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An Overview on Absorption Cooling Technology in Solar Applications

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Absorption Chillers

The absorption chiller is a device built on the principles of one of the thermodynamic absorption cooling cycles. Main components of such cycles are a generator, condenser, evaporator, absorber, solution pump and other heat exchangers. Two types of absorption chillers have been commercially available, i.e., ammonia-water and water-lithium bromide units. Ammonia-waterchillers were originally developed as gas-fired, requiring a generator input temperature of over 350°F. The condenser/absorber components are air-cooled, and the typical COP value is about 0.4-0.5. Water-lithium bromide units have also been available as gas-fired or steam-fired, requing a generator input temperature of about 245°F. Water-cooling of the condenser/absorber components is a must due to the crystallization problem of lithium bromide. The typical COP value of these units is about 0.5-0.6.

Solar Application

For the adaption of these conventional units for solar applications, generator temperature must be decreased as practically as possible to accommodate the low temperature input available from solar collectors. Modification of the absorption unit requires changes in the generator heat exchanger, refringerant-absorbent concentration, heat exchanger surface areas(condenser, absorber and/or evaporator) and solution pump capacity. At the generator temperature of 200-250OF, ammonia water chillers should be water-cooled. Air-cooling is also possible at the generator temperature of 250-350°F. A COP of about 0.5-0.7 is attainable and the need for concentrating type solar colectors is evident. For water lithium bromide units, the generator temperatre could be anywhere between 180 and 245°F. and the condenser/absorber components should always be water-cooled. The attainable COP value of about 0.6-0.8 could be expect ed. Flat plate solar cellectors and cooling towers are usually employed.

Direct use of large industrial H_2O-LiBr units for solar application is possible without any hardware modification or only slight modifica tion in generator heat transfer surface. The consequence is a decrease in unit capacity (which is approximately linear). For instance, if the unit has 100% cooling capcapacity at the generator input temperature of 240°F, about 50% of the nominal capacity is lost or derated with the 43°F reduction in generator ingenera-

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tor input temperature. The COP of the derated unit is reported to be about the same or slightly lower than that of the original unit.

Chiller Performance

The maximum performance of a single-effect absorption unit can be estimated for realistic operating conditions in solar applications. As a ideal cycle, or Carnot cycle, the COP value may range anywhere from 0.5-3.0. For non-ideal cycles, the maximum theoretical COP could be 1.0 if the dilution heat ($\varDelta H_{dil}$) is zero, greater than 1.0 if $\varDelta H_{dil} <0$ and less than 1.0 if $\varDelta H_{dil} <0$. The presently available working fluids (NH_3-H_2O and H_2O-LiBr) fall into the last category, thus the maximum theoretical COP can not exceed 1.0. Note that the realistic COP of a single-effect absorption unit is between 0.5 and 0.8.

Commercial Availability

Absorption chillers, optimized for solar applications, are now commercially available in limited quantities. These are the water-cooled H_2O-LiBr units by Arkla Industries, Incorporated. For the residential application, 3 ton-Solaire 36 (Model WF36) is available, whose rated COP is 0.72 at the generator input temperature of 195°F, and the condenser input temperature of 85°F. The trade price of the unit is $2880 (5/1/77) and the cooling tower cost of $400-500 is ad ditional. Also introduced was the 25 ton Solaire 300 (Model WFB 300) for commercial applications. The rated COP is 0.69 at the same conditions as above, and the trade price of the unit is $15,200(5/1/77) with the extra cooling tower cost of about $3100.

Other absorption chillers are also available for absorption chillers are also available for solar cooling experiments or demonstrations. These may include Trane's single effect H_2O-LiBr units (101-1660 nominal tons) with minor modification of the generator, and York's H_2O-LiBr units (110-1377 nominal tons) with no hardware modification.

