ANALYSIS OF ABSORPTION REFRIGERATION SYSTEM WITH AMMONIA-WATER

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Abstract. *The refrigeration has wide application in industry, commerce and residences. In an absorption refrigeration system was carried out an analysis of energy and exergy in an plant. The system has refrigeration capacity of 23.5 kW for production of ice using the ammonia-water mixture. The exergy analysis allows to indentify where the system must be optimized. A model was constructed to obtain the operating parameters such as heat transfer rate, coefficient of performance of the system, overall heat transfer coefficient, effectiveness of heat transfer, irreversibilities of the components. The evaporator works in a cyclical manner during 9 minutes of ammonia vapor flows into the tube to form ice and during 1 minute, steam of water flows to defrost the ice. The experimental data were used and compared the results. The model permited indentifeid which equipaments has higher irrevesibility or with wost performance.*

Keywords*: refrigeration, absorption, ammonia-water, exergy*

1. INTRODUCTION

The refrigeration system has high importance in Brazil due to owner extension tropical territory and theirs applications in industry and commerce. The appropriate utilization of electrical energy requires the development of new more efficient equipment to reduce energy demand. Environmental factors also require the development of refrigerants that are lower degradation to the ozone layer (ODP - ozone depletion potential) and has lower Global warming potential *(*GWP).

An alternative are the absorption refrigeration system. These systems do not have the compressor that consumes much electrical energy. However operate with a refrigerant solution pump, the absorber and a heat source of low cost and can use waste heat as exhaust gases from engines or any type of fuel and even solar source.

Absorption refrigeration systems are one of the oldest cooling methods. The pairs most commonly used in these systems are water-ammonia mixtures and water-lithium bromide. In the absorption refrigeration systems are used two fluids (pairs), one of them as refrigerant and the other as absorbent. The most common are the ammonia (NH_3) - water (H_2O) (ammonia operate as the refrigerant and water as the absorbent), and the water (H_2O) - lithium bromide (LiBr) (water as the refrigerant and lithium bromide as the absorbent).

An absorption system was initially designed to operate with gases from internal combustion boat. Operational problem happened that change the boat's system to at ground. The system was donated to UNICAMP for study. Several works have studied this system and propose improvements as Silva (1994), Milanés (1997). One of the improvements of these systems consist at exergy analysis based on the second law of thermodynamics.

The exergy analysis permits to identifier where is happening the greatest loss of available energy. Kotas (1985) describes exergy balance in plants. Szargut (1988) and Tsatsaronis (1993) described important methodologies of the exergetic analysis.

In this paper were evaluated the exergy destruction in each system's equipment with ammonia water.

The subject of study is a equipment builted by the MADEF S.A company with several heat exchanger and mass flow recirculation. The experimental unit use the pair ammonia-water pair as refrigerant and has nominal refrigeration capacity of 23.5 kW and evaporator temperature is -10 ° C. The heat source uses process steam (0.2 MPa), approximately at 130 ° C with a heat generation rate of 46.5 kW. The evaporator type flooded produces flake ice with a nominal capacity of 20 kg of ice per cycle (10 min). The cycle time is 10 minutes and the defrosting is realized with hot gas (condenser) during 1 minute. The ice thickness is 5-6 mm.

The unit description is as follows: The steam flows at generator between points 22 and 23, heating the mixture strong (ammonia and water solution) that leave the rectifier. This strong mixture receives heat, breaking the equilibrium condition and separate saturated ammonia vapor entering at the rectification column of a weak solution of liquid ammonia at point 18. At rectifier happened a heat transfer and mass that increases the concentration of ammonia vapor upward and reduces the concentration of ammonia wake solution downward. The steam leave at the top column rectifier almost pure and after it's cooled at condenser evaporative leaving as saturated liquid or subcooled. At subcooler, the liquid ammonia rejects heat to the ammonia vapor coming from the evaporator. The liquid ammonia is expanded in expansion valve leaving with quality before entering at the evaporator. In it the ammonia evaporates inside the tubes for 9 minutes to produce ice that is growing outside of the tube. The ammonia vapor is superheated in subcooled before enter to the absorber. This vapor mixes with the weak solution of ammonia, point 9. The weak solution coming from the generator at point 18, is expanded and cooled in 2 equipaments: at preheater of strong solution and at cooler of wake solution, leaving at point 21 before enters at the absorber. A liquid strong solution in ammonia leaves the absorber and enters at the set of filters. The strong solution have owner pressure rises until the pressure in the generator at pump before that enters at the rectifier at point 13. A flow of solution at column is recirculated at point 15 and heated in the preheater of the strong solution entering the column at point 16. The rectifier separates the saturated liquid at point 17 and the saturated steam at point 2, starting the cycle again. Observe a schematic of system in the figure.

