ACTIVE SPACE COOLING SYSTEMS

Air-conditioning is a particularly attractive application for solar energy because of the near coincidence of peak cooling loads with the available solar power. Of the air-conditioning alternatives, the absorption system appears to be one of the most promising methods. Many arrangements or cycles are possible: solar collectors can be used to provide energy for absorption cooling, desiccant cooling, and Rankine-vapour compression cycles. Solar hybrid cooling systems are also possible. Although a large potential market exists for this technology, existing solar cooling systems are not competitive with electricity-driven or gas-fired air-conditioning systems because of their high first costs. Lowering the cost of components and improving their performance could reduce the cost of solar cooling systems. Improvements such as reduced collector area, because of improved system performance, and reduced collector cost will lower the cost of solar components. Several solar driven refrigeration systems have been proposed and are under development such as **sorption systems including liquid/vapor**, **solid/vapor absorption**, **adsorption**, **vapor compression** and **photovoltaic-vapor compression systems**. Most of the above mentioned systems have not been economically justified.

The main technical problem of solar refrigeration is that the system is highly dependent upon environmental factors such as cooling water temperature, air temperature, solar radiation, wind speed and others. On the other hand, its energetic conversion efficiency is low, and from an economical point of view, solar cooling and refrigeration are not competitive with the conventional systems.

In order to evaluate the potential of the different solar cooling systems, a classification has been made by Best & Ortega [Solar Refrigeration and cooling. In: World Renewable Energy Congress, Italy, 1998]. It is based on two main concepts: *solar thermal technologies* and *technologies for cold production*. The technologies relevant are:

- Flat-plate collectors
- Evacuated tube collectors
- Stationary non-imaging concentrating collectors
- Dish type concentrating collectors
- Linear focusing concentrators
- Solar pond
- Photovoltaic; and
- Thermoelectric systems

The **cooling technologies** are:

- Continuous absorption
- Intermittent absorption

- Solid/gas absorption
- Diffusion;
- Adsorption; and
- Desiccant systems

The photovoltaic/thermoelectric have predominated in the application of small refrigerators for medical use in isolated areas like vaccine conservation where high system cost is justified. Solar thermal systems, such as flat-plate collectors with lithium bromide/water absorption cooling systems, are in the stage of pre-production and commercial introduction for small capacities.

Earlier researchers often used the intermittent absorption cycle to produce cooling effect owing to the fact that solar energy is an intermittent heat source. With the development of technologies in continuous absorption cooling systems, especially their higher system performance above intermittent alternatives and their coincidence with the requirement of the air-conditioning (especially for space cooling) demand, continuous solar absorption air-conditioning systems are widely reported and improvements made world-wide.

The performance coefficient (COP) of an absorption air-conditioner, defined as the ratio of the heat transfer rate into the evaporator to the heat transfer rate into the generator, can be calculated as a function of the temperatures identified previously. Wilbur and Mitchell ["Solar absorption air-conditioning alternatives", Solar Energy, 1975] compared the coefficient of performance (COP) of absorption systems with different working fluids. Of the various continuous solar air-conditioning systems, LiBr-H_2O and H_2O-NH_3, are the major working pairs employed in these systems. It is reported that LiBr-H_2O has a higher COP than for the other working fluids. Though it has limited range of operation, due to the onset of crystallization occurring at the point of the recouperator discharge into the absorber and stopping flows through the device, the low cost and excellent performance of this working fluid combination make it the favorable candidate for use in solar cooling cycles.

Also by comparison, the ammonia-water system has the following additional disadvantages:

- The coefficient of performance (COP) for the H_2O-NH_3 system is lower than the LiBr-H_2O system. Generally, H_2O-NH_3 systems operate at a 10-15% lower solar fraction than LiBr-H_2O systems.
- It requires a higher generator inlet temperature. Generally, LiBr-H_2O absorption units require generator inlet temperatures of 70-88 ^oC, while H_2O-NH_3 absorption units require temperatures of 90-180 ^oC; which results in the H_2O-NH_3 cooling systems achieving a lower COP when using flat-plate collectors.
- It requires higher pressures and hence higher pumping power.
- A more complex system requiring a rectifier to separate ammonia and water vapor at the generator outlet is required.

- There are restrictions on in-building applications of ammonia-water cooling units because of the hazards associated with the use of ammonia.

For these reasons the lithium bromide-water system is considered to be better suited for most solar absorption air-conditioning applications. Hence, it is the purpose of this study to review the operation of various solar powered absorption air-conditioning systems with lithium bromide and water as the working fluids. As mentioned earlier, the two main concepts to utilize LiBr-H_2O solar air-conditioning system are: cooling technologies and thermal technologies. The major components in the LiBr-H_2O solar air-conditioning systems are chillers and solar collectors. Single-effect, double convertible cycle, two-stage, dual-cycle and other chillers are employed as the cooling devices, while flat-plate collectors and evacuated tubular collectors are often used as the thermal power in these kinds of cooling unit.

Cooling Technologies

Single-effect absorption air-conditioning system

Fig. 1 shows the schematic diagram of a single-effect solar absorption system; this system has been the basis of most of the experience to date with the solar air-conditioning. To begin with, 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 vapor from a solution of lithium bromide/water. The water vapor 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 vapor 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. An auxiliary energy source is provided, so that the 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.

