PERFORMANCE CHARACTERISTICS OF SINGLE EFFECT LITHIUM BROMIDE/ WATER ABSORPTION CHILLER FOR SMALL DATA CENTERS

by

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Presented to the Faculty of the Graduate School of

The University of Texas at Arlington in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON

August 2015

Acknowledgements

I would like to thank my supervising professor Dr. Dereje Agonafer for his immense support throughout my thesis. His guidance and valuable suggestions helped me in my presentation skills. Also I would like to thank him for giving me an opportunity to attend conferences and seminars.

I am grateful to Dr. Abdolhossein Haji-Sheikh and Dr. Ratan Kumar for being my committee members and their inputs on my thesis work.

I am thankful to Ibraheem Sheerah for introducing me to the topic of solar absorption chiller technology and EMNSPC lab members mainly Betsegaw Gebrehiwot for his valuable suggestions that helped me in my research work.

Many thanks to the mechanical and aerospace engineering staff mainly Ms. Sally Thompson and Ms. Debi Barton for being supportive throughout my Master's Program.

Also I would like to thank my friend Meghana Anoop for helping me create a webpage corresponding to my research work.

My special thanks to my parents Dr. Arun Babu and Sharada A and my sister Amritha for always being there encouraging me and without whom this would have been difficult. I thank them for providing an opportunity for pursuing my goals.

July 23, 2015

Abstract

PERFORMANCE CHARACTERISTICS OF SINGLE STAGE LITHIUM BROMIDE/ WATER ABSORPTION CHILLER FOR MEDIUM DATA CENTERS

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A medium data center consists of servers performing operations such as file sharing, collaboration and email. There are a large number of small and medium data centers across the world which consume more energy and are less efficient when compared to large data center facilities of companies such as GOOGLE, APPLE and FACEBOOK. Such companies are making their data center facilities more environmental friendly by employing renewable energy solutions such as wind and solar to power the data center or in data center cooling. This not only reduces the carbon footprint significantly but also decreases the costs incurred over a period of time.

Cooling of data center play a vital role in proper functioning of the servers. It is found that cooling consumes about 50% of the total power consumed by the data center. Traditional method of cooling includes the use of mechanical

compression chillers which consume lot of power and is not desirable. In order to eliminate the use of mechanical compressor chillers renewable energy resources such as solar and wind should be employed. One such technology is solar thermal cooling by means of absorption chiller which is powered by solar energy. The absorption chiller unit can be coupled with either flat plate or evacuated tube collectors in order to achieve the required inlet temperature for the generator of the absorption chiller unit. In this study a modular data center is considered having a cooling load requirement of 23kw. The performance characteristics of a single stage Lithium Bromide/ water refrigeration is presented in this study considering the cooling load of 23kw. Performance characteristics of each of the 4 heat exchangers within the unit is discussed which helps in customizing the unit according to the users' specific needs. This analysis helps in studying the importance of different properties such as the effect of inlet temperatures of hot water for generator, inlet temperatures of cooling water for absorber and condenser and outlet chilled water temperatures of the evaporator.

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Chapter 1

INTRODUCTION

A data center is a facility which houses servers ranging from few hundred to thousand performing critical operations of a company. It is also called as the brain of the organization. These servers perform operations such as file sharing, email, storage, collaboration. The servers generate a large amount of heat which needs to be removed for proper functioning of the equipment. Data centers consume a lot of power. Studies show that cooling equipment's consume most of the total power.

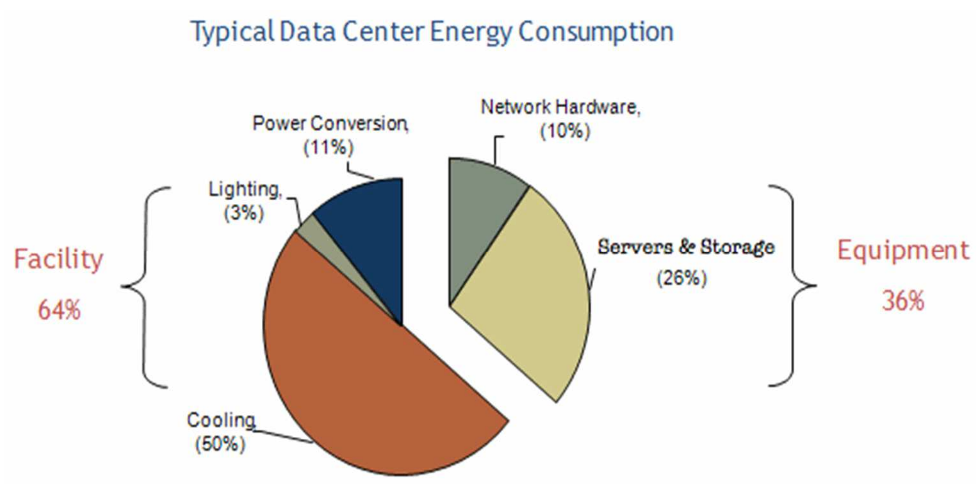

Figure 1.1 Typical Data Center Energy Consumption

To reduce the power consumed and to make it environmental friendly renewable energy such as solar is used. In this study solar thermal cooling for a modular data center is discussed and the performance parameters are determined.

In chapter 2 classifications of data centers based on size, data center cooling methods, solar technology overview and literature review

Chapter 3 discusses absorption technology, overview, and advantages of absorption chillers over vapor compression chillers.

In chapter 4 performance characteristics of a single effect lithium bromide/ water absorption chiller is evaluated for the modular data center having a cooling load of 23k.w. Thermodynamic equations are used in calculating the respective properties. Graphs are plotted between COP and the temperatures of the generator, condenser, evaporator and absorber. The analysis is done using Microsoft Excel.

In chapter 5 the performance analysis for the evaporator of the Absorption refrigeration unit is presented by considering the manufacturers product details. The thermodynamic equations are used to calculate the geometric properties of the heat exchanger and to do a heat transfer analysis.

In chapter 6 the performance analysis for the condenser of the Absorption refrigeration unit is presented by considering the manufacturers product details. The thermodynamic equations are used to calculate the geometric properties of the heat exchanger and to do a heat transfer analysis.

Chapter 2

LITERATURE REVIEW

2.1 Data Center Classification

Data centers are classified based on business needs and availability as follows:

1. Tier I
2. Tier II
3. Tier III
4. Tier IV

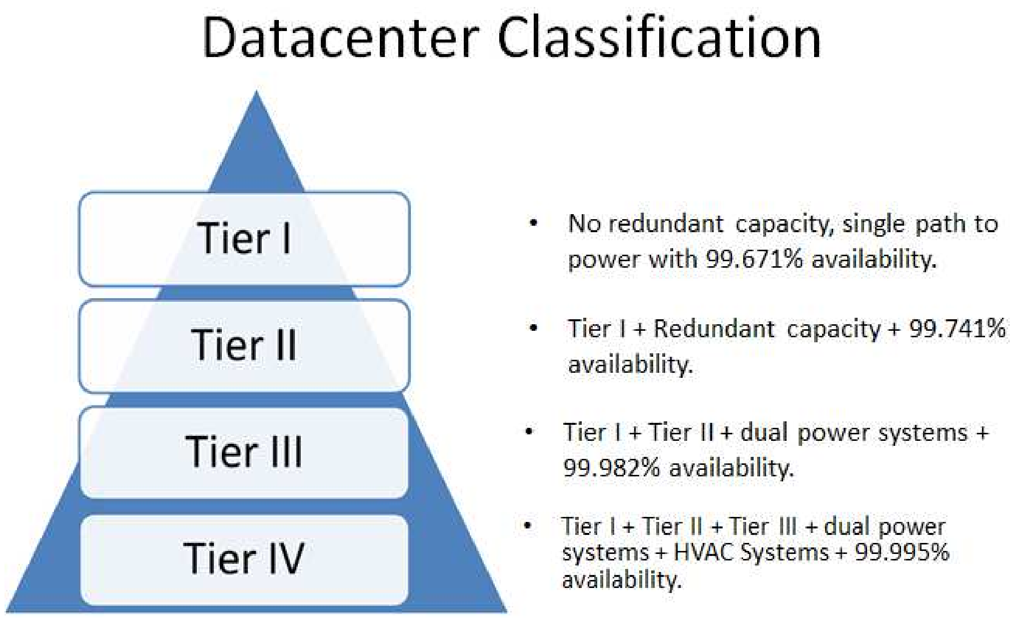

Figure 2.1 Datacenter Classification

Modular data centers fall in the category of Tier I data center. A modular data center is the one with a container which is pre-fabricated that can be shipped and deployed anywhere. Some of the advantages of modular data center are listed below:

1. Speed of deployment – It can be quickly ordered and delivered to the data center site.
2. Agility – It has the capability of meeting the needs of the organization by providing services and are hence built closely to the organization business and infrastructure.
3. Mobility – It can be delivered where ever needed. The parts can be delivered separately and are assembled together. It helps in recovery situations where a data center needs to be setup immediately.
4. Scalability – It can easily match the demand quickly and the only changes required will be that of the infrastructure at the site.
5. Efficiency – It has a higher efficiency because of the engineered products of the data center.
6. Density – The space in a modular data center is used effectively and it has a higher density when compared to a regular data center.

The modular data center (IT POD) considered in this study consists of 120 HP SE1102 servers with cooling load requirement of 23kw.Four cabinets with servers are placed in a cold aisle/hot aisle configuration. The geometric properties of the modular data center are:

Table 2.1 Geometric Properties of IT-Pod

SL No	Name	Value	Units
1.	Length	28	ft
2.	Width	12	ft
3.	Height	10	ft

2.2 Data Center Cooling Methods

The heat generated by the servers within the data center needs to be dissipated for proper functioning of the components. Improper cooling results in failure of components.

There are several data center cooling methods some of which are listed below:

CRAC (computer room air conditioning): CRAC units are used in cooling of data centers by introducing cold air through the raised floors of the data center by perforated tiles. The servers are usually placed in a hot aisle and cold aisle configuration. The warm air is rejected back to the CRAC units.

Free Cooling: cooling towers are used to cool the servers by removing the coolant heat from the heat exchanger. This is a more energy efficient solution compared to the use of chiller.

