ABSORPTION/RESORPTION REFRIGERATION SYSTEMS WORKING WITH AMMONIA/WATER MIXTURES: MODELLING AND PERFORMANCE

Miguel Berdasco*, Manel Vallès, Alberto Coronas

CREVER, Mechanical Eng. Dep., Universitat Rovira i Virgili, Av. Paisos Catalans 26, 43007 Tarragona (Spain)

* Auteur correspondant: miguel.berdasco@urv.cat

Abstract

Despite absorption/resorption refrigeration systems were first proposed long time ago, these systems have been much less studied than the compression/resorption refrigeration systems. Just a few experimental ammonia/water absorption/resorption plants have been built and tested over the last years and much more research work have to be done. The main advantage of the absorption/resorption refrigeration cycles in comparison to the conventional absorption cycles is the wide operation flexibility and the possibility of reducing the high working pressure in a very significant way. However, several authors have reported the difficulty of working under stable conditions. This paper aims to review the theoretical and experimental works carried out so far on these systems. Furthermore, a thermodynamic model is presented to be used for analysing the operation flexibility provided by these systems and the influence of the pressure ratio and the effectiveness of the solution heat exchangers on the performance of the cycle.

Keywords : Absorption, Ammonia/Water, Modeling, Refrigeration, Resorption

Introduction

Resorption refrigeration systems are a very interesting technological alternative that provide more flexible design options compared to the conventional absorption refrigeration systems. The concept of resorption is based on the following principles: a) the refrigerant fluid is a mixture of fluids (refrigerant/absorbent) having a large boiling temperature difference (typical of absorption cycles), and b) the conventional evaporating and condensing processes taking place at the evaporator and condenser are replaced by desorption and absorption processes at non-isothermal conditions (Lorentz Cycle) that take place in the desorber and the resorber, respectively[1]. As the evaporation in the desorber of the zeotropic refrigerant mixture is not complete, along with the vapor stream a residual solution stream is generated and returns to the resorber by means of a solution pump in a circuit called "resorption circuit". The two pressure levels in the conventional absorption cycle are fixed by the condensing and evaporating temperatures, however in the resorption cycle there is an additional degree of freedom that provides a great flexibility in terms of cycle operation. Depending on the requirements, this flexibility could lead into an increase of the working temperatures at the same pressure levels just modifying the concentration of the working refrigerant mixture. In the same way, a very significant reduction of the pressure level in the system can be achieved for the same working temperatures. This reduction of the pressure level opens up new possibilities for using cheaper assembly materials that could make these systems more cost competitive for applications where low-grade heat sources are available. Problems related to the large size and cost have impeded the widespread used of the thermally driven refrigeration systems. However, these problems can be faced by the combination of resorption technology and the design of more compact, cheaper and lighter components such as polymeric membrane absorbers/desorbers or polymeric heat exchangers [2].

Ammonia/water have been selected as working mixture because it is a natural refrigerant with excellent thermophysical properties. In the case of the resorption systems, the ammonia/water mixture is particularly interesting because many of the drawbacks associated to this mixture (high pressure and the need of ammonia purification) can be overcome. Resorption refrigeration systems can be classified as compression/resorption or absorption/resorption depending on how the compression process takes place: with a "mechanical compressor" or with a "thermal compressor", respectively. This paper aims to study the ammonia/water absorption/resorption refrigeration cycle. A description of the configuration of the cycle and a review about the previous studies and experimental plants was carried out. Furthermore, a thermodynamic model was presented to be used for analysing the operation flexibility provided by these systems and the influence of the pressure ratio and the effectiveness of the solution heat exchangers in the performance of the cycle.

1 – **Configuration of the ammonia/water absorption/resorption refrigeration cycle**

Figure 1 shows a scheme of the ammonia/water absorption/resorption cycle, which consists of two solution circuits (absorption and resorption circuits) coupled to each other through two vapour streams; one leaving the generator and the other one leaving the desorber. The ammonia concentration and mass flow rate of these vapour streams are different because they are generated under different conditions (pressure, temperature and composition). For this reason, it would be necessary to equilibrate the mass balance between both circuits in order to keep the system running under the desired working conditions by means of a "bleeding" or mixing line for connecting both solution circuits, thus the excess amount of water can be transferred from the resorption circuit to the absorption circuit [3]. Thus, the rectification stage after the generator is not necessary. This is one of the main advantages provided by the resorption technology due to the typically large size and complex design of the rectifier.