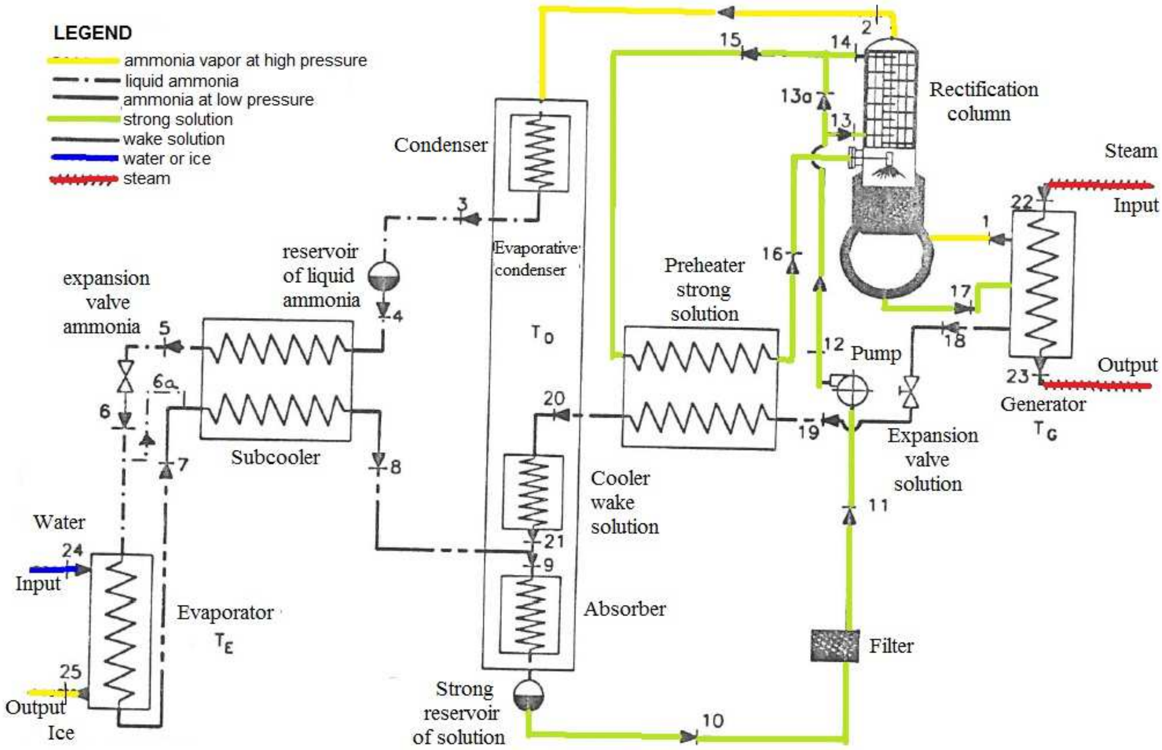

Figure 1. Absorption System with pair ammonia-water builted by the Madef S.A company

The areas of each equipments are shown in the table below.

Table 1. Area thermal each equipment

Equipament	Thermal total area[m^2]
Generator	10.6 m
Rectifier	2.4
Condenser	10
Evaporator	6
Absorber	3
Preheater strong Solution	3.12
Subcooler	2.60
Cooler wake solution	2.50

This study used experimental data from the thesis of Milanés (1997). During the test, data of temperature and pressure at various points through a system of data acquisition were collected. There were also measured the mass flow through an orifice plate and ammonia concentration. The strong concentration were measured by evaporation of ammonia in a recipient and wake concentration were measured by the temperature and density data. Through the temperature and density values the concentration of ammonia is determinate. The data were collected after approximately 2 hours from start the system in steady-state. Data are represented in the table below

Table 2. Experimental data for the System Absorption with par water-Ammonia from Milanés (1997)

