Energy and Exergy Analysis of Combined Ejector-Absorption Refrigeration System

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Abstract: In the present study, energy and exergy analysis of combined absorption refrigeration-ejector system was done. After writing and developing an application in EES software (Engineering Equation Solver), energy and exergy analysis (from the viewpoint of first and second thermodynamic laws) so as to define the outputs and results of single-effect absorption refrigeration cycle and combined absorption refrigeration cycle of ejector (ejector between condenser and generator) and the effects of change in temperature of operator and generator on the level of irreversibility, coefficient of performance (COP), exergy wastage and exergetic efficiency of intended cycles. It was observed that irreversibility of single-effect absorption refrigeration is more in absorber and generator compared with other system parts. This might be due to mixing losses of these parts. It was while pure refrigerant (i.e. water) passed through operator and condenser. Also in equal conditions (operator and condenser temperature), one can witness improvement of COP of absorption refrigeration-ejector system compared with single-effect absorption refrigeration system by 30 percent.

Keywords: Single-effect Absorption Refrigeration System, Combined Ejector-Absorption, Energy, Exergy, COP

1. Introduction

The energy crisis and environmental issues such as global warming and destruction of Ozone layer are among significant issues of contemporary world. Environmental problems by using CFC₅ refrigerants, high costs of using electric energy, legal and technical limitations of proper usage of electrical energy can be regarded as cases which add to the significance of using absorption refrigeration systems and attempt to improve them [1-2]. Ejectors are used in many engineering applications and have some advantages compared with common compressive systems. In addition to smaller liquid pumps, the cycle has no mobile parts. The cycle of ejector refrigeration can use energy sources such as solar, geothermal and waste heating energies. Ejectors can increase pressure without consuming mechanical energy and its usage with other systems is easy.

The objective of mixing different cycles is reduction of irreversibility and obtaining higher COP which leads to efficiency of refrigeration cycles. In this regard, the effects of thermodynamic parameters were examined to define efficient value and limit. In recent years, improvement of absorption refrigeration system draw the attention of researchers. In the present paper, exergy analysis of single-effect absorption refrigeration system and combined absorption-ejector system under equal conditions was done through EES application.

1- Efficiency of heat exchanger was 70 percent.
2- Cooling load of operator is 300 kilowatt.
3- Pump efficiency is 95 percent.
4- To obtain the properties of Lithium Bromide, the relations of Pa’tek et.al was used [3].

2. Problem Statement

Single-effect absorption refrigeration systems are constituted by five main parts:

1- Evaporator
2- Absorber
3- Generator
4- Condenser
5- Heat exchanger

Figure (1) shows a scheme of single-effect absorption refrigeration cycle.

Figure 1-Single Effect Absorption Refrigeration Cycle

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In the operator, refrigerant obtains the necessary energy for boiling from a fluid or a chamber with objective of cooling with refrigerant. This material is directed towards generator in absorber part and after passing through hot tubes or generator stream, refrigerant steam is separated. The output stream is distilled in condenser and returns towards operator. To reduce the necessary received energy by generator and to increase the potency of refrigerant absorption by the solution of absorber, a heat exchanger between generator and absorber is used to exchange heat between weak and strong solutions of lithium bromide-water.

Ejectors are systems which exit gases and steams from an empty space and compress them for emptying in higher pressures when the mixture of gases or streams with fluid is possible. Using ejectors for proper applications depends on the following factors:

1. Steam pressure: selection is done based on minimum line pressure.
2. Water temperature: selection is done based on maximum water temperature.
3. Entrainment pressure and temperature: selection is done based on minimum entrainment pressure (highest vacuum).

