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"Theoretical and ExperimentalAnalysis forPerformance Evaluation of anActualOperating Absorption Unit"

M. Khalil Bassiouny[1], A. A. Hussien[1], Mostafa El Shafie[2], Noriyuki Kobayashi[3]
[1]*Mechanical Power Engineering Department, Faculty of Engineering, Minoufiya University,Minoufiya,Egypt.*
[2]*Mechanical Maintenance Section Manager,Toshiba El-Araby for Lighting Technology, Quesna, Egypt.*
[3]*Department of chemical Engineering, Nagoya University, Nagoya 464-8603, Japan.*

Abstract*This paper presents a theoretical and experimental analysis for evaluation of an actual lithium-bromide/water direct-fired double effect absorption chiller in parallel flow configuration. The absorption chilleranalyzed in this work is used for air conditioning system and is allocated at El-Araby Company for Lighting Technology-Egypt. This unit is capable of providing a cooling capacity [500 R.T], [1750 kW]. A set of thermocouples used to allow the measurements of the working temperature through all operating chiller components. The measurements have been obtained at different times in July 2013 and in July 2014. A set of mathematical equations have been developed, allowing the estimation of the chiller coefficient of performance and heat transfer rates for each component. Theoretical analysis shows that increasing of thelow and high temperature HEXs effectiveness and decreasing the circulation ratio improved the COP. The experimental analysis presents that the COP value in July 2014 is obviouslylower than valuescalculated in July 2013. Theoretical and experimental analyses have been developed to study the effect of inlet cooling water temperature on the cycle COP. From the experimentalmeasurements, the inlet cooling water is adjusted to be within range [26℃– 33℃] which gives the best working condition of the absorption unit and this is clear from the COP data. Also, the effectiveness of low and high temperature HEXs obtained in July 2013 is higher than the values obtained in July 2014. This indicates that the effectiveness of HEXs is changed with the time of operation from year to year which means that the COP is sensitive to heat exchangers effectiveness. Additionally, this studywill help to identify themaintenance time of the absorption chiller components.*

Keywords:*Double-effect cycle, Absorption chiller, Li-Br/water, Coefficient of performance, Air conditioning***.**

Nomenclature

a	circulation ratio [-]	cw	cooling water
COP	coefficient of performance [-]	e	evaporator
C_p	specific heat capacity at constant pressure [kJ/kg.K]	H.H.E	high temperature heat exchanger
h	enthalpy [kJ/kg]	H.G	high pressure generator
h`	saturated liquid enthalpy [kJ/kg]	h	concentrate solution
$\dot{m}$	mass flow rate [$kg.s^{-1}$]	i	inlet
Q	thermal power [kW]	L	weak solution
T	temperature [K]	L.G	low pressure generator
X	solution concentration [-]	L.H.E	low temperature heat exchanger
ε	heat exchanger effectiveness [-]	max	maximum
		min	minimum
Subscripts			
abs	absorber	ref	refrigerant
ch	chilled water	w	water
con	condenser		

I. Introduction

In the hot regions around the world, the heating and cooling demand became important needs. Lithium bromide [$Li\text{-}Br/H_2O$] double-effect absorption system is the most suitable cooling system can be used for large zones. The absorption chiller can be powered relatively by low grade energy source such as natural gas, solar, coal, co-generation, or industrial waste stream source. The absorption chiller unit should be enhanced with the performance evaluation of each cycle component periodically.

Florides et al. [1] have been investigated a method to evaluate the characteristics and performance of a single stage lithium bromide water absorption machine. It was shown that the COP of the unit was lowered when the generator temperature was increasedandthe generator pressure was increased.

Thermodynamic analysis has been carried out by Xu et al. [2] to study the performance of double effect absorption chiller series flow typeusing [Li-Br/H_2O] solution as the working fluid. It was presented that the increase in heat recovery ratios of the high and low temperature HEXs with decreasing in the solution circulation ratio increased the coefficient of performance.

Evaluation of the seasonal effect on the performance of triple effect vapor absorption cooling system was presented byAlkaet al. [3]. It was observed from the results that maximum effectiveness of the cooling system is 0.29 in the month of April and maximum coefficient of performance (COP) is 1.56 in the month of June.

Xu and Dai[4] were studied the effect of design parameters including heat recovery ratios of the high and low temperature HEXs,circulation ratio and distribution ratio on theperformance of double effect absorption chiller parallel-flow type.From the simulation results, they were found that the increasing of heat recovery ratio of low and high temperature HEXs, the solution distribution ratio and decreasing the circulation ratio improved the performance of absorption chiller.

The comparison between performance of double effect parallel flow and series flow [Li-Br/H_2O] absorption systems were investigated by Arun et al. [5]. It has presented that the COP for parallel flow cycles always wasgreater than series flow cycles throughout range of operating conditions. Also, it has developed that parallel flow cycles more sensitive than series flow cycles to any changes in heat recovery ratio of low temperature heat exchanger.

Mathematical modeling of [Li-Br/H_2O] absorption chiller including two-dimensional distributions of temperature and concentration fields for heat and mass exchangers were presented by Krzysztof and Joachim [6].The main practical advantage of the model was the possibility of assessing the influence of both the geometry parameters and operation parameters on thermal performance.

