Simulating a 4-Effect Absorption Chiller

Performance simulations were conducted over a range of operating conditions for a 4-effect lithium bromide/water chiller

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Absorption chillers are heat-operated refrigeration machines that operate on one of the earliest known principles of refrigeration. Current absorption chillers typically use either steam or a gas-fired burner as the energy source. All current gas-fired absorption cooling systems are based on the well known single-effect or double-effect cycles. To further improve utilization of the high temperature heat available from natural gas, a variety of triple-effect cycles have been proposed and are being developed that are capable of substantial performance improvement over equivalent double-effect cycles.

This article describes a study that investigated the possibility of even further improving utilization of the high temperature heat available from natural gas combustion. During the study, performance simulation was conducted for a 4-effect lithium bromide/water cycle.

From an environmental perspective, absorption chillers provide several benefits. They use absorption pairs (such as lithium bromide/water) as the working fluids, rather than chlorofluorocarbons or hydrochlorofluorocarbons, which contribute to ozone depletion and global warming.

Background

Many single-effect lithium bromide/water absorption chillers, using low pressure steam or hot water, have been installed in commercial buildings to produce chilled water for air conditioning. Single-stage systems are also used to cool fluids in industrial processes, often using waste heat to power the system.

The thermal efficiency of single-stage absorption systems is low. They have coefficients of performance (COP) of approximately 0.6 to 0.8 out of a possible 1.0; for every unit of heat input to the generator, you get 0.6 to 0.8 units of cooling out in the evaporator.

As energy prices increased over the past 20 years, the market for such chillers has decreased significantly. Although the technology is sound, the low efficiency has reduced the cost effectiveness of single-stage systems.

Most new single-effect machines are now installed in applications where waste heat is readily available. Single-effect chillers are available with capacities ranging from 7.5 tons to more than 1,500 tons (26 to 5280 kW). Single-effect chillers have four major components: evaporator, absorber, condenser and generator.

The double-effect cycle represents a significant step in performance improvement over the basic single-effect cycle, having COPs of approximately 1.0 to 1.2 out of a possible 2. The double-effect chiller differs from the single-effect in that there are two condensers and two generators instead of only one of each.

In the double-effect cycle, the higher temperature generator receives the externally supplied heat (steam or combustion of natural gas) that boils the refrigerant from the weak absorbent. This hot refrigerant vapor goes to a lower temperature generator where, on condensing, it supplies heat to the second generator.

Due to the additional recovery of heat, two units of refrigerant vapor are available for only one unit of heat input. The second unit of refrigerant vapor comes

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from the additional recovery of heat at the lower temperature.

Although the double-effect machines are more efficient than single-effect machines, they have a higher first-cost related to special materials consideration because of increased corrosion rates (higher operating temperatures than single-effect machines), larger heat exchanger surface areas, more complicated control systems, and the related increased manufacturing costs.

Triple-effect absorption chillers have been proposed and are under development as the next logical step in the evolution of absorption technology. These chillers are capable of substantial performance improvement over equivalent double-effect chillers.

Triple-effect systems are predicted to have thermal efficiencies equal to those of the best currently available electrical chillers, while offering the ability to reduce peak electric loading and capitalize on the environmental benefits. The higher efficiency levels would open wider markets for absorption chillers and help to reduce the investment required in new electrical generation facilities by summer-peaking. Currently, there are no triple-effect absorption chillers being manufactured, although research and development on triple-effect cycles is ongoing throughout the world.

In a recent study, several of these cycles were simulated and analyzed in detail.[1] Among the cycles considered were:

- The three-condenser/three-desorber (3C3D) triple-effect cycle.[2] This forms an extension of the conventional double-effect cycle, comprising one evaporator, one absorber, three condensers and three desorbers, recovering heat from each high temperature condenser to the next lower temperature desorber;
- A variation of the 3C3D cycle with Double Condenser Coupling (DCC) where heat is recovered from the hot condensate leaving the high temperature condensers and added to the lower temperature desorbers.[3-5]

Many other triple-effect configurations are also theoretically possible.[6-8] Important considerations in comparing the various systems include not only the energy efficiency of the cycle but also its practicality and potential initial cost.

