THERMOECONOMIC ANALYSIS AIMED PARAMETRIC STUDY ON THE VAPOR COMPRESSION SYSTEM CASCADED WITH NH3/WATER ABSORPTION CASCADE REFRIGERATION CYCLE

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Abstract- Energy savings on cooling systems can be performed by using novel refrigeration cycles. For this aim, vapor compression-vapor absorption cascade refrigeration systems can be considered as substitute to single-stage vapor compression refrigeration systems. Renewable energy sources of geothermal and solar heat, waste heat of processes have been used by these cycles to provide cooling and they also require less electrical energy than vapor compression cycles having alternative refrigerants. In this study, a vapor compression (VC) and vapor absorption (VA) cascade systems are analyzed with the first law analysis for varied cooling capacities. While NH3/H2O is the working fluid in VA part, various refrigerants are tested as drop in alternatives for R12 and R22, respectively. The effects of alteration in cooling capacity, superheating and subcooling in VC part, temperature in the generator
and absorber, and degree of overlap in cascade condenser in VA part on the coefficient of system performance are studied. Validation of the results have been performed by the values given in the literature. Improvement in COP of VC, VA and cascade system are obtained separately. Electricity consumption and payback period are also determined considering the various parameters of the study.

**Keywords** Refrigeration, Cascade, Energy, Exergy.

**I. Introduction**

Cimsit and Ozturk [1] designed a vapor compression - absorption two stage refrigeration cycle and performed a thermodynamically analysis for the cycle. While NH$_3$/H$_2$O was preferred as refrigerant in the absorption section, NH$_3$ was used in the vapor compression section. As a result, it was obtained that the performance of vapor compression-absorption two stag refrigeration cycle increases with increasing generator and evaporator temperatures. What is more, the highest exergy loss occurs in the absorber and, followed by the generator.

Jain et al. [2] performed the first law analysis of a vapor compression and vapor absorption cascade system. As refrigerant, ammonia-water solution was used in the vapor absorption section and R407C was used in the vapor compression section. It was concluded that the COP of the vapor compression section of the cascade system could be improved and the electricity consumption could be reduced. Furthermore, it was obtained that the COP of the cascade system at high cooling capacity was dependent on the performance of condenser.

Talib and Vipin [3] carried out to examine refrigeration cycle in which a compression system at the reduced degree period and an absorption cycle at the superior degree cycle are cascaded to develop refrigeration system at superior degree. These system were examined thermodynamically and were compared crosscheck with each other using various liquid in the compression and absorption sections at the same operating conditions parts at the exactly alike operating state . This presented the best suitable middle degree at which the system show higher COP for the cascade system.

Jain et al [4] performed a comparative performance analysis of their models, a cascaded vapor compression–absorption system and an independent vapor compression refrigeration system for a design capacity, based on first and second laws. The results show that the electric power consumption in cascaded vapor compression–absorption system is reduced and COP of compression section is improved. And they analyzed The effect of various operating parameters, i.e., superheating, subcooling, cooling capacity, inlet temperature and the product of effectiveness and heat capacitance of external fluids on COP, total irreversibility and rational efficiency of the cascaded vapor compression–absorption system. Besides the performance of environment friendly refrigerants such as R410A, R407C and R134A is found to be almost at par with that of R22.

Kaynakli and Yamankaradeniz [5] investigated the effect of heat exchangers, which are used to recovery heat energy in the absorption refrigeration systems, on the coefficient of performance (COP). NH$_3$/H$_2$O solution is taken as an absorbent-refrigeration pair. As a result, the most effective heat exchanger on the system performance is solution heat exchanger and the system performance increases with increasing generator and evaporator temperatures, but decreases with increasing condenser and absorber temperatures.

Mukhopadhyay and Chowdhury [6] made a theoretical modeling of solar-assisted cascade refrigeration system in cold storage. The system consists of electricity-driven vapor compression refrigeration system and solar-driven vapor absorption refrigeration system. The vapor compression refrigeration system is connected in series with vapor absorption refrigeration system. They analyzed and found out COP of the cascade refrigeration system is up to the maximum when COP of the conventional vapour compression refrigeration system is minimal.