Hongxi et al.[7] were developed a model based on experimental performance analysis of a micro scale[Li-Br/H_2O] steam-driven double-effect absorption Chiller. The model has been used to size the chiller components and to determine the configurations. Also, it has been used to predict chiller performance under various design conditions in building.

A study on the advanced performance of an absorption heater/chiller with a solution preheated by using waste gases was developed by Jung-In et al. [8]. It has developed that exhaust gases with the temperature above 200 °C were recovered in an exhaust heat exchanger and can be used to preheat the dilute solution. Also, it has shown a significant improvement in the COP of cycle.Srinivas[9] was conducted an investigationof heat recovery from industrial processes with large exhaust gas flow rates but at very low temperatures. It was found that theheatsource is the most significant factor in determining the ability to recover heat usefully.

Chan et al. [10] were studied the performance characteristics during the partial load operation and calculation of energy consumption in[Li-Br/H_2O] absorption chiller with a capacity of 210 R.T. The results were presented that the performance of absorption system is more sensitive to the change of inlet cooling water temperature and flow rate.

Two approaches to the characteristic equation method compared by Maria et al. [11] in order to find a simple model that gives the best describes of the performance of thermal absorption chillers. This approach has been used to fit catalogue or the experimental data from several single-effect and double-effect absorption chillers which could be extremely useful for thermal modeling and optimization programs.

Garousi et al. [12] were developed a computational model to study and compare the effects of operating parameters on crystallization phenomena in three classes of double effect lithium bromide-water absorption refrigeration systems (series, parallel and reverse parallel flow) with identical refrigeration capacities. It has shown that the range of operating conditions without crystallization risks in the parallel and the reverse parallel configurations is wider than those of the series flow system.

The technique for energy recovery combined with particle separation from flue gas was investigatedbyWesterlund et al. [13]. It has presented that the heat recovery from flue gases increased the heat production from the plant by about 40% when wet fuels were used.

Torrella et al. [14] presented a procedure for calculating the COP and heat transfer rates based on theexperimental temperature measurements of [Li-Br/H_2O] direct-fired double-effect absorption chiller in reverse parallel flow running by natural gas. It has been allowed to analyze the behavior of the different operation stages of the chiller.

Thermodynamic analysis of a lithium bromide/water absorptionsystem for cooling and heating applications was developedby Lee and Sherief [15]. Simulation was employed to determine the coefficientof performance (COP)and the exergetic efficiency of the absorption system under different operatingconditions such as the heat source, cooling water, chilled water, and supply hot water temperatures.

The objective of this work is to present a theoretical and experimental procedure for evaluation of the actual performance of [Li-Br/H_2O] direct-gas fired double-effect absorption chiller in parallel flow using temperature sensors located on a specific point on the cycle components allows predicting the COP behavior for long timeof operation. Theoretical analysis is developed to study the effect of inlet cooling water temperature, low and high temperature HEXs effectiveness on the COP at different circulation ratio.

The absorption chiller COP is estimated during the operating period using a set of mathematical equations including mass balance and energy balance for each component. The experimental analysis is done for an actual working absorption system at El-Araby Company for Lighting Technology Company-Egypt. Measurements are taken at different periods in [July 2013 and July 2014]. A comparisonof absorption unit actual performancemeasurements arecarried out.

II. Absorption heat pump description

The internal operation of (Li-Br/H_2O) absorption chiller is intimately influenced by the pressures and concentrations of its working fluid. In its most basic form, there are four intrinsic components to (Li-Br/H_2O) absorption chiller: evaporator, generator, absorber and condenser. Double-effect absorption heat pumps can be classified depending on the solution flow path according to ASHRAE [16]as follows,

a. ***Series flow*:**the solution leaving absorber is pumped using solution pump then flows sequentially through low temperature HEX, high-temperature HEX and high pressure generator. As an intermediate solution from high pressure generator, flows through high temperature HEX, low pressure generator, low temperature HEX and absorber.

b. ***Parallel flow*:**the solution leaving absorber is pumped using solution pump then sent to each generator in appropriate distribution ratio through high and low temperature HEXs. Both flows coming from high and low pressure generatorsare mixed before entering to absorber.

c. ***Reverse parallel flow*:**the solution leaving absorber is pumped by solution pump then sent through low temperature HEX and to low pressure generator. At the exit, part of flow is sent through low temperature HEX towards absorber, and the rest is pumped to high temperature HEX then to high pressure generator.

The absorption air-conditioning heat pump was installed at El-ArabyCompany for Lighting Technology-Quesna-Egyptprovides a cooling capacity of [500 T.R], [1750 kW]. The absorption heat pump type discussed in this work is a direct-fired double-effect chiller in parallel flow, model [HAU-CGN500V] from Hitachi co., which used[Li-Br] as absorbent and water [H_2O] as a refrigerant. View of the absorption unit is shown in Figure (1).

Fig.1. Parallel-flowdouble-effect absorption chiller view.