The purpose of the present study has been to investigate the possibility of further improving utilization of the high temperature heat available from natural gas combustion. Performance simulation is conducted for a 4-effect lithium bromide/water cycle including four condensers and four desorbers coupled together, forming an extension of the conventional double-effect cycle.

Based on prior experience, a parallel flow system is used in preference over series flow, and double-condenser coupling (DCC) is employed, extending from triple-effect cycles, to further improve performance. One goal of the study is to investigate the effect of various design parameters on the cycle's performance. Parametric analyses were conducted which indicates performance trends.

The 4-effect cycle

Figure 1 describes schematically the 4-effect lithium bromide/water chiller under investigation. The system comprises an evaporator, an absorber and four pairs of desorbers/condensers coupled together for internal heat recovery. The system has 24 components or sub-units (indicated by the circled numbers) and 62 state points (indicated by the uncircled numbers).

Absorber (2) and condenser (5) are externally cooled; desorber (22) is externally heated. Chilled water is produced in evaporator (1). Heat rejected from condenser (6) powers desorber (3), heat from condenser (14) powers desorber (4) and heat from condenser (23) powers desorber (13).

The coupling between each condenser-desorber pair is through a circulating heat transfer fluid loop, as shown. However, it may also be achieved by physically combining the two components, such that the refrigerant condensing on one side of a heat exchange surface would heat up the solution desorbing on the other side of that surface.

The absorbent solution is in parallel flow, where the weak (weak in lithium bromide concentration) solution from the absorber is split and divided among the four desorbers. According to simulation results of double-effect cycles[9] and triple-effect cycles,[1] the parallel flow arrangement is superior in performance to the series flow in terms of increased COP and a lower risk of crystallization.

The condensate leaving the condensers (6), (14) and (23) is mixed with the superheated vapor leaving the desorbers (3), (4) and (13), respectively, before proceeding from each to the next lower-temperature condenser. This method, known as Double-Condenser-Coupling (DCC),[4] helps subcool each condensate stream and reject the heat to a corresponding desorber.

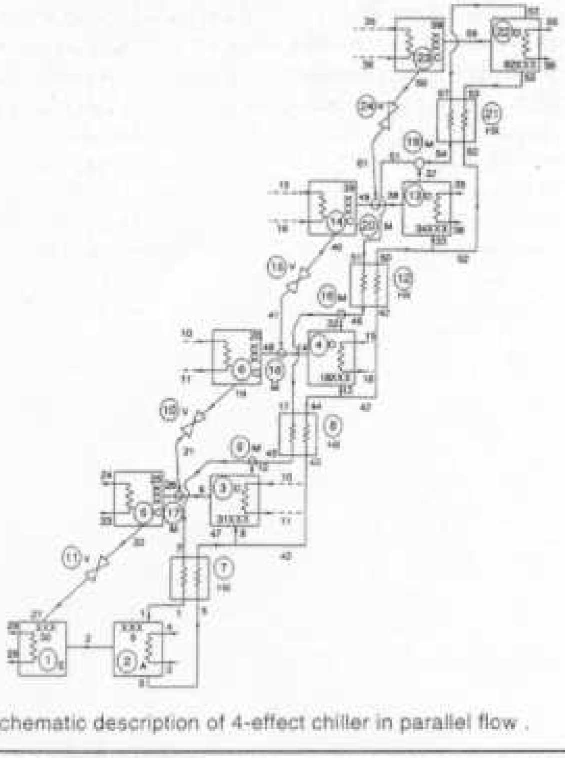

Figure 1. Schematic description of 4-effect chiller in parallel flow.

It was shown in an earlier study of triple-effect cycles[1] that the main effect of this heat recuperation is in providing extra cooling capacity to the evaporator through the now subcooled refrigerant, at no additional expenditure of high grade heat. An added benefit is a somewhat increased generation capacity of the desorbers (3) and (4).

