The study of solar absorption air-conditioning systems

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Abstract
An air-conditioning system utilizing solar energy would generally be more efficient, cost wise, if it was used to provide both heating and cooling requirements in the building it serves. Various solar powered heating systems have been tested extensively, but solar powered air conditioning systems have received very little attention. Solar powered absorption cooling systems can serve both heating and cooling requirements in the building it serves. Many researchers have studied the solar absorption air conditioning system in order to make it economically and technically viable. But still, much more research in this area is needed. This paper will help many researchers working in this area and provide them with fundamental knowledge on absorption systems, and a detailed review on the past efforts in the field of solar absorption cooling systems with the absorption pair of lithium-bromide and water. This knowledge will help them to start the parametric study in order to investigate the influence of key parameters on the overall system performance.

Keywords: solar energy, absorption cooling system, air-conditioning, lithium bromide and water

Introduction

Solar energy is one of the most available forms of energy on the Earth's surface, besides; it is very promising and generous. The earth's surface receives a daily solar dose of 10E+8 KW-hr, which is equivalent to 500 000 billion oil barrels that is one thousand times any oil reserve known to man.

The solar energy is collector area dependent, and is a diluted form of energy and is available for only a fraction of the day. Also, its availability depends on several factors such as latitude and sky clearness (Duffie & Beckman 1980. At the same time, its system requires high initial cost. But on the other hand, it has some attractive features such as its system requiring minimum maintenance and operation cost, and it does not have negative effects on the environment. Another important feature of solar energy is its ability to satisfy rural areas where conventional energy systems might be not suitable or uneconomical.

Solar energy is being invested in many forms. The first form is the most familiar and that is using it for supplying domestic hot water for residences which is the most worldwide spread form of solar energy use. Another form is the photovoltaic, and these are special cells that transfer solar energy to electric ones. Also, some power plants are now present that produce electricity from solar energy (e.g. US Pilot Power Plant of 516 degree Celsius average temperature (Friefeld & Coleman 1986) and the Japanese experiment stations of 1MW power output (Tanaska 1989).

Some other applications of solar energy being investigated are its use for cooling and heating of buildings. A lot of research is being conducted for this purpose especially in countries where there is high availability of solar energy just like in India. Solar energy is abundant in summer months where there is no heating load, but instead cooling is required. Solar air-conditioning has the advantage of both the supply of the sunshine and the need for refrigeration reaching maximum levels in the same season. As a result, solar air-conditioning is the particularly attractive application for solar energy.

Application of solar energy in cooling

In order to evaluate the potential of solar energy for the different solar cooling systems, a classification has been made by the scientists Best and Orgeta (1998). It is based on the two main concepts – solar thermal technologies for the conversion of solar heat into hot water, and the solar cooling technologies for the cold production.

The solar thermal technologies are:

- Flat plate collectors
- Evacuated tube collectors
- Stationary, non imaging concentrating collectors
- Dish type concentrating collectors
- Linear focusing concentrators
- Solar pond
- Photovoltaic

The solar cooling technologies are mainly classified into two main groups depending on the energy supply: a thermal/work driven system and electricity (Photovoltaic) driven system. Each group can be classified as the following:

1. Thermal/work driven system
    - Absorption refrigeration cycle
    - Adsorption refrigeration cycle
    - Chemical reaction refrigeration cycle
    - Desiccant cooling cycle
    - Ejector refrigeration cycle
2. Electricity (Photovoltaic) driven system
    - Vapour compression refrigeration cycle
    - Thermo-electric refrigeration cycle
    - Stirling refrigeration cycle

The solar-powered cooling system generally comprises three main parts: the solar energy conversion equipment, the refrigeration system, and the cooled object (e.g. a cooling box). A number of possible "paths" from solar energy to the "cooling services" are shown in Figure 1 (Pridasawas & Lundqvist 2003).

Solar absorption air conditioning system

Of the various air conditioning alternatives shown in Figure 1, the absorption system appears to be one of the most promising methods. The absorption cycle is similar in certain respects to the electrically driven vapour compression machines. A refrigeration cycle is operated with the condenser, expansion valve, and evaporator if low-pressure vapour from the evaporator can be transformed into high-pressure vapour and delivered to the condenser. The vapour compression system uses a compressor for this task. The absorption system first absorbs the low pressure vapour in an appropriate absorbing liquid. Embodied in the absorption process is the conversion of vapour into liquid, and since the process is akin to condensation, heat must be rejected during the process.

