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Research Article

Experimental Investigation of Two Stages Adsorption Chiller with Four Generators Utilizing Activated Carbon and Methanol as Working Pair

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Abstract

Two stages adsorption chiller with four beads using active carbon-methanol adsorption pair based on Patent No. US 8479529 B2 is studied in this work. In addition to the four sorption/adsorption generator beds the adsorption cycle consist of the following main parts, air cooled a condenser, expansion valve and coaxial evaporator where the refrigerant passes in the inner tube while the water is in the outer. To complete the cycle solenoid valves, piping system, three way valves and pumps to circulate the water in this unit were used. Four beds of inner dimensions of 66.7 c m x 52.4 cm x 23.5 cm each is imbedded with activated carbon filled in between heat transfer fins. The bed acts as a methanol adsorpber/generator. The using of four generators is to build refrigerant pressure in two stages through a continuous adsorption-desorption cycle, by allowing the generators to work alternatively either adsorbing or desorbing the medium. The switching between desorption and adsorption phases is achieved by computer controlled system. The adsorption chiller was driven by hot water ranging from 70 to 85 °C. The chiller was charged by 24 kg of active carbon and 5kg of methanol, giving an initial concentration of (0.228 kg CH3OH/kg AC). The results showed that average calculated cycle cooling power is 2.33kW while the experimentally obtained cooling power cycle is 1.98kw. The COP of that chiller was at 0.5, 0.41, and 0.1 for cooling temperature of 25 , 35, and 50 °C respectively. As such, the present chiller is proven to me much more superior for single stage Celica gel commercially available chiller at high ambient temperature conditions.

Keywords: *Adsorption, Refrigeration, multi-beds refrigeration, active carbon-methanol adsorption.*

1. Introduction

Cooling and refrigeration consumes more than 70% of residential electricity usage especially in regions like the Middle East and reaches to about 15% of worldwide consumption of electricity (L.Lucas, 1988). The amount of cooling needed is usually directly proportional with Solar Radiation which makes it logical for solar cooling to be addressed and sought for. Solar cooling can be either solar PV cooling by generating electricity form a PV system and run a traditional vapor refrigeration cycle or using solar thermal cooling system. The later has the advantage of low cost solar thermal storage and solar collectors. In the present work an investigation of an innovative double stage adsorption chiller that is air cooled. Not only does solar cooling reduces the Carbon footprint of any building or cooling process, it can also reduce the hazards of damaging the O Zone layer by eliminating the CFC materials used in traditional refrigeration units.

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A brief description of some solar thermal technologies is presented here with for the purpose of demonstrating the merit of the present work:

Three Stage Absorption Chillers: These are very efficient absorption chiller that requires steam at temperatures around 220°C or more. The coefficient of performance of these chillers is around 2.2 (that is the cooling capacity generated are 2.2 of the thermal energy input of these chillers). As such these chillers need concentrating solar collectors and systems that generate high temperature steam. The used refrigerant pair is Lithium Bromide and Water. One of the main drawbacks of these chillers is that only few manufacturers exist worldwide hence there cost is relatively high.

Two Stage Absorption chiller: This is a widely used technique for solar cooling that uses steam up to 120°C. However, its coefficient of performance is around 1.3 making it less efficient than the three stage absorption chillers but at a much lower cost. It requires less temperature hence the solar system cost can also be reduced. Usually a Lithium Bromide and Water refrigerant pair is also used.

Single Stage Absorption Chiller: although this system has a low coefficient of performance around 0.7 it can use hot water as low as 70°C to operate that chiller when a Lithium Bromide and Water pair are used. This would largely reduce the cost of storage and working fluid. However, such chillers suffer from the issue of Crystallization and special control or backup systems need to be used to overcome such problem. It should be mentioned that there exists an Aqua Ammonia Refrigerant pair chillers in this category. These chillers require high temperature than 70°C but there are no Crystallization problem and they can be air cooled (A.Elsafty and A.J.Al-Daini, 2002).

Desiccant Wheel: In this system the aim is basically to dehumidify the air by absorption (or actually adsorbing) the humidity in it and then using the solar heat to desorb the humidity. It is basically composed of a rotating wheel where filled with adsorbing (desiccant material) allowing air to flow around it. In some part of the rotation the air that is needed to be dehumidify passes around the dry adsorbing material hence the humidity from the air is adsorbed and the coming air is dry. This dry air can be cooled down by evaporative cooling or be mixed with cooled humid air to reduce its humidity ration. As the wheel turns the desiccant material now filled with humidity is exposed to solar heat by one way or another (air heated by solar collectors can be one method) hence the humidity is desorbed form the desiccant material and it becomes dry again to be rotated towards the humid air again. The cycle then continues (N.S.Edward and R.Reinhard, 1999).

Adsorption Chiller; Unlike absorption Chillers Adsorption Chillers do not have a mixture solution affected by temperature of the system or suffers from crystallization problem. It is also not so sensitive to temperature variation to the limit where a shutdown of the system is needed. The refrigerant is adsorbed on the surface of solid material rather is absorbed in solution.

A single bed adsorption refrigeration cycle (C. Hildbrand *et al*., 2004) consists of an adsorbent bed, a condenser, a reservoir, and an evaporator. This is an intermittent cycle with low efficiency. To make a continuous operation cycle two bed (generator) systems are used so that when on generator desorps the refrigerant the other adsorbs it and a higher efficiency can be obtained even with multiple beds (K.Sumathy *et al*.,2003).

Cooling the adsorbed with refrigerants coming out of the evaporator was shown to increase the efficiency of the multi stage multi bed system by Sato *et al*.(H.Sato *et al*., 1997;. H.Sato *et al*,1998).

As an example B.B. Saha,(B.B. Saha *et al*., 2003) reported a small scale adsorption water chiller with cooling power rated as 10 kW; the system achieved a cooling COP of 0.4 when was driven by 85 °C hot water. Ng *et al*.(Ng *et al*., 2009) reported the thermodynamic analysis and optimization of a combined adsorption heating and cooling system with methanol and activated carbon fiber as the working pair. It was found that the optimized adsorption system could achieve a COP of about 0.56 producing around 6 kg of ice per day. Saha *et al*. (B.B. Saha *et al*., 2003) analyzed a waste heat driven dual-mode, multi-stage, multi-bed regenerative adsorption system. The proposed system may by driving at very low temperatures between 40 and 60 °C but with low COP values reported a detailed parametric study on a dual-mode water/silica gel adsorption chiller. Simulation results showed that both cooling capacity and COP values increase with the increase of chilled water inlet temperature with driving source temperature at 50 and 80 °C in three stage mode, and single-stage multi-bed mode, respectively. A mathematical model was developed by Khattab (N.M. Khattab,2006) to simulate and optimize the performance of a solar-powered adsorption refrigeration module with the solid adsorption pair of domestic type of methanol and charcoal. After optimization it was found that the yearly average ice production increased from 0.23 to 0.25 kg/day, the yearly average bed efficiency increased from 55.2% to 58.5%, and the yearly average net COP increased from 0.146 to 0.1558.

All of the previously mentioned work needed either a low cooling (ambient) temperature to operate or very high heating temperature. Most of them requires evaporative wet cooling tower to cool the cooling water. In the present work we present an investigation of a chiller that operates on temperatures that can be generated by evacuated tube solar collectors (70-85) ^{o}C and with cooling temperatures as high as 50 ^{o}C. Such chiller will be ideal for hot humid climate like the gulf area.

The present investigation was conducted in the Labs of Millennium Energy Industries, (http:// millenniumenergy. co.uk/) and was funded by it.

2. Apparatus description

An adsorption chiller unit consists of four generators namely (G1, G2, G3, G4,) were connected on the form of two series couple. The inside of the each generator is shown in Fig.(1) where hot (or cold) water flows in pipes heating fins surrounded by activated carbon particles. The generators, G1 and G2 link in series on the right side of the unit, while the generators G3and G4 link in series on the left side of the unit, as shown in the photo of Fig. (2). Then the two groups of generator, mentioned above were connected through two points, the first one was at the high pressure side, while the second one was at the low pressure side, as shown in Fig. (3).