Sözen and Ataer [7] examined NH$_3$/H$_2$O working with heat exchangers located in the absorption cooling system, the system effects on performance. For this purpose they made 1. law and 2. law of thermodynamic analysis for 3 different situations . These three situations are two heat exchangers, only the refrigerant heat exchanger, only the mixture of the heat exchanger. System composed of condenser, evaporator, separators, pumps, expansion valves, cooling and the mixture heat exchangers. COP, ECOP and movement rate (f) calculated for different evaporator, condenser and separator, the effects of the heat exchanger system performance were examined.

Talbi and Agnew [8] examined a thermodynamic system in the absorption cooling cycle a large quantity of warmth to the habitat. The warmth is develop at degrees greatly above environment degrees, which effects in a crucial irreparable loss in the cycle.
components. They examined exergy analysis using LiBr/H$_2$O pair of fluid. Numerical consequences were arranged as a table. As a result, COP of system was calculated.

Solum and Heperkan [9] carried out the exergy analysis and the result of thermodynamic amount of geothermal origin, dual result absorption cycle working by means of the liquid pair, LiBr/H$_2$O on cycle performance. Geothermal energy system is used as the heat source. The result of system analysis showed that COP value is greater than 1. Generally, these value below 1 in the one-tier absorption cooling system. As a result exergy efficiency of the systems have been examined.

Karakas et al. [10] studied at suitability analysis system was performed for each component in the system and the consequences were arranged as a table. The LiBr/H$_2$O system was found more efficient, on the basis of both 1.law and 2.law examines, higher than O°C.

Bouaziz et al. [11] investigated single and double-stage absorption cycles using NH$_3$/H$_2$O. They presented different configurations and proposed a novel hybrid absorption refrigeration cycle. Energy and exergy analysis have been made. They concluded through this study that sources at moderate temperatures (solar, geothermal or other) can be used to power refrigeration systems absorption and the COP is acceptable and it is approximately 0.28.

Cimsit et al. [12] performed energy and exergy analysis of compression absorption cascade refrigeration cycles in order to determine the best suitable working pair. LiBr/H$_2$O and NH$_3$/H$_2$O pairs were compared by considering only R134a in the vapour compression section. The results show that, the first and second law thermodynamic analyses were carried out for different working temperatures of the system components by using only LiBr/H$_2$O in the absorption section and using various refrigerants, namely NH$_3$, R134a, R410A and CO2, in the vapor compression section.

Yakar et al. [13] performed energy and exergy analysis of absorption refrigeration system using LiBr/H$_2$O and mechanical compression refrigeration system using R134-a were performed at different evaporation temperatures. The results show that, the activity increases with increasing the evaporation temperature. However, in absorption refrigeration system as long as the evaporation temperature increases, the exergy activity decreases. In mechanical compression refrigeration system, it’s opposite way.

Kaynakli and Yaman Karadeniz [14] made a comparison between NH$_3$/H$_2$O and LiBr/H$_2$O one period absorption refrigeration cycle. Given thermodynamic quality of liquids and cycle success are examine at many different generator, condenser, evaporator and absorber degrees. In general the performance of the system using LiBr/H$_2$O liquid is better than the system using NH$_3$/H$_2$O liquid. Öcal and Phtili [15] performed first and second law analysis to single and multi-stage cooling systems. Refrigerants used in their vapor compression system model are compared. It was understood that R600a and R290 could be used as alternative refrigerant in terms of compressor outlet temperature, volumetric and second law efficiency to R717 and R22 and also R410 could be used as alternative to R22. Also necessity of multi-stage cooling system demonstrated for operating conditions based on.

Jain et al. [16] analyzed the performance of a vapor compression–absorption cascaded refrigeration system under fouled conditions. R22 and LiBr/H$_2$O were used as refrigerants in the compression and the absorption section respectively. In the final analysis, it was found that electricity consumption is less than vapor compression system for the same cooling capacity.

