1986

The Double-Effect Regenerative Absorption Heat Pump: Cycle Description and Experimental Test Results

J. Rasson

K.Eao

M. Wahlig

Rasson, J.; K.Eao; and Wahlig, M., "The Double-Effect Regenerative Absorption Heat Pump: Cycle Description and Experimental Test Results" (1986). *International Refrigeration and Air Conditioning Conference.* Paper 25.
http://docs.lib.purdue.edu/iracc/25

THE DOUBLE-EFFECT REGENERATIVE ABSORPTION HEAT PUMP: CYCLE DESCRIPTION AND EXPERIMENTAL TEST RESULTS*

JOSEPH RASSON, KIM DAO+ and MICHAEL WAHLIG
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

ABSTRACT

A double-effect ammonia-water regenerative absorption chiller/heat pump has been designed, built and tested. The heat pump cycle (2R cycle) consists of two subcycles or stages. The second low temperature stage is a conventional single-effect absorption cycle; it is driven by heat rejected from the first higher temperature stage. The first stage is a new type of absorption cycle in which the heat source drives a multi-pressure stage boiler in such a way that the boiling process and the resorption process occur essentially at constant temperatures. A regeneration process in the first stage, between the lowest-pressure stage of the absorber and the highest-pressure stage of the boiler, makes possible the recovery of heat that otherwise would be rejected to the outdoors. This heat is used for the generation of additional refrigerant, improving the efficiency of the system.

This 2R cycle heat pump has several distinct advantages over other types of double-effect machines. The 2R has a COP that increases continuously with increasing input temperature (at roughly 55% of Carnot), has a higher COP than conventional double-effect machines, and has a much lower practical cut-off input temperature.

A 3-ton prototype 2R chiller/heat pump was tested extensively to prove the feasibility of this type of regenerative cycle. Test data was collected over a boiler temperature range of 76°C (170°F) to 130°C (260°F) and a condenser temperature range of 30°C (86°F) to 40°C (104°F). The test results showed that the 2R cycle is stable and that the regenerative process is attainable. Furthermore, a cooling COP as high as 1.17 was measured at a boiler temperature of 127°C (260°F), a condenser temperature of 35°C (95°F) and an evaporator temperature of 3.3°C (38°F). In general, the experimentally measured COP values were in good agreement with the analytically predicted values.

1. INTRODUCTION

Absorption heat pumps (AHP) for <u>solar</u> heating and cooling applications should have a number of desired characteristics. The coefficient of performance (COP) should be high enough to compete on a resource energy basis with electric-driven heat pumps. The AHP should be able to operate efficiently over a broad range of inlet temperatures (e.g. 80°C to 150°C), such as would be produced by solar collectors under variable solar radiation conditions, to take full advantage of the thermodynamic potential of the collected solar energy. For residential and small commercial applications, air-cooled (rather than water-cooled) operation should be possible /1/, to avoid the maintenance associated with an evaporative cooling tower. To enable heating as well as cooling-mode operation, the refrigerant must be capable of withstanding outdoor winter temperatures without freezing.

A new type of absorption heat pump has been investigated at the Lawrence Berkeley Laboratory (LBL) that addresses all of the above concerns. Ammonia-water was selected as the refrigerant-absorbent pair to allow air-cooled operation and heating-mode operation. The nature of the cycle -- a double-effect regenerative absorption cycle (or 2R cycle, for short) -- produces a COP that

---

* This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Solar Heat Technologies, Solar Buildings Technology Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

+ Present address: 12 Nace Avenue, Piedmont, CA 94611.

increases continuously with increasing input temperature, at about 55% of the theoretically maximum Carnot efficiency. This new cycle also features a maximum condenser pressure and a theoretical pumping power that are characteristic of a single-effect cycle, not the higher pressure and pumping values normally associated with double-effect cycles.

2. CYCLE DESCRIPTION OF THE 2R HEAT PUMP

The double-effect regenerative (2R) absorption heat pump contains two stages, as shown in Figure 1 on an ammonia/water Pressure-Concentration-Temperature (PXT) diagram for cooling-mode operation. Each stage can be considered as an independent power-refrigeration cycle that receives heat at a high temperature, rejects heat at intermediate temperature, and produces a cold source at a low temperature.

