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Experimental Performance of a Finned-tube Silica Gel Adsorption Chiller for Air-Conditioning Application

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Abstract

This work presents the construction of a test apparatus for air-conditioning application that is flexible in changing a scaled down adsorbent bed modules. To improve the heat and mass transfer performance of the adsorbent bed, a finned-tube of the adsorbent bed heat exchanger was used. The results show that the specific cooling power (*SCP*) and the coefficient of performance (*COP*) are 163 W/kg and 0.16, respectively, when the cycle time is 40 min, the hot water temperature is 90^{o}C, the cooling water temperature is 30^{o}C and the evaporative water temperature is 11.4^{o}C.

Keywords: *Adsorption, refrigeration, cooling power, COP, silica gel-water.*

1. Introduction

Energy is the main driver for the well being, development and quality of life for people. Nowadays, the strength of countries depends on the extent of diversification of energy that they get it. It is no longer limited to oil as principal source of energy but diversified to include many sources of energy, called Renewable Energy [1].Electricity consumption on air-conditioning results in a shortage of the rush of electricity in summer [2]. In addition, the usage of CFC$_s$ and HCFC$_s$ in traditional air-conditioning systems causes the ozone depletion and green house effects [2]. Due to the large consumption for air-conditioning systems in building, solar cooling systems have attracted great attention nowadays [2]. There are many researches about adsorption air-conditioning. For example, in order to improve COP, C.J. Chen and his co-workers have adopted a heat and mass recovery by installing vacuum valves between the adsorption and desorption chambers of the adsorption chiller [3]. However, silica gel-water adsorption chillers are welcomed for the solar air-conditioning systems and widely studied [4]. Kahan et al. studied the influence of the overall thermal conductance of the sorption elements and evaporator as well as the adsorbent mass on the chiller performance and indicated that the cycle performance strongly influenced by the overall thermal conductance of the sorption elements [5]. Generally, a heat source with 70-80^{o}C is economical for silica gel-water adsorption chiller and easily obtained from solar energy or waste heat [6]. Demir et al. handled the mechanism of heat and mass transfer in annulus adsorbent with which shows that the adsorption period increases with increase the porosity value [7]. Al Sapienza et al. investigated a new composite adsorbent and tested it by a lab-scale adsorption chiller. They observed that the optimal cycle time performance was strongly depended on cycle time and relative duration of the isobaric desorption and adsorption steps [8]. Aristov et al. investigated, using an intermittent cycle, the effect of the relative duration isobaric adsorption/desorption stages to maximize the coefficient of performance and the specific cooling power of the cycle. They found that the desorption phase is faster than the adsorption one and this should considered as a routine case for adsorption refrigeration cycle, probably, because adsorption occurs at higher temperature and pressure and hence, they suggested practical recommendation to rationally reallocate the duration of adsorption and desorption phases [9]. A newly developed adsorption chiller was described and tested by Liu et al. In this adsorption cycle system, there is no refrigerant valve. Thus, the problem of mass transfer resistance was eliminated. The experimental results proved that it is able to produce a cooling capacity of 6.5 kW with COP of about 0.4[10]. To demonstrate the effect of mass and heat transfer on the SCP and COP, a laboratory prototype of adsorption cooling machine has been designed by Wang and his team. Experiments showed that the COP was between 0.2-0.4 for refrigeration temperature of -10 to -15^{o}C depending on the cooling water temperature. The SCP ranges from 300-500 W/kg adsorbent [11]. In order to improve the reliability of silica gel-water adsorption chiller, chillers combined by two bed cooling systems were modified. The recent results [12] were that the cooling capacity and COP of such chiller were 3.6 kW and 0.32, respectively, at the hot water inlet temperature of 57^{o}C, cooling water temperature of 27^{o}C,and chilled water temperature of 15^{o}C; those were up to 5.7 kW and COP of 0.41, respectively, when the hot water inlet temperature, cooling water temperature, were changed to 80^{o}C and 29^{o}C, respectively. Those investigation had resulted in closer steps to commercial prototypes thought so far those prototypes were not really commercial once due to its high cost [13]. A novel composite dsorbent “Silica gel modified by Calcium nitrate” (SWS-L8) for utilization in adsorption chillers driven by low temperature heat has tested by Freni et al. SWS-8L grains were embedded inside aluminium heat exchanger with high thermal efficiency. Experimental cooling COP, specific cooling power SCP and volumetric specific cooling power VSCP obtained were 0.18-0.31 (cycle time 10 min), 190-383 w/kg dry sorbent and 104-212 w/dm^3, respectively [14]. Miyazaki et al. investigated the influenced of heat exchanger parameters, such as heat capacity and NTU, on the optimum performance of a single-stage adsorption chiller using silica gel as a working pair. He concluded that the smaller heat capacity improved both the SCP and COP. While the large NTU of the adsorbent bed resulted in the decrease of COP due to the short cycle time although the maximum SCP was enhanced [15]. Niazamand and Dabadeh analyzed the effect of the bed configuration, such as fins spacing, bed high, and particle size high on the performance of the system. They showed that fins in general reduced the COP of the system; however, for a given cooling capacity CP, the bed size can be reduced dramatically, when fins were employed at the cost of slightly lower COP. Also, It is shown that there is an optimal particle diameter associated with each bed configuration that maximizes the COP and SCP [16].

