The Iraqi Journal For Mechanical And Material Engineering, Vol.18, No.4, Dec, 2018

THEORETICAL ANALYSIS ON THE PERFORMANCE OF BRANCHED GAX CHILLER CYCLE

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ABSTRACT

In this study, a branched GAX absorption cycle operating with NH_3-H_2O pair has been investigated to assess its performance under steady state conditions. The cycle modeling is implemented using Engineering Equation Solver (EES) software. Analysis includes equations of mass, species and energy conservation. The analysis is used to simulate a GAX absorption chiller utilization for air conditioning applications with a nominal capacity of 95 TR. This chiller uses solar collectors as heat source. The operating parameters are selected at different values of the heat source temperature (140 - 185°C), condenser exit temperature (30 to 48°C), evaporator exit temperature (2 to 11°C) ; split ratio (0 to 0.18); the difference in ammonia concentration(0.25-036), mass flow rate in solution pump m_r=1 kg/s; heat exchanger effectiveness $\varepsilon =$ 0.8. The results showed that the average COP is sensitive to operating conditions where the average COP and cooling capacity of the branched GAX absorption chiller increase with increasing generator and evaporator temperature whereas they decrease with increasing condenser temperature. Simulation results also show that the split ratio and ammonia concentration difference have a significant impact on the performance of absorption chiller.

Keywords: Branched GAX absorption cycle, EES software, COP, thermodynamic analysis.

تحليل نظري لأداء دورة مثلج ماء امتصاصي من نوع مبادل حراري(مولد- ماص) فرعي

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الخلاصة

في هذه الدراسة، تم تحليل دورة امتصاص من نوع مبادل حراري(مولد- ماص) فرعي تعمل بمحلول آمونيا وماء في ظروف مستقرة. تم تنفيذ الموديل الحسابي لهذه الدورة باستخدام برنامج (EES). ويشمل التحليل معادلات الكتلة والعينة وحفظ الطاقة. ويستخدم هذا التحليل لمحاكاة دورة مثلج ماء لتطبيقات تكييف الهواء بسعة تبريد قدرها (95) طن تثليج. وكما يستخدم هذا المثلج المجمعات الشمسية كمصدر للحرارة. وكذلك تم اختيار ظروف تشغيلية عند قيم مختلفة من درجات الحرارة لتقييم أداء هذا المثلج وكانت كالآتي: درجات الحرارة الخارجة من المولد(140^oC إلى 185^oC)، درجات الحرارة الخارجة من المكثف (30^oC الى 48^oC)، درجة حرارة الخارجة من المبخر ؛(2^oCالى11^oC) نسبة الانقسام (0؛الى ٠ 0.18)الفرق في تركيز الأمونيا،(0.25 الى 0.36)عدل التدفق الكتلي لمضخة المحلول عند 1 كغم / ثانية؛ فعالية المبادل الحراري عند 0.8. وأظهرت النتائج أن الظروف التشغيل كانت عامل مؤثر على معامل أداء الدورة حيث يزداد متوسط معامل أداء و سعة التبريد للدورة مع زيادة درجة حرارة المولد و المبخر في حين أن أدائها ينخفض مع زيادة درجة حرارة المكثف. كما أظهرت نتائج المحاكاة أن نسبة الانقسام وفرق تركيز الأمونيا يؤثران بشكل كبير على أداء مثلج.

الكلمات المفتاحية: مثلج ماء امتصاصي من نوع مبادل حراري(مولد-ماص) فرعي، برنامج EES، معامل أداء، تحليل ثرموديناميك.

Received: 2018 - 1 - 15
Accepted: 2018 - 1 - 24

Nomenclature		O	Outlet
C	Specific heat capacity (kJ/kg.K)	S	Strong solution
H	Enthalpy [kJ/kg]	R	Refrigerant
M	Mass flow rate [kg/s]	W	Weak solution
P	Pressure(kPa)	**Abbreviations**	
Q	Heat transfer rate(kW)	AHX	Absorber Heat Exchanger
T	Temperature (C)	COP	Coefficient of performance
W	Work (kW)	EES	Engineering Equation Solver
X	Species concentration	GAX	Generator-Absorber heat exchanger
Greek symbols		HE	Heat exchanger
ϵ	Effectiveness	H_2O	Water
Subscripts		NH_3	Ammonia
Abs	Absorber	SHX	Solution heat exchanger
Co	Condenser	TV	Expansion valve
Ev	Evaporator		
Gen	Generator		
In	Inlet		

INTRODUCTION

The ammonia-water GAX chiller is adopted in numerous applications such as space cooling, space heating and refrigeration. This chiller type has more advantages than others such as it has no crystallization risk and also it is appropriate for utilization in a medium temperature solar collector. Another advantage of this chiller, it uses for low temperatures in ranging from 5ºC down to -60ºC, which are useful for industrial cold processes. On the other side, the main disadvantage of this chiller needs to high driving temperatures (**Sabatelli et al., 2007** and **Wang et al., 2009**).

Recent research activity on absorption refrigeration shows that the increasing number of effects and stages leads to rise the cycle efficiency (**Eicker, 2009**). But, the increasing the number of heat exchangers in these cycles produces to increase of both cost and complexity. The solutions of these problems are using generator-absorber heat exchanger (GAX) cycles. These cycles are similar to a single stage cycle and it have possible to improve performance of these cycles. However, it is not easy to improve the heat transfer between the generator and absorber, which is complicated in GAX cycles.

