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Experimental and Theoretical Study of the Energy Flow of a Two Stages Four Generators Adsorption Chiller

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Abstract

This work is concerned with a two stages four beds adsorption chiller utilizing activated carbon-methanol adsorption pair that operates on six separated processes. The four beds that act as thermal compressors are powered by a low grade thermal energy in the form of hot water at a temperature range of 65 to 83 °C. As well as, the water pumps and control cycle consume insignificant electrical power. This adsorption chiller consists of three water cycles. The first water cycle is the driven hot water cycle. The second cycle is the cold water cycle to cool the carbon, which adsorbs the methanol. Finally, the chilled water cycle that is used to overcome the building load. The theoretical results showed that average cycle cooling power is 2.15kW, while the experimental measurement revealed that the cooling capacity of the cycle is about 1.98 kW with a relative error of % 0.02. The generator and condensing temperatures are 83 and 30 °C, respectively. The coefficient of performance (COP) of that chiller was in the range of 0.37 to 0.49. The best operating point and the best working conditions were also investigated. The present chiller is superior more than the single stage, two beds adsorption chiller that works on the activated carbon methanol pair that needs a high ambient temperature.

Keywords: *Adsorption, Refrigeration, Multi-beds refrigeration, Activaid carbon-methanol adsorption.*

1. Introduction:

Introduce renewable energy is a sustainable solution to a shortage in the fossil fuel and the environmental impact. The suggested solutions for the units that can work on low grade energy are (solid-vapor) adsorption systems as well as absorption (liquid–vapor) systems. Even though adsorption cycles have relatively lower performance than absorption cycles, the latter can only be used with sources of high temperature. Employing active carbon-methanol or gel-water set up as the adsorbent-refrigerant in adsorption cycles allow for these cycles to be stimulated by heat sources of near ambient or low temperature. One proven example of adsorption systems that are driven thermally is the work of Luo et al. [1]. They built an adsorption chiller that is driven by solar power. Their work depended on using substitute system cooling for grain storage. The outcome of the system has a cooling capacity from 3.2–4.4 kW in average, and COP of about 0.1–0.13. Núñez et al. [2] have demonstrate a small prototype adsorption heat pumps, the COP at heating mode exceeding 1.5, and the air-conditioning's COP was near 0.5. Moreover, Myat et al. [3] examined the performance of a low-grade waste heat cooling system based on Zeolite adsorption. According to their results, a heat source of only 55 °C can be utilized to give a COP that reaches 0.48. Qian et al. [4] studied the performance of an adsorption chiller with the synthetic water/zeolite driven by hot water at 70 °C. At various operating conditions, the recorded COP was between 0.1to 0.6 and cooling capacity of 3kW was obtained. Pons and Guilleminot [5] studied icemaker utilizing stimulated carbon–methanol pair by using solar radiation. The results showed a COP of about 0.15. Critoph [6] stated that the COP of an adsorption icemaker system using charcoal/methanol pair was in the range of

0.2–0.5 at 8 °C as the evaporation temperature. The heat source produced a temperature range of 80-140 °C. All of the researches mentioned previously proved the necessity to improve the performance of adsorption refrigeration systems. Abdual Hadi ,Fawziea and Faeza[7] The two beds adsorption chiller was driven by hot water, with a temperature range of 70 to 100oC. Used active carbon-methanol adsorption pair. It was found that using the mass recovery process increases the initial concentration of methanol in the desorption generator; hence, improving the COP and SCP of the cycle. The COP of this adsorption chiller was about 0.301, while the SCP was about 0.3532 kW/kgAC, at an outdoor temperature of 25 oC. Eventually a mass of 200 kg of water could be chilled from 10 oC to about 7 oC in about 14 min Later on, Saha BB. [8] developed a three-stage adsorption chiller which utilized silica gel–water adsorption refrigeration cycle driving heat source temperature is 50 °C and 30 °C cooling water source temperature. In Ref. [9], the simulation results of a multi-bed regenerative adsorption chiller revealed that, by employing similar source of heat to derive a four-bed chiller improved cooling capability by 70% as compared with a single stage two-bed adsorption chiller. While a six-bed adsorption chiller can improve cooling capacity by 40% refrigerating in comparison with a four-bed adsorption chiller. The adsorption chiller suggested by Alam et al. [10] utilizes a heat source that ranges from 50°C to 90 °C and is a reheat double-stage adsorption system. This system achieved a cooling temperature of 30 °C. This reheat two-stage chiller has a higher COP than two-stage chiller. Additionally, a reheat two-stage system is effective despite the low temperature of the heat source that starts from 50 °C and does not exceed 90 °C. A two stages four beds adsorption chiller utilizing activated carbon-methanol adsorption pair, based on Patent No. US 8479529 B by Prof. Ayman Al-Maaitah and Adnan Al-Maaitah [11], is investigated.

