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Modeling and Simulation of Solar Absorption Cooling System for Maiduguri, Borno State, Nigeria Using Aspen Plus Software Model

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Abstract: *This work is aim to model, simulate, analyze and optimize absorption refrigeration system using a flat-plate solar collector and LiBr-H_2O mixture as the working fluid. The cooling capacity and the coefficient of performance of the system (COP) were analyzed by varying all the independent parameters, namely: generator temperature, evaporator temperature, refrigerant concentration, and solar collector area. The COP increases slowly at first with increase in Generator temperature where it remains constant. The effects of generator temperature on the evaporator, condenser and absorber duty were also investigated. The result shows that these parameters values increases with increase in generator temperature. The cooling performance is also assessed for the year 2017 using weather data of Maiduguri. The effects of evaporator and condenser pressures on the cooling capacity and cooling performance are found to be negligible. The LiBr-H_2Osolution shows higher cooling performance compared to other mixtures under the same absorption cooling cycle conditions. Aspen plus model was used to predict the performance of the solar absorption cooling system with good accuracy shows a coefficient of performance of 0.79. Before this research, no aspen plus model existed in Maiduguri.*

Keywords: *Mathematical Model; Optimization; Simulation; Solar Energy*

Background of the Study

The energy needed to process and circulate air in residential buildings and offices to control humidity, temperature, and cleanliness has increased significantly during the last decade especially in developing countries. High consumption of electricity presents economic and social problems in hot places, caused by the massive use of cooling machines. However, prolonged used of chlorofluocarbon (CFC) and hydrochlorofluocarbon (HCFC) refrigerants cause destruction of the ozone layer, and possible global warming due to excessive burning of fossil fuel. An absorption cooling system is a preferable option for energy generation. In an absorption cooling system, physiochemical process replaces the mechanical process of the vapor compression system by using energy in the form of heat rather than mechanical work. The absorption refrigerants lithium bromide- water cycle has some attractive features when compared to the conventional cycle. In 2013, Cascales *et al* (2013) studied the global modeling of an absorption system working with LiBr/H2O assisted by solar energy. It satisfies the air-conditioning necessities of a classroom in an educational center in Puerto Lumbreras, Murcia, Spain. The absorption system uses a set of solar collectors to satisfy the thermal necessities of the vapor generator. A dynamic simulation model, for a solar powered absorption cooling system was developed, and validated using measured data. Yeung *et al* (1992) designed and installed a solar driven absorption chiller at the University of Hong Kong; this system included 4.7 kW absorption chillers, flat plate solar collectors with a total area of 38.2 m^2, water storage tank and the rest of the equipment. They reported that the collector efficiency was estimated at 37.5%, the annual system efficiency at 7.8% and an average solar fraction of 55%, respectively.

The implementation of computer modeling of thermal system places a series of advantages by eliminating the cost of building prototypes, the optimization of the system components, estimation of thermal energy loads delivered or received from or into the system, and prediction of variation of the system parameters (e.g. Temperature, pressure and mass flow rate). Sparber ***et al*** (2007) reported that till 2007 there were 81 installed large scale solar cooling systems, eventually including systems which are currently not in operation. 73 installations are located in Europe, 7 in Asia, China in particular, and 1 in America (Mexico). 60% of these installations are dedicated to office buildings, 10% to factories, 15% to laboratories and education centres, 6% to hotels and the left percentage to buildings with different final use (hospitals, canteen, sport centre, etc.). They also cited that 56 installations are belong to absorption systems and the overall cooling capacity of the thermally driven chillers amounts to 9 MW 31% of it is installed in Spain, 18% in Germany and 12 % in Greece. Renewable Energy &resources are naturally replenished on a human timescale, such as solar, wind, rain, tides, waves and geothermal heat. Solar absorption cooling system method was used for this work.

Statement of the Problem

No Aspen plus model exit in Maiduguri, hence the need to develop a model that can design and construct solar absorption cooling system. Also, the rising cost, environmental concerns, and ozone layer depletion is on the increase. For this reason, renewable energies are excellent alternatives.

Aim and Objectives of the Study

The aim of this work is to model and simulate solar absorption cooling system for Maiduguri, Nigeria using Aspen plus software and the objectives are to:

i. develop a model for vapor absorption cooling system
ii. simulate an absorption cooling system
iii. evaluate the coefficient of performance (COP) of the vapor absorption cooling system.
iv. Optimize the coefficient of performance (COP).
iv. validate the COP

Significance of the Study

The Aspen plus model developed is significance because it can design and construct solar absorption cooling system. This study, therefore, will serve as a guide in identifying the economical, less demanding and available means of alternative energy source. To researchers and students, this work will serve as a reference material for future studies on modeling and simulation of absorption cooling system.

Scope of the Study

This study covers absorption cooling system for Maiduguri, Borno State using Aspen plus software for the simulation of the model developed. The working fluid used was also limited to lithium bromide water.

Limitation of the Study

This work is limited to modeling and simulation of absorption cooling system for Maiduguri, Borno state.

LITERATURE REVIEW

Theoretical Fundamentals

Generally, there are two types of refrigeration cycle, vapor compression refrigeration cycle and vapor absorption refrigeration cycle. Vapor compression cycle is the conventional one, which consumes a lot of electrical energy in which CFC's are used as refrigerants. For large quantity of electrical energy, large amount of fossil fuels have to be burnt and it will lead to more CO2 emissions. Secondly, the working pairs used are toxic and corrosive in nature and also depletes the ozone layer. These factors raise more concern for environmental pollution and energy utilization with rapid economic growth and hence human beings have to face more and more serious environmental and energy issues. The ways to solve these problems are developing ways to utilize renewable energy resources, enhancing energy utilization efficiency and so on. Absorption chillers or absorption heat pumps are both important energy saving devices which can be driven by low-grade thermal energy, such as solar energy, geothermal energy and industrial waste heat from industrial process, so the devices will play an important role in improving energy utilization efficiency and reducing environmental pollution and carbon dioxide emissions. The absorption refrigeration technology has attracted much attention all over the world, for the reason that it is environmentally friendly and could make use of the low-grade energy, which refers to the ignored energy embedded in the exhaust steam of low pressure and low temperature.

In cooling field, the IRENA (International Renewable Energy Agency) has reported in 2021 that the extensive use of air-conditioning systems could induce more than twofold rise in the energy consumption linked to cooling purpose in buildings by 2040 O. Achkari et al 2020. However, most of the heating and cooling applications are still covered by the conventional systems which frequently use and can leak hazardous chlorofluorocarbons (CFCs) and hydro chlorofluorocarbons (HCFCs) refrigerants during their operation, which could aggravate the concern about environmental issues, such as global warming, air pollution Frazzica et al 2022 and ozone depletion. Indeed, between 1990 and 2020, CO2 emissions attributed to the use of cooling systems have become more than double and reached about 1 Gt International Energy Agency, Cooling 2022. Accordingly, eco-friendly cooling systems are gaining more attention, particularly sorption (absorption/adsorption) systems, which are low grade thermally driven cooling systems that can exploit solar energy or waste heat energy.

Compared to vapor compression systems, which use valuable electricity, the sorption ones can reduce the electricity demand and minimize the environmental impact as a significant portion of greenhouse gases (GHG) emissions could be avoided. Besides, solar energy, which is the focus of this article, has a great potential to fulfill the global energy demand and is of great interest to be used for cooling production, since the cooling demand increases particularly in the sunny areas A. El Fadar *et al.* 2009. Nevertheless, solar cooling systems have some shortcomings that limit their widespread use. Regarding the absorption systems, the main drawbacks are their low performance and system's bulkiness. With respect to the adsorption systems, one of the hurdles that prevent their improvement is the relatively low performance owing to poor heat and mass transfer in adsorbent beds M. Hamdy et al 2017 which indirectly affects the economic factors by increasing the investment cost due to the use of large size of cooling system and large installed solar collector's area.

Diverse types of solar collectors are used with sorption cooling systems, and one can distinguish two categories: stationary and concentrating solar collectors. The stationary ones do not track the sun and include: (1) flat plate collector (FPC) which is composed of an absorber plate that absorbs the solar irradiation and transfers it to a heat transfer fluid (HTF) in the flow channel, and the whole is sealed between a transparent glass layer in the upper side and an insulation material in the bottom and edges to reduce the thermal losses to the environment, (2) evacuated tube collector (ETC) made of multiple evacuated glass tubes that contain an absorber fin and a heat pipe where the HTF flows, (3) photovoltaic thermal (PVT) collector that consists of a photovoltaic panel with a flow channel mounted on its rear side to absorb the waste heat by a HTF, and (4) compound parabolic collector (CPC) which is composed of a parabolic shaped reflector that reflects the incident solar irradiation on the absorber surface placed at the bottom of the solar collector. The second category, concentrating collectors, such as linear

Fresnel collector, parabolic dish collector and parabolic trough collector (PTC) track the sun. It should be mentioned that, in addition to the stationary collectors, PTC is the focus of this study which is made of a parabolic trough concentrator that reflects the incident solar irradiation and focuses it onto a tube receiver placed at the focal line of the concentrator, the receiver comprises an absorber tube and the HTF channel sealed within a glass tube. Furthermore, hybrid concentrating solar collectors, which combine the concentrating thermal collector and the photovoltaic panels, have been gaining more attention. Compared to PVT collector, concentrating photovoltaic thermal (CPVT) collector takes advantage of an imaging (such as PTC) or non-imaging (such as CPC) optical concentrator to supply higher heat flux to a small solar receiver] X. Ju et al 2017. In this paper, CPVT collector based on PTC will be proposed and studied. The choice of the appropriate solar collector is mainly affected by its thermal performance, the driving temperature of the cooling system in addition to the climate conditions

In order to expand the knowledge on the design and operation of absorption and adsorption cooling systems driven by thermal solar energy, numerous research works have been conducted to investigate their performance and cost-effectiveness depending on the used solar collectors. For instance, Ibrahim et al. 2021 performed an economic investigation on a novel solar absorption cooling (SABC) system powered by PTC and combined with an absorption energy storage. The proposed storage system consisted of a solution storage tank and a refrigerant storage tank. The results revealed a payback period of about 5 years and a leveled cost of energy-savings of about 137.944 USD. Mokhtar et al. 2010 proposed a techno-economic assessment of solar cooling systems driven by various solar collectors. Non-concentrating and concentrating solar thermal collectors were considered with absorption chiller, while solar electric panels were evaluated with vapor compression chiller. The results indicated that multi-crystalline photovoltaic cells and Fresnel concentrator driven cooling systems were the most efficient and economical systems. Li et al. 2019 conducted a performance and economic investigation of a hybrid solar system in a residential building.

Solar absorption and vapor compression chillers were used to cover the building's cooling demand by means of FPC, CPC and photovoltaic collectors which were studied through different scenarios. The results indicated that the thermal cooling system combined with CPC reached the highest solar cooling fraction compared to the cooling system based on FPC. Besides, replacing the PV collectors with the same area of thermal solar collectors resulted in lower performance of cooling. In order to expand the knowledge on the design and operation of absorption and adsorption cooling systems driven by thermal solar energy, numerous research works have been conducted to investigate their performance and cost-effectiveness depending on the used solar collectors. For instance, Ibrahim et al. 2021 performed an economic investigation on a novel solar absorption cooling (SABC) system powered by PTC and combined with an absorption energy storage. The proposed storage system consisted of a solution storage tank and a refrigerant storage tank. The results revealed a payback period of about 5 years and a levelized cost of energy-savings of about 137.944 USD. Mokhtar et al. 2010 proposed a techno-economic assessment of solar cooling systems driven by various solar collectors. Non-concentrating and concentrating solar thermal collectors were considered with absorption chiller, while solar electric panels were evaluated with vapor compression chiller. The results indicated that multi-crystalline photovoltaic cells and Fresnel concentrator driven cooling systems were the most efficient and economical systems. Li et al. 2019 conducted a performance and economic investigation of a hybrid solar system in a residential building.