Engler et al., 1997 defined the split ratio (SR) of the branched GAX cycle to be the mass flow rate ratio between the recirculated stream and the total stream in the absorber (i.e. the high temperature end). Therefore, the conventional GAX cycle (no branch) would have an SR of 0 , while a GAX cycle with one branch recycling the entire flow would have an SR of 1.0. For an ammonia-water branched GAX cycle with evaporator exit temperature of 10°C, condenser exit temperature of 42.2°C, and generator exit temperature of 195°C. The authors found that a branch is only useful with SR between 0.0 and 0.65. Maximum performance occurs when SR = 0.3 with a COP of 1.08. For the equivalent GAX cycle without branch, they show a COP of 1. The improved thermal performance of the branched GAX cycle is somewhat offset by the increased electricity needed for the second pump. **Erickson et al., 1996** characterize another performance limitation in the ammonia-water branched GAX cycle. In an experimental comparison of a basic and a branched GAX cycle, both cycles are operated at a cooling capacity of 14.6 kW and a lift of 38.9°C. They found the steady-state basic GAX COP to be 1.06, while the branched GAX COP was only 1.04. The poor performance of the branched GAX is attributed to sub-cooling in the absorber. Sub-cooling has a greater penalty for the branched GAX cycle, as the cooler liquid is recirculated, which negates the benefits of the branch. **Erickson et al., 1996** developed prototype of air-cooled GAX chiller with a cooling capacity of 10.6kW and worked by both natural gas and solar energy. The chiller was attained COP of 0.86. **Garimella et al., 1996**, **Grossman et al., 1995** and **Grossman and Zaltash,**

2001 have using modular simulation tool for absorption cycles which is called ABSIM to design and to estimate the performance of GAX heat pumps. **Velazquez and Best, 2002** designed NH_3-H_2O absorption heat pump with an air cooled GAX worked by a hybrid natural gas and solar energy. The their heat pump has capacity of 10.6 kW. The results of their analysis indicated that the efficiency of the heat pump is reduced with an increase in the temperature difference between condenser and evaporator.

A few researches on the GAX cycles has been carried out in simulation programs. So, this study aims to simulate and evaluate different variables of operation conditions affect branched GAX cycle in detail.

branched gax cycle description and working principle

Branched GAX absorption cycle uses water (H_2O) as the transport medium (absorbent) and ammonia (NH_3) as the refrigerant. It usually constructs from an ordinary GAX absorption cycle absorption with an added second solution pump to increase the mass flow rate at the absorber, especially in the high temperature portion. As shown in **fig. 1**, it constructs from one generator with GAX-G, condenser, two solution pump, rectifier, one pre-cooler, absorber with GAX-A, evaporator, and two throttling valves. These components are connected in two closed loops. These loops are as following: the first loop for aqueous ammonia solution (H_2O-NH_3) consisted from Generator, GAX-generator, Absorber, GAX-absorber (GAX-A), two solution pumps and solution throttling valves while the second loop for the absorbent (NH_3) consisted from rectifier, condenser, pre-cooler, throttling valve and evaporator. On the other side, the auxiliary systems are connected to chiller cycle which are as following:

1- Solar collector connected with generator to heat and maintain hot water supply temperature,
2- Air-cooled system to cool the refrigerant for both the condenser and absorber,
3- System consisted of storage tank and air-handling unit to conditioning space below ambient conditions which is typically installed outside the buildings.

The Branched GAX absorption chiller has high and low pressure and two sorbent circulation paths with constant pressure. The heat coming from both the GAX-absorber and from the external source to both GAX-generator and generator, respectively is transferred to the solution where it is liberated ammonia vapor from the solution. The hot ammonia vapor exiting from generator is cooled into the rectifier (state point 5) and part of the water condenses and moves to the absorber (state point 4)after passing through the throttle valve. The hot ammonia vapor is supplied to the condenser (state point 7) where it condenses into a liquid at high pressure by removing heat to the cold surroundings. The liquid ammonia from the condenser (state point 8) exchanges the heat through precooler (state point 10) where it is cooled and throttles to the evaporator at low pressure and temperature (state point 10). After that the refrigerant (ammonia) boils by absorbing heat from the water circulated between the evaporator and the conditioning space (i.e. cooling output). The refrigerant vapor in the evaporator moves back into the pre-cooler in order to be heated before entering to absorber (state point 12). The strong solution is pumped to the absorber by a solution pump where it is preheated and then it enters the generator. On the other hand, the strong solution is also pumped by another solution pump to the generator which increases flow rate in the high temperature section of the generator. The results increases the cycle performance as well. The cycle is completed.

MATHEMATICAL MODELING

Some assumptions are made to simplify the model:
1-The model is done under steady state conditions.

2-The kinetic and potential energies are neglected.
3-Pressure losses are negligible in all components of the cycles.
4-The NH_3-H_2O solution at the absorber exit is a strong solution.
5-The ammonia leaves both evaporator and condenser at saturated vapor and liquid states, respectively.
6- Saturated vapor leaves the rectifier
7- The initial state of water inside the system is at an environment temperature of 25 °C and pressure of 1 atm.
8-The system is worked by the solar energy and the system produces chilled water,.

The general equations of these principles are specified as

Mass balance

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

Species balance

$$\sum (\dot{m}X)_{in} = \sum (\dot{m}X)_{out} \tag{2}$$

Energy balance

$$\sum \dot{Q} + \sum \dot{W} + \sum \dot{m}_{in} h_{in} - \sum \dot{m}_{out} h_{out} = 0 \tag{3}$$

The split ratio (*SR*) is defined as the flow ratio between the branch stream and the maximum stream in the absorber and is given by:

$$SR = \frac{m_{15}}{m_1} \tag{4}$$

The cooling mode coefficient of performance (COP_c) for absorption cycle is given by the following formula

$$COP_c = \frac{Evaporator\ load}{Energy\ \ input} = \frac{Q_{Ev}}{Q_G + W_{p1} + W_{p2}} \tag{5}$$

Component Analysis

The cycle was treated as an independent element for each component with a certain number of input values. The components of GAX absorption chiller with their state points can be depicted in **fig. 2**. The components are: (1) Generator, (2) Absorber, (3) Precooler, (4) Evaporator, (5) condenser, (6) Rectifier, (7) Solution expansion valve, (8) Refrigerant expansion valve, (9) Solution pump, (10) Solution pump. The mass, species and energy equations can be applied to each components of absorption cycle as shown in **Table 1**.