Simulation methodology

A modular computer code for simulation of absorption systems (ABSIM) was used to investigate the performance of the cycle under study. The code, developed specifically for flexible cycle simulation, has been described in detail by Grossman and Wilk[10] and in a related report[11] containing a user's manual. The modular structure of the code makes it possible to simulate a variety of absorption systems in varying cycle configurations and with different working fluids.

The simulation methodology in the present study has followed an approach taken in earlier studies of single- and double-effect cycles[9] and triple-effect cycles.[1] Because the performance of each system depends on many parameters, the approach has been to establish a design point for the system, and vary the relevant parameters around it. In particular, a performance map of COP and cooling capacity as functions of desorber heat supply temperature was generated for each system.

In the earlier study of simpler systems, a single-effect solar-powered lithium bromide/water chiller known as SAM-15 was selected as a reference case.[12] SAM-15 has been tested extensively. An extension of this study to triple-effect systems has employed the same approach.[1]

Here, a reference case has been created for a 4-effect lithium bromide/water chiller according to *Figure 1*, with SAM-15 size (specified in terms of its UA) of the evaporator, absorber, condensers, desorbers and heat exchangers (recuperators), and with SAM-15 flows of the external fluids. Thus, the performance of systems in single, double and triple stages could be compared not only at a single point but over the entire temperature domain applicable to the cycle.

Unfortunately, measured property data for lithium bromide/water are not available in the literature at temperatures beyond 210°C (410°F). Properties of lithium bromide/water for the simulation were taken from the 1985 ASHRAE Handbook—Fundamentals[13] and extrapolated, where necessary, to the high temperature range required by the 4-effect cycle. The extrapolation was done by employing the same correlations given in the *ASHRAE Handbook* at the high temperatures, beyond their stated range of validity.

A comparison of the properties thus obtained was carried out later with the higher-temperature lithium bromide/water data developed recently under an ASHRAE research program,[14,15] which are valid up to 210°C (410°F). The differences in vapor pressures and specific heat were on the order of a few percents, and hence the extrapolations were considered adequate for a first evaluation of the 4-effect cycle. A more detailed evaluation leading to actual design will have to rely on more accurate property data that may become available in the future.

Simulation results

In conducting the simulation to generate the operating curves of the 4-effect system, the solution outlet temperature from the gas-fired desorber (22) (state point 57) was varied while all the other design parameters were kept constant. For the exchange units, it was assumed that the values of the UAs remain constant while the temperatures and all other unspecified parameters change.

In reality, this is not strictly accurate; although the heat transfer areas (A) remain constant, the heat transfer coefficients (U) vary somewhat with the temperatures as well as with the loading conditions. However, this variation is relatively small in most cases and the assumption of constant UA is a reasonably good approximation.

Better fundamental understanding of the combined heat and mass transfer process in absorption and desorption would allow taking the variation of UA with temperature into consideration.

The coefficient of performance (COP) has been defined here as the ratio of the heat quantity in the evaporator producing the desired cooling effect, to that supplied to the externally heated high temperature desorber. The effects of pumping and other parasitic losses are not considered.

Figure 2 describes the COP of the 4-effect cycle as a function of the heat supply temperature to the externally heated desorber (22), for different cooling water inlet temperatures, and for a fixed chilled water outlet temperature. The weak solution split among the four desorbers re-

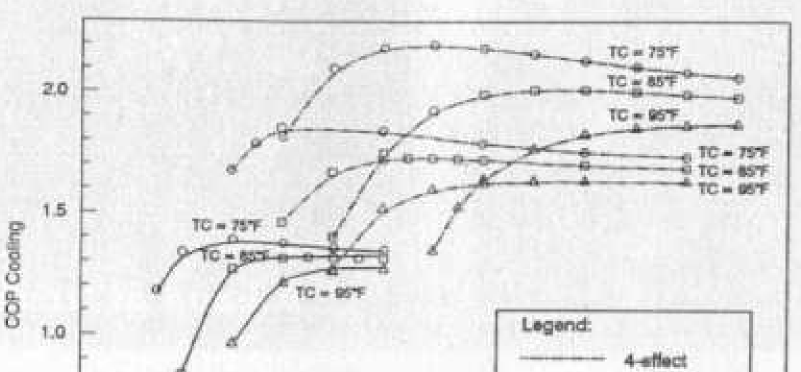

Figure 2. COP for double-effect, triple-effect, and 4-effect DCC parallel flow lithium bromide/water systems as a function of heat supply temperature (TH) for different cooling water temperatures (TC) and a chilled water temperature fixed at 45°F (7°C).

mains even. COP curves for the equivalent double- and triple-effect, DCC parallel-flow systems using comparably sized components16 are plotted for comparison.

