Experimental Investigation of Cycle and Transient Time Effect of Solar Assisted Adsorption Air Conditioning System

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Abstract**—** There are some parameters were investigated to have the most effective influence on the operation of solar assisted adsorption air conditioning system experimentally. These major parameters are very sensitive in the performance and efficiency of such a system, such as the number of cycles until the system reaches the steady state condition, the switching time between the cycles and the transient time needed for the system to be steady between two cycles. The system was tested experimentally in different procedures to get the actual number of cycles in which the system could reach the optimum operating conditions. It was found that the number of cycles need for the system to reach the steady state operating conditions was 5 cycles (about 70 min), and the optimum switching time is found to be 5.3 min, then after that the generated chilled water outlet temperature could be approximately constant at about 17.3 ºC.

Keywords— Solar Adsorption, Cycle Time, Transient Time, Air Conditioning

Introduction

Cooling and refrigeration processes are important in modern life, especially in food, vaccines, cold storage, and cooling systems of buildings [1]. Cooling systems are categorized into four major types: (a) conventional vapor compression system, (b) absorption cooling system, (c) adsorption cooling system, and (d) desiccant cooling system [2]. The last three systems are suitable for low temperature heat sources. These systems, which utilize solar energy or waste heat, are durable [3][4]. The most widely used system is the vapor compression system, which uses electric power. The vapor compressor is the main component that regulates the electricity consumption of these systems [5]. Cooling and refrigeration systems are one of the causes of the increasing demand for electric power because of their high electrical consumption [6]. The switching time has always been an important parameter in the adsorption cooling systems. The definition of the switching time could be obtained when the BED reaches the saturated temperature whether it is in hot or cold position [7]. An experimental investigation of the thermodynamic behavior and the performance of the adsorption air conditioning system have been studied in this paper. Solar assisted adsorption air conditioning system operates in single stage with two adsorption beds utilizing the activated carbon fiber and ethanol as the refrigeration pair have been presented. The effect of adsorption/desorption switching time and the optimum values for transient time are also investigated. The transient time in the solar assisted adsorption air conditioning system proposed in this study could be define as the time required for each adsorption beds in the system to reach the steady state profile of hot and cooling water temperatures while switching. In this study, the experimental procedure for the adsorption system was investigated to have the optimum transient time.

I. METJODOLOGY OF ADSORPTION SYSTEM

The thermodynamic analysis of the solar assisted adsorption refrigeration system using activated carbon fiber and ethanol as the refrigeration pair has been presented. The effect of the operating parameters such as input temperatures and flow rates on the cooling capacity and the coefficient of performance of the system are described also. The heat source temperature is very important in the adsorption cooling systems [8]. Therefore, one of the main advantages of the system is to find the optimum values of operating temperatures and flow rates. Figures (3.10) and (3.11) show the schematic diagrams of the two beds adsorption refrigeration cycle. The system consists of two adsorption beds, a condenser, and an evaporator. The adsorption beds, namely (*BED1* and *BED2*) with four operating phases, namely (Phase I, Phase II, Phase III, and Phase IV).

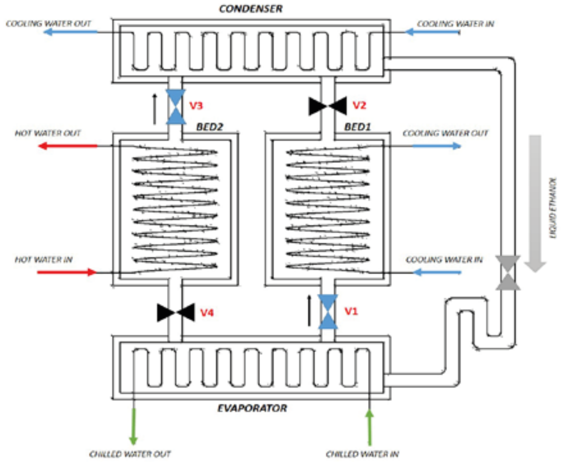

Figure 1 Schematic diagram of two bed adsorption system (Phase I)