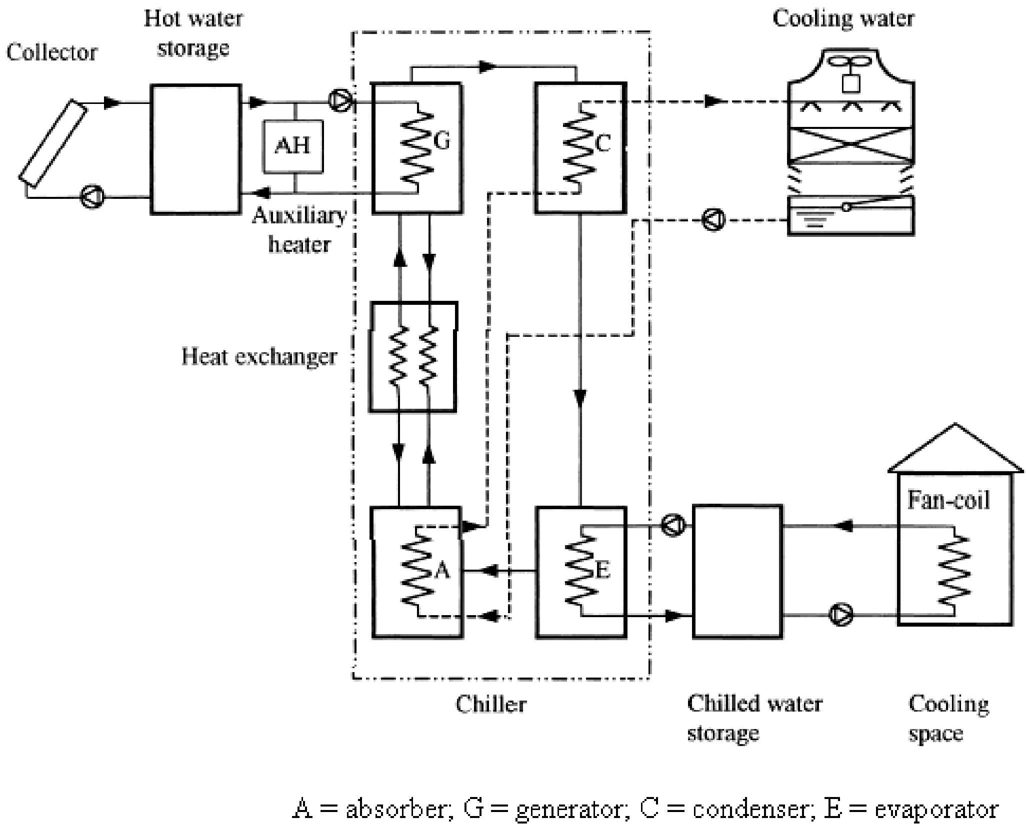

Fig. 1. Solar powered single-effect air-conditioning system (Ref. [31])

In the solar powered absorption air-conditioning system, it is very much essential to have a hot water storage. It serves as a buffer reservoir to have nearly constant heat input. Lof and Tybout ["The design and cost of optimized systems for residential heating and cooling by solar energy", Solar Energy, 1974] have reported that the optimum storage volume is about 50 kg/m^2 of collector area. Also, it has been suggested that the nominal storage amounts for cooling purposes range from 80 kg/m^2 of collector area to 200 kg/m^2. A critical problem with the hot water storage tank is its heat loss to the surrounding area. Jacobsen ["Solar heating and cooling of mobile homes, test results". In: Proc. Of the 1977 Annual Meeting of the American Section of the International Solar Energy Society (CCMS) Solar Energy Pilot Study] had observed an actual heat loss coefficient of 1.65 W/m^2 ^oC, which has approximately 50% greater than the predicted value of about 1.19 W/m^2 ^oC. Sometimes, the heat loss from the hot water storage tank could be equivalent to 2 h of operation per day of the solar air-conditioning system.

Similar to the hot water storage tank, a chilled water storage tank is often used in the solar powered air-conditioning system. While the hot water storage tank experiences considerable heat loss, the chilled water storage tank has a lower rate of heat gain because of the small temperature difference between the chilled water tank and its surroundings ($|\Delta T|_{chilled\ water\ tank} < |\Delta T|_{hot\ water\ tank}$). Furthermore, if the chilled water storage tank is installed near the air-conditioned area, its heat gain could assist in cooling.

Generally, a parallel auxiliary-heater arrangement is preferred to the series one. Since the chiller has the best performance at high temperatures (about 88 ^oC), it is better to use the auxiliary heater directly to drive the chiller when the temperature in the hot water storage tank is lower than the required level. If the auxiliary heater is connected in series between the hot water storage tank and the chiller, water is often returned to storage hotter than it is taken out, which raises the storage temperature is below the needed energizing temperature but above the return temperature from the generator, then, a series connection can be considered, since only a portion of energy need be supplied by the auxiliary heater to reach the energizing temperature. This method may be suitable in installation needing auxiliary energy only during short periods.

In the heating season, the hot water is directly provided from the hot water storage to the fan-coil of the air-conditioned space, or/and to places where the heat is used for bathing or other domestic applications.

The main parameter that governs the performance of the chiller is the chilled water temperature. This is because, as the chilled water temperature decreases, the evaporator temperature decreases, thereby decreasing the pressure in the evaporator, all of which finally results in an increased concentration of the solution. This results in the possibility of crystallization of the solution. Also, with the decrease in evaporating temperature, the coefficient of performance (COP) of the chiller would decrease. Therefore, it is suggested that the chilled water temperature should be maintained above 5-7 ^{o}C.

