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MULTI-OBJECTIVE OPTIMIZATION OF A TWO-BED SOLAR ADSORPTION CHILLER BASED ON EXERGY AND ECONOMICS

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ABSTRACT

In this present work, a two-bed solar adsorption chiller is simulated and optimized. This system uses two working-pair candidates, namely silica gel-water and zeolite-water. Optimization using a multi-objective genetic algorithm was conducted to find out the optimum condition of the system in terms of a thermodynamic analysis and an economic point of view. Exergy destruction and total annual costs were the two objective functions examined while solar collector area, cooling water mass flow rate, hot water mass flow rate, and chilled water mass flow rate were chosen as decision variables for optimizing the procedure. The results show that the zeolite-water working pair had a lower value of exergy destruction and annual cost compared to the silica gel-water working pair, which resulted in an exergy destruction of 150,938 watts at annual cost of $216,818 USD. However, the zeolite-water working pair had a lower cooling capacity and coefficient of performance (COP) than the silica gel-water working pair.

Keywords: Adsorption chiller; Economics; Exergy; Multi-objective Optimization; Solar

1. INTRODUCTION

Vapor-compression cycles in HVAC systems usually contain chlorofluorocarbon and hydrochlorofluorocarbon. Some refrigerants with high global warming potential and ozone depletion potential values have contributed to ozone layer depletion and global warming (Nasruddin et al., 2015). Therefore, an alternative refrigeration system is required. Such alternative cooling and refrigeration technology, known as an adsorption system, exists that is driven by renewable energy sources (Wang et al., 2009). In recent decades, adsorption cooling and refrigeration systems driven by solar energy have attracted increased attention because they can change heat from solar radiation into cool air without using any environmentally harmful refrigerants (Luo et al., 2007; Xua, 2012).

Besides the environmental benefits, adsorption cooling systems have many advantages (Sumathy et al., 2003; Wang & Oliveira, 2006); they use natural refrigerants like water, they lack a vibration effect, they are simple to construct and control, they use low grade heat source temperatures, they lack of moving parts, and their operating costs are low. In addition, compared to other cooling systems, the adsorption system shows no problems with corrosion of materials or substance crystallization.

The need for optimum adsorption cooling systems encourages researchers to search for possible way to improve the system. Some research has focused on the physicochemical properties of

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different adsorbent-adsorbate (Wang et al., 2004; Wang et al., 2009;). Miyazaki et al. (2009) examined a new cycle time allocation to increase the adsorption system performance. Miyazaki and Akisawa (2009) optimized the effect heat capacity and number of transfer units (NTU) of adsorption cooling systems. Boelman et al. (1995) studied the effect of operating conditions on COP and cooling capacity in adsorption cooling systems. Wang et al. (2009) investigated adsorption chillers using working pairs and varieties of heat sources. Saha et al. (1995) simulated a model to analyze the operating conditions of adsorption cooling systems with two-bed silica gel. Pan et al. (2014) examined the use of a modular-type adsorbent that can greatly reduce manufacturing costs. Nasruddin et al. (2016) simulated a silica gel-water solar adsorption chiller based in the climatic condition of a tropical country. From of all research conducted by the researchers above, it has provided a comprehensive conception of how to optimize the performance of the adsorption chiller from the cycle of system and the development of the adsorbent.

This study aims to simulate and analyze the configurations of a two-bed solar adsorption chiller by applying thermo-economic analysis. In addition, software is also used to perform multi-objective optimization by using multi-objective genetic algorithm. A thermo-economic approach is conducted to find out the optimum condition in terms of thermodynamic analysis and from an economic point of view.

2. METHODOLOGY

A method concerning the mass and energy conservation combined with the second law of thermodynamics could be synthesized for exergy analysis. Exergy analysis is a useful and efficient tool for understanding and improving performance of thermal systems (Nasruddin et al., 2018). It has been proven that exergy analysis can improve the efficiency of systems (Bindra et al., 2014; Shojaeizadeh & Veysi, 2016). In this study, exergy for all components in a two-bed solar adsorption chiller is performed using Matlab software to analyze and optimize using a genetic algorithm method for both the exergy and economic objectives.