The next step is to elevate the pressure of the liquid with a pump, and the final step releases the vapour from the absorbing liquid by adding heat. Both cycles can be shown in the same figure. Figure 2 shows the methods of transforming low-pressure vapour into high-pressure vapour in a refrigeration system.

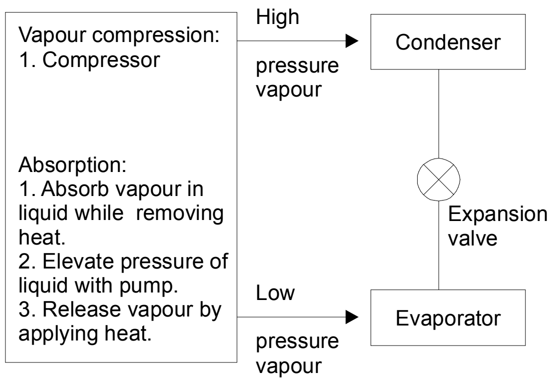

Figure 2: Methods of transforming low-pressure vapour into high-pressure vapour in a refrigeration system

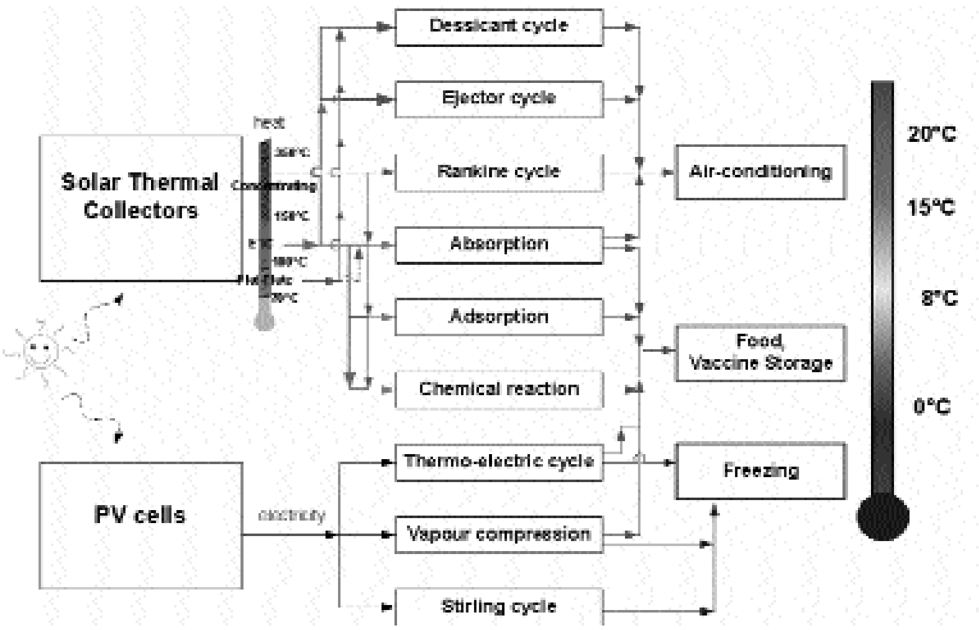

Figure 1: Solar cooling path

The vapour compression cycle (as shown in Figure 2) is a Work operated cycle because the elevation of pressure of the refrigerant is accomplished by a compressor that requires work. The absorption cycle (see Figure 2), on the other hand, is referred to as a heat operated cycle because most of the operating cost is associated with providing heat that drives off the vapour from the high pressure liquid. For a solar absorption cooling system, this heat is taken from sun energy.