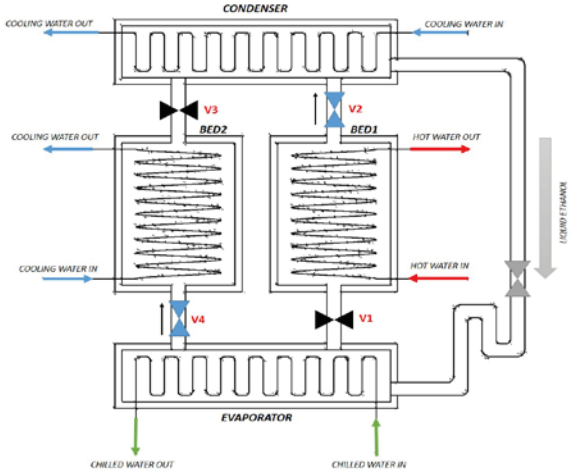

Figure 2 Schematic diagram of adsorption system (Phase III)

In phase I, both valves V1 and V3 are opened, with V2 and V4 are closed. The adsorption bed *BED 1* in a process called adsorption, as well as the evaporator, while *BED 2* and condenser are in desorption process. The adsorption process in *BED 1* and evaporator takes place when the pressure is equal to the evaporating pressure P_{evap}, thus the adsorbent (ethanol) is evaporated at the evaporator to reach the evaporation temperature T_{evap} and gained heat from the chilled water comes in. After that, the evaporated ethanol is adsorbed by the adsorbate (activated carbon fiber ACF) where the heat is removed by the cooling water. At a pressure equal to condensation pressure P_{cond}, the desorption – condensation process occurs. The hot water comes in and entering the second adsorption bed *BED 2* and heated it. The ethanol vapor cooled down to the condensation temperature T_{cond} inside the condenser by passing the cooling water in which it will remove the heat of condensation. On the other hand, when the concentration of ethanol in the adsorption and desorption process is near the equilibrium level, therefore, the cycle is continued while all the ethanol valves are closed (Phase II). Phase II starts when the hot and cooling water flows are changing their directions in order to get the isosteric heating and isosteric cooling processes at *BED 1* and *BED 2*, respectively. The valves between *BED 1* and condenser as well as between *BED 2* and evaporator are opened when the pressure of adsorption and desorption process are both equal to the condensation and evaporation pressure P_{cond} and P_{evap}, respectively. In phase III, valves 2 and 4 are opened (Figure 2), while valves 1 and 3 are closed. The condenser and *BED 1* are in desorption process, while the evaporator and *BED 2* are in adsorption process. In this phase, all the ethanol valves are opposite in operation to phase I. Phase IV takes the action in which the isosteric heating process in *BED 2* or the isosteric cooling process in *BED 1* starts, which is opposite in operation to phase II.

II. ADSORPTION ISOTHERM

The adsorption rate is estimated using equation (3.18). Glueckauf [9] found a relation between $k_s a_v$, and the constant of time diffusion D_s/R^2_p this is given in equation (1). El-Sharkawy et al. [10] studied the kinetics of the activated carbon fiber/ethanol pair using the Thermo-Gravimetric Analyzer (TGA). It was found that the numerical value of F_o was 11. The surface diffusion D_s can be found using equation (2). The values of E_a and D_{so} were found to be 306.7×10^3 and 1.8×10^{-12} respectively.

$$\frac{\partial w}{\partial t} = k_s\, a_v\, (W - w) \tag{1}$$

$$k_s\, a_v = F_o \frac{D_s}{R_p^2} \tag{2}$$

$$D_s = D_{so} \exp\left(-\frac{E_a}{RT}\right) \tag{3}$$

A. Isosteric Heat of Adsorption

El-Sharkawy [11] calculated the isosteric heat of adsorption for the activated carbon fiber/ethanol pair, as it can be described in the following equation:

$$\frac{(\Delta H_{st} - h_{fg})}{E} = [\ln(W_o/W)]^{1/n} + a\,(T/T_c)^b \tag{4}$$

Where, a= 6.717, b= 9.75.