2.1. Adsorption Cooling Description

Figure 1 shows the schematic system, which consists of six main components: (1) an adsorption bed; (2) a desorption bed; (3) a condenser; (4) an evaporator; (5) a cooling tower; and (6) a solar connector. In this study, silica gel and zeolite, used as adsorbent materials, were compared.

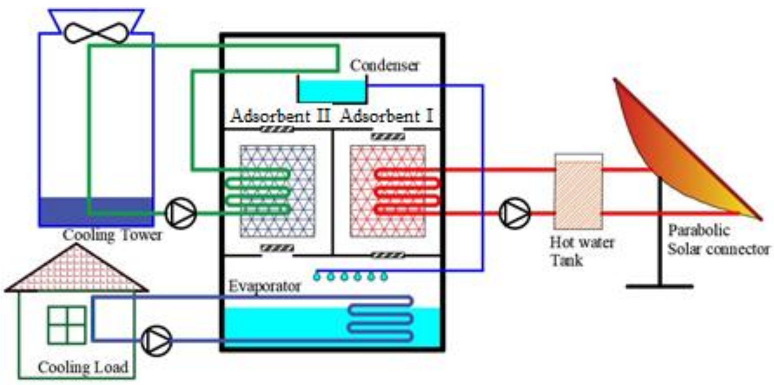

Figure 1 Schematic Diagram of a Two-bed Solar Adsorption Chiller

The operating modes for the system can be summarized in four steps: (1) refrigeration effect in the evaporator; (2) the adsorption process; (3) regeneration or the desorption process; and (4) the cooling process in condenser. In the first step, the refrigerant, i.e. water in a vacuum, removes heat from the chilled water and then evaporates at low pressure in the evaporator. In the second step, the refrigerant vapor is adsorbed by the adsorbent material. The adsorbed heat is rejected into water that is supplied from a cooling tower during the adsorption process. To keep the adsorbent bed temperature constant, the regeneration process is carried out in another adsorption bed simultaneously. In the third step, a solar collector supplies hot water to desorb the refrigerant vapor in the desorber. In the fourth step, the desorbed refrigerant vapor is condensed by the condenser and then returns to the evaporator via a narrow tube. Cooling water receives heat from condensation process. Two adsorbent beds periodically change from adsorption mode to desorption mode to obtain the continuous cooling effect. To maintain the changing process, automatic control valves are installed during the cooling and regenerating processes.

2.2. Economic Analysis

In this study, the thermoeconomics for a two-bed adsorption chiller were investigated. Thermoeconomics is a method that combines the concept of thermodynamic analysis, i.e. exergy analysis method, and economic analysis. The aim of thermoeconomic optimization is to determine a trade-off between the costs of the input exergy and capital costs of the system. Capital cost is the investment cost of each component while operational cost is calculated with the exergy input of the system. The system performance influences the total cost. If a system operates at maximum performance, it will increase the cost significantly. Therefore, multi-objectives optimization can maximize the system performance and minimize the total annual costs, both capital and operational, simultaneously. The total cost of the system can be expressed as follows (Bejan et al., 1996):

$$C_{total} = \sum C_0 \dot{E}X_{out} = \sum C_i \dot{E}X_{in} + \sum_m Z_m \tag{1}$$

where $C_{total}, C_0,$ and C_i represent the system total annual cost, the product exergy unit cost, and the input exergy unit cost, respectively. $\dot{E}X_{out}$ and $\dot{E}X_{in}$ represent the annual exergy rate for output products and from external sources, respectively. Z_m is the capital expenditures annual cost and other associated costs for the system (subscript *m* defines the number of system components).

Purchased equipment costs of the system components can be described as follows (Rezayan & Behbahaninia, 2011):

$$C_{total} = \left(I_{evap} + I_{cond} + I_{ads} + I_{pump} + I_{sc} + I_{pcm}\right) \cdot CRF + C_{cel} \cdot H \cdot \left(W_{pump} + W_{ct}\right) \tag{2}$$

where $I_{evap}, I_{cond}, I_{ads}, I_{pump}, I_{sc},$ and I_{pcm} represent the capital cost of the evaporator, the condenser, the adsorber, the pump, the solar collector, and the phase change material (PCM) material, respectively. Meanwhile W_{pump}, W_{ct}, C_{cel}, and H represent power of the pump, power of the cooling tower, electricity cost, and working hours of the components.