II. Thermodynamical energy balances of the cascade cycle and its description

The base compression-absorption cascade refrigeration cycle which illustrates five cycles in total investigated in this study is shown in the Figure 1. The cycle investigated in this study is very similar to classical cascade cycle which is a form of absorption and vapor compression cycles. The vapor compression section of the system is very similar to a basic cooling cycle. However, in the absorption section of the cycle, a generator, a heat exchanger, a pump, an expansion valve and an absorber is preferred instead of a compressor in order to provide energy efficiency. In the vapor compression section different refrigerants was used, while NH$_3$/H$_2$O was used in the absorption section of the system. In the vapor compression section R12, R22, R134a, R407c, R410a, R600a was separately employed in order to compare the performance according to different refrigerants. In P-h and T-s diagrams of the single effect compression-absorption cascade refrigeration cycle can be seen in figures 2 and 3, respectively.
Fig. 1. Schematic view of the single effect compression-absorption cascade refrigeration cycle.

In the system, the strong NH₃ solution was drawn by a pump from the absorber and then passed through a heat exchanger. Afterwards, the high-pressured solution leaves the exchanger and passes through the generator. After that, the amount of the ammonia in the solution passes through the condenser. Therefore, the low-concentrated NH₃ solution leaving the generator moves through the heat exchanger. Later on, the low-pressured solution passes through a valve. Finally, the solution goes to the absorber. At the absorption section of the system, a heat exchanger was used for energy recovering from weak solution to strong solution. After the absorption section of the system, the ammonia entered to the condenser leaves the condenser as a saturated liquid. Then, it passes through the expansion valve under the lower pressure. Finally, the refrigerant moves through the evaporator and leaves it as saturated steam.

There are some thermodynamic assumptions in order to make the thermodynamic analysis of the cycles:
1. The whole system is operated in steady-state.
2. The states of the refrigerants at the exit of the evaporator and condenser are saturated vapour and saturated liquid, respectively.
3. The weak refrigerant solution at the exit of the absorber and strong solution at the exit of the generator are saturated.
4. Pressure losses in the system components are neglected.
5. In the absorption section of the system, pump work input is negligible.
6. The isentropic efficiency of the compressor is 0.80, and its electric efficiency is 0.90.
7. The environment temperature and pressure are assumed as 298K and 101.325 kPa, respectively, for the second law analysis.
8. The changes in the kinetic and potential energies are negligible.

The mass and energy balance equations for steady-state conditions are as follows:
The heat capacity of the components in the vapor compression refrigeration section of the cascade cycle can be obtained from the given equations:

\[ W_{\text{comp}} = \dot{m}_1 (h_2 - h_1) \]  
(1)

\[ Q_{\text{cond1}} = \dot{m}_2 (h_3 - h_2) \]  
(2)

\[ Q_{\text{evap1}} = \dot{m}_3 (h_5 - h_4) \]  
(3)

Fig. 2. lnP-h diagram of the single effect compression-absorption cascade refrigeration cycle.
The heat capacity and the circulation ratio of the components in the absorption compression refrigeration section of the cascade cycle can be obtained from the following equations:

\[ \dot{Q}_{con} = \dot{m}_1 (h_{11} - h_{12}) \]  
\[ \dot{Q}_{abs} = \dot{m}_1 h_{10} + \dot{m}_4 h_{14} - \dot{m}_5 h_5 \]  
\[ \dot{Q}_{gen} = \dot{m}_1 h_{11} + \dot{m}_6 h_6 - \dot{m}_7 h_7 \]  
\[ \dot{Q}_{evap2} = \dot{m}_{12} (h_{14} - h_{13}) \]  

Furthermore, COP (the coefficient of performance) for the overall cascade cycle is defined as:

\[ COP_{cycleugen} = \frac{\dot{Q}_{evap1}}{\dot{Q}_{gen} + W_{comp}} \]  

The annual net saving is determined as follows:

\[ NS = \frac{PC_{VC}}{PC_{CS}} \]  

In those kinds of systems, the COP value is generally obtained below 1.