The chiller present in this work operates on six separate processes. The four beds that act as thermal compressors are powered by a low grade thermal energy in the form of hot water. The effect of water temperature on the cooling capacity (CC), specific cooling capacity (SCP) and Cofficient of performance (COP) is studied in this work. Find the best working zone .The present work was conducted in the Labs of Millennium Energy Industries, (http:// millenniumenergy. co.uk/) Jordan.

2. Refrigeration Cycle

The adsorption chiller is utilized an active carbon methanol pair is supported by three water cycles[12]. The first water cycle is the hot water cycle passing through the generator and heating carbon to desorb the methanol vapor. The second cycle is the cooling water cycle, in which the water provided by this cycle passes through the generator to cool the carbon to adsorb the methanol. Finally, the water from the chilled water cycle is re-circulated through an evaporator section that placed in the conditioned space. While the temperature were measured at three water cycle, fixed on inlet and outlet of each water line cycle. J type thermocouple that connected digital thermometer, with an error of $\pm 1C^{o}$. The three water circuits are shown in Fig. (1).

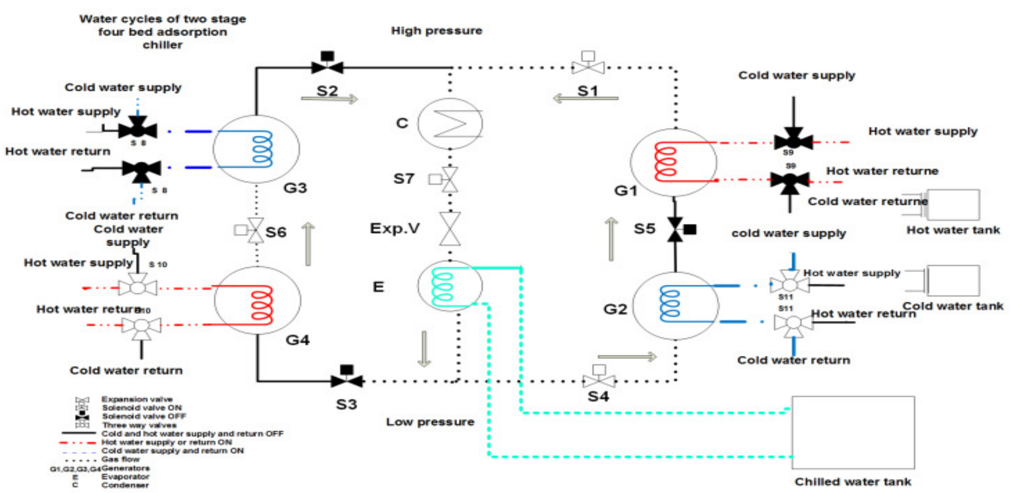

Fig. 1. The three water cycles for the adsorption chiller

3. Energy Flow for Adsorption Chiller

The operating parameters and chiller component specifications are presented in Table (1).

Table 1,
Adsorption chiller components and operating Parameters used in simulation