Airflow: In order to increase the airflow to the servers the number of perforated tiles can be varied. In order for good circulation the cold air from the perforated tiles should match the horizontal air from the servers.

In Rack Cooling: It acts like an air to water heat exchanger within the racks which allows the warm air from the servers to pass over the tubes containing cold water. This helps in lowering the load on the CRAC units.

Container Data Centers: This houses the servers and the cooling units within a shipping container. It also includes the power system. It can handle high power densities.

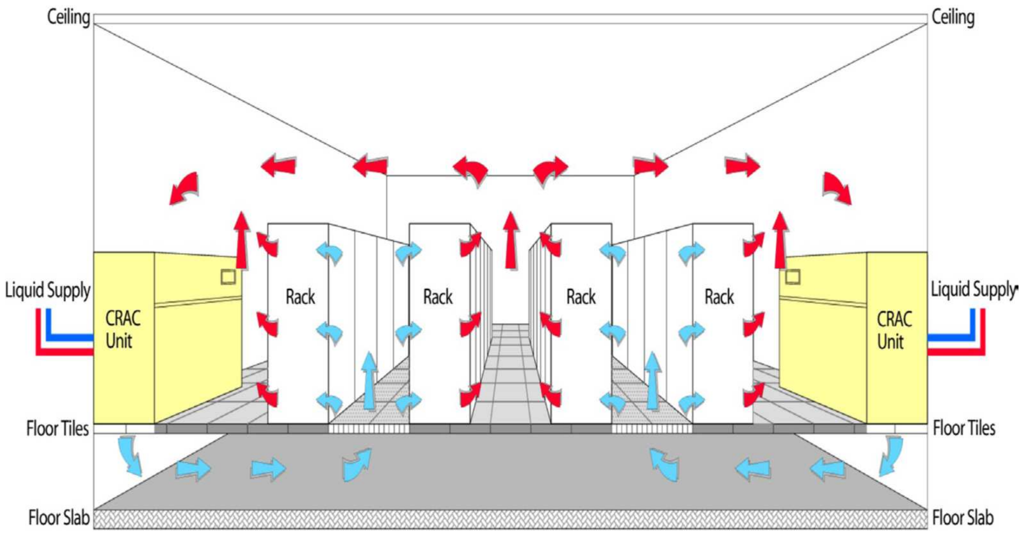

Figure 2.2 Raised floor data center with cold aisle and hot aisle configuration

2.3 Green Data Center

Green Data Centers are powered entirely or partially by renewable energy sources such as solar energy. Their dependence on non-renewable sources is minimum. They are designed in such a way that the lighting, storage, mechanical, electrical and computer systems are functioning at maximum efficiency. Due to use of renewable sources of energy their impact on the environment is minimum. In other words they help in decreasing the carbon footprint. Some of the technologies used in the construction of a green data center are:

1. Waste heat recycling
2. Free cooling
3. Photovoltaics
4. Hot aisle and cold aisle configuration
5. Low emission materials

Figure 2.3 Google's Hamina Data Center cooled by sea water

There are two ways by which renewable energy can be generated:

1. Onsite generation
2. Offsite generation

Onsite generation or self-generation involves setting up of solar farm within the facility. This minimizes the transmission losses and conversion losses that occur when the energy is generated offsite and transmitted to the facility of fed to the grid. The space required for the onsite generation will be more when compared to that of the offsite generation.

In offsite generation the energy is produced away from the data center facility and later fed to the electric grid. It is usually purchased from power generating companies which use renewable sources to generate power. A power purchase agreement (PPA's) are signed between two companies one which generates the electricity and the other which is in need of electricity. In offsite generation some losses such as transmitting power and conversion losses from AC to DC occur. In this the availability of space is not an issue. The data center facility is mainly dependent on the grid for power and this can be affected in countries where grid outages occur frequently. To overcome this problem storage devices are used as backup options for the data center. Batteries are used as storage devices.

2.4 Solar Energy Overview

Solar energy is harnessed from the incident sunlight on the earth's surface. The incident sunlight can be converted to electricity by means of photovoltaic cells. Silicon a semiconductor material is used in these photovoltaic cells. Semiconductor materials absorb sunlight which excites the valence electrons. The flow of valence electrons creates electricity.

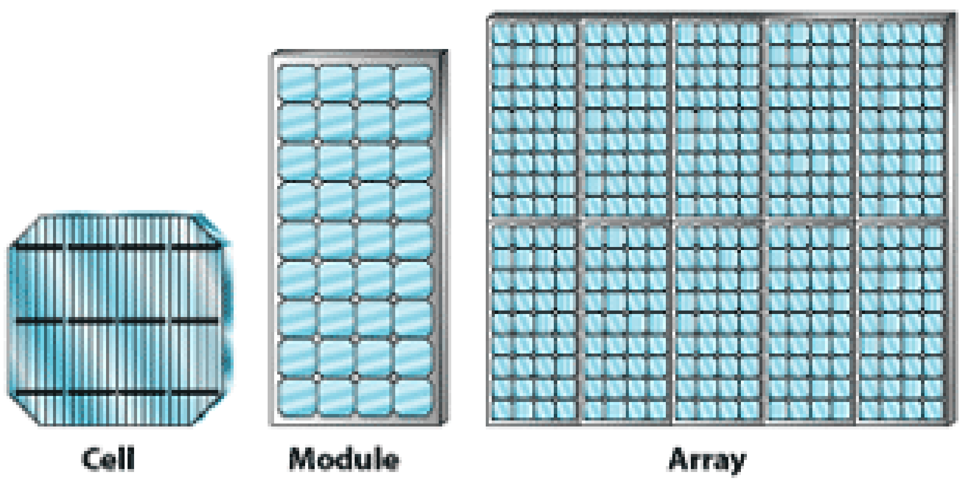

Figure 2.4 Solar cells, panels and arrays

There are three processes by which solar energy can be converted:

1. Helio chemical
2. Helio thermal
3. Helio electrical

Helio chemical is the process used by plants to convert solar energy. It is called as photosynthesis.

Helio thermal process is a solar thermal process in which the solar energy is converted by heating of a secondary fluid.

Helio electrical process involves the use of photovoltaic cells or solar cells.

Solar technologies are classified broadly into two categories as:

1. Concentrated Photovoltaic (PV)
2. Concentrating solar power (CSP)

Concentrated photovoltaic systems concentrate the sunlight onto the solar cells. They use a mirror or lens to focus the light. Such systems need to track the sunlight in order to keep the focus continuously on the cells. They are highly efficient, initial investment and the cost of these is also low.

Figure 2.5 Concentrated Photovoltaic (CPV) system

Concentrating solar power systems use mirrors to focus the sunlight. The sunlight is converted into heat to produce steam in order to run a turbine to generate electricity. Commercially available concentrated solar power technologies are classified as trough systems, tower systems, linear Fresnel reflector and dish systems.

Trough systems are parabolic with long pipes at the center or the focal point. These pipes carry oil in them. The concentrated sunlight is focused on this pipe to heat the oil which in turn is used to heat water to produce steam and thus run a turbine.

Figure 2.6 Concentrated Solar Power Parabolic Trough

Tower systems consist of a long tower at the top of which a tank with water is present. The tower is surrounded by a number of reflectors placed circularly. These reflectors focus the incident light onto the tank containing water. This increases the temperature of water thus making it boil which is used to produce steam to run the turbine. The tank is called as a receiver and the reflectors are called as heliostats. These systems are efficient and can be used to store the boiling water that can be used after sunset.

Figure 2.7 Tower Systems

Dish systems consist of large dish structure in which the receiver is mounted at the focal point of the dish. This receive is an integrated assembly of engine and generator. The engine houses cylinders consisting of hydrogen or helium gas which heats up when the light is concentrated at it. This induces the motion of the piston which rotates the crankshaft of the generator thus generating electricity.

Figure 2.8 Dish system

Linear Fresnel reflector consists of long parallel curved mirrors which are flat and low cost. They focus the light onto long pipes containing water which are elevated. These receivers generate high pressure steam which can be used to run the turbine to generate electricity.

Figure 2.9 Linear Fresnel Reflector

Solar arrays are combination of modules that extend several meters on each side. They generate few watts of electricity. They are either mounted on a tracking device which tracks the sunlight and allows for more exposure or they are fixed facing south. Solar cells are combined to form modules and these modules form arrays.

Figure 2.10 Solar Array

Chapter 3

ABSORPTION REFRIGERATION REVIEW

3.1 Absorption Refrigeration

Absorption refrigeration uses thermal energy for compression rather than conventional electric compressors. This eliminates the use of electric compressors. The form of energy input to the absorption refrigeration process is heat as compared to the work provided by motor in the traditional vapor compression process.

3.2 Solar powered absorption chiller

The basic absorption refrigeration principles are:

1. Flow of heat occurs from hot surfaces to cold surfaces.
2. Decrease in the pressure above the liquid decreases its boiling point.
3. Heating of the liquid turns it into vapor and the vapor condenses to form liquid.

Absorption chiller uses a combination of lithium bromide and water in the process. Water acts as a refrigerant and lithium bromide acts as an absorbent. The affinity of water and lithium bromide makes it a suitable pair for this process and is preferred over water and ammonia configuration because of the disadvantages such as high pressure, volatility, toxic nature and corrosive action. The lithium bromide and water combination is nonvolatile and eliminates the need of rectifier in the system.

There are four main components of an absorption chiller:

1. Generator
2. Condenser
3. Evaporator
4. Absorber

Generator:

The input to the generator is the hot water which is stored in the storage tank obtained by solar water heating. The generator consists of a mixture of lithium bromide - water which is heated by the hot water. The inlet temperature to the generator ranges between 70^0C -88^0C. When the water in the storage tank reaches within the range of the inlet temperature it passes to the generator in which it converts the water in the mixture of lithium bromide - water to vapor leaving behind the LiBr solution which is called the strong solution.

Condenser:

The condenser houses a set of tubes carrying cold water being circulated from a cooling tower. The water vapor from the generator condenses on the tubes and trickles down the condenser. The water droplets then flow to the evaporator.

Evaporator:

In the evaporator the liquid vaporizes due to low pressure which in turn helps to cool the required space. The absorption chiller unit is divided into 4 chambers, the upper half consists of generator and condenser and the lower half consists of evaporator and absorber. The pressure difference between the upper and lower chambers is about the ratio of 1:10.

