THERMODYNAMIC MODELLING AND EXERGETIC ANALYSIS OF AMMONIA-WATER REFRIGERATION SYSTEM

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Abstract:
In this study, the first and the second laws of thermodynamics (exergetic analysis) are used to analyse the performance of a single stage ammonia-water absorption cooling system operating under different working conditions. In this analysis, the performance of the system is simulated under various operating temperatures: the condenser and absorber (30 and 40°C), evaporator (-10°C, 0°C and +10°C) and generator (90 to 140°C with 10°C steps). The aim of the study is to use the exergetic analysis to identify the best operating conditions in the temperature range analysed and to evaluate the losses (exergy destruction or irreversibilities) in each component of the cooling system. The paper also investigates the relationship between the exergetic efficiency, the concentration difference between the rich mixture that enters the generator and the lean mixture leaving the generator, and the coefficient of performance (COP). The importance of determining the chemical exergy of dissolution in the analysis of each equipment is demonstrated. For each system component, mass balance, energy balance and exergy balance are carried out based on a thermodynamic model. The simulation is performed using the software EES. It is noteworthy that the exergy of each stream is divided into physical and chemical exergy, which considers both the standard chemical exergy of pure species and the chemical exergy due to dissolution. For modelling the thermodynamic properties of ammonia-water mixture, the Gibbs free energy function is used and for the liquid phase, a three constant Margules model of the excess free enthalpy is employed. The results show that the exergetic efficiency is a good tool for determining the most favourable working conditions for the cycle.

Keywords:
Absorption refrigeration, Ammonia-water, Energy Analysis, Exergy Analysis.

1. Introduction

Absorption cooling systems are important equipment for maximizing thermal energy use in cogeneration or trigeneration systems. Thus, there is a need to identify parameters that enable the identification of the best operating conditions of the absorption system. Among these parameters, the coefficient of performance is one of the most used. Another important parameter for the global analysis of absorption refrigeration cycles is the recirculation factor (ratio between the mass flow of rich solution and mass flow of the refrigerant), this factor is related to the desorption temperature as well as to the wasted energy and energy recovery efficiency. The second law analysis, on the other hand, permits the determination of the irreversibility generated in each component of the cooling system and thus helps to determine the influence of each individual component on the cycle performance.

It is important to emphasize that in the past, the performance analysis of absorption refrigeration systems was based only on the first law of thermodynamics, which involves energy and mass balances. However, recent analysis of ARSs ([1], [2], [3], [4]) included the second law of thermodynamics to provide a better understanding of the thermal performance characteristics of each component of the system. This enabled the detection of the components with higher irreversibility generation. Attention can then be focused on such component to minimize its irreversible losses.

It should be noted that there are authors like ([5], [6]) that only use physical exergy for the analysis by reasoning that the global chemical exergy change is constant throughout the process. Other authors such as ([4], [7]), consider the chemical exergy, but only the standard chemical exergy because they...
consider that the share of chemical exergy because the chemical exergy due to dissolution is small. Other authors such as ([8]) take into account the chemical exergy due to dissolution, but consider the dissolution as an ideal solution (activity coefficient of the dissolved species, water, equal 1[8]). The ammonia-water dissolution is not ideal, and the difficulty is to measure the activity or the activity coefficient for determining the portion of the chemical exergy due to dissolution.

The present study applies the second law of thermodynamics to study the performance of single-stage ammonia–water ARS under different design parameters. The performance of each component, COP and exergy efficiency of the cycle are calculated from the thermodynamic properties of the working fluids at various working conditions using the Engineering Equation Solver (EES) software ([9]). This paper presents some of the methods used for analysis of absorption of ammonia-water systems, identifying the importance of determining the chemical exergy destruction due to the dissolution process in the analysis of each equipment, although it has no influence in the overall analysis of absorption cycle.

2. Thermodynamic Analysis

The ammonia-water absorption refrigeration cycle analysed is shown in Figure 1. It is similar to the cycle proposed by [3] and is composed of absorber, solution pump, strong solution heat exchanger (HEX1), generator, reduction pressure valve (VALVE1), rectifier, condenser, strong ammonia solution heat exchanger (HEX2), expansion valve (VALVE2) and evaporator.

