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TRIPLE-EFFECT ABSORPTION CHILLER CYCLE: A STEP BEYOND DOUBLE-EFFECT CYCLES

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ABSTRACT

Many "advanced" absorption cycles have been proposed during the current century. Of the hundreds of absorption cycles which have been patented throughout the world, all commercially manufactured products for air conditioning buildings have been variations of just two basic absorption cycles: single-effect and condenser-coupled double-effect cycles. The relatively low cooling coefficients of performance (COPs) inherent in single-effect and double-effect cycles limits the economic applicability of absorption air conditioners (chillers) in the United States.

A triple-effect absorption chiller cycle is discussed. This cycle uses two condensers and two absorbers to achieve the "triple effect." Depending on the absorption fluids selected, this triple-effect cycle is predicted to improve cooling COPs by 18% to 60% compared with the equivalent double-effect cycle. This performance improvement is obtained without increasing the total amount of heat-transfer surface area needed for the heat exchangers.

A comparison between the calculated performances of a double-effect cycle and a triple-effect cycle [both using ammonia-water (NH_3/H_2O) as the absorption fluid pair) is presented. The triple-effect cycle is predicted to have an 18% higher cooling COP (1.41 compared with 1.2 for a double-effect), lower pressure [47.70 atm (701 psi) instead of 68.05 atm (1000 psi)], significantly reduced pumping power (less than one-half that of the double-effect cycle), and potentially lower construction cost (33% less total heat exchange needed). Practical implications for this triple-effect cycle are discussed.

KEYWORDS

Absorption, ammonia-water, heat pump, air conditioner, chiller, advanced cycles, single-effect, double-effect, triple-effect.

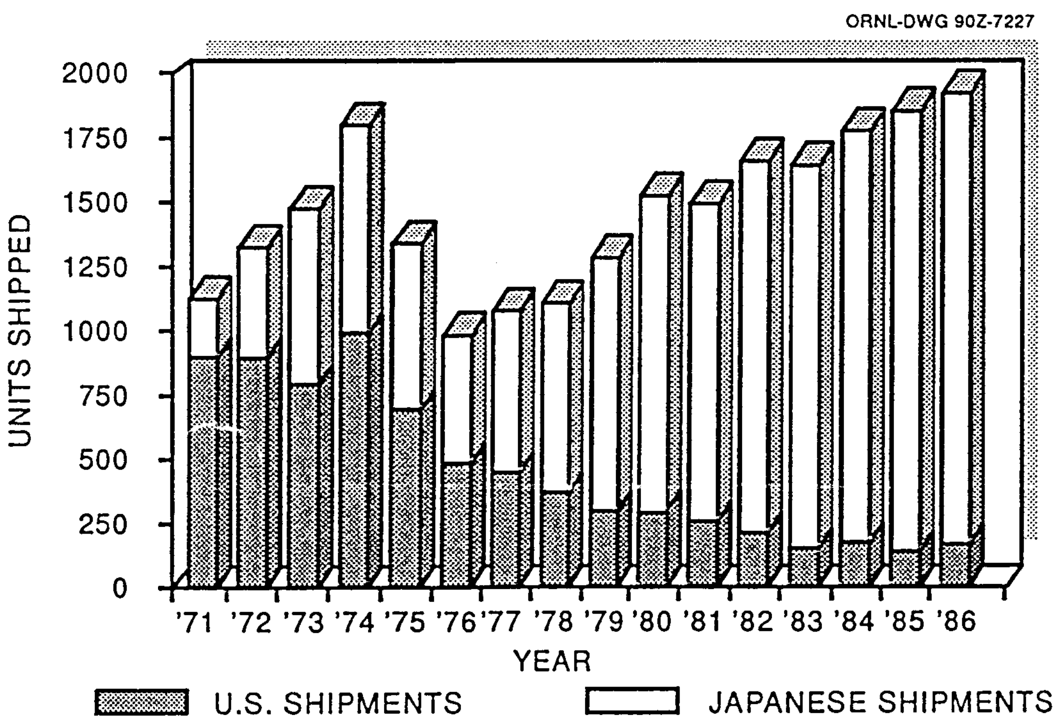
BACKGROUND

The sale of indirect-fired, packaged absorption chillers was a big business in the U.S. through the early 1970s. More than 26,000 large $LiBr/H_2O$ chillers were manufactured in the U.S. up to the mid 1970s. U.S. manufacturers were virtually without foreign competition until the late 1960s.