Absorber:

The strong solution from the generator flows to the absorber through a heat exchanger. The water vapor coming into the absorber is absorbed by the LiBr solution, this weak solution is then sent to the generator through the heat exchanger. In the heat exchanger the strong solution containing LiBr preheats the weak solution from the absorber which is a mixture of LiBr-water. The chilled water temperature from the evaporator should be maintained in the range of 5-7^0C.

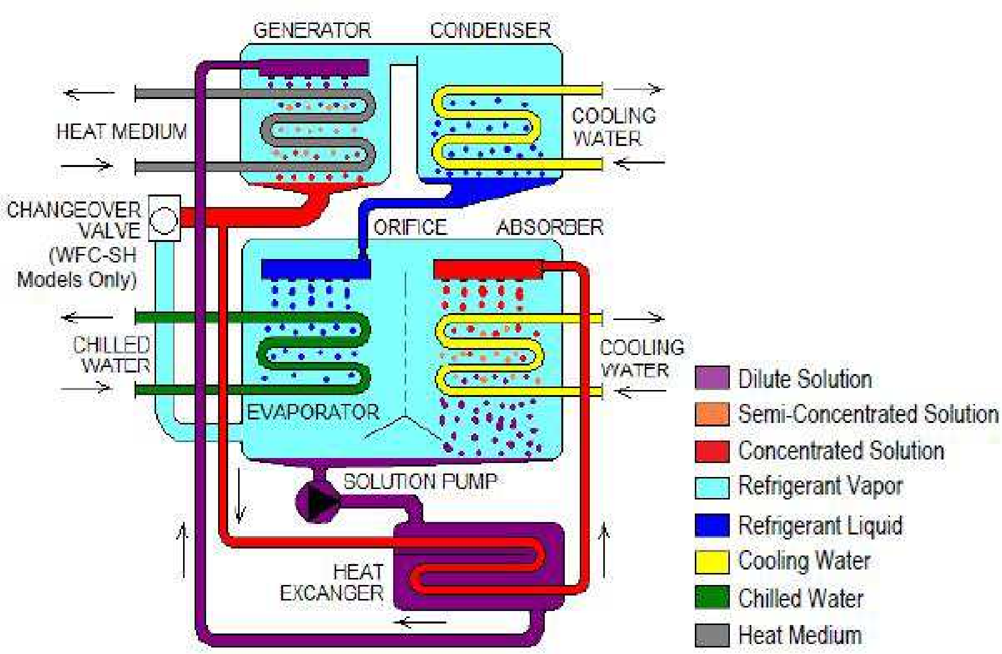

Figure 3.1 Absorption Chiller Schematic

Absorption chillers are classified based on the energy input as follows:

1. Gas driven absorption chillers
2. Hot water driven absorption chillers

They are also classified as:

1. Single effect absorption chillers
2. Multi effect absorption chillers

In multi effect absorption systems the heat rejected at a higher temperature is used as an input for the lower stage for heating of the fluid. Multi effect absorption systems have a higher range of coefficient of performance values when compared to the single effect absorption systems.

3.3 Vacuum tube solar panels

Vacuum tube solar panels operate on the principle that black body absorb maximum radiation when compared to other bodies and by the principle that water boils at lower temperature with decrease in air pressure by evacuating the tube. They are also called as evacuated tubes. It consists of four main parts they are:

1. Evacuated tube: It absorbs solar energy and converts it into usable heat.
2. Heat pipe: It is a vacuum tube made of pure copper which transfers the heat from the evacuated tube to the manifold.
3. Manifold: It is an insulated box which consists of the header pipe to which number of heat pipes are connected.

4. Mounting frame: The mounting frame holds the manifold and rest of the system and can be adjusted accordingly.

Figure 3.2 Evacuated tube solar panels

Evacuated tube is made of two glass tubes which are extremely strong. The outer tube allows the light rays to pass through it with minimal reflection. The inner tube is coated with a selective material with high radiation absorbing properties and very minimal reflection. These borosilicate tubes are fused together and the air in between them is evacuated to form vacuum.

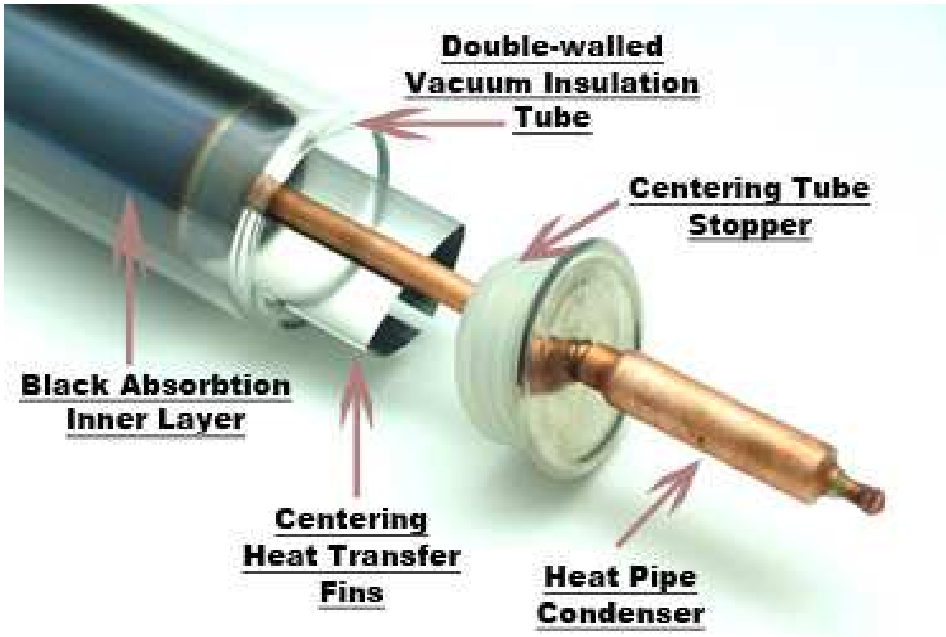

Figure 3.3 Evacuated Tube

Heat pipe contains purified water and some additives which boil at 30 ^{o}C or 86 ^{o}F due to decreased air pressure. When the tube is heated above 30 ^{o}C the liquid vaporizes and these vapors rise to the top of the tube and transfer the heat to the header pipe within the manifold. The vapors then condense and collect at the bottom of the tube and this process continues.

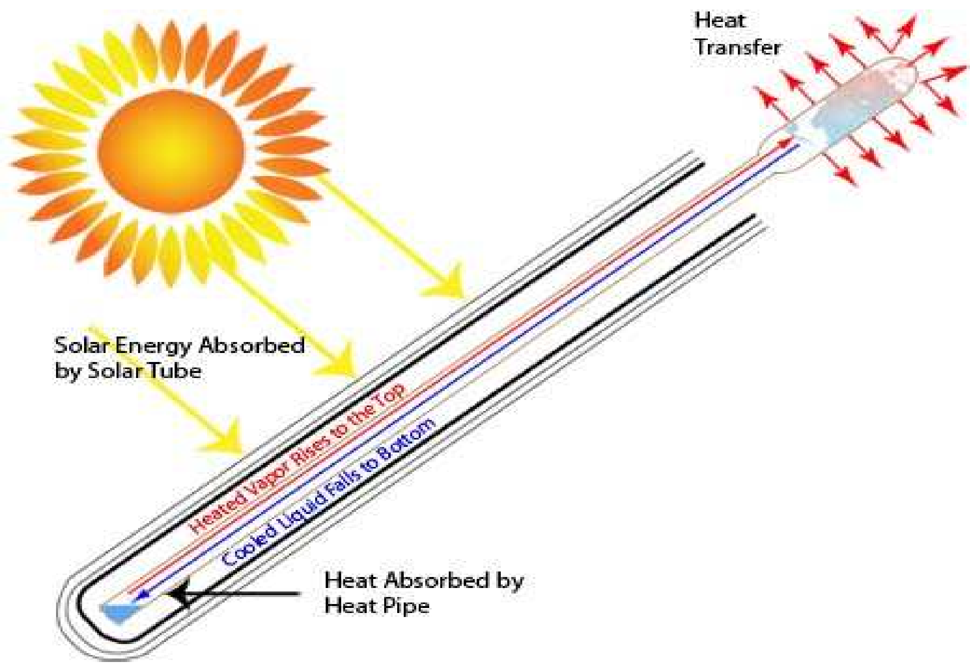

Figure 3.4 Heat Pipe

Heat pipe is a vacuum tube which consists of liquid which boils at a low temperature. When the pipe is heated the liquid boils and converts to vapor and rises to the top of the tube carrying heat. This heat is transferred to the header pipe which is located inside the manifold. The liquid then condenses and trickles back to the bottom of the tube. This process continues repeatedly and is a faster mode of heat transfer. The heat transferring fins located inside the evacuated tube helps in increasing the heat transfer to the manifold.

3.4 Difference between vapor compression and absorption refrigeration

Vapor compression systems are small in size containing moving parts. The system performance is dependent on evaporator temperatures. Due to the presence of moving parts in the system noise and vibration exits. Maintenance is required to ensure proper functioning of the machine. Coefficient of performance decreases with the variation in loads.

Absorption refrigeration systems are larger in size and do not contain moving parts. Performance of the system is not entirely dependent on evaporator temperatures. Due to the absence of moving parts in the system no noise and vibration exist. This also reduces the maintenance required for the system. Coefficient of performance does not decrease with the variation in the load. The power consumption of such systems are less when compared to that of a vapor compression system.

