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Exergy Analysis of an Air Dehumidification System Equipped with Mixing Box and Heat Exchanger Heat Recovery Units

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Abstract
Exergy analysis emboldens in cases that all the inefficiencies and bottlenecks to improve energy systems are to be addressed. In this study, a novel vapor compression air dehumidifier integrated with an auxiliary heat exchanger in series arrangement with the main condenser in order to mitigate the reheat coil, and an extra mixing box to recover the ventilated air heat has been introduced. A comprehensive methodology for exergetic analysis of vapor compression heating ventilation and air conditioning systems has been presented. The quasi-dynamic component-by-component exergy analyses of both the conventional and novel air dehumidification systems have been conducted for a specific outside air fraction. Also, sensitivity analyses have been conducted on the exergy destruction and efficiency as a function of outside air fraction. Results denote that for the outside air fraction of 53%, exergy destruction of the novel air dehumidification system has decreases up to 32.4% and exergy efficiency has ramped up by 53.45%. Moreover, by rising the outside air fraction from none to 100%, exergy destruction in the novel air dehumidification system has declined by 46% to 30.5 %, and exergy efficiency has undergone a 106% to 40.3 % increase compared with the conventional system depending on the outside.

Keywords: Exergy analysis, Exergy destruction, Exergy efficiency, HVAC systems, Heat recovery, Dehumidification

Introduction
With growing energy demand due to countries development, energy intensive technologies in different sectors that bring about comfort to human beings should be ascertained with most caution and care (International Energy Agency (IEA), 2013; Pérez-Lombard, Ortiz, & Pout, 2008; The International Energy Agency IEA, 2012). Among the aforementioned highly energy consuming technologies, Heating Ventilation and Air Conditioning (HVAC) systems are of most energy consuming technologies that comprise up to 50% of the energy use in the household sector (Caldera, Corgnati, & Filippi, 2008; El-Dessouky, Ettouney, & Al-Zeefari, 2004). As much as 80% of the refrigeration systems that are performing as HVAC systems are literally vapor compression refrigeration cycles (Chakravarthy, Shah, & Venkatarathnam, 2011), which is why these systems have to be investigated in case of any saving potentials to

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improve the system’s efficiency (Çakır, Çomaklı, Çomaklı, & Karslı, 2013). Beside energy analysis, exergy analysis is considered to be a powerful tool to improve and optimize energy systems in order to work properly. In fact exergy approach determines how much resources are used so that a required product such as heat, electricity and etc. is produced (Frangopoulos, 2009). Even though energy analysis is of most common thermodynamic assessments of energy systems, but it is not able to manifest all inefficiencies undergoing in a system. On the other hand it is the exergy analysis which can apprehend all the irreversibilities and inefficiencies within a specific system such as chemical reactions, mixing processes and so on (Bejan & Tsatsaronis, 1996). In other words, an exergy analysis is capable of discovering the locations and magnitude of the irreversibility through exergy destruction calculation within an energy system (Nguyen et al., 2013). Moreover, exergy analysis yields worthwhile measures to evaluate the extent of energy waste in both the system and its components; this measure signifies the quality of the wasted energy from thermodynamic facets (Tsatsaronis, 1993).

Many researches in the field of exergy analysis have been conducted by numerous researches to further evaluate energy systems from exergetic aspects and those that are concerned with vapor compression systems are to be argued in this section. Many studies have addressed the exergetic investigation of substituting the refrigerant in a vapor compression system (Ben Jemaa, Mansouri, Boukholda, & Bellagi, 2017; Gaurav & Kumar, 2018). Cakir and komakli (Çakır & Çomaklı, 2016) studied the interrelation between the components of a heat pump which is practically a vapor compression system. Other studies are more concerned with the exergetic merits of vapor compression systems. Among them, Jain et al. (Çakır & Çomaklı, 2016) compared the performance of a vapor compression-absorption integrated refrigeration system with a vapor compression refrigeration system. The study showed that the former is superior to the latter with the exergetic efficiencies of 27.9% and 18.8%, respectively. Other studies have put their effort to improve and optimize energy systems. Besbes et al. (Besbes, Zoughaïb, De Carlan, & Peureux, 2014) deployed exergy based methodologies to optimize the performance of heat pumps in industrial processes. Ersoy et al. (Sag, Ersoy, Hepbasli, & Halkaci, 2015) introduced a new vapor compression system equipped with an ejector instead of the compressor to improve the exergetic efficiency up to 18.62%. Al-Sulaiman et al. (Al-Sulaiman, 2017) proposed a new vapor compression HVAC system in which the fresh air was precooled with the ventilated air, also the reheat coil was omitted and instead the supply air was reheated in an auxiliary condenser. They investigated different scenarios and asserted that the proposed system significantly reduces exergy destruction.

