Performance of Hydrocarbon Based Mixed Refrigerants in Cryocoolers

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Abstract — A cryo refrigerator or a cryocooler is used to operate at cryogenic temperature, i.e., below -150 °C. Linde Hampson cryogenic refrigerator is widely used as a cryo refrigerator. Pure fluids are usually used as refrigerant. The operating pressure for pure fluids is very high. It is important to decrease the operating pressure and achieve the same amount of refrigeration. The present work deals with the same. Simulation of Linde Hampson refrigerator is carried out using hydrocarbon based refrigerant mixtures and its performance is compared with the Linde Hampson refrigerator using pure fluids and commercial refrigerants like R22 and R410a.

Keywords — COP, Linde Hampson refrigeration, refrigeration capacity, specific refrigeration effect

I. INTRODUCTION

A refrigerator is a common household appliance for storing food items. A household refrigerator has a refrigeration temperature of 3-5 °C. There are refrigerators that have refrigeration temperature below -150 °C. Scientists assume that -150 °C is the temperature from where the cryogenics begin [1]. These type of refrigerators are known as cryo-refrigerators or cryocoolers. Cryocoolers have a large number of applications. They are used for preservation of cells, tissues and cell culture. They can be used in cryosurgical devices used in gynaecology, cardiac, prostrate and dental surgeries. They can also be used for cooling of infrared, gamma-rays, and X-ray detectors used in a variety of applications.

There are different types of cryocoolers. Most commonly used are Stirling coolers, Gifford-McMahon (GM) coolers, Pulse-Tube refrigerators and Joule-Thomson cooler. Joule-Thomson cooler is widely applied as cryocooler or as the final stage of liquefaction. The Joule-Thomson (JT) cooler was invented by Carl von Linde and William Hampson so it is also called the Linde-Hampson cooler. The Linde Hampson cooler works on the basis of Linde Hampson refrigeration cycle. In this cycle, the refrigerant is compressed isothermally at ambient temperature. In practical systems, the heat of compression is rejected to a coolant in an aftercooler. The high pressure refrigerant is then cooled in a heat exchanger. Then, the refrigerant stream is expanded to the desired pressure in a throttling device known as Joule-Thomson valve. The refrigerant stream exits the valve in the mixed state. The liquid that is formed in the stream is evaporated in an evaporator. The low pressure stream is then fed to the cold side of the heat exchanger. To complete the refrigeration cycle, the stream is again fed to the compressor. The Linde-Hampson refrigeration cycle is shown in Fig. 1.

Different types of refrigerants can be used for the process. Some of them are nitrogen, argon, methane, ethane, propane. Pure fluid were used as refrigerants for cryocoolers. But recently, mixed fluids are used as refrigerants. The exergy efficiency (figure of merit) of refrigeration and liquefaction systems operating with refrigerant mixtures is many times that of systems operating with pure fluids [2]. The operating pressure is much lower when refrigerant mixtures are used, compared to pure fluids [2]. The specific refrigeration effect and the refrigeration capacity of the system is also higher for the system operating with mixtures. The use of mixed fluids as refrigerants for cryogenic refrigerators was first proposed by Podbielniak [3]. They proposed single-stage mixed refrigerant processes that can provide refrigeration at very low temperatures. Mixed refrigerant processes were also studied by Brodianskii and his colleagues for small cryocooler applications [4]. Kleemenko adopted the mixed refrigerant process for large-scale liquefaction of natural gas [5]. Lapshin studied the refrigeration capacity of regenerating plants operating on mixtures at variable temperatures [6]. Mogorychmy studied the effect of cryogenic mixed gas refrigerant operating within the temperature range of 800K-100K [7]. Boiarskii studied that refrigeration performance of the throttle cycle coolers increases while operating with mixtures [8]. Bonaiust proposed that cost can be reduced and efficiency can be increased by using mixtures for refrigeration in air separation [9]. Yagodin designed an efficient throttling cryogenic refrigerator which operates on mixtures [10].
The present work deals with the performance of Linde Hampson refrigerator operating with pure fluids like nitrogen, argon, methane, ethane and propane, refrigerant mixtures and commercially used refrigerants like R22 and R410a. Four nitrogen and hydrocarbon mixtures of various relative compositions have been considered and the specific refrigeration effect, refrigeration capacity and COP of the system using the proposed refrigerant mixtures and commercial refrigerants have been compared with the system using pure fluids. The specific refrigeration effect for the pure refrigerants is calculated.