**III. Results and Discussion**

In regard to all calculations, it is obviously seen that the usage of R600a in vapor compression system with NH3/H2O absorption cascade refrigeration cycle yields better results than other refrigerants.

**Table 1. Thermodynamic values of the compression-absorption cascade refrigeration cycle**

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Point</th>
<th>T (K)</th>
<th>h (kJ/kg)</th>
<th>m (kg/s)</th>
<th>x (NH3 %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R134a</td>
<td>1</td>
<td>243</td>
<td>392.57</td>
<td>0.2973</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>343</td>
<td>415.45</td>
<td>0.2973</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>273</td>
<td>224.45</td>
<td>0.2973</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>243</td>
<td>224.45</td>
<td>0.2973</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>303</td>
<td>-109.7</td>
<td>0.248</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>303</td>
<td>-109.7</td>
<td>0.248</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>331</td>
<td>21.5</td>
<td>0.248</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>363</td>
<td>176.7</td>
<td>0.196</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>327</td>
<td>11.3</td>
<td>0.196</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>327</td>
<td>11.3</td>
<td>0.196</td>
<td>0.38</td>
</tr>
<tr>
<td>NH3/H2O</td>
<td>11</td>
<td>363</td>
<td>1635</td>
<td>0.052</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>303</td>
<td>322.9</td>
<td>0.052</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>273</td>
<td>322.9</td>
<td>0.052</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>273</td>
<td>1443.5</td>
<td>0.052</td>
<td>-</td>
</tr>
</tbody>
</table>

Thermodynamic properties at various points of the compression-absorption cascade refrigeration system are represented in Table 1, referring to Figure 1, as R134a is used in the vapour-compression section for the sample cycle.
Figures 4 shows the COP and Q_{evap}, respectively, as a function of evaporator pressure for various refrigerants used in the vapor-compression section. As seen in these figures, the COP and Q_{evap} increase on increasing the condenser temperature, as expectedly. This increase is more obvious in the case of using R600a in the vapor-compression section of the cascade cycle. Increasing the evaporator pressure leads to increase the heat capacity of evaporator for the vapor compression section and decrease the compressor power. With the usage of R600a in the vapor compression section of the cycle, the COP and Q_{evap} are increased up to 0.82 and 115 kW, respectively.

The changes of COP and W_{comp} with the evaporator temperature are presented in Figure 5 for various refrigerants used in vapor compression section. As shown in Figure 5, COP increases with increasing evaporator temperature of the cycle. When the evaporator temperature and pressure increase, the compression power of the vapor compression section decreases. Therefore, the temperature difference between the cascade heat exchanger and the evaporator decreases, which leads to decreasing compressor power and increasing COP. Additionally, it is seen that the refrigerant R600a has the best performance and the biggest compressor power in these refrigerants with the values of 0.63 as COP and 41.25 kW as W_{comp}. Figures 6 and 7 present the COP and Q_{gen}, respectively, as a function of generator temperature for various refrigerants used in vapor-compression section. As seen in Figure 6, the COP decreases on increasing the generator temperature of the cycle. The highest COP is obtained at the minimum generator temperature. The highest COP value is obtained as 0.58 at 349 K in the generator of the absorption section of the cycle. Moreover, R12 has the poorest performance with 0.30 as seen in Figure 6.
The preliminary comparison of two alternative refrigeration systems, i.e., VC and VC–VA cascaded refrigeration system is done for different capacities. The other refrigeration system is done for different capacities. The other operating conditions for both the systems are also same.

The initial cost of the VC system includes reciprocating chiller, air fan and chilled water pump whereas cost of CS includes cost of VC (includes reciprocating chiller, cascade condenser and chilled water pump) and VA systems (includes cost of absorption system, solar system to supply heat in generator, air fan). Operating cost counts the cost of electricity for running the compressor of both the systems. The running costs of auxiliary items, maintenance costs, replacement cost salvage cost, etc. are not considered in this preliminary study.