It is evident that all systems exhibit the same typical, qualitative behavior, with the COP increasing sharply from zero at some minimum temperature, then levelling off to some constant value at a higher temperature and even decreasing slightly with further increase in temperature. The reason for this behavior is well understood and is explained in detail in Gommed and Grossman.[9]

The 4-effect system has a COP higher than the double- and triple-effect cycles but requires a higher minimum heat supply temperature to begin operating. *Figure 2* indicates that the double-effect system performs best at the heat supply temperature range of 300° to 350°F (150° to 180°C).

Above that range, from the COP point of view, it is beneficial to switch to the triple-effect system, which performs best at the heat supply temperature range of 400° to 450°F (200° to 230°C). With a still higher heat supply temperature, a 4-effect system is more desirable.

The solution flowrate distribution among the four desorbers in the 4-effect system has been selected equal at the design point. However, an equal distribution of solution is not necessarily optimal. Based on the simulation of double-effect systems[8] and triple-effect systems,[1] an improvement may be gained by deviating from an equal distribution both in increasing the COP and reducing the risk of crystallization.

The effect of varying the solution flowrate to the four desorbers has been investigated, with the system operating otherwise at the design condition. *Table 1* lists the results of several runs with different flow distribution among the four desorbers (units 3, 4, 13 and 22), showing in each case the cooling capacity and the COP. Note that the sum of the four flowrates is kept constant at the design value of 60 lb/min (27 kg/min).

While *Table 1* does not cover the entire range of possibilities, it indicates an optimal (maximum COP) distribution of solution to the high-, medium- and low-temperature desorbers of approximately 40, 10, 5 and 5 lb/min (18, 5, 2 and 2 kg/min), respectively. Under this condition, the COP reaches 2.177, instead of 2.013 at equal distribution; the solution concentration at the absorber inlet (state point 1) is

Table 1. Effect of Solution Distribution Among Desorbers in a 4-Effect $LiBr-H_2O$ Absorption Chiller*

Unit 3 mass flow s.p. 8 (lbs/min)	Unit 4 mass flow s.p. 13 (lbs/min)	Unit 13 mass flow s.p. 33 (lbs/min)	Unit 22 mass flow s.p. 53 (lbs/min)	Q_{evap} (Btu/min)	COP
5	5	15	35	3294.9	1.5578
10	15	15	20	4019.7	1.9250
15	15	15	15	3964.5	2.0131
20	15	15	10	3663.1	2.0750
30	10	10	10	3496.6	2.1374
35	10	7.5	7.5	3129.7	2.1670
40	10	5	5	2567.7	2.1768
45	5	5	5	2419.8	2.1527
35	15	5	5	2600.7	2.1646

At TH = 600°F (315°C) from lowest to highest temperature gene-- (left to right). Conversion factors: kg/min = 0.454 × lbs/min and kW = 0.01757 × Btu/min<tab cap> Table 2. Effect of UA Distribution Among the Heat-Exchange Units in a 4-Effect DCC Parallel Flow System

Table 2. Effect of UA Distribution Among the Heat-Exchange Units in a 4-Effect DCC Parallel Flow System*