For water-cooled air-conditioning systems, the climatic conditions and the availability of the cooling water determine the cooling-water temperature. From the point of view of improving the COP, it is better to use cooling water of low temperature. The normal cooling water temperature is about 25-32 ^{o}C. It should also be mentioned that, if the cooling water temperature is below the above-mentioned temperature range, there is a possibility of crystallization of the solution. Wilbur and Mancini ["A comparison of solar absorption air-conditioning systems". Solar Energy, 1974] have reported that the wet cooling tower presently used for heat rejection from solar powered absorption coolers is undesirable because it requires maintenance that the average homeowner may be unable to provide and is generally considered unattractive. It is possible o replace it with a lower-performance air-heated exchanger (dry cooling tower). However, the use of a dry cooling tower in place of a wet results in a 10-20% reduction in solar fraction. Therefore, it is suggested that the use of the lower maintenance, aesthetically more acceptable, dry cooling towers should be accompanied by the elimination of hot storage if pressurized storage is to be avoided.

Charters and Chen ["Some design aspects of air cooled solar powered LiBR-H_2O absorption cycle air-conditioning systems". In: Proceedings of the ISES, Silver Jubilee Congress, Atlanta, Georgia, 1979] had made a comparison study on air-cooled and water-cooled systems. In the case of a water-cooled system, with a cooling tower, the temperature of heat rejection from the system is directly related to the wet bulb temperature. Whereas, in air-cooled unit, the heat rejections from the condenser and the absorber are directly related to the out-door dry bulb temperature. For design point, the generally accepted standard is 35 ^oC dry-bulb and 25 ^oC wet-bulb (established by ASHRAE). Therefore, the cooling temperature needed is higher in the air-cooled than the water-cooled. Hence, the pressure in the air-cooled system is higher, which decrease the system COP. For example, if the evaporator temperature is 5 ^oC, and the generator inlet temperature is 78 ^oC for a water-cooled system, then, for an air-cooled system under the same conditions, the generator temperature should be raised to above 100 ^oC. This temperature is above the effective operating temperature range of the present day flat-plate solar collectors. In addition, Charters and Chen have conducted experiments with a high concentration of LiBr, very close to the crystallization limit of the solution. It was that a sudden drop in temperature in the generator would cause the formation of crystals and "shut-down" of the system. To overcome this problem, it was suggested that the addition of some salts (such as LiSCN) to the LiBr-H_2O solution is necessary in order to lower the solution vapor pressure and thereby improve the solution characteristics for use in an air-cooled system. The addition of LiSCN is claimed to lower the vapor pressure and hence prevent crystallization of the solution at the temperature prevalent in air-cooled system. Even if it is possible to use this new working fluid with an air-cooled absorption refrigeration system, the generator temperature required will still be above 100 ^oC.

Single-effect 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 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 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;
- The storage pressure is low so that the strength of the storage vessel is not critical;

Fig. 2 shows the schematic of the single-effect cooling system. The refrigeration circuit includes the usual generator, condenser, evaporator and absorber together with a heat exchanger, a mechanical pump and pressure reducing valves or equivalent. A refrigerant store is associated with the condenser while an absorber store is associated with the absorber. A cooling tower from which water is circulated through the absorber, condenser store and condenser series accomplishes heat rejection. Other water circuits could be used: indeed there may be some advantages to be gained in using parallel operation, notably the cooler water available for the condenser and the possibility of shutting off flow to the condenser altogether when there is no generation. Room air is circulated through the evaporator, and is maintained at a constant temperature, within the limits of the room thermostat and air-conditioner, by operating an on-off valve in the refrigerant line before the evaporator.

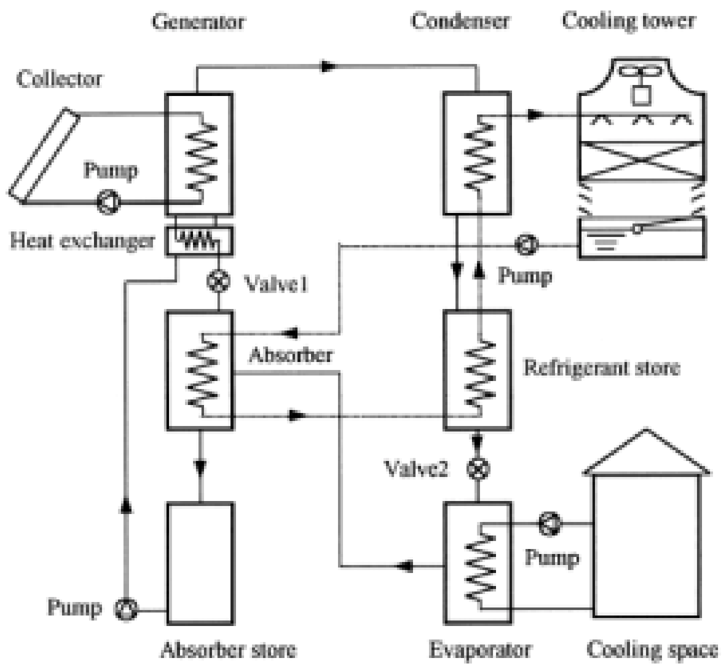

Fig. 2. Solar cooling system with refrigerant storage (Ref. [31])

Systems with refrigerant storage and heat rejection buffer require smaller cooling towers than conventional units. In such systems, hot water from the collector could be passed directly through the generator of a single stage absorption system to generate refrigerant at any time when collector temperatures were sufficient to cause vaporization in the generator. The refrigerant would be condensed at the time of generation and would be available at a later time when air-conditioning was needed. If a cooling demand removed the entire stored refrigerant, then auxiliary heat would have to be supplied to generate refrigerant.

