

Performance Assessment of Large Vapor Absorption System

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ABSTRACT: Absorption cooling offers the possibility of using heat to provide cooling. For this purpose heat from a conventional boiler can be used or waste heat and solar energy. When the latter systems are used absorption systems minimize also the adverse effects of burning fossil fuels and thus protect the environment. Absorption systems fall into two major categories, depending on the working fluids. These are the ammonia-water systems, in which ammonia is the refrigerant and lithium bromide-water systems in which water vapor is the refrigerant.

An attempt has been made in this paper to reveal the thermodynamic analysis of steam fired Water/Li-Br Vapor Absorption Refrigeration System for 30 days. The analysis includes Energy and Second Law Analysis of the system. The second law analysis is based on the concept of exergy, which can be defined as a measure of work potential or quality of different forms of energy relative to the environmental conditions. Exergy analysis applied to a system describes all losses both in the various components of the system and in the whole system. The analysis is drawn for a Vapor Absorption Plant whose cooling load on the evaporator is 1740.96 kW or 496 Ton of refrigeration. The rich solution concentration solution circulation ratio is 58%.

KEYWORDS: Lithium Bromide Vapor Absorption Refrigeration, Cooling Load, Kilo Watt, Leadership in Energy and Environmental Design, Vapor Absorption Machine.

I. INTRODUCTION

One of the oldest methods to mechanically cool a space is with absorption technology. A vapor absorption chiller machine (VAM) is a machine that produces chilled water using a heat source rather than electrical input as in the more familiar vapor compression cycle [1]. It seems unreasonable that cooling can be achieved with heat, but that is what occurs within an absorption chiller. A fluid pair lithium bromide and water is used in commercial VAM. The refrigerant used is actually water, as that is the working medium that experiences a phase change and causes the cooling effect [2]. The second fluid that drives the process is a salt, generally lithium bromide. Heat is used to separate the two fluids; when they are mixed in a near vacuum environment. The capital cost of VAM is higher compared to compression systems, but when viewed in totality of reduced electrical service size, transformer, switchgear, cabling and lack of need for an equipment room, the VAM becomes comparable to compression systems. Today's modern absorption chillers range from around 90 tons to 2000 tons. Currently there are only single stage and two stage machines in production [3]. There are several patents for 3 stage machines but they are not currently in the market. Absorption chillers have recently gained widespread acceptance due to their capability of not only integrating with cogeneration systems but also because they can operate with industrial waste heat streams.

VAPOR ABSORPTION CYCLE

In the early years of the twentieth century, the vapor absorption cycle using water-ammonia systems was popular and widely used. After the development of the vapor compression cycle, the vapor absorption cycle lost much of its importance because of its low coefficient of performance (about one fifth of that of the vapor compression cycle). Today, the vapor absorption cycle is used mainly where fuel for heating is available but electricity is not, such as in recreational vehicles that carry LP gas [4-6]. It is also used in industrial environments where plentiful waste heat overcomes its inefficiency. The absorption cycle is similar to the compression cycle, except for the method of raising the pressure of the refrigerant vapor. In the absorption system, the compressor is replaced by an absorber which

International Journal of Innovative Research in Science, Engineering and Technology

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Vol. 4, Issue 3, March 2015

dissolves the refrigerant in a suitable liquid, a liquid pump which raises the pressure and a generator which, on heat addition, drives off the refrigerant vapor from the high-pressure liquid. Some work is needed by the liquid pump but, for a given quantity of refrigerant, it is much smaller than needed by the compressor in the vapor compression cycle. In an absorption refrigerator, a suitable combination of refrigerant and absorbent is used. The most common combinations are ammonia (refrigerant) and water (absorbent), and water (refrigerant) and lithium bromide [absorbent].