Although many researches have been conducted on vapor compression HVAC systems but, a few have addressed a comprehensive and component-by-component evaluation of the whole system and brought heat recovery into consideration. This study aims to investigate a novel vapor compression air dehumidifier quasi-dynamically and component-by-component to provide useful insights for new recovery potentials and exergy loss utilization.

Material and Methods

System description

The proposed dehumidifier system is comprised of compressor, mixing box, expansion valve, condenser, evaporator, heat exchanger and their respective fans. As it is shown in Figure 1, the proposed system has a mixing box and a heat exchanger in addition to the conventional system while the reheat coil is eliminated compared to the conventional system. The ventilated air which previously was exhausted to the ambient is now recovered in a condenser-side mixing box to make amends to the cooling process of the condenser and compensate a fraction of its fan power consumption. Recovering the ventilated air in a mixing box would refrain the exergy loss from the system's boundary. Also, the supply air that was formerly reheated by a reheat coil after the dehumidification process is now reheated by the refrigerant heat in an auxiliary condenser which would lead to the mitigation of the reheat coil and avert tremendous exergy destruction within that very component. With these reconfigurations in mind, the next section would discuss that how exergy analysis is to be conducted on such an air dehumidification system.

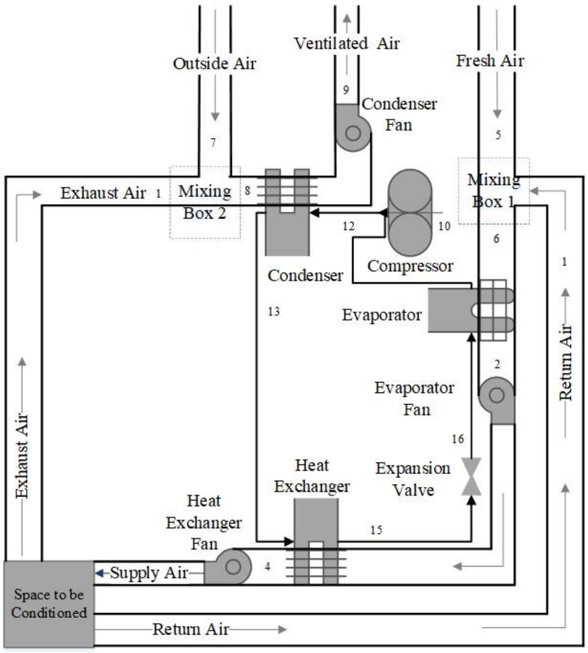


Figure 1. Proposed air dehumidification system equipped with an auxiliary heat exchanger and a mixing box

Exergy analysis

Exergy is in fact the ultimate useful work a system can do while being brought to thermodynamic equilibrium with its environment, presuming having interactions only with its surroundings (Frangopoulos, 2009). Heating and cooling processes that are undertaken in buildings are considered to be low-exergy processes due to the comparatively low operating temperatures of the heat source and heat sink that are close to the ambient temperature, also the definition of exergy which is expressed as its deviation from the reference conditions. So, it is more rational to gain more sustainability and higher efficiencies in building sector through low-exergy systems such as refrigeration cycles, heat recovery units and renewable sources, and spare the high-exergy and quality energy sources for more suitable applications (Moran, Shapiro, Boettner, & Bailey, 2010; Sayadi, Tsatsaronis, & Morosuk, 2019). It could be culminated that the aim of low-exergy systems is to decrease the feed exergy to attain a specific product exergy, which would lead to the CO2 emissions being dwindled and thermal comfort being obtained (Schmidt, 2009).