Fig.1. Diagram of single-stage ammonia-water absorption refrigeration system

The strong solution from the absorber is pumped through the strong solution heat transfer (HEX1) to the generator. The generator separates the binary solution, where ammonia is partially separated from the solution. When the volatility of the absorbent is close to the refrigerant, such as when water and ammonia are used, the system requires an extra component called “rectifier”, which will purify the
refrigerant before entering the condenser. As the absorbent used (water) is highly volatile, part of it will evaporate together with ammonia (refrigerant). Without the rectifier, this water would condense and accumulate inside the evaporator, causing the performance to drop (14). After the rectifier, high-pressure ammonia vapour with some amount water vapour (if the rectification is not perfect) will condense in the condenser. This condensate (strong ammonia solution) will pass through the strong ammonia solution heat exchanger (HEX2), through the expansion valve (VALVE2), and evaporate at low pressure in the evaporator, used to cool the space to be refrigerated. In the absorber the ammonia vapour that left the evaporator and cooled the entering strong ammonia liquid solution (HEX2) is absorbed by the lean solution that left the generator, was cooled at solution heat exchanger (HEX1) and had its pressure reduced by Valve 1.

2.1. Component Analysis

The equations for each of the components considering: mass and energy conservation and exergy and entropy balances are presented below.

**Overall and species mass balance:** For the mixture, Equation 1 is used. For the mass balance of ammonia, Equation 2 is used. These equations were used for every equipment of the system: absorber, pump, heat exchangers (HEX1 and HEX2), generator, rectifier, condenser, evaporator and valves (VALVE1 and VALVE2).

\[
\left( \sum_{i} m_{i} \right)_{out} = \left( \sum_{i} m_{i} \right)_{in},
\]

(1)

\[
\left( \sum_{i} m_{i} x_{i} \right)_{out} = \left( \sum_{i} m_{i} x_{i} \right)_{in},
\]

(2)

Where: \( m \) = mass flow rate (kg/s); \( x \) = ammonia mass fraction (kg/kg sol); \( i \) = state point or index i.

**Energy balance:** Equation 3 was also used in every equipment. In evaporator, thermal energy rate used was the cooling capacity. The generator, rectifier and absorber were considered adiabatic and the properties of the utilities were used. The pump and the heat exchangers (HEX1 and HEX2) and valves were also considered adiabatic.

\[
\dot{Q}_{K} + \left( \sum_{i} m_{i} h_{i} \right)_{in} = \left( \sum_{i} m_{i} h_{i} \right)_{out} + \dot{W}_{K},
\]

(3)

Where: \( \dot{Q}_{K} \) = thermal energy rate (kW); \( \dot{W}_{pump} \) = pump power (kW); \( h \) = enthalpy (kJ/kg).

For modelling, the heat exchangers the effectiveness method was used (Equation 4).

\[
\varepsilon = \frac{q_{actual}}{q_{max}} = \frac{q_{actual}}{C_{min} (T_{h,i} - T_{c,i})},
\]

(4)

Where: \( C_{min} = C_{h} \) if \( C_{h} < C_{c} \); \( C_{min} = C_{c} \) if \( C_{h} > C_{c} \)

\[
q_{actual} = q_{h} = m_{h} (h_{h,e} - h_{h,i}); q_{actual} = q_{c} = m_{c} (h_{c,e} - h_{c,i})
\]

\( C_{h} \) = hot fluid heat capacity; \( C_{c} \) = cold fluid heat capacity; \( C_{min} \) is equal to \( C_{c} \) or \( C_{h} \) whichever is smaller.
**Second Law balance**: For Equation 5, only evaporator uses the cooling capacity and $T_n$ (the average temperature at which heat is exchanged) is equal $T_{evap}$. For all the other equipment, only the balance of exergy of the flows are considered.

\[
\dot{S}_{gen,K} = \left( \sum m_i \dot{s}_{i,\text{out}} \right) - \left( \sum m_i \dot{s}_{i,\text{in}} \right) - \frac{\dot{Q}_K}{T_n}.
\] (5)

Where: $\dot{S}_{gen,K}$ = rate of entropy generation in each component K (kW/K); $s$ = entropy (kJ/kg-K)

**Irreversibility**: Equation 6 is used for every equipment.

\[
\dot{I}_{K,\text{2nd}} = T_0 \dot{S}_K,
\] (6)

Where: $\dot{I}_{K,\text{2nd}}$ = Irreversibility rate in each component K (kW); $T_0$ = reference ambient temperature (298 K).