B. Adsorption and Desorption Energy Balance

For the analysis of the solar adsorption system, a simple lumped model proposed by Li Yong [12] was used:

$$(MC_p)_{eff}^{bed} \frac{dT_i^{bed}}{dr} + [mC_p]_{i-phase} \frac{dT_i^{bed}}{dt} = \emptyset M_{acf} \left(\frac{dw_i^{bed}}{dt}\right)(\Delta H_{st}) - (\dot{m}\, C_p)_j (T_{j,o} - T_{j,in}) \tag{5}$$

In the above equation, $\emptyset$ = 0 for isosteric cooling and heating, and $\emptyset$ = 1 for adsorption/desorption, i indicates adsorption/desorption bed and j the cooling/heating source. The left-hand side of equation (5) represents the rate of change of internal energy, where this rate occurs due to the thermal mass of activated carbon fiber, ethanol, as well as the heat exchanger during the adsorption/desorption process. The first term in the right-hand side of the above equation represents the release of adsorption heat during desorption process, while the second term represents the total heat released to the cooling water during adsorption. The first term represents the heat input during desorption process, and the second term may represent the heat released by the hot water during desorption process. Therefore, for the small difference in temperature that occur during cooling/heating fluid such as water, the outlet temperature of the heat source is good enough to be modeled by the Logarithmic Mean Temperature Difference (LMTD) method, this is given by the following equation:

$$T_{j,o} = T_i^{bed} + \left(T_{j,in} - T_i^{bed}\right) exp\left[\frac{-(UA)_i^{bed}}{(\dot{m}\, c_p)_j}\right] \quad (6)$$

In the above equation, A^{bed}, and U^{bed} represent the heat transfer area and the overall heat transfer coefficient respectively.

III. RESULTS AND DISCUSSION

Adsorption/desorption switching time has always played an important role in the operation of adsorption cooling systems. The direct effect of this parameter on the switching between the cold and hot phases in the adsorption beds was investigated by several researches [7]. In solar assisted adsorption air conditioning systems, the switching time is directly connected to the hot and cold-water inlet temperatures. For hot water inlet temperature, the temperature depends on the solar radiation and the intensity of solar system that delivers the hot water to the system. While for the cooling water inlet temperature, it depends on the cooling tower that cools down the return temperature from the hot bed and then pass it through the insulated pipes to the cooling bed. From the description stated above, it is clear that the switching time could not have a constant value. With the minimum and maximum values of switching time in the range between 2.5 and 10 min., the optimum value of switching time between the two adsorption beds was found to be 5.3 min.