	Symbol	Value	Unit
Adsorper area	$A_{ads(area\ of\ adsorber)}$	0.9	m^2
Evaporator area	A_{evap}	0.18	m^2
Mass flow-rate of hot water	$m_{water(hotwater\ flow\ rate)}$	0.25	kg/s
Mass flow rate of coolant water	$m_{water(coolant\ water\ flow\ rate)}$	0.25	kg/s
Mass flow rate of chilled water	$m_{water(chilled\ water\ flow\ rate)}$	0.095	kg/s
Overall heat transfer coefficient of adsorber	$U_{ads(overall\ heat\ transfer\ coefficient\ of\ each\ adsorber)}$	1750	W/m^2 K
Overall heat transfer coefficient of evaporator	$U_{evaporator}$	2000	W/m^2 K
Mass of copper tubes	Pure copper (mass)	35	kg
Mass of activated carbon	Activated carbon (mass)	12	kg
Mass of methanol	Methanol (mass)	3	kg
Specific heat water	(CP_w)	4.186	kJ/kg.K
Specific heat Pure copper	(CP_{cu})	0.3831	kJ/kg.K
Specific heat activated carbon	(CP_{AC})	0.9	kJ/kg.K
Specific heat methanol	(CP_m)	0.75	kJ/kg.K

The water temperature leaving the adsorber and evaporator can be calculated as follow:

The hot water temperature leaving the adsorber in the desorption process is:

$$T_{waterOUT\ des} = T_{des} + (T_{waterIN} - T_{des}) \, .exp \left(\frac{-U_{des}.A_{des}}{m_{water}.CP_{water}} \right) \quad \ldots(1)$$

The cold water temperature leaving the adsorber in the adsorption process is:

$$T_{waterOUTads} = T_{ads} + (T_{waterIN} - T_{ads}) \, .exp \left(\frac{-U_{ads}.A_{ads}}{m_{water}.CP_{water}} \right) \quad \ldots(2)$$

The chilled water temperature leaving the evaporator in cooling process is:

$$T_{waterOUTch} = T_{ads} + (T_{waterIN} - T_{ads}) \, .exp \left(\frac{-U_{eva,}A_{eva.}}{m_{water}.CP_{water}} \right) \quad \ldots(3)$$

The heat provided by the hot water to the generator in desorption process is:

$$Q_{hot\ water} = m_{water}.CP_{wtater} \cdot (T_{out\ des} - T_{in\ des}) \quad \ldots(4)$$

The energy provided by the hot water is:

$$\text{Energy of hot water (kW)} = \frac{Q_{hot\ water}}{Time\ (S)} \quad \ldots(5)$$

The heat added to the cooling water of generator in adsorption process is:

$$Q_{cold\ water} = m_{water}.CP_{wtater} \cdot (T_{out\ ads} - T_{in\ ads}) \quad \ldots(6)$$

The energy flow by cooling water of generator in desorption process is:

$$\text{Energy of cold water(kW)} = \frac{Q_{cold\ water}}{Time\ (S)} \quad \ldots(7)$$

The cooling capacity in evaporation process is:

$$Q_{child\ water} = m_{water}.CP_{wtater} \cdot (T_{out\ ch} - T_{in\ ch}) \quad \ldots(8)$$

The energy of chilled water is:

$$\text{Energy of chilld water (kW)} = \frac{Q_{child\ water}}{Time\ (S)} \quad \ldots(9)$$

Excel sheet was used to solve the system equations 1 to 9 [13] with the aid of Table (1) and used climatic data measured (hot ,cold and chilld water temperature inlet). In the simulation, the temperature along the heat exchanger of bed, evaporator and condenser are assumed to be uniform, 1.5 second interval time is used for the calculations.

The design consideration Evaporator temperature 7°C and condenser temperature 45 °C with standard value as the aid of table (2)

Table 2,
Standard value and operating condition.

Water cycle	Mass flow rate (kg/s)	Inlet temperature ©	Temperature range for testing (°C)
Hot water (heating generator)	0.25	95	65-83
Cold water (cooling generator	0.25	25	22-35
Chilling evaporator	0.095	12	6 -25

The Steps Include as Follow

Identification of inputs from initial temperatures water inlet, water flow rate to three cycles water, a fixed cycle time and design conditions for each component (evaporator, condenser desorption and adsorption generator temperature). We calculate the water temperature outlet for each water cycle then calculate the energy flow, then introduce a new temperature and repeat steps.

4. Uncertainties Analysis

All quantities that are measured to estimate the cooling capacity are subjected to certain uncertainties due to error in the measurement. These individual uncertainties (Uq) are presented. The analysis is carried out on the base of the suggestion made by Kline and McClintock [14].