II. THERMODYNAMICS OF THE SYSTEMS

A. T-s diagram

Fig. 2 T-s diagram for nitrogen as refrigerant

Fig. 2 shows the variation of temperature with entropy for nitrogen as the refrigerant in the Linde Hampson refrigerator [2]. The operating pressure is 200 bar for nitrogen as the refrigerant. Here, 1-2 is the isothermal compression, 2-3 is the decrease in temperature in the heat exchanger. The refrigerant is in the two phase state here. The evaporator converts the liquid portion to vapour (4-g). Then the stream is passed through the heat exchanger cold side which causes increase in the temperature of the cold low pressure stream.

Reference [2] suggests the T-s diagram for Linde Hampson refrigeration process for nitrogen hydrocarbon mixture refrigerant is as shown in Fig. 3. The operating pressure is much lower in case of the mixture (15-20 bar) in comparison to the pure nitrogen as shown in Fig. 2.

B. T-h diagram

Fig. 4 T-h diagram for nitrogen as refrigerant

Fig. 4 shows the variation of temperature with enthalpy for nitrogen as the refrigerant in the Linde Hampson process [2]. The compressor outlet pressure is 200 bar and inlet pressure is taken as 3.6 bar.

Fig. 5 T-h diagram for nitrogen hydrocarbon mixture as refrigerant

Reference [2] suggests the T-h diagram for Linde Hampson refrigeration process for nitrogen hydrocarbon mixture refrigerant is as shown in Fig. 5.

C. Specific Refrigeration effect(SRE)

From Fig. 1, specific refrigeration effect can be calculated by an energy balance around the heat exchanger, expansion valve and the evaporator.

\[ \frac{Q}{\dot{n}} = h_5 - h_2 = \Delta h_{\text{min}} \]  

(1)

Where Q is the refrigeration load at temperature T, \( \dot{n} \) is the molar flow rate of the refrigerant. \( h_5 \) and \( h_2 \) are the specific molar enthalpies of the low and high pressure fluid on the warm end of the heat exchanger. \( \Delta h_{\text{min}} \) is the minimum enthalpy difference between
the cold and hot streams at any location in the heat exchanger. It is in terms of KJ/mol.

**D. Refrigeration Capacity**

Refrigeration capacity is the effective cooling power of a refrigerator. It can be formulated as the product of the molar flow rate of the refrigerant and the specific refrigeration effect. It is in terms of KJ/sec or KW.

\[
\text{Refrigeration Capacity} = \text{SRE} \times \dot{m}
\]  

(2)

Where, SRE is the specific refrigeration effect and \(\dot{m}\) is the molar flow rate of the refrigerant.

**E. Coefficient of Performance**

Coefficient of performance (COP) is the ratio of energy output to energy input. For a refrigerator it is the ratio of the amount of refrigeration produced to the work required by the compressor.

\[
\text{COP} = \frac{\text{Refrigeration Capacity}}{\text{Compressor work}}
\]  

(3)

### III. Simulation

**A. Conditions for the simulation**

Ambient temperature = 25°C.
Ambient pressure = 1 bar.
Compressor type = polytropic compressor.
Compressor efficiency = 100%
Outlet pressure of the expansion valve = 1 bar.
Molar flow rate of refrigerant = 10 kmol/hr.
Heat exchanger temperature approach= 5K.
No pressure drop in evaporator, aftercooler and heat exchanger

**B. Refrigerants used for Simulation**

Nitrogen, argon, methane, ethane, propane, R22, R410a, mixture M1, mixture M2, mixture M3, mixture M4.