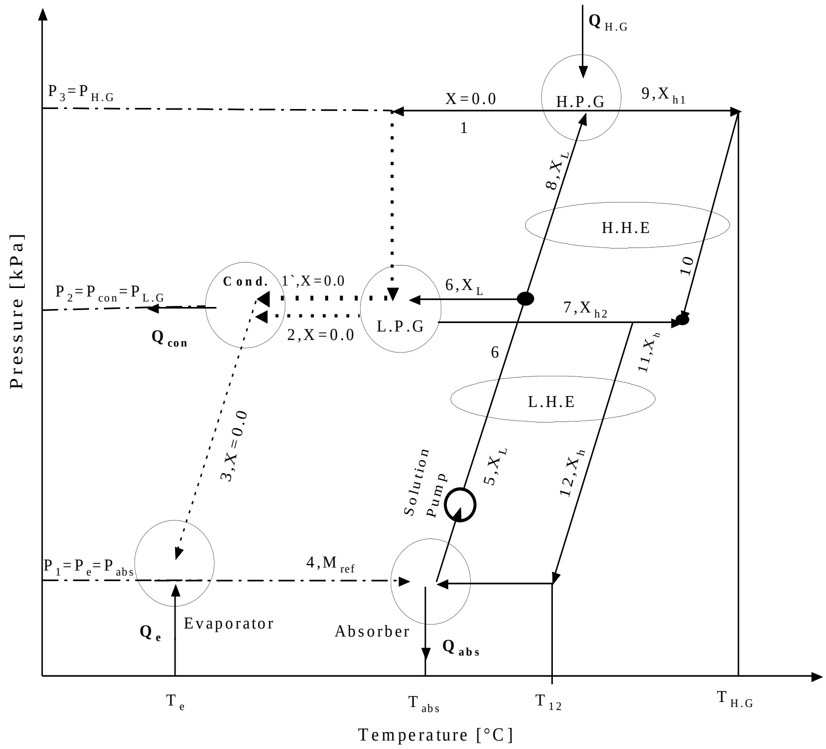

Fig.2. Parallel-flow double-effect absorption chiller (P-T-X) diagram.

Figure (2) demonstratesthe parallel-flow double-effect absorption chiller [P-T-X] diagram. From the absorption chiller [P-T-X] diagram, cycle can be described. The refrigerant sprayed over the surface of the evaporator tubes boils at the saturation temperature corresponding to this pressureand is evaporated by taking heat from the chilled water flowing in the evaporator tubes.The lithium bromide solution in the absorber absorbs the evaporated refrigerant to be dilute solution. The absorption heat generated is taken out by the cooling water. The solution diluted by absorbing the refrigerant in the absorber is sent to the low temperature HEX and is carried partially to the low pressure generator and the rest is sent tothe high pressure generator through the high temperature HEX using solution pump.The solution in the high pressure generator is heated and boiled by the burning gas flowing around the surface of the generator tubes to make the refrigerant evaporated.

The evaporated refrigerant flows into the low pressure generator tubes and heats the solution around the tubes. The refrigerant vaporcondenses and flows into the condenser to be cooled by the cooling water flowing in the condenser tubes. It was noticed that heat reject from absorber and condenser by using a series flow of cooling water. The condensed refrigerant is sent to the evaporator by differential pressure and gravity to be sprayed in the evaporator. The dilute solution which is diverged from the outlet of the low temperature HEX is sprayed on the surface of the low pressure generator tubes and heated to be concentrated. The concentrated solution is heated in the high pressure generator enters the outlet box of the low pressure generator through the high temperature HEX then it is mixed and sent to the absorber through the low temperature HEX to absorb the refrigerant vapor. Thus, one cycle of parallel-flow direct-fired [Li-Br/H_2O] absorption heat pump is completed.

III. Cycle Calculation Procedures

The absorption heat pump has four main processes, generation, condensation, evaporation and absorption process. Generation-condensation processes are in one phase and evaporation-absorption processes are in one phase.The cycle efficiency can be evaluated in terms of the coefficient of performance [COP] which is defined as the ratio of produced cooling capacity divided by heat supplied and pump power.

A mathematical model is developed by using a FORTRAN program. Theoretical and experimental analysis is made using this model to evaluate the actual performance of parallel-flow absorption heat pump with a long time operation.Some basic assumptions are considered in calculation proceduresas follows:

i. There is no pressure difference due to piping system.
ii. There is no heat loss to the ambient.
iii. Saturation state prevails in generation and absorption processes.
iv. Pure vapor refrigerant migrates from generator to condenser.
v. Pure vapor refrigerant migrates from evaporator to absorber.
vi. The exit state of evaporator is saturated vapor.