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Papakokkinos *et al.* 2020 developed a dynamic simulation of SADC system driven by FPC for building's air-conditioning. The results revealed that the system could achieve a solar fraction over 67%. Besides, CO2 emissions decreased by up to 90.7% in comparison with conventional cooling system powered by electricity. Buonomano et al. 2017 investigated a novel solar poly generation system based on absorption and adsorption chillers driven by parabolic dish shaped CPVT collector in addition to PVT collector. The results showed that the use of CPVT collector enabled a simple payback period as low as 5.6 years. Buonomano *et al*. 2014 evaluated a new solar polygeneration system based on CPVT collectors equipped with triple-junction photovoltaic cells; the solar collectors were used for cooling, by means of single effect absorption chiller, heating and electricity production. The authors developed a performance and economic model to investigate the solar system. It was found that the system had a high performance and saved up to 1, 1.5 and 1.2 GWh of electrical, cooling and thermal energy, respectively. Besides, 253 k€/year were saved in terms of operating costs with a simple payback period of 14 years. Al-Nimr et al. 2020 carried out a performance and economic investigation of a hybrid cooling system powered by CPVT collectors. The cooling system consisted of thermoelectric cooler powered by the produced electricity of CPVT panels, while the thermal energy was used to drive an absorption chiller. The authors reported that the system's overall COP ranged between 0.143 and 0.232 under Mediterranean climate condition. Bellos et al. 2016 conducted a comparative study of SABC system driven by various solar collectors (FPC, ETC, CPC and PTC). A numerical model was developed for energetic and exergetic evaluation along with a financial analysis based on total capital cost. It was shown that the use of PTC exhibited higher solar COP and exergetic efficiency, whereas the system with ETC led to lower investment cost. Asadi et al. 2018 performed a techno-economic study of SABC system driven by multiple solar collectors (FPC, ETC, CPC and PTC) along with a multi-objective optimization.

Energy and exergy analysis was elaborated together with a particle swarm optimization model to maximize the COP, solar COP, chiller exergy efficiency and solar exergy efficiency, and to minimize the system's capital cost. The results revealed that the SABC system combined with ETC was the most economical system, while PTC system had the highest solar exergy efficiency. In light of the above survey, it could be concluded that despite the aforementioned benefits of solar sorption cooling systems, they suffer from low performance, which induces a large size of solar system leading to higher investment cost. In this regard, several research works were devoted to improving the performance of these systems by investigating the effect of solar collector types on absorption cooling system. However, there is a dearth of economic and environmental analysis of these systems along with the concentrating photovoltaic thermal collectors that was rarely assessed for a solar cooling application. Besides, to the best of the authors' knowledge, no work evaluated the effect of solar collectors' types on adsorption cooling system performance. Therefore, the focus of this study is to bring to light an exhaustive analysis of solar absorption and adsorption cooling systems driven by various solar collectors, namely: flat plate collector, evacuated-tube collector, compound parabolic collector, parabolic trough collector.

A number of experimental and theoretical studies of solar-powered air-conditioning systems have been done in the past. Wilbur et al 1975 compared theoretically single-stage, lithium bromide-water absorption cooling system heated from flat-plate solar collector to an ammonia-water system, and the lithium bromide system was preferred. It was shown that it required smaller cooling towers than the conventional one.

Modeling in Aspen Plus

Modeling in ASPEN plus is based in taking a process and breaking it down into more simple components, also known as "blocks".

State point 1 refers to the refrigerant liquid which is at a saturated state and needs to evaporate.

The evaporator is modeled as a heater block using the steam NBS property method. The inputs to the model were zero pressure drops and a vapor quality of 1 at the exit. Steam NBS is a FORTRAN90 library which computes the various physical properties of water, related to temperature, pressure and density.

The absorber is modeled as a heater block with two inputs, the exit of the evaporator and the exit of the solution valve. The inputs are zero pressure drop and zero vapor quality.

Desorber or generator is modeled by using a flash block which separates the vapor from the liquid. Along with the flash block a heater block is used to provide the heat needed for generating the refrigerant, which is equivalent to the waste heat energy. Its inputs are zero pressure drop and outlet temperature (based on the temperature of the heat input into the cycle).

The condensers were modeled as heater blocks. Assuming no pressure drop, the only input necessary is to specify a vapor quality of 0 at the exit.

A solution heat exchanger (SHE) is modeled as two heaters joined by heat stream to indicate that the heat rejected on the hot side was to be added to the cold side. Heat is transferred from state 10 (the hot side inlet) to state 3 (the cold side inlet), resulting in states 11 (the hot side exit) and 4 (the cold side exit). Assuming no pressure drop, the only two unknowns are the exit temperatures. One unknown was described by assuming heat exchanger effectiveness, defined below.

Effectiveness, $e = (T_{11}-T_{12})/ (T_{11}-T_{3})$…………………… (i)

Pumps are used between states 2 and 3. Pumps require only one input, the exit pressure. The default value of 100% efficiency was used because of the negligible effect on the overall cycle of picking a different efficiency (the pump work is several orders of magnitude smaller than the heat duties of other components).

Based on the blocks we have used, the complete flow sheet for the absorption refrigeration cycle will be as follows:

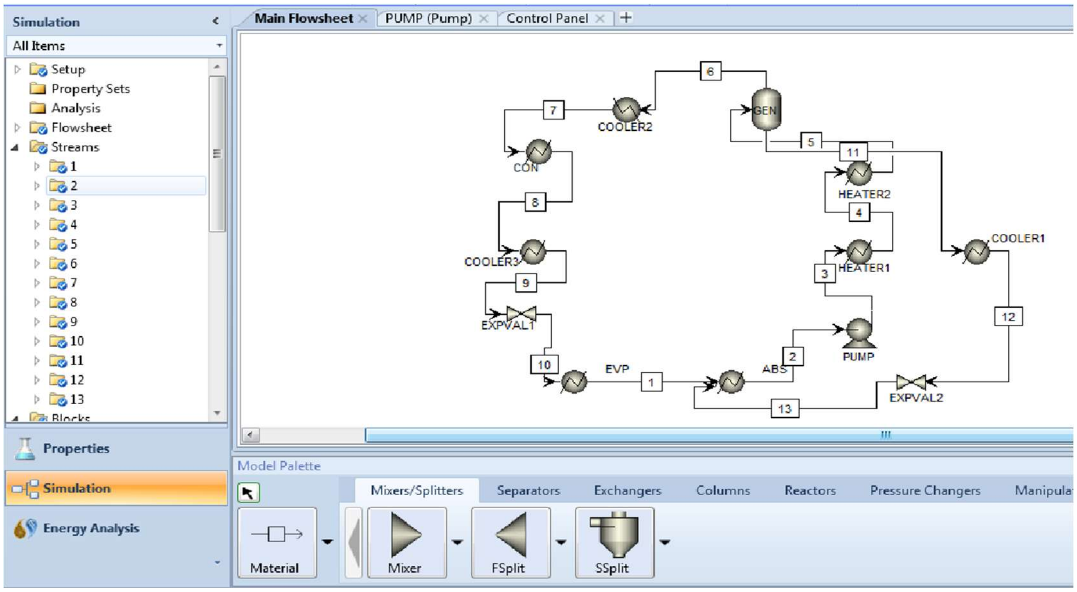

Figure. 2.1 Complete flow Chart of Absorption refrigeration cycle in Aspen Plus

Solar Collectors

The solar thermal collector is the device in charge of transforming the incident solar radiation energy into thermal energy by means of heat exchange through a thermal fluid that circulates within. This is the most important element in a solar facility. The thermal fluid can be water, air, oil, water-antifreeze mixture, etc. There are different types of solar thermal collectors and its selection depends on the necessities of the user. Flat-Plate Collector (FPC) can be designed for applications requiring energy delivery at moderate temperatures, up to perhaps 100°C above ambient temperature. The major applications of these units are in solar water heating, building heating, air-conditioning and industrial process heat. (Duffie and Beckman 2006). Evacuated tube collectors (ETC) have lower heat losses than FPC due to the vacuum surrounding the absorber plates, and thus are capable of working at higher temperatures than FPC. An improvement that can be done to ETC is to integrate them with compound parabolic concentrators (CPC) which are non-imaging concentrators, having the capability of reflecting to the absorber all of the total (direct and diffuse) incident radiation within wide limits. Using this device it is possible to achieve higher temperatures, than with a simple ETC, moreover, this kind of collector doesn't need a tracking system Duffie et al (2006).

`Thermodynamic Analysis

The general solar cooling system scheme is presented in Figure 1.0, the heat supplied by the solar collectors Q_{Heat} at temperature TH drives the generator of the sorption chiller, which absorbs the heat from the cooling load Q_{Cold} at a temperature of T_C and rejects that heat Q_M to the ambient at temperature T_M.

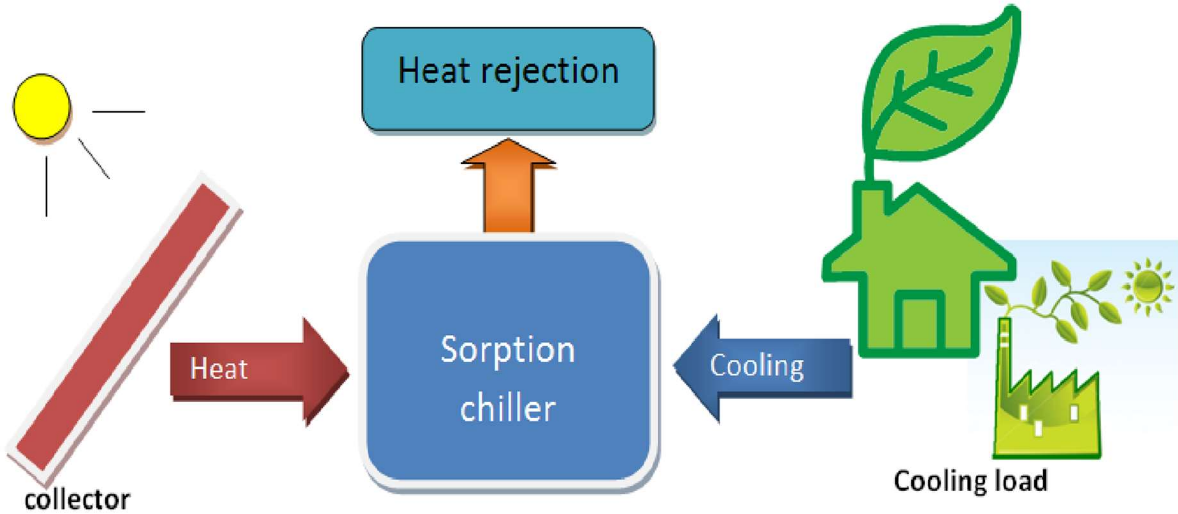

Figure 2.2 General scheme of solar cooling system.

System Concept Development

Based on the aforementioned thermodynamic analysis the system concept consists of an air cooled single-effect ammonia-water absorption chiller driven by heat produced by a medium temperature concentrating collector that could be a Linear Fresnel Reflector (LFR) collector or a Parabolic Trough Collector (PTC) as presented in Figure 2.2.

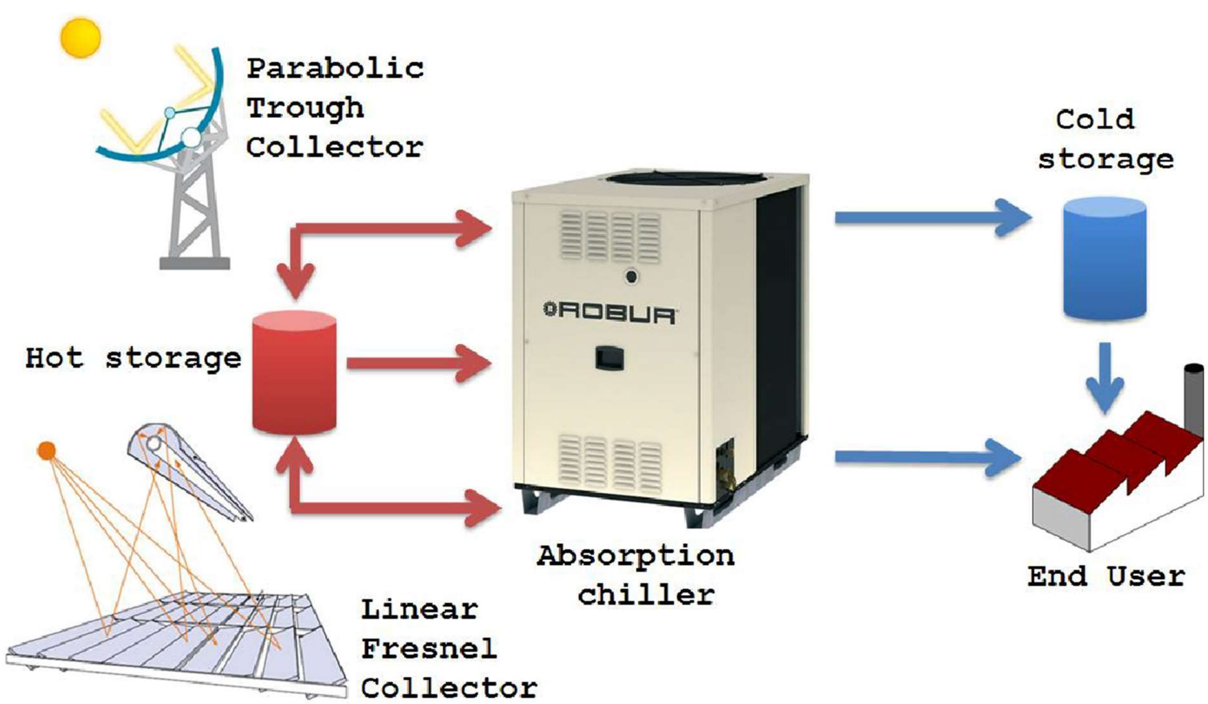

Figure 2.3 General scheme of a solar cooling system.