Figure (2) shows a scheme of a normal steam ejector. In figure (3), the scheme of enthalpy-entropy in ejector is provided. In point (p), the fluid is in the mode of high pressure which is called “Primary Fluid”. This fluid expands in primary nozzle (i) and it accelerates. The flow exists the nozzle in supercritical mode so as to generate very low pressure in the difference unit (i.e. Mixing Chamber). Due to high pressure of secondary fluid, the input and pressure difference with output flow of the nozzle, the secondary flow is sucked inside. The primary fluid exiting the nozzle leads to a convergent flow which doesn’t mix with secondary flow. In a cross-section of this output convergent flow, the velocity of secondary flow increases to sound speed and then drops (iii). This cross section is called “Effective Area” [5]. The difference of these two flows occurs after the suppression of secondary flow. This difference leads to slowing of primary flow and acceleration of secondary flow. In the end of mixing unit, the two flows are completely intermixed. The pressure of mixing unit is deemed as constant (iv). The value of pressure in mixing unit is a function of primary flow, secondary flow and pressure behind the ejector. Due to existence of a high-pressure region below the mixing point, a shockwave of relatively zero thickness occurs (7). This shock causes significant changes of pressure and sudden drop of spree from supersonic to subsonic level.

Figure 2: A Scheme of Ejector and Changes of Velocity and Pressure During it

Figure 3: Plot of Enthalpy-Entropy in an Ejector [6]
There are two types of design based on location of nozzle for ejector: 1- Ejector with fixed pressure difference (Constant-Pressure Mixing Ejector) 2- Ejector with Constant Mixing Area

The tests show that the first type of ejector has a better performance than the second one.

Figure.4-Scheme of Different Types of Ejectors

A: Constant Pressure Mixing Ejector

B: Constant Area Mixing Ejector

Figure.4-Scheme of Different Types of Ejectors [4]

Now, the mixture of combined absorption with ejector is used to improve the performance of single-effect absorption refrigeration system. One of the ways of improving the performance of this system is enhancing COP. In these systems, the objective is getting pressure of absorber to the pressure of operators so as to reduce the concentration of solution.

Now, the composition of mixed absorption cycle with ejector to improve the performance of single-effect absorption refrigeration is applied. One of the proper methods of enhancing efficiency of these systems is enhancing COP. In these systems, the aim is getting absorber pressure to the level of operator’s pressure so that solution concentration decreases. Different plans were provided by different researchers such as Chung Kuhlenschmidt et.al [4], Li – Ting Chan [6] to combine the absorption refrigeration cycle with ejector leading to significant improvement of COP of absorption refrigeration systems. No, the scheme of absorption refrigeration cycle with ejector provided by Eames and Aphornratana [8] is shown in figure (5) in which ejector is located between generator and condenser of single-effect absorption refrigeration

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system. The fluid is lithium bromide. The investigations showed that COP increases in a satisfactory manner.

Figure 5. Scheme of Absorption Refrigeration Cycle-Ejector Provided by Eames & Aphornratana [8]

In table (1), the advantages of absorption refrigeration system with ejector is discussed [9].

Table 1. Advantages of Absorption Refrigeration System with Ejector

<table>
<thead>
<tr>
<th>Advantage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Lack of need to system repair and maintenance</td>
<td></td>
</tr>
<tr>
<td>2. Usage in places with steam boiler</td>
<td></td>
</tr>
<tr>
<td>3. Using hot steam instead of power</td>
<td></td>
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<tr>
<td>4. Reduction of dimensions of refrigeration system</td>
<td></td>
</tr>
<tr>
<td>5. Increase of COP of refrigeration system</td>
<td></td>
</tr>
<tr>
<td>6. Decrease of crystallization phenomenon</td>
<td></td>
</tr>
<tr>
<td>7. Easier transportation compared with other refrigeration systems</td>
<td></td>
</tr>
</tbody>
</table>

Thermodynamic Analysis

Energy and exergy analysis based on first and second thermodynamic laws as shown in table (2) compares the two concepts of energy and exergy from different perspectives [10].