Two changes occurred in the marketplace to reduce U.S. manufacturing of absorption equipment. Japanese manufacturers entered the world market in the late 1960s, and the "energy crisis" changed fuel price and availability throughout the world in the 1970s. In the U.S. there were shortages of natural gas, and many gas utilities limited the availability of gas for new customers. The U.S. manufacturers' main products were inefficient single-effect chillers that had been developed decades earlier. Only Trane sold a double-effect chiller in the U.S. These factors combined to dramatically reduce sales of absorption equipment by U.S. manufacturers.

Figure 1 shows the declining sales of U.S. absorption chillers, with a concurrent increase in Japanese sales, since 1970. U.S. sales declined from 1000 machines per year in 1974 to 150 in 1986. Japanese manufacturers now dominate world production and sales of absorption chillers, and double-effect absorption chillers are widely available from Japanese manufacturers. At current exchange rates (1989), over $200 million in absorption chillers is sold annually.

FIGURE 1: U.S. AND JAPANESE ABSORPTION CHILLER SALES

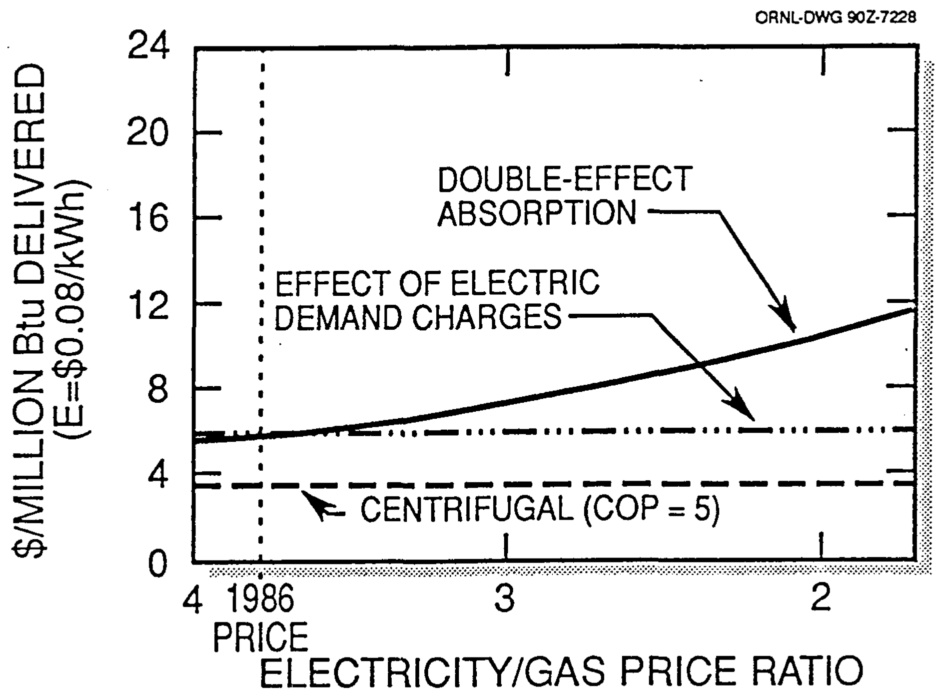


Japanese manufacturers have continually improved their absorption products throughout the 1970s and 1980s. As an example, Japanese companies now engaged in manufacturing and sales of absorption equipment have conducted major programs to improve double-effect products. Published information from certain manufacturers (Kurosawa 1988) shows ambitious goals for double-effect machines: COPs of 1.2 for small- and medium-sized machines and 1.3 for large sizes, compared with 1.0 to 1.07 as previously produced. These improved double-effect machines are likely pushing the practical limits for double-effect equipment efficiency (Wilkinson 1987).

CURRENT MARKET

Absorption chillers are economically marginal in the U.S. Even the "ultra-efficiency" Japanese double-effect chillers would use more primary energy than the better electric centrifugal chillers. Figure 2 compares the fuel costs of a double-effect absorption chiller with those of a good electric centrifugal chiller for a range of gas-to-electric price ratios.