Unit No.	Unit type	UA base case	UA Case #1	UA Case #2	UA Case #3	UA Case #4	UA Case #5	UA Case #6
1	Evap.	377.0	377.0	377.0	377.0	377.0	377.0	377.0
2	Abs.	193.0	193.0	193.0	100.0	250.0	300.0	400.0
3	Des.	268.0	150.0	100.0	100.0	100.0	100.0	100.0
4	Des.	268.0	150.0	100.0	100.0	100.0	100.0	100.0
5	Cond.	565.0	200.0	100.0	100.0	100.0	100.0	100.0
6	Cond.	565.0	200.0	100.0	100.0	100.0	100.0	100.0
7	HX	64.0	100.0	100.0	100.0	100.0	100.0	100.0
8	HX	64.0	100.0	100.0	100.0	100.0	100.0	100.0
12	HX	64.0	100.0	100.0	100.0	100.0	100.0	100.0
13	Des.	268.0	150.0	100.0	100.0	100.0	100.0	100.0
14	Cond.	565.0	200.0	100.0	100.0	100.0	100.0	100.0
21	HX	64.0	64.0	64.0	64.0	64.0	64.0	64.0
23	Cond.	565.0	200.0	100.0	100.0	100.0	100.0	100.0
Total (Btu/min.°F)		3890.0	2184.0	1634.0	1541.0	1691.0	1741.0	1841.0
COP		2.0130	2.1117	2.0617	1.9212	2.0980	2.1190	2.1460
Q_{evap} (Btu/min)		3964.5	3733.6	3322.4	2291.9	3715.1	3977.1	4357.1
Q_{evap}/UA_{total} (°F)		1.02	1.71	2.03	1.49	2.20	2.28	2.37

*At a fixed total solution flowrate of 60 lb/min or 27 kg/min (equal distribution) and fixed heat supply temperature of 600°F (315°C). Conversion factors: kW/°C = 0.0317 × Btu/min.°F, kW = 0.01757 × Btu/min and Δ°C = Δ°F/1.8

reduced to 59.2 wt% lithium bromide, compared to 63.5 wt% lithium bromide at equal distribution.

The capacity is reduced somewhat due to the lower concentration, to 2567.7 from 3964.5 Btu/min (45.1 kW from 69.7 kW) at equal distribution. Note that the optimum flow distribution at the design temperatures is not necessarily preserved in off-design conditions. Also, in the extreme cases where either of the four desorbers is starved for solution, the entire system goes out of balance and both the COP and capacity tend to zero.

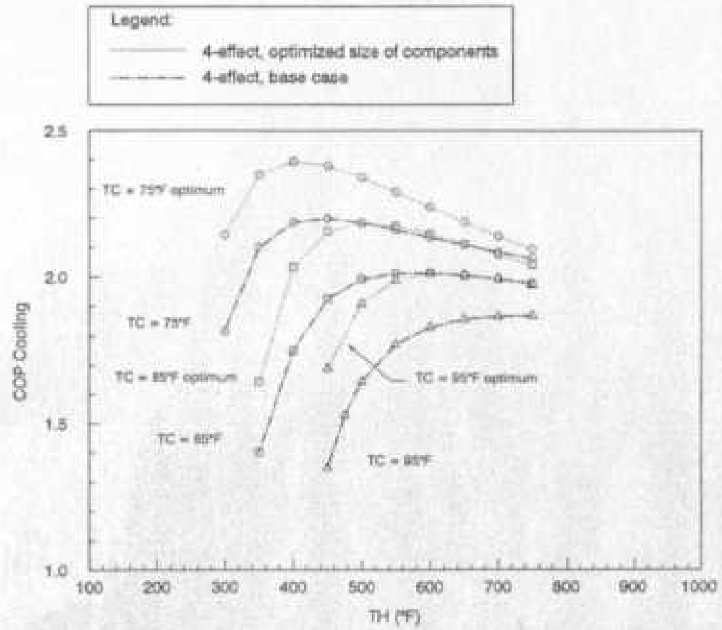

Figure 3. COP for 4-effect base case and 4-effect optimum case (#6 per *Table 2*) DCC parallel flow lithium bromide/water systems as a function of heat supply temperature (TH) for different cooling water temperatures (TC) and a chilled water temperature fixed at 45°F (7°C).