In order to perform exergy analyses on an energy system, first the energetic preferences of the energy system is to be calculated. In this research, the energy analysis and preferences of the proposed system have been studied previously by the author (Jafarinejad, Yousefi, & Choubinehb, 2018). The energy analysis has been carried out cell-by-cell and quasi-dynamically on a sample building located in Bandar-e-Abbas (a hot and humid city in southern Iran) in two modeling compartments, in which the firs model compartment yielded the sample building's cooling load and the second modeling compartment simulated the vapor compression air dehumidification system in EES software. As it is exhibited in Figure 2, the data flowchart exploited in EES software to obtain outputs of the energy analysis is demonstrated. Afterwards, these outputs are used directly to conduct the exergy analysis.

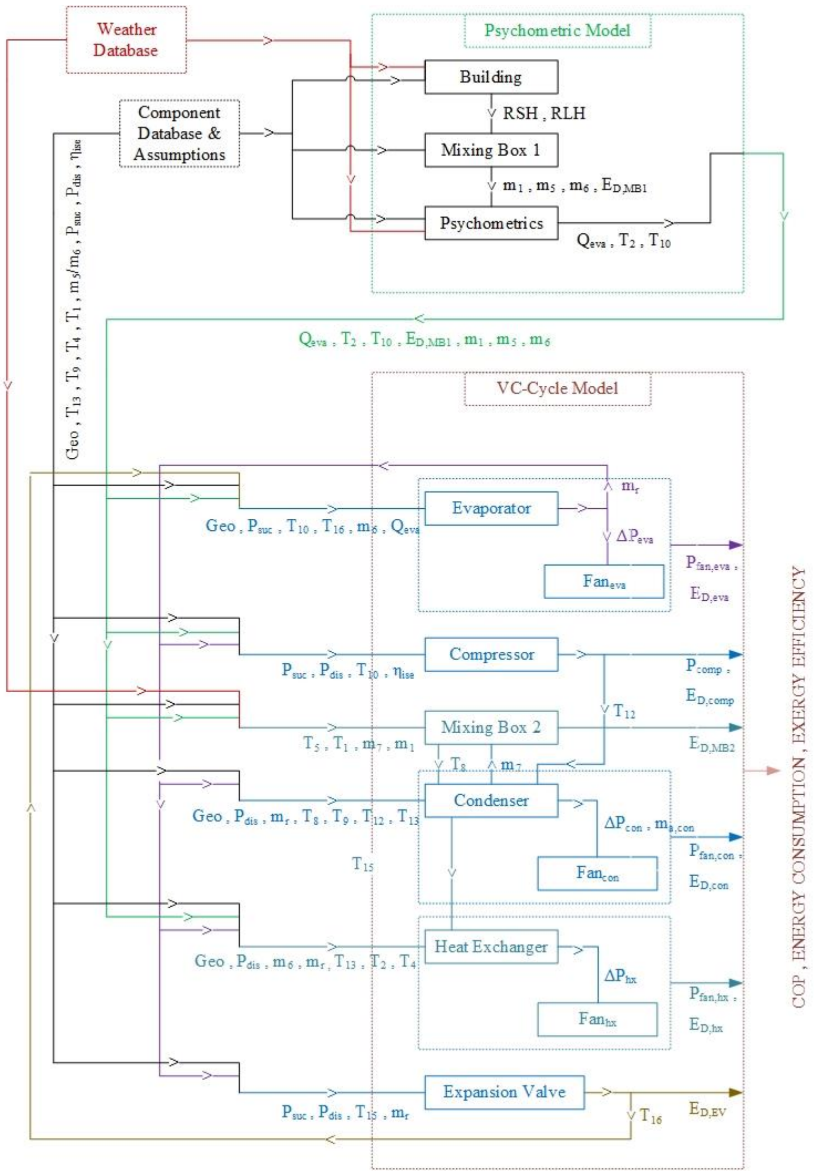
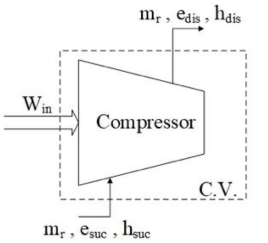
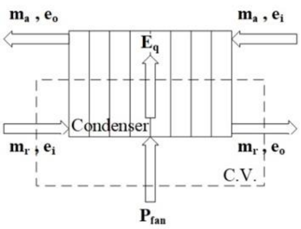
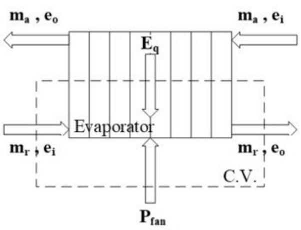
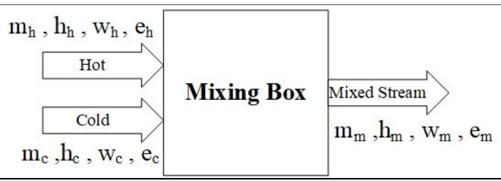
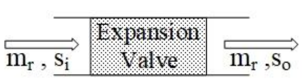