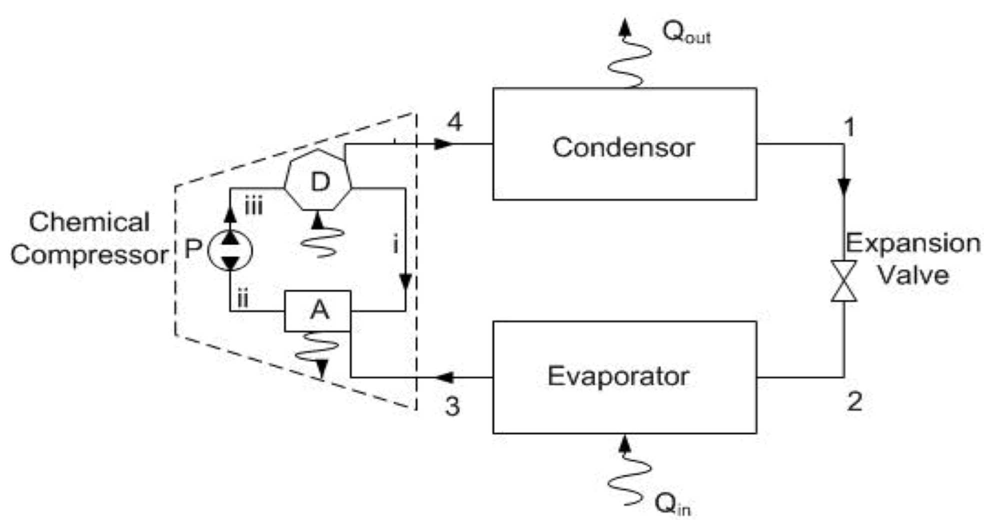

Figure 3.5 Vapor Absorption system

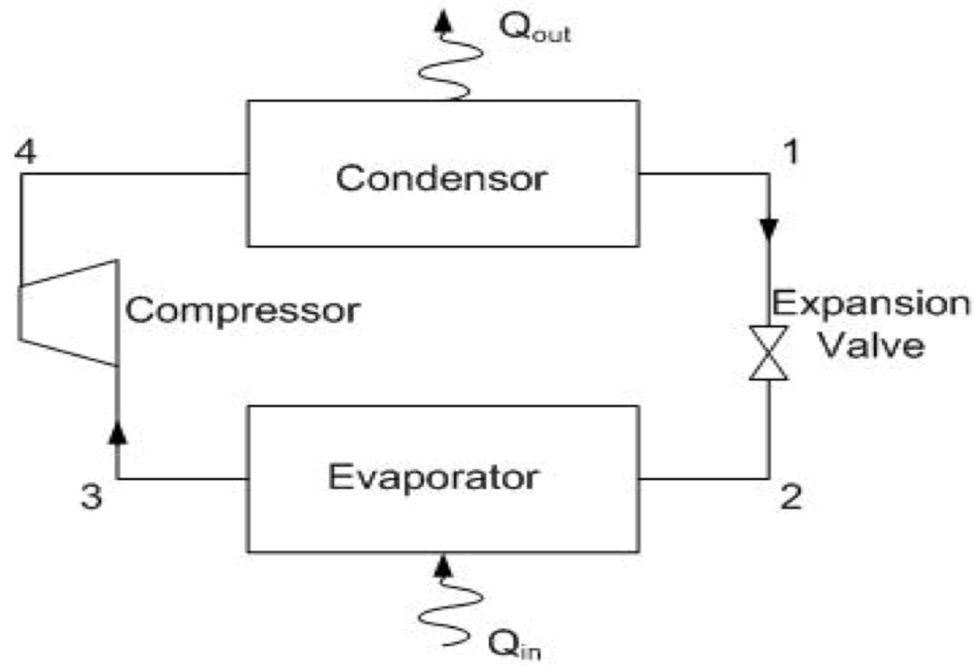

Figure 3.6 Vapor Compression System

3.5 Literature Review

Absorption systems have been studied in great detail. Some of the topics discussed in the literature papers are mass and energy balance between components of the system, construction details of each component based on the dimensions, different working fluids and arrangements within the system, impact of working fluid mixtures on the coefficient of performance, 1st and 2nd law analysis of the system, losses and thermodynamic analysis on single effect and double effect systems, use of heat pipe exchanger over the conventional heat exchanger.

Chapter 4

PERFORMANCE CHARACTERISTICS

4.1 Input Parameters and procedures

The performance characteristics for a single effect lithium bromide – water absorption chiller is calculated using the thermodynamic equations listed in [23]

The input parameters used in calculating the performance characteristics are:

1. Generator inlet temperature – 85 ^{0}C
2. Evaporator outlet temperature – 8 ^{0}C
3. Condenser cooling water temperature – 30 ^{0}C
4. Absorber cooling water temperature – 30 ^{0}C
5. Exchanger effectiveness – 0.7
6. Evaporator heat capacity – 23 kw or kcal/hr

The generator temperatures are varied in the increments of 5 ^{0}C starting from 85 ^{0}C till 105 ^{0}C. Evaporator temperatures are varied in the increments of 0.5 ^{0}C starting from 8 ^{0}C till 10 ^{0}C. Condenser and Absorber cooling water temperatures are varied in the increments of 0.5 ^{0}C each starting from 30 ^{0}C till 32 ^{0}C. The exchanger effectiveness is kept at a constant value of 0.7 throughout the calculation. Evaporator heat capacity is varied in the increments of 1000 kcal/hr starting from 19789 kcal/hr to 23789 kcal/hr. The performance characteristics are calculated based on these values and tables are created in Microsoft Excel software.

4.2 Tabulated Results

Table 4.1 Coefficient of Performance for different evaporator and generator heat capacities

Rate of Heat Transfer (Qe) kcal/hr	Rate of Heat Transfer (Qg) kcal/hr	Coefficient of Performance (COP)
19789.67	24183.0593	0.82
20789.67	25577.2522	0.81
21789.67	26997.2067	0.81
22789.67	28440.1893	0.80
23789.67	29904.3748	0.80

Table 4.2 Evaporator Pressure for different evaporator temperatures

Evaporator Temperature (te) ^{o}C	Evaporator Pressure (Pe) mmHg
8	7.99
8.5	8.26
9	8.55
9.5	8.85
10	9.15

Table 4.3 Condenser Pressure for different condenser temperatures

Condenser Temperature (tc) ^{o}C	Condenser Pressure (Pc) mmHg
30	31.81
30.5	32.74
31	33.69
31.5	34.66
32	35.66

4.3 Graphical Results

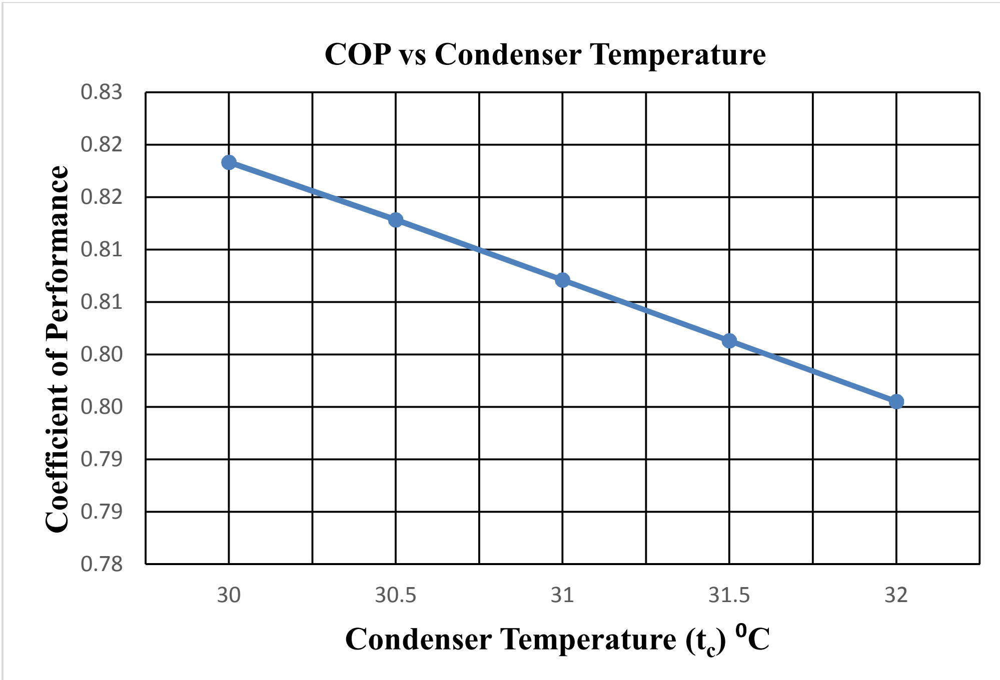

Figure 4.1 Effect of Condenser Temperature values on COP

The above figure shows the effect of condenser temperature values on the COP of the system. It can be seen that increasing the cooling water temperature to the condenser results in decrease of the Coefficient of Performance. Therefore condenser temperatures need to be kept as low as possible in order to maintain a high COP. Keeping the temperature of the cooling water low helps it to absorb maximum heat rejected from the mixture of lithium bromide and water.

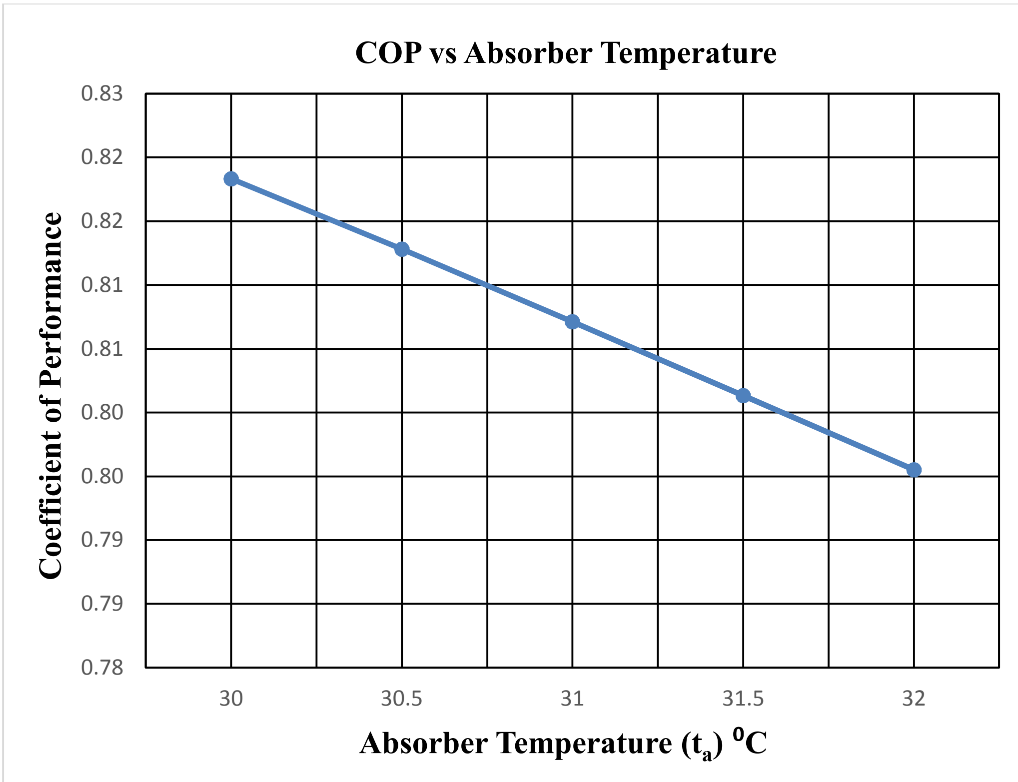

Figure 4.2 Effect of Absorber Temperature values on COP

The above figure shows the effect of absorber temperature values on the COP of the system. It can be seen that increasing the cooling water temperature to the absorber results in decrease of the Coefficient of Performance. Therefore absorber temperatures need to be kept as low as possible in order to maintain a high COP. Keeping the temperature of the cooling water low helps it to absorb maximum heat rejected from the mixture of lithium bromide and water. High temperature cooling water cannot dissipate enough heat as compared low temperature cooling water.