The cooling capacity uncertainty analysis can be calculated as follows:

$T_{ch,i}$= 10 °C, $T_{ch,o}$= 7 °C, $\mathring{m}_{ch}$=0.095 kg/s

$$q = \mathring{m}_{ch}\ Cp_{ch}\ (T_{ch,i} - T_{ch,o}) \quad \ldots(10)$$

$$U_q = \pm\left[\left(\frac{T_{ch,i}}{q}\cdot\frac{\partial q}{\partial T_{ch,i}}\cdot U_{T_{ch,i}}\right)^2 + \left(\frac{T_{ch,o}}{q}\cdot\frac{\partial q}{\partial T_{ch,o}}\cdot U_{T_{ch,o}}\right)^2 + \left(\frac{\mathring{m}_{cw}}{q}\cdot\frac{\partial q}{\partial \mathring{m}_{ch}}\cdot U_{\mathring{m}_{ch}}\right)^2\right]^{1/2} \quad \ldots(11)$$

The uncertainty in the cooling capacity= ±0.10 or 10%

5. Results and Discussion

Figure (2) presents the theoretical results of the variation of energy delivered by hot, cold and chilled water with time. The figure also shows, practically, the highest heat transfer rate is for the hot water circuit of 38 kW, offset by the heat transfer-rate to the cold water of (-33.5 kW), while the maximum heat transfer rate for the chilld water was 2.5 kW.

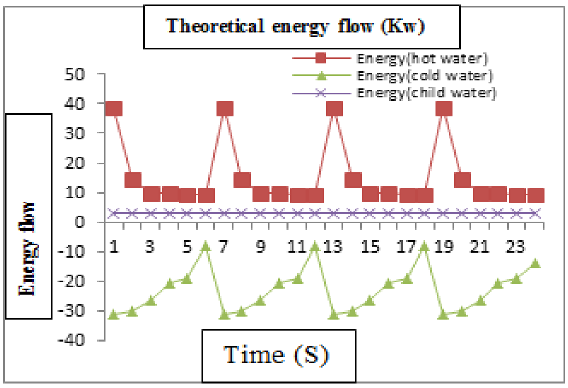

Fig. 2. Theoretical energy flow of three water cycles

The experimental water temperature variation for three cycles is shown in Fig. (3). The highest temperature difference between entering and leaving water is shown to be at the generator and evaporator. Fig. (4) Shows the diagram for the energy flow used equation (12-13) of each of the three water circuits based on experimental registered data for water flow rates shown in Table (1) and temperature variation of water in the three cycles as show in fig.(3) . It shows the variation of cooling capacity, specific power consumption and heating load with the time. The variation of the refrigeration cycle performance (COP) as the ratio of the refrigeration capacity (SCP, specific power consumption) to the heat addition in adsorbent bed is presented in Figure (5) can be calculated as follow:

$$SCP = Q_{Ch.} = (m_{water} \times Cp_{water} \times (T_{ch.inlet} - T_{ch..outlet}))/tim(S) \quad \ldots(12)$$

$$Q_{hot.w} = (\mathring{m}_{h.water} \times Cp_{water} \times (T_{hotw.outlet} - T_{hotw.inlet}))/tim(S) \quad \ldots(13)$$

$$COP = \frac{Q_{chl.w}}{Q_{hot.w}} \quad \ldots(14)$$

The figure shows that, as the hot water temperature increases, the specific cooling capacity the refrigeration capacity (SCP) increases too, with little decrease in the COP. This may be attributed the increasing of heat input to the generator. The best working zone is at the intersection point between the COP and SCP curves.From figure (5) it can be seen that maximum SCP is achieved at the desorption cycle temperature (driving heat source temperature) between 93 and 95 °C while the cooling temperature is 30 °C. The reason for this is the availability of enough refrigerant desorbed and adsorbed that can achieved the cooling capacity. This increase in specific cooling capacity is association with the lowest COP. The lowest COP is correspond to the maximum heating power, while the lowest SCP and highest COP are when the heating water temperature is at its lower value of 63 °C with a temperature of cooling that is 30 °C. The reduction in cooling capacity is due to the reduction in refrigerant mass flow rate. The values of COP andSCP peak at desorption temperature that is 78 °C and adsorption temperature 30 °C. The best working point and the best working area are between 73 °C – 83 °C desorption temperature of the chiller.