Point	Temp [ºC]	Pressure [kPa]	conc [%]	fx mass [kg/h]	Point	Temp [ºC]	Pressure [kPa]	conc [%]	fx mass [kg/h]
1	111.01	1407	92.12		14	50.02	1407	38	727.82
2	40.05	1407	99.97	73.86	15	50.02	1407	38	727.82
3	28	1297	99.97	73.86	16	92.03	1407	38	727.82
4	28	1297	99.97	73.86	17	-	1407	38	727.82
5	13	1297	99.97	73.86	18	111.01	1407	31	653.95
6	-9.0	301	99.97	73.86	19	105	1407	31	653.95
7	-8.5	301	99.97	73.86	20	55	1407	31	653.95
8	20	271	99.97	73.86	21	41.5	1407	31	653.95
9	-	271	38	727.82	22	127.7	252		96.06
10	39.5	271	38	727.82	23	127.7	252		96.06
11	39.5	271	38	727.82	24	22.5	101		172.8
12	39.5	1407	38	727.82	25	0.0	101		172.8
13	39.5	1407	38	727.82					

With the experimental datas were developed mass balance, conservation of chemical species, energy and exergy within each device.

The characteristic of system are: The temperature of the condenser and evaporator are 28 °C and -9 ºC, respectively. The pump is isoentropic. The temperature of the mixture leaves the absorber is 39.5 °C. The vapor ammonia leave the rectifier with concentration 99.97. The strong and wake solution concentration are 38% and 31% respectively.

The exergy analysis has already become an essential parameter for the equipments' and thermal systems'optimization to reducing the detected irreversibilities (Bejan *et al.*, 1996).

The Irreversibility rate for control volumes for steady-state was defined for the equation below:

$$\dot{I}_{cv} = \left(\sum \dot{m}_{in} . e_{in} - \sum \dot{m}_{out} . e_{out} \right) + \sum \left(1 - \frac{T_o}{T_j} \right) . \dot{Q}_{cv} - \dot{W}_{cv} \quad (1)$$

According to (Van Wylen at al., 2003) the rate of exergy destruction is equal rate of exergy transfer at the inlet and exit of the control region (E) accompanying mass flow plus rate of exergy associated with rate of heat transfer on the boundary at temperature T_j plus rate of exergy transfered by work.

The specific flow exergy (e) can be represented in a convenient form as:

$$e = (h - h_0) - T_o . (s - s_o) + \frac{v^2}{2} + g.z \quad (2)$$

Where h and s represent the specific enthalpy and entropy, respectively. The subscripts o represent the values of these properties at the dead state. The kinetic and potential energy effects are ignored.

The Coefficient of performance of the absoption cycle (COP) is defined as:

$$COP = \frac{refrigeration\_capacity}{heat\_generation + pump\_work} \quad (3)$$

The overall heat transfer coefficient is determinate by the temperature difference between the refrigerant and the cooling fluid is represented by the LMTD (log mean temperature difference) and thermal surface area showed at table 1. The following equation represents the overall heat transfer.

$$q = U.A.LMTD \quad (4)$$

The heat exchange effectiveness may be expressed as

$$\varepsilon = \frac{q}{q_{\max}} = \frac{(\dot{m}.c_p).\Delta T}{(\dot{m}.c_p)_{\min}.\Delta T_{\max}} \tag{5}$$

At thesis of Silva (1994) and Milanés (1997), the properties of the mixture were used AQUAMAR program developed by Jordan (1996). The properties of saturated liquid and vapor and owner mixture can be determined only by three properties (pressure, temperature and concentration). The program does not allow estimation process is isentropic isoentalpicos. The properties of subcooled liquid and superheated steam are approximate using data concentration and pressure. The reference is saturated liquid of ammonia at -40C.

At this paper, the properties of the mixture were estimated using the software EES (Engineering Equation Solution) through Correlations from Ibrahim and Klein (1993) apud Tutorial of ESS software.

2. RESULTS

The heat transfer between the equipment and an exergy analysis were performed. There are compared the values of this paper with data from Milanés (1997). In the evaporator, preheater and subcooler have 2 refrigerants flowing, therefore were estimated rate of heat transfer at the two refrigerants. The comparisons of rates of heat transfer are in the table.