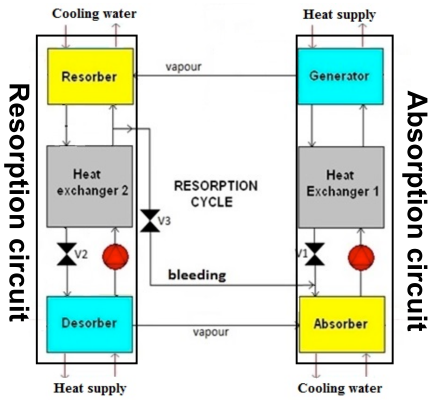

Figure 1: Scheme of the ammonia/water absorption-resorption cycle.

2 – **Review of the ammonia/water absorption/resorption systems**

Despite absorption/resorption systems were first proposed by Altenkirch [1], these systems have been much less studied than the compression/resorption refrigeration systems, probably due to the difficulty of keeping the system working under steady-state conditions that was pointed out by several authors. Very few studies are available in the literature related to the ammonia/water absorption-resorption systems. Baehr [4] proposed this system for the space heating of buildings in order to reduce the relatively high working pressures of the conventional ammonia/water absorption heat pumps. It was concluded that the advantage of having lower working pressure must be paid for by a reduction in the COP. Pande and Herold

[5] described and modelled an ammonia/water absorption-resorption heat pump for high-temperature applications. They observed that the resorption cycle is unstable because any mismatch in the mass balance between both solution circuits tends to cause more mismatches, so it would be required an active control to maintain operation of the system under steady-state conditions.

Regarding the experimental plants, just a few have been built and tested over the last years. In 1994, in the frame of a European Project [6], the company Deutsche Babcock-Borsig AG designed and tested a 500-kW ammonia/water absorption/resorption refrigeration system to produce chilled water using district heating at very low supply temperatures (80^{o}C). More recently, the company Makatec GmbH, in collaboration with various research centres, designed and tested several ammonia/water absorption/resorption machines over the last years. One of them was presented by Helle et al. [7]. They designed and tested a 1-2 kW experimental prototype of an absorption/resorption refrigeration system; problems related to the process stability were pointed out. However, they showed that a stable and reliable process is possible. The Zentrum für Energietechnik (ZET) of TU Dresden (Germany), in collaboration with Makatec GmbH, designed, build and tested a 25-kW refrigeration system with an attached ice storage system. In Grund et al. [8] all the start-up process and a more detailed description of this system can be found. There is also another ammonia/water absorption/resorption machine at TU Dresden with a smaller cooling capacity (1 kW) which was designed to withstand a maximum pressure of 3 bar using some plastic-made components to reduce the cost of the system [8]. An 80-kW refrigeration plant was delivered by Makatec GmbH to a chicken farm, Geflügelhof Zapf, in Gengenbach (Germany) [9]. The resorption system used for the cold production in a trigeneration plant, provided all the energy requirements (heat, electricity and cold) of the farm. Finally, a 60-kW refrigeration system driven by waste heat of the exhaust gases of a boiler was set up at the Institute of Combustion and Power Plant Technology of the University of Stuttgart (Germany) [10].

3 – **Thermodynamic model of the absorption/resorption cycle**

A thermodynamic model of the cycle was developed to analyse the operation flexibility provided in terms of working pressure, temperature in the generator and temperature glides in the desorber and resorber. Moreover, the influence of the pressure ratio on the COP and the cooling capacity as well as the influence of the effectiveness of the solution heat exchanger on the cycle thermodynamic performance were also studied. The model is based on the mass and energy balances on each component of the cycle. Typical key assumptions on absorption cycles were made: negligible heat losses/gains, steady-state conditions, saturation conditions of the solution streams at the exit of the sorption components... A detailed description of the model can be found in reference [3].

