ANALYSIS OF A BUBBLE PUMP DRIVEN ABSORPTION REFRIGERATION SYSTEM (EINSTEIN-SZILARD REFRIGERATOR VARIANT)

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ABSTRACT

In the present work an attempt has been made to experimentally investigate the theoretical performance of a variant of an Einstein-Szilard Refrigerator. The refrigerator studied requires only heat input for its working and uses a bubble pump. Analysis involving conservation of mass and first law of thermodynamics were carried out to calculate COP, capacity and energy requirement of the system. The analysis proved the effective working of this variant of the absorption refrigerator with an COP of 0.17.

Key words: Absorption refrigerator, Einstein-Szilard Refrigerator variant, mass flow analysis


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1. INTRODUCTION

Current refrigeration cycles used in air conditioning, refrigeration, and heat pump systems are two-pressure cycles. The temperature difference between the condenser and the evaporator is established by a pressure difference that is produced by a compressor in a compression cycles or a solution pump in absorption cycles. These two-pressure cycles require mechanical devices with moving parts and access to electrical power. The compressor or pump adds significantly to the system costs, reduces reliability, generates noise, requires energy and limits portability.

The diffusion–absorption refrigeration (DAR) cycle invented in the 1920s by Platen and Munters is based on the ammonia/water mixture as working fluids and uses hydrogen as an auxiliary inert gas to establish a lower refrigerant partial pressure in the evaporator, while maintaining a higher refrigerant pressure in the condenser. Its efficiency is lower compared to the bi-pressure absorption cycles. It has limited commercial applications; it is used specially in the hotel room refrigerators.

In 1930, Einstein and Szilard obtained a US patent for another single pressure absorption refrigeration cycle. This cycle consists of a generator, a combined condenser/absorber, an evaporator, a pre-cooler and a solution heat exchanger. It operates with butane as a refrigerant, ammonia as a pressure equalizing inert gas, and water as absorbent.
2. CYCLE DESCRIPTION

The variation of the Einstein refrigeration cycle studied in this work can be described as follows: Liquid butane and ammonia vapour flow into the evaporator (see Fig. 1). The butane vaporizes into the ammonia and takes heat from the refrigerated space. The ammonia controls the saturation pressure of the butane. The gas-vapour mixture formed by ammonia and butane leaves the evaporator and then passes through a heat exchanger where it is preheated. Then the mixture goes into the absorber-condenser. A stream of water flows into this vessel. Ammonia vapor is absorbed in this water stream and heat is released by the process. The absorber-condenser is cooled to remove this heat and the heat released by the continuous condensation of the butane fed to the vessel. The condensed butane leaves the absorber-condenser, passes through a preheater and returns to the evaporator. The ammonia strong solution is preheated and then it goes into the generator. The ammonia strong solution is boiled in the generator to split off ammonia from water. The ammonia weak solution is preheated and then flows into the accumulator. In the accumulator water and ammonia are further separated and water is returned to the absorber condenser after losing more heat. Pure ammonia goes thru a heat exchanger where it losses heat and then goes into the evaporator. The Einstein refrigeration cycle does not need a mechanical energy input to induce motion, input which is required by traditional absorption cycles. Instead, the Einstein cycle uses a bubble pump, a device driven by thermal energy that is part of the generator.

It is important to note that, although the Einstein cycle works with ammonia, water and butane, the only substances that can form a liquid solution are ammonia and water; ammonia is almost immiscible in liquid butane, and butane and water are not miscible at all. Therefore, the liquid mixtures present in the Einstein refrigeration device can be treated as binary systems.

Figure 1 Original patent diagram
3. ANALYSIS

3.1 Assumptions

- The Pressure of the system is fixed at 4 bar.
- The system is considered to be under steady state while performing mass flow and first law analysis.
- The behavior of Ammonia-Butane mixture in the evaporator is assumed to be azeotropic in nature.
- Since the pressure of the system is 4 bar, the ammonia-butane mixture condenses at 315 K, hence the temperature of the condenser is assumed to be 315 K.
- The Temperature of the generator is assumed to be 375 K.
- The Ammonia-Butane mixture for the same assumed system pressure boils as low as 266 K, hence the temperature of the evaporator = 266 K.

3.2 Thermodynamic Properties of Working Fluids

The Patel-Teja cubic equation of state, fitted to experimental data, is used for all fluid modeling (pure substances and mixtures). For the ammonia-butane mixture, the Patel-Teja equation of state predicts vapor-liquid-liquid equilibrium and azeotropic behavior at the pressures and temperatures in the evaporator. Experimental measurements on the ammonia butane system verify this and the equation of state was fit to the experimental data.