In addition to the main system components i.e. the collector and the chiller, a hot and/or cold storage might be required to match the cooling production in the chiller during the sunny hours of the day with the cooling required by the end user. The general scheme of a solar cooling system presented the LFR and the PTC collectors as the different approaches to integrate a hot and cold storages to the system is presented in Figure 2-3. In the next paragraphs, the main components used in the system are presented. Further, the system configuration is discussed based on its ability to match the end user's cooling load demand.

Solar collectors' typologies investigated:

According to the efficiency curve, three types of solar collectors have been investigated:

1. Parabolic trough collectors (PTC)
2. Linear Fresnel Reflector collectors (LFR)
3. Evacuated tube collectors with compound parabolic concentrator (ETC with CPC).

Hereafter a brief overview on physical principles and technical characteristics of solar collectors mentioned above is presented.

Parabolic Trough Collectors

Parabolic Trough Collectors (PTC) is made by bending sheets of reflective material into a parabolic shape. A high absorbing black metal tube, covered with a glass tube to reduce heat losses, is placed along the focal line of the mirror (see Figure 1.2). When the parabola is pointed towards the sun, parallel rays incident are reflected onto the receiver tube. Such a collector is able to concentrate only the beam radiation. The main advantages of the parabolic trough collector are:

i. No use of secondary reflector, thus high optical efficiency;
ii. Ability to capture sunlight in the early morning and late evening hours.

Because of the apparent movement of the sun across the sky, conventional concentrating collectors must follow the sun's daily motion so that a tracking system is required. Temperatures up to 400 °C can be reached.

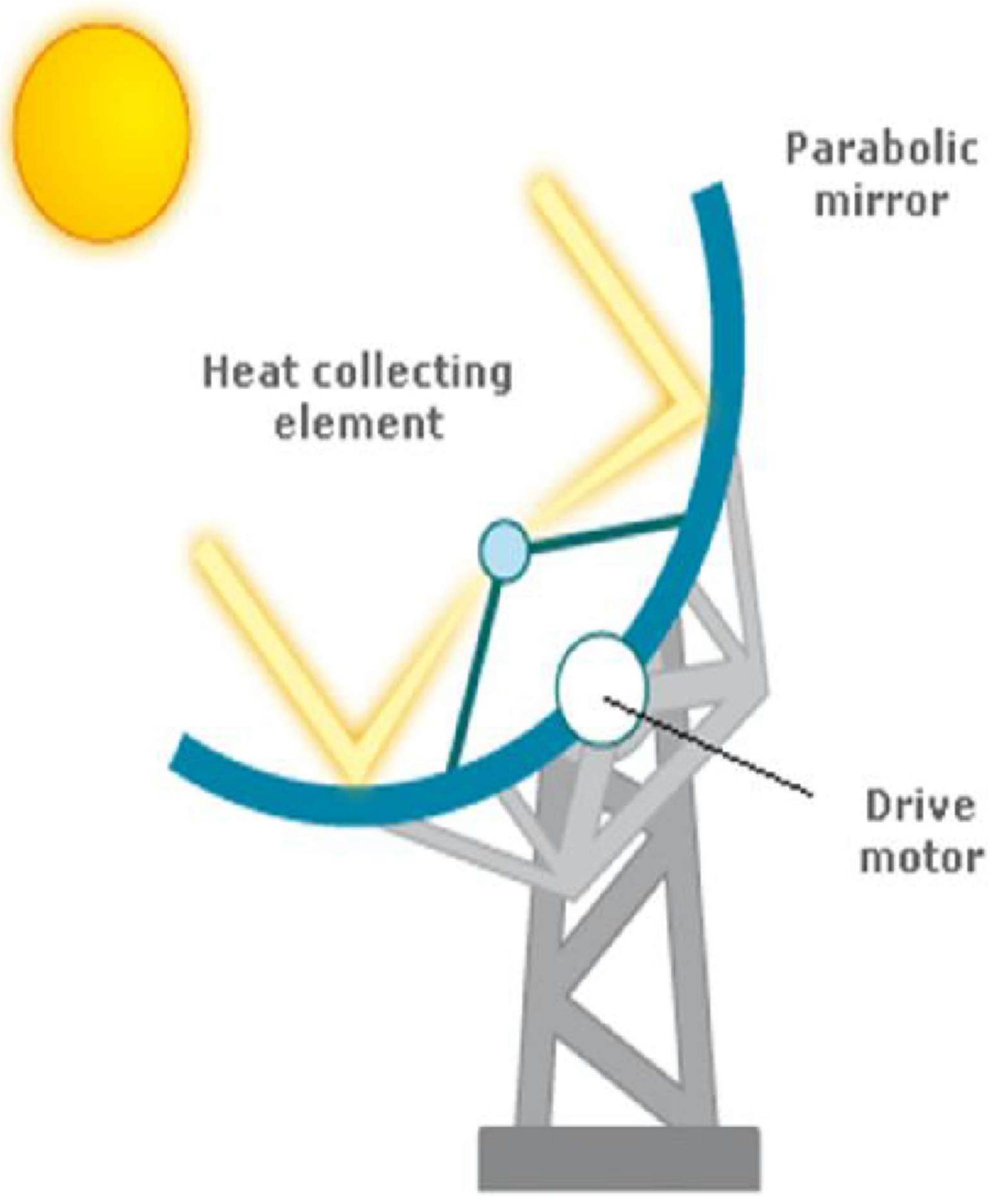

Figure 2.4 linear parabolic trough concentrating collector.

Linear Fresnel reflector (LFR) technology relies on an array of linear mirror strips which concentrate light on to a fixed receiver mounted on the array. The Fresnel collector is made of a primary planar Fresnel reflector, a secondary compound parabolic reflector and an absorber tube. The primary reflector is composed of several reflecting stripes, which concentrate direct beam radiation on the secondary reflector. Mirror strips orientation can be varied according to radiation incident angle by means of a tracking system in order to maintain a fixed focus line. The main advantages of the Fresnel collector, compared to trough collectors, are:

Planar mirrors are easier to manufacture, consequently the collector is less expensive;

The tracking system is simpler and more reliable;
The absorber tube doesn't need flexible high pressure joints;
The planar reflector offers less resistance to the wind, consequently the risk of breakages due to storming is reduced and larger mirrors can be used;
Overheating protection can be easily made by setting part of the mirrors out of focus.

Evacuate Tube Collectors with Compound Parabolic Concentrator

In order to increase the efficiency of a collector, beyond selective surfaces, it's possible to create a vacuum envelope between the absorber and the glass cover. In this way it's possible to reduce convection and conduction losses, so the collectors can operate at higher temperatures than flat plate collectors (FPC). This is very difficult to be accomplished in FPC due to both the mechanical resistance of the glass as well as problems related to a state of vacuum. It's easier instead to create vacuum in a tubular structure; an evacuated tube collector (ETC) is made of a certain number of glass tubes, in which there is an absorbing plate sealed to a tube. Typical operational range of ETC is 80 – 110 °C. There are two kinds of ETC classified based on how the heat is transferred from the tubes is done:

Direct connections "flow through"
Direct means that the fluid of the solar circuit is directly going through the collector,
Dry connection "heat pipe" Jack et al (2013).

In the heat pipe systems, the working fluid is not in contact with the inner tube, that instead contains a small amount of fluid (e.g. methanol), that undergoing an evaporating-condensing cycle, transfers heat to working fluid at high efficiency level. Compound parabolic concentrators (CPC) are non-imaging concentrators, having the capability of reflecting to the absorber all of the total (direct and diffuse) incident radiation within wide limits error**.** Using this device it is possible to achieve higher temperatures, than with a simple ETC, in the range of (80°C – 135 °C). This kind of collector does not need a tracking system.

Evacuated Tube Collectors with CPC

Apart from the efficiency curve of CPC collectors which shows an efficiency higher than 50% at temperatures above 150°C, practically, only one prototype utilizing thin gases and optimized geometry showed an experimental results for operation at 150°C Buttinger et al (2010). The majority of other CPC collectors are experimentally tested at working temperatures below 135°C which do not present an optimal value for the operation of the chiller. And thus, CPC collectors were excluded from the selection procedure Buttinger et al (2010).

Parabolic Trough Collectors

Several producers have been contacted, but only the collectors from the American company IST was ready to be provided within the available budget and time limits of the project. IST's PT-1 collector presents very good thermal performance and technical characteristics. Another important aspect is that it is a commercial product that has proven to be a very successful in several systems, some of which have been operating continuously for more than fifteen years "reliability aspects". Beckman et al (2006)

Linear Fresnel Reflector Collector

Two LFR collectors have been found suitable for the application, but only the German company PSE was able to supply a prototype suitable for a pilot plant. The thermal performance, the technical characteristics and the price of such a collector make it suitable for the solar cooling concept. Moreover, regarding the fact that two plants are planned within the project, it would be preferred to test both typologies of concentrating collector i.e. the PTC and the LFR in order to test and compare their performance Wendelin et al (2014).

Property Method Selection

The first and most crucial step in the modeling process was finding a suitable property method for the water/lithium bromide mixture. At this point it should be pointed out that except for very common fluids, ASPEN does not use look-up tables for property data. Instead, the user must select a property method based on operating conditions, fluid characteristics, etc. As a result, there is an error inherent to any model created in ASPEN. This should not be taken as a deterrent, as even look-up tables will have some errors due to interpolation. Rather, it is a warning to the potential user to select the property method wisely when modeling in ASPEN. The ASPEN developers suggested that the ELECNRTL property method to be chosen for the water/lithium bromide solution based on the operating conditions and fluids being modeled. As the name suggests, it is a method designed for electrolytes. To use it properly, the user must select the relevant components (in this case, water and lithium bromide) and use the electrolyte wizard, which will generate a series of reactions. In this case, the only relevant reaction was the dissociation of lithium bromide. For the states that are pure water, the steams were used (Herold et al, 1996). Since look-up tables are available for pure steam, the property data induced error will be much smaller.

Component Breakdown and Modeling

As alluded to in the introduction, modeling ASPEN plus is based in taking a process and breaking it down into more simple components, also known as “blocks”. For example, a gas turbine could be decomposed into a compressor block, a combustion chamber block, and a turbine block. While this allows the user to model complex processes more easily, there is a certain level of subjectivity involved. Thus, some of the decisions made in the following section could have been done in a different way. However, every effort will be made to point out these instances.

The following section is an in-depth description of the component breakdown used to produce the models. It is intended to act as a guide for anyone who would like to recreate or modify the described models. Many simple components (pumps, valves, etc.) could be modeled simply by selecting the equivalent block in ASPEN, while others did not have an exact analogue. Naturally, much more time will be spent on the instance, as these components may have required further assumptions or multiple blocks to model. Finally, it should be noted that in this section, the goal was only to produce a running model, not one with realistic inputs. The adaptation to realistic inputs is described in section 2.4.

State Point 1

Aspen plus uses a sequential solver; it is necessary to model a break" in closed cycles to give inputs to the model. For both the single and double effect cycles, this break was inserted at state point 1. In other words, the exit of the absorber (stream 1A) and the inlet of the pump (stream 1) are not connected (see the overall process flow diagrams in section 2.5). If these two fluid streams give the same results (which is to be expected; they represent the same state!), this is evidence of a well formulated problem.

This was verified throughout the modeling process and found to be consistently satisfied. The break in state 1 allows for inputs to be given for the pump inlet. For now, these inputs were the low side pressure, a vapor quality of zero, the mass flow rate, and the concentration of water and lithium bromide.

Pumps

Pumps are used in the following instances, between states 1 and 2 in both models and between states 11 and 12 in the double effect model. Pumps require only one input, the exit pressure. One could also include pump efficiency, but the default value of 100% was used because of the negligible effect on the overall cycle of picking a different efficiency (the pump work is several orders of magnitude smaller than the heat duties of other components).

Valves

The other pressure changes devices needed to model the cycle are valves. For the single effect cycle there is one refrigerant and one solution valve, for the double effect cycle there are two of each. The valve model is self-explanatory; one only needs to give the exit pressure or some equivalent (i.e. pressure ratio).