In this work, a fine-tube silica gel-adsorption chiller for air-conditioning application built in order to generate cooling energy and evaluate the cooling output performance. The experimental data evaluated in terms of cooling output (or specific cooling power *SCP*) and coefficient of performance *COP*. This study will benefit the further application and development of the solar adsorption air-conditioning system.

2. Description of the Prototype

The optimization of the refrigeration adsorption cycle conducted at the Solar Energy Laboratory / Federal University of Paraiba by the use of a lab-scale facility realized to the support the development of the solar adsorption chiller.

Fig. 1 (A) shows the schematic diagram of the experimental adsorption chiller prototype. The adsorption chiller has a single bed, a condenser, an evaporator and heating/cooling water system. The evaporator lies at the bottom of the chiller, and the condenser is located at the top of the conditions and operating adsorption cycles. The whole prototype connected to a water heating system, for refrigeration, tape water for cooling, and a vacuum pump system. The heating system is next to the adsorber. All the valves controlled manually. The prototype designed to test various operations. Two main parameters measured during the experiment: temperature and pressure. All sensors connected to a data logger and recorded every 8.5 seconds. The data measurements taken after the cycle steady has been reached. A computer used to collect and process the data measurement acquired by the data logger. The flow rate of the hot water and cooling water are constant at 0.4 kg/s. The adsorber is of a shell-and-tube configuration, which readily manufactured, and it withstand high operating pressure and incur low energy mass.

Using fins and tubes design, (Fig. 1 (B)), made the surface area to volume relatively low. The fins on the adjacent tube overlap slightly in order to reach all the portions of the shell voids. They allowed tubes to be more widely spaced to accommodate greater proportion of adsorbent. Furthermore, the fins have several times a wider surface area than the bare tube, which counter the low conductance through the contact between the metal and the adsorbent. This design has 905 m^2 surface area / m^3 volume. The main properties are resumed in Table. 1.

3. Measurements

The experimental conditions are stated in Table. 2. The temperature are measured at the inlet and outlet of the heat exchanger of the adsorber during cooling and heating periods. The pressures are measured at the adsorber. The amount of the desorbed water, Δx, are measured by the level graduated cylinder.

The performance evaluation of the adsorption chiller is calculated from the terms of cooling power Q_{ev} [w], specific cooling power SCP [w/kg] , and coefficient of performance COP, which are calculated as follows:

$$Q_{evp} = \frac{M_{ads}\Delta H_{evp}\,\Delta x}{t_a} \quad \ldots(1)$$

$$\Delta x = x_t - x_{t-1} \quad \ldots(2)$$

$$SCP = \frac{Q_{evp}}{M_{ads}} \quad \ldots(3)$$

$$COP = \frac{Q_{evp}}{m_{hw}\,cp_{hw}\,(T_{hwi} - T_{hwo})} \quad \ldots(4)$$

Table 1,
Main properties of the adsorber bed.