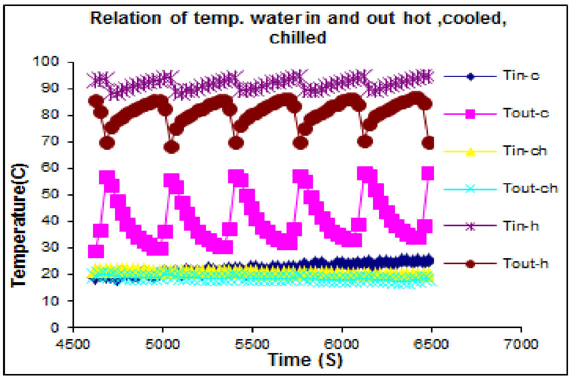

Fig. 3. Experimental temperature variation with time for the three water cycles.

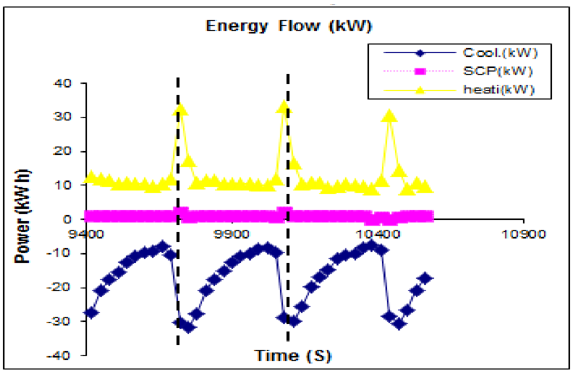

Fig. 4. Energy flow of the three water cycles.

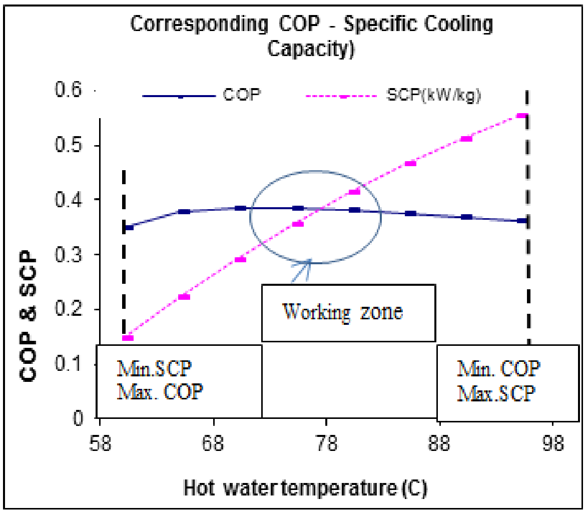

Fig. 5. Variation of source temperature and its effect on COP and Cooling capacity.

Figure (6) presents cooling water temperature and its effect on COP and (CC). The chosen inlet hot water-temperature was 85 °C for the four bed two stage operation. The capacity and COP are reduced when cold water temperature is increased because the adsorption process is delayed. Thus the methanol pressure in the generator restricted the flow of vapor from the evaporator to the generator. As well, as the saturation temperature of methanol increased, it leads to reduce the amount of desorb methanol. However the reduction of cooling water temperature increased the cooling capacity and COP, due to the improvement in the amount of the refrigerant that been adsorbed.

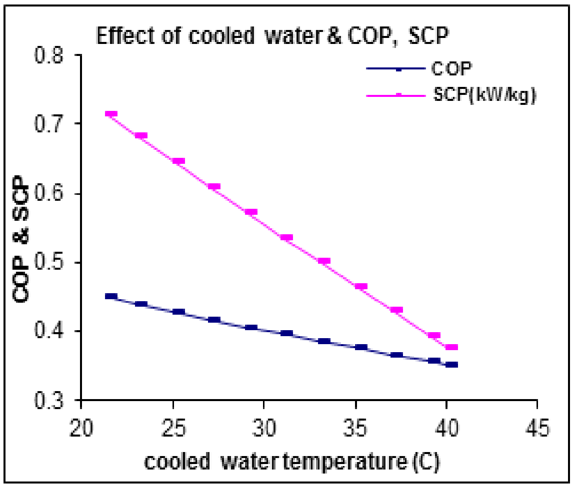

Fig. 6. Water temperature variation and its effect on COP and CC.

