STUDY OF A DIFFUSION-ABSORPTION REFRIGERATION CYCLE USING AMMONIA-WATER-HELIUM AS WORKING FLUIDS

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Abstract. *This article presents a thermodynamic model based on the first and second laws of thermodynamics, applied to a diffusion-absorption refrigeration cycle using ammonia-water-helium as working fluids. This cycle is of simple pressure and it can be operated without electric power or mechanics, only by thermal energy. The circulation of the working fluids is accomplished through a bubble pump, whose acting depends strongly on the mass transfer in the evaporator and in the absorber. The simulation was made in the EES (Engineering Equation Solver) Software having been supplied as main entrance parameters the concentrations of the solution ammonia-water in the input to the generator and in the input to the rectifier of the system, condensation temperature and heat supplied to the steam generator. The cycle of diffusion cooling is applied in domestic refrigerators.*

Keywords: *Absorption system, diffusion, simulation*

1. Introduction

The diffusion absorption refrigeration cycle, subject of this study, was invented by Platen and Munters and patented in 1928 (*apud* Srikhirin and Aphornratana, 2002). It is operated by thermal energy, that can be powered by kerosene or liquid petroleum gas and do not require electrical and mechanical energy. As it consists of no moving parts and not presents noise and vibration during the operation, it is recommended to application in hotel rooms, offices, camping and as recreative vehicle refrigerator. The working fluids are ammonia-water: ammonia as an absorbent, water as a refrigerant. It uses hydrogen or helium as an auxiliary gas. The system is of single pressure and the circulation of the working fluids is driven by a bubble-pump and the pressure equalization throughout the cycle is provided by the auxiliary gas.

Beyond these advantages, the system exhibits good reliability, durability and minimum maintenance costs. It operates without chlorofluorcarbons.

Recently, the system has been studied by every researchers to improve the current cycle performance. Chen *at al.*(1(1996) modified the original system whit the inclusion of an heat exchanger at the generator. The working fluids are ammonia-water-hydrogen. The system with the new generator demonstrated a significant improvement in the cooling COP of as much as 50% compared to the original system.

Srikhirin and Aphornratana ((2002) studied the cycle with the working fluids ammonia-water-helium. They fabricated an experimental unity based on the Platen and Munters cycle. The results of their developed mathematical model was compared with the experimental results, and showed that the system performance is strongly dependent upon the bubble-pump characteristics and the absorber and evaporator mass transfer performance.

Zohar *et al*.(2005) developed a thermodynamic model for an ammonia-water diffusion absorption refrigerator, manufactures by Eletrolux Sweden, whose inert gas was hydrogen or helium. The performance of the cycle was investigated by computer simulation and their results showed that the best performance was obtained for a concentration range of the rich solution of 0.2-0.3 ammonia mass fraction and the recommended concentration of weak solution was 0.1. The results showed that the system operating with helium as auxiliary gas presented the coefficient of performance up to 40% higher than a system working whit hydrogen.

In this work is proposed um thermodynamic model for an ammonia-water diffusion absorption refrigeration cycle, whit helium as inert gas. A computational code was developed at the EES (Engineering Equation Solver) Software for the energetic and exergetic analysis, that are made through the first and second laws of thermodynamics and whose results will be used for the system components design.

2. Cycle description

The diffusion absorption refrigeration cycle studied is showed in the Figure 1.

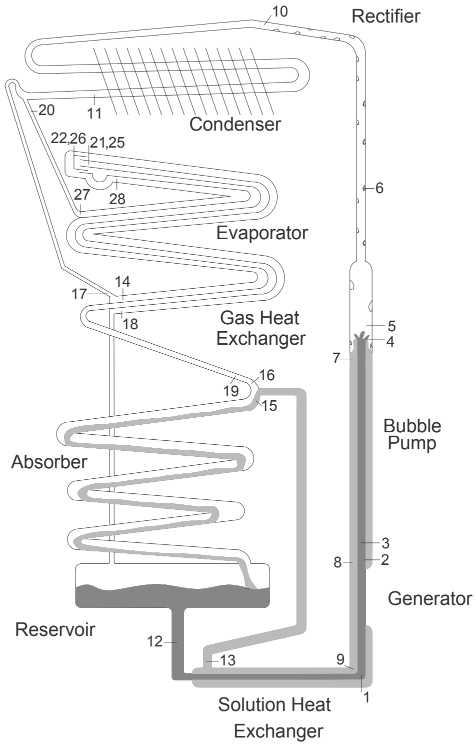

Figure 1. Schematic diagram of the diffusion absorption refrigerator cycle.