Property	**Value**	**Unit**
Total mass of adsorbent	4	Kg
Grain size	7	mm
Tube length	0.5	m
Number of tube	4	
Inside tube diameter	0.017	m
Outside tube diameter	0.19	m
Fin diameter	0.05	m
Fin space	0.008	m

Table 2,
Prototype experimental conditions.

Parameter	**Value**	**Unit**
T_c	30	℃
T_h	90	℃
T_a	35	℃
T_d	90	℃
t_d	18.5	min
t_a	18.5	min
$t_{iso-heating/cooling}$	1.5	min
t_{cycle}	40	min

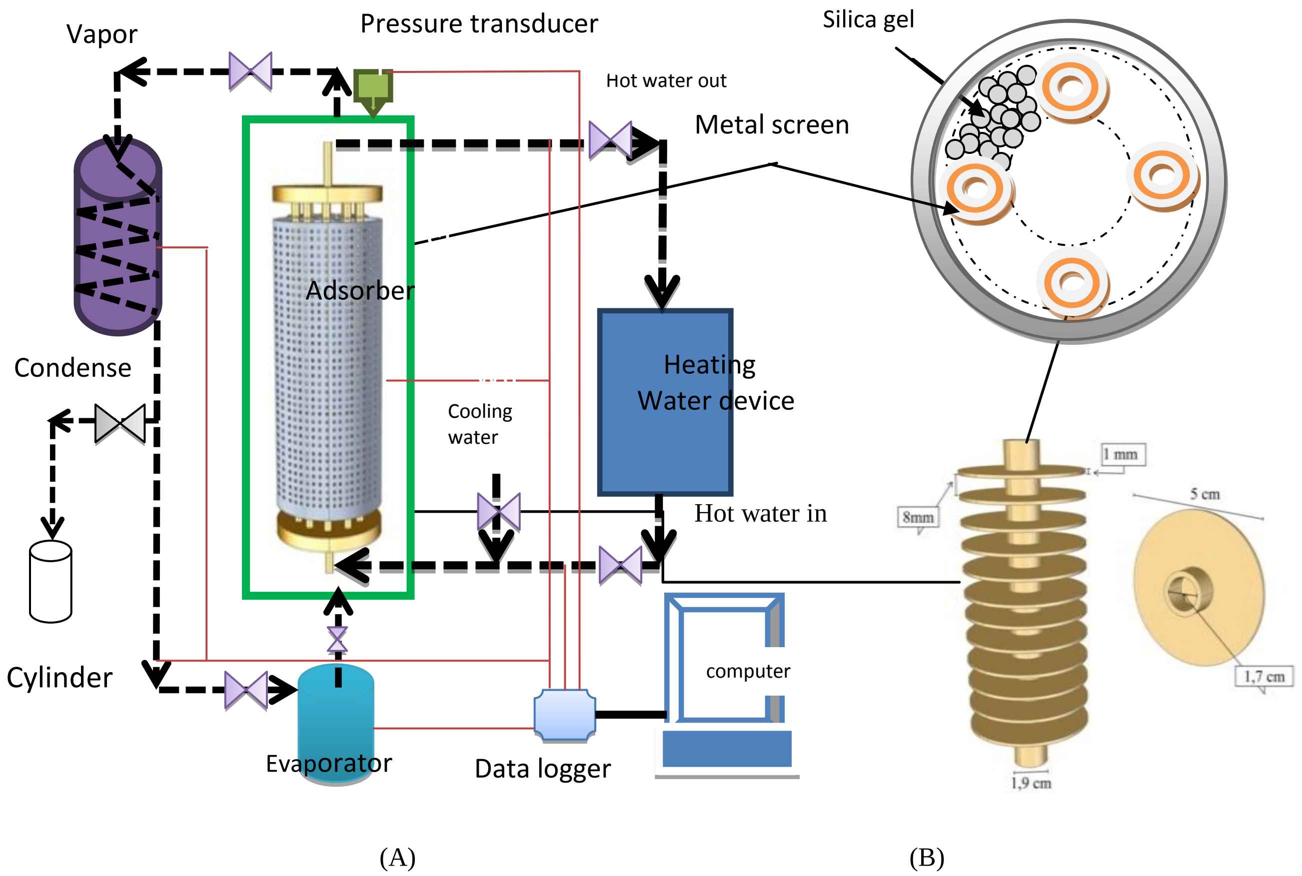


Fig. 1. Schematic of experimental adsorption chiller (A), adsorber (B)