Each generator filled with adsorbent activated carbon of type (NORIT PK 1-3) with a particle size of 3.15mm in diameter, of apparent density of 290 kg/m3,Iodine number is 800 and ash content 3%, The generators, are connected with each other by a 16mm diameter copper tube. Six solenoid valves namely S1, S2, S4, S5 and S6 were installed at inlet and outlet of each generator to prevent rear flow of methanol. Inlet and outlet water pipes were installed at each generator, for heating and cooling processes. Three way valves, one for each generator, were used to switch between hot and cold-water circuits. The water was circulated by hot and cold water pumps. Finally, the adsorption chiller having three cycles, two as refrigeration cycles, and the remains one for water. The refrigeration cycles consist of generators G2 ,G1 , condenser(C) , solenoid valve (S7), expansion valve and evaporator(E) and the second generators G4,G3, condenser(C), solenoid valve (S7), expansion valve and evaporator .

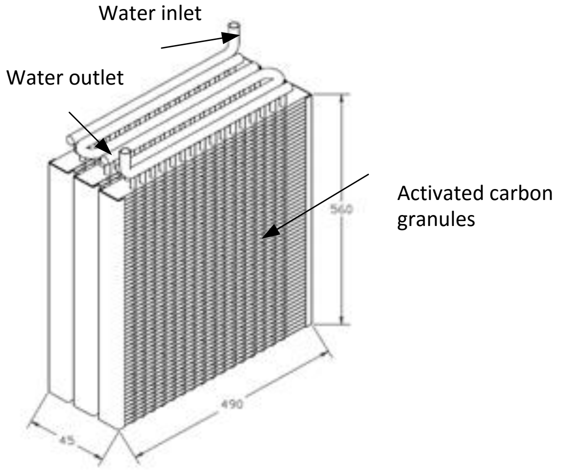

Fig.1 Inside of the generator Radiator

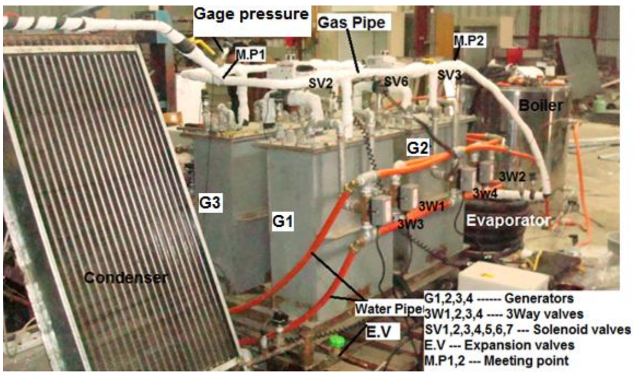

Fig.2 Photo of Two stage four bead adsorption chillers

2.1 Adsorption Chiller Working Cycles:

The continuous operation of refrigeration cycle can be achieved via eight processes; electrical circuit controls each process. To explain the operation of the chiller the reader is referred for the nomenclatures in Fig. (3) to (10). The system operates in two modes: the startup transition mode and the steady state mode as show herewith.

2.1.1 The Transient Startup mode

To reach steady stat operation for the chiller, four transient processes are required. These four processes shift the pressure and temperature in each component of chiller to a starting point for continuous steady state operation. To prevent the flow of refrigerant from condenser to evaporator solenoid valve (S7) is in off mode in all of transient process A.A.Al-Maaitah,(2013). The first process is achieved by heating generators (G2) and (G4) by hot water through (3W2, 3W4), leading to rise the temperature and pressure of the mentioned generators to 85 ^{o}C and 14.5 kPa. Simultaneously generators (G1) and (G3) are cooled by cold water. The desorb methanol leaving hot generators (G2) and (G4) through solenoid valves (S5) and (S6) to cold generators (G1) and (G3) respectively. As the generators (G1) and (G3) charged by methanol vapor. The heat of desorption is removed from two generators mentioned above by opening the valves (3W1, 3W3) and allowing the cold water to flow through the generators, as shown in Fig. (3).

By continues heating generator (G4), and cooling generators (G1) and (G3), the pressure of desorbed methanol from generator (G4) to generator (G3) increases from 14.5 to 35 kPa. This process tends to empty generator (G4) and full generator (G3) by methanol vapour at a pressure of 35 kPa. Simultaneously, the pressure of generator (G2) falls to about 4kPa, this lead to adsorb about 50% of methanol from evaporator, during this process the valves (S4), (S5) and (S6) is just open, as shown in Fig.(4). The time required to complete this process is about 3 min.

The third process is achieved by receiving generator (G2) hot water that valve (3W2) allow and desorbing the whole methanol vapour to cold generator (G1) through the solenoid valve (S5) at a pressure of (14.5kPa), at the end of this process (G1) is super charged by methanol vapour. The heat of desorption is removed from (G1) by cooled water that valves (3W1) allowing the cold water to flow through the generators At the same time generators, (G3) and (G4) cooled by flow of water through valves, (3W3) and (3W4) as the generators cooled the pressure goes to a lower level tends to adsorb the remainder of refrigerant from evaporator, through solenoid valves (S3) and (S6) as shown in Fig. (5),

In The fourth process, the methanol is charged, from supercharge generator (G1) to condenser through solenoid valve (S1) , by receiving hot water that valve(3W1) allowed and increasing its presser to condenser presser (35) kPa, at same time cold water flows to (G2) that valve (3W2) allowed, lowering its presser to evaporators presser and adsorb the refrigerant through (S4) . (G4) receives hot water that valve (3W4) allowed, desorbing vapor methanol to (G3) through solenoid valve (S6) and become empty. Cold water flows through valve (3W3) to supercharge generator (G3) removing adsorption heat and adsorbed refrigerant by activated carbon, as shown in Fig. 6. At the end of this process the refrigeration cycle ready for start steady state operation.