In the generator of this system, vapor of ammonia is separated from the rich solution and the vapor bubbles then rises inside the bubble pump. Weak solution and the ammonia-water vapor exit the bubble pump. In the rectifier, the ammonia vapor is purified and flows to the condenser, and the water vapor condenses to joint the weak solution, that flows to the absorver through solution heat exchanger. The condenser is cooled by air and the ammonia liquid flows to the evaporator. Uncondensed ammonia flows to the reservoir through the gas bypass. At the evaporator entrance the sub-cooled liquid ammonia meets helium arriving from the absorber after having passed through the gas heat exchanger and its partial pressure drops. In the absorber, ammonia absorption takes place and turning into rich solution, which flows into the reservoir and continues to the generator. The auxiliary gas is not absorbed and returns to the evaporator.

3. Mathematical model

To developed the mathematical model, the mass, concentration and energy conservation laws (First and Second Laws of the Thermodynamics) (Bejan *et al.*,1996), was applied in each component of the cycle, where the established control volume for each one of them includes the external reservoir. Every element of the system was analyzed separately. The subscripts of the various properties are relations to the locations indicated in Figure 1.

The properties of the working fluids was found at the EES Software.

3.1. Generator

Mass balance:

$$\dot{m}_9 + \dot{m}_2 + \dot{m}_3 = \dot{m}_1 + \dot{m}_8 \tag{1}$$

Mass concentration balance:

$$\dot{m}_9 x_9 + \dot{m}_2 x_2 + \dot{m}_3 y_3 = \dot{m}_1 x_1 + \dot{m}_8 x_8 \tag{2}$$

Energy balance:

$$\dot{m}_9 h_9 + \dot{m}_2 h_2 + \dot{m}_3 h_3 = \dot{m}_1 h_1 + \dot{m}_8 h_8 + \dot{Q}_{ger} \tag{3}$$

Entropy balance:

$$\dot{m}_9 s_9 + \dot{m}_2 s_2 + \dot{m}_3 s_3 = \dot{m}_1 s_1 + \dot{m}_8 s_8 + \frac{\dot{Q}_{ger}}{T_2} + \dot{S}_{ger} \tag{4}$$

Gouy-Stodola theorem:

$$\dot{I}_{ger} = T_0 \dot{S}_{ger} \tag{5}$$

3.2. Bubble pump

Mass balance:

$$\dot{m}_4 + \dot{m}_5 + \dot{m}_8 = \dot{m}_2 + \dot{m}_3 + \dot{m}_7 \tag{6}$$

Mass concentration balance:

$$\dot{m}_4 x_4 + \dot{m}_5 y_5 + \dot{m}_8 x_8 = \dot{m}_2 x_2 + \dot{m}_3 y_3 + \dot{m}_7 x_7 \tag{7}$$

Energy balance:

$$\dot{m}_4 h_4 + \dot{m}_5 h_5 + \dot{m}_8 h_8 = \dot{m}_2 h_2 + \dot{m}_3 h_3 + \dot{m}_7 h_7 \tag{8}$$

Entropy balance:

$$\dot{m}_4 s_4 + \dot{m}_5 s_5 + \dot{m}_8 s_8 = \dot{m}_2 s_2 + \dot{m}_3 s_3 + \dot{m}_7 s_7 + \dot{S}_{ger} \tag{9}$$