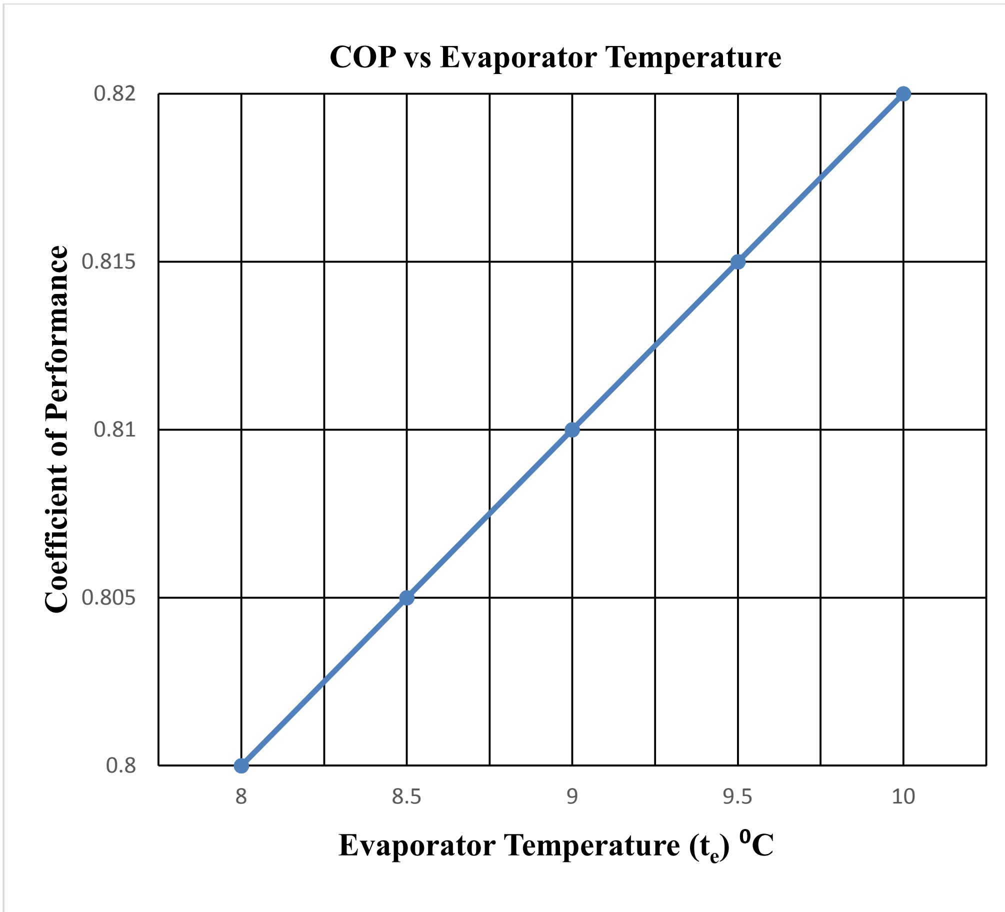

Figure 4.3 Effect of Evaporator Temperature values on COP

The above figure shows the effect of evaporator temperature values on the coefficient of performance of the system. It can be seen that the coefficient of performance gradually increases with the increase in evaporator temperature values. Therefor it is ideal to maintain the evaporator temperatures within the range of 8-10 ^{0}C.

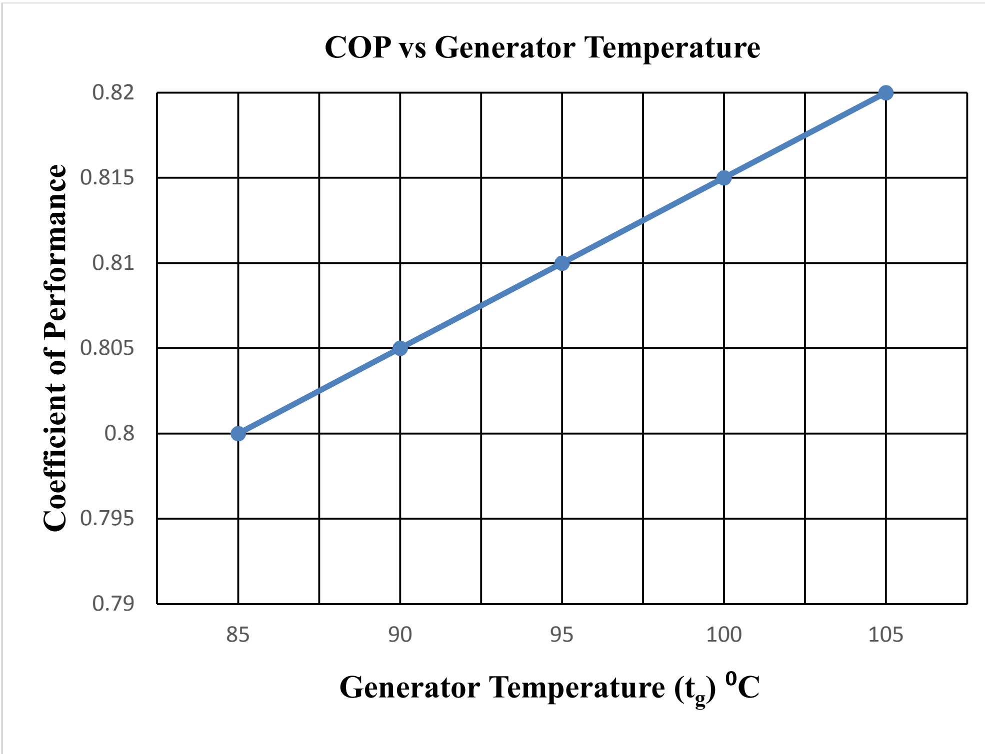

Figure 4.4 Effect of Generator Temperature values on COP

The above figure shows the effect of generator temperatures on the coefficient of performance of the system. It can be seen that as the generator temperature increases the coefficient of performance of the system increases. This also helps in deciding the type of collectors that can be used to obtain these temperatures. There also exists a low generator temperature limit below which the cycle does not operate. The ideal temperature range for generator temperature is between 85 – 100 ^{0}C.

Chapter 5

GASKETED PLATE HEAT EXCHANGER

A plate heat exchanger uses plates to transfer heat between fluids. The entire surface area of the plates are exposed to the fluids thereby allowing better heat transfer and to decrease the temperature rapidly. Large sized plate heat exchangers use gasket between the plates and small sized heat exchangers are generally brazed. It was invented in 1923 by Dr. Richard Seligman. The plates used in this heat exchanger is usually made of stainless steel and are obtained by pressing of metal plates. The plates are arranged in such a way that there are troughs in direction of the flow of liquid between the plates. These plates are then compressed to form one unit.

The fluid flows through the channels located in the plates when they are compressed to form one unit, the channels form a parallel flow arrangement alternating between the hot and cold fluids respectively. High heat transfer coefficient can be achieved in such heat exchangers due to more exposure of the surface area of the plates to the fluids.

Based on the flow of fluid in the headers there are two possible configurations they are:

1. U – Type
2. Z – Type

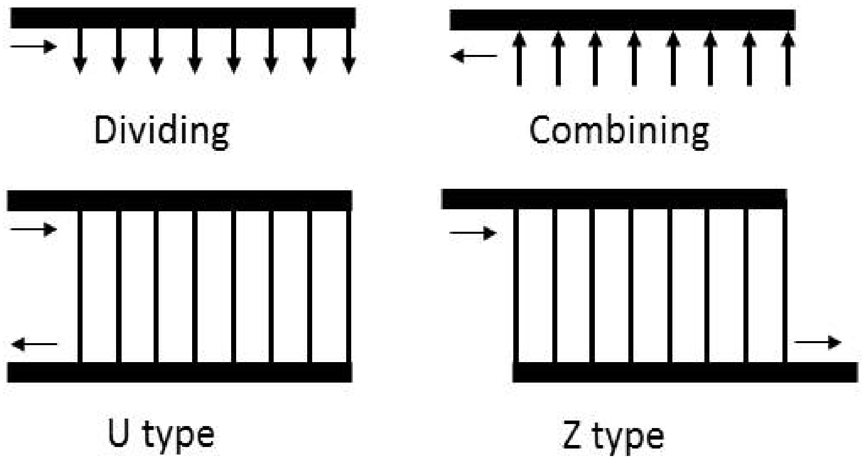

Figure 5.1 Types of configuration in PHE

Some of the advantages of using plate heat exchanger over shell and tube heat exchanger are:

1. Compact and smaller in size
2. Replacement of plates is easy
3. High heat transfer coefficient
4. Maintenance is easy

There are two types of corrugation within the plates of the heat exchanger they are:

1. Intermating
2. Chevron

Chevron type of corrugation is most commonly used when compared to intermating because of high heat transfer rates.