Solution Heat Exchangers

Heat is transferred from state 4 (The hot side inlet) to state 2 (the cold side inlet), resulting in states 5 (the hot side exit) and 3 (the cold side exit). It is used in the same spot in the double effect cycle, as well as to transfer heat from state 14 (the hot side inlet) to state 12 (the cold side inlet), resulting in states 15 (the hot side exit) and 13 (the cold side exit). This was modeled using two heater blocks, connected by a heat stream to indicate that the heat rejected on the hot side was to be added to the cold side. A screen shot of this part of the model is shown in Figure 1.4. Assuming no pressure drop, the only two unknowns are the exit temperatures. One unknown was described by assuming heat exchanger effectiveness, defined below.

$$\in = T4\text{-}T5T4\text{-}T2 \ldots\ldots\ldots\ldots\ldots\ldots \quad \text{(ii)}$$

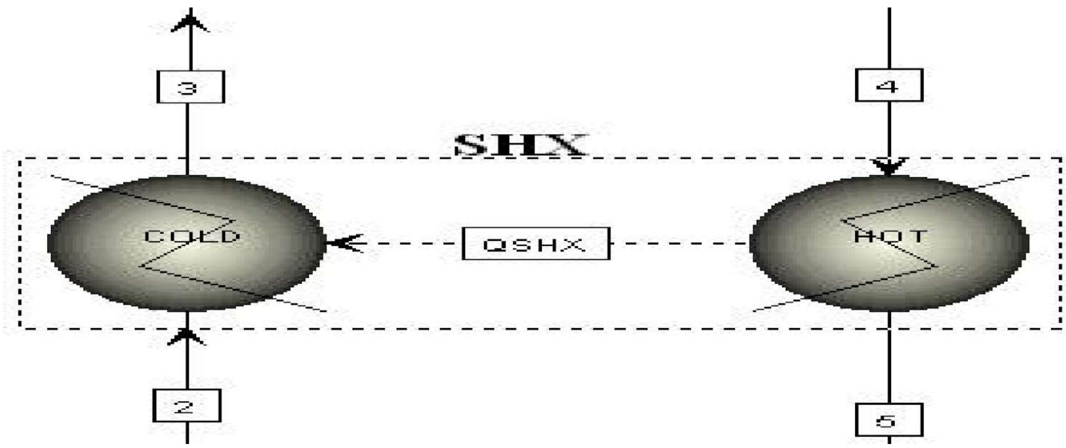

Fig. 2.5 SHX model in ASPEN

This sets T_5. The model now knows the amount of heat lost from states 4 to 5, and matches this to the amount of heat gained from states 2 to 3, setting T_3. To implement the heat exchanger effectiveness equation, a calculator block was used.

Condensers

The condensers were modeled as heater blocks. Assuming no pressure drop, the only input necessary is to specify a vapor quality of 0 at the exit. Since the refrigerant is pure water, the property method for this component, as well as any refrigerant-only components, should be changed to steam NBS for improved results. The condenser model is used three times, once in the single effect cycle and twice in the double effect cycle (at middle and high pressures). The middle pressure condenser has two inputs: the refrigerant coming from high pressure and the refrigerant coming from the middle desorber. Modeling the condensers using the heater block model introduces a new assumption, that heat is being added at constant temperature. However, one could model the condenser as a heat exchanger rather than a heater to eliminate this approximation, if one were so inclined.

Evaporators

Modeling the evaporators was very similar to modeling the condensers. The evaporator was modeled as a heater block using the steam NBS property method. The inputs to the model were zero pressure drops and a vapor quality of 1 at the exit. This model is used one time each in the single and double effect cycles.

Note that the caveat about using a heater in the model rather than a heat exchanger applies for the evaporator model as well.

Absorbers

The absorber is modeled as a heater block with two inputs, the exit of the evaporator and the exit of the solution valve. The inputs are zero pressure drop and zero vapor quality. The absorber model is used once in the single and double effect cycles. The caveat about using a heater in the model rather than a heat exchanger applies for the absorber model as well.

Desorbers

To this point, modeling components has been relatively straightforward, as they all involved simple processes like pressure changes, heat addition or rejection, mixing, or some combination. Desorbers, on the other hand, involve separating components, which makes them much more difficult to model. The desorber in the single effect cycle and the high pressure desorber in the double effect cycle have similar inputs and requirements; thus, they have the same design. They are:

i. Single inlet (stream 3 in the single effect, 13 in double effect);
ii. Saturated vapor outlet (stream 7 in the single effect, 17 in double effect), which is pure water;
iii. Saturated liquid outlet (stream 4 in the single effect, 14 in double effect), which is solution.

An assumption needs to be made about the vapor outlet stream. In this model, it was assumed to be the saturation temperature of the liquid solution at state 3. This was chosen to correspond to the assumption made in the EES model, but could be easily altered Herold et al (1996). The mass split between the two outlet streams and the liquid output temperature is dictated by the temperature of the heat input to the cycle. To accomplish these requirements, three heater blocks and a flash block were used. The flash is used to separate vapor and liquid. Its inputs are zero pressure drop and outlet temperature (based on the temperature of the heat input into the cycle). However, this gives the vapor stream the same temperature as the liquid stream, which would not meet the assumption stated in the previous paragraph. Thus, a heater block is added to reduce the temperature of the vapor stream to the saturation temperature of the inlet stream. To keep this heat internal to the desorber, a second heater block is added at the inlet, where the heat can be added. The final heater block raises the inlet stream to liquid saturated temperature, which allows a calculator block to reference the liquid saturation temperature of the inlet stream for the purpose of setting the outlet vapor stream temperature.

The middle pressure desorber in the double effect cycle has different inputs and requirements:

Two inlets (streams 3 and 16)
Saturated vapor outlet (pure water, stream 7)
Two saturated liquid solution outlets (stream 11 to upper cycle, and stream 4 to lower cycle)

Solar Energy

The plant primary energy source is the solar energy, which is absorbed by heat pipe solar collector and stored in an insulated storage tank. Heat pipes are widely used for heat recovery and energy saving in various ranges of applications because of their simple structure, special flexibility, high efficiency, good compactness and excellent reversibility Parand et al (2009). The heat pipe vacuum tube collects heat from the sun at high efficiency. It is important that heat pipe solar collectors must be installed with a tilt of at least. They operate like a thermal diode where the flow of heat is in one direction only Facao et al (2008). This type of collector commonly filled with alcohol or water in a vacuum and operates in two versions, one with a dry and one with a wet connection (German Solar Energy Society 2010). The most important difference between evacuated tube solar collectors and heat pipe solar collectors is that the heat carrier fluid inside of the copper heat pipe is not connected to the solar loop.

How Absorption Cooling System Works

The initial flow of the refrigerant from the evaporator to the absorber occurs because the vapor pressure of the refrigerant-absorbent in the absorber is lower than the vapor pressure of the refrigerant in the evaporator. The vapor pressure of the refrigerant-absorbent inside the absorbent determines the pressure on low-pressure side of the system and also the vaporizing temperature of the refrigerant inside the evaporator. The vapor pressure of the refrigerant-absorbent solution depends on the nature of the absorbent, its temperature and concentration. When the refrigerant entering in the absorber is absorbed by the absorbent its volume decreases, thus the compression of the refrigerant occurs. Thus absorber acts as the suction part of the compressor. The heat of absorption is also released in the absorber, which is removed by the external coolant.

1. **Condenser:** Just like in the traditional condenser of the vapor compression cycle, the refrigerant enters the condenser at high pressure and temperature and gets condensed. The condenser is of water cooled type.
2. **Expansion valve or restriction:** When the refrigerant passes through the expansion valve, its pressure and temperature reduces suddenly. This refrigerant (LiBr in this case) then enters the evaporator.
3. **Evaporator:** The refrigerant at very low pressure and temperature enters the evaporator and produces the cooling effect. In the vapor compression cycle this refrigerant is sucked by the compressor, but in the vapor absorption cycle, this refrigerant flows to the absorber that acts as the suction part of the refrigeration cycle.
4. **Absorber:** The absorber is a sort of vessel consisting of water that acts as the absorbent, and the previous absorbed refrigerant. Thus the absorber consists of the weak solution of the refrigerant (LiBr in this case) and absorbent (water in this case). When ammonia from the evaporator enters the absorber, it is absorbed by the absorbent due to which the pressure inside the absorber reduces further leading to more flow of the refrigerant from the evaporator to the absorber. At high temperature water absorbs lesser ammonia, hence it is cooled by the external coolant to increase it ammonia absorption capacity.
5. **Pump:** When the absorbent absorbs the refrigerant strong solution of refrigerant-absorbent (ammonia-water) is formed. This solution is pumped by the pump at high pressure to the generator. Thus pump increases the pressure of the solution to about 10bar.
6. **Generator:** The refrigerant-ammonia solution in the generator is heated by the external source of heat. This is can be steam, hot water or any other suitable source. Due to heating the temperature of the solution increases. The refrigerant in the solution gets vaporized and it leaves the solution at high pressure. The high pressure and the high temperature refrigerant then enters the condenser, where it is cooled by the coolant, and it then enters the expansion valve and then finally into the evaporator where it produces the cooling effect. This refrigerant is then again absorbed by the weak solution in the absorber.

Differences between Absorption Cooling System and Vapor Compression

i. In vapor compression system the energy input is given in the form of the mechanical work from the electric motor run by the electricity.

ii. Vapor compression uses compressor to create the pressure rise between evaporator and condenser, whereas absorption cooling system use a liquid pump.

iii. Absorption cooling system uses lithium bromide whereas vapor compression uses halocarbon.

Comparing the absorption refrigeration cycle with the more familiar vapor compression refrigeration cycle is often an easy way to introduce it. Figure 1.5 and figure 1.6 shows the essential components of the vapor compression and absorption cycles.

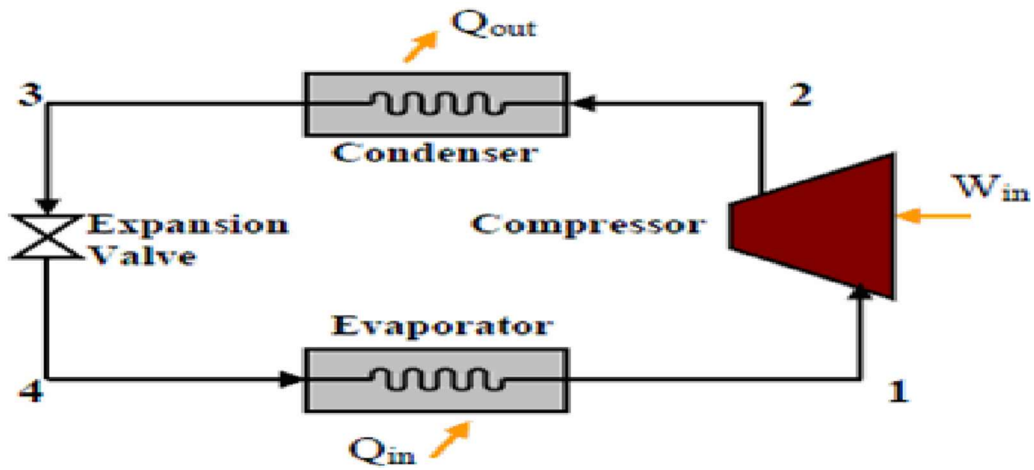

Fig2.6 Essential components of a vapor compression refrigeration system

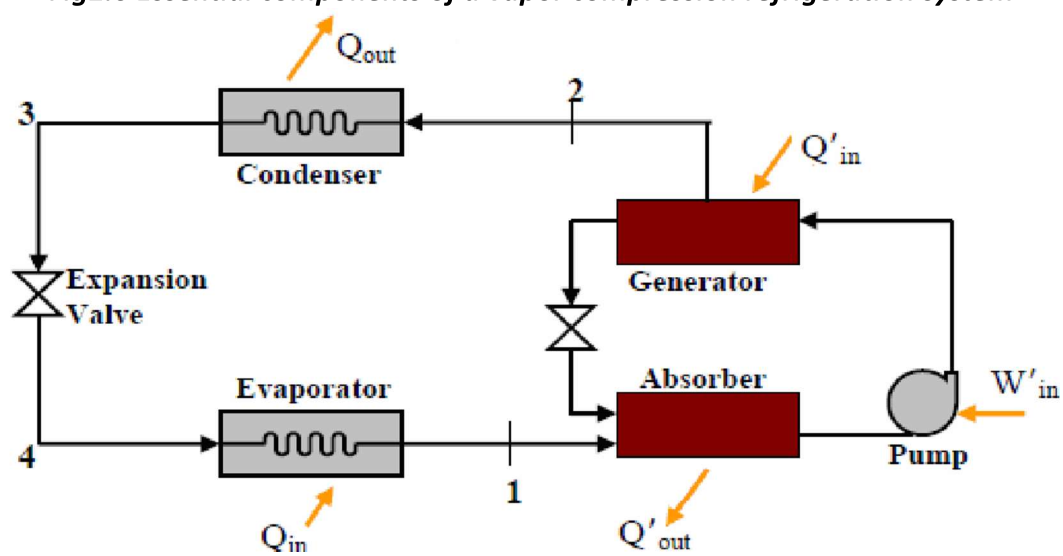

Fig.2.7. Essential components of a vapor absorption refrigeration system

In the vapor-compression refrigeration cycle, refrigerant enters the evaporator in the form of a cool, low-pressure mixture of liquid and vapor (4). Heat is transferred from the relatively warm air or water to the refrigerant, causing the liquid refrigerant to boil. The resulting vapor (1) is then pumped from the evaporator by the compressor, which increases the pressure and temperature of the refrigerant vapor.