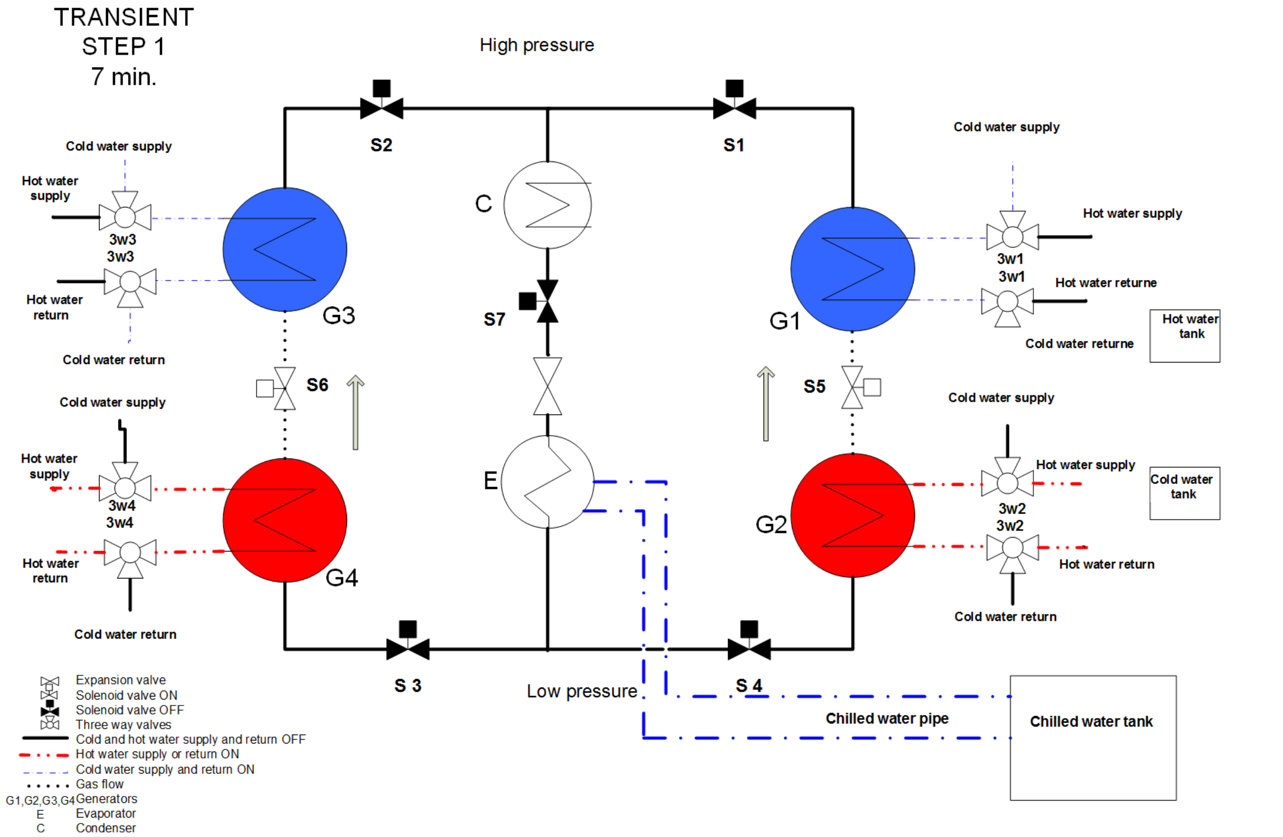

Fig.3 transient process of the adsorption chiller (Step 1)

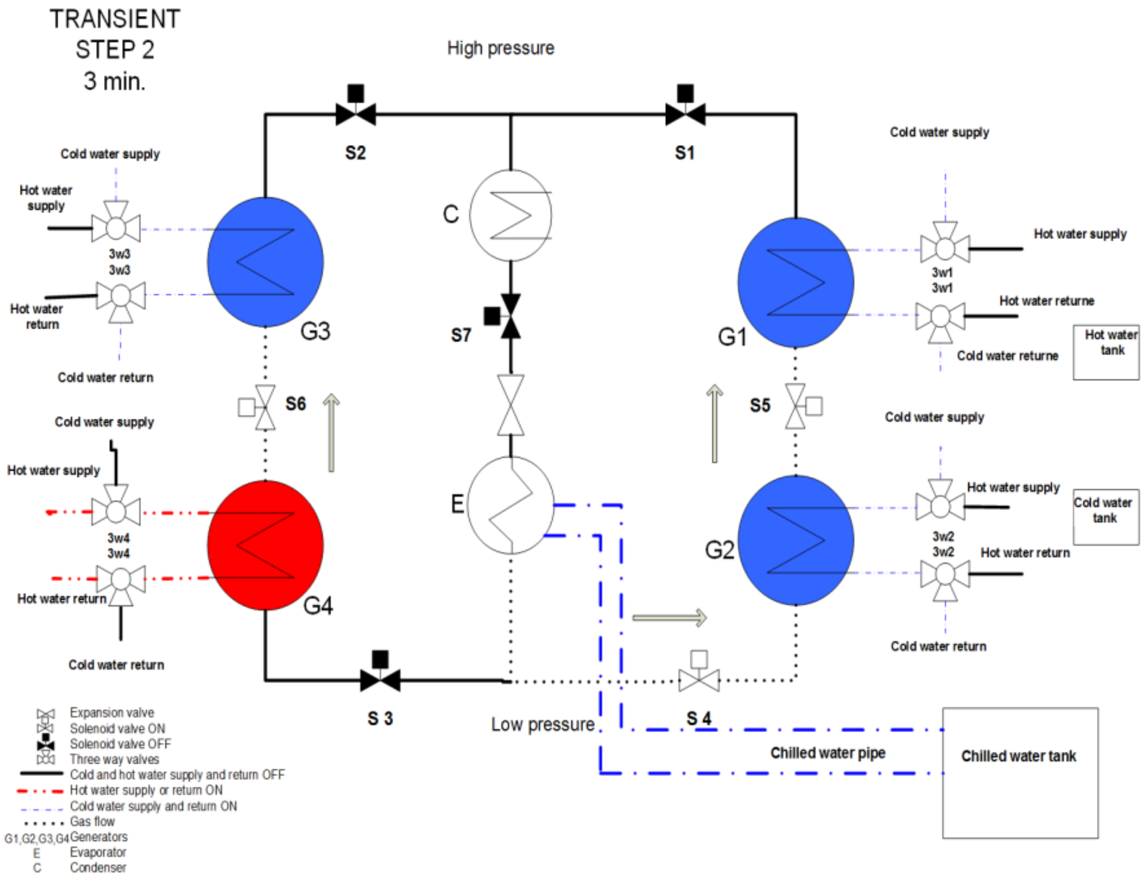

Fig.4 Transient process (Step 2)

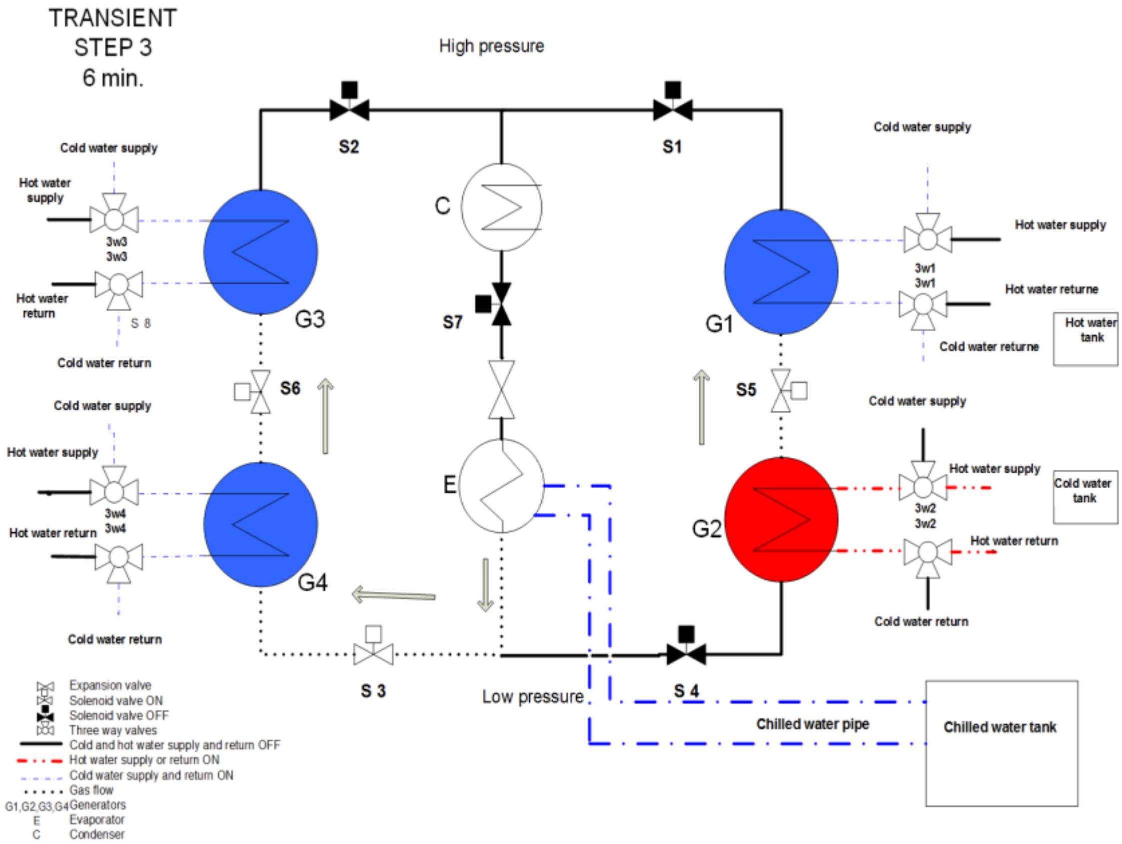

Fig.5 Transient process (Step 3)