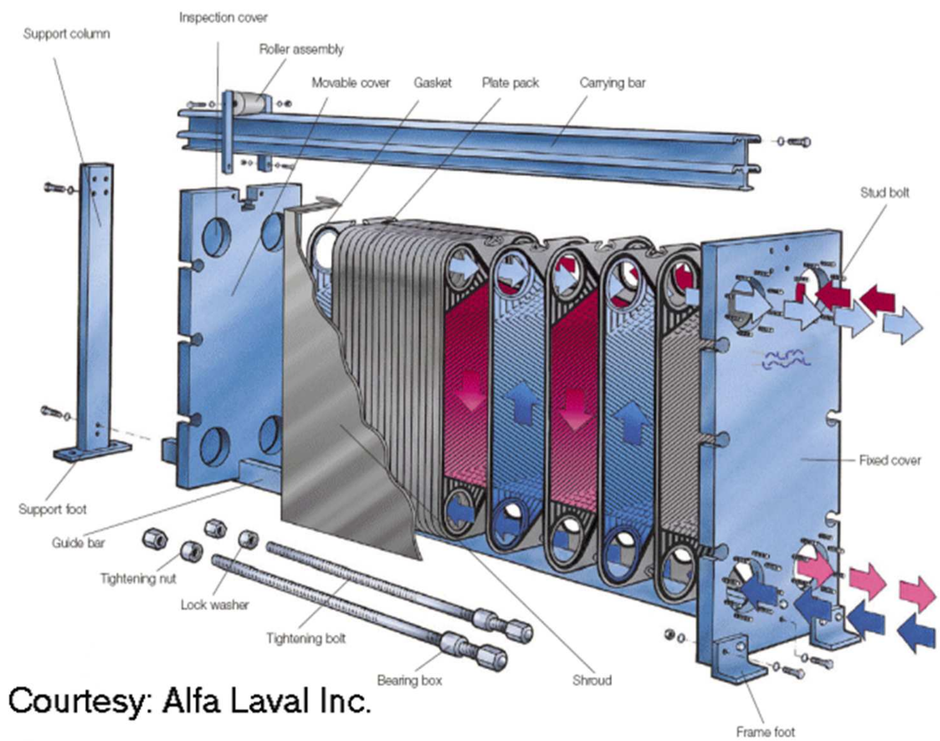

Figure 5.2 Alfa Laval Plate Heat Exchanger Block Diagram

Chapter 6

STEPWISE PERFORMANCE & THERMAL ANALYSIS OF ABSORPTION CHILLER COMPONENTS

The stepwise performance & thermal analysis is carried out by using the following thermodynamic equations listed in [21]

6.1 Evaporator Performance and Thermal Analysis

The brazed plate heat exchanger considered for the analysis of evaporator is “Alfa Laval AC30EQ/ACH30EQ”.

Figure 6.1 Alfa Laval Brazed Heat Exchanger AC30EQ/ACH30EQ

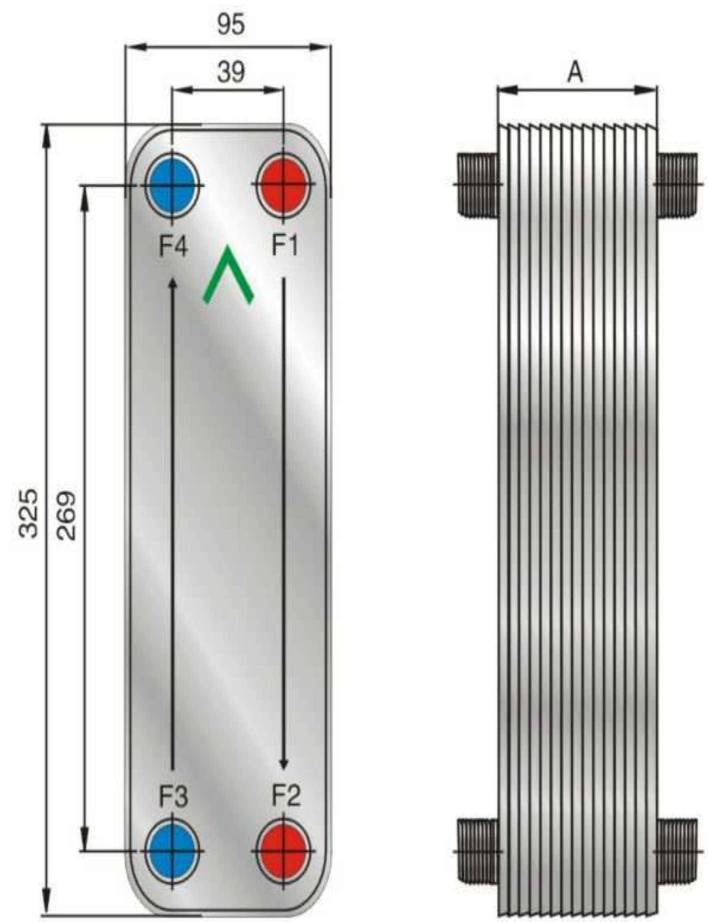

Figure 6.2 Alfa Laval Brazed Plate Heat Exchanger AC 30/ACH 30 Product Specifications

The condensed refrigerant liquid from the condenser flows into the evaporator due the pressure difference between the condenser and evaporator. The refrigerant liquid boils on the chilled water tubes thereby converting to vapor and passes to absorber. The refrigerant vapor absorbs the heat from the cooling water being circulated from the space to be cooled.

Table 6.1 Process and constructional specifications for evaporator

Symbol	**Name**	**Value**	**Units**
a	Height	0.325	m
b, L_w	width	0.095	m
L_v	Vertical Connection distance	0.269	m
L_h	Horizontal Connection distance	0.039	m
L_c	Plate Pack Length	0.053	m
D_P	Port Diameter	0.03	m
ṁ	Flow Rate	0.8	kg/sec
	Flow Rate	0.17	kg/sec
T	Chilled water inlet temperature	13	^{0}C
	chilled water outlet temperature	7	^{0}C
	Condensate to expansion device	38	^{0}C
	Vapor to absorber	6	^{0}C
C_P	Specific heat of water	4186	J/kg. k
N_t	Number of plates	20	
t	plate thickness	0.0006	m
A_e	Heat exchanger area	1	m^2
μ_h	Viscosity of hot fluid	0.001	N.s/m^2
μ_c	Viscosity of cold fluid	0.001	N.s/m^2
	Total Fouling Resistance	0.0001	m^2.K /W
k	Thermal Conductivity of SS	17	W/m.K

Results obtained:

Table 6.2 Safety Factor for Evaporator

Fouled Surface heat load “Q_f” kW	Required heat load “Q_r” kW	Safety Factor "C_S"
29611.4	23232.3	1.27

6.2 Condenser Performance and Thermal Analysis

The brazed plate heat exchanger considered for the analysis of the condenser is “Alfa Laval CB 30/CBH 30”.

Figure 6.3 Alfa Laval Brazed Plate Heat Exchanger CB 30/CBH 30

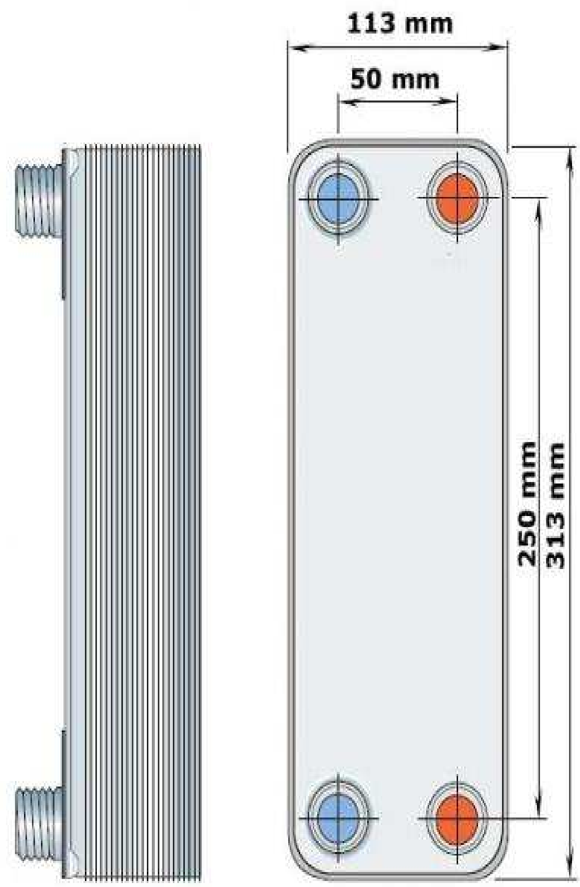

Figure 6.4 Alfa Laval Brazed Plate Heat Exchanger CB 30/CBH 30 Product Specifications

The refrigerant vapor from the generator enters into the condenser and condenses over the tubes of cooling water thereby forming droplets. The heat from the vapor is absorbed by the cooling water which exits the condenser and is sent to a cooling tower.

Table 6.3 Process and constructional specifications for Condenser

Symbol	**Name**	**Value**	**Units**
a	Height	0.313	m
b, L_W	width	0.113	m
L_v	Vertical Connection distance	0.25	m
L_h	Horizontal Connection distance	0.05	m
L_c	Plate Pack Length	0.056	m
D_P	Port Diameter	0.03	m
$\dot{m}_h$	Flow Rate of hot fluid	1.9	kg/sec
$\dot{m}_c$	Flow Rate of cold fluid	1.8	kg/sec
T	Vapor from generator to condenser	40	^{0}C
	Condensate to expansion device	37	^{0}C
	Outlet Cooling water from condenser	36	^{0}C
	Inlet cooling water to condenser	33	^{0}C
C_P	Specific heat of water	4186	J/kg. k
N_t	Number of plates	20	
t	plate thickness	0.0006	m
A_e	Heat exchanger area	1	m^2
μ_h	Viscosity of hot fluid	0.001114	N.s/m^2
μ_c	Viscosity of cold fluid	0.001428	N.s/m^2
	Total Fouling Resistance	0.00005	m^2. K /W
k	Thermal Conductivity of AISI 316	16.3	W/m. K

Results obtained:

Table 6.4 Safety Factor for condenser

Fouled Surface heat load “Q_f” kW	Required heat load “Q_r” kW	Safety Factor "C_S"
29611.4	23232.3	1.27

6.3 Generator Performance and Thermal Analysis

The brazed plate heat exchanger considered for the analysis of the condenser is “Alfa Laval CB 76/CBH 76”.