The first step of chiller characterization procedures starts with the calculation of thermodynamic properties of each solution in each component of the cycle.For cycle simulation, the mass balance, energy balance and equation of state for [Li-Br/H_2O] solution and refrigerant at each component involved in the absorption system cancalculated as follows,

a. Evaporator analysis:
Energy balance,
$Q_e[kW] = m^{\cdot}_{ref}.(h_4 - h_3) = m^{\cdot}_{ch}.C_{pw}.\Delta T_{ch}$(1)

b. Absorber analysis:
Mass balance,
$m^{\cdot}_{\mathrm{ref}} + m^{\cdot}_{11} = m^{\cdot}_{5}$(2)
$m^{\cdot}_{12}\mathrm{X_h} = m^{\cdot}_{5}\mathrm{X_L}$(3)
Energy balance,
$m^{\cdot}_{\mathrm{ref}}\mathrm{h_4} + m^{\cdot}_{12}\mathrm{h_{12}} - m^{\cdot}_{5}\mathrm{h_5} = \mathrm{Q_{abs}}$(4)

c. High pressure generator:
$m^{\cdot}_{1} + m^{\cdot}_{9} = m^{\cdot}_{8}$(5)
$m^{\cdot}_{9}\mathrm{X_h} = m^{\cdot}_{8}\mathrm{X_L}$(6)
Energy balance,
$\mathrm{Q_{H.G}[kW]} = m^{\cdot}_{1}\mathrm{h_1} + m^{\cdot}_{9}\mathrm{h_9} - m^{\cdot}_{8}\mathrm{h_8}$(7)

d. Low pressure generator:
Mass balance,
$m^{\cdot}_{6} = m^{\cdot}_{7} + m^{\cdot}_{2}$(8)
$m^{\cdot}_{6}\mathrm{X_L} = m^{\cdot}_{7}\mathrm{X_h}$(9)
Energy balance,
$\mathrm{Q_{L.G}[kW]} = m^{\cdot}_{2}\mathrm{h_2} + m^{\cdot}_{7}\mathrm{h_7} - m^{\cdot}_{6}\mathrm{h_6} = m^{\cdot}_{1}(\mathrm{h_1} - \grave{\mathrm{h}}_1)$(10)

e. High temperature heat exchanger:
The heat exchanger effectiveness can be calculated as follows,
$\varepsilon[-] = \frac{\mathrm{Q}}{\mathrm{Q_{max}}} = \frac{\mathrm{Q}}{\mathrm{C_{min}}\ (\mathrm{T_{hi}} - \mathrm{T_{li}})}$(11)
$\mathrm{Q_{H.H.E}[kW]} = m^{\cdot}_{9}(\mathrm{h_9} - \mathrm{h_{10}})$(12)

f. Lower heat exchanger:
$\mathrm{Q_{L.H.E}[kW]} = \mathrm{m}^{\cdot}_{11}(\mathrm{h_{11}} - \mathrm{h_{12}}) = \mathrm{m}^{\cdot}_{5}(\mathrm{h_6} - \mathrm{h_5})$(13)

g. Condenser:
Mass balance,
$m^{\cdot}_{3} = m^{\cdot}_{2} + m^{\cdot}_{1}$(14)
From energy balance:
$\mathrm{Q_{con}}\ [\mathrm{kW}] = m^{\cdot}_{2}\mathrm{h_2} + m^{\cdot}_{1}\grave{\mathrm{h}}_1 - m^{\cdot}_{3}\mathrm{h_3}$(15)

h. Coefficient of performance:
Once all of thermodynamics properties of each component have been obtained, the COP resulting from eqn. (16) as follows,
$\mathrm{COP}[-] = \frac{Q_e[kW]}{Q_{H.G}[kW]}$(16)

IV. Results and Discussion

4.1 Theoretical Analysis

Theoretical analysis is enhanced to study the effect of inlet cooling water temperature, circulation ratio and effectiveness of low and high temperature HEXs on the coefficient of performance [COP].Figure (3) shows the effect of effectiveness of hightemperature HEX on the coefficient of performance at different circulation ratio (a). Circulation ratio [a] is defined as the ratio of the strong solution mass flow rate to the refrigerant mass flow rate. This figure demonstrates the coefficient of performance increase with increasing the effectiveness of heat exchanger decreasing with the increasing of circulation ratio.

Figure (4) shows the effect of effectiveness of low temperature HEX on the COP at different circulation ratio (a). This figure presents that the COP increases with increasing the effectiveness of low temperature HEX and decreases with the increasing of the circulation ratio [a].

Figure (5) investigates the effect of inlet cooling water temperature on the coefficient of performance. This figure shows that the COP decreases with increasing the inlet cooling water temperature. Also, it was noticed that there is a limit of increase inlet cooling water temperature. The COP starts to decrease when the inlet cooling water temperature reaches to 36 ℃ and after 37 ℃ the COP values falls to zero. The heat of absorption and condensation process is removed by using cooling water. The condensation process stops eventually when the exit and inlet temperatures of the cooling water become almost equal in the condenser unit.

The cooling water starts to enter to the absorption system from the absorber then to condenser. The concentration of the dilute solution is determined based on the inlet cooling water temperature.

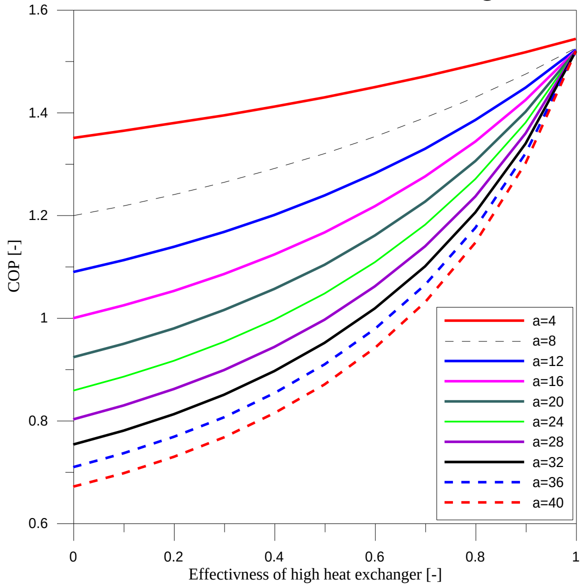

Fig.3. Effect ofhigh temperature HEX effectiveness on the COP.