The hot, high-pressure refrigerant vapor (2) leaving the compressor enters the condenser where heat is transferred to ambient air or water at a lower temperature. Inside the condenser, the refrigerant vapor condenses into a liquid. This liquid refrigerant (3) then flows to the expansion device, which creates a pressure drop that reduces the pressure of the refrigerant to that of the evaporator. At this low pressure, a small portion of the refrigerant boils (or flashes), cooling the remaining liquid refrigerant to the desired evaporator temperature. The cool mixtures of liquid and vapor refrigerant (4) travels to the evaporator to repeat the cycle.

Much like in the vapor compression cycle, refrigerant in the absorption cycle flows through a condenser, expansion valve, and an evaporator. However, the absorption cycle uses different refrigerants and a different method of compression than the vapor compression cycle.

2.11 Similarities between Vapor Absorption and Vapor Compression

1. Both cycles circulate refrigerant inside the chiller to transfer heat from one fluid to another.
2. Both cycles include a device to increase the pressure of the refrigerant and expansion device to maintain the internal pressure difference.
3. Refrigerant vapor is condensed at high pressure and temperature, rejecting heat to the surround.
4. Refrigerant vapor is vaporized at low pressure and temperature absorbing heat from the chilled water vapor.

METHODOLOGY

Materials

Aspen Plus V8.4 Software was used for the modeling and simulation of the Solar absorption cooling system. The inputs to the Model were mainly data collected from Borno state meteorological Agency for the year 2016.

Methods

The theory of absorption refrigeration system working with Lithium Bromide (LiBr) and water, illustrated by Figure 3.1, consist of a condenser, an expansion valve, an evaporator and a thermal compressor. In this cycle, water condenses (rejecting heat) and evaporates (extracting heat from the thermal load) similar to a refrigeration cycle by mechanical compression. However, the thermal compressor located between the evaporator and condenser, performs vapor compressor by using energy in the form of heat (solar energy in this case).

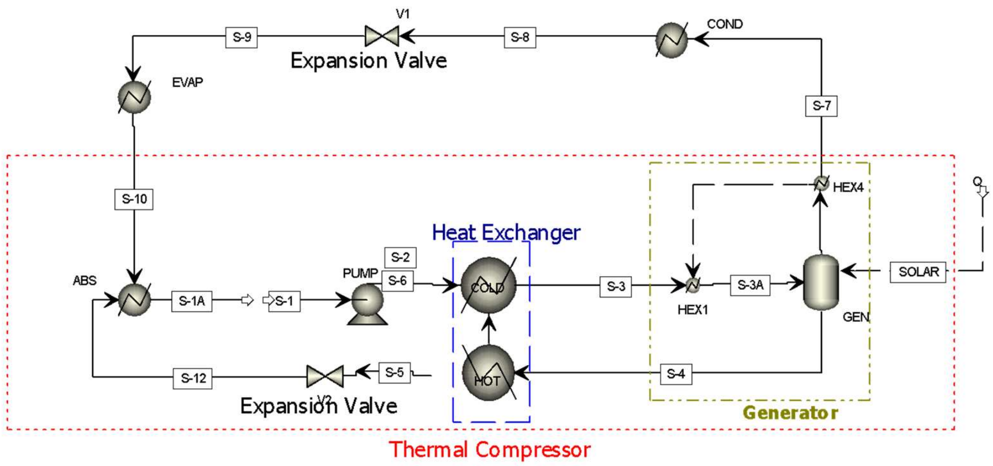

Figure 3.1: Process Diagram of the Water-LiBr absorption refrigerator

Process Description

The thermal compressor consists of two major unit operations: Absorption and distillation. In the absorption water vapor is absorbed by LiBr due to it affinity with water forming a weak LiBr/water solution in the absorber and in distillation (generator) the water vapor is separated from the strong LiBr/Water solution consuming heat. For a better cycle efficiency, separation must be almost complete, and water quality must be close to 1 (~0.999) in the generator output (Herold, et al., 1996). For improvement of the efficiency of the system, a regenerative heat exchanger is used between the absorber and generator.

Generally, the heat is removed from the system by cooling tower. The cooling water passes through the absorber first then the condenser. The temperature of the absorber has a higher influence on the system efficiency than the condensing temperature of the cooling tower where the heat is dissipated to the environment. In the case that the sun is not shining, an auxiliary heat source is used by electricity or conventional boiler to heat the water to the required generator temperature. It is highly recommended to use a partitioned hot-water storage tank to serve as two separate tanks. In the morning, the collector system is connected to the upper part of the tank, whereas in the afternoon, the whole tank would be used to provide heat energy to the system.

Electrical energy consumption in an absorption cycle is minimal when compared to a compression cycle, since only the pump uses this energy to raise the pressure of the liquid solution formed in the absorber. In a vapor compression cycle, the compressor consumes much more electrical energy to raise the pressure of the refrigerant vapor that comes out of the evaporator. Table 3.1 describes the block used in ASPEN PLUS to represent each unit operation in the process.

ıble 3.1: **ASPEN PLUS** Model Representation adopted from Balghouthi et al, 2008.

Units	Block	Descriptions
ond	Heater (Exchanger)	Condenser
V1 and V2	Valve	Expansion Valve 1 and 2
Evap	Heater (Exchanger)	Evaporator
ABS	Heater (Exchanger)	Absorber
PUMP	Pump	Pump
Heat Exchanger	Heater (Exchanger)	Regenerative Heat Exchanger
GEN	Flash2	Distillation
Hex1	Heater (Exchanger)	vapor heat control
Hex4	Heater (Exchanger)	vapor heat control

Table 3.2 below shows average solar radiation collected from Borno state meteorological Agency for the year 2017.

Month	T.max	T. min	T.mean	R.H	Evaporation	Sunshine
No	0C	0C	0C	%	Mm	0C
January	31.6	0.9	26.1	19	10.8	9.0
February	33.0	14.5	28.7	16	13.7	9.1
March	38.5	18.8	29.3	12	16.8	9.6
April	41.1	25.3	33.3	26	15.9	9.0
May	40.2	26.7	31.0	39	13.4	9.1
June	36.0	24.7	29.1	57	3.8	6.5
July	33.0	23.6	27.4	67	5.5	7.2
August	30.9	22.6	27.2	75	2.9	6.6
September	33.3	22.5	27.2	69	3.7	7.9
October	35.3	19.9	28.5	43	7.6	7.2
November	35.2	14.8	27.6	26	9.7	7.9
December	35.7	12.9	26.2	25	9.5	7.8

T. max = Temperature maximum
T. min = Temperature minimum
T. Mean = Average
R H = Relative Humidity

Model Assumptions

Mass, energy, and species conservation principles was applied to each component in the process With ASPEN PLUS. The following assumptions were considered (Vargas & Parise, 1995):

1. Refrigerant and solution in each component are homogeneous, thus, each component is treated as a lumped system;
2. The refrigerant in the condenser and evaporator is considered as a pure and simple substance;
3. The fluid in the thermal compressor is treated as a solution of LiBr and water;

4. Kinetic and potential energy variations of the refrigerant are negligible with respect to internal energy variations;
5. The expansion valves operate as throttling thermodynamic processes;
6. The refrigerant in the condenser outlet is taken as a sub cooled liquid;
7. The refrigerant in the evaporator outlet is taken as superheated vapor;
8. The solution leaving the absorber is at the same temperature and concentration as in the absorber;
9. The refrigerant leaving the rectifier is at the same temperature and concentration as in the rectifier (distillation);
10. Refrigerant mass in vapor or liquid phase are negligible with respect to mass in the region of phase change in the condenser and evaporator (Vargas & Parise, 1995).
11. The mass of vapor is negligible compared to the mass of the liquid phase in the thermal compressor;
12. Liquid phase is assumed to behave as an incompressible fluid, and
13. The pump is adiabatic and isenthalpic.

System Description

The solar-powered absorption cycle consists of four major parts, i.e., a generator, a condenser, an evaporator and an absorber. These major components are divided into three parts by one heat exchanger, two expansion valves and a pump. Schematic diagrams of the solar-powered cooling system are shown in Figures 3.2 and 3.3. Initially, the collector receives energy from sunlight and heat is accumulated in the storage tank. Subsequently, the energy is transferred through the high temperature energy storage tank to the refrigeration system. The solar collector heat is used to separate the water vapor, stream number 2, from the lithium bromide solution, stream number 3, in the generator at high temperature and pressure resulting in higher lithium bromide solution concentration. Then, the water vapor passes to the condenser where heat is removed and the vapor cools down to form a liquid, stream number 4. The liquid water at high pressure, stream number 4, is passed through the expansion valve, stream number 9, to the evaporator, where it gets evaporated at low pressure, thereby providing cooling to the space to be cooled. The weak solution, stream number8, is then pumped into the generator and the process is repeated.

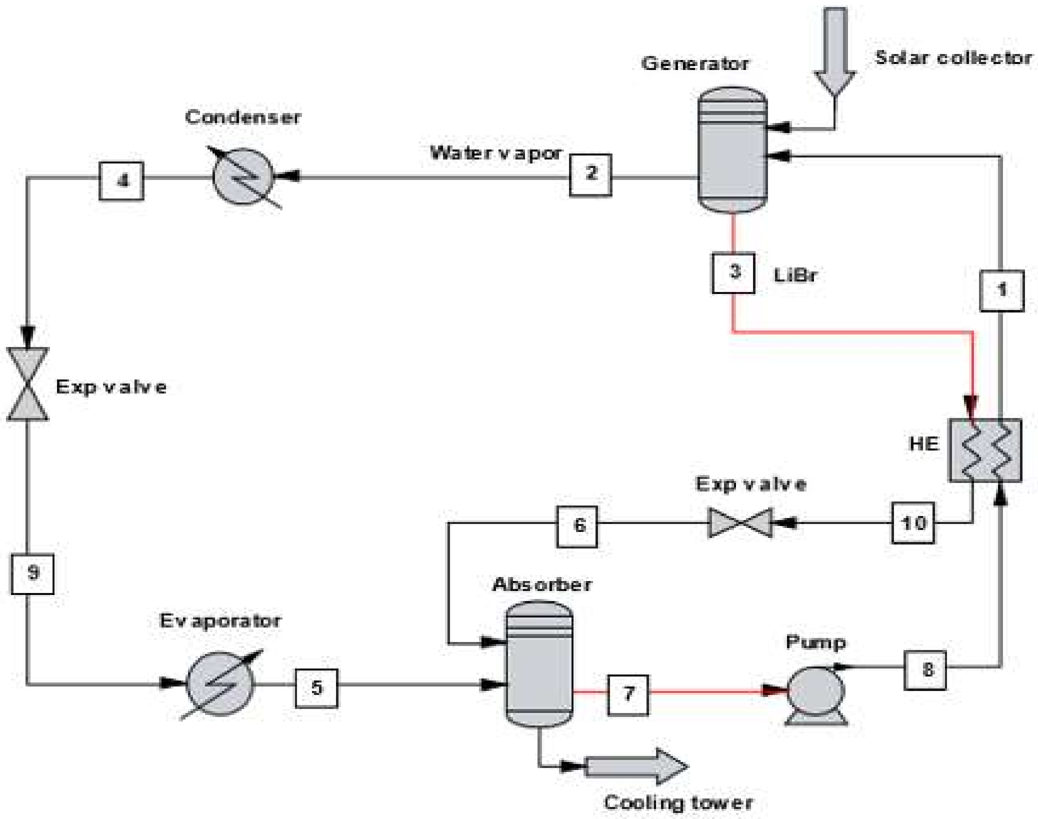

Figure 3.2: Schematic diagram of the absorption cycle adopted from Balghouthi, et al 2008.