Finally, the average cycle performance of real and measured present value is compared with that for the predicted value. It is clear from Fig.7. that there is a good agreement between the two curves.

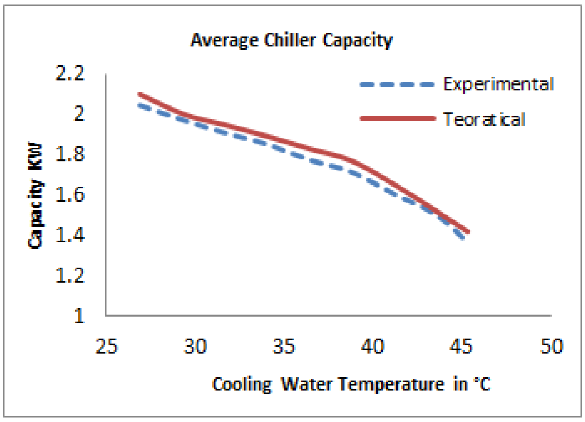

Fig. 7. Comparison of average cycle cooling capacity between measured and that predicted by the theoretical model.

6. Conclusion

The conclusions that can be derived from the performance of the two-stage four bed adsorption chiller with activated carbon methanol pair are as follows:

1. The cooling capacity increases with the increase of inlet heat source temperature 83 °C.
2. The suggested design has less chilled water outlet temperature than that of single stage two bed adsorption chillers.
3. Increasing hot water temperature leads to increase the cooling capacity and reduces the COP.
4. The best operating conditions for such chiller is at hot water temperature of 76 °C.
5. The best working zone was found to lie between 73 °C – 83 °C for the chiller that operates with cooling temperatures of 30 °C – 50 °C.
6. The COP and cooling capacity increase by the reduction of cooling water.

Nomenclature

T temperature °C
Cp specific heat
A heat transfer area (m^2)
m mass flow rate (kg/s)
Q heat (J/kg)
t time (S)
U overall heat transfer coefficient (W/m2K)
COP Cofficient of performance
CC Cooling capacity
SCP Specific cooling capacity

Subscripts

ads adsorption
des desorption
ch chilled water
hot hot water
cold cold water
water heat transfer fluid
evap Evaporator
w water

7. References

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دراسة عملية ونظرية لتدفق الطاقة لمثلج امتزازي ذي أربعة مولدات ومر□لتين ملخص

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الخلاصة

مثلج الماء الامتزازي ذو الاربع مولدات للبخار ولمرحلتين باستخدام زوج الامتزاز الكربون- الميثانول والذي يعمل على ست عمليات منفصلة. إن المولدات الاربع التي تعمل كضواغط حرارية بشوطين مدعومة بالطاقة الحرارية للماء الساخن عند درجة حرارة تتراوح بين ٦٥ و٨٣ درجة مئوية. وكذلك، فإن مضخات المياه ودورة التحكم تستهلك طاقة كهربائية ضئيلة. ويتكون مثلج الامتزاز اضافه الى دوره وسيط التبريد الميثانول من ثلاث دورات ماء. دورة الماء الأولى هي دورة الماء الساخن لتسخين الكاربون وتحرير الميثانول. الدورة الثانية هي دورة الماء البارد لتبريد الكربون وامتزاز الميثانول. وأخيرا، دورة الماء المثلج التي يتم استخدامها للتغلب على الحمل الحراري للمبنى. وأظهرت النتائج النظرية أن متوسط طاقة دورة التبريدkW2.1 ، في حين كشف القياس التجريبي أن قدرة التبريد للدورة حوالي kW1.98 مع خطأ نسبي ٪ ٠,٠٢. درجة حرارة المولدات في توليد بخار الميثانول وامتزازه هي ٨٣ و ٣٠ درجة مئوية، على التوالي. وكان معامل الأداء لهذا المثلج في حدود ٠,٣٧ إلى ٠,٤٩. كما تم التحقيق في أفضل نقطة تشغيل وأفضل ظروف العمل .المثلج ذو الاربعه مولدات ولمرحلتين متفوق أكثر من المثلج لمرحلة واحدة ومولدين امتزاز يعمل بنفس زوج الامتزاز الذي يحتاج إلى درجة حرارة تسخين للماء اعلى.