Table 2. Major Differences between Two Fundamental Concepts in Thermodynamics: Energy and Exergy

<table>
<thead>
<tr>
<th>Energy</th>
<th>Exergy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependent on parameter “material flow” or “energy” and independent of setting parameters.</td>
<td>Dependent on parameter “material flow” or “energy” and setting parameters.</td>
</tr>
<tr>
<td>With different values (equal with mc² in regard to Einstein equation)</td>
<td>In balance with setting (dead mode) it is equal with zero.</td>
</tr>
<tr>
<td>In all processes, we deal with the first law of thermodynamics.</td>
<td>In all reversible processes, we deal with the second law of thermodynamics.</td>
</tr>
<tr>
<td>There is survival in a process so there is no generation or destruction.</td>
<td>In reversible processes, there is survival but it is more the case in irreversible processes.</td>
</tr>
<tr>
<td>A scale of quantity</td>
<td>A scale of quality and quantity due to entropy</td>
</tr>
</tbody>
</table>

Flow exergy parameter is defined in the following manner.

\[ \psi = (h - h_0) - T_0(s - s_0) \]  \hspace{1cm} (1)

Parameters \( h \) and \( s \) are enthalpy and entropy of fluid, respectively so that \( h_0 \) and \( s_0 \) shows fluid enthalpy and entropy in setting temperature \( T_0 \) which is supposes as \( T_0 = 25°C \) in the present paper.

The equations of mass balance, energy balance and exergy balance for each part of system are to calculate COP and Exergetic output of the system [11].

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The equations of refrigerant and solution mass are:

\[ \sum m_i - \sum m_o = 0 \quad (2) \]
\[ \sum (m_i x) - \sum (m_o x) = 0 \quad (3) \]

So that \( i \) and \( o \) are input and output flow of system parts. \( M \) is the rate of passing flow from system parts and \( x \) is the concentration of cycle concentrations.

Energy balance equation:

\[ \sum (m_i h) - \sum (m_o h) + \sum (Q) + \sum (W) = 0 \quad (4) \]

Exergy balance equations:

\[ i = \sum_{in} m_i \psi - \sum_{out} m_o \psi + \sum (\dot{Q}) (1 - \frac{T_o}{T_i}) + \dot{w}_{act} \quad (5) \]

The “\( i \)” shows the system irreversibility and \( \psi \) is flow exergy parameter.

The value of system COP is defined as the proportion of transferred heat into operator to that of generator:

\[ \text{Cop} = \frac{Q_{\text{Evap}}}{Q_{\text{Gen}}} \quad (6) \]

The proportion of proper exergy output to the system input exergy is defined as system exergetic efficiency \( (E) \) which due to insignificance of action, we have:

\[ E = \frac{\Delta \psi_{\text{Evap}}}{\Delta \psi_{\text{Gen}}} \quad (7) \]

The output exergy value is:

\[ (s = (h_2 - h_o) - [(T_o + 273.15) \times (S_2 - S_o)] \psi \quad (8) \]

The irreversibility of ejector is defined from the following relationship:

\[ I_{\text{Ejector}} = (T_o + 273.15)(m_2 s_2 - m_1 s_1 - m_{13} s_{13}) \quad (9) \]

The initial hot steam of generator in high pressure \( P_{\text{gen}} \) and temperature \( T_{\text{gen}} \) and zero speed (mode.1) inserts the ejector and secondary flow is sucked from operator in \( P_{\text{gen}} \) and zero speed into the ejector.

On the other hand, the output of second law (exergetic) for the ejector is:

\[ \varepsilon_{\text{Ejector}} = 1 - \frac{I_{\text{Ejector}}}{m_i (\psi_1 - \psi_2)} \quad (10) \]

Results:

In different forms, the effects of thermodynamic parameters and comparison of two modes of single-effect absorption refrigeration cycle and mixed ejector-absorption refrigeration cycle are provided to define proper value and limit.

To analyze the results of systems, previous presuppositions are considered for doing computations. Figure (6) and (7), the effects of changes of operator temperature on irreversibility of system parts for both cycles are shown.