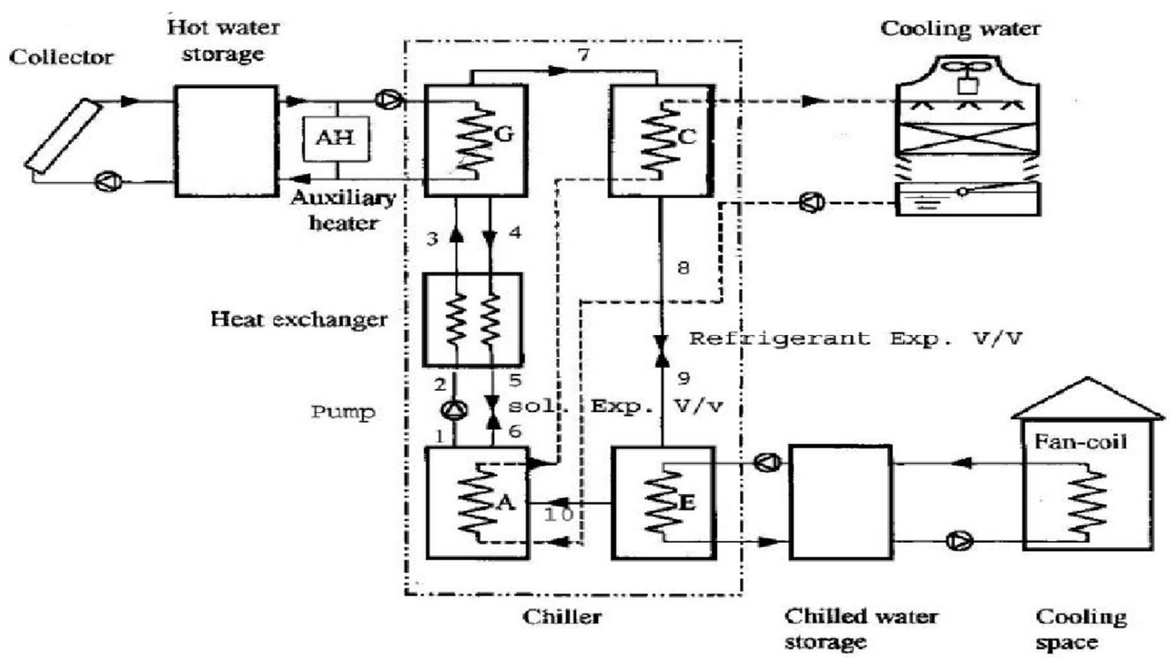

Figure 3.3 Schematic Diagram of the solar-powered cooling system adopted from Balghouthi, et al 2008.

A-Absorber, G- generator, C- Condenser, E- Evaporator

Generally, the heat is removed from the system by a cooling tower. The cooling water passes through the absorber first then the condenser. The temperature of the absorber has a higher influence on the system efficiency than the condensing temperature of the cooling tower where the heat is dissipated to the environment. In the case that the sun is not shining, an auxiliary heat source is used by electricity or conventional boiler to heat the water to the required generator temperature.

Mathematical Model

Preliminary material balance is taken across each unit i.e. the generator, absorber, evaporator, condenser and heat exchanger to analyze the working conditions of all components of the system. Energy balances are performed and a computer simulation is developed for the cycle analysis. A control volume analysis around each component, which covered the rate of heat addition in the generator, and the energy input of the cycle, is given by equation Klein, *et al*.(1994). (3.1):

QGenerator=QSolar=m4h4+m7h7-m3h3 (3.1)

The rate of heat rejection out of the condenser is given equation (3.2):

QCond=m7(h7-h8) (3.2)

The rate of heat absorption of the evaporator is given by equation (3.3):

QEvap=m9(h10-h9) (3.3)

The rate of heat rejection of the absorber is given by equation (3.4):

QABS=m10h10+m12h12-m1h1 (3.4)

An energy balance on the hot side of the heat exchanger is given by equation (3.5):

Qshx-hot=m4(h4-h5) (3.5)

Similarly, an energy balance on the cold side of the heat exchanger is given by equation (3.6):

Qshx-cold=m2(h3-h2) (3.6)

Coefficient of performance (COP) according to Figure 3.1. is defined as follows:

COP=QEvapQGenerator+QPump (3.7)

The solar collector was modeled in this manner proposed by Klein, et al.(1994). The basic equation for the rate of useful energy gain by a flat-plate solar collector is given by:

QS=FrAC(IR-UL(Tci-Ta) (3.8)

Where:

Fr = collector heat removal factor (0.8)

I = radiation intensity, W/m^{2}K

R = ratio of total radiation on tilted surface to that on plane of measurement (1.08)

UL = overall loss heat transfer coefficient, W/m2oK, (7.811)

Tc = temperature of the Collector surface (48^{o}C)

Ta = ambient temperature (25^{o}C)

For simplicity, the above values in bracket will be use based on the results obtained by Ezechi *et al* (2010).Radiation Intensity (I)was obtained from monthly daily average solar energy parameters measured in Maiduguri by (Luqman, et al., 2016).

Setting Up Aspen Plus V8.4

The first step was to add the components of interest, in this case water, lithium bromide as well as the lithium-ion Li+ and the bromide ion Br- as seen in Figure 3.1. Then the electrolyte wizard was used in order to add the chemistry and specify the property method.

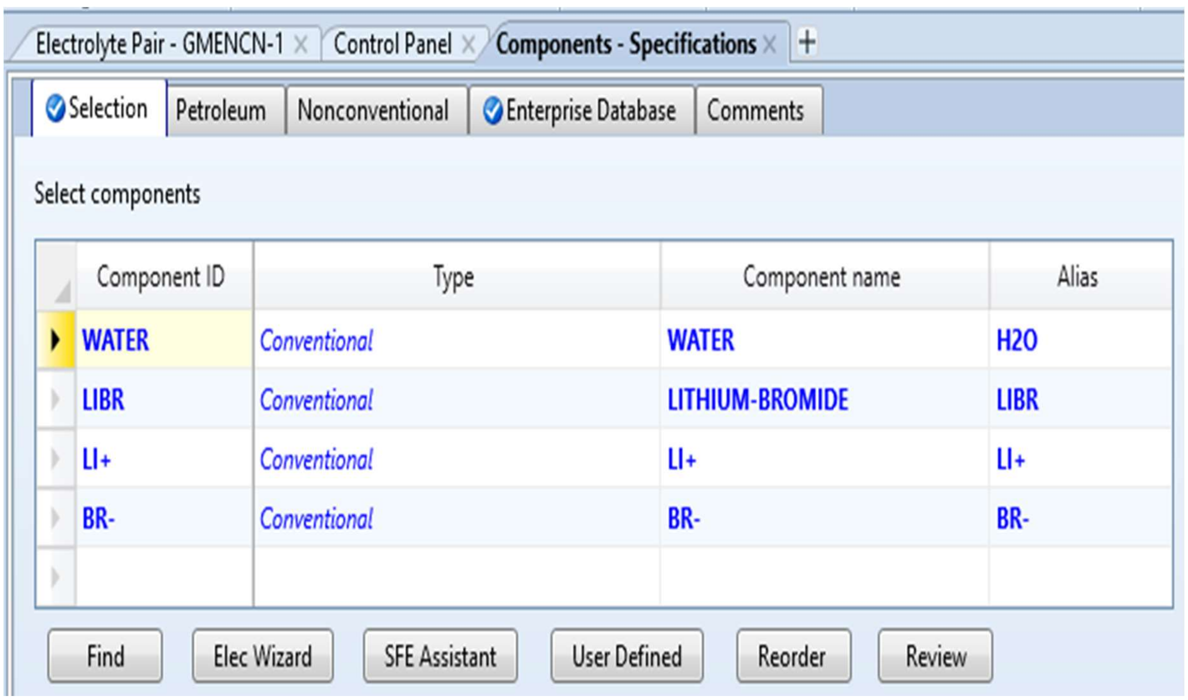

Figure 3.3: Component specifications required for the absorption cooling system.

The base method of ENRTL-RK, anunsymmetric model, was automatically chosen for the thermodynamics fluid properties base on the chemistry produce by the electrolyte wizard. Once the required components are added the missing data for the components of interest need to be pulled from various Aspen databases. This can be done by clicking on retrieve parameters under the tools heading in the home ribbon. In the case of some electrolytes, in this case lithium bromide, the Aspen database does not contain all of the necessary properties to perform the simulation using Redlich-Kwong as the EOS therefore they must be added in manually. The missing parameters are the critical pressure Pc, critical temperature Tc, critical volume VcandZc of the LiBr. These four values were obtained from the literature (Wikipedia, 2018) as 50, 1726.85, 100 and 0.2 for Pc, Tc, Vc and Zc respectively. These values were entered in the LiBr property column using the review button of Figure 3.2.

Model Simulation

Aspen plus was used to simulate the solar-powered lithium bromide absorption system. The generator and absorber were modeled by using a multipurpose flash column. ASPEN PLUS uses the flash column to visualize generator and absorber operations. Simultaneously, a modular mode was used to solve the algebraic equations of the flow sheet. The Non-random two-liquid (NRTL) model and latent-heat enthalpy model were used in the simulation to obtain the thermodynamic properties and phase equilibrium of the Lithium bromide solution. The NRTL model software keeps all flashes as three-phase flashes (LLV) or two-phase flashes (LV). Liquid phase activity coefficients are calculated by the NRTL equation by the known values of the liquid phase mass fraction. The NRTL equation is a good method to solve the binary mixture where equilibrium prevails between liquid and vapor. Previous studies have shown that the NRTL equation is in good agreement with the experimental phase equilibrium of Lithium Bromide solution. The numerical data obtained are in good agreement with Balghouthi et al. results adopted.

The input data required for simulating the system consists of the following: generator temperature, absorber temperature, generator and condenser pressure, evaporator and absorber pressure, pump output pressure, mass flow rate entering generator, lithium bromide solution concentration entering the generator and fixed saturated liquid state from heat exchanger to generator. Figure 3.3 shows flow-diagram for how simulation works using input data. The output includes the generator heat gain, cooling capacity and COP.

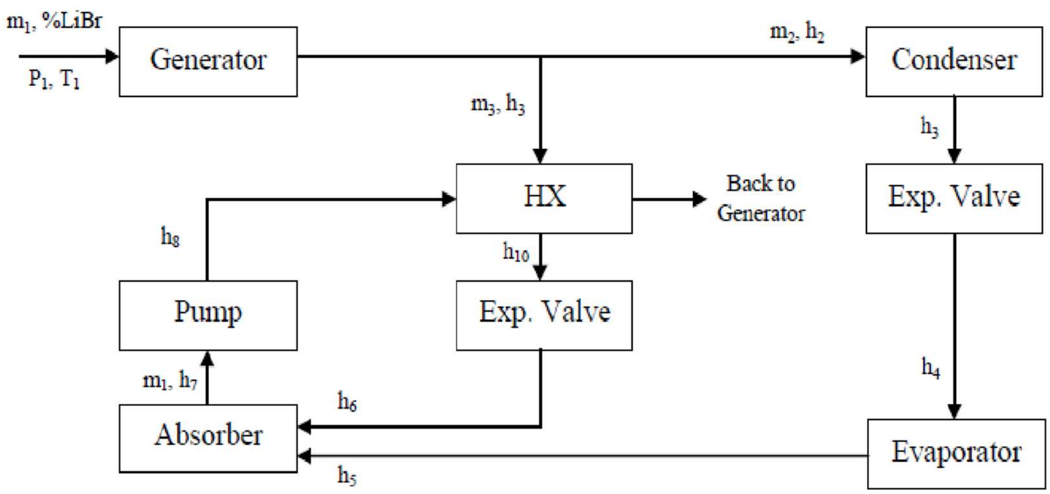

Figure 3.4: Modified Information-flow diagram for solar-powered absorption cooling system.

List of Symbols

AC=Collector Area (m^2)

ci=Correlated Constants

CFD= Computational fluid dynamics

COP =Coefficient of performance

EER= Energy efficiency ratio

FR=Collector heat removal factor

h =Enthalpy (kJ/kg)
HX= Heat exchanger
H_2O= Water
LV= Liquid-vapor
LLV Liquid-liquid vapor
M=Mass flow rate (kg/s)
m_a=Air curtain mass flow rate (kg/s)
NP= Number of people
NRTL= Non-random two-liquid
P= Pressure (kPa)
q =Volume flow rate (m^3/s)
Q= Heat transfer (kW)
QL=Latent heat (kW)
R= Refrigerant
RH= Relative humidity (%)
S=Solar intensity (W/m^2)
T=Temperature (^{0}C)
UL=Collector overall loss coefficient

RESULTS AND DISCUSSIONS

Introduction

With the absorption-cooling model completed, results of the simulation of the model will be study and discuss in this chapter. Two distinct studies were conducted. Firstly, sensitivity analysis study was conducted on the model in other to know the effect of different operating parameter on it Coefficient of Performance (COP). Parameters selected were based on the four major part of the system i.e. Generator temperature and duty, Evaporator Temperature and duty, condenser duty, absorber duty, LiBr-concentration, Solar insolation, and Solar collector area. Finally, an optimization study was conducted to determine the optimum performance of the solar-powered absorption cooling system.

Variation of Generator Temperature against COP

The effect of the variation of the generator temperature with Coefficient of performance (COP) and cooling capacity against generator temperature is shown in figure 4.1. The cooling capacity increases rapidly from a low value of 13 kW (at 79^{o}C) up to 669 kW (at 150^{o}C). The COP rises from a low value of 0.24 (at 79^{o}C) to reach a constant value of 0.781 (at 111^{o}C). The cooling capacity increases as the generator temperature increases.