FIGURE 2: CURRENT EFFICIENCY ABSORPTION CANNOT COMPETE WITH ELECTRIC CHILLERS IN BROAD U.S. MARKET



Because of the low efficiency inherent in single- and double-effect chillers, customers in most locations in the U.S. would pay higher fuel costs for absorption chillers as compared with electric chillers. In some locations in the U.S., high electricity demand charges do make gas-fired double-effect chillers marginally competitive.

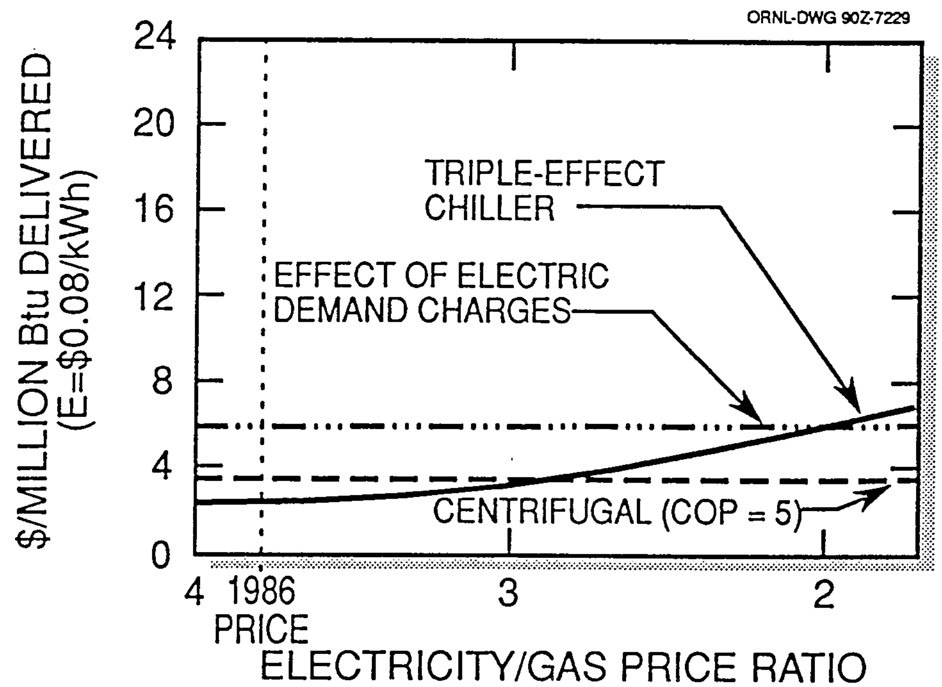
BEYOND DOUBLE-EFFECT

One approach to further improving the relatively inefficient cooling COP of even the best double-effect absorption equipment is to develop completely different, more complex absorption cycles with significantly higher theoretical efficiency potentials in cooling (Alefeld 1983, 1985; DeVault 1988a,b).

The double-effect cycle represents a significant step performance improvement over the basic single-effect cycle (COP = 1.2 for the double-effect cycle compared with COP = 0.77 for the equivalent single-effect cycle). There are a variety of "triple-effect" cycles that could produce comparable significant step improvements in cooling efficiency compared with the equivalent double-effect cycle.

Figure 3 shows the customer fuel costs for a theoretical triple-effect chiller compared with electric centrifugal chillers for a range of gas to electric prices. As can be seen, a triple-effect chiller should cost less to operate than an electric centrifugal chiller for any credible electric to gas price ratio.

FIGURE 3: TRIPLE-EFFECT ABSORPTION CHILLER COULD BE FULLY COMPETITIVE WITH ELECTRIC CHILLERS IN THE UNITED STATES



Since the cooling performance of even the best double-effect chiller is not adequate to conserve primary energy compared with high-efficiency electric chillers, and since the goal of the United States Department of Energy (DOE) absorption program is to save primary energy, DOE initiated a project to identify absorption technology that could improve cooling efficiency substantially beyond performance levels possible for double-effect cycles. At Oak Ridge National Laboratory, a particular triple-effect cycle was selected that has the potential for low cost and simultaneously offers much higher efficiency than double-effect cycles (DeVault 1988a). This particular triple-effect cycle has the potential to save energy even when compared with the best electric centrifugal chillers.