Figure 2. Data flowchart exploited in EES software to conduct energy and analysis

Unlike energy, exergy does not adhere to the first law of thermodynamics and the net amount of exergy transferred through the control volume's boundary is not supposed to be balanced. This phenomenon happens due to the irreversibilities and entropy generations within the system, which results in the notion of exergy destruction and exergy loss. The amount of destructed exergy is either calculated via exergy balance or summation of the generated entropy within the whole system (Frangopoulos, 2009). In the present study exergy analysis encompasses assessing component-by-component exergy destruction and the whole system exergy efficiency. Components that are to be studied are compressor, condenser, evaporator, expansion valve, heat exchanger, first mixing box and second mixing box. Required relations to obtain exergy destruction within each component are listed in Table 1 (Dincer & Rosen, 2015; Frangopoulos, 2009; Sayadi et al., 2019). Compressor's exergy destruction is formulated as Equation 1 assuming the control volume as depicted. It is worthwhile to mention that in condenser, where refrigerant cooling takes place, the exergy and energy flows are in opposite direction; on the contrary, in evaporator where refrigerant heating occurs, energy and exergy flows are in the same direction. This is the reason that the term of heat transfer consequent exergy flow in the condenser is subtracted, whereas, in the evaporator the respective exergy flow term is summed. It is worth mentioning that the auxiliary heat exchanger is in fact an extra condenser in series arrangement with the system's main condenser, hence in case of exergy destruction calculations Equation 2 should be applied to this component. Moreover, T_b that denotes control volume boundary temperature is assumed to be the logarithmic mean temperature difference of the heat exchanger. In the mixing box where two streams with different temperatures are mixed, if the purpose of mixing is to cool the hot stream, Equation 4 has to be utilized to obtain the exergy destruction but, if the purpose of mixing is to heat the cold stream, Equation 5 should be used. In this study both mixing boxes' angle is to cool the hot stream; one to cool the fresh air before entering the apparatus and the other one to precool the condenser cooling air. One of the components that best manifests the notion of exergy destruction and is defiant to the first law of thermodynamics, is expansion valve. Expansion valve undergoes the Joule-Thomson effect (Cengel & Boles, 2011) and as a result is considered as an isentropic process, where no energy is attenuated but due to entropy generation, exergy destruction soars.

Table 1. Exergy destruction equations within each component of the system (Dincer & Rosen, 2015; Frangopoulos, 2009; Sayadi et al., 2019)

Component	Equation	
	$E_{D,comp} = \dot{m}_r .(e_{dis} - e_{suc}) + W_{in}$	(1)
	$E_{D,con} = \dot{m}_r .(e_i - e_o) + P_{fan,con} - Q_{con} \cdot \left[1 - \frac{T_0}{T_{b,con}}\right]$	(2)
	$E_{D,eva} = \dot{m}_r .(e_i - e_o) + P_{fan,eva} + Q_{eva} \cdot \left[1 - \frac{T_0}{T_{b,eva}}\right]$	(3)
	$E_{D,MB} = \dot{m}_h .(e_h - e_m) - \dot{m}_c .(e_m - e_c)$ cooling	(4)
	$E_{D,MB} = \dot{m}_h .(e_h - e_m) - \dot{m}_c .(e_m - e_c)$ heating	(5)
	$E_{D,EV} = \dot{m}_r .(s_i - s_o)$	(6)