According to the method described by Ayou et al. [11], nine independent variables should be chosen for modelling the cycle. The selected independent variables were the following: the temperatures of the solution leaving the generator (T_G), desorber (T_D), absorber (T_A) and resorber (T_R), the effectiveness of the solution heat exchangers of the absorption and resorption circuits (Eff_{HEX1} and Eff_{HEX2}, respectively), the high and low working pressures (p_{high} and p_{low}) of the cycle and the volume flow rate of the stream pumped in the resorption circuit (q_{vp2}). Table 1 lists the values of all the input variables selected for a case study. These input values were taken from the typical operating conditions of the absorption/resorption refrigeration cycle [3].

Table 1: input values of the independent variables selected in the base case.

T_G [^{o}C]	T_D [^{o}C]	T_A=T_R[^{o}C]	Eff_{HEX1}= Eff_{HEX2}	p_{high}[bar]	p_{low}[bar]	q_{vp2} [l/min]
80	-5	25	0.85	5	1.3	9

4 – **Results and discussion**

As mentioned before, the additional degree of freedom provided by the resorption systems leads into a wide operation flexibility. As an example, the base case of Table 1 was represented on a PTX diagram to show how the working pressure, the temperature glide in the desorber and the temperature in the generator can be modified by means of increasing or decreasing the ammonia concentration in the solution circuits. Figure 2a shows that the p_{high} can be increased from 5bar to 10bar (at the same working temperatures in each component) when the ammonia mass fraction at the outlet of the resorber increases to 1.0. Figure 2b shows that the temperature glide in the desorber can be increased from the 4°C to 22.6°C when the ammonia mass fraction at the outlet of the resorber approaches 1.0 and the temperature at the outlet of the resorber is reduced but working at the same pressure level. Finally, Figure 2c shows that the maximum working temperature in the generator for the same pressure level is 151°C. This value is obtained when the ammonia mass fraction at the outlet of the generator approaches 0.