A water tank used for heat storage during winter months would not be required in such a system. It could, however, be used to advantage if it were cooled continuously by a cooling tower and if its contents circulated through the absorber and condenser to receive heat rejected from the conditioner. In this configuration, the water tank (heat rejection buffer) could be cooled to near the ambient wet bulb temperatures during periods of low heat rejection, and it should facilitate system operation at lower peak absorber/condenser temperatures and hence lower generator temperatures. In addition, such a configuration should permit use of a smaller cooling tower operating continuously near the mean, rather than peak heat rejection rate, for the system. The **disadvantages of the kind 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 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. One storage 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 ^{o}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 ^{o}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 full-road operation without significant temperature change. In Fig. 3 the pump P circulates the liquid from either the low or high temperature storage. Valves 1 and 2 are opened when the system is 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 pump is turned on whenever the difference in temperature between the sensors S, and L or H is positive and large enough to indicate that sufficient insolation exists to begin to charge the storage. Choice is also made as to which storage is to receive the heat. The control sequence is typical and the detailed description is as follows:

1. Sensor S measures a representative temperature of the collector array. It may, for example, be attached to the liquid outlet tube of the top of one of the collectors or the collector absorber. Before sunrise it will substantially be at the ambient temperature and therefore below the temperature of the low temperature storage L.
2. As soon as the sun warms the collectors so that the sensor temperature exceeds that of the low-temperature storage sensor L, the solid-state device energizes relay R_1 to start the pump and open valves V_1 and V_2. The stored liquid is then circulated to the low-temperature collector to add heat.

3. As insolation increases, the temperature differential between S and L increases, until the control stops the pump at a predetermined difference. It is an indication, that heat can be collected in a significant amount at the higher temperature. At this time the collector closes all valves for a short time interval of 2-3 min. The best time interval will vary from one installation to another and hence some adjustment of this interval is desirable.
4. If during the time interval of step 3, the sensor S reaches a temperature above that in the high-temperature storage as measured by sensor H, the solid state device (differential temperature controller) restarts the pump and opens valves V_3 and V_4 to add heat to the high-temperature storage. If the required temperature level is not reached within the 2-3 min time-interval, the control restarts the pump and opens valves V_1 and V_2 to continue collection of heat into the low temperature storage. The solid state device may include a time function which assures that the operation in the low temperature mode will continue for a minimum time such as 15 or 30 min to prevent cycling from high to low temperature storage.
5. The solid-state device may also use the temperature sensed by either H or L as a high limit to discontinue heat into either storage when its maximum desired storage temperature is reached. This action prevents boiling or other unsafe operation.

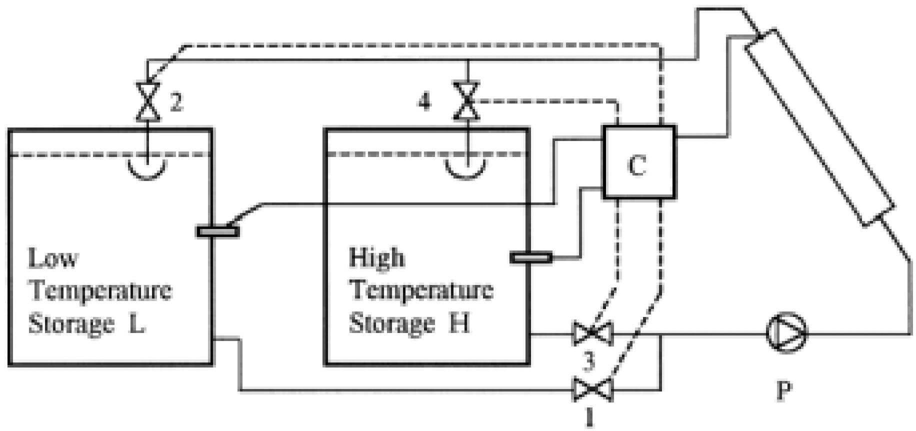

Fig. 3. Schematic diagram of a dual storage system (Ref. [31])

The advantages of the above system are that separation of the storage into a high and low temperature subsystems 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%-a considerable saving.

Double-Effect Convertible System

As technical development of absorption chillers allowed for lower generating temperatures as low as 73^{o}C, the percentage of the solar contribution to air-conditioning became higher. However, if it worked at a lower COP with the same generation temperature when conventional fuel was used as the auxiliary, it would not be considered sensible. Some years ago an absorption chiller was introduced that works in double effect principle by using fuel at a higher COP, and in single effect using solar energy, so as to achieve an overall high coefficient of performance.

The principle of the system is explained using the figure below; it is fundamentally a double effect absorption chiller where in the weak 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 [30].

The high-pressure generator for steam is independently located from the low-pressure generator for solar and hot water vapor 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.

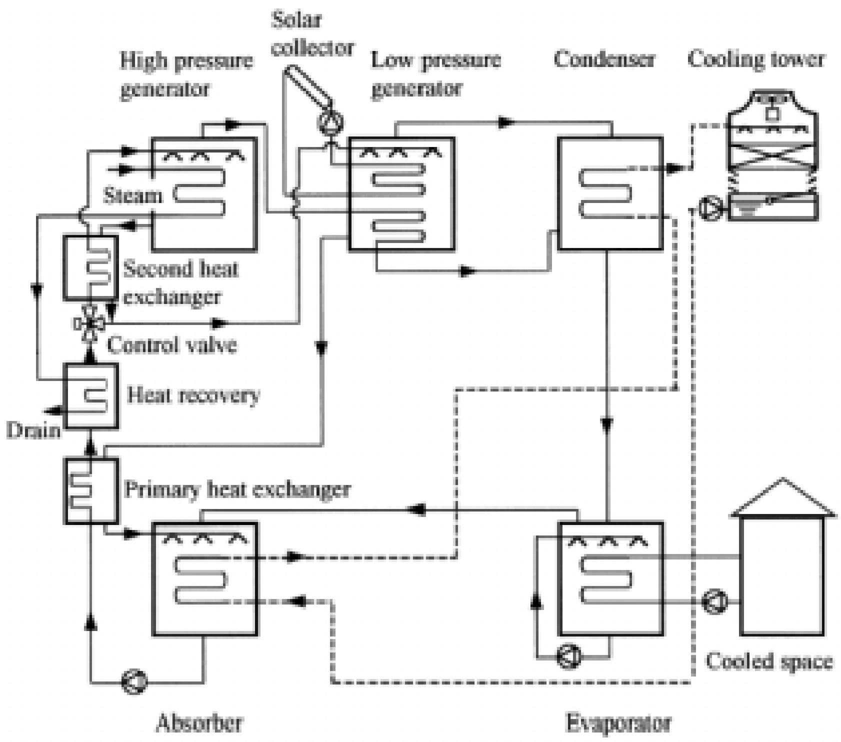

Fig. 4. Single/Double Effect Convertible Absorption Cooling System (Ref. [31])