**Exergy balance**: Equation 7 is used for every equipment.

\[
\dot{I}_K = \left( \dot{E}_x_{in} - \dot{E}_x_{out} \right) + \dot{Q}_K \left( 1 - \frac{T_K}{T_0} \right) - \dot{E}_x - W_K.
\] (7)

Where: $\dot{I}_{K,\text{ex}}$ =Irreversibility rate in each component, K, calculated from the exergy balance (kW); $\dot{E}_x$ =total exergy rate (kW).

**2.2. Parameters of Analysis**

**The coefficient of performance**, Equation 8 is used in the single-stage ammonia-water absorption refrigeration system.

\[
COP = \frac{\dot{Q}_{evap}}{\dot{Q}_{ger} + \dot{W}_{pump}},
\] (8)

**The circulation rate** ($f$), Equation 9, can be defined as the ratio of mass flow rate of the solution through the pump to the mass flow rate of the refrigerant. It must be noted that “$f$” represents the required pumping energy.

\[
f = \frac{\dot{m}_i}{\dot{m}_o} \quad \text{or} \quad f = \frac{(x_o - x_d)}{(x_i - x_d)},
\] (9)

**The exergy efficiency**, Equation 10 is used in the single-stage ammonia-water absorption refrigeration system.
\[
\eta_\text{ex} = \frac{\dot{Q}_{\text{evap}} \left( \frac{T_0}{T_{\text{evap}}} - 1 \right)}{\dot{Q}_{\text{gev}} \left( 1 - \frac{T_0}{T_{\text{gev}}} \right) + W_{\text{pump}}}, \quad (10)
\]

2.3. Thermodynamic properties

The calculations were carried out using the software EES ([9]) with the ammonia-water library, and the routines used the correlation described by [10]. The total exergy becomes the summation of physical and chemical exergy, as presented in Equation 11 ([8], [11]).

\[
ex = ex^{\text{ph}} + ex^{\text{ch}}, \quad (11)
\]

Equation 12 defines the physical exergy of a fluid stream.

\[
ex^{\text{ph}} = (h - h_0) - T(s - s_0), \quad (12)
\]

Where: \( h_0 \) and \( s_0 \) enthalpy and entropy, respectively, in reference state (\( T = 25^\circ \text{C}; P = 101,325 \text{ kPa} \)).

The chemical exergy of the mixture is defined in Equation 13. Equation 14 is the standard chemical exergy and Equation 15 is mixture chemical exergy. Equation 16 was used to calculate the chemical exergy due to dissolution process in actual conditions (\( T, P \) and \( x \)). Equation 17 was used to calculate the chemical exergy due to dissolution process in reference conditions (\( T_0, P_0 \) and \( x \)).

\[
ex^{\text{ch}} = ex^{\text{ch,0}} + ex^{\text{ch,mist}}, \quad (13)
\]

\[
ex^{\text{ch,0}} = \left( y_{\text{NH3}} e_{\text{ch,NH3}}^{\phi} + (1 - y_{\text{NH3}}) e_{\text{ch,H2O}}^{\phi} \right)/MW_{\text{mix}}, \quad (14)
\]

\[
ex^{\text{ch,mist}} = ex^{\text{ch,mist,T,P,x}} - ex^{\text{ch,mist,T_0,P_0,x}}, \quad (15)
\]

\[
ex^{\text{ch,mist,T,P,x}} = \frac{RT_0}{MW_{\text{mix}}} \left[ y_{\text{NH3}} \ln(y_{\text{NH3,T,P,x}}y_{\text{NH3}}) \right.
\]
\[+ \left( (1 - y_{\text{NH3}}) \ln(y_{\text{H2O,T,P,x}}y_{\text{H2O}}) \right], \quad (16)
\]

\[
ex^{\text{ch,mist,T_0,P_0,x}} = \frac{RT_0}{MW_{\text{mix}}} \left[ y_{\text{NH3}} \ln(y_{\text{NH3,T_0,P_0,x}}y_{\text{NH3}}) \right.
\]
\[+ \left( (1 - y_{\text{NH3}}) \ln(y_{\text{H2O,T_0,P_0,x}}y_{\text{H2O}}) \right], \quad (17)
\]