### TABLE I MIXTURE COMPOSITIONS

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Components</th>
<th>Composition</th>
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<tbody>
<tr>
<td>M1</td>
<td>Nitrogen</td>
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</tr>
<tr>
<td>M2</td>
<td>Nitrogen</td>
<td>0.3</td>
</tr>
<tr>
<td>M3</td>
<td>Nitrogen</td>
<td>0.5</td>
</tr>
<tr>
<td>M4</td>
<td>Nitrogen</td>
<td>0.5</td>
</tr>
</tbody>
</table>

### IV. RESULTS AND DISCUSSIONS

**A. Variation in SRE**

Fig. 6 shows the variation of SRE with operating pressure. The variation for mixture M1 and M2 is shown in [2]. From the plots, it is evident that the SRE increases with increase in operating pressure. For nitrogen, the maximum value of SRE is 1.29543 KJ/mol at 442 bar. For argon, the maximum value of SRE is 2.2376 KJ/mol at 617 bar. For methane, the maximum value of SRE is 3.9006 KJ/mol at 511 bar, for ethane the maximum value of SRE is 3.61 KJ/mol at 40 bar and for propane the maximum value is 1.04 KJ/mol at 9 bar. For ethane and propane, 40 bar and 9 bar are the limiting pressure, as liquid is formed at the outlet of the heat exchanger beyond this pressure which is not desirable for the process. The plots show that the operating pressure for pure refrigerants is much higher than the mixed refrigerants and the commercial refrigerants. However, for the commercial refrigerants like R22, 10 bar is the limiting pressure. From the P-T envelope of R22, it is revealed that at 25°C and 11 bar pressure, R22 exists in liquid phase and hence, after isothermal compression, liquid will be formed. Similarly for R410a, the limiting pressure is 15 bar.
B. Variation in refrigeration capacity

Fig. 7- (a) Variation of refrigeration capacity and operating pressure for pure refrigerants. (b) Variation of refrigeration capacity and operating pressure for mixed refrigerants and commercial refrigerants.

Fig. 7 shows the variation in refrigeration capacity with operating pressure for the refrigerants. From the plots it is revealed that the refrigeration capacity increases with increase in pressure. For the mixtures and the commercial refrigerants, the refrigeration capacity is much higher than the pure fluids and also the operating pressure is much lower.

C. Variation in COP

Fig. 8- (a) Variation of COP and operating pressure for pure refrigerants. (b) Variation of COP and operating pressure for mixed refrigerants and commercial refrigerants.

Fig. 8 shows the variation in COP with operating pressure for the refrigerants. From the plot, it is evident that the COP of the system using nitrogen and argon as refrigerant are almost same. The COP of the system using refrigerant mixtures and commercial refrigerant is higher than the system using pure refrigerants.

The commercial refrigerants like R22 and R410a has 10bar and 15 bar as the limiting pressure. These refrigerants can be used as the replacement of the pure refrigerants. The commercially available R22 and R410a compressors can be used in the Linde Hampson refrigerator when the pressure is lower than 10 bar and 15 bar for R22 and R410a respectively. But, R22 is a HCFC (hydrochlorofluorocarbon) and R410a is a HFC (hydrofluorocarbon). The HCFCs have ozone layer depletion potential and high global warming potential and HFCs have global warming potential. The SRE is limited to 1.048 KJ/mol at 10 bar and 1.678 KJ/mol at 15 bar for R22 and R410a respectively. To increase the refrigeration capacity, the flow rate has to be increased for these refrigerants. But, this is not the case for the refrigerant mixtures. The refrigerant mixtures can be used at higher pressure and achieve higher refrigeration capacity by virtue of increased the specific refrigeration effect which increases with increase in operating pressure. Hence, it is beneficial to use refrigerant mixtures at higher pressures.

V. CONCLUSION

The variation in specific refrigeration effect, refrigeration capacity and COP with the operating pressure is studied for different pure refrigerants, refrigerant mixtures and commercial refrigerants. The SRE, refrigeration capacity and the COP of the refrigerant mixtures and the commercial refrigerants is higher than the pure refrigerants. The operating pressure is also lower for the refrigerant mixtures.
and the commercial refrigerants. The commercially available R22 and R410a refrigerator compressor can be used in Linde Hampson refrigerator if the operating pressure is less than 10 bar and 15 bar for R22 and R410a respectively. Although the refrigeration capacity for these commercial refrigerants have to be increased by increasing the flow rate. The refrigerant mixtures can work at higher pressure and deliver the same refrigeration capacity. Hence, the refrigerant mixtures can serve as a replacement of the pure refrigerants for Linde Hampson cryo-refrigerators.

REFERENCES