Performance and selection of working pairs for a solar absorption cooling system

Performance of the refrigeration system is represented as a 'coefficient of performance (COP)'. It shows how much heat can be removed from a cold region (Q_e) for each unit of energy used (Q_g).

$$COP = \frac{Q_e}{Q_g} \qquad (1)$$

For the solar-driven systems, the performance can be written as the product of the COP and the solar collector efficiency (η_c). Besides, it can be defined as a ratio of the refrigeration effect and the solar energy input (I) for the thermal-driven systems, which is called 'system thermal ratio (STR)'.

$$\eta_{system} = COP \times \eta_c \qquad (2)$$

$$STR = \frac{Q_e}{I \cdot A} = \frac{Q_e}{Q_g} \times \frac{Q_g}{I \cdot A} = COP \times \eta_c \qquad (3)$$

Wilbur and Mitchell (1975) compared the Coefficient of Performance (COP) of the absorption system with the different working fluids. Of the various solar absorption air conditioning systems, LiBr-H_2O and H_2O-NH_3 are the major working pairs available in these systems. It is reported that the LiBr – H_2O pair has higher COP than any other pair of the working fluids.

Though it has a limited range of the operations, due to the onset of the crystallization occurring at the point of the recouperator discharges into the absorber and stopping solution flows through the device, the low cost and the excellent performance of this system make it a favourable candidate for the solar absorption cycle systems. Also by the comparison (Ward 1979; Ward et al 1979), the ammonia water pair has the following disadvantages:

- The coefficient of the performance for the H_2O-NH_3 systems is lower than for the LiBr-H_2O system. Generally, the H_2O-NH_3 system operates at 10-15% lower solar fraction than the LiBr-H_2O systems.
- It requires a higher generator inlet temperature. Generally, the LiBr-H_2O system requires the generator inlet temperature of the 70-88°C, while the H_2O-NH_3 system requires 90-180°C; which results in the H_2O-NH_3 system achieving a lower COP when using a flat plate collector.
- It requires higher pressures and hence higher pumping power.
- A more complex system requiring a rectifier to separate ammonia and water vapour at the generator outlet is required.
- There are restrictions on the in-building applications of the ammonia –water-cooling units because of the hazards associated with the use of ammonia.

For these reasons, the LiBr-H_2O system is considered to be the better suited for the solar absorption air conditioning applications.

Single effect solar absorption air-conditioning system

Figure 3 shows the schematic diagram of a single effect solar absorption air-conditioning system. This system has been the basis of most of the experience to date with solar air- conditioning. Here, the solar energy is gained through the collector, and is accumulated in the storage tank. Then, the hot water in the storage tank is supplied to the generator to boil off water vapour from a solution of Lithium Bromide and water.

The water vapour is cooled down in the condenser and then passed to the evaporator where it again is evaporated at low pressure, thereby providing cooling to the required space. Meanwhile, the strong solution leaving the generator to the absorber passes through a heat exchanger in order to preheat the weak solution entering the generator. In the absorber, the strong solution absorbs the water vapour leaving the evaporator.

Cooling water from the cooling tower removes the heat by mixing and condensation. Since the temperature of the absorber has a higher influence on the efficiency of the system than the condensing temperature, the heat rejection (cooling water) fluid, is allowed to flow through the absorber first, and then to the condenser (Li & Sumathy 2000). An auxiliary energy source is provided, so that hot water is supplied to the generator when solar energy is not sufficient to heat the water to the required temperature level needed by the generator.

The main process taking place in the chiller is as follows (as shown in Figure 4).

- Line 1-7: The weak solution from the absorber at point 1 is pumped through the heat exchanger to the generator; point 7 indicates the properties of the solution at the outlet of the heat exchanger. During the process 1-7, the concentration of the weak solution is held constant.
- Line 7-2-3: Process 7-2 shows the sensible heating of the weak solution in the generator, and 2-3 indicates the boiling of water vapour from the

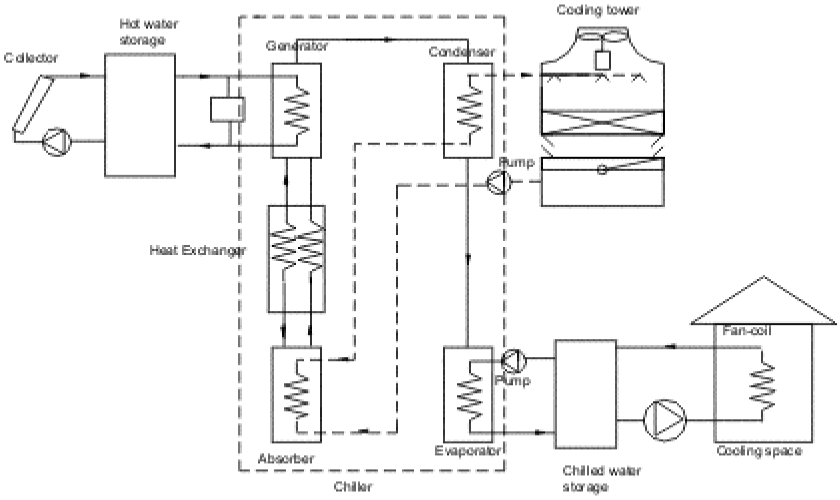

Figure 3: Schematic diagram of single effect solar absorption air-conditioning system

