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Second Law Analysis of an Adsorption Air-Conditioning System

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Abstract. Air conditioning systems are designed to improve people's living standards and provide comfort. The use of this system brings together with environmental problems, energy consumption and costs. These problems can be reduced by making studies on energy efficiency and saving in air conditioning systems. Adsorption (dehumidification, desiccant) air conditioning systems, which have widely being used in recent years, can be evaluated in terms of energy efficiency. In this study, a desiccant based air-conditioning system was considered to evaluate the system performance by using second law analysis (exergy analysis) for Yozgat province. Psychometric properties for each state and system performance parameters were calculated using Engineering Equation Solver (EES). It was found from the results that maximum exergy destruction occurs in electric heater unit and the total exergy destruction of the system is 24.66 kW. It was also found that the exergy efficiency of this system is 19.87 %. The results showed that this system can be used for air conditioning in Yozgat climate conditions and the performance of the system can be increased by using waste heat or renewable energy resources for regeneration heat.

Keywords Air conditioning, Second law analysis, exergy, irreversibility

Adsorbsiyonlu Bir İklimlendirme Sisteminin İkinci Yasa Analizi

Özet. İklimlendirme sistemleri insanların yaşam standartlarını yükseltmek ve konfor sağlamak için tasarlanmaktadır. Bu sistemlerin kullanımı enerji tüketimi, enerji maliyetleri ve çevre problemlerini de beraberinde getirir. Bu problemler, iklimlendirme sistemlerinde enerji verimliliği ve tasarrufuna yönelik çalışmalar yapılarak azaltılabilmektedir. Enerji verimliliği açısından değerlendirilebilecek iklimlendirme sistemlerinden biride son yıllarda yaygın bir şekilde kullanılmakta olan adsorbsiyonlu (nem almalı, desisif) iklimlendirme sistemleridir. Bu çalışmada, nem almalı bir iklimlendirme sistemi ele alınarak sistem performansı, ikinci yasa analizi (ekserji analizi) yapılarak Yozgat iklim şartları için değerlendirilmiştir. Sistemde bulunan bütün noktaların psikrometrik özellikleri ve sistem performans parametreleri, Engineering Equation Solver (EES) programı kullanılarak hesaplanmıştır. Yapılan çalışma sonunda ele alınan sistemde en çok tersinmezliğin (ekserji yıkımı) ısıtma ünitesinde meydana geldiği ve sistemin toplam tersinmezliğin 24.66 kW olduğu tespit edilmiştir. Ayrıca sistem ikinci yasa (ekserji) verimi %19.87 olarak hesaplanmıştır. Elde edilen sonuçlardan sistemin Yozgat iklim şartlarında iklimlendirme uygulamalarında kullanılabileceği ayrıca bu tür sistemlerde rejenerasyon ısısının elde edilmesinde atık ısı veya yenilenebilir enerji kaynaklarının kullanımıyla sistem performansının arttırılabileceği belirlenmiştir.

Anahtar Kelimeler: İklimlendirme, ikinci yasa analizi, ekserji, tersinmezlik

1. INTRODUCTION

Increasing energy consumption in cooling applications is one of the prime concerns of the present age all over the world. Environmental issues associated with the production of high grade electrical energy and increasing demand for cooling applications have thrown researchers to investigate newer technologies for air conditioning. Desiccant cooling is an approach for air conditioning towards resolving the environmental and economic issues of the conventional vapor compression cooling systems [1]. In addition, evaporative and desiccant cooling technologies for air conditioning systems have increased as an alternative or as an addition to conventional vapor compression systems. These systems are mainly used in places where thermal energy sources are easily found, where the price of electrical power is high, the latent heat percentage is high or the needed dew point of the air is low [2]. Desiccant air conditioning systems can be classified into two categories, solid and liquid desiccant air

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conditioning systems. These technologies have been used widely; because of being advantageous in handling latent heat load [3]. Desiccant cooling systems were studied experimentally and theoretically by several researchers. In these studies, it was shown that desiccant cooling systems is suitable for hot and humid environment conditions [4-6]. Desiccant air-conditioning systems do not use harmful to the environment refrigerants, neither do they consume electrical energy for the cooling process, but thermal energy, in temperature levels that favor the use of solar energy, and more specifically flat plate solar collectors [7].