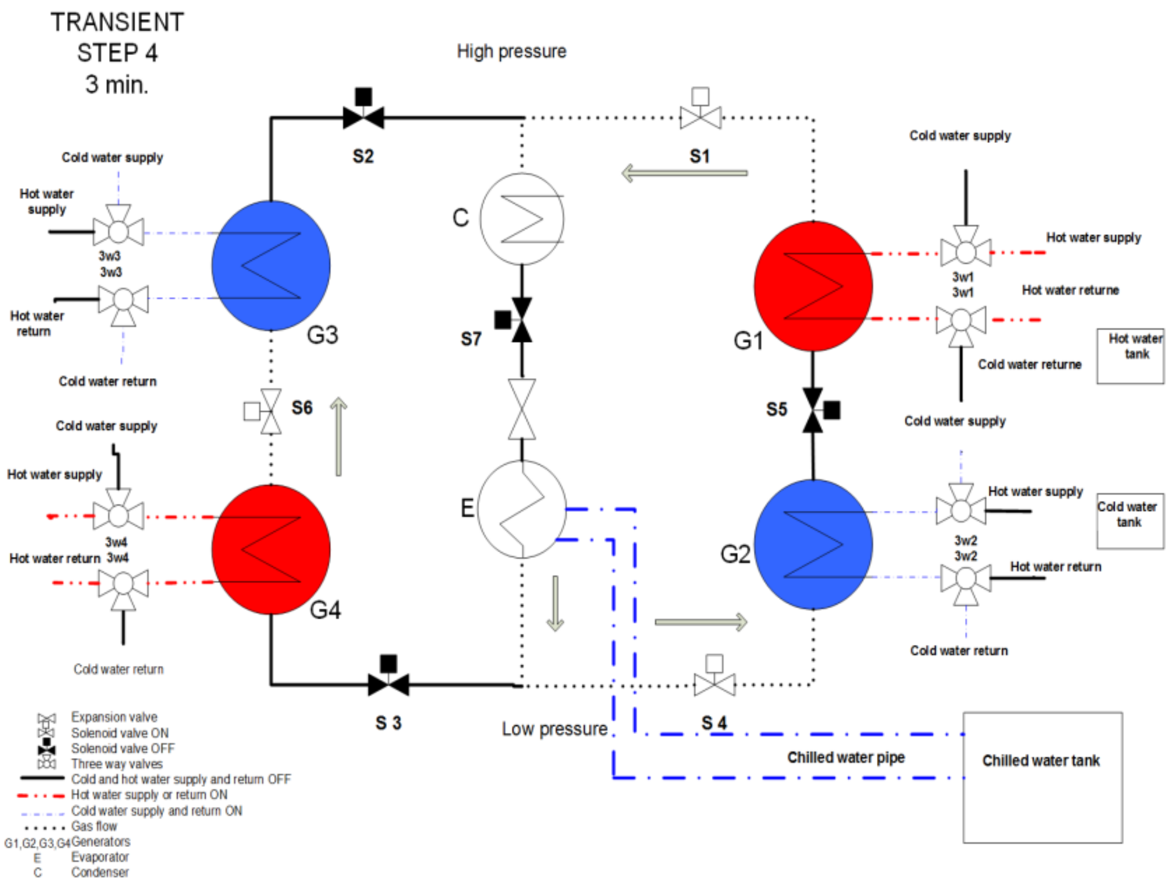

Fig.6 Transient process (Step 4)

Four processes achieve the continuous operation refrigeration cycle; electrical circuit controls each process.

The first process of continuous operation cycle starts by opening solenoid valve S7. (3W1) valve allowed hot water flows through (G1) leading increasing the pressure and temperature of supercharge generator (G1) to condensing pressure and desorb methanol vapor to condenser through solenoid valve (S1). To insure continues operation to the cycle, the condensate methanol in the condenser expand through expansion valve from about (35 to 4.5 kPa) to about 5 kPa, and to the evaporator at a saturation temperature of 0oC, extracting heat from evaporator and evaporates. The produced vapour adsorbed by cold generator (G2) through valve (S4). At the same time generator (G4) desorb methanol vapour to generator (G3) through solenoid valve (S6). At the end of these process generators, (G1) and (G4) are empty while generator (G2) and (G3) are charged by methanol vapour, the time required for this process is about 4 min. Fig. (7) Shows the first process of the continuous operation cycle.

The second process: The time required for this process is about (2) min its intermediate process to prepare generators operation process three, solenoid valve (S7) is off.

The second process is prepared for the second round of cooling process, in which generator (G3) supplies condenser by methanol vapour through solenoid valve S2, while generator (G2) supplies generator (G1) by methanol vapour through solenoid valve (S5), at the same time generator (G4) continues in receiving vapour from evaporator through solenoid valve(S3). The time required for this process is about 2 min. Fig. (8) shows the second process of the steady state operation cycle.

The third process is just mirror the first process of the steady state cycle, in which methanol vapour leaving generator (G3) to the condenser through solenoid valve (S2), and condensate in the condenser. Condensate methanol flows through solenoid valve (S7) expand through expansion valve from (35-40 kPa) to evaporator pressure of 4 kPa. As low pressure liquid methanol evaporates due to absorb heat in the evaporator, goes to generator (G4) through solenoid valve (S3). Associate with the cooling process, generator (G2) supplies generator (G1) with methanol vapour through solenoid valve (S5). This process tends to empty generators (G3) and (G2), while generators (G1) and (G4) charges with methanol vapour. The time required to complete this process is about 4 min. Figure (9) shows the third process of the steady state cycle.