TRIPLE-EFFECT CYCLE

Figure 4 shows the basic triple-effect cycle configuration. The triple-effect cycle consists of two simple single-effect chillers operating together. A small "high-temperature" chiller's rejected heat (both condenser heat and absorber heat) is used to run a larger conventional chiller. The combined cooling effect of both chillers is used. Operating together, these chillers give approximately three times the efficiency of a single-effect chiller. This triple-effect cycle is calculated to have an 18% to 60% higher COP than the equivalent double-effect cycle. Cooling COPs from 1.4 to 2.0 have been calculated for the triple-effect cycle using known absorption-fluid combinations (DeVault 1989, Carrier 1989, Nagaoka and Nishiyama 1989).

FIGURE 4: TRIPLE-EFFECT CYCLE

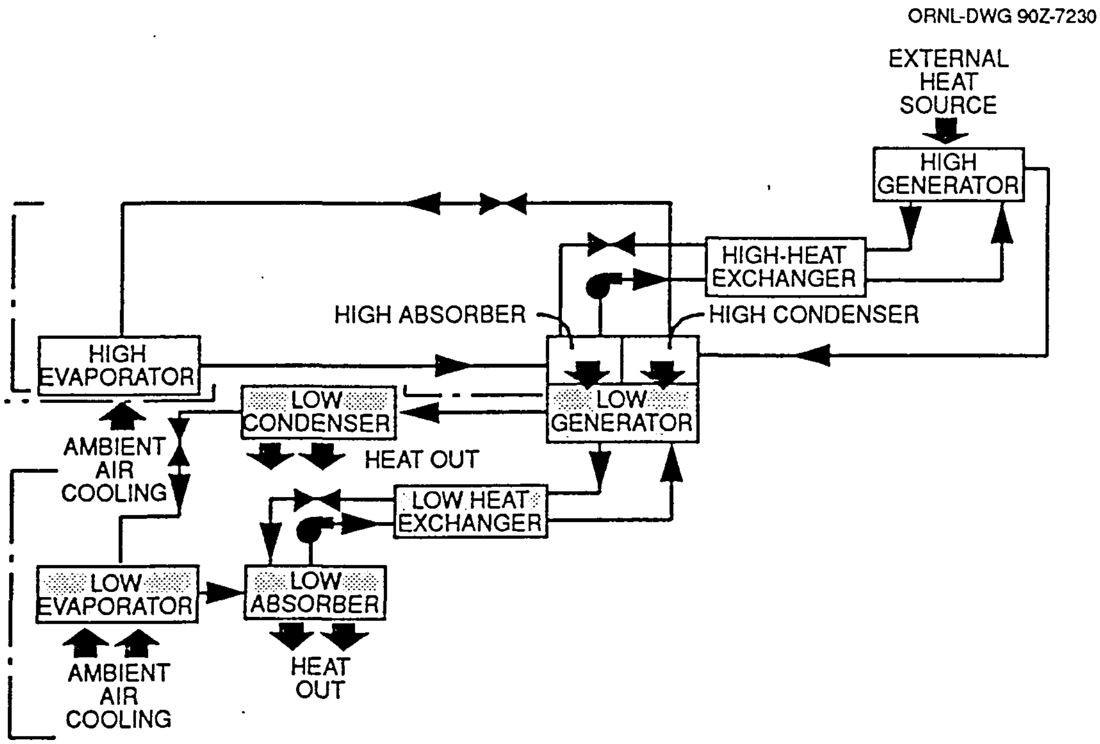


Figure 5 shows one possible arrangement of absorption components for a triple-effect apparatus. The components are arranged in four pressure-containing shells. Other component configurations have been evaluated, including the possibility of arranging the complete triple-effect apparatus into a machine with only two shells.