Using the economic analysis, it can be presented that, even though the initial installation cost for the proposed CS is higher than conventional VC chiller but the shorter payback period makes it a commercially. Moreover, we can see the other refrigerants’ payback period at Table 2.

### IV. Conclusion

Compression-absorption cascade refrigeration cycle has been analysed with using various refrigerants in vapour compression section and NH₃/H₂O fluid pair in absorption section in terms of first and second law of thermodynamics. The performance of refrigerants R12, R22, R134a, R407c, R410a and R600a have been compared at same conditions. NH₃/H₂O has been used in absorption section in order to compare the refrigerants’ effects on the performance of the system. The results obtained from the analysis are summarized as follows:

- Considering the same input temperatures for evaporator and condenser, R600a has the best efficiency. Other refrigerants will follow R410a, R22, R407c, R134a and R12, respectively. The reason that R600a has the best COP is because R600a has the biggest values of enthalpy for the mentioned temperatures. Since evaporator capacities are up to enthalpy values, COP is affected in the same way with capacities.

- According to five different generator temperatures, COP has been investigated with six different refrigerant and found out COP decrease on increasing the generator temperature of the cascade system. With this analysis, it can be clearly seen that the most efficient one is R600a in these refrigerants. Other ones will follow R410a, R22, R407c, R134a and R12 respectively in terms of...
efficiency. R600a’s COP is nearly one and a half times bigger than R12’s.

- If we evaluate the capacities of condenser1, it’s proven that R600a has the highest capacity and R12 has the lowest capacity in these six refrigerants. R600a has nearly three times bigger capacity than R12’s.

- According to calculations, R600a has the shortest and R134a has the longest payback period in these refrigerants. The other ones follow like R407c, R22, R12, R410a, respectively. R134a’s payback period is nearly six times longer than R600a’s.

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Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>COP</td>
<td>coefficient of performance</td>
</tr>
<tr>
<td>CS</td>
<td>cascade system</td>
</tr>
<tr>
<td>e</td>
<td>specific exergy [kJ kg(^{-1})]</td>
</tr>
<tr>
<td>(\dot{E})</td>
<td>exergy flow rate [kW]</td>
</tr>
<tr>
<td>ECOP</td>
<td>exergetic efficiency</td>
</tr>
<tr>
<td>f</td>
<td>circulation ratio</td>
</tr>
<tr>
<td>(\varepsilon)</td>
<td>effectiveness of the solution heat exchanger</td>
</tr>
<tr>
<td>h</td>
<td>enthalpy [kJ kg(^{-1})]</td>
</tr>
<tr>
<td>(\dot{m})</td>
<td>mass flow rate [kg s(^{-1})]</td>
</tr>
<tr>
<td>P</td>
<td>pressure [kPa]</td>
</tr>
<tr>
<td>s</td>
<td>specific entropy [kJ kg(^{-1}) K(^{-1})]</td>
</tr>
<tr>
<td>(\dot{Q})</td>
<td>heat flow rate [kW]</td>
</tr>
<tr>
<td>T</td>
<td>temperature [K]</td>
</tr>
<tr>
<td>VA</td>
<td>vapor absorption cooling system</td>
</tr>
<tr>
<td>VC</td>
<td>vapor compression cooling system</td>
</tr>
<tr>
<td>W</td>
<td>work flow rate or power of compressor [kW]</td>
</tr>
<tr>
<td>x</td>
<td>concentration</td>
</tr>
<tr>
<td>NS</td>
<td>annual net saving ratio</td>
</tr>
<tr>
<td>PC</td>
<td>power cost [$]</td>
</tr>
</tbody>
</table>

Subscripts

- abs: absorber or absorption system
- comp: compressor
- con: condenser
- cyclegen: cycle general
- evap: evaporator
- gen: generator
- HX: heat exchanger
- i: input
- o: output
- 0: ambient
- rev: refrigerant expansion valve
- sev: solution expansion valve
- she: solution heat exchanger
- VC: vapor compression
- CS: cascade system

References