As shown in Figure 1, the first stage is a new type of absorption cycle (called the regenerative cycle). Its boiler element is driven by the heat source (such as solar collectors) at a temperature ranging from 80°C to 130°C, depending on the heat source temperature. The resorber element rejects heat at about 76°C to the second stage. The boiling process and the resorption process of the first stage are multi-pressure processes, and thus they occur at nearly constant temperatures. Each pressure step in the boiling process is connected to an equal pressure step in the resorption process through vapor feed lines.

The regenerator of the first stage is a two-stream heat exchanger. One stream is the low pressure, weak solution exiting the lowest pressure step of the boiler, and the other stream is the high pressure, strong solution leaving the highest pressure step of the resorber. A heat recovery process takes place in which the high pressure side receives, from the low pressure side of the regenerator, heat of absorption that otherwise would be rejected to the outdoors. This recovered heat is used for the generation of high-pressure refrigerant vapor, which passes to the condenser.

The second stage (the lower temperature stage in Figure 1) of the 2R heat pump is a conventional single-effect absorption cycle. Its generator element is driven (at about 76°C) by heat rejected from the first-stage resorber. The additional high pressure refrigerant vapor produced by the generator of this stage is also condensed in the condenser element (which is common to both stages). The refrigerant passes through an expansion valve into the lower-pressure evaporator element (which is also common to both stages), in which the refrigerant vaporization produces the cooling effect.

Part of the low pressure refrigerant vapor leaving the common evaporator is absorbed in the first-stage, low-pressure side of the regenerator and part is absorbed in the second-stage absorber. During the cooling mode operation of the 2R heat pump, both the second-stage absorber and the common condenser reject heat to the outdoors at about 38°C. During the heating mode, the heat rejected from the second-stage absorber and the common condenser is used to heat the conditioned space, and heat from the outdoors is used to boil the refrigerant in the common evaporator.

The above 2R cycle description is applicable when the input temperature is higher than the conventional single-effect cut-off (T_{CO}) temperature. During operating conditions when the input temperature is less than T_{CO} (as in some solar applications), the 2R heat pump will continue to operate, although the COP decreases with decreasing inlet temperature. Thus there is effectively no cut-off temperature for the 2R cycle. When the inlet temperature is less then T_{CO}, the first-stage will operate as a heat transformer that uses the boiler heat input to pump heat to a temperature high enough to run the second-stage generator. The low pressure side of the regenerator would thus generate vapor that is absorbed in the second-stage absorber, and the high pressure side of the regenerator will absorb part of the vapor produced by the second-stage generator. Thus this operating mode decreases the vapor output to the condenser, reducing the cycle COP, as expected for the lower input temperature.

The proper flow direction of the vapor in the regenerator is controlled by placing a set of check valves at both ends of the regenerator. The check valves at the high-pressure end of the regenerator operate in response to the pressure drop between the generator and the regenerator, and the check valves at the low-pressure end operate in response to the pressure drop between the absorber and the regenerator.

3. EXPERIMENTAL PROCEDURES

A 3-ton nominal capacity 2R heat pump was designed, built, and tested at LBL. A description of the experimental unit is given in more detail in Reference 2.

The single-effect stage of the 2R heat pump incorporated many design improvements that were developed in an earlier project at LBL /3/. These design improvements included new vapor heat recovery paths and a work recuperating pump.

The first-stage of the 2R heat pump consisted of seven boiling and resorption steps. At the end of each boiling step the vapor is separated from the solution and is fed to the corresponding resorption step. The solution then passes through a restrictor where the pressure drops to the next lower pressure step to continue the boiling process. Similarly, in the resorber, after each resorption step the solution is pumped up to the next higher pressure step to continue the resorption process. A small portion of the solution (about 10%) at each resorption step is bled to the corresponding boiler step to balance the solution flow rate (see Figure 1). Seven diaphragm pumps of adjustable capacities were used in the resorber during the experimental testing to allow for individual control of the flow rate in every step, but one multi-stage pump could have been used instead, as would be the case for a production version of the 2R heat pump.