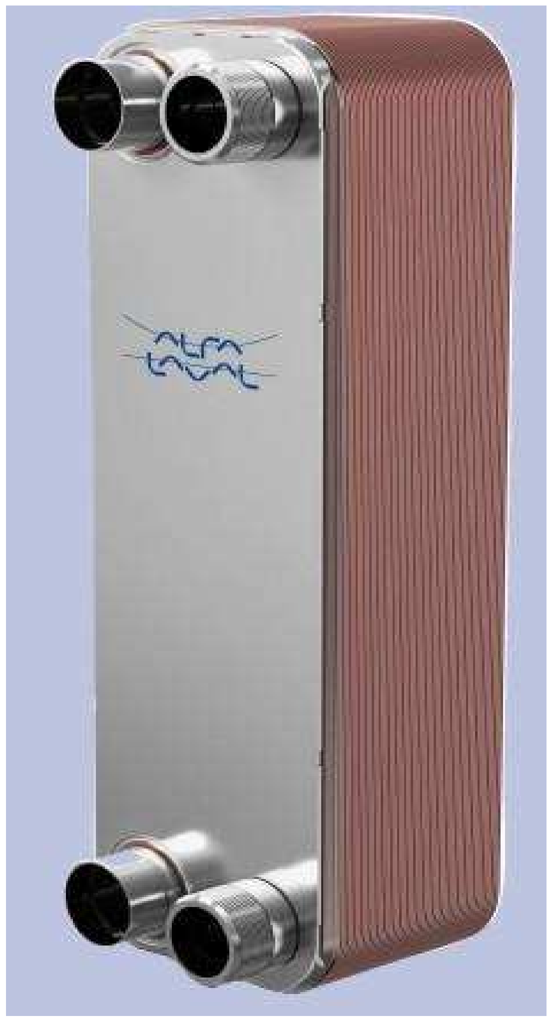

Figure 6.5 Alfa Laval Brazed Plate Heat Exchanger CB 76/CBH 76

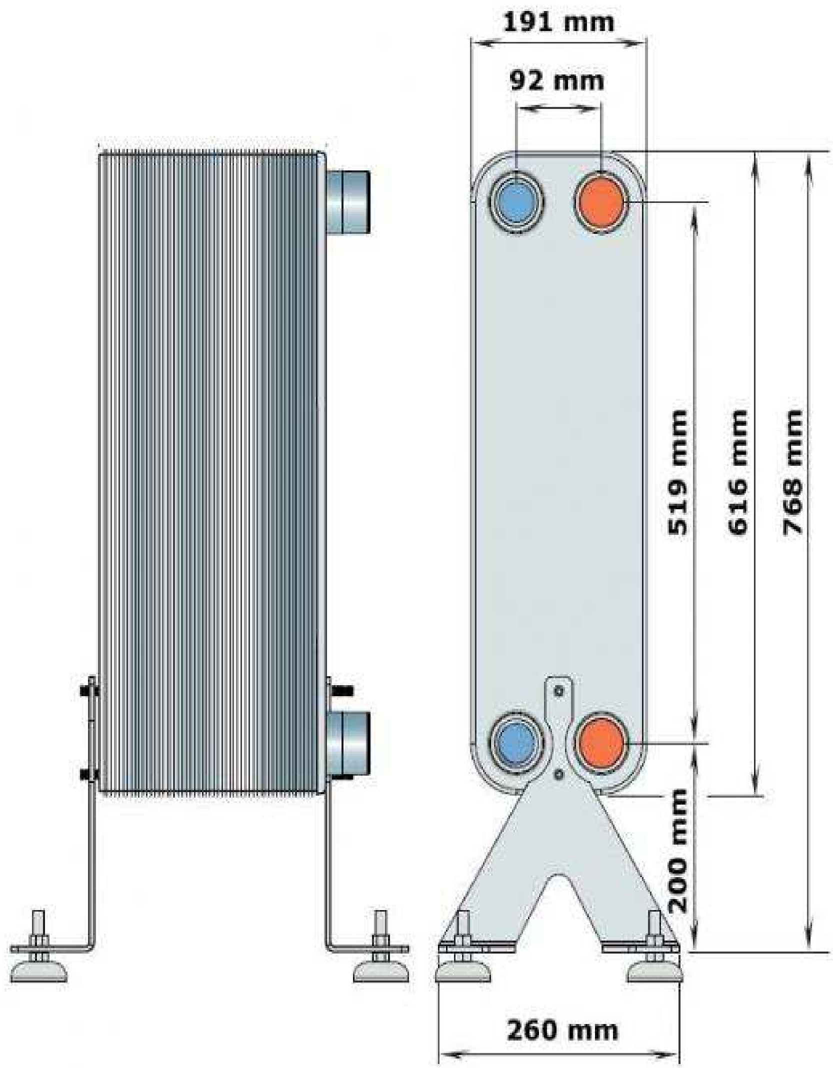

Figure 6.6 Alfa Laval Brazed Plate Heat Exchanger CB 76/CBH 76 Product Specifications

Generator consists of a mixture of lithium bromide and water. The water in the mixture acts as the refrigerant and the lithium bromide acts as an absorbent. The water is converted into vapor by means of solar energy input from the collectors. The refrigerant vapor passes over to the condenser where it condenses over the cooling water tubes. The absorbent remaining in the generator is known as strong solution due to the absence of the refrigerant and it flows to the solution heat exchanger where it transfers the heat onto the incoming weak solution from the absorber. In other words preheating the weak solution before it enters the generator.

Table 6.5 Process and constructional specifications for Generator

Symbol	**Name**	**Value**	**Units**
a	Height	0.618	m
b, L_W	width	0.191	m
L_v	Vertical Connection distance	0.519	m
L_h	Horizontal Connection distance	0.092	m
L_c	Plate Pack Length	1.057	m
D_P	Port Diameter	0.03	m
$\dot{m}_h$	Flow Rate of hot fluid	1.1	kg/sec
$\dot{m}_c$	Flow Rate of cold fluid	0.8	kg/sec
T	Hot water inlet to generator	85	^0C
	outlet hot water from generator	80	^0C
	strong solution outlet from generator	74	^0C
	weak solution inlet to generator	67	^0C
C_P	Specific heat of water	4186	J/kg. k
N_t	Number of plates	20	
t	plate thickness	0.0006	m
Ae	Heat exchanger area	6	m^2
μ_h	Viscosity of hot fluid	0.001114	N.s/m^2
μ_c	Viscosity of cold fluid	0.001428	N.s/m^2
	Total Fouling Resistance	0.00005	m^2. K /W
k	Thermal Conductivity of AISI 316	17	W/m. K

Results obtained:

Table 6.6 Safety Factor for Generator

Fouled Surface heat load "Q_f" kW	Required heat load "Q_r" kW	Safety Factor "Cs"
24223.7	23232.3	1.04

6.4 Absorber Performance and Thermal Analysis

The brazed plate heat exchanger considered for the analysis of the condenser is "Alfa Laval CB 30/CBH 30".

Figure 6.7 Alfa Laval Brazed Plate Heat Exchanger CB 30/CBH 30

Table 6.7 Process and constructional specifications for Absorber

Symbol	Name	Value	Units
a	Height	0.313	m
b, L_w	width	0.113	m
L_v	Vertical Connection distance	0.25	m
L_h	Horizontal Connection distance	0.05	m
L_c	Plate Pack Length	0.056	m
D_P	Port Diameter	0.03	m
$\dot{m}_h$	Flow Rate of hot fluid	1.4	kg/sec
$\dot{m}_c$	Flow Rate of cold fluid	1.8	kg/sec
T	outlet cooling water from absorber	34	^{0}C
	Inlet cooling water to Absorber	30	^{0}C
	Intermediate Solution	36	^{0}C
	weak solution outlet	33	^{0}C
C_P	Specific heat of water	4186	J/kg. k
N_t	Number of plates	20	
t	plate thickness	0.0006	m
A_e	Heat exchanger area	1.2	m^2
μ_h	Viscosity of hot fluid	0.001114	N.s/m^2
μ_c	Viscosity of cold fluid	0.001428	N.s/m^2
	Total Fouling Resistance	0.00005	m^2. K /W
k	Thermal Conductivity of AISI 316	17	W/m. K

Results obtained:

Table 6.8 Safety Factor for Absorber

Fouled Surface heat load “Q_f” kW	Required heat load “Q_r” kW	Safety Factor "Cs"
26585.9	23023	1.15

The refrigerant vapor from the evaporator passes to the absorber where it is absorbed by the strong solution from the generator containing lithium bromide. The affinity of water and lithium bromide helps in absorbing of water. This solution is now called the weak solution due to the presence of water. This solution then passes into the solution heat exchanger wherein it is preheated by the incoming strong solution from the generator. In this way the process continues repeatedly.