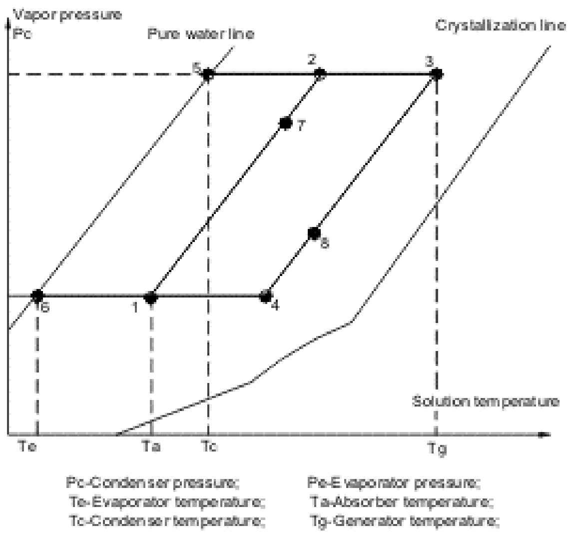

Figure 4: Process diagram of a Single-effect solar absorption air-conditioning system cycle

solution at the constant condensing pressure Pc (although the boiling pressure is a little higher than the condensing pressure, the difference is negligible). During this process, the weak solution becomes a strong solution.

- Line 3-8: Symbolizes the strong solution passing to the absorber through the heat exchanger, in which it preheats the weak solution flowing from the absorber to the generator. During this process, the concentration of the strong solution is constant.
- Line 8-4-1: Indicates the idealized process of absorption of water vapour from the evaporator by the strong solution in the absorber.
- Line 2-5: Denotes the condensation of water vapour in the condenser by the cooling water from the cooling tower, at constant condensing pressure Pc.
- Line 5-6: Shows the flow of condensed water from the condenser to the evaporator.
- Line 6-1: Indicates the evaporation of the water in the evaporator due to the prevailing low pressure Pe. Also, the water absorbs the heat from the space to be cooled. The water vapour from the evaporator is, in turn, absorbed by the strong solution in the absorber, thus completing the cycle of refrigeration.

Single-effect solar absorption air-conditioning system with refrigerant storage

One of the improvements that would make the absorption machine more suitable for solar operation is refrigerant storage. Basically, the idea is to provide, in association with the condenser, a storage volume where the refrigerant can be accumulated during the hours of high solar insolation. Then, this stored liquid refrigerant can be expanded at other times to meet the required loads. Storage is also needed in the absorber to accommodate, not only the refrigerant, but also sufficient absorbent to keep the concentration within allowable limits.

The advantages of the refrigerant storage over other methods include:

- The energy storage per unit volume is high as the latent heat of evaporation, which is larger, compared to available sensible heat changes, is involved;
- Losses are low as the storage occurs at or near room temperature;
- Further advantages arise when the storage is applied to the lithium bromide-water cycle;
- Water has one of the highest enthalpies of evaporation among known liquids;