As shown in Fig. 4, during the refrigeration circulation, the water vapor produced in the high-pressure generator, heats the solution in the low-pressure generator, thereby giving up its heat, and then is passed to the condenser. Meanwhile, the generated water vapor in the low-pressure generator also passes to the condenser. The condensed water vapor is then passed to the evaporator to collect heat from the space to be cooled, thereby producing the refrigerating effect. Obviously, compared to the single effect system, the double effect cycle has an additional advantage of having a reduced condensing demand.

Similarly, in the solution circulation, the double effect is again realized by circulating the solution from the absorber to the high-pressure generator through the primary and secondary heat exchangers and the heat recovery unit. This process preheats the weak solution. Also, the strong solution from the high-pressure generator is circulated to the low-pressure generator and is then allowed to pass through the primary heat exchanger back to the absorber, for mixing. If solar energy is used in the system as the heating source, then, the control valve will be such that the weak solution from the absorber will be directly fed to the low-pressure generator through the primary heat exchanger and heat recovery unit.

This kind of machine was originally suggested by Tanaka, it was first installed at anew building of the Energy Engineering Department of Oita University, Kyushu. After successful operation for a two-year test period, the solar air-conditioning system was operated with steam as the auxiliary fuel.

Double effect absorption chillers ranging from 2 RT (tons of refrigeration) to 10 RT in modular designs are also available. If the customer needs a larger capacity than 10-ton chillers, multiple 10-ton units may be installed so that some work under the conditions of lower solar intensity and less cooling load by automatic control. The performance of the smaller machines is almost the same as the larger ones. They use the bubble pumping effect in transporting the LiBr solution from the generator absorber, while larger ones use a circulating pump for that purpose.

Two-Stage System

One of the restrictions for the practical use of the single stage cooling system is an economical aspect-the capital cost of the 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 instead of single-stage chiller. Therefore, to bring down the initial cost of the system, the important variable is the generating temperature:

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

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 solar cooling application.

Fig. 5 shows the flowchart of the two-stage absorption chiller. The cycle is divided into high-pressure stage and low-pressure stage. Diluted LiBr solution in the high-pressure generator is heated by hot water. Generated water vapor 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 vapor generated from the low-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 vapor from the evaporator. The diluted solution from the low-pressure 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 lower pressure, completing a full refrigeration cycle.

Kaushik and Kumar ["Computer-aided conceptual thermodynamic design of a two-stage dual fluid absorption cycle for solar refrigeration", Solar Energy, 1985] introduced a **two-stage dual fluid absorption refrigeration**. The system uses LiBr-H_2O and H_2O-NH_3 as working fluids at the first and second stage, respectively. A schematic of this system is shown in Fig. 6. The first stage operates through a LiBr-H_2O combination, while the second stage uses a H_2O-NH_3 combination. Therefore, a rectifier is needed only at the second stage and is avoided at first stage. The first stage is assumed to operate with the condenser and absorber maintained at a temperature of 30 ^{o}C by the circulation of cooling water, and the evaporator operated at a temperature of 5 ^{o}C. In the second stage, the absorber is assumed to be maintained at 5 ^{o}C by the evaporator of the first stage. The operation principles at the second are the same as for the first except that a rectifier is needed as low as –20 ^{o}C can easily be produced at the second stage. Through the system analysis, they found that at the second stage, low condenser temperatures can yield a better performance at lower generator temperatures but a higher generator temperatures, a high value of COP is obtained at a higher condenser temperature. Secondly, an increase in the COP value with the evaporator with the evaporator temperature is more within the lower generator temperature range than for the higher generator temperatures. Furthermore, it is evident that lower evaporator temperatures require either higher generator temperatures or lower absorber temperatures.

A two-stage dual fluid absorption system can be operated with ordinary flat-plate collectors at the first stage and evacuated tube solar collectors at the second stage for the production of very low evaporator temperatures. The COP of the system is lower than the LiBr-H_2O two-stage system, but higher than the H_2O-NH_3 two-stage system.