4. Results and Discussion

4.1. Temperature Profile of System

As the driving forces, the hot water inlet temperature is very important to the adsorption refrigeration system. A high water temperature causes a large temperature lifts for the system at the same cooling temperature. Then, the larger temperature lifts results in a high refrigeration capacity. Fig. 2 illustrates the cycle variation of the adsorbent temperature with inlet hot water temperature of 90^{o}C (with constant cooling water of 30^{o}C) in the adsorber heat exchanger packed with silica gel grains. Fig. 2 also shows that, the temperature effectiveness of the adsorbent element's capability to exchange sensible heat is based on the actual and maximum temperature difference. This difference decreases with time. According to this figure, the bed temperature rises sharply before the 10 mins, but after 20 mins this temperature difference becomes small. The reason of this small difference is the water vapour releases from the silica gel grains. After 60 mins, this difference reduced to a very small value. Fig. 3 shows the temporal evolution of the isosteric cooling, isosteric heating, desorption and adsorption phases at a steady state for the following operating conditions concluded from the experiment test (Table 2). It is observed that during the isostering cooling, the temperature of the bed will decrease from 90^{o}C to 62^{o}C (blue linear line) at after this moment the valve between the adsorber and the evaporator will open until the temperature of the adsorbent bed becomes 35^{o}C (blue curve line). After elapsed of 20 mins, the isostearing heating will start and the temperature of the adsorbent bed increases from 35^{o}C to 62^{o}C (red linear line), then the valve between the condenser and the adsorber will open for desorption process until the temperature becomes 90^{o}C again (red curve line).

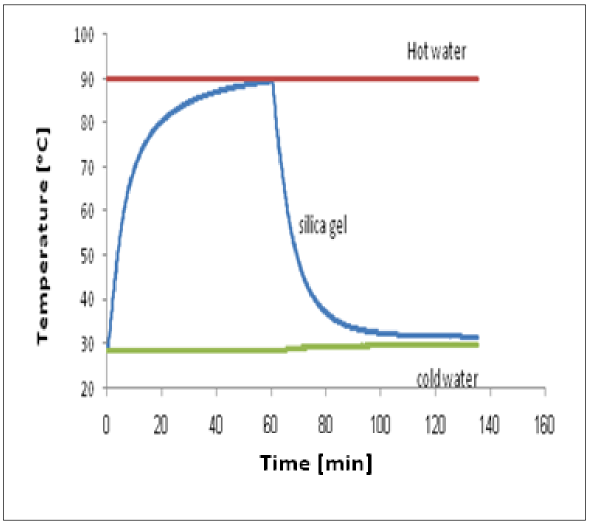


Fig. 2. Isosteric heating/cooling cycles.

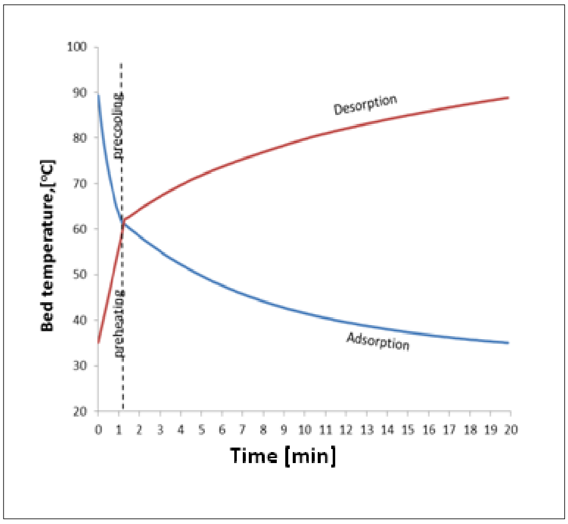
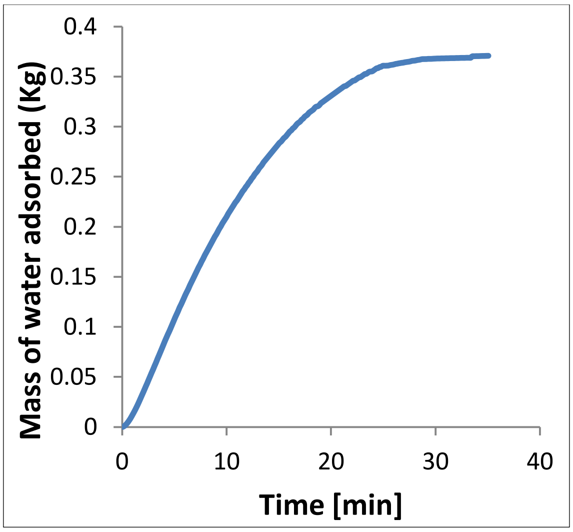