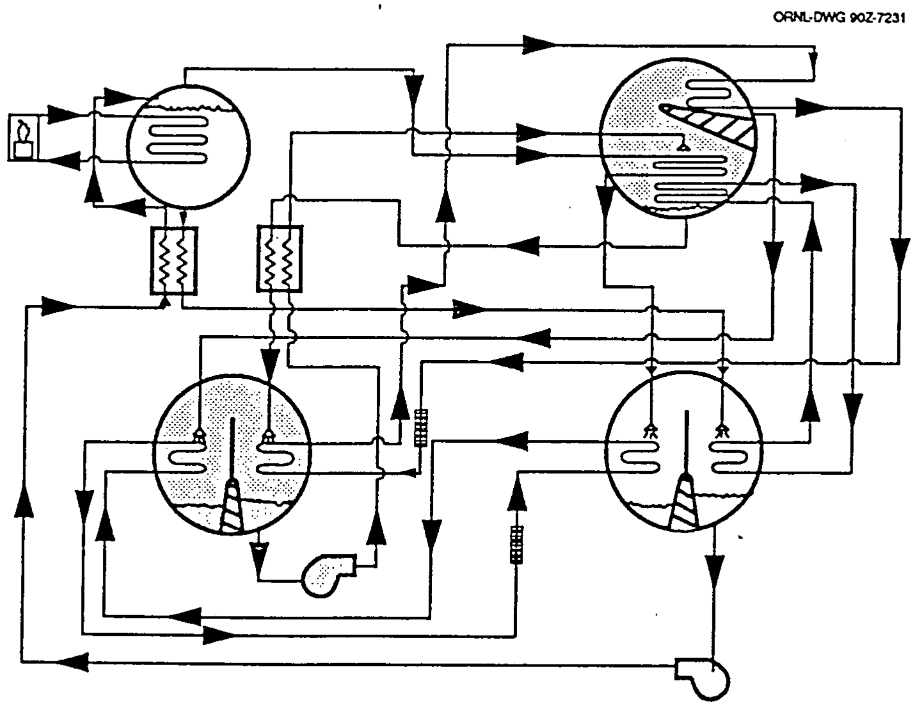
The triple-effect chiller can use several existing absorption fluids, uses only conventional heat exchangers, and needs less total heat exchange per unit of capacity than the equivalent double-effect cycle. For these reasons, the triple-effect chiller has the potential to be no more, and possibly less, expensive than existing double-effect chillers.

DEVELOPMENT PROJECTS

Two U.S. companies have licensed the triple-effect chiller. These companies are Trane, the second largest manufacturer of building HVAC equipment, and Apache, an independent oil and gas production company. Negotiations for licenses for other possible applications are continuing.

In 1988 Trane licensed the triple-effect, and, with Gas Research Institute (GRI) participation, is working on a project to develop the triple-effect cycle for 150-ton and larger commercial chiller

FIGURE 5: TRIPLE-EFFECT APPARATUS



applications. The performance goal is to achieve a gas-fired cooling COP of 1.5. Proof-of-concept demonstration for the 150-ton and larger chiller application is projected for 1991 (Gas Research Institute 1988).

In 1989, Apache licensed the triple-effect for use with cogeneration systems smaller than 150 tons in cooling capacity. Development of the triple-effect cycle by Apache was started late in 1989, and the development schedule has not been announced.

WATER REFRIGERANT TRIPLE-EFFECT

Several organizations have evaluated the triple-effect cycle for use with water as the refrigerant combined with a number of absorbents. The lower-temperature single-effect part of the triple-effect can use lithium-bromide/water ($LiBr/H_2O$) because operation is identical to that of a conventional single-effect chiller. The high-temperature single-effect cycle cannot use $LiBr/H_2O$, because the absorber must operate at a temperature well beyond the $LiBr/H_2O$ crystallization limit in order to achieve the triple effect. Projects are currently underway to develop and test the triple-effect cycle using water as the refrigerant with a variety of absorbents. The exact absorption fluid combinations being used in these development projects are considered to be business proprietary, and will not be further discussed in this paper.

AMMONIA-WATER TRIPLE-EFFECT

Calculations for the triple-effect cycle have been made for a variety of absorption fluids. The following example uses ammonia-water (NH_3/H_2O) as the absorption fluid pair in both the high-temperature and low-temperature single-effect cycles that are used to obtain the triple-effect (DeVault and Marsala 1990). Performance calculations for the triple-effect cycle were made using available NH_3/H_2O data (Gillespie et al. 1985, Macriss et al. 1988).

Table 1 shows a summary comparison of equivalent single-effect, double-effect, and triple-effect absorption cycles using NH_3/H_2O. The refrigerant and absorbent operating conditions are shown in the Appendix. The calculations show that the triple-effect cycle offers significant performance improvements compared with the double-effect cycle using NH_3/H_2O. At the standard rating condition for air-cooled residential air conditioners, the triple-effect cycle is 18% more efficient than the equivalent double-effect cycle (COP = 1.41 compared with COP = 1.20).