3.3 System Components Modeling

All components in the system shown in Fig. (1) are modeled by applying conservation of mass and energy laws. All components are assumed to operate under steady state conditions with fixed inlet and exit velocities and cross sectional areas. Both the heat exchangers are assumed adiabatic.

3.3.1 Evaporator

Mass conservation must be satisfied in the evaporator for both ammonia and butane.
Substituting values from property modelling and phase diagrams in the equations (1) and (2) given above,

\[ 0.55m_3 = m_4 \]  
\[ 0.45m_3 = m_2 \]  

Using conservation of energy,

\[ Q_{\text{evaporator}} = m_3 \cdot h_3 - m_1 \cdot h_2 - m_4 \cdot h_4 \]  

### 3.3.2 Heat Exchanger 1 (Pre-Cooler)
Conservation of mass will be satisfied between the evaporator and condenser/absorber.

\[ \dot{m}_2 = \dot{m}_1 \]  
\[ \dot{m}_6 = \dot{m}_3 \]
Analysis of a Bubble Pump Driven Absorption Refrigeration System (Einstein-Szilard Refrigerator Variant)

\[ \dot{m}_5 = \dot{m}_4 \]  \hspace{1cm} (9)

Applying conservation of energy

\[ \dot{m}_3 \cdot h_3 + \dot{m}_1 \cdot h_1 + \dot{m}_4 \cdot h_5 = \dot{m}_3 \cdot h_6 + \dot{m}_1 \cdot h_2 + \dot{m}_4 \cdot h_4 \]  \hspace{1cm} (10)

Since the heat exchanger transfers heat between three streams it requires two terminal temperature differences. For the analysis, the base case is taken and the terminal temperature differences are assumed to be zero.

### 3.3.3 Condenser/Absorber

Applying conservation of mass,

\[ \dot{m}_3 = \dot{m}_6 \]  \hspace{1cm} (11)

\[ \dot{m}_9 = \dot{m}_{Bf} \]  \hspace{1cm} (12)

\[ x_{L1} \cdot \dot{m}_1 + x_{L7} \cdot \dot{m}_7 = x_{L9} \cdot \dot{m}_9 + y_{L3} \cdot \dot{m}_3 + y_{L8g} \cdot \dot{m}_{Bg} \]  \hspace{1cm} (13)

Since there are three fluids present in the condenser/absorber, the species equation should be stated for any two of them to completely specify this control volume. Applying conservation of mass separately for ammonia and water,

\[ x_{W7} \cdot \dot{m}_7 = x_{W8f} \cdot \dot{m}_{Bf} + y_{W8g} \cdot \dot{m}_{Bg} \]  \hspace{1cm} (14)

\[ x_{A7} \cdot \dot{m}_7 = x_{A8f} \cdot \dot{m}_{Bf} + y_{A8g} \cdot \dot{m}_{Bg} \]  \hspace{1cm} (15)

Substituting values from property modelling and phase diagrams in the equations (14) and (15) given above,

\[ 0.55\dot{m}_7 = 0.84\dot{m}_{Bf} + 0.02\dot{m}_{Bg} \]  \hspace{1cm} (16)

\[ 0.45\dot{m}_7 = 0.16\dot{m}_{Bf} + 0.55\dot{m}_3 + 0.98\dot{m}_{Bg} \]  \hspace{1cm} (17)

Using Conservation of energy,

\[ Q_{\text{condenser}} = \dot{m}_1 \cdot h_1 + \dot{m}_7 \cdot h_7 - \dot{m}_9 \cdot h_9 - \dot{m}_3 \cdot h_6 - \dot{m}_{Bg} \cdot h_{Bg} \]  \hspace{1cm} (18)
3.3.4 Heat Exchanger 2

Applying conservation of mass,

\[ \dot{m}_{8f} = \dot{m}_9 \]  
\[ \dot{m}_7 = \dot{m}_{7f} \]  

Applying conservation of energy,

\[ \dot{m}_7 \cdot h_{7f} + \dot{m}_9 \cdot h_{8f} = \dot{m}_7 \cdot h_7 + \dot{m}_9 \cdot h_9 \]  

Since the heat exchanger transfers heat between two streams it requires a terminal temperature difference. For the analysis, the base case is taken and the terminal temperature difference is assumed to be zero.