Fig. 3. Cycle time of the system.

4.2. Refrigerant Exchange Amount (Δx)

Desorptoin process is very close in concentration change to adsoption process at the same temperature, and many researches assume both are the same in adsorption refrigeration process [17] . Working on the temperature of 90°C tends to decrease the water content to the minimum and, consequently, it results in increasing the water adsorbed during the adsorption process and that increases the cooling capacity. Fig. 4 aims to determine the desorbed water, which represents the amount of water involved in one adsorption-desorption cycle. The experiment has consisted of loading adsorbent with water under a temperature desorbed at the temperature of 90°C in the same of 35°C, then the adsorbent were, afterwards, duration as the adsorption time. The difference between adsorbent loading at the end of the adsorption, and its loading at the end of desorption constitutes the water exchanged amount (Δx). Therefore, during the desorption phase, the refrigerant vapor was allowed to be collected via the flask by opening valve 6 (Fig. 1). The measurment of the adsorpion capacity of this type of silica-gel showed that it is able to exchange a large amount of water of 0.08 kg/kg under operating conditions so it is typical for air conditioning applictions as well as to be driven by hot water temperaure of 90°C.



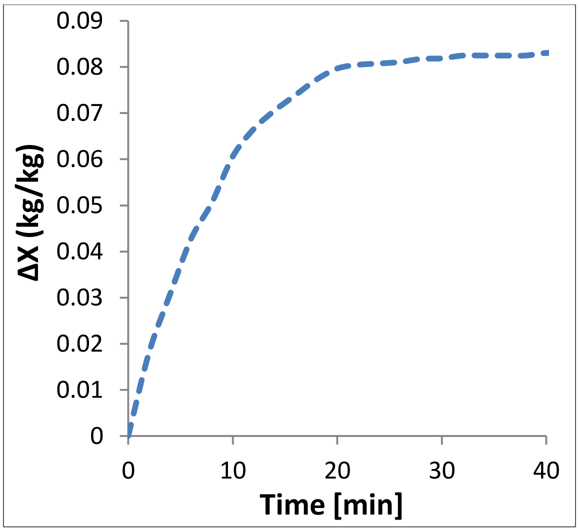


Fig. 4. Mass and concentration of water desorbed variation with time.

4.3. Cooling power, SCP, and COP

Generally, cooling capacity, *CP* (or specific cooling capacity, *SCP*) and *COP* are two parameters to determine the performance of the refrigeration cycle. The cycle time will be the best when the *CP* and *COP* reach their maximum values at the same time, but in real system, they are not [18]. The results for cooling capacity, *COP*, and *SCP* values are shown in Fig. 5. The *COP* has an optimum value of about 0.16 at the proposed first half cycle of 20 mins. Indeed, the *COP* is affected by the dynamic limitations of the adsorbent bed, parasitic losses and inert mass of the heat exchangers. The *SCP* reaches the peak value of 198.2 W/kg of dry adsorbent when the cycle time is 9.1 mins and decreases for a higher cycle time with minimum value of 163 W/kg at a time of 20 mins. Cycle time at 9.1 mins or shorter resulted in lower performance of heat transferred/extracted to/from the adsorbent bed. Moreover, in our case, the cycle time at 9.1 mins was not sufficient to complete the hydration of silica gel during adsorption phase. The obtained results indicate that the cycle time of 20 mins gives a reasonable compromise between the *SCP* and *COP*.