Figure 5 shows the schematic diagram of the sin-

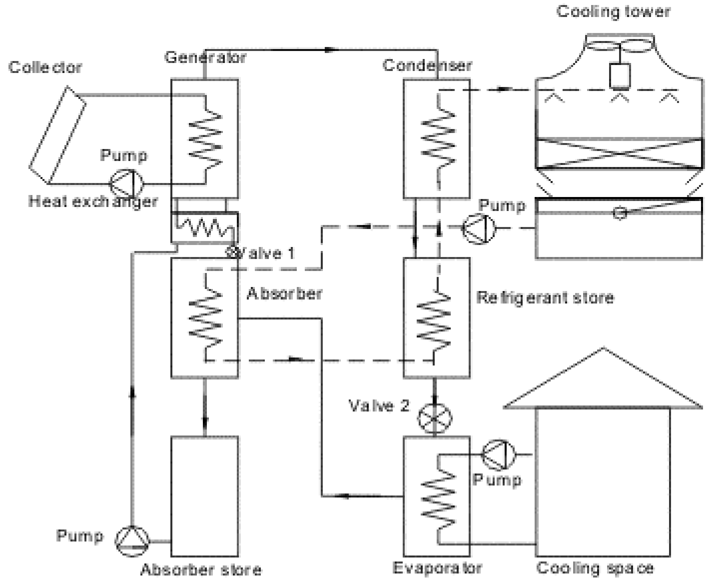

Figure 5: Schematic diagram of single effect solar absorption air-conditioning system with refrigerant storage

gle-effect solar absorption air-conditioning system with refrigerant storage (Grassie & Sheridan 1977). The refrigeration circuit includes the usual generator, condenser, evaporator and absorber together with a sensible heat exchanger, a mechanical pump and pressure reducing valves. A refrigerant store is associated with the condenser, while an absorber store is associated with the absorber. Heat rejection is accomplished by a cooling tower from which water is circulated through the absorber, condenser store and condenser in series.

The disadvantages of this system may be that:

- Generation of refrigerant ceases several hours before sunset and, although a significant amount of energy is still being collected, a lot of useful solar energy is wasted;
- The system may be very complicated. The generation power is not easily matched with the absorption and refrigeration power; besides, the control of valves 1 and 2 is difficult;
- Although the machine could store sufficient refrigerant during a typical day to allow overnight operation, the performance of the chiller is very low because of the decrease in concentration of the solution and the increase of the temperature and pressure in the system.

Single-effect solar absorption air-conditioning system with hot water storage

Efficient operation can be achieved by using two hot storage units for the collection of solar energy in different temperature ranges (Kreider & Krieth 1981). One storage unit would provide 70-75% of the total heat required at the lowest temperature, which can be utilized effectively at the part-load conditions.

Typical temperature may be from 50 to 70°C depending on the building load pattern and the expected pattern of ambient temperature. The remaining 25-30% of the storage volume would be in a smaller tank, with more insolation in order to store the heat collected in 85-95°C. Still, higher temperatures may be used in this storage if it can be pressurized to prevent boiling, and if collectors are used which are capable of operating at higher temperature levels with good efficiency. Latent heat storage may be particularly worthwhile in the higher-temperature unit since it tends to reduce its physical size for a given amount of kWh stored, and provides more heat at the levels needed for a full-loaded operation without significant temperature change.

In Figure 6, the pump P circulates the liquid from either the low or high temperature storage. Valves 1 and 2 are opened when the system is to add heat to the low temperature storage L, and valves 3 and 4 are opened for adding heat to the higher temperature storage H. Control C determines when the pump operates and which valves are opened.

The advantages of the above system are that separation of the storage into a high and low temperature subsystem may increase the heat collected by a given collector array by a factor of 1.30-1.50, depending on location and type of collectors. At the same time, the COP on a seasonal basis may rise from approximately 0.65 to 0.75, a 15% improvement. Taken together, these benefits may decrease the required collector area to cool a given building by 30-40%.

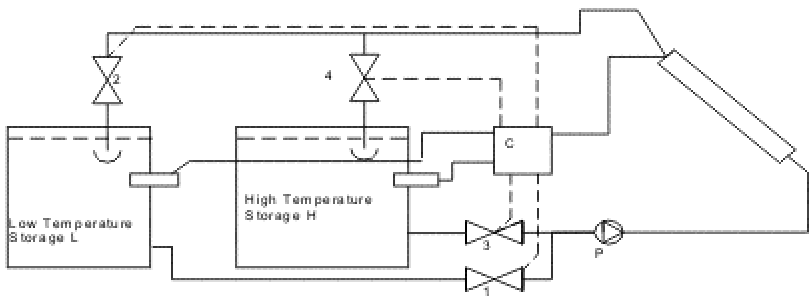

Figure 6: Schematic diagram of dual storage solar absorption air-conditioning system

Double-effect solar absorption air-conditioning system

As technical development of absorption chillers allowed for lower generating temperatures as low as 73°C, the percentage of the solar contribution to air-conditioning become higher. The principle of the system is explained by using Figure 7. It is fundamentally a double effect absorption chiller, where the weak solution is circulated in series. In addition to the components listed in the single effect system, the double effect convertible system has a high pressure generator, a secondary heat exchanger and a heat recovery unit (Dai 1997).