The high temperature heat input source to the boiler was water heated by an electrical resistive element rather than solar heated water, in order to facilitate the experimental procedures. Similarly, the heat load to the evaporator was supplied by electrically heated water.

The common condenser and the second-stage absorber were cooled by a closed-loop water circuit, the temperature of which was controlled by first rejecting heat to an outdoor air coil, then heating to the desired operating temperature by electrical resistive elements.

Temperatures were measured by placing thermocouples at the inlet and outlet of each stream. Pressure was measured using Bourden tube pressure gauges connected to common pressure manifolds. Flow rates were measured using rotometer and turbine-type flow meters. The concentrations of the saturated solution leaving the absorber and the liquid refrigerant leaving the condenser were calculated from the ammonia/water PXT diagram.

The unit was insulated by wrapping fiberglass wool around the heat exchangers except for the condenser and the second-stage absorber. As part of the calibration procedures, hot water was circulated inside the insulated heat exchangers in order to calculate heat loss to the ambient. Formulas for heat loss to the ambient were obtained as a function of operating temperature and room temperature.

The 2R heat pump was tested at predetermined temperature conditions. The boiler temperature was operated in the range of 76 - 135°C, and the absorber/condenser temperature was set in the range of 30 - 40°C which corresponded to either water cooled or air-cooled operating modes.

The evaporator temperature was modulated by controlling the absorber pressure. This was accomplished by varying the ammonia concentration of the solution leaving the absorber by removing or adding ammonia to the system. The chilled water temperature was set such that the temperature of the vapor refrigerant leaving the evaporator was about 1.5°C higher than the chilled water temperature. This criterion insured complete vaporization at the lowest evaporator temperature.

The 2R heat pump cooling capacity was dependent mainly upon the solution circulation rate and the strong solution ammonia concentration. Since the circulation rate was kept constant throughout most of the experimental runs, the capacity was allowed to fluctuate depending on the solution concentration of each run. Data were collected after the system had attained a steady state condition, following each change in operating conditions. Pressures and flow rate measurements were collected manually at the end of each run. The temperature measurements were recorded by an HP 3497A electronic voltmeter, which was integrated into an HP 9845B desk top computer for the transient graphic display of temperatures. When it was observed on the graphic display terminal that the inlet and outlet temperatures of the hot water to the boiler and the chilled water to the evaporator had reached steady state conditions, a data point was recorded. The data were then fed to the computer for analysis and calculation of heat pump performance.

4. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental test results showed first that the 2R regenerative cycle operated as designed and was stable. The stability of the cycle was studied by perturbing the operating conditions of the heat pump during the experimental runs. When the operating conditions were returned back to their original values, the heat pump would also return to its original steady state condition. Generally, the system would reach its steady state operating condition after about one or two hours from a cool start-up, due to the large heat capacity of the system. However, it took only a few minutes to reach steady state when the system operating conditions were changed from one state to another.

The cooling mode performance of the 2R heat pump is presented in terms of the thermal COP which is defined as

$$\mathrm{COP} = \frac{\text{Cooling effect}}{\text{Heat input}} \qquad (1)$$

The cooling effect was calculated by two different methods to insure experimental accuracy. The first method calculates the enthalpy increase of the ammonia side of the evaporator by measuring the temperatures and ammonia mass flow rate in the evaporator. The second method calculates the enthalpy decrease of the water side of the evaporator by measuring the water flow rate and the water temperature drop across the evaporator. The two methods were compared to check measurement accuracy and to insure that the system had reached steady state conditions.

The heat input to the system was calculated by measuring the enthalpy decrease of the hot water stream flowing to the boiler.

The experimental COP values were corrected taking into account the amount of heat loss to the ambient and using a constant effectiveness value (90%) for the single-effect stage solution heat exchanger.

The experimental results of the 2R heat pump are presented in Figures 2, 3, 4 and 5. Figure 2 shows a plot of the experimental COP vs the ideal Carnot COP, which is given by the following equation:

$$\mathrm{COP}_{\mathrm{Carnot}} = (T_B - T_0) / (T_B + 273) * (T_E + 273)/(T_C - T_E) \ , \qquad (2)$$

where T_B, T_C and T_E are the boiler, condenser and evaporator temperatures in °C. T_0 is the saturation temperature of the solution leaving the second stage absorber.