System Performance

Actual performance of an absorption unit, when installed in a solar cooling system, may differ significantly from its steady state performance. A detailed experimental study of CSU Solar House I revealed that the performance of the solar cooling system could be significantly improved by minimizing the heat loos from the thermal storage and other solar equipment, reducing the unit cycl ing, and employing the best control strategy.

performance degradation of absorption systems often results when the cooling load demand is low. Energy loss from the generator component during frequent cycling (on-off) contributes to the significant degradation of the system COP. The use of cold-side storage could significantly reduce the unit cycling and the degradation of system COP due to cycling coud be minimized since the coolness produced by the continuous running of the unit can be stored and can be used later. In addition, the use of cold storage would allow the cooling capacity of the unit to be smaller without decreasing the performance of the subsystem to meet the same cooling load. The cooling unit does not have to be sized to meet the peak cooling load, but the daily steady state cooling capacity of the unit should be at least large enough to match the total daily cooling load.

For example, if the thermal capacity of the cold storage is 47,000 Btu and a 2 ton cooling unit is used for the Solar House III (CSU), the minimum operating period of the unit would be 2 hours. This would provide the cooling unit's COP in excess of 0.57 on a seasonal basis. However, when the capacity of the cold storage is reduced to 14,000 Btu, the cooling unit's capacity of 2.4 tons is required with the minimum operating period of 0.5 hr. In this case, the minimum COP of the cooling unit is expected to be about 0.45 (21% reduction from 0.57).

Internal Energy Storage

Storage of solar energy has been usually shown as an external component to the absorption unit, i.e., a hot-side storage or a cold-side storage. Recently there have been several suggestions of storing solar energy within the absorption cycle. These are the liquid refrigerant storage, strong solution storage and weak solution storage.

During the period of insufficient supply of solar energy, required cooling load could be met be vaporizing the stored refrigerant in the evaporator. Refrigerant vapor from the evaorator is then abpsorbed into the stored weak solution to generate strong solution which can also be stored. When the sufficient solar energy is available, the stored strong sulution is fed to the generator and is heated to produce refrigerant vapor is liquified in the condenser before storing.

Major advantages for adopting internal energy storages are:

a) The cooling unit is more adaptive to solar energy supply, environmental conditions(heat sink temperature) and especially the cooling load. Thus, the system performance degradation due to cycling loss is significantly reduced or eliminated.

b) Component sizes can be made smaller since each component does not have to be designed at its maximum capacity. In addition, the storage volume is also smaller since the stored energy is of latent type compared to that of sensible type.

c) Thermal losses of the storages are small since they are kept at near ambient temperature.

d) An expensive auxiliary heat supply system can be minimized.

The disadvantages are:

a) It needs larger volume of worknig fluids as well as additional equipments; mainly storage tanks with insulations, thus significant increase in initial cost, especially for small capacity units, may result.

b) It requires complex system controls, which must be adaptive to the solarenergy input, the environment, the building load requirements, etc.

Water-Cooling Limitation

As mentioned before, the major drawback of the H_2O-LiBr unit is the requirement of water-coolng. The addition of the cooliing tower could increase the initial cost and create maintenance problems especially when the unit is of residential size. In 1968, however, a new refrigerant-absorbent solution for possible use in an air-cooled asbrption unit was introduced by IGT. The working fluid comprises 3 components: water as a refrigerant, lithium bromide/lithium thiocyanate mixture (LiBr/LiSCN) as the absorbent. The adddition of the third component, LiSCN, to the H_2O-LiBr pair does prevent crystallization at temperatures prevalent in an air-cooled unit. Although the possible air-cooling with the new working fluid is indicated, the fully air-cooled unit still requires a generator temperature of about 245°F, which is somewhat higher than the temperature obtainable from the present flat plate solar collectors. Other potential problems could be the decomposition of the new working fluid due to the catalytic action of the metal impurities existing in the system. Intensive R&D work is believed under way to solve the above problem.

The ammonia-water absorption unit usually requires water-cooling when powered by hot water from the flat-plate solar collectors. Recently an experimental study of NH_3-H_2O absorption chillers at low generator temperatures(175–210°F) was performed by LBL and possible operating conditions for air-cooled, NH_3-H_2O unit were indicated, i.e., for $181 \leq Tg \leq 195$°F, $43 \leq Te \leq 47$°F or $51 \leq Tcw$ (chilled water) ≤ 55°F and $104 \leq$ Tc (or Ta) ≤ 111°F or $9 \leq \Delta Tc$ $(=Tc-95) \leq 16$°F. In order to operate the unit at the above conditions, the following remedies are required:

a) Remedies for high evaporating temperature
   —Heat transfer surfaces of evaporator and/or chilled water fan/coil be increased.
   —Horse power requirement of chilled water pump may be increased.
b) Remedies for small ΔTc
   —Heat transfer area of absorber-condenser components be increased (or doubled).
   —Cooling air flow rate for absorber-condenser components be increased (or doubled).
c) Remedies for high relative circulation ratio
   —power requirement of solution pump must be increased for 3 ton cooling capacity when the relative circulation ratio is 16 (compared with about 3 for conventional gas-fired NH_3-H_2O unit).