The term e is the specific exergy which demonstrate the amount of exergy that a kilogram of a substance embeds and could be found as below:

$$e=(h-h_0)-T_0(S-S_0) \tag{7}$$

It should be brought into consideration that the exergy destruction within the reheat coil is calculated with the single assumption of the coil being fully efficient, as a result the amount of exergy destruction is equal to the energy that should be consumed in the reheat coil to heat up the supply air to the predefined set-point temperature and it is formulated as Equation 8, where Δh denotes the difference of fresh and supply air. Finally, exergy efficiency of each air dehumidifier system would be obtained via Equation 9.

$$E_{D,reheat}=\dot{m}_{air}\,\Delta h \tag{8}$$

$$\varepsilon_{tot}=\left|\frac{Q_{eva}.\left[1-\dfrac{T_0}{T_{b,2}}\right]}{E_{feed,tot}}\right| \tag{9}$$

The exergy product of the air dehumidification systems is the evaporator’s cooling duty that is responsible to handle both the sensible and latent loads of the building. Hence, exergy product is the heat transfer subsequent exergy flow that is rejected to the system’s ambient.

Results and Discussion

Exergy analysis has been conducted for cooling seasons of a year that the air dehumidifier should treat a considerable load of latent heat as well as sensible heat. Simulation of the system’s model has been conducted quasi-dynamically for 4440 hours from April 21st to October 23rd. First, results are discussed for the outside air fraction (fresh air fraction) of 53%, then a sensitivity analysis would be conducted on the outside air fraction to track the exergy destruction with respect to the fraction of the supplied fresh air to the conditioned space. Figure 3 depicts the quasi-dynamic exergy destruction of the proposed and conventional vapor compression air dehumidifiers for the outside air fraction of 53%, while Figure 4 compares the net amount of exergy destruction of both systems. As it could be elicited from both figures, in the proposed air dehumidification system, exergy destruction within compressor decreases owing to the auxiliary heat exchanger implemented in the system. This auxiliary heat exchanger decreases the temperature of the refrigerant before entering the expansion valve, as a result the refrigerant flow rate in the system falls and consequently the compressor exergy destruction that is a function of refrigerant mass flow rate decreases compared with the conventional air dehumidification system.

Exergy destruction in the condenser of the proposed system decreases substantially due to the added mixing box that precools the condenser cooling air by means of mixing it with the building’s ventilate air. This precooling leads to less power consumption in the condenser’s fan, and as a result lower exergy destruction. Moreover, the existence of the auxiliary heat exchanger that reduces the refrigerant mass flow rate is a bit of help to lowering the exergy destruction within the condenser. As it is evident, in the proposed system the reheat coil which previously was used to reheat the supply air, is replaced with an auxiliary heat exchanger. This replacement would eliminate the tremendous exergy destruction associated to the reheat coil, and instead, exert a much lower exergy destruction that is implicated to the auxiliary heat exchanger (exergy destruction of heat transfer and axial work) on the proposed dehumidification system. It should be noted that exergy destruction in both mixing boxes is trifling compared to other system's components and exergy destruction in evaporator in both systems are equal due to the fixed demand side.