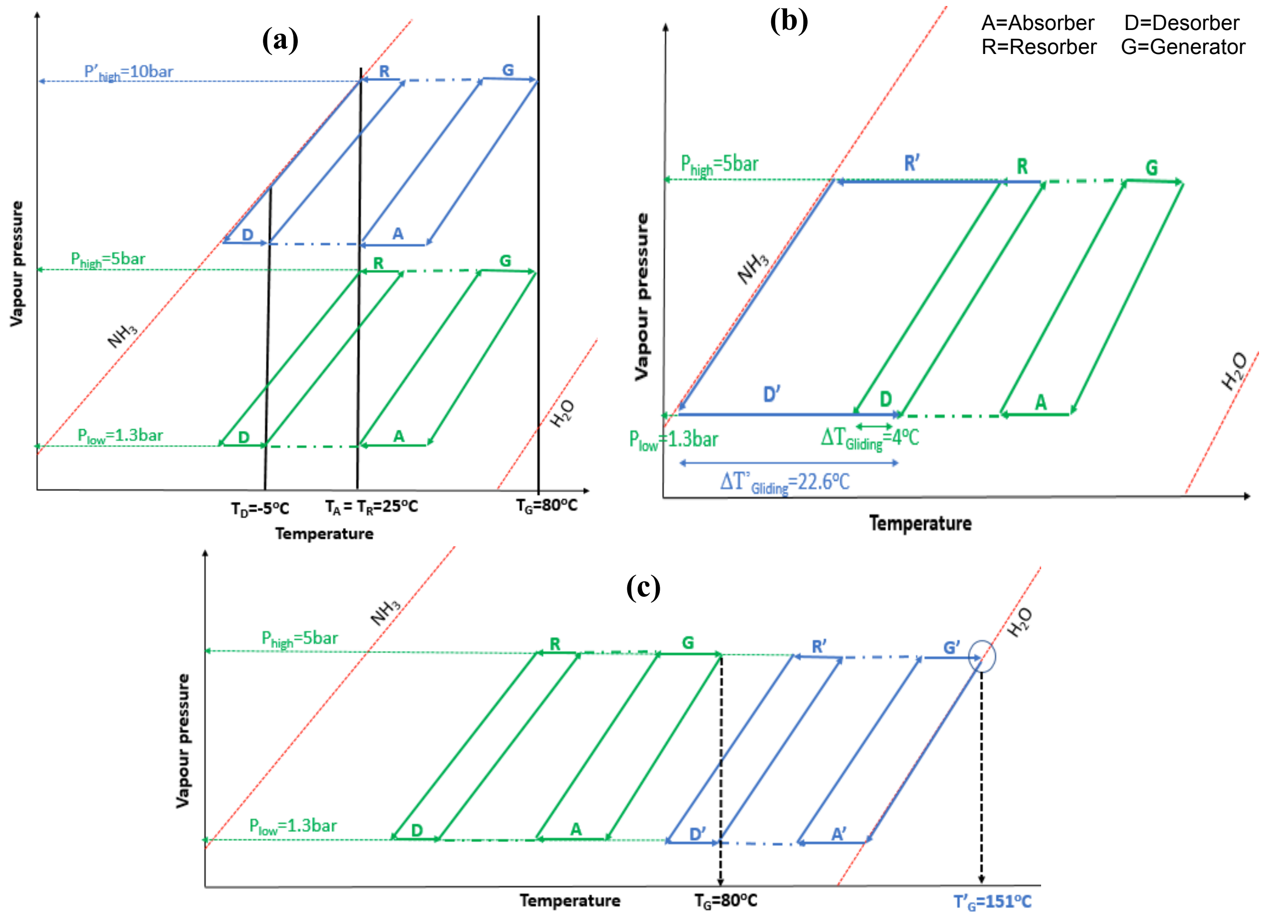

Figure 2: Absorption-resorption cycle on the PTX diagram of the ammonia/water mixture. Operation flexibility in terms of (a) working pressures; (b) temperature glide in the desorber; (c) temperature in the generator.

The influence of the pressure-ratio (β) on the COP is shown in Figure 3a. It can be observed that all the curves show a maximum value. The higher the value of p_{high}, the higher the maximum value of COP is. This effect is in good agreement with Baehr [2] because the advantage of having lower working pressure must be paid for by a reduction in the COP. Regarding the p_{low}, it would be interesting to avoid working in the upper end of the operating pressure range (lowest β) because the COP drops rapidly in that zone. Figure 3b shows the influence of the pressure-ratio on the cooling capacity. The higher p_{high} and the higher β, the higher the cooling capacity is. This conclusion is in good agreement with the previous one because the lowest β leads to a cooling capacity and a COP close to zero. Comparing Figure 3a and 3b can be concluded that is not possible to reach a maximum COP and a maximum cooling capacity at the same time just varying the pressures. It would be necessary to find a compromise between the cooling capacity and COP depending on the process requirements.

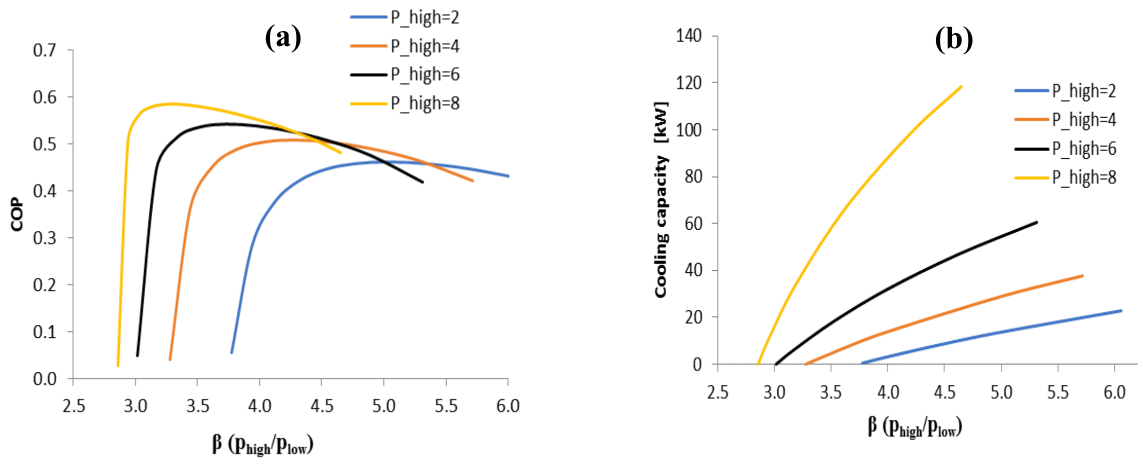

Figure 3: (a) Pressure ratio influence on the COP. (b) Pressure ratio influence on the cooling capacity.