An air-cooled NH_3-H_2O absorption unit at low generator temperature (corresponding to flat plate solar collector) is technically feasible. Practicality of the proposed unit, however, needs to be proven.

COP Limitation

In general, the COP of a single effect absorption unit using conventional working fluid is limited and is always less than 1.0. There exists, however, other high efficiency absorption cycles. Some of the selected cycles include double-effect absorption cycle, combination Absorption-Resorption Cycle (CAR cycle), Generator-Absorber Heat Exchange Cycle, various hybrid cycles, and perhaps absorption cycles using working fluid thas hats positive deviation from Raoult's Law.

If the genreator inlet temperature of steam or hot water is avilable at 350°F–400°F, double effect absorption cycle can be employed and the significant improvement in COP can result. Typically COP of the water-cooled, double-effect, H_2O-LiBr unit is improved to 0.99 from the 0.67 of single effect unit, and also the COP of the double effect unit is no longer limited to 1.0. For the solar application, the unit could be optimized at much lower generator input temperature, say as low as 290°F. The concentrating type solar collector is a must to operate the double-effect, H_2O-LiBr absorption unit. The capacities of the double-effect, industrial absorption units usually come in large sizes (400–1100 tons).

The double-effect operation with air-cooled NH_3-H_2O unit is not practical due to the facts that the first effect pressure is too excessive (>1100 psia), the pumping power requirement increases (7 times that of the single-effect cycle), and the second refrigeration effect reduces to 1/3 or less of that in the first effect.

The CAR cycle is a combination of the standard absorption cycle and the simple resorption cycle. The cycle needs two solution pumps and has two separate evaporators for the double refrigeration effect. The COP of such a unit is about two times that of the standard cycle or 0.8–1.0 at about 300°F heat source temperature when the unit is water cooled. This cycle has particular advantage in that the two evaporating temperatures in Evaporators 1 and 2 can be made different. For instance, Evaporator 1 can be used for air conditioning and Evaporator 2 for refrigeration.

The possibility of using an air-cooled, CAR, NH_3-H_2O unit at a slightly higher generator temperature (330°F) has also been indicated. In this cycle, sub-atmospheric conditions exist as in H_2O-LiBr cycles. It is, however, obvious that the unit is not well suited for small tonnage applications due to the added initial cost of construction.

The Generator-Absorber Heat Exchange Cycle proposed recently by Phillps. The proposed cycle is the same as the standard NH_3-H_2O cycle except that an absorber heat exchanger is added as an integral part of the absorber and that a generator-absorber heat exchanger is also introduced between the generator and absorber. With the addition of these two heat exchangers, a significant portion of the absorption heat could be utilized in the distillation process, thus the external heat input to the generator could be reduced and the significant improvement of COP may result. It was reported that for an air-cooled NH_3-H_2O unit, a COP of 1.0 or more could be realized if all absorption heat at temperatures higher than the feed solution temperature by 20°F, is used to heat the cool end of the distillation column. No actual unit using this concept exists, and the concept of GAX may generate difficult hardware problems.

Proposed recently are the various types of hybrid cycles, which are the combinations of an electric vapor compressor with the various types of absorption cycles. A significant improvement on chiller performance may result from the application of the hybrid cycle, but the major drawback seems to be the increase in the initial cost of construction, added problems associated with the vapor compressor, and control problems. The detailed description of hybrid cycles is omitted here since the information is premature and also is proprietary in nature.