Model Validation

The theoretical results done by Engler et al., 1997 for the conventional and branched GAX absorption cycle are used to validate the simulation results of present study. The results are compared under steady state operation conditions: evaporator exit temperature of 10°C, condenser exit temperature of 42.2°C, and generator exit temperature of 195°C.The comparative of the COP values is highlighted in **Table 2**. Good agreements were observed between the present results and the presented by Engler et al., 1997.

Simulation model

In this study, a computational program is carried out using EES software (**Klein, 2009**). This program is based on equations of mass and heat balances for the thermodynamic properties of NH_3-H_2O pair. Simulation of one-stage GAX absorption chiller cycle includes inputs and outputs. The inputs of the system include the evaporator exit temperature , generator exit temperature, condenser exit temperature, absorber exit temperature, mass flow rate of refrigerant, and effectiveness of heat exchangers. The outputs include the enthalpies, mass flow rates, ammonia concentrations, temperatures, and pressures at each state points as well as heat transfer rates, cooling capacity, and coefficient of performance (COP).

Simulations are done for a constant cooling load Q_{Ev} = 95 TR, generator exit temperature of 163°C, condenser and absorber exit temperature of 40°C, evaporator exit temperature of 5°C, solution mass flow rate through the first pump 1 kg/s, heat exchanger effectiveness condensate precooler ϵ=0.8 and pump efficiency of 50% . Under these operating conditions, the output parameters (temperature, pressures, vapor quality, flow rate, concentration and concentration) and various state points (1-17) are delineated in **Table 3**. The performance parameters results and heat transfer rates generated by EES for absorption chiller cycle are reported in **Table 4**.

RESULTS AND DISCUSSION

The present study focuses on the effect of generator temperature , evaporator temperature, condenser temperature on the system performance. The results of this cycle are summarizes in Tables (2 and 3)

Effect of generator temperature

The effect of generator temperature on the performance of branched GAX chiller cycle as shown in **fig. 3**. As the generator temperature increases from 140 to 185 °C, the COP of the system increases from 0.87 to 1.225 and also the cooling load increases from 393 kW to 430 kW.

Fig. 4 shows the relationship between the temperature of generator and thermal load of the cycle. It can be found that the heat loads of GAX and both condenser, evaporator are increased linearly with the increase of the generator temperature. Also, the thermal loads of generator and absorber have a contra relation with the increase of temperature generator**.**

Effect of condenser temperature

Fig. 5 shows the effect of condenser temperature on the performance of branched GAX chiller cycle. It is found that the COP of the system decreased from 1.465 to 0.833 as the condenser temperature increases from 30°C to 48°C. As shown in same figure, the cooling load decreases from 502 kW to 413 kW with the same condenser temperature increment.

While in **fig. 6**, all the curves of the thermal loads of generator and absorber increased with the increasing of the temperature of condenser. The two curves of condenser and evaporator load have inversely behavior.

Effect of evaporator temperature

The temperature of evaporator has a different effect on the performance of branched GAX chiller as shown in **fig. 7**. It can be found the COP and cooling load of the system increases from 0.97-1.29 and 435-512kW, respectively as the temperature of the evaporator increased from 2°C to 11°C.

While in **fig. 8**, all the curves of the thermal load of GAX, condenser, generator, rectifier and pre-cooler increase with the increasing of the temperature of generating. The other two curves of generator load and absorber have inversely behavior.

Effect of split ratio (SR)

Fig. 9 shows the effect of split ratio (SR) on the performance of branched GAX chiller cycle. It is found that a branch is only useful with SR ranged between (0-0.124) as the COP increases from 1.1 to 1.16. After this range of SR, the performance starts to decrease to 1.109 with increasing SR to 0.18. Also, the cooling load increased with increasing SR. i.e. the split ratio has the restrictions on the cycle performance.

Fig. 10 shows the relationship between the SR and thermal loads for the cycle. The heat loads of GAX and condenser are increased linearly with increasing SR. The heat loads of both rectifier and pre-cooler slightly increased with SR. While the other loads of generator and absorber have different behaviors.

Effect of ammonia concentration

Fig. 11 illustrates the system COP and cooling load as function of difference in ammonia concentration between rich and weak solution. The system COP and cooling loads increased as the difference in ammonia concentration increased. This is because of the increasing the ammonia (refrigerant) in account of water (absorbent) inside the system.

CONCLUSIONS

In this work, a branched GAX absorption cycle utilizing a NH_3-H_2O solution as working fluid has been investigated under steady state conditions. According to the simulation results, we concluded the following:

1-As the generator exit temperature ranged from 140-185°C, the COP and cooling load of the cycle increased from 0.87-1.225 and 393 kW to 430 kW, respectively.

2-Reducing the condensing temperature as low as possible is incapable of maximizing the chiller COP.

3-A branch is only useful with SR between 0 and 0.124 where the COP increases from 1.1 to 1.16. on the other hand, the cooling load increases with increasing SR.

4-The system COP and cooling loads increase as the difference in ammonia concentration increases.

Table 1: Summary of equations for each component of the cycle.