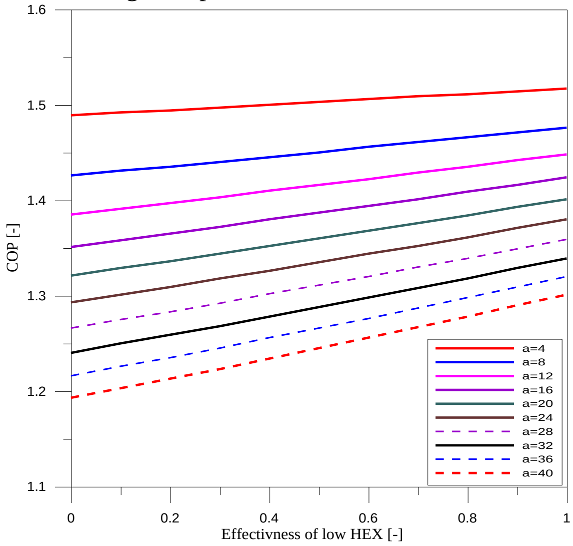

Fig.4. Effect oflow temperature HEX effectiveness on the COP.

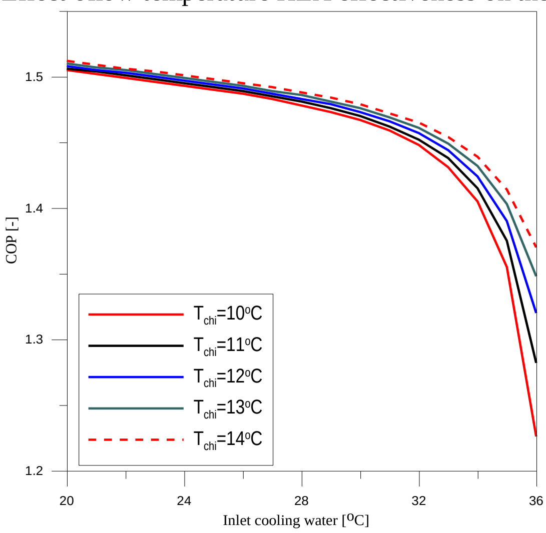

Fig.5. Effect ofinlet cooling water temperature on the COP.

4.2 Experimental Analysis

The measurements are made at different moments on the plant during summer period in Egypt [July 2013, July 2014]. During this period of the year temperature is so high which is always need high cooling capacity and the absorption unit is loaded for long time. Therefore, it is selected to experiment and study the performance of the absorption unit. The measurementsare taken by reading thermocouples data of absorption chillerare presented and analyzed. These measurements of the parallel-flow direct-fired absorption unit are taken for six hours on the site.The absorption chiller setting data is entered to the system as the chilled water temperature outlet setting value. The cooling water utilizes in absorber and condenser is cooled by using cooling tower.

As for, the effect of inlet cooling water temperature is an important parameter, figure (6) presents the oscillations of the temperature in the lowtemperatureregion, which correspond to the inlet cooling water temperature and absorber temperature. The cyclic behavior of the chiller is induced bythe mechanism of regulation, which controls the chilled waterleaving temperature and the burner valve open.

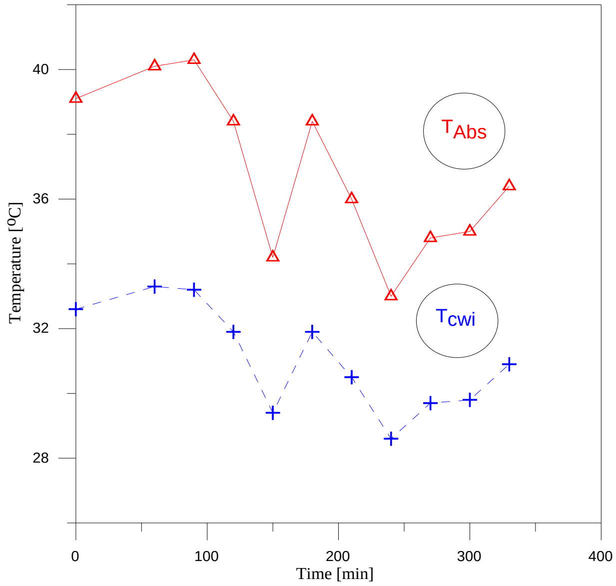

Fig.6. Inlet cooling water and absorber temperatures.