The capital recovery factor (CRF) parameter is used to calculate the annual capital cost. It can be expressed by the following equation (Smith, 2005):

$$CRF = \frac{int(1+int)^n}{(1+int)int^n - 1} \tag{3}$$

where n is operating period and int represents the annual interest rate.

The capital cost of each component in the system is determined by (NIST, 1998; Shah & Sekulic, 2003; Bejan & Kraus, 2003; Shojaeizadeh & Veysi, 2016; Feng et al., 2016):

$$I_{evap} = C_0 \cdot \left(A_{evap}\right)^{0.8} \tag{4}$$

$$I_{cond} = C_0 \cdot (A_{cond})^{0.8} \tag{5}$$

$$I_{ads} = C_0 \cdot (A_{ads})^{0.8} \tag{6}$$

$$I_{pump} = C_1 \cdot (0.01 \cdot W_{pump})^{0.6} \tag{7}$$

$$I_{sc} = 12 \cdot A_c \tag{8}$$

$$I_{pcm} = n_{pcm} \cdot 5 \tag{9}$$

$$W_{ct} = 0.00279 \cdot hr \cdot 3.6 \cdot \dot{m}_{Tcool} \tag{10}$$

2.3. Energy Analysis

The governing equations of energy for all components can be written as follows:

- For the condenser (Bejan & Kraus, 2003):

$$Q_{cond} = \dot{m}_{Tcool} \cdot Cp_w \cdot \left(T_{cool,out} - T_{cool,in}\right) \tag{11}$$

- For the desorption process (Boelman et al., 1995):

$$Q_h = \dot{m}_{Thw} \cdot Cp_w \cdot \left(T_{hot,in} - T_{hot,out}\right) \tag{12}$$

- For the adsorption process (Boelman et al., 1995):

$$Q_r = \dot{m}_{Tchill} \cdot Cp_w \cdot \left(T_{chill,in} - T_{chill,out}\right) \tag{13}$$

- For all system processes (Boelman et al., 1995), the coefficient of performance (*COP*) of the system:

$$COP = \frac{Q_r}{Q_h} \tag{14}$$

2.4. Exergy Analysis

The governing equations of exergy analysis for all components ($\dot{X}_i$) for solar adsorption cooling may be written as follows:

- For the cooling tower (Singh & Das, 2017):

$$\dot{X}_{ct,in} = \dot{m}_{Tcool} \cdot \left(\left(h_{ct,in} - h_0\right) - T_0 \cdot \left(S_{ct,in} - S_o\right) - R_v \cdot T_0 \cdot \frac{\log(RH_{air})}{\log(\exp(1))}\right) \tag{15}$$

$$\dot{X}_{ct,out} = \dot{m}_{Tcool} \cdot \left(\left(h_{ct,out} - h_0\right) - T_0 \cdot \left(S_{ct,out} - S_o\right) - R_v \cdot T_0 \cdot \frac{\log(RH_{air})}{\log(\exp(1))} \right) \tag{16}$$

$$\dot{X}_{air,in} = \dot{m}_{air,in} \left((Cp_w - Rh_{in} \cdot Cp_v) \cdot (T_{air,in} - T_0 - T_0 \cdot \frac{\log\left(T_{air,in}/T_0\right)}{\log(\exp(1))}) \right) \tag{17}$$

$$X_{air,out} = \dot{m}_{air,out} \left((Cp_{air} - Rh_{out} \cdot Cp_v) \cdot (T_{air,out} - T_0 - T_0 \cdot \frac{\log\left(T_{air,out}/T_0\right)}{\log(\exp(1))}) \right) \tag{18}$$

$$\dot{X}_{ct} = \left(\dot{X}_{ct,in} - \dot{X}_{ct,out}\right) - \left(\dot{X}_{air,in} - X_{air,out}\right) \tag{19}$$