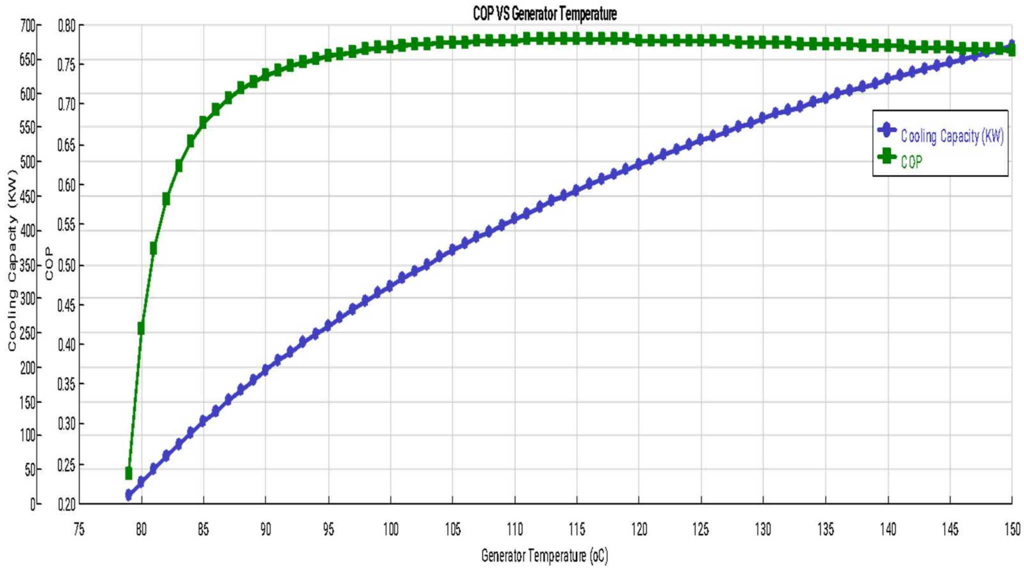

Figure 4.1: Effect of generator temperature on cooling capacity and COP as Predicted by ASPEN model.

The COP increase significantly with increasing generator/collector temperature, but as the generator/ collector temperature increases, the heat transfer in all the heat exchangers of the system also increases as shown in Figure 4.2. The figure shows similar increase in the heat transfer in all of evaporator, condenser and absorber when varying the generator (or collector) temperature. The concentration of Lithium Bromide (LiBr) solution increases rapidly with increase in generator temperature (See Figure 4.3). This is expected, since more water evaporate with temperature which result in more LiBr with less water in the generator (hence higher concentration).

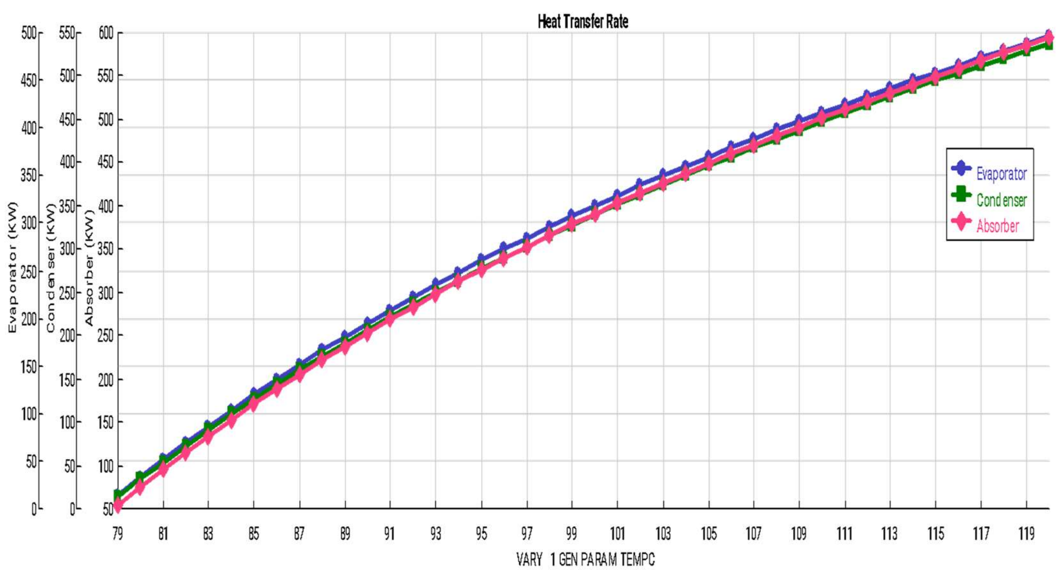

Figure 4.2: Effect of generator inlet temperature on evaporator, absorber, condenser against generator heat transfer rates.

The concentration of Lithium Bromide (LiBr) solution increases rapidly with increase in generator temperature (See Figure 4.3). This is expected since more water evaporates with temperatures which result in more LiBr with less water in the generator (hence higher concentration).

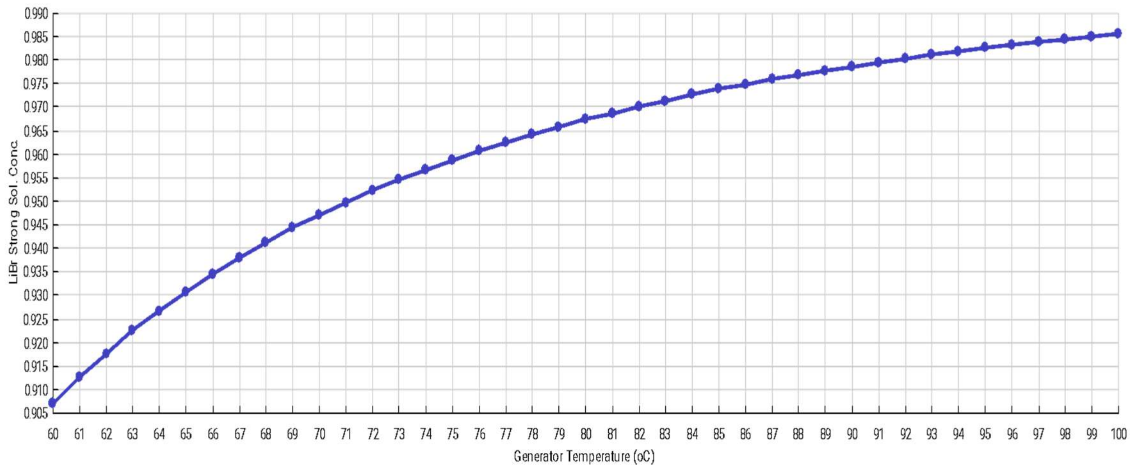

Figure 4.3: Effect of generator temperature (^{0}C) on LiBr-H_2O concentration (kg)

The generator inlet temperature could not be increased or decreased too much because of the crystallization of the lithium bromide as seen in figure 4.4. Because lithium bromide is a salt, in its solid state it has a crystalline structure. There is a specific minimum solution temperature for any given salt concentration when lithium bromide is dissolved in water. The salt begins to leave the solution and crystallize below this minimum temperature. In an absorption system, if the LiBr-solution concentration is too high or if the LiBr-solution temperature is reduced too low, crystallization may occur. The crystallization influences the cycle performance and the temperatures at different streams.

There are several causes for crystallization. Air leakage into the system is one of most common reason for crystallization. Air leakage results in increased pressure in the evaporator. This, in turn, results in higher evaporator temperatures and, consequently, lower cooling capacities. In the other case, at high load conditions, the control system increases the heat input to the generator, resulting in increased solution concentrations to the level where crystallization may occur. Non-absorbable gases, like hydrogen, produced during corrosion, can also be present; this can reduce the performance of both the condenser and the absorber. Electric power failure is found to be another reason for crystallization. Crystallization is most likely to occur when the machine is stopped while operating at full load, when highly concentrated solutions are present in the solution heat exchanger. To solve this problem, during normal shutdown, the system should go into a dilution cycle, which lowers the concentration of the LiBr-solution throughout the system, so that the machine may cool to ambient temperature without crystallization occurring in the solutions.

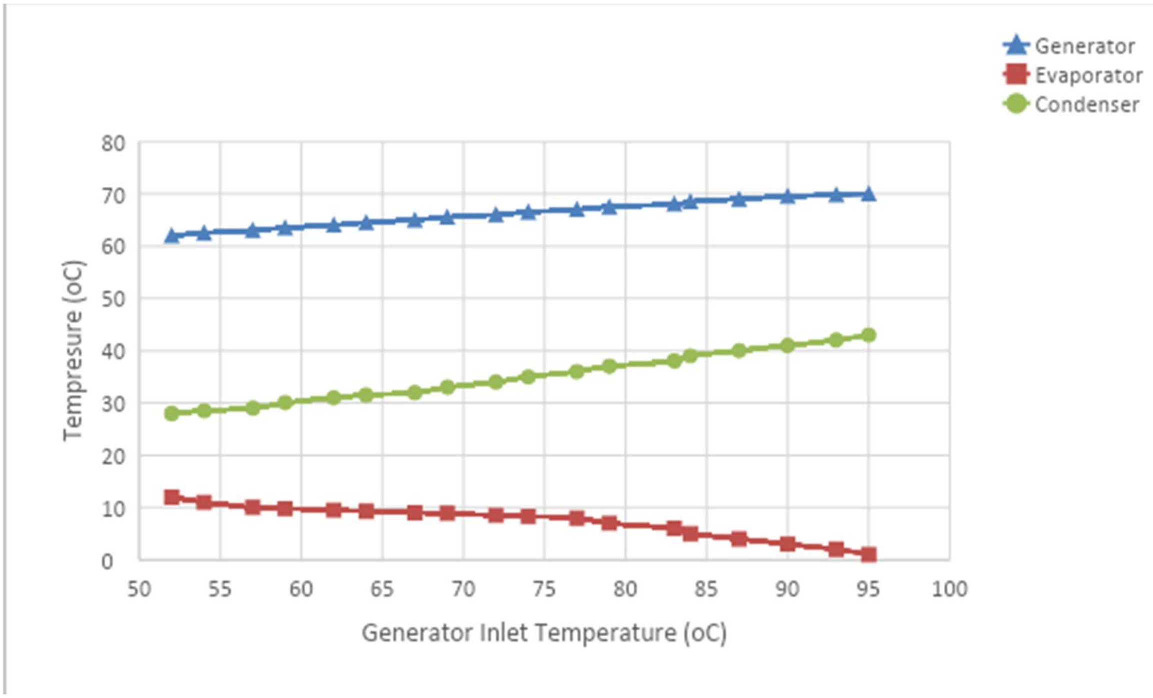

Figure 4.4: Effect of generator inlet temperature on generator, evaporator and condenser temperatures.

Variation of Evaporator Temperature against COP

The greater the collector area the greater the heat gained. This can be good for the auxiliary boiler as seen in figure 4.4 above. Once the heat gained is increased, less heat is required from the auxiliary boiler to maintain the required generator temperature. The next parameter of interest is evaporator temperature. This is an important parameter to consider because it has a significant effect on chiller performance, as a higher evaporator temperature means a higher COP. The evaporator temperature is a set value that is dictated by the desired cooling temperature, but since a variety of cooling temperatures are needed in an LNG plant, it is important to consider a variety of evaporator temperatures.

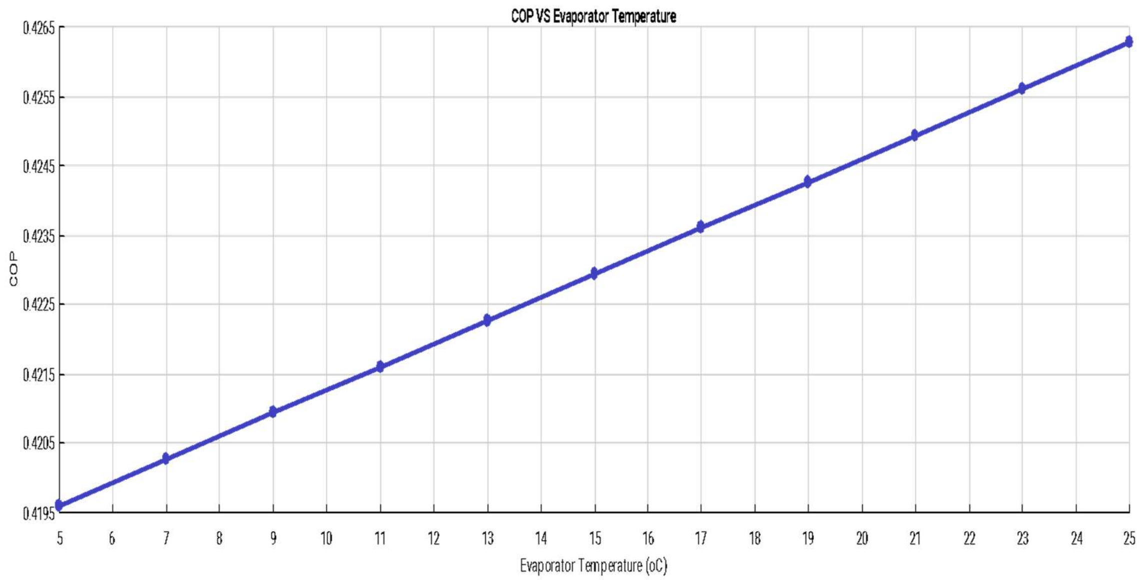

Figure 4.5: Effect of evaporator temperature on absorption cooling system COP as predicted by ASPEN model

From this Figure, it can be seen that; within the range of temperature investigated, the absorption cooling system COP Increases from 0.4195 to 0.4262.