Desiccant cooling systems can be categorized based on operating cycles, such as ventilation, recirculation, dunkle cycles and etc. [3]. Performance of desiccant cooling systems with different operation cycle was evaluated by many researchers. Jain et al. [8] investigated various solid desiccant cycles (the ventilation cycle, the recirculation cycle, the Dunkle cycle and the wet surface heat exchangers cycle (SENS cycle)) for various outdoor conditions of many cities in India. It was shown that performance (COP) is 2.63 for wet surface heat exchangers cycle, while it is 0.46 for Dunkle cycle. Meckler [9] has proposed a two-stage solid desiccant air conditioning system integrating with a HVAC system. It was reported that 30–50% of the dehumidification task could be accomplished by the enthalpy exchanger. Sheridan and Mitchell [10] have analyzed the performance of a hybrid desiccant cooling system for hot-humid and hot-dry climates. The results showed that the energy savings ranged from 20% to 40% in high sensible heat load applications and the hybrid system saved more energy in a hot-dry climate than that in a hot-humid climate, where it might even use more energy than a conventional system. In another study, Hong et al.[11] were studied the performances of the two different hybrid cycles (vapor compressor and desiccant cooling system; vapor compressor, desiccant and direct evaporative cooler cooling system) in China. They showed that more energy was saved in hot, dry climates and less was saved in hot, humid climates for the conventional hybrid cycles, while the solar hybrid cycles always saved more energy than conventional vapor compression cycles.

Exergy analysis has be conducted for desiccant cooling systems by many researchers [12-16]. La et al. [12, 16] investigated the performances of a ventilation system from the perspective of exergy destructions. It was found that exergy destructions of the desiccant wheel and the heat source accounted for around 50% the total exergy destruction. The influences of the effectiveness of each component on the exergy efficiency of the ventilation system were investigated afterwards. Similar study has been carried out based on a novel desiccant cooling system by Uçkan et al. [13]. The results show that exergy destructions of the electrical heater and the desiccant wheel were the top two highest, to which 65% and 18% of the total exergy destruction were attributed, respectively. The work of Kanoglu et al.[17] shows that the desiccant wheel and the heating source took 33.8% and 31.2% of the total exergy destruction, respectively. Similar results can be found in the experiment study of Hürdogan et al. [14], where the electrical heater took almost 70% of the total exergy destruction. Sheng et al. [18] found that when the electrical heater was replaced by the heat pump, exergy efficiency was increased by nearly 50%.

In this study, a desiccant cooling system [13] was evaluated by using Engineering Equation Solver (EES). This paper presents also the exergy analysis of the system for Yozgat climate conditions, Turkey. The performance of the system was evaluated and compared with each other by using the following indicators: the COP and exergy efficiency of the whole system, the exergy efficiency of each component of the system.

2. MATERIALS AND METHOD

A desiccant cooling system (DCS) considered in this study mainly consists of rotary desiccant dehumidifier, heat exchangers, humidifier (evaporative coolers), fans, control units and channels.

Figure 1 illustrates the schematic view of DCS. Three air channels which are composed fresh air (process 1-6); waste air (process 7-10) and regeneration air (process 11-17) are used in DCS. In the system rotary desiccant dehumidifier removes moisture from the fresh air (process 1–2). The dry fresh air is cooled first by the regeneration air in the heat exchanger 1 (process 2–3). In the second step, the fresh air is entering into the heat exchanger 2 (process 3–4) where fresh air is cooled again by exhaust air. After these processes, fresh air is entering into the evaporative cooler 1 (process 4–5) where last cooling process occurs. The fresh air cooled in these processes is supplied into the air conditioning room (state 6).