ADVANTAGES OF VAPOR ABSORPTION SYSTEM

The main advantages of installing VAHP are as follows:

- Environment friendly
- Very low power consumption Part load efficiency is as good as efficiencies at full load.
- Requires negligible maintenance since there are no moving parts
- Noiseless and vibration free operation

APPLICATIONS OF ABSORPTION SYSTEMS

The main advantage of absorption chillers is their ability to utilize waste heat streams that would be otherwise discarded. In terms of energy performance, motor-driven vapor compression chillers will beat absorption chillers every time. Still there are specific applications where absorption chillers have a substantial advantage over motor-driven vapor compression chillers. Some of those applications include

- For facilities that use lot of thermal energy for their processes, a large chunk of heat is usually discarded to the surrounding as waste. This waste heat can be converted to useful refrigeration by using a VAM.
- For facilities that have a simultaneous need for heat and power (cogeneration system), absorption chillers can utilize the thermal energy to produce chilled water.
- For facilities that have high electrical demand charges. Absorption chillers minimize or flatten the sharp spikes in a building's electric load profile can be used as part of a peak shaving strategy.
- For facilities where the electrical supply is not robust, expensive, unreliable, or unavailable, it is easier to achieve heat input with a flame than with electricity. Absorption chillers uses very little electricity compared to an electric motor driven compression cycle chiller.
- For facilities, where the cost of electricity verses fuel oil/gas tips the scale in favor of fuel/gas. Various studies indicate that the absorption chillers provide economic benefit in most geographical areas, due to the differential in the cost between gas and electric energy.

RECENT IMPROVEMENTS TO ABSORPTION CHILLERS

Since the 1960's, several improvements have been made to absorption chiller, which include:

- Automatic purges systems eliminating the need for manual purging and lowering the potential for corrosion.
- Faster system response due to the use of electronic controls and solution concentration sensing
- Electronic controls and sensors that make crystallization of the chiller far less likely than in the past.
- Lower water flow requirements.
- Absorption chillers can provide water temperature as low as 3.5 Deg C allowing for the use of reduced air flow and duct size in delivery systems

II. VAPOR ABSORPTION REFRIGERATION SYSTEM

A vapor absorption chiller machine (VAM) is a machine that produces chilled water using a heat source rather than electrical input as in the more familiar vapor compression cycle. It seems unreasonable that cooling can be achieved with heat, but that is what occurs within an absorption chiller.

BASIC PRINCIPLE OF ABSORPTION COOLING

Water boils and evaporates at 212 °F [100 °C] at standard atmospheric pressure 14.7psia [101.3kPa]. When the pressure is reduced, water boils at a lower temperature. The following table gives the total pressure in inches of mercury and the corresponding approximate water boiling temperature at different pressures.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 3, March 2015

Absolute Pressure	Water Boiling Point (°F)
760 mm-Hg (1atm)	212
76 mm-Hg (0.1atm)	115
25.6 mm-Hg (0.34atm)	80
7.6 mm-Hg (0.01atm)	45
6.5 mm-Hg	40

ABSOLUTE PRESSURE CORRESPONDING TO WATER BOILING TEMPERATURE

The fundamental principle of VAM is that water boils at about 40°F at the low-pressure vacuum condition of 6.5 mm-Hg.

Consider a closed vessel placed under a vacuum of say, 6.5 mm Hg (refer to the figure below). Assume the closed vessel contains a high quality absorbent material such as dry silica gel, and a heat transfer coiled tube through which warm water is circulated. When water is sprayed on the outer wall of the heat transfer tube

- It gets boiled at low temperature 40°F (4°C) under vacuum, and in doing so, absorbs heat from the running water in the heat transfer tube. (The sprayed water is also called the refrigerant).
- The running water in the heat transfer tube is optimally cooled equivalent to the heat of evaporation. The vapors produced, as a result of evaporation, will immediately be absorbed by the silica gel. But when the silica gel reaches the limit of its absorbing capacity, the process continuity cannot be maintained. To ensure a continuous process, some means of converting the absorbent to its original concentration is necessary. In commercial practice, silica gel is replaced with an aqueous absorbent solution. Continuing with the same explanation, as the aqueous absorbent solution absorbs refrigerant vapors; it becomes diluted and has less ability to absorb any further water vapor. To complete the cycle and sustain operation, the dilute solution is pumped to higher pressure where with application of heat, the water vapor is driven off and the re-concentrated absorbent is recycled back to the absorber vessel. The released refrigerant vapor is condensed in a separate vessel and returned for evaporation. The simplified diagram here illustrates the overall flow path.