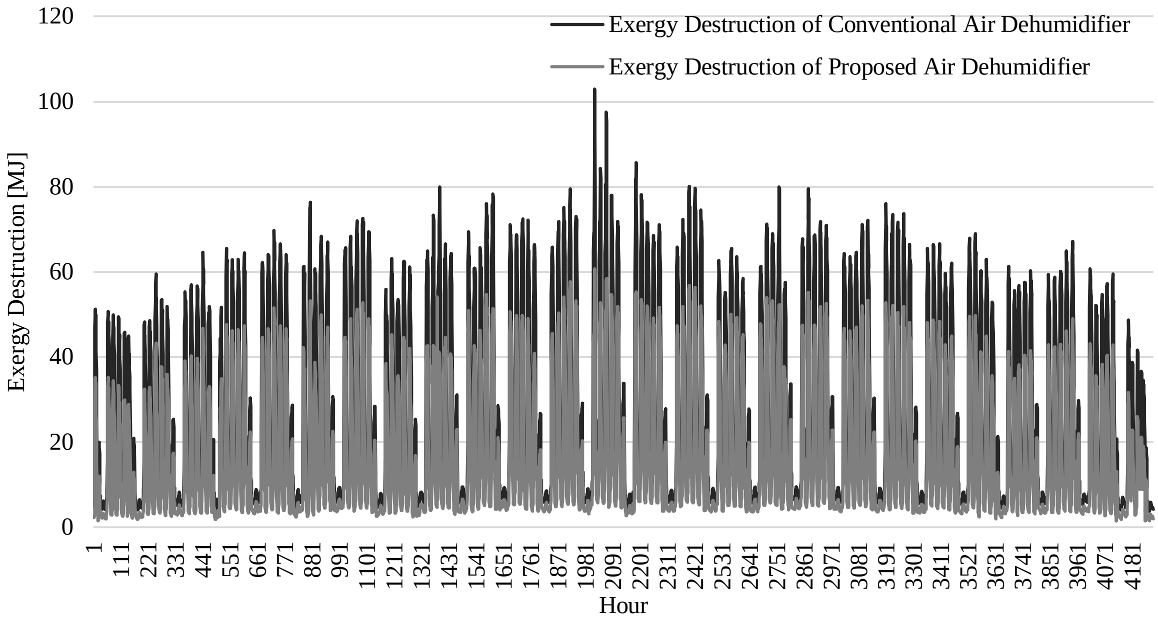


Figure 3. Quasi-dynamic exergy destruction in both air dehumidifiers

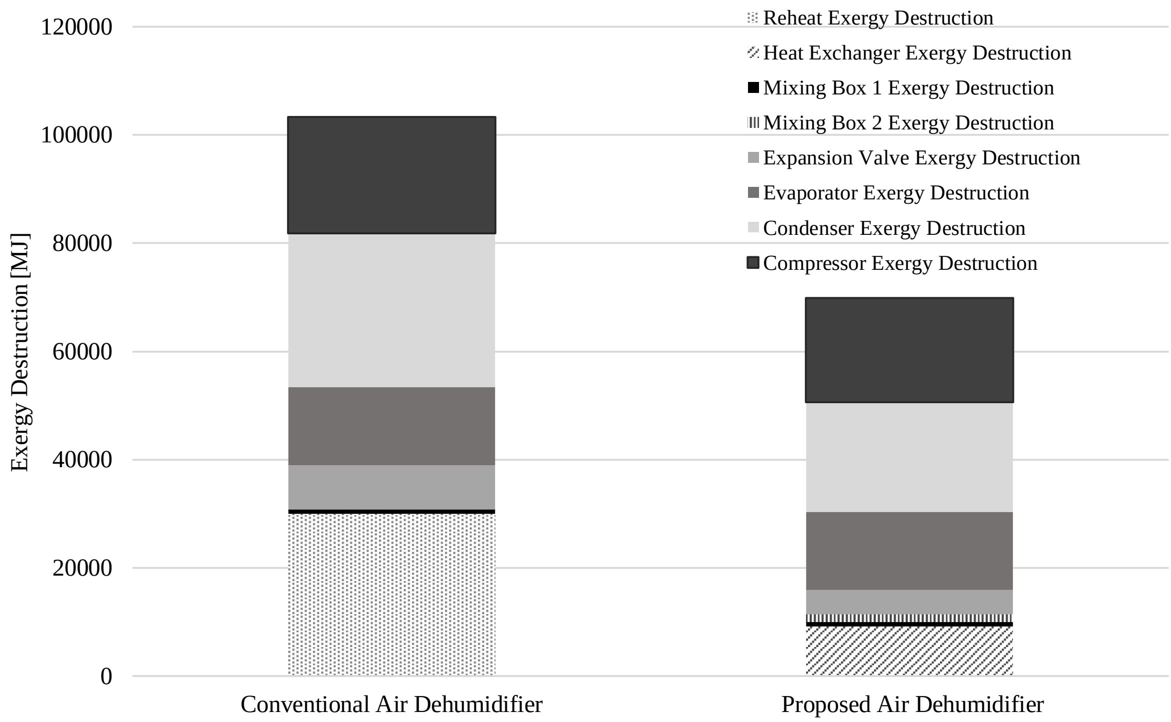


Figure 4. Net exergy destruction in both air dehumidifiers

It is of great interest to understand the trend of exergy destruction in HVAC systems under different outside air fractions (fresh air fractions). Outside air fraction is in fact the building's air change rate that is dominated by the application of the studied building. Figure 5 illustrates the total exergy destruction in both the conventional and the proposed air dehumidifiers under different fresh air fractions. As it is evident, the proposed system has undergone a tangible down shift in its overall exergy destruction. This shift is on the account of mitigating the reheat coil and replacing it with an auxiliary heat exchanger. With rising the outside air fraction, exergy destruction in both dehumidification systems increases but, the slop of this increment for the conventional system tends to be steeper than that of the proposed system. The reason that such thing takes place is that with increasing the outside air fraction, the amount of the air that is mixed in the second mixing box proliferates subsequently and the condenser cooling air gets cooler and relinquishes the condenser of excessive air mass flow rates to reject the heat. In other words, more the condenser cooling air cools down, less the fan power is required to handle the condenser load.