The cycle time of 9.1 mins allows maximizing the *SCP*, while the maximum *COP* is obtained when the cycle time is 31 mins. This information is of a high practical significance when optimized for high *COP* and *SCP*. In general, there designing an adsorption chiller that must be is a maximum of the cooling power (*Qe)* at a specific cycle time. Larger cycle time leads to higher coefficient of performance *COP*, but less cooling power. The relation is shown in Fig. 5, it can be noted that by increasing the cooling time, the cooling power *(Qe)* value increases and there is a maximum *Qe* value (793 W) when the cooling time is 9.1 mins, after that the *Qe* decreases as the cooling time increases. This time of 9.1 mins, is enough just to cool the adsorbent up to 42.5^{o}C, not to 35^{o}C, and the adsorbers are insufficiently cooled or heated during the adsorption and desorption processes respectively. However, the value of *Qe* at 20 mins is 664 W, which is less than the maximum value by 149 W. But, it is still an acceptable value to work on. Consequently, a strategy was adopted to assess the adsorption time of 20 mins. The same results are obtained for the *COP* and *SCP*: increasing the temperature of the bed leads to increase the cooling power.

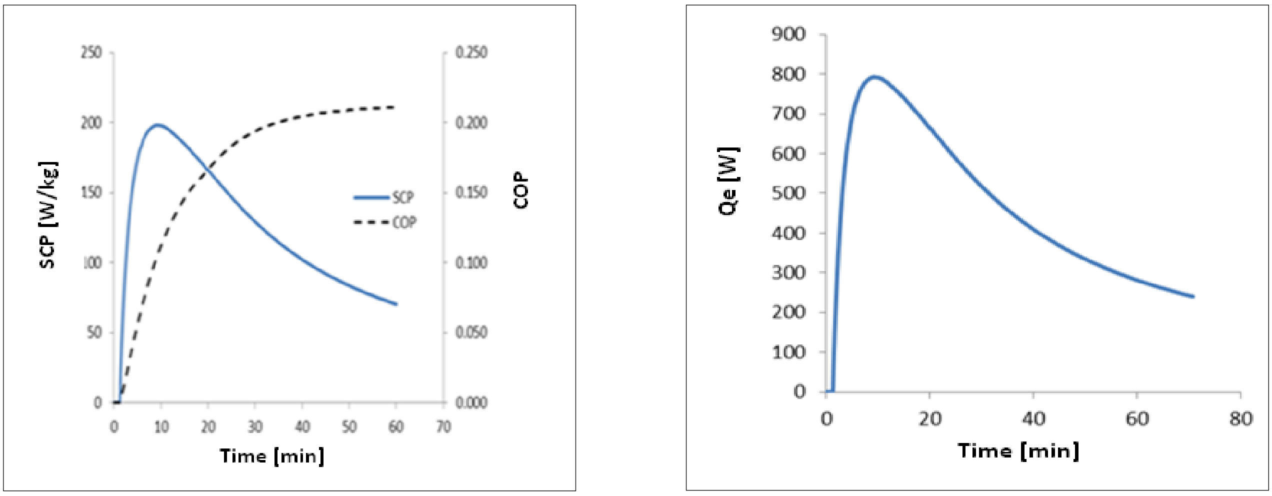
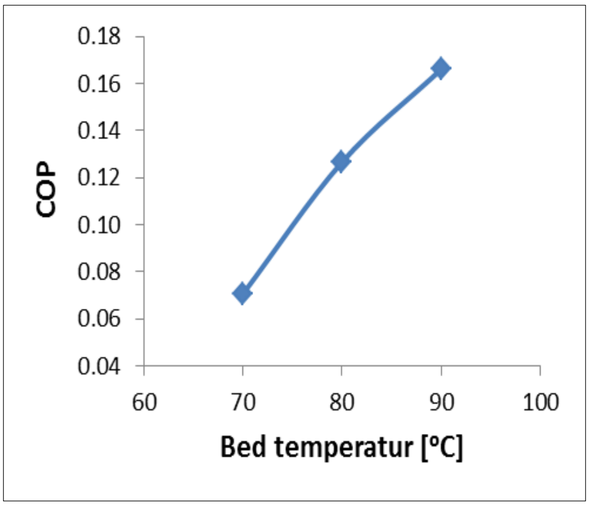


Fig. 5. Experimental results of *COP*, *SCP*, and cooling capacity as a function of the time.