Variation of Lithium Bromide Concentration against COP

In this section, Lithium Bromide concentration was varied in the refrigerate solution in other to determine it significant on the COP. From Figure 4.6, it is shown that the COP decreases rapidly with increase in LiBr-concentration. From this Figure, an increase in the concentration of LiBr from 0.03 to 0.88 LiBr kg/kg solution resulted in a decrease in the COP from 37 to 2 %. This is due to the little or lack of the absorbent (water) present for circulation in higher concentration of LiBr. Since higher LiBr concentration means lower water present.

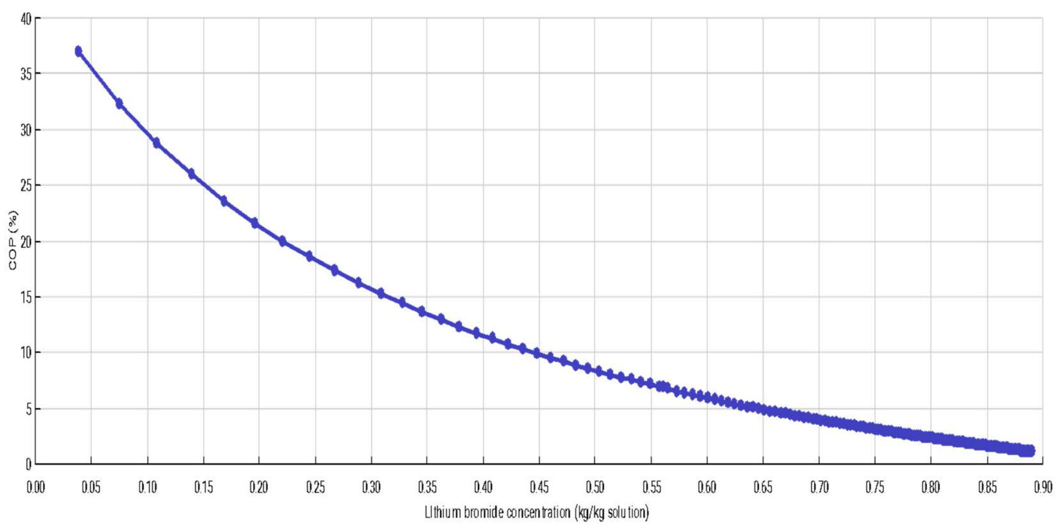

Figure 4.6: Effect of lithium-bromide concentration on the COP as predicted by Aspen model.

Variation of Solar Collector Area against COP

Increase in solar collector area on the same setting will supply more energy to the system, which in turn increase the temperature of the generator thereby making more water to evaporate, this decreases the performance of the system. This behavior is depicted in Figure 4.7.

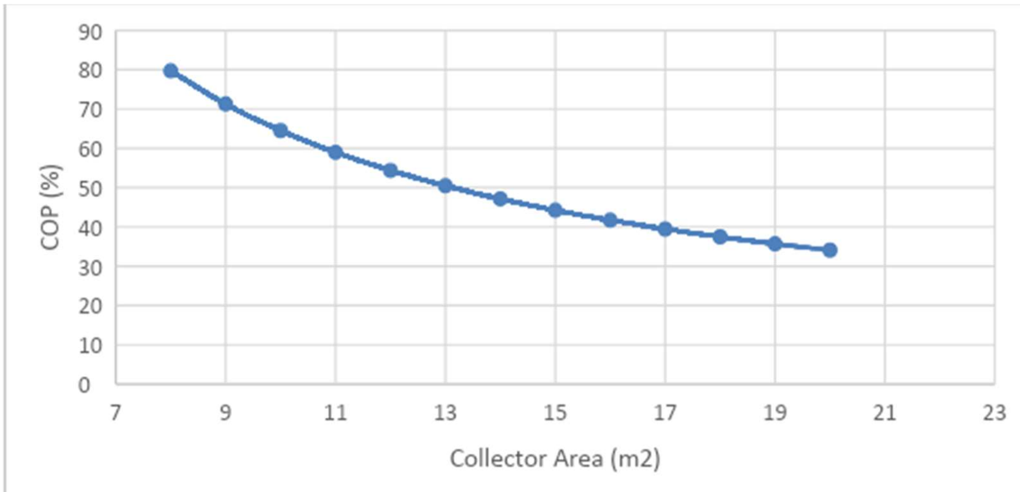

Figure 4.7: Effect of Solar Collector area on the COP as predicted by Aspen model.

Variation of Solar Insolation against Months of the Year.

Figure 4.8. Illustrate a typical climatic condition of Maiduguri in a particular month, as depicted by the insolation variation in the month. These values used in the model to provide the heat required in the generator based on Equation 3.8. From this Figure, it can be seen that more heat (energy) is expected between Augusts to December of the year.

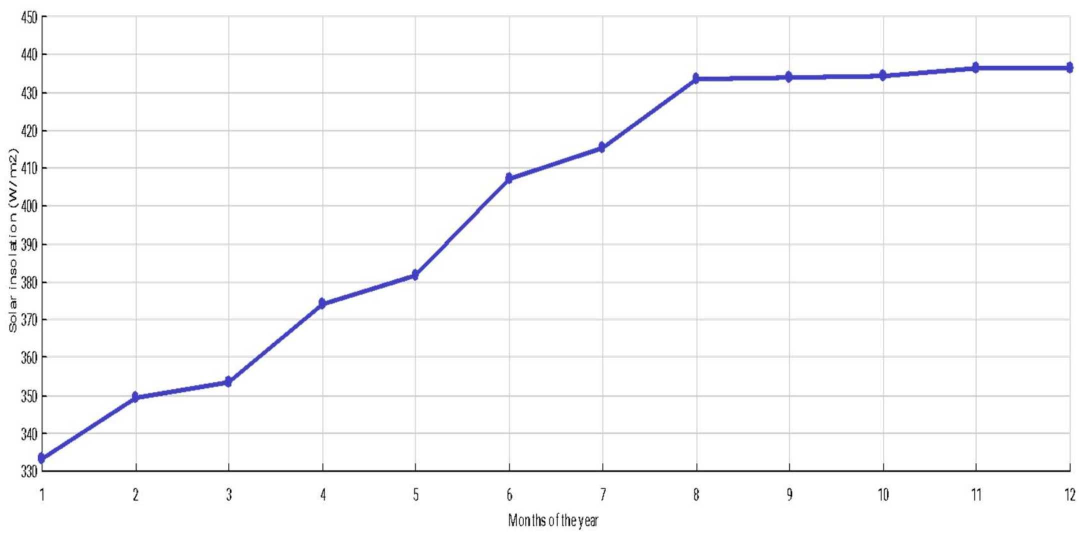

Figure 4.8: Effect of Solar Collector area on the COP as predicted by Aspen model.

Validation of the Developed Model

The operational validation of the developed model in table 4.1 shows comparismbetween TRNSYS (a) adopted from Balghouthi et al, 2008 and Aspen plus (b)

Table 4.1: Modified Operational condition (a) (Balghouthi, et al., 2008), adopted and (b) ASPEN PLUS process model.

		T (^oC)		P (kPa)		x(kg LiBr/kg solution)		m (kg/s)	
Stream		(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
1	Pump Outlet	36.2	8.1	6.601	6.601	0.561	0.561	0.056	0.056
2	Condenser Inlet	70	78	6.601	6.601	0	0	0.0048	0.023419
3	Generator Outlet	84.6	78	6.601	6.601	0.613	0.964	0.0512	0.032581
4	Condenser outlet to exp. Valve	38	37.8	6.601	6.601	0	0	0.0048	0.023419
5	Vapor from evaporator to absorber	4.4	5	0.9	0.9	0	0	0.0048	0.023419
6	Solution inlet in absorber	47.1	39.1	0.9	0.9	0.613	0.964	0.0512	0.023419
7	Absorber outlet	36.2	8.1	0.9	0.9	0.561	0.561	0.056	0.032581
8	Generator inlet from heat exchanger	62.4	62.4	6.601	6.601	0.556	0.561	0.056	0.032581
9	Evaporator inlet from expansion valve	5.5	4.5	0.9	0.9	0	0	0.0048	0.023419
10	Absorber inlet from heat exchanger	53.6	53.6	6.601	6.601	0.613	0.964	0.0512	0.032581
11	Absorber inlet from exp. Valve	62.4	39.1	0.9	0.9	0.556	0.964	0.056	0.032581

Optimization Process

As can be observed from the above analyses based on the input variables (generator temperature and evaporator temperature), the tangible input value(s) that will give highest COP and high cooling capacity has not been obtained. This called for the optimization of the process using the same Aspen Plus model. The optimization of this process was carried out to obtain the optimum input variables that would give the maximum COP and Cooling Capacity on bi-objective function using equation 4.1, where α varied from 0 to 1. The input variables were varied based on the knowledge gained from the parametric analysis (see second column in Table 4.2) and COP_{max} was set as the objectives function. The optimum input variables obtained from the optimization carried out and those of the steady-state simulation carried out prior to it (the optimization) are also presented in Table 4.2. From the table, it was discovered that the input values obtained from the optimization (the final values) were different from those of the steady-state simulation carried out prior to the optimization (initial values), also noticed that the final values were within the ranges specified for the input variables during the optimization.

$$COPmax=\alpha COP+(1-\alpha)(\text{Cooling Capacity}) \quad (4.1)$$

Table 4.2: Initial input (or steady-state) and optimum parameters obtained from the process

Variable	Initial value	Final Value	Units
Generator Temperature	48	110	°C
Evaporator Temperature	5	24	°C

Presented in Table 4.3 are the initial and final values of the objective function recorded before and after optimization;

Table 4.3: Objectives Function

Variable	Initial value	Final Value
Cooling Capacity	32.3 kW	430.7 kW
COP	0.684	0.793

From Table 4.3, it was noticed that the optimized values were different from their steady-state values, just as it was discovered in the case of the steady-state and the optimum input variables. Specifically, the cooling capacity was increase from 32.3 to 430.7 kW while COP increased from 0.684 to 0.793 after optimization.

SUMMARY, CONCLUSION AND RECOMMENDATION

Summary

The use of solar energy for cooling purposes is an attractive prospect; the key factor for this application is the availability of solar energy for Maiduguri climate and suitable cooling technology. Flat plate collector with solar absorption cooling technology was used for cooling systems as an alternative to fossil fuel based conventional electrically powered cooling systems. For hot climate like Maiduguri, Borno State, a solar cooling system found to be a sustainable, clean, and viable system for cooling demand.

Conclusion

This study successfully modeled and simulated a solar absorption cooling system for Maiduguri, Borno State, Nigeria, using Aspen Plus software. The model was developed to analyze the vapor absorption refrigeration system using Lithium Bromide (LiBr) and water. The simulation aimed to evaluate and optimize the coefficient of performance (COP) of the system under varying conditions. The results demonstrated the system's sensitivity to generator temperature, evaporator temperature, Lithium Bromide concentration, solar collector area, and solar insolation. The study found that higher generator temperatures increased cooling capacity and

COP but risked lithium bromide crystallization due to increased concentration. Conversely, higher LiBr concentrations reduced the COP due to reduced water availability for circulation. An optimization study was conducted, resulting in improved cooling capacity and COP by adjusting the generator and evaporator temperatures. Overall, the study highlights the potential of solar absorption cooling systems as sustainable alternatives for cooling demands in hot climates like Maiduguri, Nigeria. Further research could focus on integrating storage solutions to enhance system performance and reliability.**5.3**

Recommendation

a. Solar absorption cooling systems can be a sustainable and green solution as cooling demand for office buildings and residential areas are on the increase. Therefore, it is recommended to promote use of these systems for cooling in Maiduguri, Borno State.

b. Further research should consider other refrigerant other than LiBr-H_2O

c. Design specification for each components of the system i.e generator, evaporator, condenser and absorber be taken into consideration.

d. Other renewable energy sources (wind, briquette and hydroelectric energy) should be utilized to help meet current and future energy demand.

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