- For the desorption bed (Xua, 2012):

$$\dot{X}_{des,in} = (h_{des,in} - h_o) - (T_o(S_{des,in} - S_o) \tag{20}$$

$$\dot{X}_{des,out} = (h_{des,out} - h_o) - (T_o(S_{des,out} - S_o) \tag{21}$$

$$\dot{X}_{des} = \dot{m}_{tw}(\dot{X}_{des,in} - \dot{X}_{des,out}) \tag{22}$$

- For the evaporator (Rezayan & Behbahaninia, 2011):

$$\dot{X}_{ads,in} = (h_{ads,in} - h_o) - (T_o(S_{ads,in} - S_o) \tag{23}$$

$$\dot{X}_{ads,out} = (h_{ads,out} - h_o) - (T_o(S_{ads,out} - S_o) \tag{24}$$

$$\dot{X}_{ads} = \dot{m}_{tw}(\dot{X}_{ads,in} - \dot{X}_{ads,out}) \tag{25}$$

- For the adsorption bed (Rezayan & Behbahaninia, 2011):

$$\dot{X}_{bed} = (\dot{X}_{des} - \dot{X}_{ads}) \tag{26}$$

- For the parabolic solar collector (AlZahrani & Dincer, 2018):

$$\dot{X}_{sc} = J \cdot \left(1 + \left(\frac{1}{3} \cdot \left(\frac{T_o}{T_{sun}} \right)^4 - \frac{4}{3} \cdot \frac{T_o}{T_{sun}} \right) \right) \tag{27}$$

- For the condenser (Rezayan & Behbahaninia, 2011):

$$\dot{X}_{cond,in} = (h_{cond,in} - h_o) - (T_o(S_{cond,in} - S_o) \tag{28}$$

$$\dot{X}_{cond,out} = (h_{cond,out} - h_o) - (T_o(S_{cond,out} - S_o) \quad (29)$$

$$\dot{X}_{cond}(i) = \dot{m}_{cool}(\dot{X}_{des,cond,in} - \dot{X}_{des,cond,out}) \quad (30)$$

Finally, exergy destruction of the overall system can be described by the following equation (Rezayan & Behbahaninia, 2011):

$$\dot{X}_{total} = \dot{X}_{cond} + \dot{X}_{ads} + \dot{X}_{bed} + \dot{X}_{sc} + \dot{X}_{ct} \quad (31)$$

2.5. Optimization Procedure

The two objective functions to be optimized are minimum of exergy destruction and minimum of total specific cost. To determine the thermodynamic and economic cost of the system, a multi-objective optimization with the genetic algorithm (GA) method was used to obtain convergent values of the Pareto-front of the optimum system parameters. Some data and assumptions used as inputs in simulations are shown in Table 1. The parameters chosen as decision variables were area of the solar collector (A_c), cooling water mass flow rate ($\dot{m}_{Tcool}$), hot water mass flow rate ($\dot{m}_{Thw}$), and chilled water mass flow rate ($\dot{m}_{Tchill}$), with details:

$300 \leq A_c$ (m^2) ≤ 900

$9 \leq \dot{m}_{Tcool}$ (kg/s) ≤ 15

$6 \leq \dot{m}_{Thw}$ (kg/s) ≤ 12

$0.5 \leq \dot{m}_{Tchill}$ (kg/s) ≤ 3

Table 1 Data and assumptions used as inputs in simulations

Parameters	Unit	Value
Specific heat of silica gel	kJ/kg K	0.924
Specific heat of zeolite	kJ/kg K	0.805
Temperature chilled	K	285
Temperature cool	K	303
Electricity cost	$/kwh	0.07
Interest	%	8
Period of operation per year	Hours	6570
Lifetime of operation	Years	15
Operating hours of cooling tower	Hours	12

3. RESULTS AND DISCUSSION

Figures 2 and 3 show the Pareto-frontier solution for a two-bed solar adsorption chiller performance with two working pairs, silica gel-water (Figure 2) and zeolite-water (Figure 3). Each point of the Pareto frontier is the optimal solution for the two objective functions under consideration: the exergy destruction and the total annual cost. The best thermodynamic performance for silica gel-water (Figure 2) is obtained at point A where the exergy destruction is 151,010 watts with an annual cost of $216,906 USD. Meanwhile, at point B, the best economic performance is achieved, where the annual cost is $216,818 USD with the highest exergy destruction of 157,803 watts. Similarly, in other working pairs, point A shows the best thermodynamic performance where there is a minimum value of exergy destruction while point

B shows the best economic performance where there is a minimum annual cost. The points A and B values of each working pair (Figures 2 and 3) are shown in Table 2.