4.4. Effect of Operating Conditions on the System Performance

The tests for measuring the performance of the adsorber were continued by carrying out a large number of experiments under various operating temperatures. Fig. 6 shows the *COP* and *SCP* as a function of the bed temperature for the time of 20 mins. As expected, the variation of the bed temperature had strong effect on the performance. It can be observed that the performance increases when the bed temperature increases. However, adequate performance can be achieved even for a lower bed temperature. In particular, the *COP* of 0.072 and *SCP* of 71 W/kg were measured for a bed temperature of 70^{o}C, demonstrating that this adsorbent can be driven by a low-temperature heat source. In general, there is a maximum of the cooling power (*Qe)* at a specific cycle time. Larger cycle time leads to higher coefficient of performance *COP*, but less cooling power. The relation is shown in Fig. 7, it can be noted that by increasing the cooling time, the cooling power *(Qe)* value increases and there is a maximum *Qe* value (793 W) when the cooling time is 9.1 mins, after that the *Qe* decreases as the cooling time increases. This time of 9.1 mins, is enough just to cool the adsorbent up to 42.5°C, not to 35°C, and the adsorbers are insufficiently cooled or heated during the adsorption and desorption processes respectively. However, the value of *Qe* at 20 mins is 664 W, which is less than the maximum value by 149 W. But, it is still an acceptable value to work on. Consequently, a strategy was adopted to assess the adsorption time of 20 mins. The same results are obtained for the *COP* and *SCP*: increasing the temperature of the bed leads to increase the cooling power.



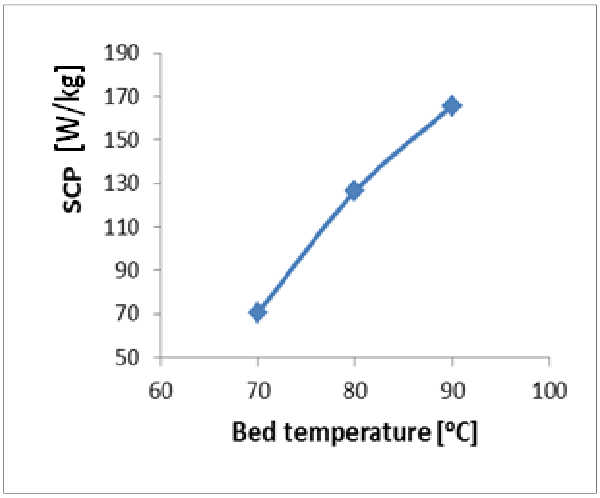


Fig. 6. Experimental results of *COP* and *SCP* as a function of the bed temperature.

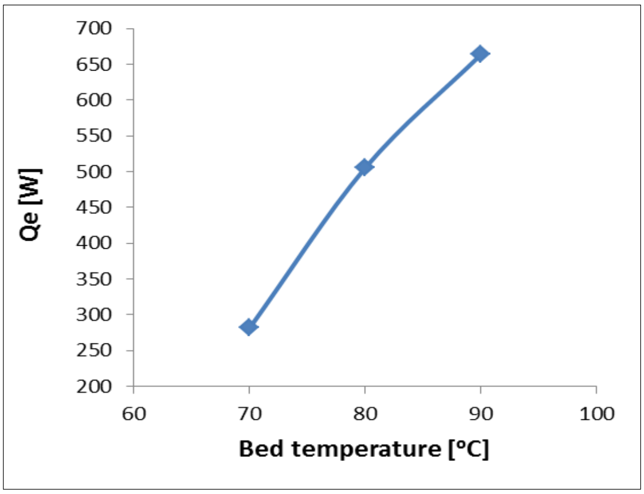


Fig. 7. Cooling capacity variations with bed temperature.