Chapter 7

PERFORMANCE CHARACTERISTICS CALCULATIONS WEBPAGE

This webpage is used in calculating the performance characteristics of a single effect lithium bromide/water absorption chiller unit for IT-POD having evaporator capacity of 23kW. The input values are:

1. Generator Temperature (t_g) ^0C
2. Evaporator Temperature (t_e) ^0C
3. Condenser Temperature (t_c) ^0C
4. Absorber Temperature (t_a) ^0C
5. Exchanger Effectiveness (E_L)
6. Evaporator heat capacity (Q_e) kW

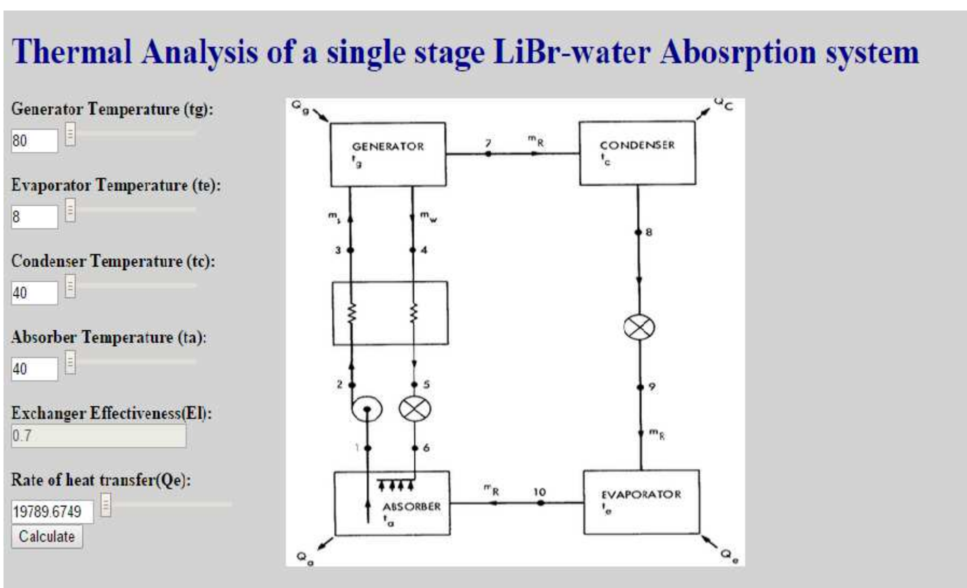

Figure 7.1 Performance Characteristics Webpage calculations

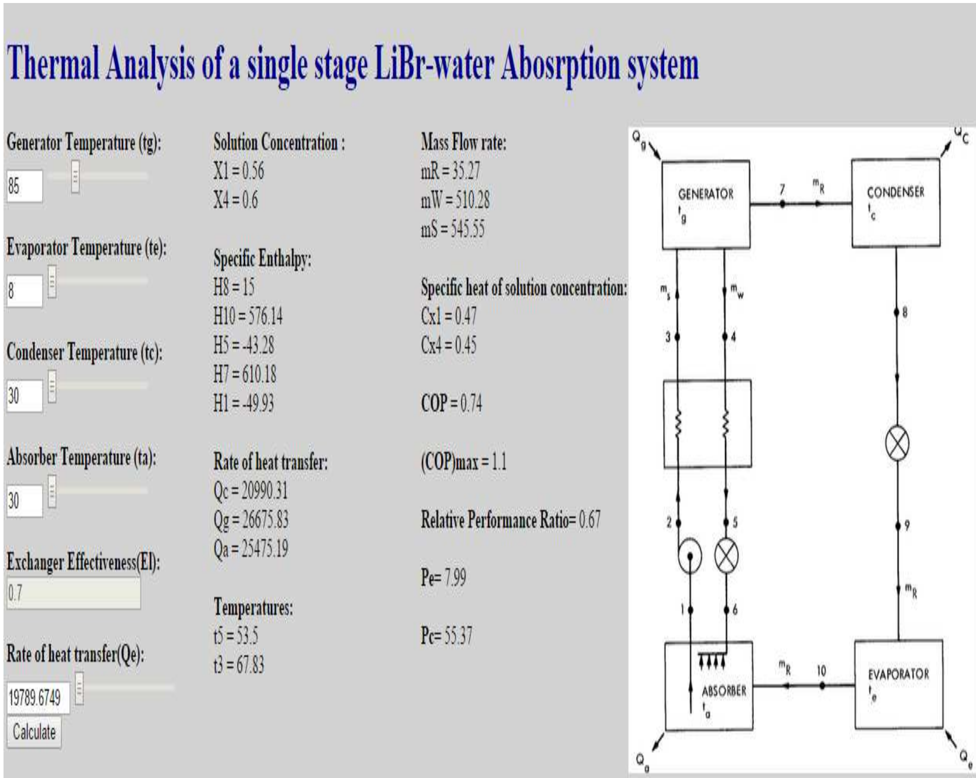

Figure 7.2 Performance Characteristics calculated values

Chapter 8

CONCLUSION

Some of the noted findings of this work are:

- Decrease in COP with increase in absorber and condenser temperatures.
- Increase in COP with increase in evaporator and generator temperatures.
- Ideal cooling water temperature range for condenser and absorber temperatures are between 25 – 32 ^{0}C
- Ideal chilled water temperature range for evaporator temperature is between 7 – 10 ^{0}C
- Ideal hot water temperature range for generator temperature is between 85 – 95 ^{0}C

Solar thermal cooling has tremendous potential on becoming one of the important cooling technologies available for data centers. It paves the way for a greener environment and future making use of the renewable energy sources. However there are challenges that need to be addressed before implementing this technology on a larger scale. The trends indicate the decrease in the cost of installation of solar energy equipment thus making this technology more preferable and widely used in the future. This analysis helps in a better understanding of the absorption refrigeration system. It helps in deciding the feasibility of such systems for small data centers. In addition to this it also helps in sizing of the individual heat exchangers in the system. Therefore these systems have great potential in becoming the main source of cooling in a data center facility and making it environmental friendly.

Future work can include a detailed cost analysis of such systems for small data centers. Study of single effect absorption chillers by considering different types of solar collectors such as flat plate and evacuated tube collectors. Finally to study double effect absorption chillers.

Appendix A

THERMODYNAMIC EQUATIONS FOR PERFORMANCE CHARACTERISTICS OF SINGLE EFFECT LITHIUM BROMIDE/WATER ABSORPTION CHILLER

1. $X_1 = \frac{(49.04 + 1.125t_a - t_e)}{(134.65 + 0.47t_a)}$ kg LiBr/kg solution

2. $X_4 = \frac{(49.04 + 1.125t_g - t_c)}{(134.65 + 0.47t_g)}$ kg LiBr/kg solution

IF 0.5 < (X_1 and X_4) < 0.65

3. $H_8 = (t_c - 25)$ kcal/kg

4. $H_{10} = (572.8 + 0.417t_e)$ kcal/kg

5. $m_R = \frac{Q_E}{(H_{10} - H_8)}$ kg/hr

6. $m_S = m_R \times \frac{X_4}{(X_4 - X_1)}$ kg/hr

7. $m_W = m_R \times \frac{X_1}{(X_4 - X_1)}$ kg/hr

8. $t_5 = t_g - E_L(t_g - t_a)$ ^{0}C

9. $C_{X_1} = 1.01 - 1.23X_1 + 0.48X_1^2$ kcal/kg ^{0}C

10. $C_{X_4} = 1.01 - 1.23X_4 + 0.48X_4^2$ kcal/kg ^{0}C

11. $t_3 = t_a + \{E_L \times \frac{X_1}{X_4} \times \frac{C_{X_4}}{C_{X_1}} \times (t_g - t_a)\}$ ^{0}C

12. $H_1 = (42.81 - 425.92X_1 + 404.67X_1^2) + (1.01 - 1.23X_1 + 0.48X_1^2) \times (t_a)$ kcal/kg

13. $H_5 = (42.81 - 425.92X_4 + 404.67X_4^2) + (1.01 - 1.23X_4 + 0.48X_4^2) \times (t_5)$ kcal/kg

14. $H_7 = (572.8 + 0.46t_g - 0.043t_c)$ kcal/kg

15. $Q_c = m_R(H_7 - H_8)$ kcal/hr

16. $Q_G = (m_w H_5 + m_R H_7 - m_S H_1)$ kcal/hr

17. $Q_A = (m_w H_5 + m_R H_{10} - m_S H_1)$ kcal/hr

18. $COP = \frac{Q_E}{Q_G}$

19. $(COP)_{max} = \frac{(t_e+273.15)(t_g-t_a)}{(t_g+273.15)(t_c-t_e)}$

20. $Relative\ performance\ ratio = \frac{COP}{(COP)_{max}}$

21. $P_e = antilog\{7.8553 - \frac{1555}{(t_e+273.15)} - \frac{11.2414\times10^4}{(t_e+273.15)^2}\}$ mmHg

22. $P_c = antilog\{7.8553 - \frac{1555}{(t_c+273.15)} - \frac{11.2414\times10^4}{(t_c+273.15)^2}\}$ mmHg

Appendix B

EQUATIONS FOR PERFORMANCE ANALYSIS AND THERMAL ANALYSIS OF PLATE HEAT EXCHANGERS

1. Required heat load: $Q_{rh} = \dot{m} \times C_p \times \Delta T$ kW

2. Required heat load: $Q_{rc} = \dot{m} \times C_p \times \Delta T$ kW

3. The Effective Number of Plates: $N_e = N_t - 2$

4. The Effective flow length between the vertical ports is: $L_{eff} \approx L_v$ m

5. The plate pitch: $p = \frac{L_c}{N_t}$ m

6. One channel flow area: $A_{ch} = b \times L_w$ m^2

7. Single plate heat transfer area: $A_1 = \frac{A_e}{N_e}$ m^2

8. The projected plate area: $A_{1p} = L_p \times L_w$ m^2

9. The enlargement factor: $\Phi = \frac{A_1}{A_{1p}}$

10. The channel hydraulic diameter: $D_h = \frac{2b}{\Phi}$ m

11. The number of channels per pass: $N_{cp} = \frac{N_t - 1}{2N_p}$

12. Mass flow rate per channel: $\dot{m}_{ch} = \frac{\dot{m}}{N_{cp}}$ kg/s

13. The mass velocity: $G_{ch} = \frac{\dot{m}_{ch}}{A_{ch}}$ kg/m^2.s

14. Reynolds number of hot fluid: $Re_h = \frac{G_h D_h}{\mu_h}$

15. Reynolds number of cold fluid: $Re_c = \frac{G_c D_h}{\mu_c}$

16. Hot fluid heat transfer coefficient: $h_h = \frac{Nu_h k}{D_h}$ W/m^2.K

17. Cold fluid heat transfer coefficient: $h_c = \frac{Nu_c k}{D_h}$ W/m^2.K

18. Clean overall heat transfer coefficient: $\frac{1}{U_c} = \frac{1}{h_c} + \frac{1}{h_h} + \frac{0.0006}{17.5}$ W/m^2.K

19. Fouled overall heat transfer coefficient: $\frac{1}{U_f} = \frac{1}{U_c} + 0.00005$ W/m^2.K

20. Cleanliness factor: $CF = \frac{U_f}{U_c}$

21. Actual heat duties for clean and fouled surfaces: $Q_c = U_c A_e \Delta T_m$ kW

$Q_f = U_f A_e \Delta T_m$ kW

22. Safety Factor: $C_s = \frac{Q_f}{Q_r}$

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