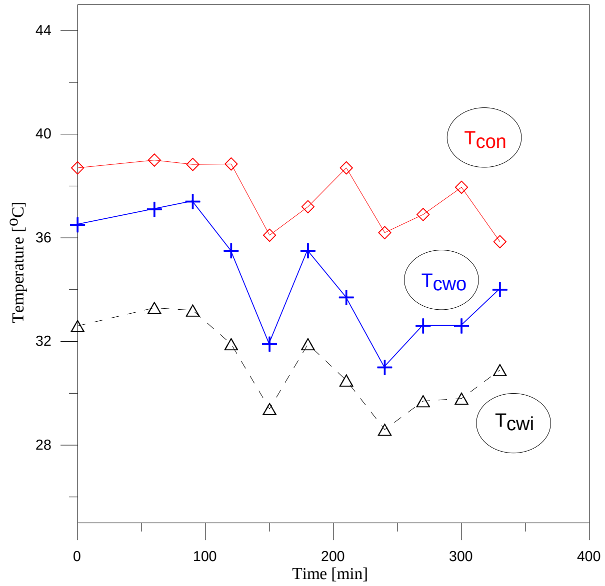

Fig.7. Condensing, inlet and outlet cooling temperatures.

The oscillations of the high temperature region, condensing temperature and inlet and outlet temperatures of the cooling water are shown in figure (7). It should be remarked that the inlet cooling water temperature is the main parameter which controls on the pressure and temperature of the absorber and condenser components. Furthermore, should be stated that the water flow through the condenser–absorber is kept constant. Thus, the condensing temperature decreases when the chiller is out of operation.

The periods when the absorption chiller is running and the effectiveness of the low and high temperature HEXs are presented in figure (8), figure (9). These figures show the effectiveness of the high and low temperature HEXs are affected with long operation time of the absorption chiller. Due to the deposits composed on the heat exchanger tubes which it makes fouling layer, the overall heat transfer coefficient is decreased. Also, the oscillation demonstrates that the effectiveness of the low and high temperature HEXs in [July 2014] is lower than effectiveness of the HEXs in [July 2013]. This means that the effectiveness of HEXs is changed with the time of operation from year to year although the maintenance is made periodically.

The cooling capacity and the heat supplied to the high pressure generator are presented in figure (10). Both of the cooling capacity and the heat supplied expressed in [kW]. It should be highlighted that the absorption chiller is continuously produce chilled water whereas the heating power is supplied intermittently by the natural gas burner, which is started up when the outlet temperature of the chilled water in the evaporator goes beyond to the reference value. This means that the signal sent from the temperature sensor installed at the water head of the chilled water outlet controls the combustion ratio of the high pressure generator burner to ensure an operation even to part load.

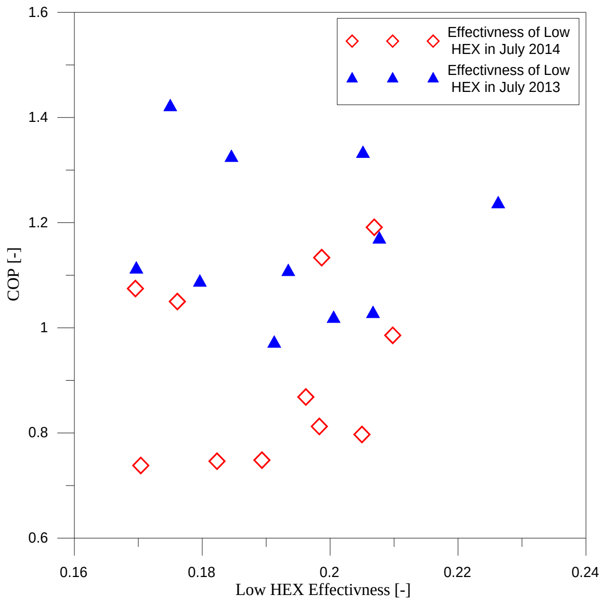

Fig.8. Effectoflow temperature HEX effectiveness on COP.

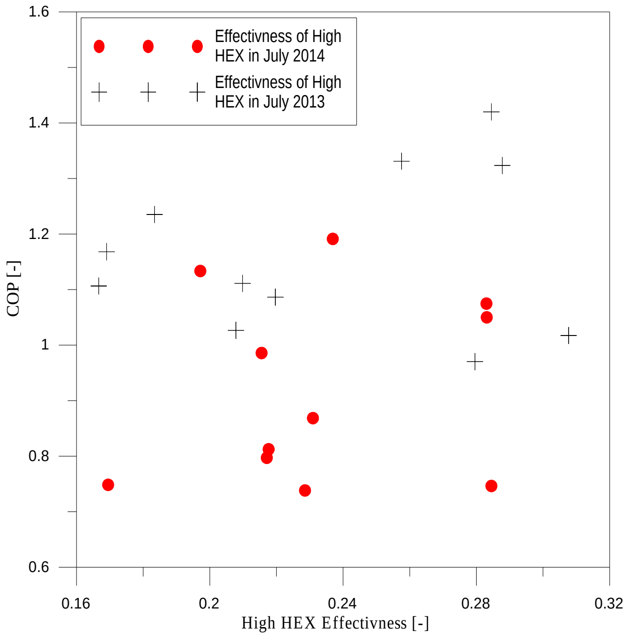

Fig.9. Effectofhigh temperature HEX effectiveness on COP.