Where:

\( y_{\text{NH3}} \) = molar fraction of ammonia; \( e_{\text{ch,NH3}}^{\phi} \) = ammonia standard chemical exergy (337900 [kJ/kmol], [8]); \( MW_{\text{mix}} \) = molar mass mixture [kg/kmol]

\( e_{\text{ch,H2O}}^{\phi} \) = water standard chemical exergy (900 [kJ/kmol], [8]);

\( y_{\text{NH3,T,P,x}} \) and \( y_{\text{H2O,T,P,x}} \) ammonia and water activity coefficients in temperature \( T \), pressure \( P \) and ammonia mass fraction \( x \), respectively; \( y_{\text{NH3,T_0,P_0,x}} \) and \( y_{\text{H2O,T_0,P_0,x}} \) ammonia and water activity coefficients in reference temperature \( T_0 \), reference pressure \( P_0 \) and ammonia mass fraction \( x \), respectively.
As presented by [12], the ammonia activity coefficient is given by Equation 18 and water activity coefficient by Equation 19.

\[
\ln \gamma_{NH3} = (\alpha_1 + 3\alpha_2 + 5\alpha_3)(1 - y_{NH3})^2 - 4(\alpha_2 + 4\alpha_3)(1 - y_{NH3})^3 + 12\alpha_3(1 - y_{NH3})^4 \tag{18}
\]

\[
\ln \gamma_{H2O} = (\alpha_1 + 3\alpha_2 + 5\alpha_3)y_{NH3}^2 + 4(\alpha_2 + 4\alpha_3)y_{NH3}^3 + 12\alpha_3y_{NH3}^4 \tag{19}
\]

All parameters are function of the temperature and pressure, as expressed in equations 20.

\[
\alpha_1 = a_0 + a_1P + a_2P^2 + \frac{a_3 + a_4P}{T} + \frac{a_5 + a_6P^2}{T}
\]

\[
\alpha_2 = b_0 + b_1P + b_2P^2 + \frac{b_3 + b_4P}{T} + \frac{b_5 + b_6P^2}{T}
\]

\[
\alpha_3 = c_0 + c_1P + c_2P^2 + \frac{c_3 + c_4P}{T}
\]

In Equation 20 the temperature (T) is expressed in Kelvin and the pressure (P) in MPA. The coefficients of these equations are presented in “Table 1”.

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### 3. Numerical example

A typical example, discussed by [3] and [14], is considered in this study. The hypotheses used in the simulation model are presented:

1- The analysis is done considering steady state conditions;
2- There is thermodynamic equilibrium at all points;
3- Rich solution mass flow in point 1 is equal to 1 kg/s; ammonia vapour concentration leaving rectifier is 0,9996 (point 9);
4- Refrigerant leaving the condenser is saturated liquid at condenser pressure;
5- Refrigerant leaving the evaporator is has an ammonia vapour concentration of 0,998 ([14]) in the same pressure of entrance of evaporator;
6- Solutions leaving the absorber and the generator are assumed to be saturated in equilibrium conditions at their respective temperatures and pressures;
7- Pressure drop due to friction is negligible in heat exchangers and the piping system;
8- Direct heat transfer from the components of the system to the surroundings is negligible;
9- The isentropic efficiency of the pump between the absorber and solution heat exchanger is 50% and the effectiveness of the heat exchangers is 0.8;
10- Cooling water inlet is equal to 20°C and it has a 5°C increase at the exit; the steam at the inlet of the generator is saturated and at the exit it is saturated liquid;

11- Kinetic and potential energy variations through the equipments are neglected;

12- The temperature of the lean solution leaving the generator (point 4) is the same temperature of the generator.

The results presented in "Table 2" were obtained by considering generator temperature 110°C, absorber and condenser temperature 40°C and evaporator temperature 0°C. “Table 2” presents the general results of the whole system for the pressure, temperature mass flow rate, enthalpy, entropy, mass fraction, quality, physical exergy, standard chemical exergy, chemical exergy destruction due to the mixing process and total exergy. In this simulation COP was 0.5306, exergy efficiency 0.2112 and circulation rate 8.059.