Components	Mass, spices and energy balances	State points
Generator	$m_2 + m_6 + m_{16} = m_3 + m_5$ $m_2.X_2 + m_6.X_6 + m_{16}.X_{16} = m_3.X_3 + m_5.X_5$ $Q_{GenTot} = m_3.h_3 + m_5.h_5 - (m_2.h_2 + m_6.h_6 + m_{16}.h_{16})$	2, 3, 5, 6, 16
GAX-Generator	$m_2 + m_6 + m_{16} + m_{14v} = m_5 + m_{14l}$ $m_2.X_2 + m_6.X_6 + m_{16}.X_{16} + m_{14v}.X_{14v} = m_5.X_5 + m_{14l}.X_{14l}$ $Q_{GAX-G} = m_5.h_5 + m_{14l}.h_{14l} - (m_2.h_2 + m_6.h_6 + m_{16}.h_{16} + m_{14v}.h_{14v})$	2, 5, 6, 14v, 14l, 16
Absorber	$m_{12} + m_4 = m_1 + m_{15}$ $m_{12}.X_{12} + m_4.X_4 = m_1.X_1 + m_{15}.X_{15}$ $Q_{AbsTot} = m_{12}.h_{12} + m_4.h_4 + m_{17}.h_{17} - (m_1.h_1 + m_2.h_2 + m_{15}.h_{15})$	1, 4, 12, 15
GAX-Absorber	$m_4 + m_{13v} = m_{15} + m_{13l}$ $m_4.X_4 + m_{13v}.X_{13v} = m_{15}.X_{15} + m_{13l}.X_{13l}$ $Q_{GAX-A} = m_4.h_4 + m_{13v}.h_{13v} - (m_{13l}.h_{13l} + m_{15}.h_{15})$	4, 13v, 13l, 15
Evaporator	$m_{10} = m_{11}$ $m_{10}.h_{10} + Q_{Ev} = m_{11}.h_{11}$ $Q_{Ev} = m_{11}.(h_{11} - h_{10})$	10, 11
Rectifier	$m_5 = m_6 + m_7$ $m_5.X_5 = m_6.X_6 + m_7.X_7$ $Q_{Rect} = m_5.h_5 - (m_6.h_6 + m_7.h_7)$	5, 6, 7
Solution pump	$m_1 = m_2$ $W_{p1} = v_1.(p_{17} - p_1)/\eta$ $W_{p1} = m_1.(h_{17} - h_1)$	1, 2, 17
Expansion valve	$h_3 = h_4$ $h_9 = h_{10}$	3, 4, 9, 10
Condenser	$m_7 = m_8 = m_9 = m_{10} = m_{11} = m_{12}$ $Q_{Co} = m_7.(h_7 - h_8)$	7, 8, 9, 10, 11, 12
Precooler	$m_8 = m_9$, $m_{11} = m_{12}$	8, 9, 11, 12
Effectiveness of precooler	$\varepsilon_{PC} = \frac{(T_8 - T_9)}{(T_8 - T_{11})}$	8, 9, 11

Table 2: Comparison of results between the percent study and Engler et al., 1997.

Cycle type	Present Study	Engler et al., 1997	Difference
Conventional GAX cycle	1.05	1.0	4.7%
branched GAX cycle	1.12	1.08	3.5%

Table 3: The computed state point results for the cycle.

State points	Temperature (°C)	Pressure (kPa)	Quality Kg/kg	Mass flow rate(Kg/s)	Enthalpy KJ/kg	Con.(X) (kg/kg)
1	40.0	478.4	0.000	1.000	-60.6	0.489
2	83.7	1548.0	0.000	1.000	139.8	0.489
3	163.0	1548.0	0.000	0.698	607.4	0.140
4	123.4	478.4	0.095	0.698	607.4	0.140
5	83.7	1548.0	1.000	0.435	1440.4	0.984
6	83.7	1548.0	0.000	0.009	139.7	0.489
7	67.3	1548.0	1.000	0.426	1383.3	0.995
8	40.0	1548.0	0.000	0.426	187.3	0.995
9	12.2	1548.0	-0.001	0.426	53.5	0.995
10	3.1	478.4	0.034	0.426	53.5	0.995
11	5.0	478.4	0.940	0.426	1198.0	0.995
12	30.2	478.4	0.993	0.426	1331.8	0.995
13	83.7	478.4				
14	123.4	1548.0				
15	83.7	478.4	0.000	0.124	189.4	0.261
16	84.1	1548.0	-0.001	0.124	191.8	0.261
17	40.4	1548.0	-0.001	1.000	-58.0	0.489

Table 4: The performance parameter results of the cycle.

Parameter	
Q_{abs}(kW)	362
Q_{GAX}(kW)	468.7
Q_{CO}(kW)	509
Q_{Ev} (kW)	487
Q_{gen} (kW)	417
Q_{rect}(kW)	36
Q_{PC}(kW)	57
P_{low}(kPa)	478.42
P_{high}(kPa)	1548
P_{ratio}	3.24
Solution pump, W_p(kW)	2.6
Solution pump, W_{p1}(kW)	0.3
COP(-)	1.16