Gouy-Stodola theorem:

$$\dot{I}_{ger} = T_0 \dot{S}_{ger} \tag{10}$$

3.3. Rectifier

Mass balance:

$$\dot{m}_{10} + \dot{m}_6 = \dot{m}_5 \tag{11}$$

Mass concentration balance:

$$\dot{m}_{10} y_{10} + \dot{m}_6 x_6 = \dot{m}_5 y_5 \tag{12}$$

Energy balance:

$$\dot{m}_{10} h_{10} + \dot{m}_6 h_6 = \dot{m}_5 h_5 + \dot{Q}_{ret} \tag{13}$$

Entropy balance:

$$\dot{m}_{10}s_{10} + \dot{m}_6 s_6 = \dot{m}_5 s_5 + \frac{\dot{Q}_{ret}}{T_{10}} + \dot{S}_{ret} \tag{14}$$

Gouy-Stodola theorem:

$$\dot{I}_{ret} = T_0 \dot{S}_{ret} \tag{15}$$

3.4. Condenser

Mass balance:

$$\dot{m}_{11} = \dot{m}_{10} \tag{16}$$

Mass concentration balance:

$$\dot{m}_{11}x_{11} = \dot{m}_{10}y_{10} \tag{17}$$

Energy balance:

$$\dot{m}_{11}h_{11} = \dot{m}_{10}h_{10} + \dot{Q}_{Cond} \tag{18}$$

Entropy balance:

$$\dot{m}_{11}s_{11} = \dot{m}_{10}s_{10} + \frac{\dot{Q}_{Cond}}{T_{11}} + \dot{S}_{Cond} \tag{19}$$

Gouy-Stodola theorem:

$$\dot{I}_{Cond} = T_0 \dot{S}_{Cond} \tag{20}$$

3.5. Solution heat exchanger

Mass balance:)

$$\dot{m}_1 + \dot{m}_{13} = \dot{m}_9 + \dot{m}_{12} \tag{21}$$

Mass concentration balance:

$$\dot{m}_1 x_1 + \dot{m}_{13}x_{13} = \dot{m}_9 x_9 + \dot{m}_{12}x_{12} \tag{22}$$

Energy balance:

$$\dot{m}_1 h_1 + \dot{m}_{13}h_{13} = \dot{m}_9 h_9 + \dot{m}_{12}h_{12} \tag{23}$$

Entropy balance:

$$\dot{m}_1 s_1 + \dot{m}_{13}s_{13} = \dot{m}_9 s_9 + \dot{m}_{12}s_{12} + \dot{S}_{SHE} \tag{24}$$

Gouy-Stodola theorem:

$$\dot{I}_{SHE} = T_0 \dot{S}_{SHE} \tag{25}$$

3.6. Absorber and reservoir

Mass balance:

$$\dot{m}_{12} + \dot{m}_{16} + \dot{m}_{19} = \dot{m}_{17} + \dot{m}_{14} + \dot{m}_{15} + \dot{m}_{18} \tag{26}$$

Mass concentration balance:

$$\dot{m}_{12} x_{12} + \dot{m}_{16} y_{16} + \dot{m}_{19} y_{19} = \dot{m}_{17} y_{17} + \dot{m}_{14} y_{14} + \dot{m}_{15} x_{15} + \dot{m}_{18} y_{18} \tag{27}$$

Energy balance:

$$\dot{m}_{12} h_{12} + \dot{m}_{16} h_{16} + \dot{m}_{19} h_{19} = \dot{m}_{17} h_{17} + \dot{m}_{14} h_{14} + \dot{m}_{15} h_{15} + \dot{m}_{18} h_{18} + \dot{Q}_{Abs} \tag{28}$$

Entropy balance:

$$\dot{m}_{12} s_{12} + \dot{m}_{16} s_{16} + \dot{m}_{19} s_{19} = \dot{m}_{17} s_{17} + \dot{m}_{14} s_{14} + \dot{m}_{15} s_{15} + \dot{m}_{18} s_{18} + \frac{\dot{Q}_{Abs}}{T_{12}} + \dot{S}_{Abs} \tag{29}$$