3.3.5 Generator

Applying conservation of mass,

\[ \dot{m}_4 = \dot{m}_5 \]  
\[ \dot{m}_{8f} = \dot{m}_9 \]  
\[ \dot{m}_8 = \dot{m}_{8f} + \dot{m}_{8g} \]
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\[
\dot{m}_1 = \dot{m}_4 + \dot{m}_8g + \dot{m}_9 \tag{24}
\]

\[
x_{a,71} \cdot \dot{m}_{71} = x_{a,9} \cdot \dot{m}_9 + \dot{m}_4 + y_{a,8g} \cdot \dot{m}_8g \tag{25}
\]

Substituting values from property modelling and phase diagrams in the equation (25) given above,

\[
0.44\dot{m}_{71} = 0.16\dot{m}_9 + \dot{m}_4 + 0.62\dot{m}_8g \tag{26}
\]

Using First Law of Thermodynamics,

\[
Q_{\text{generator}} + Q_{\text{bubble pump}} = \dot{m}_5 \cdot h_5 + \dot{m}_9 \cdot h_9 + \dot{m}_8g \cdot h_8g - \dot{m}_{71} \cdot h_{71} \tag{27}
\]

Taking the enthalpy values from the Patel-Teja property modeling, we get

\[
\begin{align*}
h_1 &= 106.8 \text{ kJ/kg}, & h_2 &= 13.74 \text{ kJ/kg}, & h_3 &= 936.6 \text{ kJ/kg}, & h_4 &= 1427 \text{ kJ/kg}, & h_5 &= 1511 \text{ kJ/kg} \\
h_6 &= 1037 \text{ kJ/kg}, & h_7 &= h_{71} = 163.6 \text{ kJ/kg}, & h_8g &= 1794 \text{ kJ/kg}, & h_9 &= 243.5 \text{ kJ/kg}
\end{align*}
\]

4. RESULTS AND DISCUSSIONS

Assuming the mass flow rate of bubble pump as 0.005 kg/s and solving using the above equations,

<table>
<thead>
<tr>
<th>Mass flow rates</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\dot{m}_1)</td>
<td>0.0019 kg/s</td>
</tr>
<tr>
<td>(\dot{m}_2)</td>
<td>0.0019 kg/s</td>
</tr>
<tr>
<td>(\dot{m}_3)</td>
<td>0.00425 kg/s</td>
</tr>
<tr>
<td>(\dot{m}_4)</td>
<td>0.0023 kg/s</td>
</tr>
<tr>
<td>(\dot{m}_5)</td>
<td>0.0023 kg/s</td>
</tr>
<tr>
<td>(\dot{m}_6)</td>
<td>0.00425 kg/s</td>
</tr>
<tr>
<td>(\dot{m}_7)</td>
<td>0.00735 kg/s</td>
</tr>
<tr>
<td>(\dot{m}_8)</td>
<td>0.005 kg/s</td>
</tr>
<tr>
<td>(\dot{m}_9)</td>
<td>0.005 kg/s</td>
</tr>
</tbody>
</table>

Substituting enthalpy values in the above thermodynamic first law equations,

\[
Q_{\text{condenser}} = -4.602 \text{ kW}
\]

\[
Q_{\text{generator}} + Q_{\text{bubble pump}} = 3.872 \text{ kW}
\]

Refrigeration Capacity = \(Q_{\text{evaporator}} = 0.672 \text{ kW}\)

\[
\text{COP} = \frac{Q_{\text{evaporator}}}{Q_{\text{generator}}} = 0.17
\]

5. CONCLUSION

A thermodynamic model of the Einstein absorption cycle is developed to simulate its operation and investigate its feasibility limits via a careful calculation of the thermodynamic properties of the ternary working fluid mixture water–ammonia–butane with the help of the Patel–Teja cubic equation of state. The thermodynamic analysis has proved the viability of the proposed system. The cycle effectively demonstrates a different approach to achieving absorption refrigeration by using a bubble pump.
At a given system pressure, there is a minimum evaporator temperature and a maximum condenser/absorber temperature. The maximum condenser/absorber temperature is the saturation temperature of the refrigerant at the system pressure.

In the above experiment, the terminal temperature difference for the heat exchangers was assumed to be zero for base case of calculation. Incorporation of suitable heat exchangers with sufficient terminal temperature differences can lead to corresponding increase in the COP.

REFERENCE


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