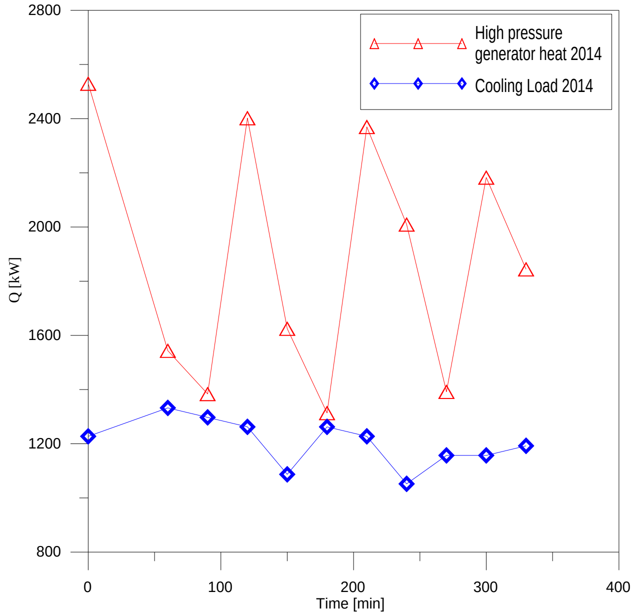

Fig.10. Cooling capacity and heat supplied.

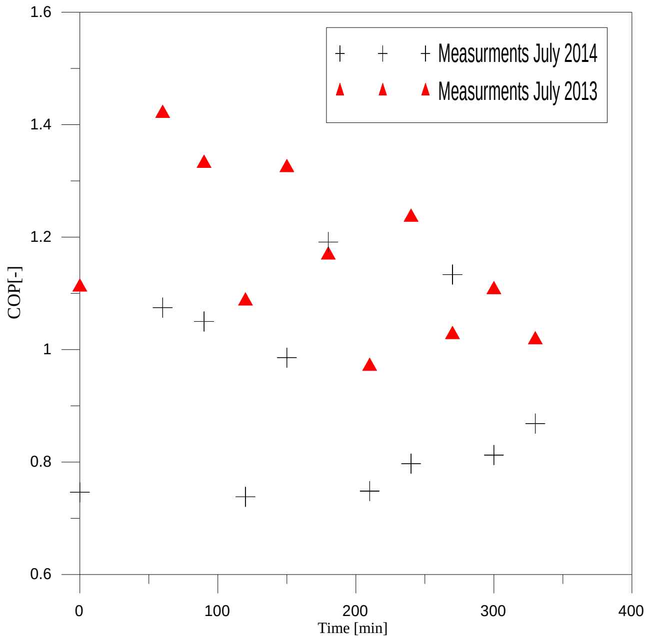

Fig.11. Instantaneous COP.

The COP values based on measured data are presented in figure (11). At this point of calculation there are two aspects related to the presented COP values need to be considered. Firstly, the cooling power produced by the chiller when there is no gas consumption has not been considered, even though the water pumps keep operating all the time and secondly, the COP values represent only the performance of the absorption cycle, without considering efficiency of the combustion of natural gas. The instantaneous COP values are calculated for the absorption chiller reading data which are measured at the selecting operating period of the absorption chiller unit. The instantaneous COP values obtained in [July 2014] are varied with the ones obtained in [July 2013]. The difference in the COP is due to the effect of the heat exchangers effectiveness with the long operating period and different operating conditions. Accordingly, the instantaneous COP presented in figure (11), it is also, presents the difference between the values recorded in [July 2013] which is higher than the values recorded in [July 2014] at different loads.

In Figure (12) demonstrates the actual change of refrigerant mass flow rate [$\dot{m}_{ref}$] with the cooling capacity [Q_e]. This figure presentsthe refrigerant mass flow rate increases with the cooling capacity increase. Also, this increase in the refrigerant mass flow rate based on the increasing in heat supplied in high pressure generator.

Figure (13) presents the change of strong solution concentration with different actual cooling capacity load. This figure demonstrate that the concentration of strong solution increase with increase of cooling capacity. Also, it was noticed that the heat added to the cycle increases with the cooling capacity increase and due to this raising in solution temperature the strong solution concentration also increases.

Figure (14) shows long time period of operation for the absorption chiller unit. Input parameters of the absorption unit such as heat supplied, cooling capacity and inlet cooling water temperature are followed for (14 hours). Also, the COP during this period is calculated and is presented in the same figure. This figure illustrates the change of inlet cooling water temperature with the instantaneous time and with the cycle COP in addition to the cooling capacity and the heat supplied at the same period.In this measured data the inlet cooling water was adjusted to be within range [26℃– 33℃] which it gives the best working condition of the absorption unit and this is clear from the COP data.