Table 2. Result obtained from thermodynamic simulation.

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<th>Point</th>
<th>P (kPa)</th>
<th>T (°C)</th>
<th>m (kg/s)</th>
<th>h (kJ/kg)</th>
<th>s (kJ/kgK)</th>
<th>x (kg/kg)</th>
<th>Qu (kJ)</th>
<th>Ex_{ph} (kJ/s)</th>
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<td>0.25</td>
</tr>
<tr>
<td>16</td>
<td>101</td>
<td>25</td>
<td>6,582</td>
<td>104.8</td>
<td>0.367</td>
<td>-----</td>
<td>-----</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>17</td>
<td>101</td>
<td>30</td>
<td>6,582</td>
<td>125.8</td>
<td>0.436</td>
<td>-----</td>
<td>-----</td>
<td>1.14</td>
<td>0.00</td>
<td>0.00</td>
<td>1.14</td>
</tr>
</tbody>
</table>

**COP** 0.5306  **Absorver Thermal energy rate (kW)** -247.40

**Exergy Efficiency (\( \eta_{\text{ex}} \))** 0.2112  **Pump Power (kW)** -2.84

**Circulation Rate (f)** 8.0586  **Generator Thermal energy rate (kW)** 268.43

**Total Irreversibility (kW)** 45.770  **Rectifier Thermal energy rate (kW)** -30.14

**Condenser Thermal energy rate (kW)** -137.67

**Evaporator Thermal energy rate (kW)** 143.94
In “Table 2” it is possible to check the order of magnitude of exergy portions of the currents in absolute terms. It is noted that the value of the physical exergy is less than the total chemical exergy (chemical standard exergy plus the chemical exergy due to dissolution). The chemical exergy due to dissolution is negative because the dissolution process decreases the energy availability. It is possible to check that the contribution of the chemical exergy due to dissolution is small total chemical exergy.

To check the influence of the use of chemical exergy due to dissolution in the analysis “Table 3” was elaborated, to present the irreversibilities of each component of the cycle calculates using five different methods:

Method 1: Irreversibility obtained from the entropy balance ($I_{2nd}$);

Method 2: Irreversibility obtained from the exergy balance, only consider physical exergy ($I_{Ex1}$);

Method 3: Irreversibility obtained from the exergy balance, considering physical exergy and chemical standard exergy ($I_{Ex2}$);

Method 4: Irreversibility obtained from the exergy balance, considering physical exergy, chemical standard exergy and chemical exergy due to dissolution as an ideal solution ($I_{Ex3}$);

Method 5: Irreversibility obtained from the exergy balance, considering physical exergy, chemical standard exergy and chemical exergy due to dissolution as a real solution real ($I_{Ex4}$)

The results presented in "Table 3" were obtained using the same temperatures used to build “Table 2” that is boiler temperature 110°C, absorber and condenser temperature 40°C and evaporator temperature 0°C.

Table 3. Result obtained from thermodynamic simulation: influence of the use of chemical mixture exergy in the analysis.