The COP of a single-effect absorption cycle can theoretically break the 1.0 barrier if the employed working fluid has positive deviation from Raoult's Law, or $\Delta H_{dil} < 0$. The COP of the new fluid system depends strongly on the magnitude of the heat of dilution of the positive deviation fluid pair, which is usually 10–20% of the heat of vaporization (ΔHv). Fluid combinations that have positive deviation from Raoult's Law exist, but none of them has been identified adequate for practical use. Recently vigorous R&D plans have been formulated to find or create such a fluid pair in a systematic approach by IGT. Application of such new working fluids in a variety of absorption cycles would create a new horizon in solar application of the absorption technolgy.

Absorption Heat Pump

Efficienct year round use of the solar collector is the key to the success of the economically viable solar heating/cooling system, since the cost of the collector component covers the significant portion of the total system cost. The solar powered (and solar assisted) absorption heat pump is thus believed to be the best candidate since it offers excellent year round funciton.

The absorption heat pump cycle is basically the same as the absorption cooling cycle. The cycle can provide heating, cooling, or simultaneous heating/cooling. When in the heating mode, heat dissipated from absorber-condenser components can be utilized while the outside air provides heat to the evaporator. Operating under the cooling mode, heat from absorber-condenser components is dissipated to the outside air and the room air is cooled by providing its heat to the evaporator. when all three heat exhcangers (absorber, condenser, and evaporator) are connected to the different zones of a building, simultaneous heating/cooling can be obtained.

The solar powered absorption heat pump could also be solar-assisted in the heating mode of operation. Improved heating COP of the solar assisted unit could be expected due to the boost in heat source temperature by solar energy.

The heating COP of the Carnot absorption heat pump cycle is greater than the cooling COP of the same cycle by 1.0. This fact holds approximately true for non-ideal cycles such as NH_3H_2O or H_2O-LiBr cycles. If cooling COP of about 0.7 is assumed for a typical absorption unit, the heating COP of about 1.7 could be expected for the same unit. The ratio of heating to cooling capacity is estimated to be about 2.8 when the working fluid of NH_3-H_2O is employed. In other words, the heating capacity of an absorption heat pump would be about 100,000 Btuh if the same unit has 3 ton cooling capacity.

Working fluids for absorption heat pump needs additional property requirements other than those for the conventional absorption air-conditioners. One of such requirements is the non-freezing property of the working refriger ant. Thus, the NH_3-H_2O pair may be a good candidate, while H_2O-LiBr may be not. However' the toxic nature of ammonia refrigerant does not allow direct heat exchange to take place between the refrigerant and the room air, thus requiring an additional heat exchange loop in absorber, condenser, and evaporator components separately.

At the present time, no solar absorption heat pump is commercially available. Development of gas-fired absorption heat pumps, however, is in progress and such heat pumps may be available in the near future.

Several other refrigerant pairs for the absorption heat pump have been recently proposed. York Division of Brog-Warner Corporation suggested the LZM system (Methanol in LiBr and ZnBr), and the new fluid pair suggested by Allied Chemical Corporation is Genetron 21 in ETFE (high boiling organic ether).

DOE Activities

The current SHACOB (Solar Heating and Cooling of Buildings) activities of DOE mainly consists of the Demonstration program and the Technology program. The Demonstration program has three elements; commercial demon strations, development in support of demonstration, and residential demonstions.

As of July, 1976, 25% of the residential demonstration cooling projects employed absorption chillers, and 82% of the commercial demonstration cooling projects also used the absorption units. From the early cycle demonstration projects, it is also seen that most of the cooling systems employed solar-powered absorption units and that the application of the chiller units were dominant in commercial buildings. Arkla was the primary supplier of the absorption prototype units for the cooling demonstration in both residential and commercial sizes. The majority of the demonstration projects (except residential/non federal buildings) are to be instrumented so that both the technical evaluation and the economic assessment of the solar energy systems could be made.

The Technology Program is basically a R&D program. The Solar Applications Branch in the Division of Conservation and Solar Applications, DOE, has developed a vigorous national R&D program plan, which is well documented in ERDA 76-144 and ERDA 76-145. In FY 76 and 77, there were about 7 ERDA contractors in the solar cooling area, 4 of which were directly involved in absorption cooling technology.