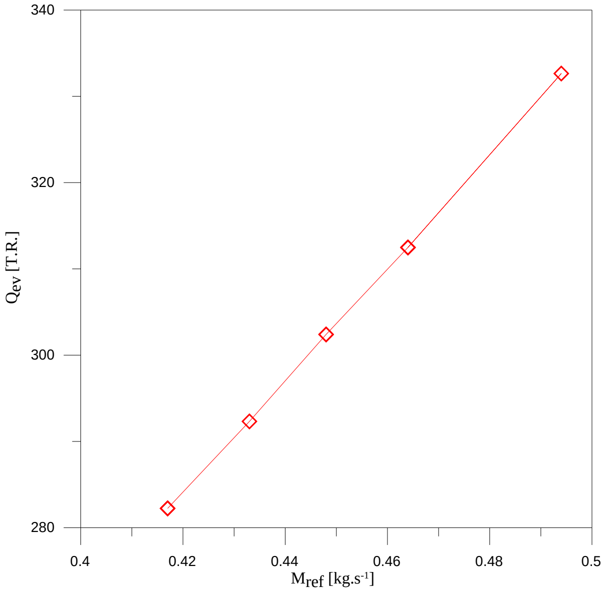

Fig.12. Cooling capacity and refrigerant flow rate.

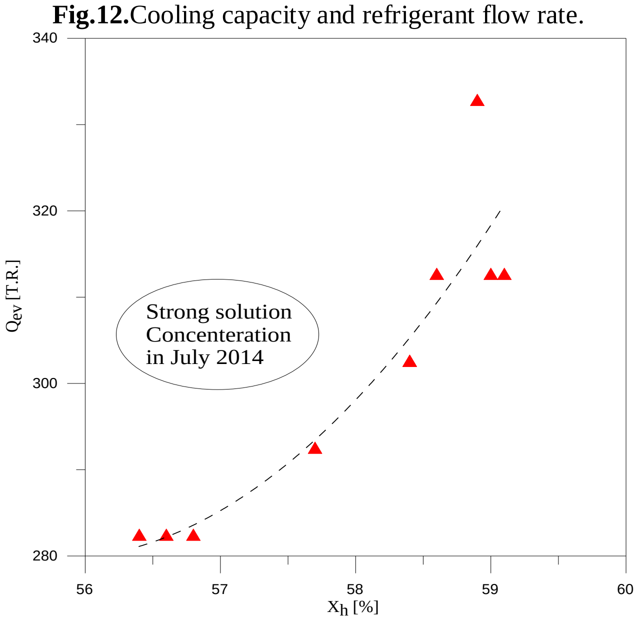

Fig.13. Cooling capacity and strong solution concentration.

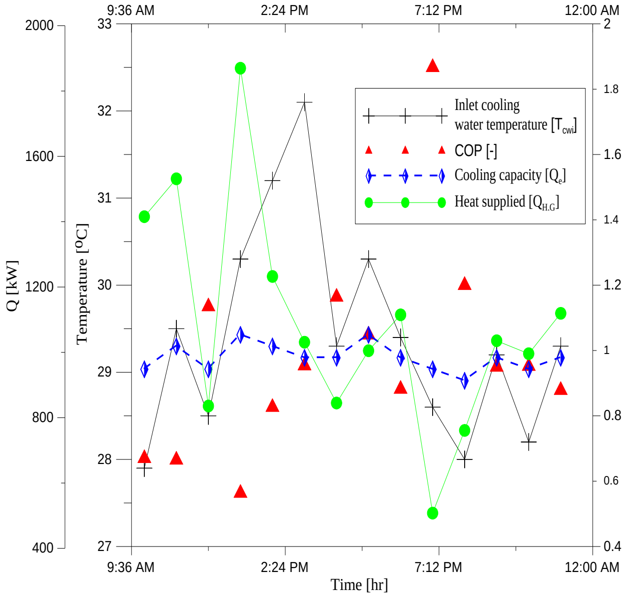

Fig.14. Absorption unit inputs data and the COP for long time period.

V. Conclusion

This paper presents a theoretical and experimental procedure for evaluation of the performance of a lithium-bromide water direct-gas fired double-effect absorption chiller in parallel flow by using temperature measurements using temperature sensors located on a specific point on the cycle components helped to follow up the COP behavior for long time period of operation. The absorption chiller [P-T-X] diagram has been developed.

The cycle COP is estimated during the operating period using a set of mathematical equations including mass balance and energy balance for each component. The cooling capacity [kW], the heat supplied [kW], the effectiveness of the low and high temperature HEXs at the same operating periods have been calculated.

Theoretical and experimental analysis have been developed to show the effect of inlet cooling water temperature and the effectiveness of low and high temperature HEXs on the absorption unit COP. Theoretical analysis presents that cycle COP increase with increasing heat exchangers effectiveness. Also, the temperature of cooling water enters to the unit should be in definite range to preserve the absorption unit.

The experimental analysis is done for an actual working absorption system at El-ArabyCompany for Lighting Technology Company-Egypt. The experimental COP values have been calculated in July2013 is higher than obtained in July 2014for different operating conditions considering continues chilled water mass flow rate. Also, the effectiveness of low and high temperature HEXs obtained in July 2013 is higher than the values obtained in July 2014, although maintenance is made periodically for absorption unit components butthis mean the COP is sensitive to heat exchangers effectiveness. The combustion efficiency and the heat losses to the environment were not considered in the calculated COP values. This study allows evaluatingthe COP with the operation time and also, aids tostand on the actual performance of the absorption unit to determine the time of maintenance.

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