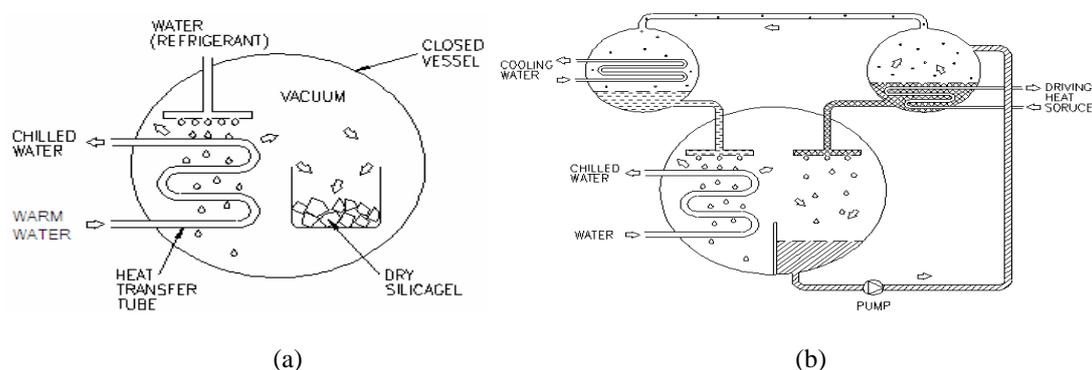


Fig.1 (a) Vapor Absorption System with Silica Gel Absorbent (b) Lithium Bromide (Li-Br) – Water Absorption System

LITHIUM BROMIDE (Li-Br) – WATER ABSORPTION SYSTEM

The chemical details of Li-Br are as follows:

Chemical Formula: Li Br

Molecular Weight: 86.856

Component: Li = 7.99% / Br = 92.01%

Specific Gravity: 3.464 at 25°C (77°F)

Melting Point: 549°C (1,020.2 °F)

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 3, March 2015

Boiling Point: 1,265°C (2,309°F)

Key Characteristics are

- Lithium bromide is a salt and desiccant (drying agent). The lithium ion (Li⁺) in the lithium bromide solution and the water molecules have a strong association, producing the absorption essential for the chiller to operate. Water is the refrigerant and LiBr is the absorbent;
- LiBr system operates under vacuum; the vacuum pumps are needed only for short duration while starting the machine; after that, equilibrium condition is maintained by physical and chemical phenomena;
- Since water is the refrigerant for the LiBr absorption system, the minimum possible chilled water temperature, at its lowest, is about 44° F; consequently, LiBr absorption chillers are used in large air-conditioning applications;
- The advantage of the water-LiBr pair includes its stability, safety, and high volatility ratio.

EFFICIENCY OF VAPOR ABSORPTION MACHINE (VAM)

Efficiencies of absorption chillers is described in terms of Coefficient of Performance (COP), and is defined as the refrigeration effect, in Btu, divided by the net heat input, in Btu. The COP can be thought of as a sort of index of the efficiency of the machine. The absorption systems with a COP of 1.0 will burn 12,000 BTUs of heat energy for each ton-hour of cooling. For example, a 500-ton absorption chiller operating at a COP of 0.70 would require: (500 x 12,000 Btu/h) divided by 0.70 = 8,571,429 Btu/h heat input. Cooling capacity is measured in tons of refrigeration. A ton of refrigeration is defined as the capacity to remove heat at a rate of 12,000 Btu/hr at the evaporator

III. DESCRIPTION OF THE SYSTEM TO BE ANALYSED

In an absorption chiller, water is the refrigerant, and aqueous lithium bromide (Li-Br) is the absorbent. Double-effect, steam-fired absorption chillers are most commonly used today because of their higher coefficient of performance. Double-effect means that there are two generators. Steam-fired means that the heat input is supplied to the direct input of steam. Steam operated lithium bromide chiller, an equipment which uses saturated steam as heat source, water as refrigerant, lithium bromide as absorbent and produces the chilled water under vacuum conditions for the purpose of air conditioning and technology process. The double-effect, steam-fired absorption chiller consists of following main parts:

- High pressure generator
- Low pressure generator
- Evaporator
- Condenser
- Absorber
- Heat Exchangers
- Throttling Devices
- Purging unit

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 3, March 2015



(a)

(b)

Fig.2. (a) External View of Double-Effect, Steam-Fired Absorption Chillers (b) Side View of Double-Effect, Steam-Fired Absorption Chillers

ENTHALPY-CONCENTRATION DIAGRAM

When water is mixed with anhydrous lithium bromide at the same temperature to form a solution adiabatically, there is a significant increase in the temperature of the solution. If the mixing process is to be an isothermal process, i.e., if the temperature of the process is to be kept constant, then heat must be removed from the solution. Such a heat transfer per unit mass of solution is called the integral heat of the solution h_i , or heat of absorption, in Btu / lb (kJ / kg). Based on the common rule of thermodynamics, h_i is negative.

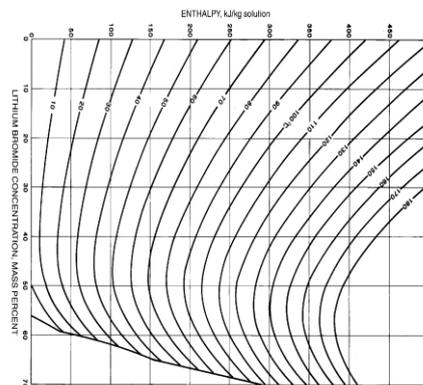


Fig.3. Specific Enthalpy (H) Vs. Concentration (X) Diagram for Water/LiBr Vapor Absorption Refrigeration System

EQUILIBRIUM CHART

The properties of an aqueous lithium bromide solution, including vapor pressure, temperature, and the mass fraction at equilibrium, may be illustrated on an equilibrium chart based on the Dühring plot, as shown in figure. The ordinate of the equilibrium chart is the saturated vapor pressure of water in log-scale millimetres of mercury absolute (mm Hg abs) and the corresponding saturated temperature ($^{\circ}$ F). The scale is plotted on an inclined line. The abscissa of the chart is the temperature of the solution ($^{\circ}$ F). Mass fraction or concentration lines are inclined lines and are not parallel to each other. At the bottom of the concentration lines, there is a crystallization line or saturation line. If the temperature of a solution of constant mass fraction of LiBr drops below this line—or if the mass fraction of LiBr of a solution of constant temperature is higher than the saturated condition—the part of LiBr salt exceeding the saturated condition tends to form solid crystals.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 3, March 2015

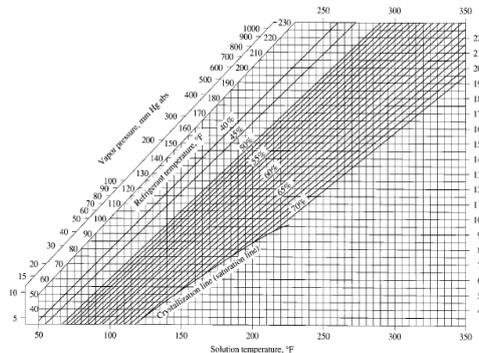


Fig.4. Equilibrium Chart for Aqueous Lithium-Bromide (LiBr) Solution.

OPERATING PARAMETERS

The base operating conditions of vapor absorption refrigeration system are given below

Absorber temperature (Ta)	= 36 °C
Generator temperature (Tg)	= 154 °C
Evaporator temperature (Tce)	= 5°C
Condenser temperature (Thc)	= 30 °C
Inlet steam temperature in HP generator	= 111°C
Exit steam temperature from HP generator	= 80 °C
Inlet steam pressure in HP generator	= 33.8 kPa
Inlet steam temperature in LP generator	= 88.5 °C
Condensate temperature	=71.7°C
Inlet cooling water temperature in absorber	= 30.8°C
Exit cooling water temperature from absorber	= 33 °C
Inlet cooling water temperature in condenser	= 27 °C
Exit cooling water temperature from condenser	= 30 °C
Inlet temperature of chilled water in evaporator	= 8 °C
Exit temperature of chilled water from evaporator	= 7 °C
Ambient temperature of air (Tair, in)	= 28 °C
Volumetric air flow rate (V)	= 86 cu.m/s

At the base operating conditions, the cooling capacity of the system is 1740.96 kW or 496 Ton of refrigeration. The rich solution concentration solution circulation ratio is 58%.