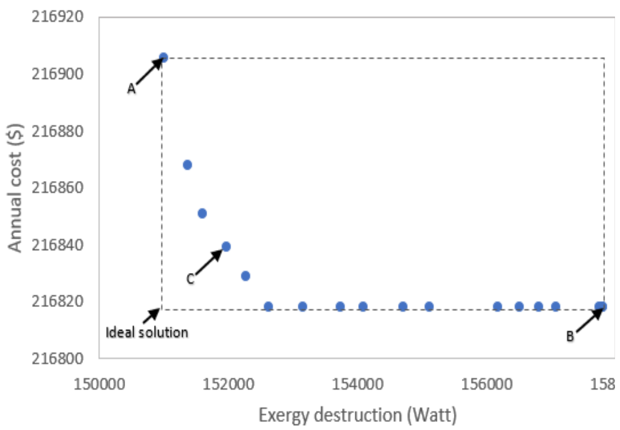

Figure 2 Result of multi-objective optimization for silica gel-water working pairs

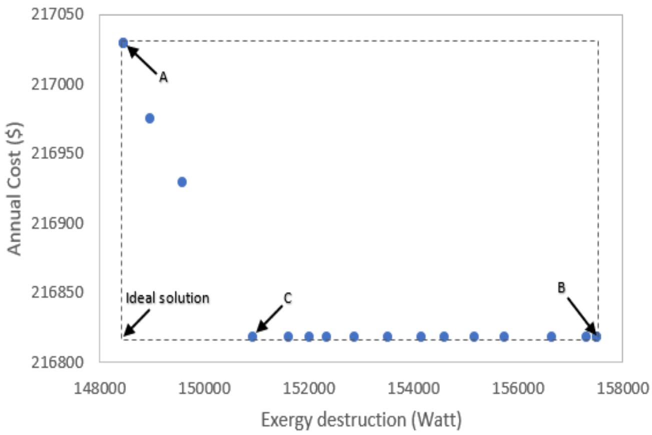

Figure 3 Result of multi-objective optimization for zeolite-water working pairs

From Table 2, it can be seen that, of the working pairs considered, zeolite-water is the best thermodynamic performance fluid because it produces the lowest value of exergy destruction. From the economic side, silica gel-water and zeolite-water have the same value for economic performance.

Table 2 Value of the best thermodynamic and economic performance for each working pair

Working Pairs	The Best Thermodynamic Performance (point A)		The Best Economic Performance (point B)	
	Exergy destruction (Watt)	Total annual cost (USD)	Exergy destruction (Watt)	Total annual cost (USD)
Silica gel-Water	151.010	216.906	157.803	216.818
Zeolite-Water	148.456	217.030	157.509	216.818

By multi-objective optimization, the results obtained are usually in the form of a range consisting of several optimal solutions. This solution is known as the pareto-optimal solutions or pareto frontier. In this study, the nearest point with the ideal solution in the Pareto frontier is called the final optimal point (point C). Using this approach for the system under consideration, the final optimal point for each working fluid can be found in Pareto, as shown as points A and B in Figure 2. The exergy destruction and annual cost at the final optimum point (point C) for each working pair can be seen in Table 3.

Table 3 shows that the zeolite-water working pair had a lower value of exergy destruction and annual cost compared to the silica gel-water working pair, which resulted in an exergy destruction of 150.938 watts and an annual cost of $216.818 USD. However, in the value of cooling capacity and COP, the zeolite-water working pair had a lower value than the silica gel-water working pair.

Table 3 Performance comparison of the final optimum point for each working pair

No	Parameters	Unit	Final optimum point (point C)	
			Silica gel-Water	Zeolite-Water
1	Cooling Capacity (Qr)	kW	6.91	6.28
2	COP	-	0.41	0.38
3	Exergy Destruction	Watt	151.979	150.938
4	Annual Cost	USD	216.839	216.818

4. CONCLUSION

In this study, a configuration of the a two-bed solar adsorption chiller is simulated and optimized using Matlab software. To determine the system performance from a thermodynamic and economic point of view, a thermoeconomic analysis was performed with exergy destruction and annual costs as objective functions of this analysis The results showed that by comparing the working pairs of water-silica gel with zeolite-water, the zeolite-water working pair had a lower value of exergy destruction and annual cost. However, the cooling capacity and COP of zeolite-water working pair has a lower value of than the silica gel-water working pair.

5. ACKNOWLEDGEMENT

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