<table>
<thead>
<tr>
<th>EQUIP</th>
<th>$I_{2nd}$ (kW)</th>
<th>%</th>
<th>$I_{Ex1}$ (kW)</th>
<th>%</th>
<th>$I_{Ex2}$ (kW)</th>
<th>%</th>
<th>$I_{Ex3}$ (kW)</th>
<th>%</th>
<th>$I_{Ex4}$ (kW)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump</td>
<td>1,3505</td>
<td>2,9505</td>
<td>1,3505</td>
<td>2,9505</td>
<td>1,3505</td>
<td>2,9505</td>
<td>1,3505</td>
<td>2,9505</td>
<td>1,3505</td>
<td>2,9505</td>
</tr>
<tr>
<td>HEX1</td>
<td>9,6461</td>
<td>21,075</td>
<td>9,6461</td>
<td>21,075</td>
<td>9,6461</td>
<td>21,075</td>
<td>9,6461</td>
<td>21,075</td>
<td>9,6461</td>
<td>21,075</td>
</tr>
<tr>
<td>Valve 1</td>
<td>1,1018</td>
<td>2,4072</td>
<td>1,1018</td>
<td>2,4072</td>
<td>1,1018</td>
<td>2,4072</td>
<td>1,1018</td>
<td>2,4072</td>
<td>1,1018</td>
<td>2,4072</td>
</tr>
<tr>
<td>Generator</td>
<td>4,1249</td>
<td>9,0119</td>
<td>4,1249</td>
<td>9,0119</td>
<td>4,1249</td>
<td>9,0119</td>
<td>3,9817</td>
<td>8,6991</td>
<td>3,5198</td>
<td>7,6899</td>
</tr>
<tr>
<td>Rectifier</td>
<td>4,0577</td>
<td>8,8651</td>
<td>4,3130</td>
<td>9,4299</td>
<td>4,3130</td>
<td>9,4299</td>
<td>4,2970</td>
<td>9,3880</td>
<td>4,2988</td>
<td>9,3920</td>
</tr>
<tr>
<td>Condenser</td>
<td>5,7891</td>
<td>12,648</td>
<td>5,7891</td>
<td>12,648</td>
<td>5,7891</td>
<td>12,648</td>
<td>5,7886</td>
<td>12,647</td>
<td>5,7885</td>
<td>12,647</td>
</tr>
<tr>
<td>HEX2</td>
<td>0,1139</td>
<td>0,2489</td>
<td>0,1139</td>
<td>0,2489</td>
<td>0,1139</td>
<td>0,2489</td>
<td>0,1139</td>
<td>0,2489</td>
<td>0,1139</td>
<td>0,2489</td>
</tr>
<tr>
<td>Valve 2</td>
<td>1,0605</td>
<td>2,3169</td>
<td>1,0605</td>
<td>2,3169</td>
<td>1,0605</td>
<td>2,3169</td>
<td>1,0605</td>
<td>2,3169</td>
<td>1,0605</td>
<td>2,3169</td>
</tr>
<tr>
<td>Evaporator</td>
<td>2,1126</td>
<td>4,6155</td>
<td>2,1126</td>
<td>4,6155</td>
<td>2,1126</td>
<td>4,6155</td>
<td>2,1126</td>
<td>4,6155</td>
<td>2,1126</td>
<td>4,6155</td>
</tr>
<tr>
<td>Total Irreversibility</td>
<td>45,771</td>
<td>45,771</td>
<td>45,771</td>
<td>45,771</td>
<td>45,771</td>
<td>45,771</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>COP</td>
<td>0,5306</td>
<td>0,5306</td>
<td>0,5306</td>
<td>0,5306</td>
<td>0,5306</td>
<td>0,5306</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exergy Efficiency ($\eta_{ex}$)</td>
<td>0,2112</td>
<td>0,2112</td>
<td>0,2112</td>
<td>0,2112</td>
<td>0,2112</td>
<td>0,2112</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circulation Rate (f)</td>
<td>8,0586</td>
<td>8,0586</td>
<td>8,0586</td>
<td>8,0586</td>
<td>8,0586</td>
<td>8,0586</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It is possible to observe in Table 3 that the total irreversibility, COP, exergy efficiency and circulation rate of the absorption cycle, are exactly the same as calculated using any of the methods mentioned.
above. Analysing the irreversibility of each equipment, though, it can be observed that the reported amounts of irreversibility in the simulations considering method 1, method 2, method 3 and method 4 are very similar.

The results presented in Table 3 are equivalent, mainly due to the influence of the standard chemical exergy of ammonia and water, which due to its high value diminishes the influence of smaller parameters. However, it should be noticed that when using the actual chemical exergy due to dissolution the influence of the dissolution process is highlighted in the absorber, indicating that the irreversibility of the process is higher than when using other presented methods.

Observing the results outlined in method 5 in comparison with the other methods, there is a small decrease in the irreversibility presented by the generator and rectifier and increasing the irreversibility of the absorber. This increase can be attributed the dependence of the chemical exergy due to dissolution with the temperature, such that for lower temperatures there is an increased exergy of dissolution and methods 1, 2 and 3 the dissolution exergy was not considered.