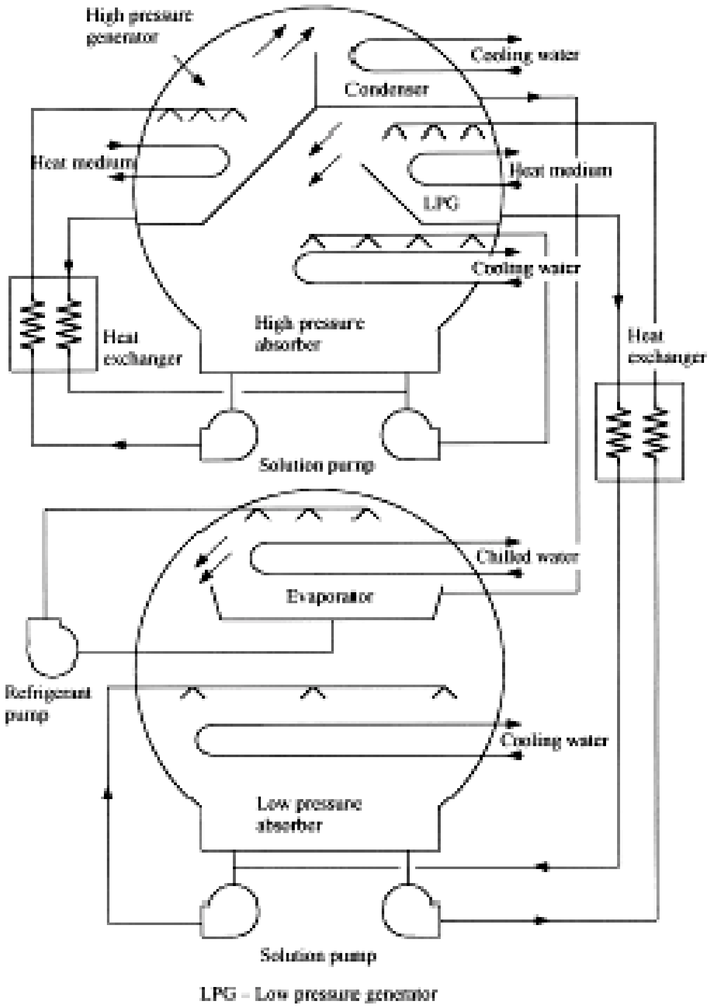

Fig. 5. Two stage absorption chiller (Ref. [31])

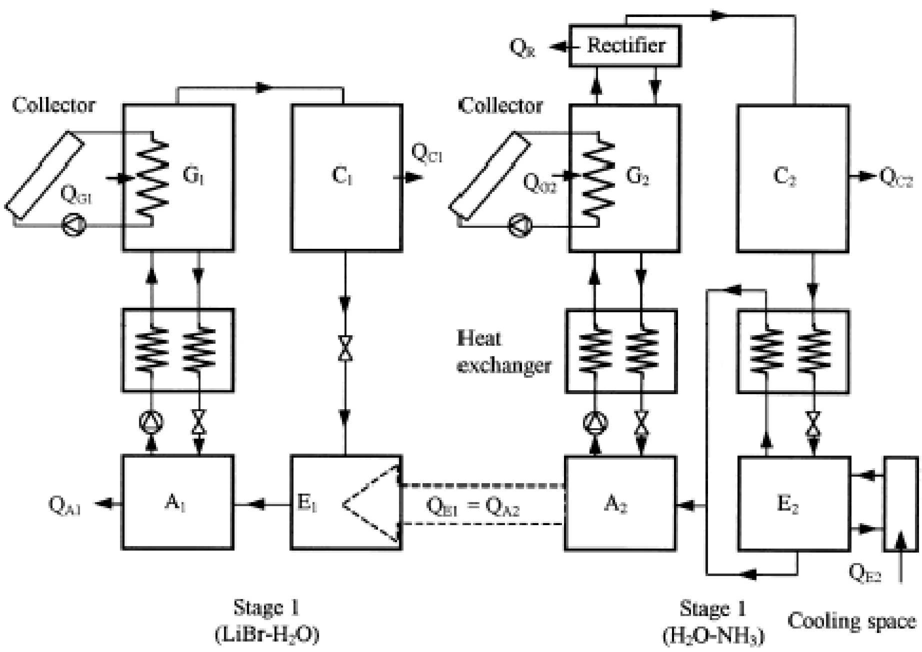

Fig. 6. Two-stage dual fluid solar absorption cycle (Ref. [31])

The two-stage system has the following **advantages**:

1. The cooling system can work steadily though solar input is unsteady;
2. The lower generator inlet and outlet temperatures both increase instantaneously and daily efficiencies of solar collector system;
3. A required lower operating temperature provides the possibility to 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.

Dual-Cycle System

Although, the above mentioned absorption systems use solar energy directly with minimum conversion, they consume considerable quantities of water for the cooling tower. This is a serious disadvantage where solar energy is available whilst water is scarce. The dual cycle, however, may be used in arid areas. It has the advantage of avoiding the use of the wet cooling tower. However, its COP is very low. Fig. 7 shows the schematic diagram of the dual cycle solar powered air-conditioning system. The dual cycle consists of a high- and a low-temperature cycle. Each cycle is similar to a conventional single-effect absorption cycle. The main heat energy supplier to the generator of the **high temperature level cycle (HTLC)** may be solar energy. The HTLC absorber rejects its heat to the atmosphere and this is the main advantage of using such a cycle. The cooling effect of the system will be through the **low temperature level cycle. (LTLC)** evaporator. At this stage, the heat exchange between the system as a whole and the environment has been accomplished.

The interchange of heat between the HTLC and LTLC occurs as follows. The HTLC condenser supplies heat energy to the LTLC generator. The temperature level of this heat supply should be high enough to generate water vapor in the LTLC. The HTLC evaporator will serve as a heat sink for both the absorber and the condenser of the LTLC. At this stage, also, the heat exchange between the two cycles has been completed. The heat balance requires, for both the HTLC and the LTLC, that the sum of the heat supplied to the generator and the cooling effect by the evaporator must equal the heat rejected by the condenser and the absorber. Simultaneously, for the best design, the LTLC condenser heat must just equal the heat required for the LTLC generator. In addition, the cooling effect of the HTLC must equal the sum of the heat rejected by the LTLC of the absorber and the condenser. With these points in mind and to satisfy the physical constraints (crystallization and water icing) of the LiBr and water working pair, tedious calculations may be needed to construct the dual cycle.