Gouy-Stodola theorem:

$$\dot{I}_{Abs} = T_0 \dot{S}_{Abs} \tag{30}$$

3.7. Expansion chamber

Mass balance:

$$\dot{m}_{22} + \dot{m}_{26} = \dot{m}_{20} + \dot{m}_{21} + \dot{m}_{25} \tag{31}$$

Mass concentration balance:

$$\dot{m}_{22} y_{22} + \dot{m}_{26} y_{26} = \dot{m}_{20} y_{20} + \dot{m}_{21} x_{21} + \dot{m}_{25} y_{25} \tag{32}$$

Energy balance:

$$\dot{m}_{22} h_{22} + \dot{m}_{26} h_{26} = \dot{m}_{20} h_{20} + \dot{m}_{21} h_{21} + \dot{m}_{25} h_{25} \tag{33}$$

Entropy balance:

$$\dot{m}_{22} s_{22} + \dot{m}_{26} s_{26} = \dot{m}_{20} s_{20} + \dot{m}_{21} s_{21} + \dot{m}_{25} s_{25} + \dot{S}_{EC} \tag{34}$$

Gouy-Stodola theorem:

$$\dot{I}_{EC} = T_0 \dot{S}_{EC} \tag{35}$$

3.8. Evaporator, ammonia sub-cooling and gas heat exchanger

Mass balance:

$$\dot{m}_{14} + \dot{m}_{18} = \dot{m}_{22} + \dot{m}_{26} \tag{36}$$

Mass concentration balance:

$$\dot{m}_{14} x_{14} + \dot{m}_{18} y_{18} = \dot{m}_{22} y_{22} + \dot{m}_{26} x_{26} \tag{37}$$

Energy balance:

$$\dot{m}_{14} h_{14} + \dot{m}_{18} \cdot C_P \left(T_{18} - T_{26}\right) = \dot{m}_{20}\left(h_{28} - h_{27}\right) + \dot{m}_{21} h_{21} + \dot{m}_{26} \cdot C_P \left(T_{25} - T_{19}\right) + \dot{Q}_{Evap} \tag{38}$$

Entropy balance:

$$\dot{m}_{14} s_{14} + \dot{m}_{18} \cdot C_P \cdot \left(ln\left(\frac{T_{18}}{T_{26}}\right) - R\, ln\left(\frac{P_{18}}{P_{26}}\right)\right) = \dot{m}_{20}\left(s_{28} - s_{27}\right) + \dot{m}_{21} s_{21} + \dot{m}_{26} \cdot C_P \left(ln\left(\frac{T_{25}}{T_{19}}\right) - R\, ln\left(\frac{P_{25}}{P_{19}}\right)\right) + \dot{Q}_{Evap} \tag{39}$$

Gouy-Stodola theorem:

$$\dot{I}_{Evap} = T_0 \dot{S}_{Evap} \tag{40}$$

3.9. Coefficient of performance

The COP is defined as the ratio between the heat removed by the evaporator to that supplied at the generator.

$$COP = \frac{\dot{Q}_{Evap}}{\dot{Q}_{Ger}} \tag{41}$$

Table 1 shows the entrance parameters for the silmulation.

Table 1. Entrance parameters for the simulation.

Available heat at the generator	3.0 kW
Generator temperature	200 °C
Bubble-pump temperature	195 °C
Condenser temperature	58 °C
Evaporator temperature	-5 °C
Absorber temperature	58 °C
Rich solution concentration	0.3
Weak solution concentration	0.1
Total pressure of the system	25 bar
Partial pressure of the ammonia at the evaporator	3 bar
Partial pressure of the helium at the evaporator	22 bar
Refrigerant concentration	0.9996

4. Results and discussion

The results obtained from computer simulation for the diffusion absorption refrigeration cycle are showed non the Figures 2, 3 and 4. They were based on the thermodynamics model having as initial parameters those indicated in Table 1. The irreversibilities of the components are provided in Table 2.