Another measure to evaluate and compare energy systems in order to be judged upon is exergy efficiency. This simple but profound concept indicates that how much exergy has been destroyed so that a particular amount of exergy is produced. For comparing two these air dehumidification systems with a fixed demand side, the produced exergies, which is the generated cooling loads, are analogous. Hence, a system with higher exergy efficiency destructs less exergy and resources to come up with the same demand. Figure 6 shows the exergy efficiency of both the conventional and proposed air dehumidifier under various outside air fractions. As it is depicted in the figure, the conventional system’s exergy efficiency rises with increasing the outside air fraction by 55%, and then falls. This happens because of the constant exergy destruction of reheat coil under any fresh air fraction and the linear increase that cooling load experiences, whereas, the destructed exergy increases quadratically. The up shift that happens to the exergy efficiency in the proposed system is due to the elimination of the reheat coil and replacing it with an auxiliary heat exchanger. Also, the inexistence of the reheat coil justifies the declination of the exergy efficiency with the outside air fraction in the proposed system.

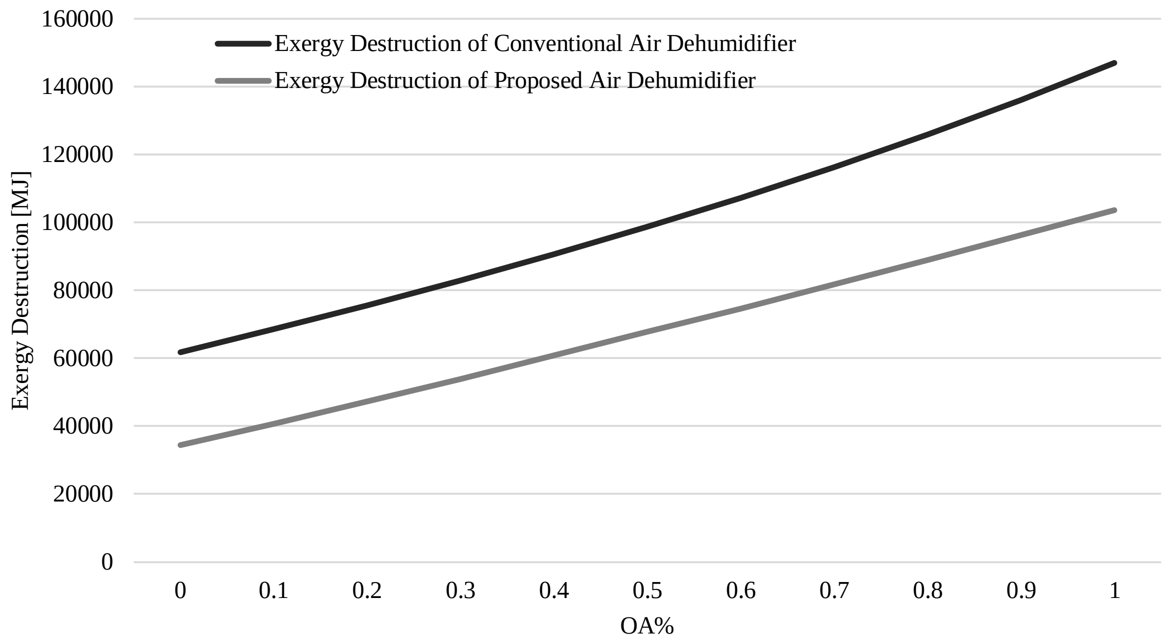


Figure 5. Net exergy destruction variations versus different outside air fractions