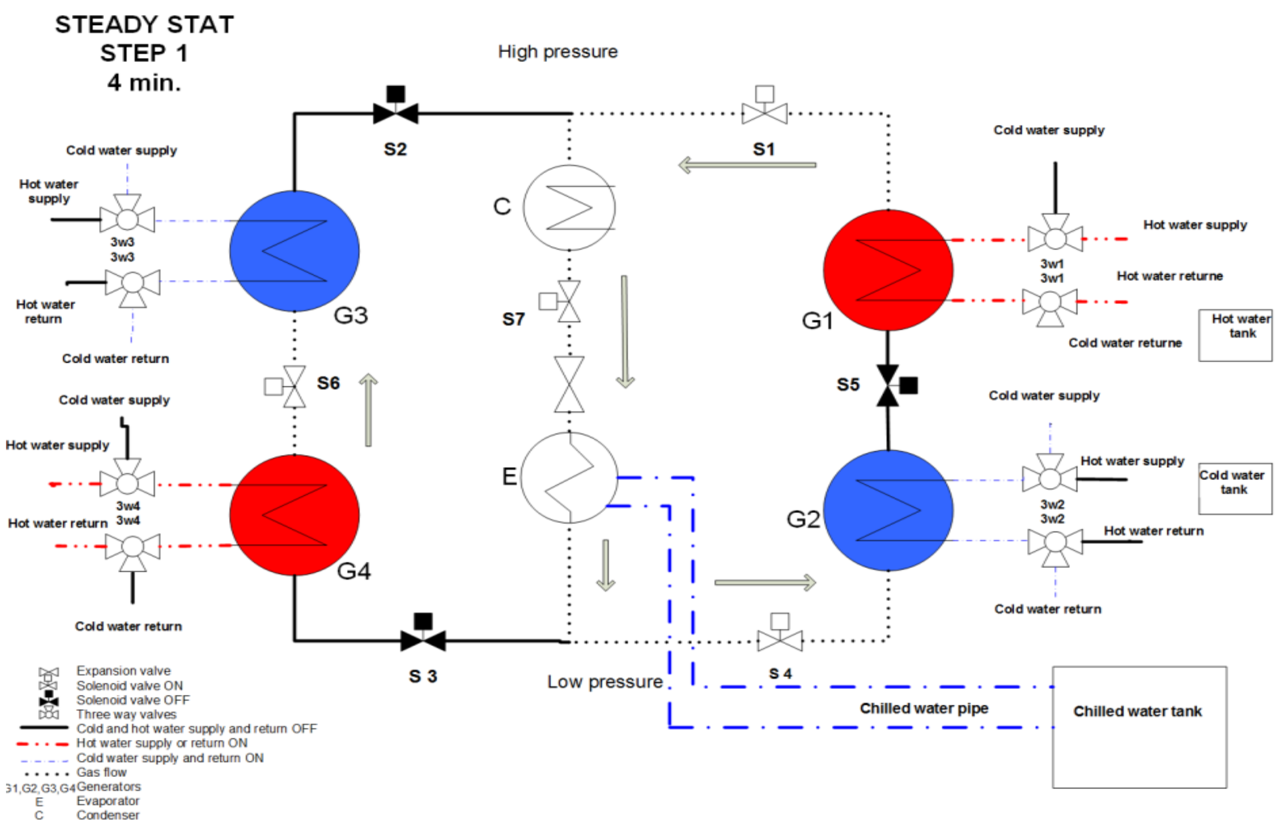

Fig.7 Steady state process (Step 1)

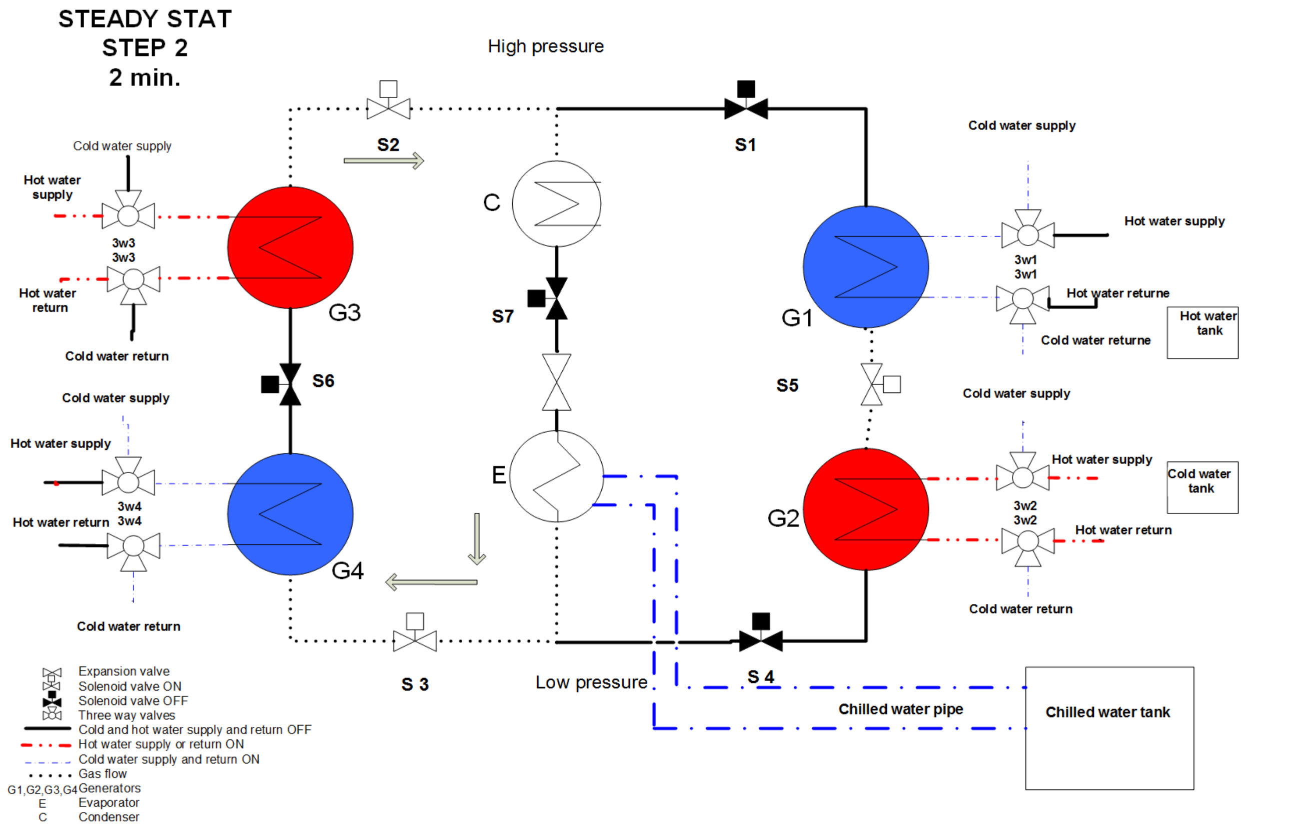

Fig.8 Steady state process (Step 2)

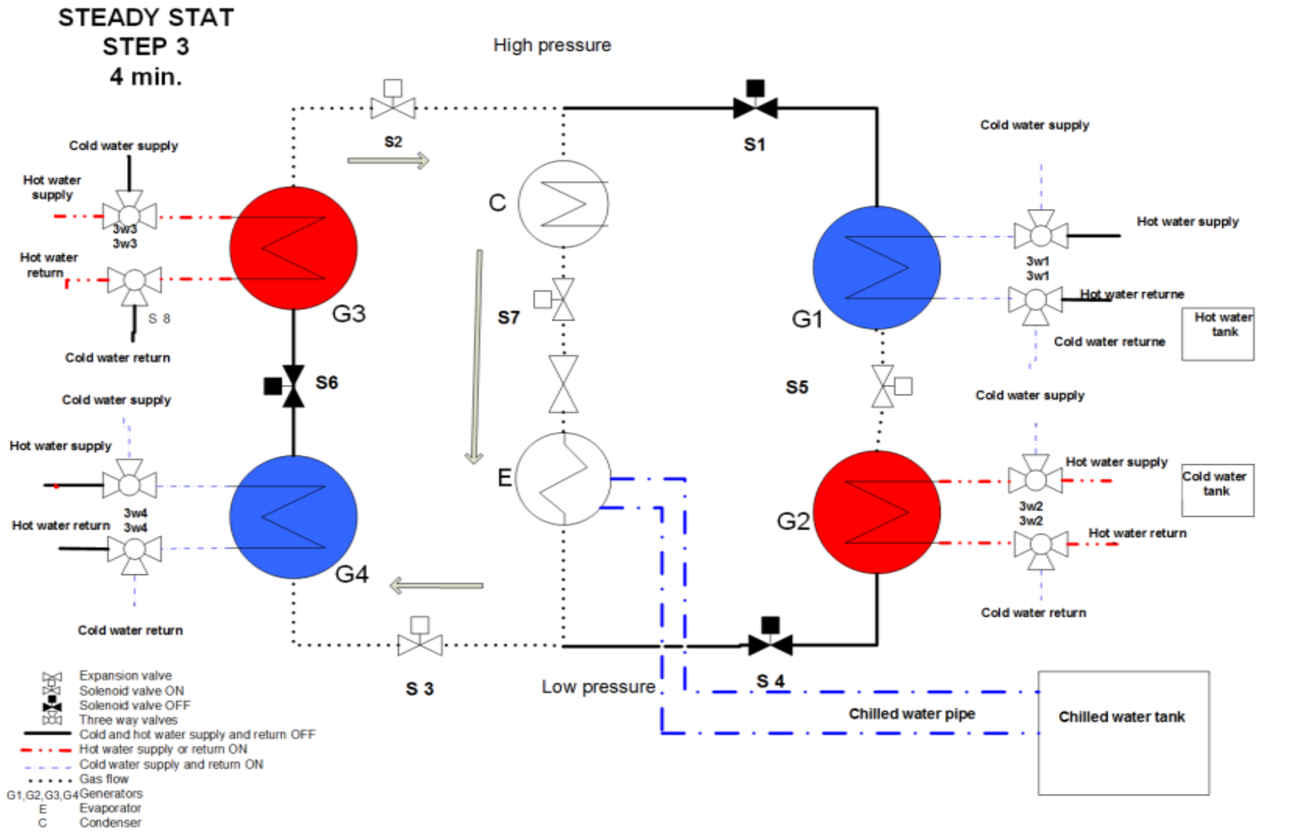

Fig.9 Steady state process (Step 3)