In Figure 2 the COP variation is presented versus generator temperature in the range of 195 to 210 °C, calculated for the range of weak solution concentration of 0.06 to 0.12. In Fig. 3 the COP variation is presented versus generator temperature, from 195 to 210 °C, calculated for the range of rich solution concentration of 0.2 to 0.35. In Fig. 4 the COP variation is presented versus generator temperature, from 195 to 210 °C, calculated for the range of evaporator temperature of 0.2 to 0.35.

The Table 3 showed the values of COP for the system studied by the researchers cited in the literature presented.

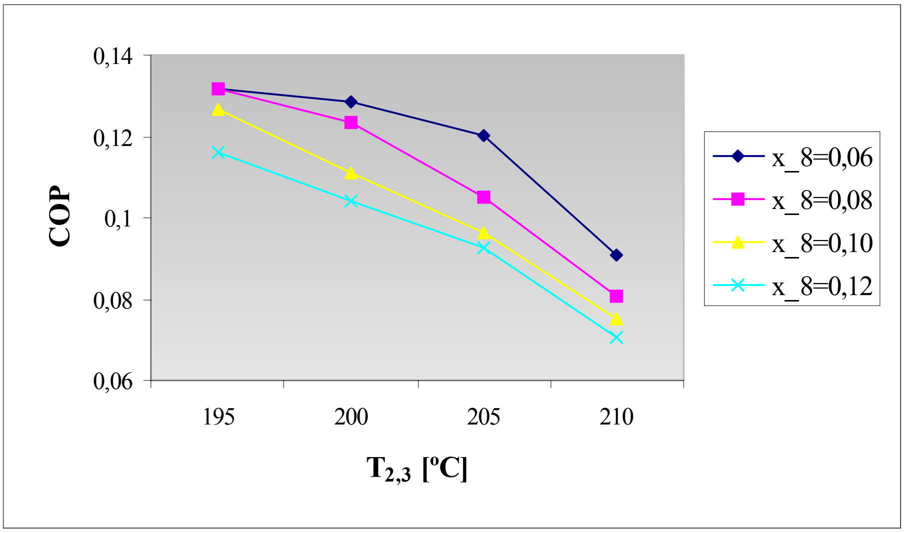

Figure 2. COP variation versus generator temperature, for weak solution concentration of 0.06 to 0.12.

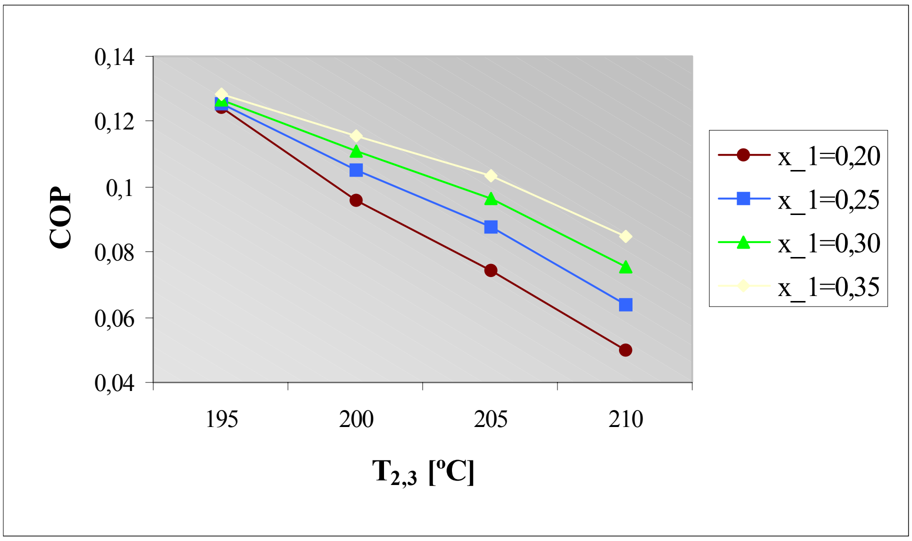

Figure 3. COP variation versus generator temperature for rich solution concentration of 0.2 to 0.35.