Waste air first passes through the evaporative cooler 2 (process 8–9), then it enters the heat exchanger 2 (process 9-10). As the waste air passes through the heat exchanger 2 its temperature is increasing but temperature of the fresh air is decreasing at the same time. After that, air is discharged to atmosphere.

For regeneration, the regeneration air is sucked from outdoor by a fan through the filter. Thereafter the regeneration air is sent into heat exchanger 1 where it is heated (process 11–12) but the fresh air is cooled. After that it is sent into the heat exchanger 3 (process 12–13). Electric heater is used for heating the regeneration air before entering into the rotary dehumidifier (state 14). After the regeneration air passes from the desiccant wheel (process 14–15), its moisture contents increase and it is sent into another part of heat exchanger 3 (process 15–16). Finally the regeneration air is discharged to atmosphere [19].

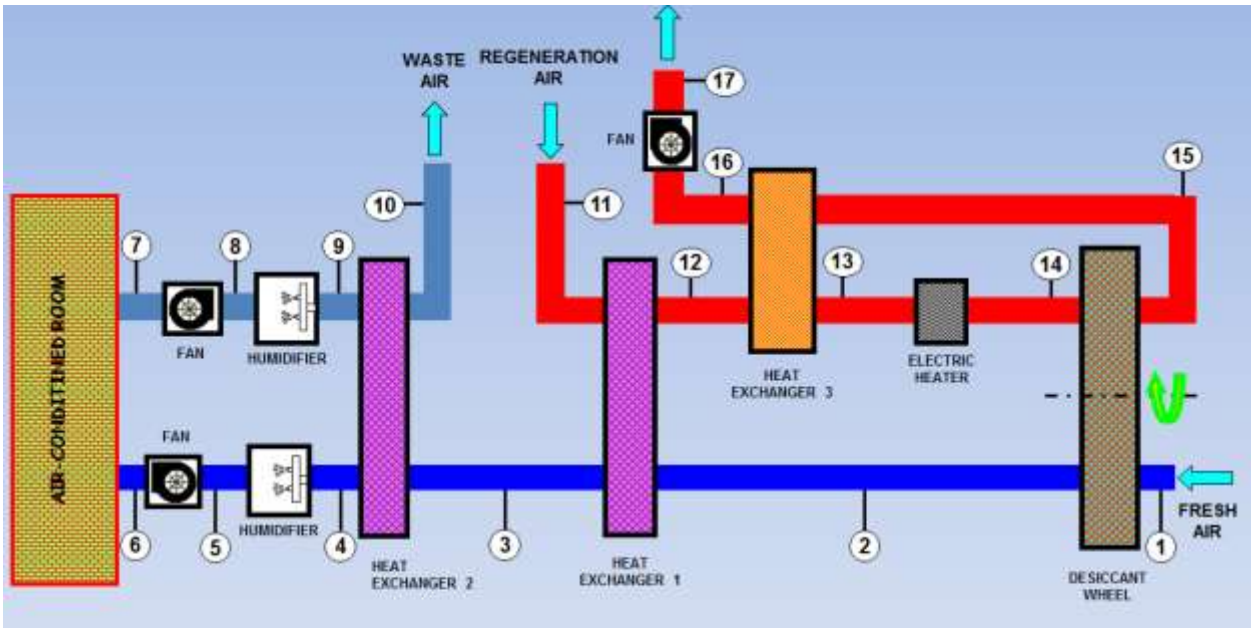

Figure 1. Schematic representation of DCS

3. PERFORMANCE CALCULATIONS

In the analysis, various calculations (cooling capacity, COP, exergy efficiency, etc.) are carried out to determine the performance of the system and its components [20-23]. The parameters used for calculations are given in Table 1.