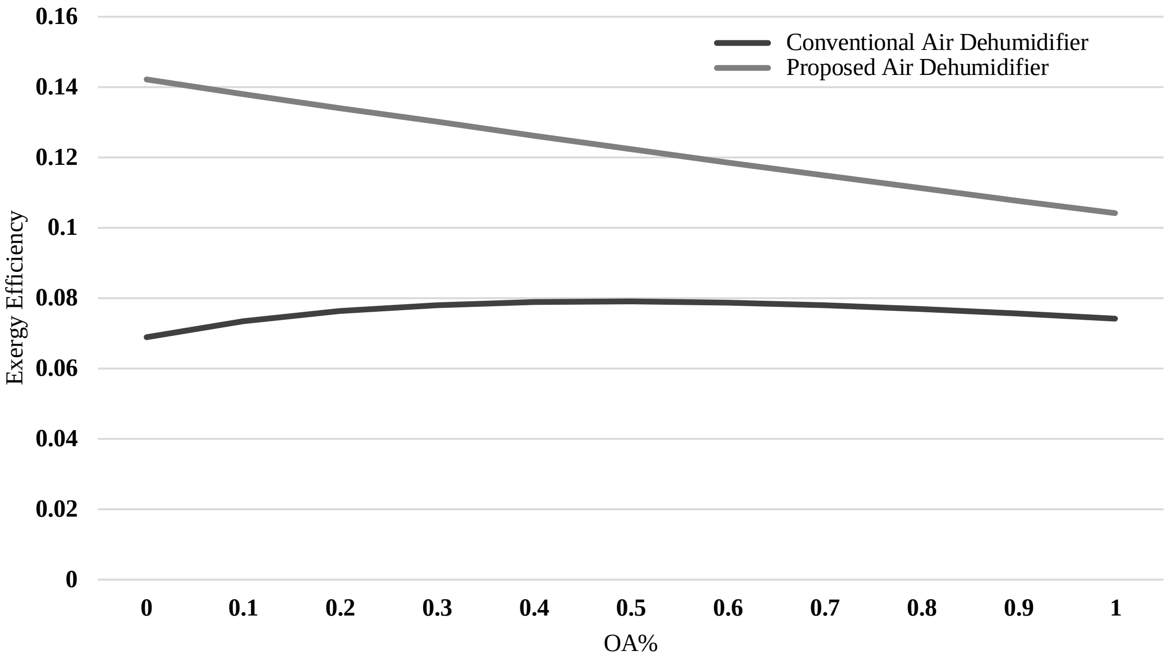


Figure 6. Exergy efficiency versus outside air fraction

Conclusion

In this study an improved air dehumidification system, equipped with an extra mixing box to recover the ventilated air heat, and an auxiliary heat exchanger in series arrangement with main condenser in order to mitigate the reheat coil has been introduced. Mitigation of the reheat coil and avert tremendous exergy destruction; also, it would refrain the exergy loss from the system's boundary. A comprehensive methodology to assess the exergy preferences of both the conventional and proposed air dehumidifiers has been provided. Also, exergy analysis has been conducted on both systems and results were compared together. Results signifies that:

- For the outside air fraction of 53%, exergy destruction of the proposed air dehumidification system has reduced by 32.4% compared with that of the conventional system.
- Proposed system's exergy efficiency has increased up to 53.45% for the outside air fraction of 53%.
- Exergy destruction in the proposed air dehumidification system has undergone reduction of 46% to 30.5 % compared with the conventional system.
- The proposed system's exergy efficiency has experienced a 106% to 40.3 % boost compared with the conventional system, depending on the outside air fraction.

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