditions of Bam, air leaving the direct evaporative cooler does not meet the comfort conditions. Thus, the best climate conditions for DEC are the climate of Tabriz and Tehran. Furthermore, these results show that an investigation only based on the first law of thermodynamics or the second law of thermodynamics is not sufficient for a comprehensive understanding of the cooling efficiency for various weather conditions.

Another type of evaporative cooling is the indirect evaporative cooling in which, through the primary passage, the air temperature reduces while its moisture remains constant. In other words, the thermal exergy increases while the chemical exergy remains constant. But through the secondary passage, the air temperature increases and its moisture drops. In this process, the exergy of secondary air is partially transferred to the primary air. So, investigating variations in the temperature and the thermal exergy of primary air lead us to a better understanding. Changes in the temperature and the thermal exergy are tabulated in Table 4. Like DEC, because of the same amount of the pressure drop, the mechanical term of exergy equally lessens in all cities, but the pressure drop and consequently, the mechanical exergy drop in IEC is higher than that of DEC.

The exergy efficiency and the irreversibility of IEC are shown in Figs. 8 and 9, respectively.

The exergy efficiency of IEC is mainly related to amount of the exergy transfer associated with heat transfer or the thermal exergy. The highest and the lowest amount of the thermal exergy belong to Yazd and Babolsar, respectively. As a result, the exergy efficiency for the conditions of Yazd is highest and it is lowest for that of Babolsar.

The irreversibility depends on both the dry-bulb temperature and the amount of the heat exergy transfer (or the temperature drop). For instance, the city BandarAbass has a high dry-bulb temperature and its thermal exergy increases insignificantly so, its irreversibility is high. Drop in the temperature or the thermal exergy for the conditions of Babolsar is also insignificant, but its dry-bulb temperature is low so, its irreversibility is low. But, for the conditions of Tabriz, the thermal exergy is high and the dry-bulb temperature is low so, its irreversibility is the lowest value.

Based on Figs. 5, 8 and 9, except for the conditions of BandarAbass and Babolsar, IEC can be used as an efficient cooling system. It is worth mentioning that, by taking advantage of a bigger indirect evaporative cooler or another type of IEC such as regenerative type, the output air can meet the comfort conditions on the psychrometric chart.

The two-stage indirect/direct evaporative cooling is applicable in regions where a stand-alone DEC unit cannot provide the comfort conditions. Both the temperature and the humidity ratio of air change through the IDEC. Table 5 lists the drop in the dry-bulb temperature, increase in the humidity ratio, the thermal exergy, and the chemical exergy of conditioned air in the two-stage IDEC.

The exergy efficiency and the irreversibility of each city are shown in Figs. 10 and 11, respectively.

In view of the fact that a two-stage evaporative cooler is the combination of a direct and an indirect evaporative cooler, all
parameters that affect the irreversibility and the exergy efficiency of DEC and IEC have effect on those of IDEC.

As shown in Fig. 5, IDEC is able to provide the comfort conditions in all cities other than BandarAbass and Babolsar. Due to the high exergy efficiency and the low irreversibility for the climates of BandarAbass and Babolsar, IDEC is the most efficient in this city. Also, based on Figs. 5, 10 and 11, a two-stage evaporative cooler can provide suitable conditioned air with a proper exergy efficiency in a wider climate conditions of different cities, such as Tehran, Yazd, and Tabriz. Previous investigations [11] based on the first law of thermodynamics also show that IDEC can be used in various climate conditions.

Results presented cover all climatic conditions in Iran. Also, for cities with climatic conditions in between, we suggest engineers estimating proper results based on results presented above. Estimated results can be used in order to employ a suitable cooler.

5. Conclusion

The exergy efficiency and the irreversibility are studied on different types of evaporative cooling for five different climate conditions. Simulated conditions cover all various climates in the country. The results show that besides exergy efficiency and irreversibility, the capability of a cooler to meet comfort conditions should be considered. The Comprehensive analysis exhibits that direct, indirect and indirect/direct evaporative coolers are respectively suitable for cities of Tehran, Yazd, and Bam and their associated climates. Apart from temperate and humid regions, exergy efficiency of indirect/direct evaporative cooling is on average 22% higher than that of direct or indirect evaporative cooling. Except for humid climates such as climate of Babolsar and BandarAbass, the lowest irreversibility belongs to indirect evaporative cooling which is on average 22% lower than irreversibility of indirect/direct evaporative cooling.

References


Nomenclature

\( C_p \): specific heat at a constant pressure (J/kg·C)  
\( Ex \): exergy (J)  
\( i \): specific enthalpy (J/kg)  
\( f \): irreversibility (J)  
\( m \): mass flow rate (kg/s)  
\( P \): pressure (Pa)  
\( R \): specific gas constant (J/kg·K)  
\( s \): specific entropy (J/kg K)  
\( T \): temperature (°C)  
\( w \): axial work (J)  
\( \phi \): relative humidity (%)  
\( a \): humidity ratio (kg/kg)  
\( \gamma \): specific exergy (J/kg)

Subscripts  
\( a \): air  
\( c.v. \): control volume  
\( dest \): destruction  
\( gen \): generated  
\( Q \): heat transfer  
\( v \): vapor  
\( w \): water  
\( 0 \): dead state  
\( number \): state indices

Superscript  
\( rev \): reversible