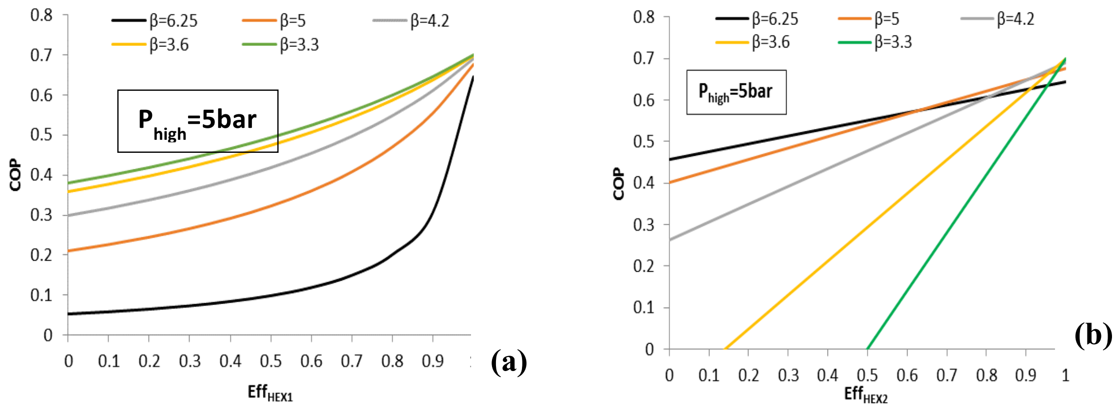

Figure 4: (a) Effect of the effectiveness of the heat exchanger 1 on the COP (p_{high}=5bar). (b) Effect of the effectiveness of the heat exchanger 2 on the COP (p_{high}=5bar).

Figure 4 shows the influence of the effectiveness of the solution heat exchangers on the COP at several pressure-ratio values (β). In a conventional absorption refrigeration cycle, there is only one solution heat exchanger placed in the absorption circuit but in the absorption-resorption refrigeration cycle there are two solution heat exchangers; one placed in the absorption circuit and the other one in the resorption circuit (Figure 1). Both heat exchangers are very important elements for the study of the performance of the cycle. In the results showed in Figure 4, p_{high} was set at 5bar and p_{low} was varied from 0.8 to 1.6 bar. Comparing Figures 4a and 4b, the following conclusions can be made: a) the value of the effectiveness of the resorber circuit Eff_{HEX1} has a stronger effect on the performance of the cycle than the other one Eff_{HEX2} at values of the pressure-ratio higher than 4; b) Eff_{HEX2} becomes critical at lowest pressure-ratio values. The cycle cannot work below certain values of Eff_{HEX2}. This fact is due to the configuration of the resorption circuit, where the absorber is placed at the high-pressure side of the cycle and the desorber at the low-pressure side, so the strong and hot solution coming from the resorber is cooled down in the heat exchanger 2 by the cold and weak solution leaving the desorber. Therefore, the lower the Eff_{HEX2}, the higher the inlet temperature of the solution in the desorber is. If the inlet temperature of the solution in the desorber is higher than the desired outlet temperature of the solution in the desorber, the cooling production stops, so the cycle cannot work under the working temperatures previously fixed. Therefore, a proper design of the solution heat exchanger in the resorption circuit becomes crucial.

Conclusions

In this work the ammonia/water absorption/resorption cycle was presented and a review of the theoretical and experimental works carried out so far was done. According to the results obtained with the thermodynamic model it can be concluded that absorption/resorption systems provides a wide operation flexibility that make this technology particularly interesting for the use of cheaper, lighter and more compact components that could make them more competitive in the market. In terms of performance, reducing the pressure level in the resorption systems must be paid for by a reduction of the COP. Finally, a proper design of the solution heat exchanger of the resorption circuit is crucial to ensure the cycle works properly.

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