As shown in Figure 2, the experimentally measured cooling COP of the 2R heat pump is approximately 55% of the ideal Carnot COP, over a wide range of temperature conditions.

Figures 3 and 4 show the experimental cooling mode COP vs. the boiler temperature for various condenser and evaporator temperatures. As shown in Figure 3, the 2R heat pump COP is 1.17 at 127°C (260°F) boiler temperature, 35°C (95°F) condenser temperature and 3.3°C (38°F) evaporator temperature.

Similarly, Figure 4 shows that the COP is 1.38 at the same boiler and condenser temperature, but at an evaporator temperature of 10°C (50°F).

Figure 5 shows a comparison between the experimentally measured COP and the theoretically calculated COP. The theoretical COP was calculated from a mathematical model developed to calculate the performance of the 2R heat pump in an earlier work /4/. The proper values of temperatures and flow rates of each run were fed into the mathematical model to calculate the theoretical COP values. Agreement between experimental and theoretical COP values is less than ± 2%, which lends confidence to the analytical method used to predict the performance of regenerative absorption heat pump cycles.

5. CONCLUSIONS

A regenerative absorption heat pump suitable for variable temperature heat input was designed, built, and successfully tested. Test results showed that the regenerative process is attainable and stable, and achieved approximately 55% of the ideal Carnot COP, over a wide range of operating conditions. For example, a cooling COP as high as 1.17 was measured at a boiler temperature of 127°C (260°F), condenser temperature of 35°C (95°F), and an evaporator temperature of 3.3°C (38°F).

The good agreement between the measured COP values and the analytically calculated COP values lends confidence to the analytical methods used to predict heat pump performance of regenerative absorption heat pump cycles.

The successful completion of this work portends future development of yet higher efficiency regenerative-cycle designs; e.g., for higher temperature, gas-driven applications.

REFERENCES

1. B. Phillips: Absorption Cycles for Air-Cooled Solar Air Conditioning. ASHRAE Trans, Vol. 82, Part 1. (1976) pp 966.

2. J. Rasson, K. Dao and M. Wahlig: Test Results of the Double-Effect Regenerative Absorption Heat Pump. Lawrence Berkeley Laboratory Report LBL-21533 (1986).

3. K. Dao, J. Rasson and M. Wahlig: Testing Results of an Ammonia-Water Absorption Air Conditioner Designed for Solar Cooling Applications. Lawrence Berkeley Laboratory Report LBL-16929 Draft (1983).

4. K. Dao: Conceptual Design of an Advanced Absorption Cycle: The Double-Effect Regenerative Absorption Cycle. Lawrence Berkeley Laboratory Report LBL-8405 (1978).

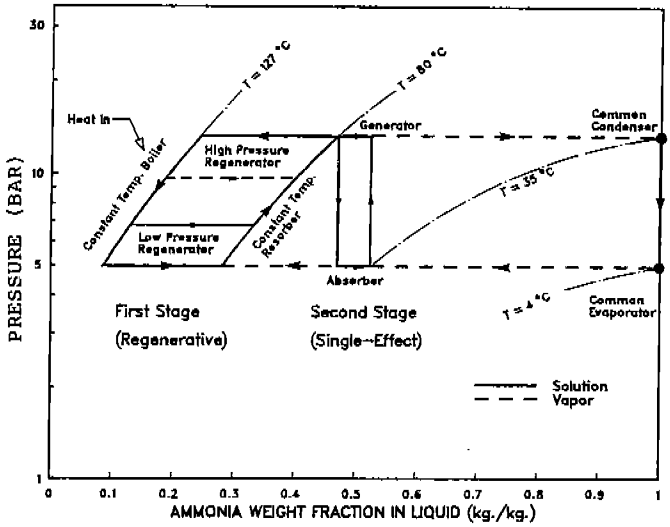

Fig. 1 - Schematic diagram of 2R absorption heat pump cycle on a pressure-concentration-temperature diagram for the ammonia-water working fluid pair.