Table 3. Comparison of heat transfer rate

Equipments	Heat Changer [kW] from author		Heat Changer [kW] from Milanés (1997)	
Pump	0		0.174	
Column	0		-	
Group generator-column	0		-5.42	
Condenser	-24.05		-24.00	
Evaporator (ammonia/Water-ice)	+24.32	-20.55	+24.16	-20.53
Generator	51.48		57.92	
Preheater strong solution (solution strong/wake)	+37.97	-40.18	+38.52	-40.22
Cooler wake solution	-10.59		-10.56	
Sub cooler (liquid/vapor ammonia)	-1.464	+1.72	-1.464	+1.677
Absorber	-34,4		-35.57	

The comparison of heat transfer equipment between the two studies were very similar. There were some differences due to lack of experimental data at some point and procedure to determine the enthalpy at each point. The heat transfer rate at pump is null due the supposition of isentropic pump. At this paper is possible to determine an isentropic process, different the thesis of Milanés (1997) that have to use as input data pressure, temperature and concentration. The heat pump rate for Milanes (1997) produces a positive value indicating that the effect of heat is entering the pump. This value is inconsistent due the temperature of the solution after the pump increases slightly by around 0.1 ^{o}C. The temperature sensor does not detect this increase; the value of enthalpy of compressed liquid at the exit of the pump is inaccurate.

There is no experimental measure at point 17, therefore the author conducted a global balance on the generator-column considering adiabatic. This balance was performed to estimate their concentration and posterior their properties. Soon the steam leaves the generator at point 23 with quality 0.11. Milanés (1997) considers, at point 23, that all steam condensed, becoming saturated liquid water, then the group generator-column is not adiabatic. The largest difference of the heat transfer in the generator was due to these different hypotheses.

The system shows in both cases that have a loss of heat in the equipments: evaporator, pre heated strong solution and subcooler. Where the greatest loss occurs in the evaporator. According to Silva (1994) that loss occurs due to lack of isolation and loss of water from a reservoir of ice generator.

The Irreversibility rates for each equipment was determinate from equation (1) and also were compared with values of Milanés (1997). For estimating of the irreversibility at this paper, were used the higher values of heat transfer of the evaporator, preheater and subcooler. Comparison of irreversibility data are in the table.

Table 4. Comparison of Irreversibility rate

Equipments	Irreversibility [kW] from author	Irreversibility [kW] from Milanés (1997)
Pump	0.0	0.14
Column	1.029	-
Group generator-column	3.004	5.15
Condenser	0.949	0.881
Evaporator	1.337	1.439
Generator	1.975	-
Preheater strong solution	1.171	1.159
Cooler wake solution	0.7644	0.7658
Sub cooler	0.4082	0.1136
Absorber	2.935	3.25
Expansion valve ammonia	0.119	0.180
Expansion valve wake solution	1.09	-

The evaluation of irreversibility shows a difference between the two works. The largest irreversibilities occur on the generator-column and the absorber. Different of the work of Milanés (1997), the largest irreverssibilities occurs on the generator-column. Milanés (1997) affirm that the results of other authors find that the generator and absorber were the equipment with higher irreversibility rate, in all cases. To understand such differences, the differences in properties enthalpy, entropy and exergy in the 25 points that paper with the thesis of Milan (1997) were indentified. There values are shown in the figure.