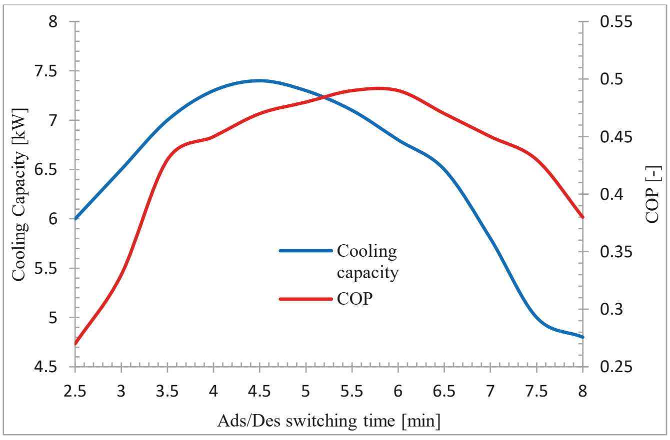

Figure 3 Effect of switching time on cooling capacity and COP

The variation of switching time between adsorption and desorption process was examined and investigated with a wide range of data in the experimental analysis. The first procedure was set to fix the switching time between each cycle to 10min, where the (transient time) between the cycles is 10min to let the temperature profiles return to the optimum values. The second experimental procedure was to decrease the switching time between the cycles to 7min. It is found that when decreasing the switching time from its maximum value (10min), then the adsorption/desorption process could not be completed. Therefore, it is very difficult to get an optimum switching time due to the actual experimental work, while in the simulation always the switching time is fixed at a certain value. The variation of the switching time between the cycles actually depends on the time that the BED consumed to reach the optimum value of hot or cold temperature in order to switch and pass the Ethanol to them. In figure 4, the cycles show the temperature profile of BED1 and BED2 for a 10 cycles experiment, where the switching time was set to be 13min to obtain a fixed value of hot and cooling temperature to each BED.

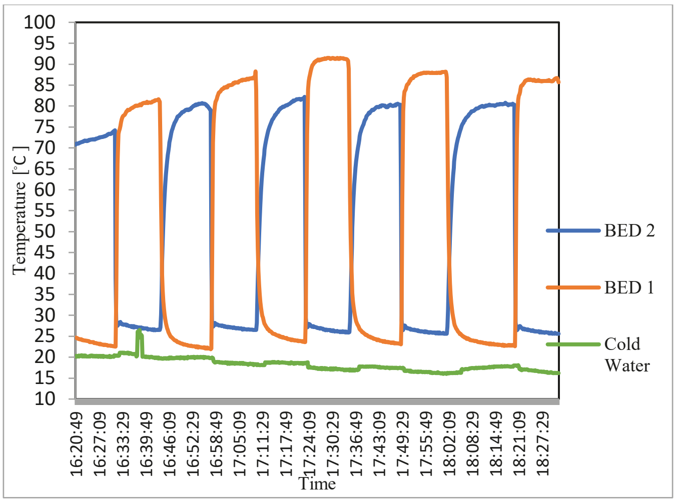

Figure 4 Temperature profile for 10 cycles with 13min switching time

From the figure above, it can be noticed that the hot and cooling water for each cycle in each BED is almost has the same profile. After each cycle the temperature profile for BED1 or BED2 has the same input and output values of temperature. It has been conducted that BED2 has a lower temperature than BED1; this is due to the losses in heat as BED2 is located far from the heat source. While in BED1, the temperature is slightly higher as BED1 is very close in position to the hot water source.

From figure 5 below, the switching time between BED1 and BED2 is about 1 min in the case when BED1 is switched from hot phase to cold phase, while BED2 is switched from cold to hot phase. This is due to the fact that BED2 needs longer time to gain the heat as it is positioned slightly far from the main hot water inlet source. While in BED1, it has been noticed that when switching BED1 from cold phase to hot phase, the ability to gain heat is higher than in BED2, or on another word, the ability of releasing heat in BED2 is less than in BED1.