IV. ENERGY ANALYSIS AND ENERGY ANALYSIS

ENERGY ANALYSIS

For the thermodynamic analysis of vapour absorption refrigeration system, the energy and mass balance equations of the various components are given below.

Evaporator

The energy balance in evaporator is given by

$$Q_e = m_{19} (h_{19} - h_{20})$$

Where,

Q_e = Cooling load in evaporator in kW.

m_{19} = Mass flow rate of chilled water to evaporator in kg/s.

h_{19} = Specific enthalpy of inlet chilled water in evaporator in kJ/kg.

h_{20} = Specific enthalpy of outlet chilled water in evaporator in kJ/kg.

Condenser

The energy balance in condenser is given by

$$Q_c = m_{17} (h_{18} - h_{17})$$

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 3, March 2015

Where,

Q_c = Heat rejected in condenser in kW.

m_{17} = Mass flow rate of cooling water entering condenser in kg/s.

h_{18} = Specific enthalpy of cooling water leaving condenser in kJ/kg.

h_{17} = Specific enthalpy of cooling water entering condenser in kJ/kg.

Generator 1

The energy balance for generator 1 is

$$Q_{g1} = m_{15} (h_{15} - h_{16})$$

Where,

Q_{g1} = Heat load in generator 1 in kW.

m_{15} = Mass flow rate of hot water entering generator 1 coils in kg/s.

h_{15} = Specific enthalpy of hot water entering generator 1 in kJ/kg.

h_{16} = Specific enthalpy of hot water leaving generator 1 in kJ/kg.

Generator 2

The energy balance for generator 2 is

$$Q_{g2} = m_6 (h_6 - h_7)$$

Where,

Q_{g2} = Heat load in generator 2 in kW.

m_6 = Mass flow rate of hot water entering generator 2 coils in kg/s.

h_6 = Specific enthalpy of hot water entering generator 2 in kJ/kg.

h_7 = Specific enthalpy of hot water leaving generator 2 in kJ/kg.

Absorber

The heat balance in absorber is represented by

$$Q_a = m_{21} (h_{22} - h_{21})$$

Where,

Q_a = Heat rejected in absorber in kW

m_{21} = Mass flow rate of cooling water in absorber in kg/s.

h_{22} = Specific enthalpy of cooling water leaving absorber in kJ/kg.

h_{21} = Specific enthalpy of cooling water entering absorber in kJ/kg.

Pump

Work supplied to the pump is given by

$$W_p = m_l (P_g - P_a) / \rho$$

Where, W_p = Power consumption of pump in kW.

P_g = Pressure in generator in kPa.

P_a = Pressure in absorber in kPa.

ρ = Density of Water/LiBr solution (2238.5 kg/cu.m).

COP

Coefficient of performance of the system is given as

$$COP = Q_e / (Q_{g1} + Q_{g2} + W_p)$$

Where

COP = Coefficient of Performance

Q_e = Cooling load in evaporator in kW

Q_{g1} = Heat load in generator 1 in kW.

Q_{g2} = Heat load in generator 2 in kW.

W_p = Power consumption of pump in Kw

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 3, March 2015

SECOND LAW ANALYSIS

Second law analysis is a relatively new concept, which has been used for understanding the irreversible nature of real thermal processes and defining the maximum available energy. The second law analysis is based on the concept of exergy, which can be defined as a measure of work potential or quality of different forms of energy relative to the environmental conditions. In other words, exergy can be defined as the maximum theoretical work, derivable by the interaction of an energy resource with the environment. Exergy analysis applied to a system describes all losses both in the various components of the system and in the whole system. With the help of this analysis, the magnitude of these losses or irreversibilities and their order of importance can be understood. With the use of irreversibility, which is a measure of process imperfection, the optimum operating conditions can be easily determined. The advantage of exergy analysis based on thermo economic optimization is that the different elements of the system could be optimized independently. It is possible to say that exergy analysis can indicate the possibilities of thermodynamic improvement of the process under consideration. The physical exergy component is associated with work obtainable in bringing a stream of matter from initial state to a state that is in thermal and mechanical equilibrium with the environment.