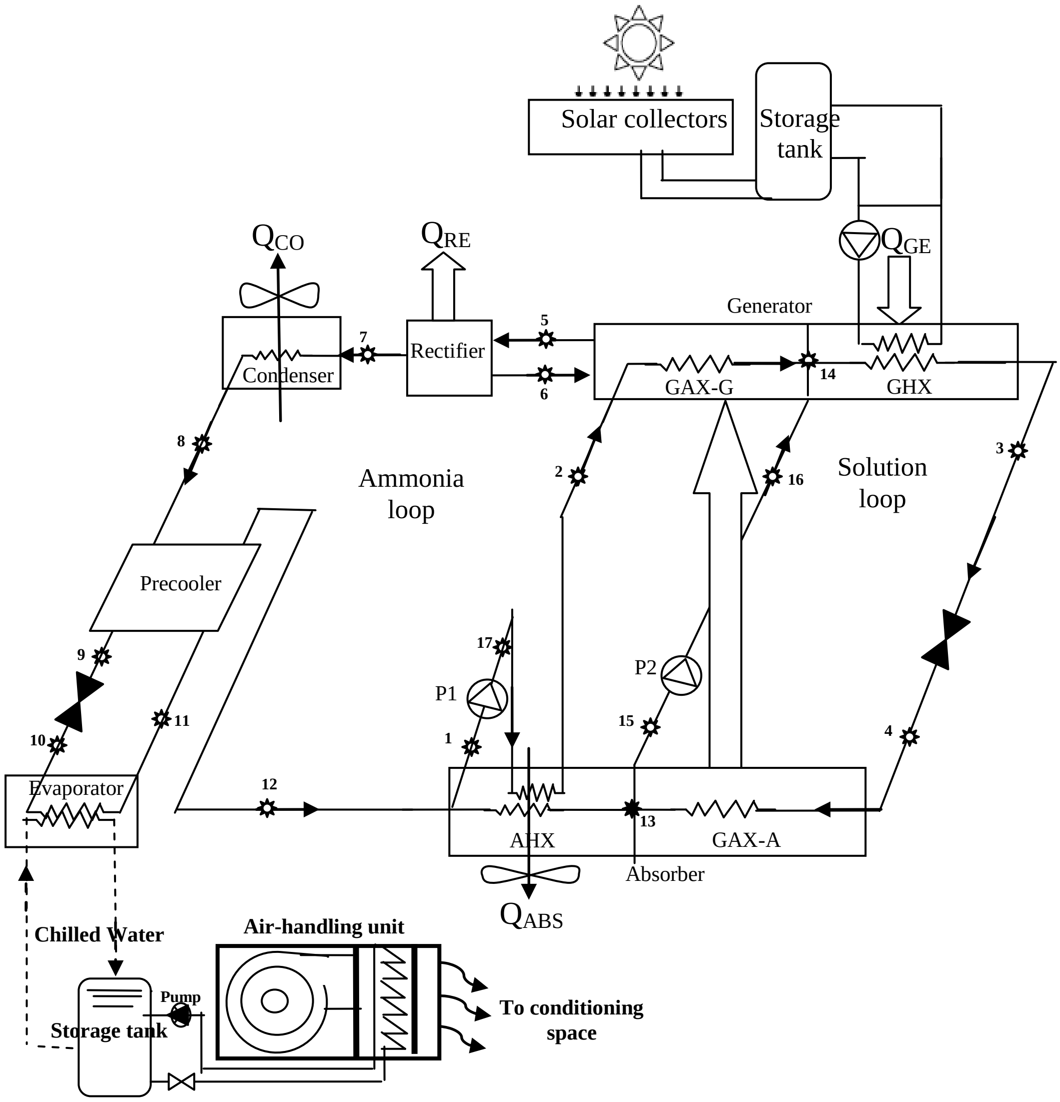

Fig. 1: Block diagram of a branched GAX absorption cycle.