Since the dual system requires higher generating temperatures, evacuated tube collectors would be used. In addition, the whole system is appropriate for locations where solar energy is available but where water is scarce, as the cooling tower may be eliminated.

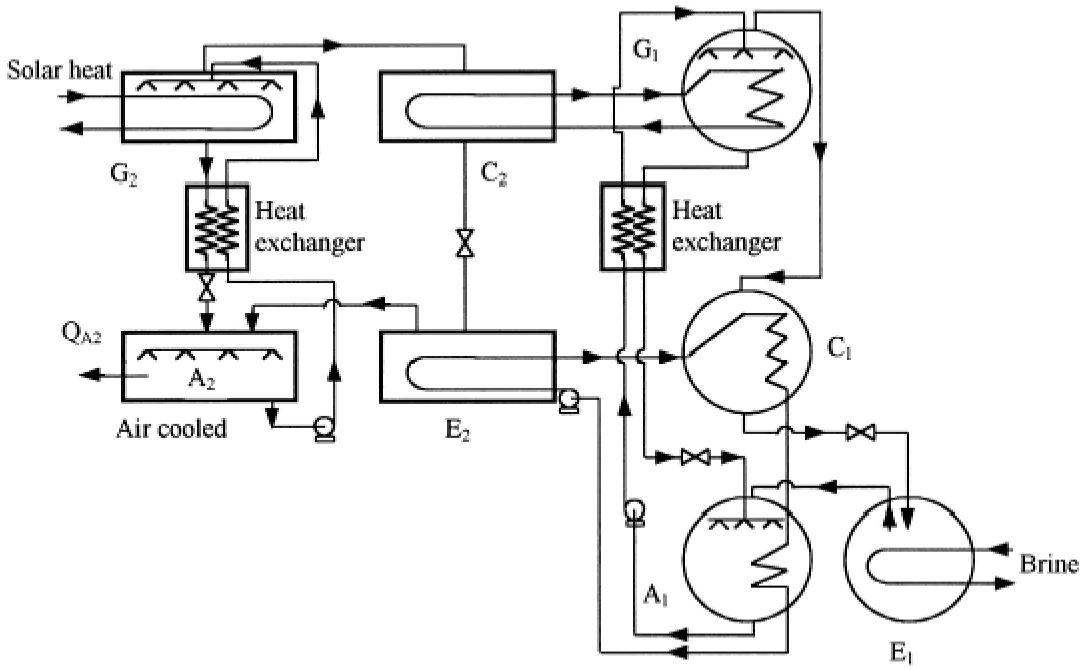

Fig. 7. Dual-cycle block diagram (Ref. [31])

Triple-Effect System and Multistage System

Absorption technology may be extended to a multistage system. When solar energy is not available, auxiliary heat (fuel) would be used for the absorption air-conditioning system. Triple-effect systems are currently being developed by manufacturers and researchers. However, these units are currently not commercially available.

In a triple-cycle, higher COP is obtained by adding a topping cycle to a double-effect machine. In order to achieve three effects (using the heat three times), the heat of condensation from the topping-cycle refrigerant and the heat produced in the topping-cycle absorber section are used to power the high-stage generator of the double-effect cycle. The heat of condensation for the high-stage refrigerant is used to power the low-stage generator, just as in a double-effect LiBr machine. The refrigerant for the system is shared by all three parts of a triple-effect machine (topping, high stage, and low stage). Due to the high temperatures needed to power the topping cycles, the triple-effect systems currently under development will all be direct-fired machines. A typical generator temperature of approximately 250 ^{o}C is used for the heat input to the topping cycle. The stainable cooling COP for a triple-effect machine is approximately 1.5.

Conclusion

Solar absorption air-conditioning has the advantage of both the supply of the sunshine and the need for refrigeration reach maximum levels in the same season. Although solar powered air-conditioning systems are readily available in commercial sizes, existing solar cooling systems are not competitive with conventional electricity-driven or gas-fired air-conditioning systems because of their first cost. Several technical problems associated with the design and development of absorption chillers based on continuous cycles has been successively resolved, and new trends gradually developed towards the redesign of the chiller generator for operation at temperatures lower than 100 ^{o}C.

It is shown that although the single-effect system with refrigerant storage has the advantage of accumulating refrigerant during the hours of high solar insolation, the double-effect convertible systems has a higher overall COP. And the two-stage system has the advantage of lowering the generator temperature, which improves the system performance and the use of conventional flat-plate collectors to achieve high COP. There are many other achievements carried out by researchers, nevertheless, further improvements should be made to the solar powered air-conditioning systems in order to compete with the conventional air-conditioning systems.

GLOSSARY OF TERMS

- **Absolute humidity**: In a system of moist air, the ratio of the mass of water vapour present to the volume occupied by the mixture; that is, the density of the water vapour component. Absolute humidity is normally expressed in grams of water vapour in a cubic meter of air (25 g/m^3).
- **Absorber**: In an absorption cycle, the vessel in which a lithium bromide solution absorbs low-pressure refrigerant water vapour produced in the evaporator.
- **Absorption Cycle**: Absorption chillers differ from mechanical vapour compression chillers in that they utilize a thermal or chemical process to produce the refrigeration effect necessary to provide chilled water. There is no mechanical compression of the refrigerant taking place within the machine as occurs within more traditional vapour compression type chillers. Most commercial absorption chillers utilize lithium bromide (a salt) and water as the fluid pair; lithium bromide being the absorbent, water being the refrigerant. In order to produce the refrigeration effect necessary to make, for example, 44F chilled water, the shell side of the machine must be maintained in a deep vacuum to allow the refrigerant (water) to boil at approximately 40F. The lithium bromide solution absorbs the vaporized refrigerant, diluting it before it is pumped to the generator section of the machine where heat is added to reconcentrate the dilute solution. The water vapour boiled off in the generator is then condensed, returning to the evaporator as liquid. The reconcentrated lithium bromide returns to the absorber section as strong solution to begin the cycle again.