Mathematically, physical exergy is expressed as

$$E_{\text{in}} = m [(h_1 - h_0) - T_0 (s_1 - s_0)]$$

Where,

h_1 = Specific enthalpy of inlet fluid in kJ/kg.

s_1 = Specific entropy of inlet fluid in kJ/kg K.

h_0 = Specific enthalpy of water at ambient temp in kJ/kg.

s_0 = Specific entropy of water at ambient temp in kJ/kg K.

T_0 = Ambient temperature in K

$$E_{\text{out}} = m [(h_2 - h_0) - T_0 (s_2 - s_0)]$$

Where,

h_2 = Specific enthalpy of outlet fluid in kJ/kg.

s_2 = Specific entropy of outlet fluid in kJ/kg K.

h_0 = Specific enthalpy of water at ambient temp in kJ/kg.

s_0 = Specific entropy of water at ambient temp in kJ/kg K.

T_0 = Ambient temperature in K

V. RESULTS AND DISCUSSIONS

Finally, Fig. 5(b) shows the effects of varying COP of the System with Generator 1 Temperature. It can be observed that the COP of generator increases with the increase in the generator temperature or vice versa within the respective limits. It is clear from the results that the generator temperature should be above 132°C for the effective running of the plant. Hence from the Fig. 5(d) shows the effects of varying work done of the Generator 1 Q with Generator 1 Temperature, it is cleared that the work done by the generator will also increase with increase of its temperature.

The exergy graphs of the evaporator and generator i.e. from Fig. 5 (e) and Fig.5 (g) show the effects of varying inlet exergy and outlet exergy of the evaporator and generator corresponding to generator temperature. It can be seen that in the evaporator and generator, the value of exergy increases with increase in their corresponding temperature. From these graphs we observed that the minimum value of exergy is at temperature of 119°C and the maximum value of exergy is at temperature of 139°C. The exergy graphs of the condenser and absorber i.e. from Fig. 5(f) and Fig.5 (i) show the effects of varying inlet exergy and outlet exergy of the condenser and absorber corresponding to generator temperature. It can be seen that in the condenser and absorber, the value of exergy decreases with increase in their corresponding temperature. From these graphs we observed that the minimum value of exergy is at temperature of 119°C and the maximum value of exergy is at temperature of 139°C.