Recently, the Solar Applications Branch placed an emphasis on the directed R&D activities as opposed to the unsolicited proposal mode of operations in the past. As a result, five PRDA's (Program Research and Development Anoucements) and five RFP's (Request For Proposals) have been issued for solar heating and cooling research and development. Among the above PRDA's/RFP's, one RFP, which is closely related to the development of solar absorption cooling technology, is the "Solar Activated Cooling Projects for Solar Heating and Cooling Applications" (RFP EG-77-R-03-1439, released in April, 1977). Two of the four tasks were relevant to the absorption technology, and they are:

a) "Analysis of Advanced Conceptual Designs for Single Family-Size Absorption Chillers," and

b) "Development of Single Family Size Absorptin Chillers for Use in a Solar Heating and Cooling System"

Task (a) is the software development of the advanced absorption technology, and Task (b) covers the hadware development. Both Tasks (a) and (b) emphasize the development of the absorption cooling units for residential applications. It is expected that IGT and Southern Research Institute will carry Task (a) and Carrier Corporation will perform Task (b).

As a result of the increased R&D activity, the cooling projects have expanded from 7 in FY 76 and 77 to about 20 in FY 78, including 6 additional absorption related projects which have been newly generated. Arkla is presently developing residential size, 3 ton H_2O-LiBr absorption chillers which contain an evaporative cooling package as an integral part of the unit. A separate cooling tower is no longer required since the absrober/condenser components are evaporatively cooled inside the unit. Other advantage of the third generation unit over the second generation unit are: significant reduction in auxiliary power requirement (about 35% less), less scaling on the heat transfer surface area of absorber/condenser components due to the increase in surface area, significant reduction in both the first cost and the installation cost (competitive to the present gas-fired units). The design generator inlet water temperature will remain at 195°F, and the unit will employ a mechanical solution pump.

As mentionded previously, LBL is working on solar-powered NH_3-H_2O absorption air conditioners for residential use. The air conditioner will have a 3 to 5 ton cooling output and will operate with air cooling, with input temperatures obtainable from the flat-plate solar collectors.

The University of Maryland will continue to develop a generalized computer program for predicting subsystem/system performances of H_2O-LiBr absorption cycles and Rankine/Vapor Compression Cycles, respectively. Modeling of the cooling system performance will include storage, transients, and a very simplified economic model similar to that developed by the University of Wisconsin. Also, the program will be designed to conduct optimization studies under various control strategies. Validation of performance models will follow the above efforts.

Arkla is also performing the development of 3 ton and 25 ton H_2O-LiBr absorption chiller systems as a part of DOE's accelerated cooling program in support of the Demonstration Program. An evaporatively cooled absorption chiller which is currently developed, would be used in the 3 ton chiller system, and the 25 ton chiller system would employ the solaire 300 chiller with a cooling tower.

Brookhaven National Laboratory (BNL) provides the technical support to the Solar Applications Branch of DOE in the areas of solar cooling and solar assisted heat pumps. As an in-house R&D effort, BNL is currently developing harwdare simulators for thermally activated cooling/heating subsystem/systems and for solar-assisted heatpump subsystem/systems.

Concluding Remarks R&D work on absorption chillers has been focused on better adaptability to solar energy, COP improvement, and initial cost reduction. Substantial R&D efforts on residential absorption chillers are in progress. Emphasis on air-cooled units for the residential applications has lead to a search for new refrigerant-absorbent pairs. Still needed, however, are innovative ideas in the small capacity range or 1-3 tons of cooling.

Applications of larger absorption units are wide open in the multi-family, commercial, agricultural, and industrial applications. R&D work on presently available absorption units of large size (25-1600 tons) is needed to modify them for better adaptability to the proper grade solar energy, thus maintaining desired performance and capacity. R&D work on high efficiency absorption cycles, should be under the consideration in this capacity range.

R&D work on system technology should focus on system configuration, subsystem options, control strategy, and parasitic power requirement by use of computer and/or hardware simulations. We should also explore and utilize the refrigeration and heat pump capabilities of the solar absorption cycles.

We understand absorption technology, comprehend the limitations of the subsystem (chiller) and system, and are actively involved in R&D efforts for advanced technologies. We also believe that the absorption technology is still the best candidate for solar cooling applications.

REFERENCES

Paul C. Auh, "A Survey of Absorption Cooling Technology in Solar Applications" (with complete bibliography). BNL 50704, July, 1977 (Available from NTIS).