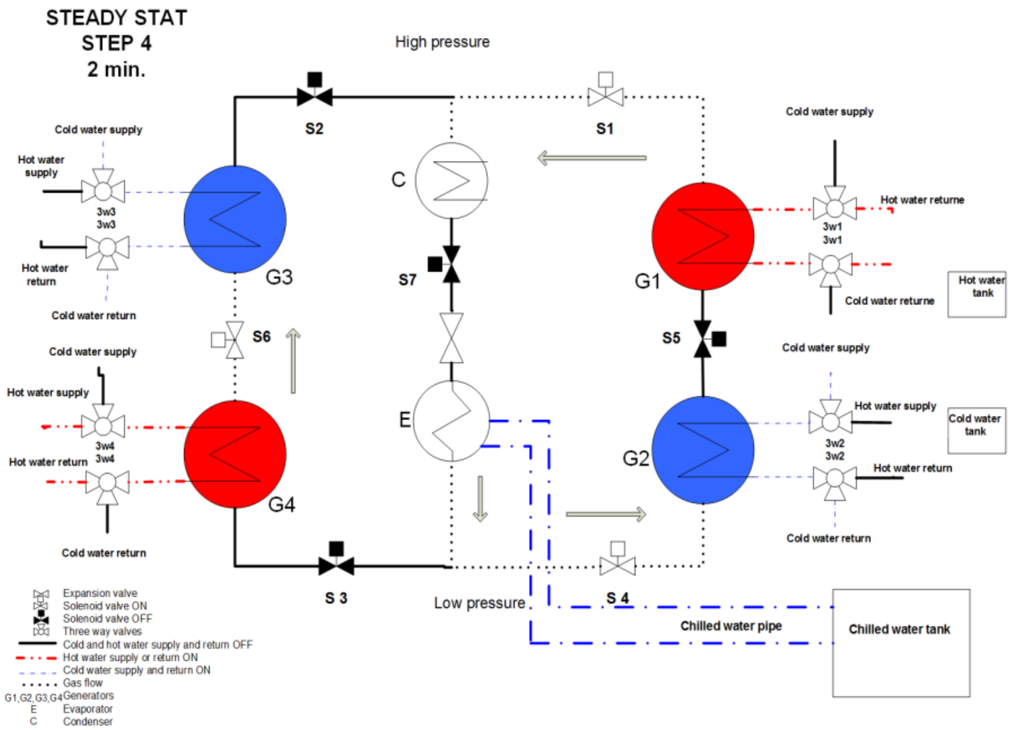

Fig.10 Steady state process (Step 4)

The fourth process: is just mirror the second process of the steady state cycle. The time required for this process is about (2) min its intermediate process, solenoid valve (S7) is off. The fourth process is prepared for the there'd round of cooling process, in which generator (G1) supplies condenser by methanol vapour through solenoid valve S1, while generator (G4) supplies generator (G3) by methanol vapor through solenoid valve (S6), at the same time generator (G2) continues in receiving vapor from evaporator through solenoid valve (S4). The time required for this process is about 2 min. Fig. (10) Shows the fourth process of the steady state operation cycle.

3. Basic Theoretical Model for Two Stages, Four Generators Adsorption Chiller

For Single generator or two generators adsorption cycles the Pressure, Temperature diagrams and the relation with the concentration of the refrigerant are well known and can be seen in References (L.W.Wang *et al.*, 2009; R.Z. Wang, 2002; R. Wang *et al.*, 2014). However, for the two stages four generators cycle, we present the following diagrams to explain it.
As described in the working cycles the chiller is consists of four generators heated and cooled in the sequences prescribed in section 2. As there is a symmetry between what happens in (G1) –(G2) pair and (G3) –(G4) pair we will describe the details of (G1)-(G2) pair as shown in Fig. (11). Starting with (from) point (1) on Fig. (11) which represent the pressure and the temperature of the activated carbon-Methanol pair in (G2) at the end of the adsorption stage where the activated carbon is fully saturated. At this stage the pressure of this specific case is around 6 kP while the temperature of the activated carbon is around 30 ᵒC. Then (G2) is heated to point (2) where the pressure increased to 14 kPa and the carbon temperature reached 83 ᵒC. The methanol concentration (x) from (1) to (2) is constant. At this point the solenoid valve between (G2) and (G1) is opened allowing for the methanol to flow from (G2) to (G1) hence reducing the concentration. Then as (G2) is cooled, hence generator pressure and temperature are reduced to point (3) at which adsorption from the evaporator at constant pressure starts until the activated carbon temperature reaches that of point (1) and the cycle in (G2) is then repeated.

Next the pressure and temperature of Generator (G1) is discussed:

Starting from point (6) in Fig. (11) where the solenoid valve between (G1) and (G2) is open. At this point the methanol vapoure flows from G2 to G1 while cooling G1 until G1 reaches to point (5) at the temperature of 30 oC and Pressure of 14 kPa. At this stage the activated carbon in G1 will have maximum concentration and have adsorbed all the methanol desorbed from G2. At this point the valve between G1 and G2 is closed and G1 is heated until the carbon reaches the temperature of 83 oC at point (4). The concentration between points (5) and (4) is constant. At point (4) the methanol is at 35 (or 40) kPa which can be condensed at 43 or 50 ᵒ C). At this stage the solenoid valve between G1 and the condenser is opened allowing for the Methanol to be flown out of G1 and get condensed for the refrigeration cycle. Hence the condensed methanol is throttled through the expansion valve to the evaporator completing the refrigeration cycle.

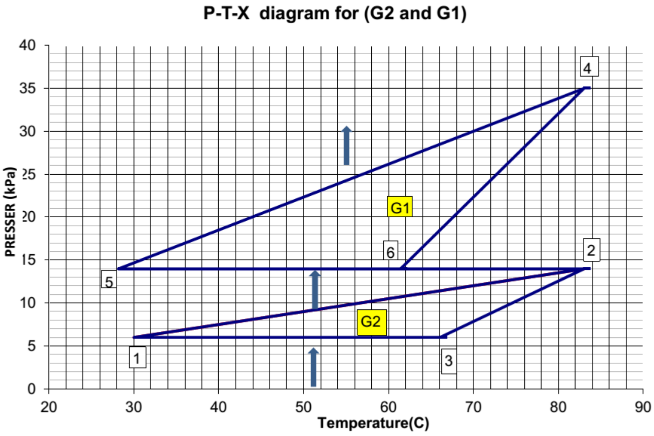

Fig.11 An approximate presentation of the Pressure and Temperature Diagram of the Two Stages Four Generator Adsorption Chiller Cycle

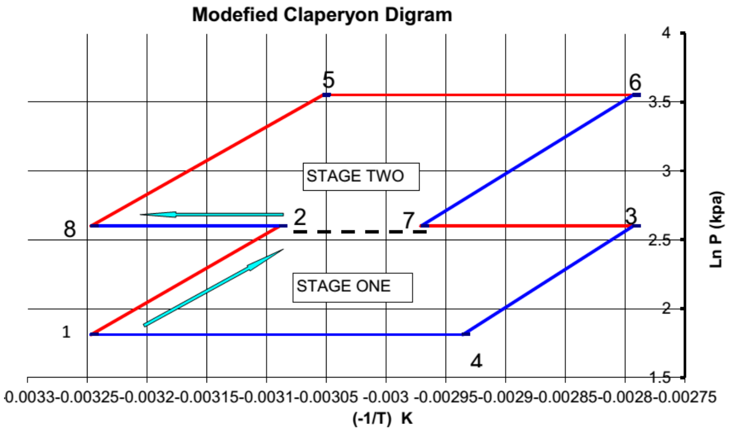

Fig.12 Modified Claperyon diagram (ln P versus -1/T(K) of theoretical cycle for the Two Stages Four Generator Adsorption Chiller Cycle

However, it should be noted that while G2 is going in the pressurizing stage between points (1) and (2), generator (G4) is going through the adsorption stage between points (3) and (1) but on the other side of the chiller. Similarly, as G1 goes through the compression stage between points (5) and (4), generator (G3) is going the desorption stage allowing methanol to flow to the condenser similar to the case between (4) and (6). As such, the refrigeration cycle is a continuous cycle where when on side adsorbs from the evaporator the other side desorbs to the condenser and vice versa.