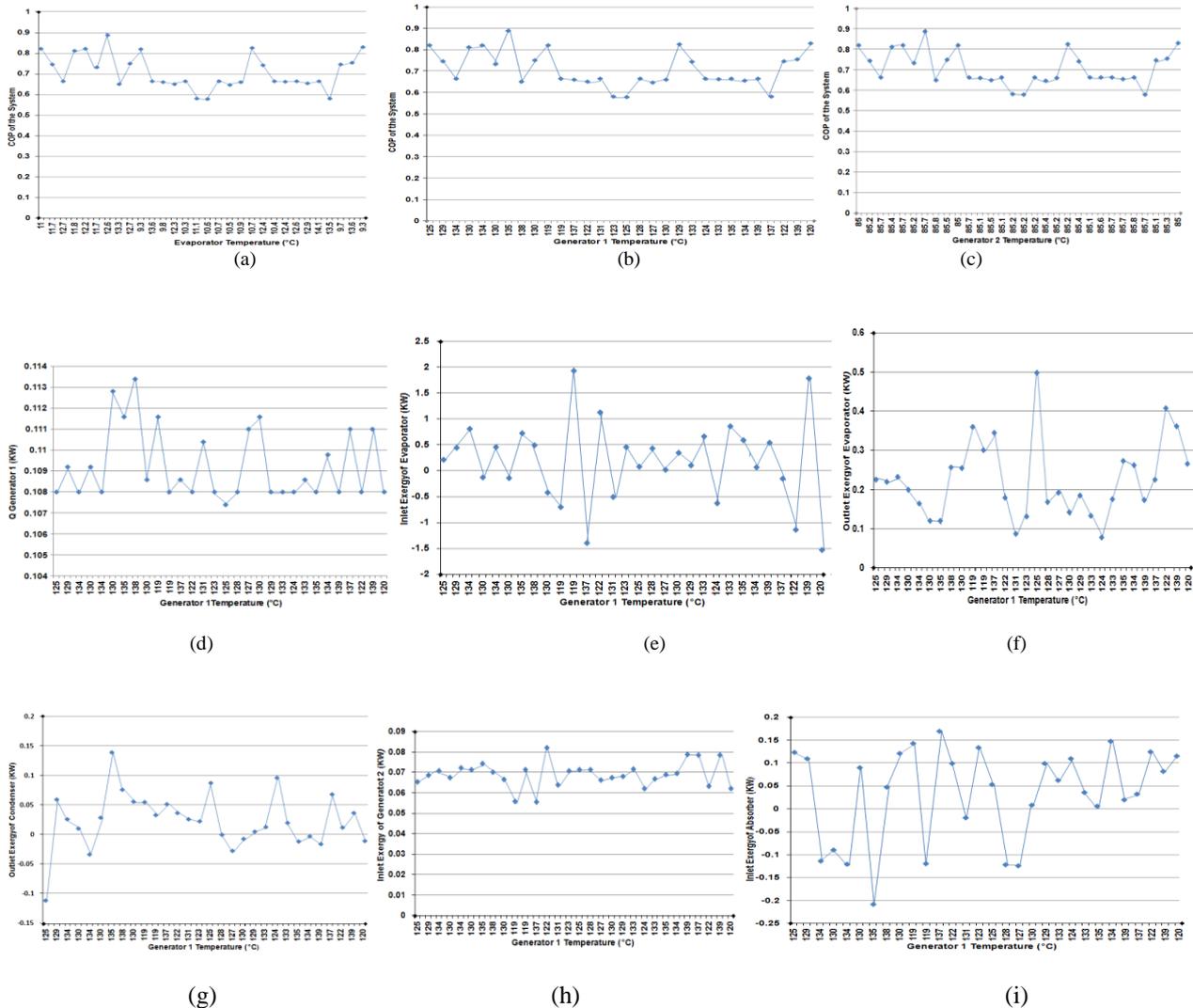


Fig. 5(a) Plot of COP of the System with Evaporator Temperature (b) Plot of COP of the System with Generator 1 Temperature (c) Plot of COP of the System with Generator 2 Temperature (d) Plot of Q Generator1 with Generator 1 Temperature (e) Plot of Exergy of Evaporator with Generator 1 Temperature (f) Plot of Exergy of Condenser with Generator 1 Temperature (g) Plot of Exergy of Generator 1 with Generator 1 Temperature (h) Plot of Exergy of Generator 2 with Generator 1 Temperature (i) Plot of Exergy of Absorber with Generator 1 Temperature

VI. CONCLUSION

From the Performance assessment of double-effect Water/Li-Br Vapor Absorption Refrigeration System following conclusion can be given:

- The coefficient of performance of the system is 0.7088.
- The COP of generator increases with the increase in the generator temperature or vice versa within the respective limits. The generator temperature should be above 132°C for optimum performance.
- The work done by the generator will also increase with increase of its temperature.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 3, March 2015

- The exergy graphs of the evaporator and generator concludes that in the evaporator and generator, the value of exergy increases with increase in their corresponding temperature. The minimum value of exergy is at temperature of 119°C and the maximum value of exergy is at temperature of 139°C.
- The exergy graphs of the condenser and absorber concludes that in the condenser and absorber, the value of exergy decreases with increase in their corresponding temperature. The minimum value of exergy is at temperature of 119°C and the maximum value of exergy is at temperature of 139°C

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BIOGRAPHY



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