Table 1. The values used in the calculations

Parameter	Value
Total cooling load of the air-conditioned room (kW)	10
Design dry bulb temperature (°C) and relative humidity (%) of the air-conditioned room	26 - 50
Flow rate of the fresh air (m^3/h)	4000
Flow rate of the exhaust air (m^3/h)	4000
Flow rate of the regeneration air (m^3/h)	4000
Effectiveness of the recuperators (%)	65
Effectiveness of the regenerator (%)	85
Sensible heat ratio of the air-conditioned room	0.9
Effectiveness of the evaporative cooler (%)	90
Efficiency of the fans (%)	60
Powers of the fans (kW) (Fresh-Waste-Regeneration)	3-1-4
Climate conditions for Yozgat (Dry and wet bulb temperature, °C)	32 - 20

The coefficient of performance (COP) of the systems is defined as the ratio between the cooling capacity obtained and total energy input ($\dot{E}_{tot}$) to the system:

$$COP = \frac{\dot{Q}_{CC}}{\dot{E}_{tot}} \tag{1}$$

Cooling capacity of a desiccant cooling system $\dot{Q}_{CC}$ is obtained from:

$$\dot{Q}_{CC} = \dot{m}_f (h_b - h_f) \tag{2}$$

where $\dot{m}_f$ is the mass flow rate of the fresh air stream, h_b is the enthalpy of the air at the inlet of air-conditioned room and h_f is the enthalpy of the ambient air.

$\dot{E}_{tot}$ is the sum of energy consumption of regeneration heat ($\dot{Q}_{reg}$), fans ($\dot{W}_{fan}$), and other electrical components ($\dot{W}_{oth}$) such as pump of the humidifiers, control panels etc.:

$$\dot{E}_{tot} = \dot{Q}_{reg} + \dot{W}_{fan} + \dot{W}_{oth} \tag{3}$$

In this study, since electric heaters are used to simulate regeneration heat source, the heat input for the regeneration is almost same as power consumption of electric heaters ($\dot{W}_{eh}$) when the daily total values are considered ($\dot{Q}_{reg} = \dot{W}_{eh}$).

Electric heater capacity of a desiccant cooling system is obtained from:

$$\dot{W}_{eh} = \dot{m}_r (h_{eo} - h_{ei}) \tag{4}$$

where $\dot{m}_r$ is the mass flow rate of the regeneration air stream; h_{eo} and h_{ei} is the enthalpy of the air at the inlet and outlet of electric heater.

General mass, energy, entropy and exergy balance equations are given in more detail elsewhere [14], while the following section covers the relations on the system component basis illustrated in Fig. 1 is reported in Table 2. The subscript “c”, “h”, “i” and “o” refers to cold air stream, hot air stream, inlet and outlet of devices respectively.

The assumptions made during the analyses are given below;

- DCS is steady-state and steady-flow with negligible potential and kinetic energy effects and no chemical or nuclear reactions.
- Heat transfer to the system and work transfer from the system are positive.
- Heat transfer and refrigerant pressure drops in the tubing connecting the components are neglected
- The dead (reference) state values were considered to be 15 ºC and 101.325 kPa.

Table 2. Mass, energy, exergy balances and exergy efficiency for the system components