Table 1: Cycle Comparisons for Ammonia-Water Cycles[a]

CYCLE:	SINGLE EFFECT	DOUBLE EFFECT	TRIPLE EFFECT
COP	0.77	1.20	1.41
TOTAL HEAT EXCHANGE NEEDED (Btu/h)	250,000	390,000	260,790
HIGH PRESSURE	12.57 atm (184.8 psi)	68.05 atm (1000 psi)	47.70 atm (701 psi)
NO. OF PUMPS	1	2	2
PUMPING POWER REQUIRED	35 W	370 W	151 W
NO. OF MAJOR COMPONENTS	5	7 (8)[b]	7 (10)[c]
PEAK GENERATOR TEMPERATURE	115.7°C (240.3°F)	199.6°C (391.3°F)	218.7°C (425.7°F)

[a]All values calculated for a 3-ton cooling capacity (36,000 Btu/h) residential air conditioner at the standard rating conditions for unitary air conditioners (ARI Standard 210-81), assuming commercially achievable heat-exchanger performance [approximately 5.6°C (10°F)].

[b]Eight actual functions performed by seven components.

[c]Ten actual functions performed by seven components.

Some of the calculated values shown in Table 1 may at first appear surprising. The triple-effect cycle is calculated to operate at lower pressure, to have much lower pumping-power requirements, and to need less total heat exchange for the same cooling capacity compared with the double-effect cycle. There are fundamental reasons why the triple-effect operates at lower pressure, needs less power for solution pumping, and has less total heat exchange than the equivalent double-effect cycle. Each of these calculated results will be discussed in the following sections.

High Pressure

For the double-effect cycle, the high-temperature NH_3 condenser is primarily used to provide energy to the low-temperature generator. For systems with a volatile absorbent, such as NH_3/H_2O, some additional energy can be recovered from the high-temperature rectifier. As shown in the Appendix, the low-temperature generator can accept heat from 69.7°C (157.4°F) up to 115.7°C (240.3°F). However, most of the energy available from the condenser is available from the heat of condensation of the refrigerant, with only a small quantity of energy being available from sensible cooling of the condensed refrigerant. This means that the high-temperature condenser needs to operate at 107.7°C (225.8°F) [102.1°C (215.8°F) generator temperature + 5.6°C (10°F) for heat exchange] in order to supply all of the available condenser energy to the low-temperature generator. The high-temperature rectifier then provides the rest of the energy needed to heat the low-temperature generator to the 115.7°C (240.3°F) peak temperature. For NH_3/H_2O, this means the double-effect cycle will operate at 68.05 atm (1000 psi pressure), since the pressure is determined by the NH_3 condenser operating temperature.

For the triple-effect cycle, both the high-temperature absorber and the high-temperature condenser are used to provide energy to the low-temperature generator. The absorber, rather than the condenser, can be used to provide energy to the hotter parts of the generator, so the condenser can operate at a lower temperature while still supplying energy to the cooler parts of the generator. For the triple-effect cycle the high-temperature condenser can operate at about 87.8°C (190°F) and reject all of the condenser energy to the low-temperature generator. Additionally, the high-temperature absorber can operate conveniently over a temperature range of 90.6°C (195°F) to 110°C (230°F), thereby providing additional energy input to the low-temperature generator. Finally, as in the double effect, the high-temperature rectifier can be used to provide the rest of the energy needed to heat the low-temperature generator. The NH_3 condenser operating temperature for the triple-effect cycle corresponds to a pressure of 47.70 atm (701 psi), rather than 68.05 atm (1000 psi) for the double-effect cycle.

A fundamental advantage of a triple-effect cycle that uses NH_3/H_2O is that the high-temperature side is coupled to the low-temperature side to reduce pressure compared with a condenser-coupled double-effect cycle.