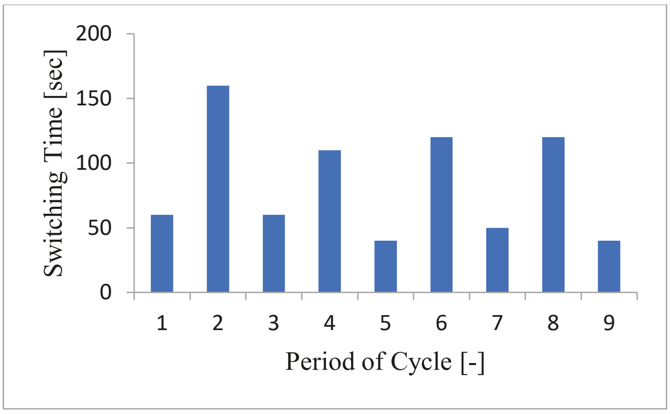

Figure 5 Switching time values for each cycle period

IV. CONCLUSIONS

The system was examined to get the steady state condition of an approximately constant outlet chilled water and hence a constant cooling capacity for the mentioned building to be cooled during the working hours. The solar system was operated early morning to get the proper hot water temperature inlet to the system by first switching ON the auxiliary heater until the water reached a temperature of about 50 ºC then switching OFF the heater to let the evacuated tube solar collector increase the water temperature before entering the adsorption bed. The system was tested experimentally in different procedures to get the actual number of cycles were the system could reach and in which the system could reach the optimum operating conditions. It was found that the number of cycles need for the system to reach the steady state operating conditions was 5 cycles (about 70 min), then after that the generated chilled water outlet temperature could be approximately constant at about 18 ºC. Another procedure under different cycle time was also be investigated, where the control system was programmed to have different cycle and switching time more or less than the optimum time for the cycle and/or switching. Figure 6 represents an operated cycle time under the same operating conditions. The first attempt was to define the cycle time was variable, i.e, different cycle time for each cycle with different switching time and the transient time depends on how the adsorption bed could reach the steady state condition.

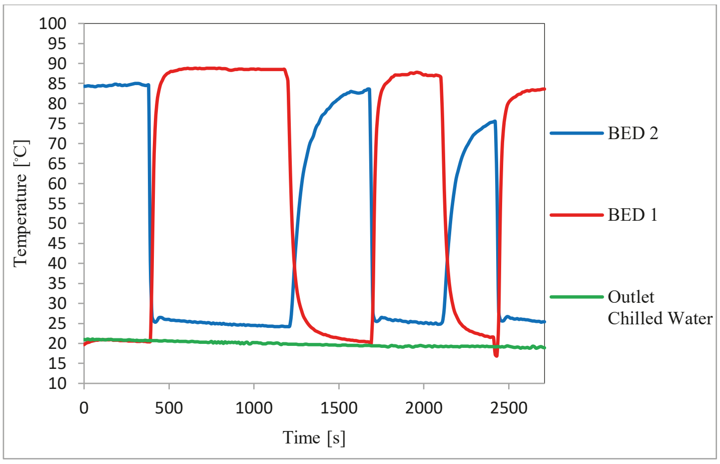

Figure 6 Adsorption air conditioning system with variable cycle time

It was found that the variable cycle time could decrease the chilled water outlet temperature of the system but for almost 2-5 ºC only and then the value of the chilled water temperature could increase as well after processing for long time operating conditions. The second experiment was proposed to calculate the outlet chilled water temperature of the adsorption system for 15 cycles in which each cycle has 5 min and without switching time between the adsorption beds, Figure 7.

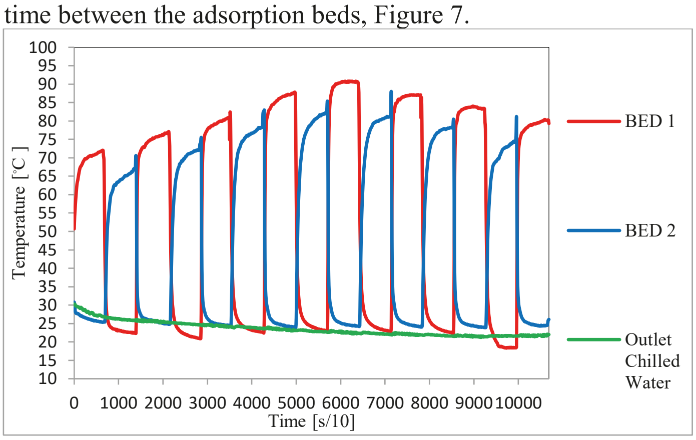

Figure 7 Adsorption air conditioning system with 15 cycles - 5 min/cycle

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