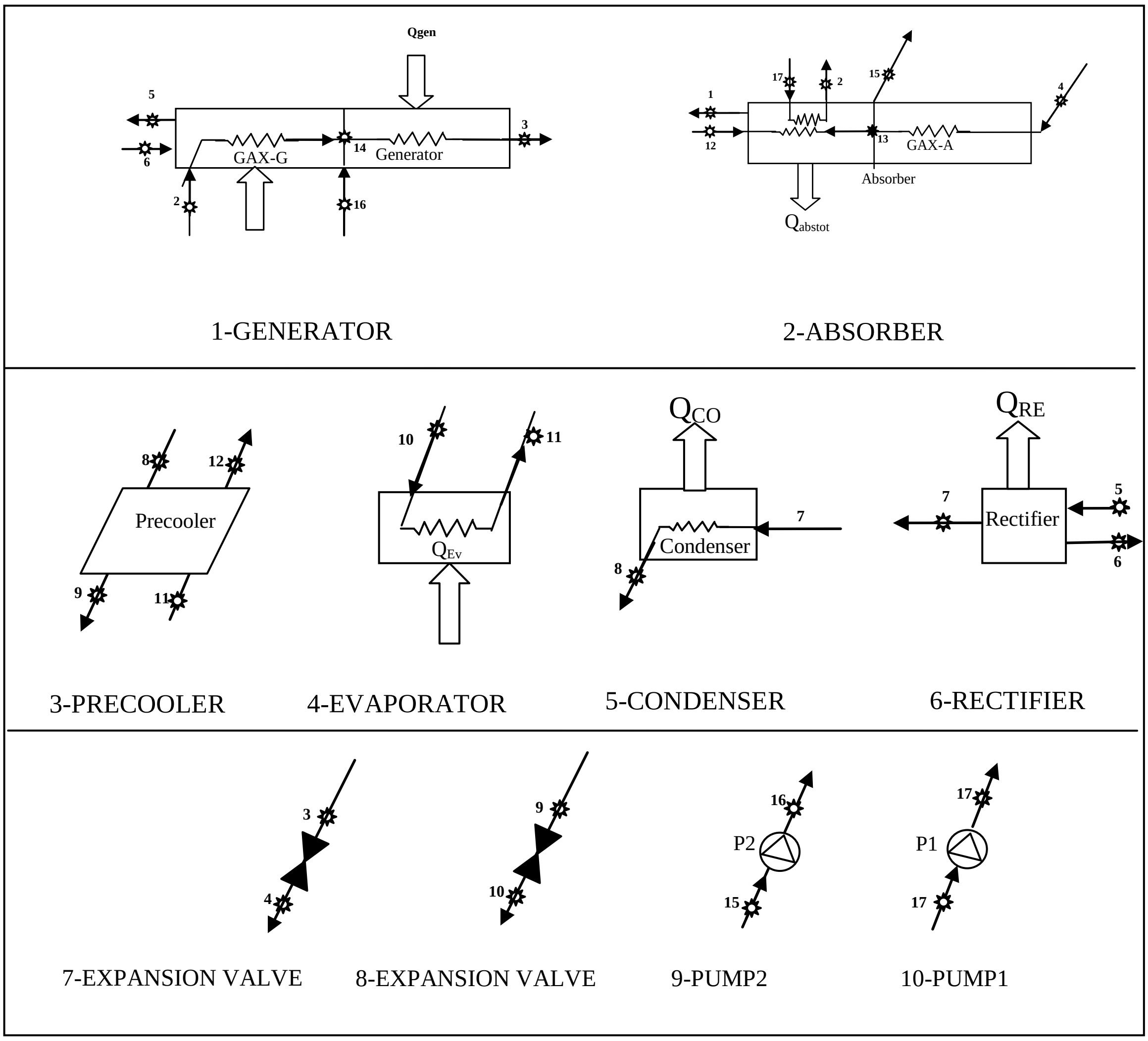

Fig. 2: Sketch of individual components for absorption chiller

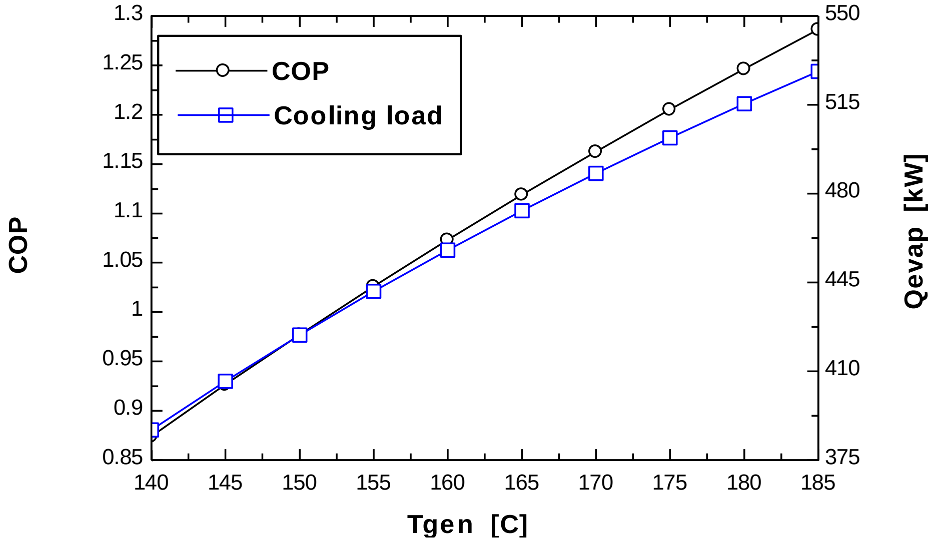

Fig. 3: System COP and cooling load as a function of generator temperature

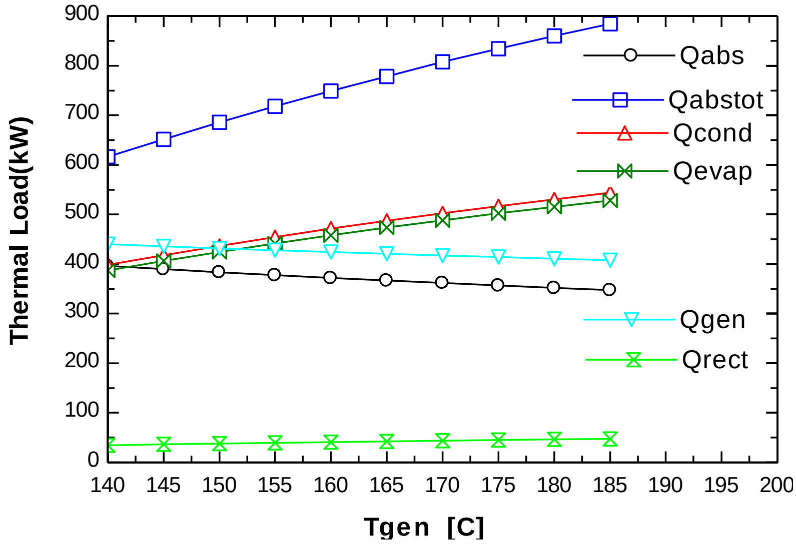

Fig. 4: Thermal loads as a function of generator temperature.

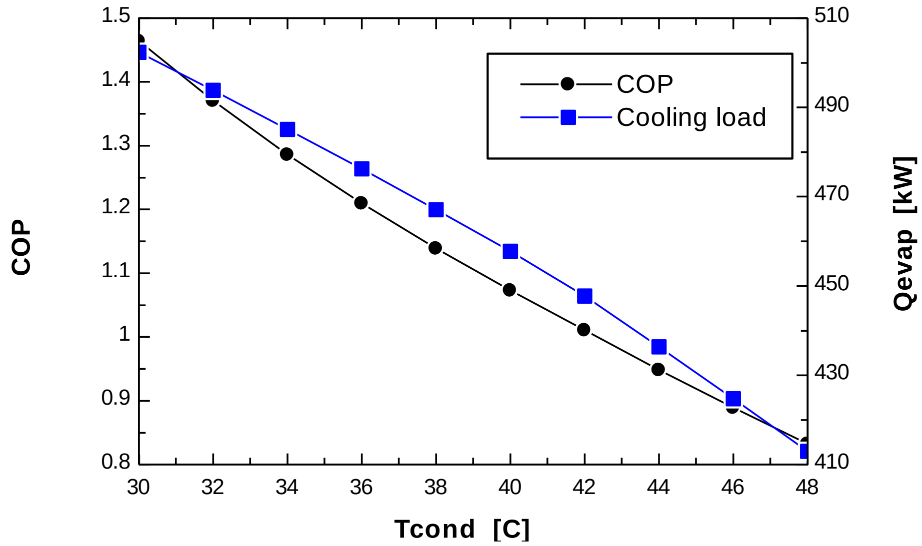

Fig. 5: System COP and cooling load as a function of condenser temperature.