Desiccant wheel (dw)	Energy Balance	$\dot{Q}_{dw} = \dot{m}_f (h_{dwco} - h_{dwci})$; $\dot{Q}_{dw} = \dot{m}_r (h_{dwhi} - h_{dwho})$
	Exergy Balance	$\dot{E}x_{dest,dw} = \dot{m}_f (\psi_{dwci} - \psi_{dwco}) + \dot{m}_r (\psi_{dwhi} - \psi_{dwho}) + \dot{W}_{dw,elec}$
	Exergy Efficiency	$\varepsilon_{F,dw} = \dfrac{\dot{E}x_{dwco} - \dot{E}x_{dwci}}{\dot{E}x_{dwhi} - \dot{E}x_{dwho} + \dot{W}_{dw,elec}}$
Heat exchanger (he)	Energy Balance	$\dot{Q}_{he} = \dot{m}_f (h_{heci} - h_{heco})$; $\dot{Q}_{he} = \dot{m}_r (h_{hehi} - h_{heho})$
	Exergy Balance	$\dot{E}x_{dest,he} = \dot{m}_f (\psi_{heci} - \psi_{heco}) + \dot{m}_r (\psi_{hehi} - \psi_{heho})$
	Exergy Efficiency	$\varepsilon_{F,he} = \dfrac{\dot{E}x_{heco} - \dot{E}x_{heci}}{\dot{E}x_{hehi} - \dot{E}x_{heho}}$
Fan (f)	Energy Balance	$\dot{W}_{fan} = \dot{m}_f (h_{fco} - h_{fci})$
	Exergy Balance	$\dot{E}x_{dest,fan} = \dot{m}_f (\psi_{fci} - \psi_{fco}) + \dot{W}_{fan,f,elec}$
	Exergy Efficiency	$\varepsilon_{F,fan} = \dfrac{\dot{E}x_{fco} - \dot{E}x_{fci}}{\dot{W}_{fan}}$
Humidifier (ec)	Energy Balance	$\dot{m}_w h_{eci} + \dot{m}_{water,ec} h_{water,ec} = \dot{m}_w h_{eco}$
	Exergy Balance	$\dot{E}x_{dest,ec} = \dot{m}_w (\psi_{eci} - \psi_{eco}) + E_{water,ec}$
	Exergy Efficiency	$\varepsilon_{U,ec} = \dfrac{\dot{E}x_{eco}}{\dot{E}x_{eci} + \dot{E}x_{water,ec}}$
Electric heater unit (eh)	Energy Balance	$\dot{W}_{eh} = \dot{m}_r (h_{ehho} - h_{ehhi})$
	Exergy Balance	$\dot{E}x_{dest,eh} = \dot{m}_r (\psi_{ehhi} - \psi_{ehho}) + \dot{W}_{eh}$
	Exergy Efficiency	$\varepsilon_{F,eh} = \dfrac{\dot{E}x_{ehho} - \dot{E}x_{ehhi}}{\dot{W}_{eh}}$
Overall System	Mass Balance	$\dot{m}_f = \dot{m}_r = \dot{m}_w$
	Exergy Efficiency	$\varepsilon_{F,sys} = \dfrac{\Sigma \dot{P}_{sys}}{\Sigma \dot{F}_{sys}}$
	Total Exergy Destruction	$\dot{E}x_{dest,total} = \dot{E}x_{dest,fan} + \dot{E}x_{dest,eh} + \dot{E}x_{dest,he1} + \dot{E}x_{dest,dw} + \dot{E}x_{dest,ec}$

4. RESULT AND DISCUSSION

Temperature, pressure and mass flow rate data for DCS is given in Table 3 according to their state numbers specified in Figure 1. The exergy rates were also calculated for each state as presented in Table 3 while exergy destruction and exergy efficiency data for representative components of the whole system are given in Table 4.

As can be seen from Table 4, the greatest exergy destruction on the system basis occurs in the electric heater unit (12.29 kW), followed by regeneration air fan (3.86 kW), the fresh air fan (2.98 kW), heat exchanger 1 (0.07 kW) and the whole system (24.66 kW). COP of the system was calculated to be 0.66.

COP of the systems can be increased with usage of waste heat or renewable energy sources. Exergy efficiency of the system and the heat exchanger 1, which is maximum, are calculated to be 19.87% and 86.6%, respectively.