4.5. Comparison with Other Adsorption Chillers

As discussed from the results, the chiller performance is quite similar to that on the former adsorption chiller [19-21]. Compared with adsorber presented by Chang et al. [19], this adsorber shows a lower refrigerant exchange amount ($\Delta x = 0.08$ kg H_2O / kg adsorbent). According to Chang et al., $\Delta x > 0.1$ kg H_2O / kg adsorbent, that the rectangular fins were used to extend the mass transfer area, while in this study, circular fin tubes were adopted in the adsorber. Geyer and Paar [20] built up a laboratory unit (approx. 1000 w cooling capacity) using a flat fin- tube heat exchanger. The maximum values of the cooling capacity and COP under operating conditions of hot water (= 80°C), cooling water (= 27°C), and entire cyle time (= 45 mins), were 700 w and 0.3, respectively [20]. It was close to the operating conditions of our results, but the difference is with the value of COP, which is higher in Geyer and Paar silica gel used in the experiment. Another work. May be the reason is due to the properties of considered comparison is with the work of Kubota et al. [21], who used 5.8 kg of dry silica gel in a circular finned-tube heat exchanger. However, his results showed that water exchange amount, $\Delta x = 0.11$ kg H_2O / kg adsorbent, for 6 min, hot water of 80°C, and cooling water of 30°C. While the cooling capacity and COP are 1200 W and 0.25, respectively.

4. Conclusions

In this paper, a new design of a fin-tube heat exchanger was presented and tested in adsorption chiller prototype.

The measurement of the equilibrium properties showed that the silica gel adsorbent is able to exchange amount of 0.08 kg H_2O/kg silica gel under the operating conditions of air-conditioning applications.

Considering, the results of this work for 20 mins adsorption time demonstrated that the values of cooling power, SCP, and COP are 664 w, 163 w/kg adsorbent, and 0.16, respectively [21].

Acknowledgment

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Nomenclature

A_p	Specific Surface area, [m²/g]
COP	Coefficient of performance
cp_{hw}	Specific heat of hot water, [kJ/kg.°C]
d_p	Average particle diameter, [mm]
ΔH_{evp}	latent heat of evaporation, [kJ/kg]
k	Thermal conductivity, [W/m. °C]
M_{ads}	Mass of adsorbent, [kg]
m_{hw}	Mass flow rate of hot water, [kg/s]
Q_{evp}	Cooling power, [W]
SCP	Specific cooling power, [W/kg]
t_a	Adsorption time, [min]
t_d	Desorption time, [min]
t_{iso}	Isostering time, [min]
t_{cycle}	Cycle time, [min]
T_c	Cooling water temperature, [°C]
T_{hwi}	Hot water in, [°C]
T_{hwo}	Hot water out, [°C]
T_a	Adsorption temperature, [°C]
T_d	Desorption temperature, [°C]
x_t	Concentration at specific time,[kg/kg]
Δx	Concentration at specific time,[kg/kg]
ρ	Apparent density, [kg/m³]

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الأداء التجريبي لمبرد امتزازي ذو انبوب زعنفي للسيلكا جل لاغراض تبريد الهواء

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الخلاصة

يعرض هذا البحث بناء جهاز اختبار لمنظومة تبريد الهواء يتسم بالمرونة في تغيير موديل وحدة الامتزاز. فمن اجل تحسين كفاءة انتقال الحرارة والمادة، تم استخدام مبادل حراري مزود بزعانف لوحدة الامتزاز . أظهرت النتائج أن سعة التبريد (SCP) ومعامل الأداء (COP) هي ١٦٣ واط / كجم و ٠,١٦، على التوالي، عندما يكون وقت الدورة هو ٤٠ دقيقة، ودرجة حرارة الماء الساخن ٩٠ درجة مئوية،ودرجة حرارة مياه التبريد ٣٠ درجة مئوية ودرجة حرارة الماء المبرد ١١,٤ درجة مئوية .