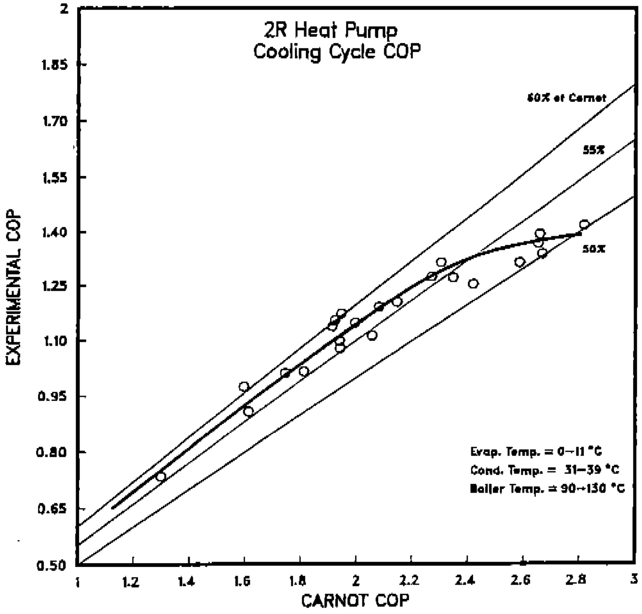

Fig. 2 - Experimentally measured values of the cooling cycle COP for the 2R heat pump vs. the calculated Carnot COP for the same operating conditions. The solid lines represent a constant percentage of Carnot efficiency. The solid curved line is a fit to the experimental data points.

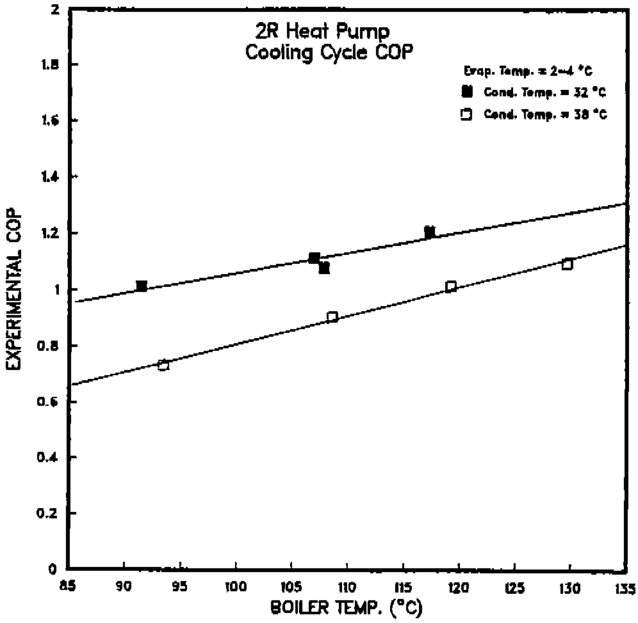

Fig. 3 - Experimentally measured values of the cooling cycle COP as a function of boiler temperature, for an evaporator temperature of 3°C.

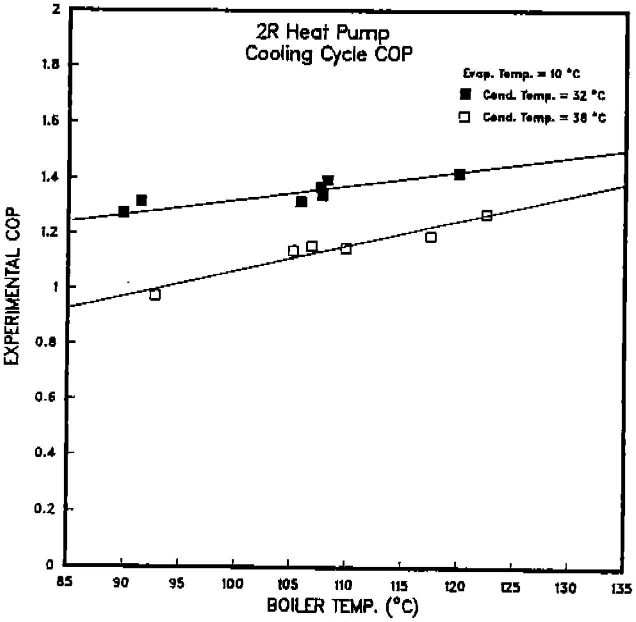

Fig. 4 - Experimentally measured values of the cooling cycle COP as a function of boiler temperature, for an evaporator temperature of 10°C.