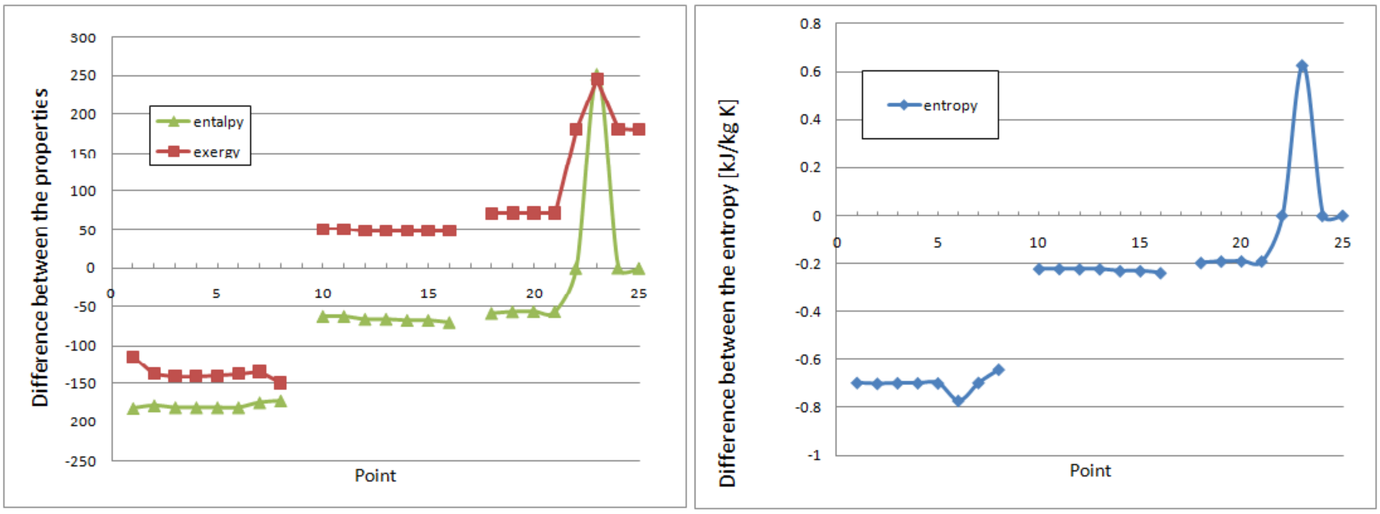

Figure 2. Difference between the properties
(a) Enthalpy/exergy (b) Entropy

Silva (1994) and Milanes (1997) determinated the properties of saturated liquid, and vapor and its mixture utilizing AQUAMAR program. Between the points 1 to 8, there is vapor or liquid and mixed with saturated concentration of nearly pure ammonia. There is a difference between the properties due to be different of the reference at the programs AQUAMAR and ESS. Milanés (1997) did not measure the experimental data at point 9 and 17.

Among the points 10 to 16 and 18 to 21 are, at most, subcooled liquid, except at point 18 and 19 which are saturated liquid and mixture of vapor and liquid, but their concentrations of ammonia are 38 to 31%. It is observed that the difference between the properties are reduced, however different of points 1 to 8.

Among the points 22 to 24 this difference is zero for enthalpy and entropy for the fluid is water. There is a difference in point 23 due the hypothesis at this paper to make global balance in generator-column where that point was estimated with quality 0.11. and Milanés (1997) considers this point as saturated liquid. At exergy, there are difference due at different reference h_o and s_o in equation (2).

The coefficients of performance (COP) were determined using the eq. (3). Their value at absorption system is 0.47, while the value of Milanés(1997) is 0.42. The difference is due the different hypothesis at Group generator-column that is adiabatic in this paper and has heat transfer for has for Milanés (1997), as explained earlier.

The overall heat transfer coefficient (U) and effectiveness (ε) were determinate at table.

Table 5. Comparison of effectiveness, log mean temperature difference and overall heat transfer

	By author			By Milanés (1997)		
Equipment	Effectiveness (ε)	LMTD [^oC]	U [$W/m^2\,^oC$]	Effectiveness (ε)	LMTD [^oC]	U [$W/m^2\,^oC$]
Evaporator	-	9.1	449	0.016	17.8	192
Preheater	0.909	8.35	1540	0.901	8.41	1260
Subcooler	0.780	13.7	48.4	0.780	11.6	46

The values of effectiveness for preheater and subcooler were equals, however for evaporator that it is a heat exchanger with phase change at both refrigerants, do not make sense to utilize the methodology of specific heat constant due phase change. This fact explains the low value of evaporator effectiveness.

The values of mean temperature difference for preheater and subcooler were almost equals again, however for evaporator, Milanés utilized all experimental data of input and output temperature. Therefore for heat exchanger with phase change utilized the constant temperature of each refrigerant (T_{25}-T_6). At this paper were used the constants temperature.

The overall heat transfer coefficients are very different at evaporator, the different procedure to estimate the LMTD explain the values. At Preheater, there is a discrepancy due Milanés (1997) utilized the low heat transfer at evaluation at preheater. At Subcooler the values are almost equal. The low difference at estimative of heat transfer of these equipments propagates a low discrepancy.

3. CONCLUSION

An energetic and exergetic analysis were performed in each equipment of absorption system for ice formation at the Hospital das Clinics, Unicamp. The dates were compared with the thesis of Milanés (1997).

The heat transfers in each component were similar except in the generator due the different hypothesis of the state of steam leaving the generator.

The exergy analysis indicates that the equipments with the higher irreversibility are the group generator- column and absorber. According Milanés (1997) the equipment with higher irreversibility is group generator-column. There were differences at values of the irreversibility of the equipment due to different procedures of estimate the properties of water-ammonia solutions.

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