The high pressure generator for steam is independently located from the low-pressure generator for solar and hot water vapour from the high-pressure generator before being condensed. A high pressure generator gives a primary effect and a low-pressure generator a secondary effect, thus being called a double effect. Therefore, a double effect cycle requires lower heat input to produce the same cooling effect, when compared to a single effect system. Therefore, a double effect system results in higher COP.

Two stage solar absorption air-conditioning systems

One of the restrictions for the practical use of the single stage cooling system is an economical aspect. The capital cost of single stage cooling system is too high. It is reasonable to lower the solar collector cost by using collector models of a lower temperature range, if the generator temperature of the chiller can be lowered by using two stages LiBr system instead of single stage system. Therefore, to bring down the initial cost of the system, the important variable is the generating temperature.

Alizadeh et al. (1979) have pointed out that the

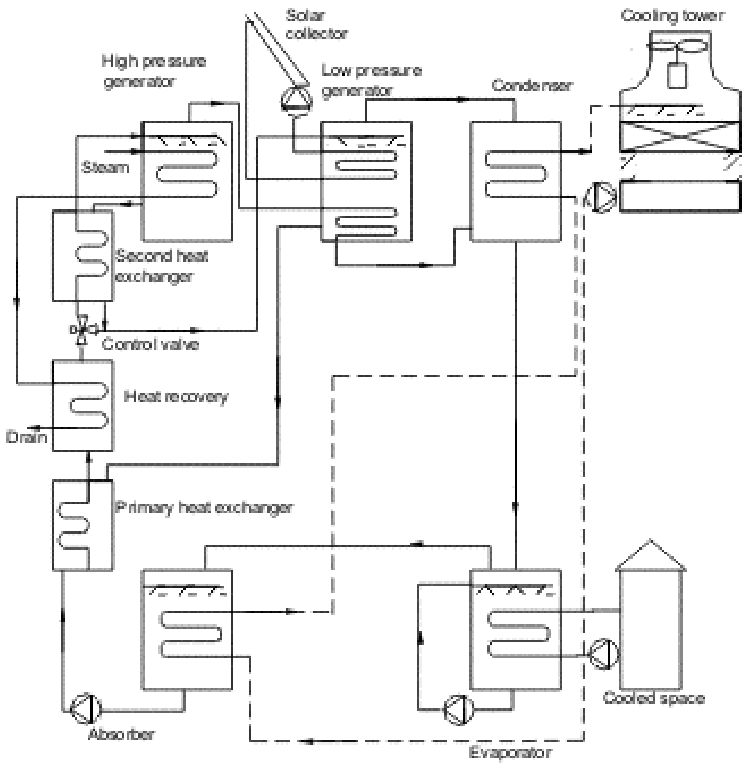

Figure 7: Schematic diagram of double effect solar absorption air-conditioning system

advantages of lowering the generator temperature are:

1. The ordinary flat plate collectors can be employed, thereby bringing down the cost of the system; and
2. Crystallization of the LiBr-H_2O solution could be avoided.

In order to search for an approach to a more economical solution of solar absorption air- conditioning, a two-stage LiBr absorption chiller prototype, working on lower temperature heat source, has been designed and tested successfully by Huang et al. (1991) Initially, the two-stage LiBr absorption-cooling machine was designed for the purpose of low temperature industrial waste heat recovery, but it seems also suitable for a solar cooling application.

Figure 7 shows the schematic diagram of the two-stage solar absorption air-conditioning. The cycle is divided into a high-pressure stage and low-pressure stage. Diluted LiBr solution in the high-pressure generator is heated by hot water. Generated water vapour is condensed in the condenser. The condensed water flows into the evaporator (low-pressure stage) to be evaporated, producing the refrigerating effect. A concentrated solution from the high-pressure generator enters into the high-pressure absorber and absorbs water vapour generated from the low-pressure generator, thus changing back to a diluted solution. This solution is then pumped back to the high-pressure generator, completing a high-pressure cycle.