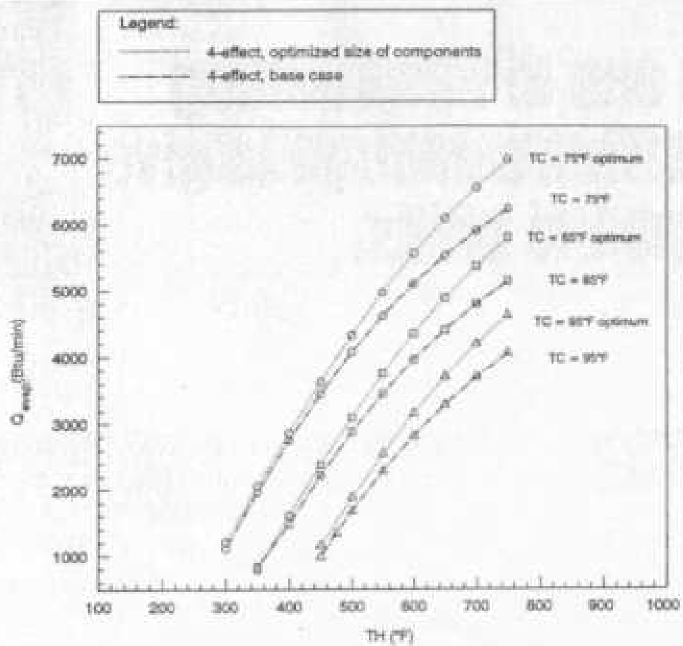

Figure 4. Cooling capacity for 4-effect base case and 4-effect optimum case (#6 per Table 2) DCC parallel flow lithium bromide/water systems as a function of heat supply temperature (TH) for different cooling water temperatures (TC) and a chilled water temperature fixed at 45°F (7°C).

As mentioned earlier, the system's performance under a given set of operating conditions depends on the design characteristics and particularly on the size of the heat transfer surfaces in its exchange units. As a base case, a practical system was considered with economically reasonable, if not optimized, heat transfer areas.

In search of the optimum size of the components, several runs were made with different UAs of the components, as presented in *Table 2*. The results show case #6 to give the best COP, cooling capacity and Q_{evap}/UA_{total} among the test cases studied.

Performance maps of COP and cooling capacity with case #6 UAs as functions of desorber heat supply temperature (see *Figure 3* and *Figure 4*) show the significant improvement over the base case. As can be seen, with some optimization of the UAs, the COP was raised above 2.2, with approximately one-half the heat transfer surface of the base case system's components.

Technical outlook

The results of the present simulation have shown the 4-effect cycle capable of providing a COP increase on the order of 15% over the equivalent triple-effect cycle;[1] 2.013 versus 1.724, respectively, at the design point. The UA investment relative to the equivalent triple-effect in the base case is an additional 27% (4158 Btu/min F total UA versus 3261 Btu/min F, respectively).

There is still room for optimizing the flow split among the four desorbers, the UA distribution in the system, etc., which have not been fully investigated. However, there are several practical considerations that will determine the potential commercial feasibility of the 4-effect and its capability to replace the triple-effect cycle:

- Flue losses. The need to provide a higher firing temperature is associated with a lower combustion efficiency due to higher flue gas losses. While some of the exhaust heat may be recovered through an economizer (air preheater), the usefulness of doing this is not clear and must still be determined.

• Corrosion. A higher corrosion rate is expected at the high temperature components (Desorber 22 and Recuperator 21), which may require more expensive materials of construction and corrosion inhibitors.

• Heat/mass transfer enhancement additives. The ability of the commonly used additives (such as 2-ethyl-hexanol) to survive at the high temperature is very limited. This is also a problem, for that matter, in triple-effect cycles and requires further study.

Conclusion

Performance simulation has been carried out for a lithium bromide/water chiller based on the 4-effect cycle. A reference condition was established based on the component sizes and flowrates of the single-effect SAM-15 system. Performance simulation was carried out over a range of operating conditions, including some investigation of the influence of the design parameters. A COP of 2.013 was calculated at the design point.

The study showed ample room for substantial optimization of the COP, capacity and Q_{evap}/UA_{total} by varying the flow and UA distribution among the components with little increase in potential cost. ■

Acknowledgments

This work has been supported in part by the Office of Building Technologies, U.S. Department of Energy under Oak Ridge National Laboratory Subcontract 80X-SK033V.

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