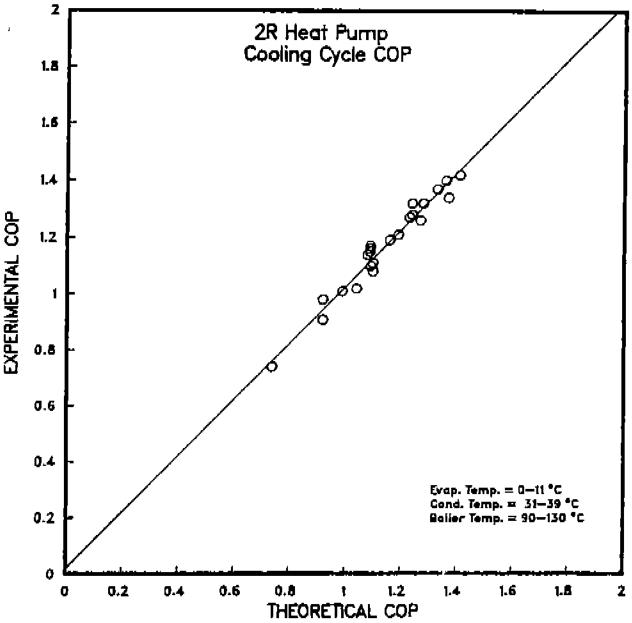

Fig. 5 - Comparison of the experimentally measured and theoretically calculated cooling cycle COP values, over a broad range of operating conditions. The solid line is a least squares fit to the data points.

LA POMPE À CHALEUR DOUBLE À ABSORBTION RÉGÉNÉRANTE

RÉSUMÉ

On a conçu, réalisé et essayé une double pompe à chaleur et refroidissement, à absorbtion régénérante et à eau ammoniacale. Le cycle d'une pompe à chaleur (cycle 2R) comprend deux sous-cycles ou phases. La seconde phase de basse température est un cycle simple d'absorbtion classique: il est entraîné par la chaleur rejetée lors de la première phase de haute température. La première phase constitue une nouvelle sorte de cycle d'absorbtion dans lequel la source de chaleur entraîne une chaudière à plusieurs pressions, de façon à ce que le processus d'ébullition et de résorbtion ait toujours lieu à température constante. Un procédé de régénération lors de la première phase, entre la phase de plus basse pression de l'absorbeur et celle de plus haute pression de la chaudière, permet de récupérer la chaleur qui autrement serait rejetée à l'exterieur. Cette chaleur sert à créer du liquide réfrigérant supplémentaire, et améliore les performances du système.

Ce cycle 2R de pompe à chaleur a plusieurs avantages, par rapport à d'autres machines doubles. Le rendement de ce 2R augmente régulièrement avec la température intérieure (à environ 55% de Carnot), il est plus élevé que pour un appareil classique double, et il a une température intérieure d'interruption pratique beaucoup plus basse.

Un prototype de 3 tonnes de cette, pompe à chaleur et refroidissement 2R a été essayée pour prouver les possibilités de ce cycle régénérant. Les résultats ont été pris, pour la chaudière à une temperature comprise entre 76°C (170°F) et 130°C (260°F), et pour le condensateur entre 30°C (86°F) et 40°C (104°F). Les resultats montrant que le cycle 2R est constant et qu'on peut obtenir le cycle régénérant. De plus, on a mesuré un rendemant de refroidissement égal à 1,17, pour une température de 127°C (260°F) dans la chaudière, de 35°C (95°F) dans le condensateur et de 3,3°C (38°F) dans le vaporisateur. En général, les chiffres mesurés expérimentalement allaient dans le même sens que les calculs déjà faits.