Table 3. Exergy analysis results of DCS

State No	Description	Fluid	Phase	Temperature (^oC)	Pressure (kpa)	Specific humidty ratio (kg water/kg dry air)	Specific Enthalpy (kj/kg)	Mass flow (kg/s)	Specific Exergy(kj/kg)	Exergy rate (kW)
0		Moist Air	Dead State	15	101.325	0.0166	-	-	-	-
0		Water	Dead State	15	101.325	-	63	-	-	-
1, 11	Outdoor	Moist Air	Gas	32	101.325	0.0097	56.97	1.278	0.709	0.906
2	Dehumidifier outlet / Heat ex. 1 inlet	Moist Air	Gas	40.59	101.325	0.0071	59.08	1.278	1.569	2.005
3	Heat ex. 1 outlet / Heat ex. 2 inlet	Moist Air	Gas	34.92	101.325	0.0071	53.3	1.278	1.126	1.439
4	Heat ex. 2 outlet / Heat ex. 3 inlet	Moist Air	Gas	25.71	101.325	0.0071	43.92	1.278	0.647	0.827
5	Heat ex. 3 outlet / F.fan inlet	Moist Air	Gas	18.89	101.325	0.0099	44.1	1.278	0.230	0.294
6	F.fan outlet / Conditioned room inlet	Moist Air	Gas	19.82	101.325	0.0099	45.06	1.278	0.244	0.312
7	Conditioned room outlet / W.fan inlet	Moist Air	Gas	26	101.325	0.0105	52.87	1.278	0.375	0.489
8	W.fan outlet / Evaporative cooler inlet	Moist Air	Gas	26.3	101.325	0.0105	53.18	1.278	0.387	0.504
9	Evaporative cooler outlet/ Heat Ex. 2 inlet	Moist Air	Gas	19.56	101.325	0.0133	53.4	1.278	0.081	0.106
10	Heat Ex. 2 outlet	Moist Air	Gas	29.54	101.325	0.0133	63.68	1.278	0.411	0.535
12	Heat Ex. 1 outlet / Heat ex. 4 inlet	Moist Air	Gas	37.59	101.325	0.0097	62.69	1.278	1.091	1.395
13	Heat Ex. 4 outlet / Elec. Heater unit inlet	Moist Air	Gas	49.35	101.325	0.0097	74.73	1.278	3.135	4.006
14	Elec. Heater unit outlet / Dehumidifier inlet	Moist Air	Gas	60	101.325	0.0097	85.64	1.278	4.970	6.351
15	Dehumidifier outlet / Heat ex. 4 inlet	Moist Air	Gas	51.43	101.325	0.0123	83.6	1.278	3.478	4.445
16	Heat ex. 4 outlet / R. Fan inlet	Moist Air	Gas	39.67	101.325	0.0123	71.51	1.278	1.235	1.579
17	R. Fan outlet	Moist Air	Gas	40.91	101.325	0.0123	72.78	1.278	1.344	1.717

Table 4. Exergy data for representative components of the whole system

Item number	Component	Exergetic product (exergy output) rate (kW)	Exergetic Fuel (exergy ınput) rate (kW)	Exergy destruction rate (kW)	Exergy efficiency
I	Dehumidifier	1.063	1.737	0.673	0.612
II	Heat Exchanger 1	0.467	0.539	0.072	0.866
III	Heat Exchanger 2	0.425	0.603	0.177	0.705
IV	Heat Exchanger 3	0.295	0.940	0.645	0.314
V	Fresh air fan	0.018	3	2.982	0.006
VI	Waste air fan	0.015	1	0.984	0.015
VII	Evaporative cooler	0.106	0.617	0.510	0.172
VIII	Heat Exchanger 4	1.377	1.672	0.294	0.824
IX	Electric heater	1.681	13.97	12.29	0.120
X	Regeneration air fan	0.130	4	3.869	0.032
XI	Overall system	5.581	28.08	24.66	0.1987

5. CONCLUSION

In this study, a desiccant based air-conditioning system was considered. Performance of the system was evaluated by using exergy analysis (second law) method. It was found for the results that:

- Maximum exergy destruction occurs in electric heater unit and the total exergy destruction of the system is 24.66 kW.
- The COP of the system is found to be 0.66.
- Exergy efficiency of the system is 19.87 %. System can be used for air conditioning in Yozgat climate conditions and the performance of the system can be increased by using waste heat or renewable energy resources for regeneration heat.

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