- **Air Conditioning:** The treatment of air temperature, humidity, cleanliness and circulation so as to achieve a controlled, desired result.
- **ASHRAE**: American Society of Heating Refrigeration and Air Conditioning Engineers
- **BTU (British Thermal Unit)**: The amount of heat required to raise the temperature of 1 pound of water by 1^{o}F. A quantity of heat.
- **BTUH (BTUs per hour):** The basic small unit for measuring the rate of heat transfer.
- **Capacity:** The measure of the amount of heat removed by a chiller, measured in tons of refrigeration (English units) or kilowatts of refrigeration (SI Metric units).
- **Centigrade (Represented as degrees "C"):** The scale of temperature measurement most commonly used worldwide.
- **Centrifugal Compressor:** A type of compressor used in vapour compression refrigeration cycles where a rotating impeller is the device, which compresses the refrigerant vapour. The vapour is drawn into the impeller axially, and is discharged radially after energy is added to the vapour within the impeller.
- **CFM (Cubic Feet per Minute):** The unit of measure of the volume rate of airflow, as in a heating system.
- **Chlorine-Free Refrigerant:** A refrigerant containing no chlorine. The presence of chlorine in refrigerant compounds contributes to the depletion of ozone in the atmosphere.
- **Compressor**: In a vapour compression cycle, the device that increases the pressure and temperature of refrigerant vapour. It continuously draws low-pressure refrigerant vapour from the cooler, adds energy to increase the refrigerant pressure and temperature, and discharges the high-pressure vapour to the condenser.
- **Condensation**: The process by which a gas is changed into a liquid at constant temperature by heat removal.
- **Condenser:** A heat exchange coil within a mechanical refrigeration system used to reject heat from the system. The coil where condensation takes place.
- **Cooler:** A device for absorbing unwanted heat into a refrigeration system. This heat exchanger typically consists of a hollow steel shell with copper tubes running through it. The fluid being chilled (relatively warm water) is pumped through the tubes. Heat is transferred from the chilled fluid to the refrigerant liquid inside the shell, boiling it and changing its state to a vapour.
- **Cooling Load**: Heat, which flows into a space from outdoors and/or indoors.
- **COP:** Coefficient of performance. This is a measure of the energy efficiency of a chiller.

- **Damper**: A bladed device used to vary the volume of air passing through the air outlet, air inlet, or duct.
- **Dehumidification:** The condensation of water vapour from air by cooling the air below the dew point or the removal of water vapour from air by chemical or physical methods.
- **Diffuser**: Part of a centrifugal compressor that transforms the high velocity, low pressure gas exiting the impeller into higher pressure, low velocity gas discharged into the condenser.
- **Dry Bulb Temperature**: Temperature measured using a standard thermometer. A measure of the sensible heat of the air or surface being measured.
- **Economizer**: In a chiller with a two-stage centrifugal compressor, the discharge from the first stage impeller and the inlet to the second stage impeller are at a pressure level approximately half way between the cooler pressure and condenser pressure. With this arrangement, an economizer may be used. This is a shell within which refrigerant liquid from the condenser drops down to the interstage pressure, flashing off some of the refrigerant, which is drawn directly into the second stage impeller. This reduces the amount of refrigerant that has to be compressed by the first stage impeller, improving the refrigeration cycle efficiency. A similar arrangement may be used with a screw compressor when the compressor is equipped with an intermediate inlet port. Evacuation:
- **Evaporator:** A heat exchange coil within a mechanical refrigeration system used to absorb heat into the system. The coil where evaporation takes place.
- **Fahrenheit (Represented as degrees "F")**: The scale of temperature measurement most commonly used in the United States of America.
- **Generator:** In an absorption cycle, the vessel in which the lithium bromide solution is reconcentrated by boiling off the previously absorbed water.
- **High-Stage Generator:** In an absorption cycle, the vessel that performs the first stage of reconcentration of the lithium bromide solution by boiling off the water contained in the solution. The hot water vapour boiled off within the high-stage generator is used as the heat source for the low-stage generator.
- **Low-Stage Generator:** In an absorption cycle, the vessel that performs the second stage of reconcentration of the lithium bromide solution. The heat source for the low-stage generator is the steam created in the high-stage generator.
- **Perfect Vacuum:** The absolute absence of any pressure, even atmospheric (O PSIA or O In. Hg. Abs. or about 30 In. Hg. Vac).
- **Refrigerant Ton (RT):** The basic large unit for measuring the rate of heat transfer (12,000 BTUH).

- **Refrigerant:** A fluid (liquid or gas) that picks up heat by evaporating at a low temperature and pressure. It gives up heat by condensing at a higher temperature and pressure.
- **Relative Humidity:** The ratio of the amount of vapour contained in the air to the greatest amount the air could hold at that temperature. Normally expressed as a percentage.
- **Vapour Compression Cycle**: A refrigeration cycle consisting of a cooler, a compressor, a condenser, and an expansion device. In the cooler, heat is removed from the fluid being cooled by the boiling of liquid refrigerant into vapour. The compressor continuously draws this low pressure vapour from the cooler, and adds energy to the refrigerant, increasing its pressure and temperature, and discharges the high pressure vapour to the condenser. In the condenser, the cooling fluid removes heat from the refrigerant, which is condensed into liquid. The expansion device, which may be a float valve or an orifice, drops the pressure of the refrigerant liquid back down to cooler pressure.

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