To increase the temperature of operator, the rate of heat transfer in different parts of refrigeration stems and output mass flow changes from operator and generator show that in single-effect refrigeration cycle, irreversibility of condenser and operator experiences small decline while irreversibility of absorber and generator increases but in mixed cycle, irreversibility of all parts decreases while it declines more in absorber and ejector.
Figure 7- Effects of Temperature Changes of Operator on Irreversibility of Mixed Ejector-Absorption Refrigeration System

Figure (8) and (9) show the effects of operator temperature on system COP in both cycles.

For implementations of 3 different temperatures, due to reduction of thermal load of generator in all cases, increase of system COP in both cycles occurred. In higher temperatures of generator, higher COP was obtained due to increase of its thermal load. Finally, in higher operator temperatures it was shown that COPs finally converge towards a distinctive value.

Figure 8- Effects of Operator Temperature on System COP of Single-effect Absorption Refrigeration System

Figure 9- Effects of Operator Temperature Changes on COP of Mixed Ejector-Absorption Refrigeration System

Figure (10) and (11) show the effects of operator temperature changes on exergy wastage of the whole system for both cycles.

It was observed that increase of operator temperature, mixture of irreversibility changes in each part and thermal load of generator leads to increase of this parameter which in single-effect refrigeration cycle, reduction of this parameter occurs only for $T_{\text{gen}} = 85^\circ\text{C}$ to 700 Celsius degree but in mixed refrigeration cycle for $T_{\text{gen}} = 180^\circ\text{C}$, decline of this parameter is up to $12^\circ\text{C}$ Celsius degree for operator. From this temperature on, increase of casualty occurs.

Figure 10- Effects of Operator Temperature Changes on Exergy Waste of the Whole System

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Figure 11 - Effects of Operator Temperature Changes on Exergy Waste of the Whole Mixed Ejector-Absorption Refrigeration System

Figure (12) and (13) show the effects of operator temperature changes on exergetic output (second law) of the system in both cycles.

In single-effect refrigeration cycles, increase of operator temperature is accompanied by decline of system exergetic output. But as expected, the trend of exergetic output for higher generator temperatures in mixed refrigeration cycle decreases significantly which is due to increase of irreversibles which results in increase of exergetic waste in the whole system and the same case applies for output of second law. As shown in figure (13), this parameter initially increases and finally decreases for lower temperatures.

Figure 12 - Effects of Operator Temperature Changes on Exergetic Output (Second Law) of Single-effect Absorption Refrigeration System

Figure 13 - Effects of Operator Temperature Changes on Exergetic Output (Second Law) of Mixed Ejector-Absorption Refrigeration System

In figure (14), the effects of operator temperature changes on entrainment ratio of mixed ejector-absorption refrigeration system are analyzed so that increase of operator temperature was followed by vivid increase of entrainment ratio which is due to increase of input mass flow from operator. On the other hand, these changes in the three previous implementations under three operator temperatures remained without variation which showed lack of influence of operator temperature changes on entrainment rate.

Figure 14 - Effects of Operator Temperature Changes on Entrainment Ratio of Mixed Ejector-Absorption Refrigeration System

In figure (15) and (16), the effects of generator temperature changes on irreversibility of system constituents in both cycles are shown.

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Increase of generator temperature is followed by increase of irreversibility of condenser, absorber and generator in both cycles. Also, irreversibility of ejector for the mixed refrigeration cycle will increase while irreversibility of operator remains changeless.

Figure 15 - Effects of Generator Temperature Changes on Irreversibility of Parts of Single-effect Absorption Refrigeration System

Figure 16 - Effects of Generator Temperature Changes on Irreversibility of Parts of Mixed Ejector-Absorption Refrigeration System

Figure 17 - Effects of Generator Temperature Changes on System COP of Single-effect Absorption Refrigeration System

Figure 18 - Effects of Generator Temperature Changes on System COP of Mixed Ejector-Absorption System

Figure (19) and (20) show the effects of generator temperature changes on system COP in both cycles.