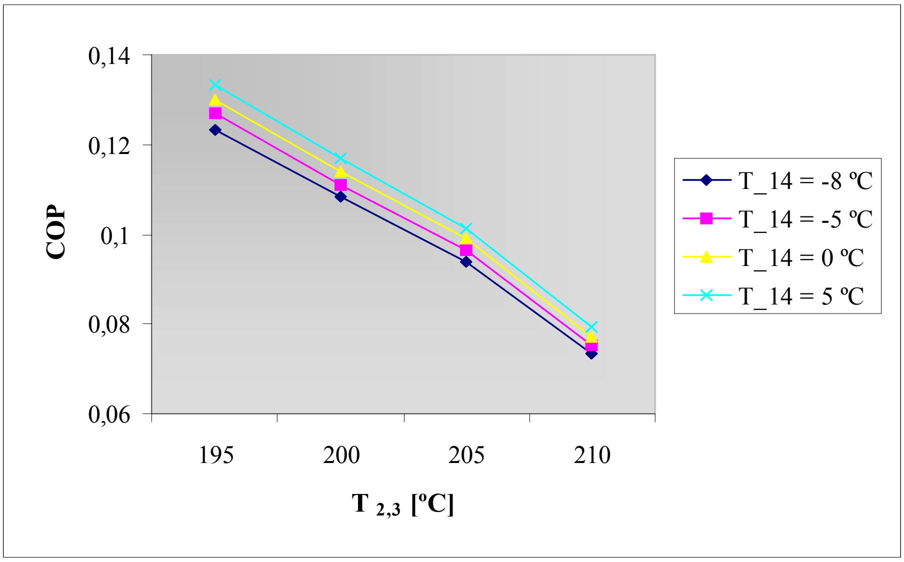

Figure 4. COP variation versus generator temperature for output evaporator temperature of-8 ^{o}C to 5 ^{o}C.

Table 2. Irreversibilities of the components of the system.

$T_{2,3}$ [ºC]	I_{Ger} [J]	I_{Evap} [J]	I_{Cond} [J]	I_{Abs} [J]	I_{SHE} [J]
195	84.46	194.0	2.97	106.8	99.77
200	92.82	170.0	2.60	111.0	166.30
205	97.93	147.6	2.26	127.6	244.60
210	90.24	115.2	1.76	157.6	335.50

Table 3. COP comparison between our result and published data.

	Present Study	Chen *et al.*	Srikhirin and Aphornratana	Zohar *et al.*
COP	0.09649	0.1-0.2	0.09-0.15	0.15

Analyzing the figures, it can be noticed that in all of them the COP decrease with the increase of the generator temperature.

In Figure 2 shows that while the weak solution concentration increase the coefficient of performance decrease and the higher COP is observed for the weak solution concentration equal to 0.06.

As in Figure 2, it is observed in Fig. 3 that, while the rich solution concentration increase the coefficient of performance decrease and the higher coefficient of performance was obtained for rich solution concentration of 0.20.

The Figure 4 shows the same behavior of the COP variation observed in Figs. 2 and 3. The COP decrease with the increase of the generator temperature, for the range of the output evaporator temperature of-8 ^{o}C to 5 ^{o}C. It is observed that the higher COP versus generator temperature was for the output evaporator temperature of -8 ^{o}C.

In Table 2 it can notice that the irreversibilities in the components generator, absorber and solution heat exchanger increase when the generator temperature increase, while the irreversibilities in the condenser and evaporator decrease. It can also be noticed that the most sensitive component to the generator temperature variation is the solution heat exchanger, with high losses temperatures above of 200 ºC. The evaporator has significant losses in temperatures below of 205 ºC.

5. Conclusion

The comparison of the COP, for validation of the simulation under particular operating conditions showed that the prediction of our model are according to that published dates.

The results of the energetic and exergetic analysis, made through the first and second laws of thermodynamics, will be used for the system components design. It was observed that, the improvement of the system should begin of the optimization of the solution heat exchanger and evaporator.

This study means a development of own technology for this kind of system that can assist to the needs of economy of energy and for application in hotel rooms, offices, camping and as recreative vehicle refrigerator.

6. Acknowledgements

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7. References

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