The concentrated solution in the low-pressure generator goes down into the low-pressure absorber and absorbs water vapour from the evaporator. The diluted solution from the low-pressure absorber is then pumped back to the low-pressure generator, completing a low-pressure cycle. Thus, refrigerant water is made in the high-pressure stage and the absorbent-concentrated solution is made in the low-pressure stage. So, through the high-pressure absorption process, the generation process in the low-pressure generator occurs under a low pressure, completing a full refrigeration cycle.

The two-stage system has the following advantages:

- The cooling system can work steadily though solar input is unsteady;
- The lower generator inlet and outlet temperature both increase instantaneously, and the daily efficiencies of the solar collector system;
- A required lower operating temperature provides the use a simpler model of a solar collector, e.g. flat plate collectors, instead of vacuum tube collectors, which are 3-4 times more expensive than the flat plate collectors, thus reducing the construction cost of the solar system.

The disadvantages of this system are the complexity of the chiller's construction and the COP at the nominal generator temperature is lower than the single effect one. Meanwhile, the amount of cooling water needed is double that of the single effect one, so that the cooling tower should be larger.

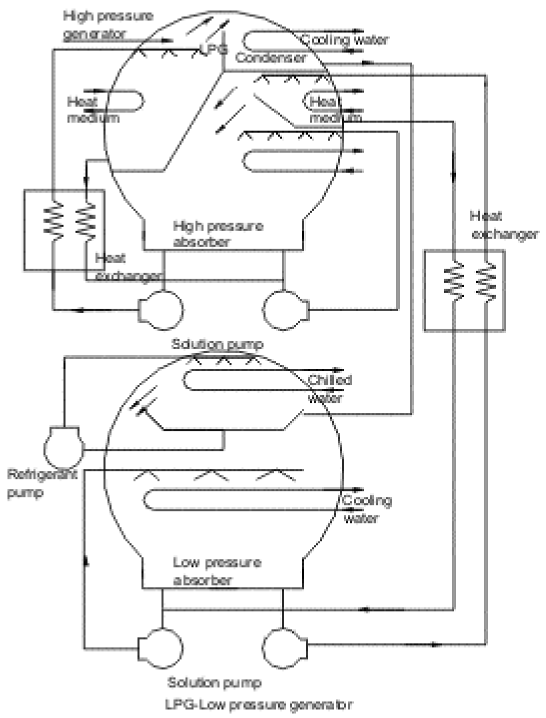

Figure 8: Schematic diagram of two-stage solar absorption air-conditioning system

Recommendations for future research work

A solar powered absorption air-conditioning system is a complex, dynamic system and it is difficult to predict with any certainty the annual energy saving, and therefore, the return on investment. This uncertainty in system evaluation is a further obstacle to the wider application of solar cooling.

In order to improve the system design of a solar powered absorption air-conditioning system, a parametric study must be carried out to investigate the influence of key parameters on the overall system performance. If experiments were used to perform the parametric study, effects of one key parameter on the overall system performance would normally require several cooling seasons and hence, years to establish a conclusion. Also, it is extremely difficult to keep the performance of the system components to be constant over entire experimental period as the components deteriorate with time.

Therefore, in order to avoid extremely difficult and expensive experimentation, researchers can develop and validate a robust dynamic model of the solar powered absorption air- conditioning system and simulation can be done to study the system. This will help to perform the parametric study on the model rather then the physical system itself.

Conclusion

Solar absorption air-conditioning has the advantage of both the supply of sunshine and the need for refrigeration to reach maximum levels in the same season. Of the two main technologies of solar cooling systems namely, solar thermal technology and solar cooling technology, the emphasis in this paper is placed on solar cooling technology.

Some of the findings of this paper are as follows:

- Among the major working pairs available, LiBr-H_2O is considered to be better suited for solar absorption air-conditioning applications.
- Generator inlet temperature of the chiller is the most important parameter in the design and fabrication of a solar powered air-conditioning system.
- A Single effect system with refrigerant storage has the advantage of accumulating refrigerant during the hours of high solar insolation but the double effect convertible system has a higher overall COP.
- A Two-stage system has the advantage of lowering the generator temperature, which provides the use of conventional flat plate collectors, thereby bringing down the cost of the system.

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