Pumping Power

The triple-effect cycle has a substantially lower solution-pumping power requirement than the double-effect cycle. The double-effect cycle needs 370 W of pumping power (ideal pumping power excluding pump or motor efficiency), whereas the triple-effect cycle needs only 151 W. There are two reasons for the triple-effect cycle's reduced need for solution pumping power. The first is simply that the solution is pumped to 47.70 atm (701 psi) instead of 68.05 atm (1000 psi), as discussed before. The second reason is that far less solution needs to be pumped to the high-pressure generator in the triple-effect cycle configuration.

The refrigeration effect obtained from the high-temperature (i.e., high-pressure) side of the double-effect cycle is about 57% of the capacity of the complete double-effect air conditioner. Therefore, as a first approximation, about 57% of the total absorption solution needs to be pumped to the high-pressure (68.05 atm, 1000 psi) generator. For the triple-effect cycle, the refrigeration effect obtained from the high-temperature part of the cycle is only 25.4% of the total refrigeration effect, with the remaining 74.6% being obtained from the lower-temperature part of the cycle. Therefore, substantially less absorption solution is pumped to the high-pressure generator in the triple-effect cycle.

Combining these two advantages (less solution being pumped to a lower pressure) for the triple-effect cycle results in substantially less solution-pumping power needed compared with the double-effect cycle.

Heat Transfer

The triple-effect cycle recovers more energy internally than the equivalent double-effect cycle, which means there is a substantial reduction in the total heat transfer needed for any given refrigeration capacity. Heat transfer is reduced because the triple-effect cycle recovers the high-temperature absorber energy and substitutes this absorber energy for external energy that would be needed in the equivalent double-effect cycle. The double-effect cycle "throws away" this absorber energy to the outside air, adding to the total heat transfer taking place in the cycle. A second advantage of a triple-effect cycle that uses NH_3/H_2O is that less heat transfer is needed for rectification compared with the double-effect cycle (also because of the advantages of lower pressure and less solution flow, as previously discussed).

Therefore, as a first approximation, 33% less heat-exchanger surface area is needed for the triple-effect cycle compared with the double-effect cycle. Since absorption machines are mostly heat exchangers, this means that it should cost less to construct a triple-effect NH_3/H_2O air conditioner than to construct a double-effect NH_3/H_2O air conditioner of the same capacity.

Maximum Temperatures

A disadvantage of the triple-effect cycle compared with the double-effect cycle is the higher temperature necessary to operate the high-temperature generator. For the same external conditions and equivalent heat exchangers, the triple-effect generator will operate at 218.7°C (425.7°F) compared with 199.6°C (391.3°F) for the double-effect cycle. If the same absorption fluids are used, along with equivalent heat exchangers, higher-efficiency cycles can only be obtained by using higher driving temperatures for the absorption cycle.

The higher generator temperatures will increase potential corrosion rates, possibly affecting material choices and material costs. Reliability and maintenance requirements could also be affected.

Hardware Implications

Except for the higher temperatures, it would seem preferable to build NH_3/H_2O absorption air conditioners using the triple-effect cycle rather than a two-condenser double-effect cycle.

Within the last few years, every individual component needed to build and operate the triple-effect cycle has been developed and tested, although not by a single organization. The basic evaporator, absorber, and condenser are the same as components that have been manufactured for decades for single-effect NH_3/H_2O air conditioners.

The high-temperature condenser, which supplies heat to the low-temperature generator, is technically the same for the double- and triple-effect cycles. This high-temperature condenser, using NH_3 refrigerant, has been designed, built, and demonstrated for a double-effect cycle (Reid et al. 1987). The high-temperature, double-effect NH_3 condenser has been designed to operate as high as 102.07 atm (1500 psi), and has been operationally tested to the design point. High-temperature condenser operation at conditions far beyond those needed for the triple-effect cycle has therefore been demonstrated.

The high-temperature absorber/low-temperature generator combination has also been designed, built, and tested (Modahl and Hayes 1988). The high-temperature absorber was built and tested for an NH_3/H_2O heat-pump development project to obtain the equivalent of double-effect efficiency in a heating and cooling heat pump using a "generator-absorber heat-exchange cycle." This high-temperature absorber, combined with a low-temperature generator, has also been demonstrated at operating conditions beyond those needed for the triple-effect–cycle air conditioner.

The equivalent high-temperature generator needed for the NH_3/H_2O triple-effect cycle has also been developed and tested for a number of other applications (Phillips 1988, Modahl and Hayes 1988).