4. Result and discussion

From the previous discussion, the method 5 was used for the simulations, which were carried out to identify the best operating condition of the simple absorption cycle. For these simulations the temperature of the generator varied from 57 to 140°C, considering evaporator temperatures of -10°C, 0°C and 10°C, and condenser temperature and absorber temperatures of 30°C (Figure 2) and condenser and absorber temperatures of 40°C (Figure 3).

![Fig.2. Results obtained from the simulation: T_{cond} = 30°C; T_{abs} = 30°C; T_{evap} = -10°C, 0°C, 10°C.](image)
Fig. 3. Results obtained from simulation: $T_{\text{cond}} = 40^\circ\text{C}$; $T_{\text{abs}} = 40^\circ\text{C}$; $T_{\text{evap}} = -10^\circ\text{C}$. It can be observed in the behaviour of the exergetic efficiency in Figures 2 and 3 that it is possible to identify intervals of most suitable operating condition for the system from considering the region of maximum exergetic efficiency of the cycle, which is difficult to identify for some cases, simply from first law analysis (determination of the COP). As can be observed in “Table 4” the region of maximum efficiency also identifies the best range of operation with respect circulation rate ($f$) or process width ($\Delta x = x_1-x_4$). Increasing the circulation factor enhances recirculation process, but hinders the rectification (lowering the temperature of the fluid vaporized in the generator), which is made at the expense of vaporization of the liquid ammonia produced by the generator.

Table 4. Ideal operating range obtained from exergy efficiency.

<table>
<thead>
<tr>
<th>Evaporator Temperature</th>
<th>Exergy Efficiency ($\eta_{\text{ex}}$)</th>
<th>Generator Temperature (C)</th>
<th>Circulation Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-10°C)</td>
<td>0.3232 – 0.3238</td>
<td>95 – 103</td>
<td>10.7 – 7.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0°C)</td>
<td>0.3018 – 0.3016</td>
<td>76 – 84</td>
<td>12.2 – 6.7</td>
</tr>
<tr>
<td>(10°C)</td>
<td>0.2610 – 0.2613</td>
<td>62 – 69</td>
<td>13.6 – 6.5</td>
</tr>
</tbody>
</table>

On the other hand, the width reduction process is not advantageous because it greatly increase the quantity of the solutions in circulation, resulting in an overestimation of HEX1 heat exchanger. Either this means that the solution pump needs to run faster or a bigger pump is required. If the generator temperature approaches its low temperature limit, the circulation ratio Increases Dramatically. Therefore, it is highly impractical to operate the cycle generator at a temperature too low.

Experimental studies [14] show that the solution circulation ratio (solution circulation rate per unit of refrigerant generated) is found to be 2 to 5 times greater than the theoretical value. This is due to a non-equilibrium state of the solution at the exit of the absorber. For a given temperature and pressure...
in the absorber, the solution absorbs less refrigerant than that of the theoretical value. Many researches have been conducting experimental researches in order to understand and to improve the process of absorption of the vapour refrigerant by the solution [14].

5. Conclusions

From the presented results, it is possible to demonstrate that for determination of the total irreversibility, exergetic efficiency, and COP, it is possible to use any of the five methods shown. In exergetic balance, in absolute terms, it appears that due to the high values of chemical exergy values of ammonia and water the value of the chemical exergy due to dissolution is very low. However, when performing the exergetic balance it was found that the consideration of the chemical exergy due to dissolution indicates that separation equipment (generator) and mixing equipment (absorber) have different irreversibilities from the calculated by methods that do not consider the chemical exergy due to dissolution.

The highest exergy efficiency values were obtained for evaporator temperature of -10°C, whereas the best COP was obtained with an evaporator temperature of 10°C. It can also be noted that for the condenser and absorber temperature ranges analysed, the generator maximum temperature should be lower than 130°C.

The exergy analysis proved to be a suitable tool to identify the best operating range of the recirculation factor as a function of generator operating temperature. The determination of recirculation factor is important because, increasing the circulation factor enhances recirculation process, but hinders the rectification (lowering the temperature of the fluid vaporized in the generator), which is made at the expense of vaporization of the liquid ammonia produced by the generator. A high circulation factor increases the solution flow, which causes an oversizing in the heat exchangers.

References