A famous presentation of the Pressure Temperature Diagram is the Claperyon Diagram where the (ln P) is plotted against -1/T hence transforming equation (1) into a linear equation where constant x is a straight tilted line. This Diagram is known for single and tow generators system. However, we present in Fig. (12) a modified Claperyon Diagram for the Two Stages Four Generator Adsorption Chiller Cycle. Unlike Fig.(11) Fig.(12) represents the cycle in the entire chiller and not in each separate generator.

It should be noted that in this theoretical model that the steady state conditions are calculated and the transient process is not considered as it is beyond the scope of this investigation. As such, the steady state design conditions for this cycle are as follows:

1) Condenser Pressure about 35 kPa, at saturation temperature of about 40oC..
2) Evaporator pressure about 6 kPa, at saturation temperature of about 7oC.
3) Intermediate Pressure in the regeneration stage about 14 – 14.5 kPa.
4) Hot water temperature is 93^{o}C, assuming that the temperature of activated carbon is 10^{o}C degrees lower than the hot water temperature; i.e. the maximum carbon temperature is 83 ^{o}C.
5) Cold-water temperature is 25^{o}C, assuming that the temperature of activated carbon is 5^{o}C higher than water temperature, then minimum carbon temperature is 30 oC.

Starting from the point where any two parameters (P and T, or x and To) are known in fig.(10). Let's the starting point is point 1.

Point 1 is the end of the adsorption methanol from the evaporator by generator (G2), at this point, the carbon temperature (T) is the minimum carbon temperature that equals to 30oC. The pressure of generator (G2) is 6 kPa. as evaporator pressure. Hence from the modified DR equation (1) the concentration of methanol in generator (G2) can be calculated.

$$x = x_o \exp\left[-k\left(\frac{T}{T_{Sat}} - 1\right)^n\right] \qquad (1)$$

Where:

x adsorption capacity (kg-adsorbate/kg adsorbent) at the adsorbent temperature K.

x_o saturate adsorption capacity (kg-adsorbate/kg-adsorbent)

T_s the saturated temperature of refrigerant K

(K) and (n) are adsorption parameter for different refrigerant,

(T) adsorption temperature K,(. K.Sumathy *et al*., 2003).

From the experimental work the values of constants of equation (1) can be found as, xo = 0.284, K = 10.21 and n = 1.39, the concentration of methanol in generator (G2) X1 can be calculated as 0.228 kg methanol/ kg carbon

Point -2 is the end of the regeneration stage as methanol goes from (G2) to (G1). The pressure is 14 kPa that is the intermediate pressure, and the carbon temperature is 83°C that is the maximum temperature. From equation 1, methanol concentration at point 2 is 0.0994 kg methanol/ kg carbon

Point -3- As G2 is cooled down its pressure drops to evaporator pressure or lower. Up to this point there is no desorption or adsorption process occur, since the non-return valves prevent methanol to flow to or out from (G2), hence the concentration of methanol in carbon in (G2) is constant, then x3= x2= 0.0994 kg/kg. The concentration and pressure at point 3 are known, The temperature at point 3 can be calculated from equation 2 (H.Sato *et al*., 1997) bellows:

$$T = T_{Sat}\left[\left(\frac{\ln\frac{x_o}{x}}{k}\right)^{\frac{1}{n}} + 1\right] \qquad (2)$$

T3 = 65 °C.

When the cycle of G2 backs to point 1, the amount of methanol adsorbed from the evaporator can be calculated as follows:

The amount of methanol adsorbed from evaporator = mass of carbon × (X1 − X3)

Each generator contains 6 kg of activated carbon.

The amount of methanol adsorbed from evaporator = 6 × (0.228 − 0.0994)

amount of methanol adsorbed from evaporator = 0.77 kg Methanol evaporation =1180 kJ/kg

Time of cycle = 6.5minutes

$$\text{Average cycle Power} = 1180 \times \frac{0.77}{(6.5 \times 60)}$$

= 2.33kW

Point -4- Which is the end of the desorption process of (G1) as it desorbs methanol to the condenser. At this point the carbon is at the maximum temperature which is about 83 °C, that is the same as maximum, while the pressure is the same as the condenser pressure, which is 35kPa. The, from equation 1 the methanol concentration at point 4 is:

x4 = 0.1487 kg/kg.

Point -5-: is the end of process of (G1) at which methanol is desorbed from (G2) to (G1). At this point the temperature is the minimum at about 30°C, that is the carbon temperature, and the pressure is the intermediate pressure which is equal to 14kPa, the concentration at point 5 from equation 1 equals to x5 = 0.277 kg/kg.

Point -6-: as G1 cools down, its pressure reduces from P4, but the solenoid valve don't allow methanol to flow in or out from G1until reaches the pressure of G2, or lower P4 is the intermediate pressure (14kPa). Then, the concentration at point 6 equals that at point 4 (X6 = X4). Since both the values of pressure and concentration are known, then the temperature at point 6 can be calculated from equation 2, at it is equals to: T6 = 60 °C.

The amount of methanol dsorbed from G1 to condenser = mass of carbon × (X5 − X4) = 6 × (0.277 − 0.148) = 0.77kg

That is 0.77kg of methanol is desorbed from G1 and condensed while 0.77kg of methanol adsorbed by G2 from the evaporator, the cycle is balanced.

4. Theoretical and Experimental Results

In addition to the calculations show in Section 4 above an adsorption refrigeration cycle is built as shown in Fig. (1 and 2). Digital pressure sensors are placed on each generator and temperature sensor on the inlets and outlets of each inner radiator. Furthermore, flow rate and temperature of chilled water is measured. From these data both the cooling capacity and the COP of the chiller is calculated and the results are depicted as below.

Fig. (13) Shows the comparison of the pressure for generators (G3) and (G4) with time, for both experimental and theoretical results. It can be seen from the figure that generator (G3) works between high and low pressures of the cycle, while generator (G4) works between intermediate and low pressures of the cycle. The figure shows that the trends of both generators for theoretical and experimental results are the same and the peak value of the experimental results actually reaches the predicted value of the theoretical result since the theoretical model does not take into account the transient model but rather the steady state case.

The data show in fig. (12) was not for the optimized, practical cycle. The cycle time was 4 minutes and 1 minute for switching. The optimized cycle generator pressure is shown in fig. (13) and demonstrates a smooth and total agreement with theoretical models.

Both theoretical and experimental results show that the methanol maximum pressure in the condenser reaches 40 kPa which allows it to condense at an ambient of 40 ºC while the minimum pressure in the evaporator reaches as low as 7kPa hence the evaporator temperature can reach 7 ºC. This demonstrates that such chiller can operate at high ambient temperature to produce cold chilling temperature with low heating temperature. In general the operating conditions are quite suitable.

What is left to check is the COP (efficiency) of this chiller as shown below.