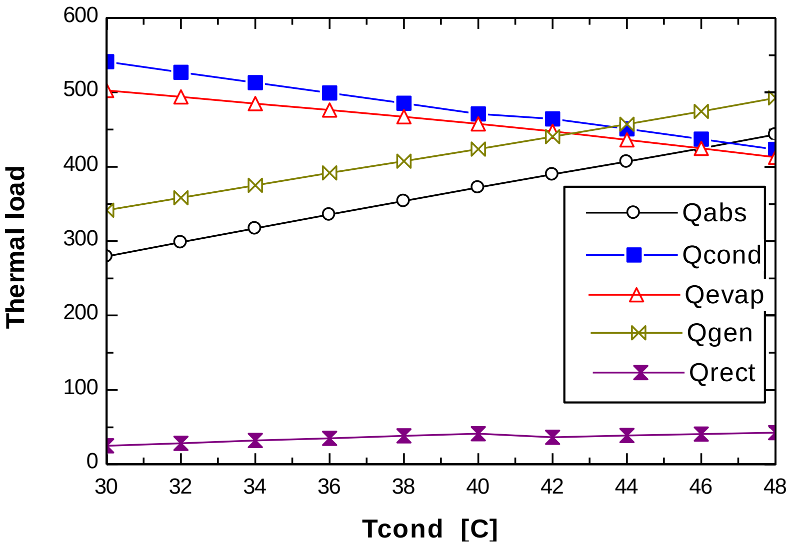

Fig. 6: Thermal loads as a function of condenser temperature.

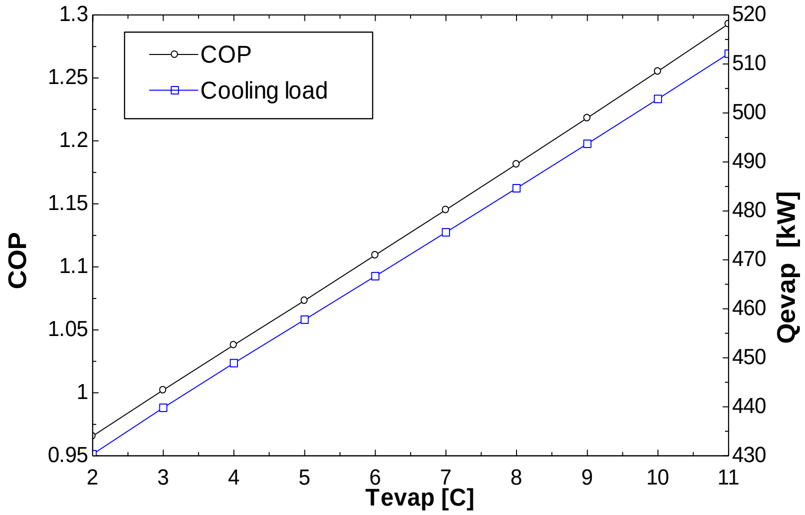

Fig. 7: System COP and cooling load as a function of evaporator temperature.

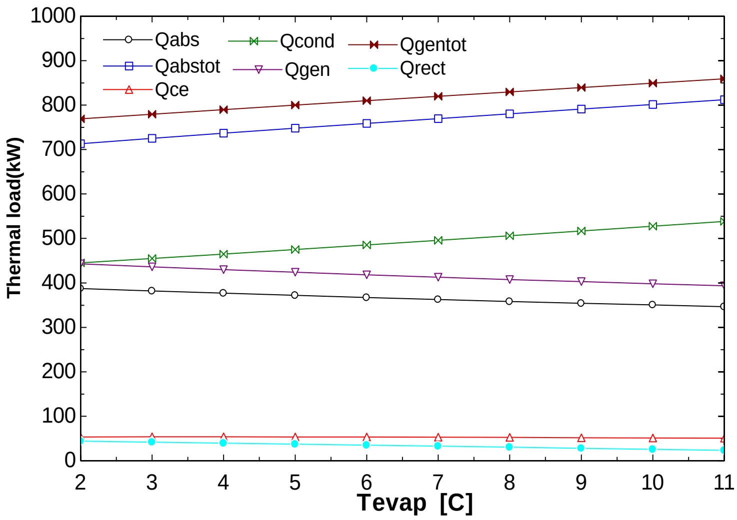

Fig. 8: Thermal loads as a function of evaporator temperature.

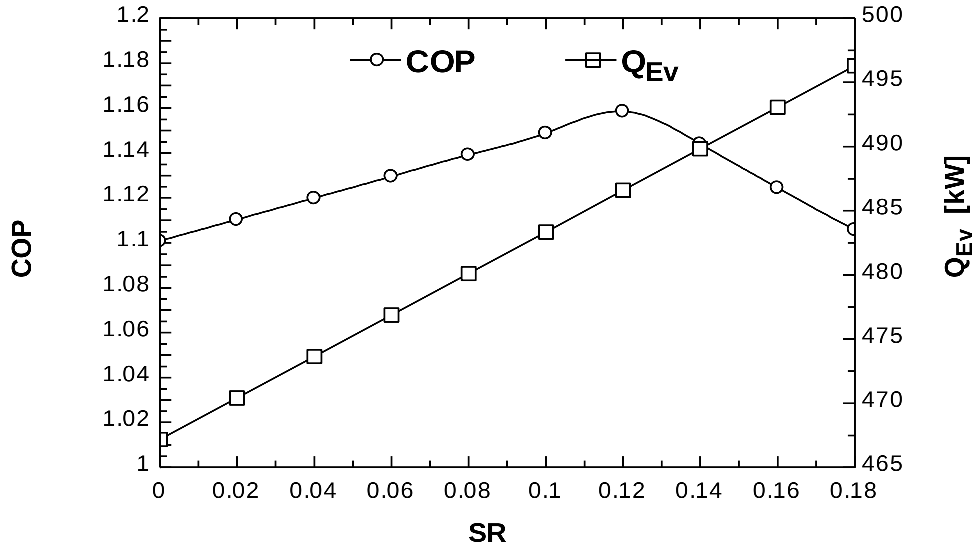

Fig. 9: Variation in system COP and cooling load as a function of SR.