As it can be observed, for implementations in three different generator temperatures within single-effect refrigeration cycle, all cases showed initial increase and then decrease of COP. Increase of generator temperature leads to increase of refrigerant and solution temperatures. So, increase of mean temperature of condenser and absorber is observed which in turn leads to increase of irreversibility of constituents. Therefore, positive effects of increase of generator temperature on increase of COP is neutralized by increase of temperatures of absorber and condense which leads to decline of COP. But as observed in mixed cycle, all cases showed increase of COP to a maximum degree.

Figure 19 - Effects of Generator Temperature Changes on Exergetic Waste of Single-effect Absorption Refrigeration System

Figure 20 - Effects of Generator Temperature Changes on Exergetic Waste of Mixed Ejector-Absorption System

As observed, increase of generator temperature in single-effect refrigeration cycle results in these wastes. Only for $T_{evap} = 40^\circ C$ to temperature of...
95°C, this parameter decreases while for the mixed refrigeration cycle, increase of generator temperature leads to initial reduction of these wastes which finally results in an increase. For the three operator temperatures, these parameters finally increase so that one can say that in proper limit, each operating condition of the system can be defined which has the least waste.

Increase of generator temperature due to increase of total exergetic waste, reduction of exergetic output of single-effect refrigeration system occurs but in mixed refrigeration cycle, initial decline and then increase of total exergetic waste by increase of generator temperature, one can observe increase and then decrease of exergetic output of mixed ejector-absorption refrigeration system.

Figure 19 - Effects of Generator Temperature Changes on Exergetic Waste of the Whole Single-effect Absorption Refrigeration System

Figure 20 - Effects of Generator Temperature Changes on Exergetic Waste of the Whole Mixed Ejector-Absorption Refrigeration System

Figure 21 - Effects of Generator Temperature Changes on Exergetic Output of Single-effect Absorption Refrigeration System (Second Law)

Figure 22 - Effects of Generator Temperature Changes on Exergetic Output of Mixed Ejector-Absorption Refrigeration System (Second Law)

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In figure (23), the effects of generator entrainment ratio of mixed ejector-absorption refrigeration system is shown.

Increase of generator temperature, entrainment ratio significantly reduces which is due to increase of generator pressure and then generator temperature rise. These changes in the previous three implementations under three operator temperature declines with equal slope. Increase of operator temperature is followed by increase of entrainment ratio in equal generator temperature.

The increasing trend of COP is more for higher generator pressures. Due to the figures of generator temperature changes for system COP, higher COP is attained for lower generator pressure and temperature but addition of generator temperature is accompanied by higher COP in higher generator pressures more than lower pressures.

An increase of generator temperature in both modes, higher exergetic waste is achieved for higher operator temperatures.

Exergetic output of both modes has less values for higher generator and operator temperatures which is due to increase of irreversibility which is accompanied by increase of exergetic waste and decline of second law output.

As observed, better COP results were achieved for distinctive generator temperatures while it should be mentioned that lower temperatures produce better results of exergetic output (single-effect) but for higher generator temperatures, the operator witnessed better COP results while the reverse is the case for the output of second law.

In sum, for equal conditions and similar operator and condenser temperature, one witnesses about 30 percent increase of COP in ejector absorption refrigeration system compared with single-effect absorption refrigeration.

Conclusion:

In distinctive temperatures of operator, depending on functioning condition of the whole system, one can expect minor changes of COP with increase of generator temperature which means that low generator temperature results on relatively similar COP.

Increase of operator temperature in higher temperatures of generator in a single-effect refrigeration cycle, total exergetic waste increases and it is observed that in low temperatures of operator, increase of generator temperature is better justified while in mixed refrigeration cycle, increase of operator temperature is more for lower temperatures and finally, these casualties are more for higher generator temperatures.

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