Effect of cooling water temperature on Cooling capacity and Coefficient of Performance

To demonstrate the effectiveness of such chillers Fig.(14) and (15) Show the effect of cooling water temperature on cooling capacity (CC) and coefficient of performance (COP). The operating conditions of these Figures are as follows:

Hot water inlet temperature is chosen as 83 oC for regenerative four bed two,-stage operation.

-The evaporator temperature is taken to be 7 in one case and 12 ºC in another.

For four bed-two stage operations, cooling capacity (CC) and coefficient of performance (COP) increases as the cooling water temperature is lowered. This result is expected because the lower adsorption temperature the higher the amounts of refrigerant being adsorbed. When the temperature increases cold water delayed adsorption process. This increases the methanol pressure in the generator. Thus, it impeded the flow of methanol vapor from the evaporator to the generator so that the amount of methanol separated will be reduced and as a result increase pressure system. And increasing saturated temperature show this phenomenon clearly in Fig. (14 ,15) and can be seen cooling powerless rapidly with increasing temperature the water.

Quantitatively, a cooling capacity of 3 kW was reached at 25 ºC cooling temperatures and 12 ºC evaporator temperature. This is a good value as compared with silica gel adsorption chillers for example. What is interesting is the measured COP. At 25 ºC cooling water temperature and 12 ºC evaporator temperature the COP reached 0.5 which is near commercial silica gel adsorption chillers rage. Howerever, at 35 ºC cooling water the COP reaches more than 0.4 while commercially available silica gel chillers cannot operate or operates at much lower COP. However, for cooling water temperature of 45 ºC the COP is still above 0.3 while no known silica gel adsorption chillers are known to operate. Even for the extreme cooling water temperature of 50 ºC the chiller still operates although at a low COP of 0.1

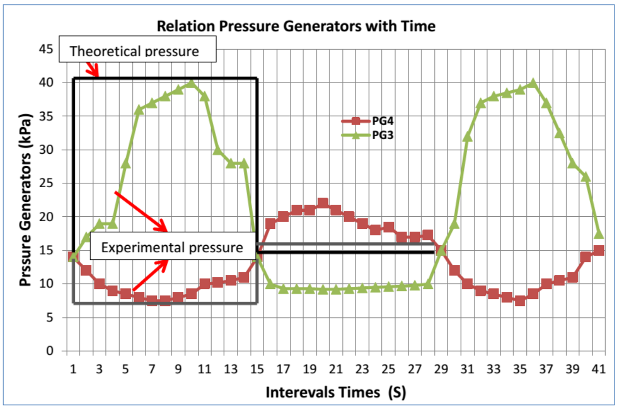

Fig.13 Comparison between Pressure predictions of real cycle with that of the theoretical model

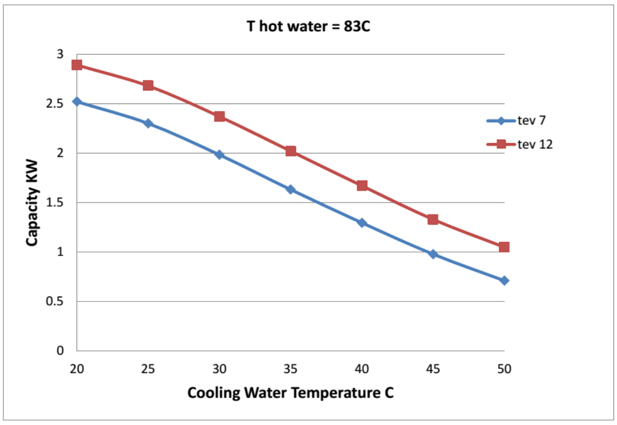

Fig.14 Variation of Chiller capacity with cooling water temperature for evaporator temperatures of 7 º C and 12 º C. Hot water temperature is 85 º C

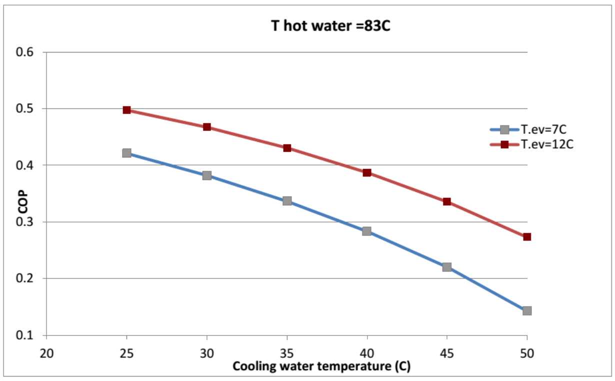

Fig.15 Variation of the Coefficient of Performance (COP) with cooling water temperature for evaporator temperatures of 7 ºC and 12 ºC. Hot water temperature is 85 ºC

Conclusion

1- Two stage four bed adsorption unit can give continue cooling effect, contrary to single bed adsorption unit with acceptable low evaporator temperatures at high ambient conditions.

2- Using two stage process increases the amount of refrigerant in the second stage (concentration, of methanol), in the desorption process lead to improving the cycle COP and CC.

3-The optimum cooling effect obtained in this work, theoretical and experimental is 2.33kW and 1.98 kW respectively, when the evaporator temperature is7 ^oC, condensing temperature is 40oC, cold water temperature of 25oC and hot water is 83^{o}C.

4- Compared to commercially available silica gel, single stage adsorption conditions the present system is more superior at high temperature conditions where it operates at COP of 0.41 at cooling water temperature of 35 ^oC and can still provide cooling even at cooling water temperature of 50 ^oC.

References

L.Lucas,(1988), IIR news, *International Journal of Refrigeration,*21,87-88.

A.Elsafty, A.J.Al-Daini, (2002), Economical comparison between a solar-powered vapour absorption air-conditioning system and a vapour compression system in the Middle East, *Renewable Energy,*25,569-583.

N.S.Edward, R.Reinhard, (1999) Performance analysis of a Combined Desiccant Absorption Air-Conditioning System*, HVAC&R Research,* 5,77-84.

C. Hildbrand P. Dind, M. Pons, F. Buchter, (2004), A new solar powered adsorption refrigerator with high performance, *Solar Energy*, 77,311–318.

K.Sumathy, K.H.Yeung, L.Yong, (2003), Technology development in the solar adsorption refrigeration systems, *Progress in energy and combustion science* 29,301-327.

H.Sato, K.Tanaka, S.Honda, S.Inous, M. *Terao, (1997), Adsorptive type refrigeration apparatus,* Patant No. US5619866.

H. Sato, , K.Tanaka, S. Honda, , K.Fujiwara, , Y. Tanaka, (1998),Adsorptive-type refrigeration apparatus, Patent No. US5775126.

B.B. Saha, S. Koyama, T. Kashiwagi, A. Akisawa, K.C. Ng, H.T. Chua, (2003),Waste heat driven dual-mode, multi-stage, multi-bed regenerative adsorption system, Int.J.Refrig., 26,749–757.

K.C. Ng, K. Thu, A. Chakraborty, B.B. Saha, W.G. Chun, (2009), Solar-assisted dual-effect adsorption cycle for the production of cooling effect, Int. J. Low-Carbon Tech,4,61–67. and potable water

N.M. Khattab,(2006), Simulation and optimization of a novel solar-powered adsorption refrigeration module, Solar Energy, 80,823–833.

A.A.S.Al-Maaitah, A.A.Al-Maaitah,(2013), Two-stage low temperatue air cooled adsorption cooling unit, patent No.: US8,479,529 B2.

L.W.Wang, R.Z. Wang, R.G. Oliveira,(2009), A review on adsorption working pairs for refrigeration, Renewable and Sustainable Energy 13, 518-534.

R.Z. Wang, (2001),Adsorption refrigeration research in Shanghai Jiao Tong University, Renewable and Sustainable Energy , Energy Review,5 , 1-37.

R. Wang, L. Wang, J.Wu,(2014), Adsorption refrigeration technology: theory and application, John Wiley & Sons, Singapore.