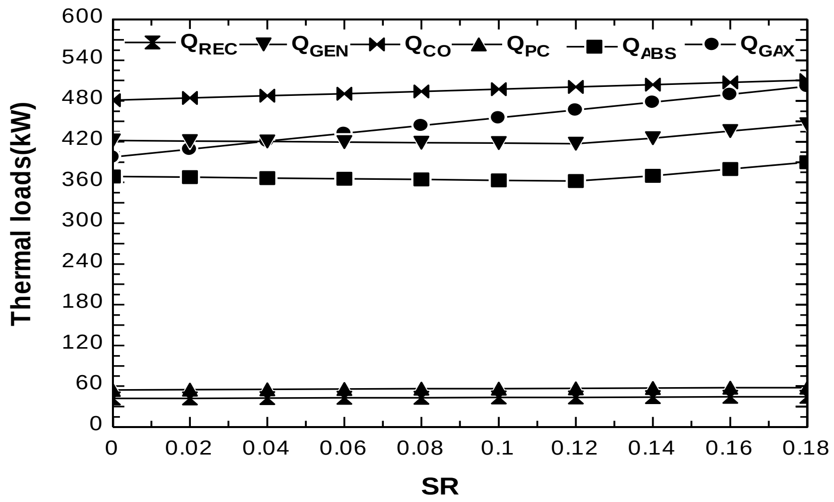

Fig. 10: Variation in system thermal loads as a function of SR.

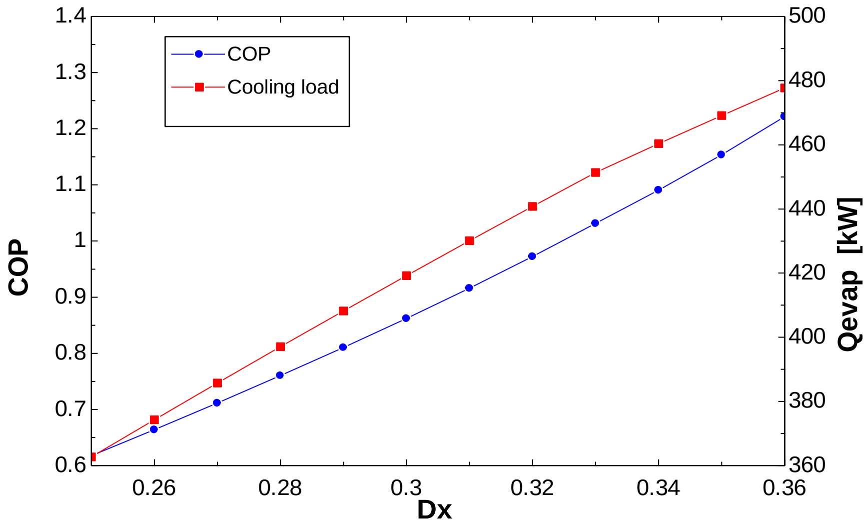

Fig. 11: System COP as a function of concentration difference.

5. REFERENCES

Eicker U. Low energy cooling for sustainable buildings: John Wiley & Sons 2009.

Engler, M., Grossman, G., and Hellmann, H. M., 1997, "Comparative Simulation and Investigation of Ammonia-Water: Absorption Cycles for Heat Pump Applications," International Journal of Refrigeration. Vol. 20, (7), pp. 504-516.

Erickson, D. C., Anand, G., and Papar, R. A., 1996, "Branched Gax Cycle Gas Fired Heat Pump," Energy Conversion Engineering Conference, 1996. IECEC 96. Proceedings of the 31st Intersociety, Vol. 2, pp. 1078-1083.

Garimella S., Christensen R.N., Lacy D., 1996, Performance evaluation of a generator-absorber heat-exchange heat pump. Applied Thermal Engineering, Vol. 16, (7), pp. 591-604.

Grossman, G., DeVault, R.C. and Creswick, F.A. 1995. Simulation and Performance Analysis of an Ammonia-Water Absorption Heat Pump Based on the Generator-Absorber Heat Exchange (GAX) Cycle. *ASHRAE Transactions*, Vol. 101(Pt. 1), pp. 1313–1323.

Grossman, G. and Zaltash, A. 2001. ABSIM—Modular simulation of advanced absorption systems. International Journal of Refrigeration, Vol. 24, pp. 531–543.

Klein, S.A., 2009. Engineering Equation Solver, v8.411. F-Chart Software, Madison, Wisconsin.

Sabatelli, V., Fiorenza, G., Marano, D., 2007. Technical status report on solar desalination and solar cooling. New Generation of Thermal Solar Systems, http://www.swt-technologie.de/html/publicdeliverables3.html.

Velazquez N. , Best R., 2002, Methodology for the energy analysis of an air cooled GAX absorption heat pump operated by natural gas and solar energy, Applied Thermal Engineering, Vol. 22, pp.1089–1103.

Wang R.Z., Ge T.S., Chen C.J., Ma Q., Xiong Z.Q., 2009, Solar sorption cooling systems for residential applications: Options and guidelines, International journal of refrigeration Vol. 32, pp. 638–660.