The remaining step, not yet taken, would be to design, construct, and test a complete triple-effect machine using NH_3/H_2O.

CONCLUSION

All current gas-fired absorption air conditioners and chillers are based on well-known single-effect or double-effect cycles. These products are relatively "mature," and the existing single- and double-effect products are already—for all practical purposes—cost-performance "optimized." Even the "ultra-efficiency" Japanese double-effect chillers would use more primary energy than the better electric centrifugal chillers. The remaining small incremental improvements possible for single- and double-effect products are not likely to make a major difference in efficiency or in market share compared with electric equipment in the United States.

Just as the double-effect cycle is a significant step performance improvement over the single-effect cycle, the triple-effect cycle can be a significant step improvement compared with the cooling efficiency of the equivalent double-effect cycle.

Because cooling performance of even the best double-effect chiller is not adequate to conserve energy compared with high-efficiency electric chillers, and because the primary goal of the U.S. DOE absorption program is to save energy, DOE initiated a project to identify absorption technology that could improve cooling efficiency substantially beyond performance levels possible for double-effect cycles. At Oak Ridge National Laboratory, a particular triple-effect cycle was selected that has the potential for low cost while offering much higher efficiency than double-effect cycles. This particular triple-effect cycle has the potential to save energy compared with the best electric centrifugal chillers.

It is technically feasible to build and operate a two-condenser, two-absorber triple-effect cycle using ammonia-water (NH_3/H_2O) as the absorption fluid. This particular triple-effect cycle offers a number of significant advantages compared with the equivalent two-condenser double-effect cycle. These advantages are substantially higher efficiency (COP = 1.41, about 18% higher), lower pressure [47.70 atm (701 psi) instead of 68.05 atm (1000 psi)], significantly reduced pumping power (151 W instead of the 370 W needed for the double-effect cycle), and potentially lower construction costs (33% less total heat exchange needed). In order to achieve the triple-effect levels of performance, however, peak generator temperatures are higher than for the equivalent double-effect cycle, adding technical risk because of potentially higher corrosion rates.

AUTHOR

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APPENDIX

Standard rating conditions for SEER: outdoor air = 27.8°C (82°F), indoor air = 26.7°C (80°F) return, 19.4°C (67°F) supply; 5.6°C (10°F) for heat exchangers

Refrigerant/Absorbent Conditions

- Lower Loop:

evaporator: 2.2°C (36°F); 4.54 atm (66.7 psi); 99% NH_3 purity

absorber: 33.3°C (92°F); 4.54 atm (66.7 psi); 52.0% conc.
75.2°C (167.4°F); 4.54 atm (66.7 psi); 29.1% conc.

condenser: 33.3°C (92°F); 12.57 atm (184.8 psi); 99% conc.

generator: 69.7°C (157.4°F); 12.57 atm (184.8 psi); 52.0% conc.
115.7°C (240.3°F); 12.57 atm (184.8 psi); 29.1% conc.

•Upper Loop:

evaporator: 8.3°C (47°F); 5.65 atm (83.1 psi); 99% conc. (the evaporators are staged to keep temperatures and pressures as low as possible)

condenser: 87.8°C (190°F); 47.70 atm (701 psi); 99% conc.

absorber: 90.6°C (195°F); 5.65 atm (83.1 psi); 25.6% conc.
110°C (230°F); 5.65 atm (83.1 psi); 17.0% conc.

rectifier: 105.3°C (221.6°F); 47.7 atm (701 psi); 99% conc. (vapor to condenser)
190.3°C (374.5°F); 47.7 atm (701 psi); 78.4% conc. (vapor from generator)

generator: 184.7°C (364.5°F); 47.7 atm (701 psi); 25.6% conc. (rich liquid)
218.7°C (425.7°F); 47.7 atm (701 psi); 17.0% conc. (weak liquid)

Other Notes

For the above conditions, the upper loop supplies 25.4% of cooling capacity and the lower loop supplies the remaining 74.6% of capacity.

The lower-loop generator receives heat input from the upper-loop condenser, 87.8°C (190°F); absorber, 90.6°C to 110°C (195°F to 230°F); and rectifier, 105°C to 190°C (221°F to 374°F).

This calculation is for an air-conditioner only. Temperatures for the lower loop would not work for a reversible heat-pump configuration.