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THERMAL PERFORMANCE ANALYSIS OF CASCADE REFRIGERATION SYSTEM BY NUMERICAL SIMULATION METHOD

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ABSTRACT :

In recent years, concern about global warming and ozone layer depletion has been growing. Increasing attention is being given to refrigerants used in refrigeration and air-conditioning systems as they have a significant contribution towards these environmental issues. As industries and different chemical plants are increasing day by day, it is becoming a challenge for researchers to find suitable refrigerants that will be safe for the environment and maintain the desired performance. In the case of different ultra-low temperature (-100oC to -150oC) applications (e.g., LNG, LPG liquefaction, cryogenic engineering, food, and medicine storage), it is even more challenging to satisfy environmental conditions and performance. This study aims to find suitable environment-friendly refrigerants and implement them in a triple cascade refrigeration system (TCRS) for low-temperature application (-100oC to -150oC). For this purpose, a simulation model for the system was developed and validated. Based on low global warming potential, and low ozone depletion poten- tial; eco-friendly hydrocarbon (HC) refrigerants were selected for implementation in the triple cascade refrigeration system (TCRS). In the lower temperature cir- cuit (LTC), 1-butene was used as working fluid, and in the higher temperature circuit (HTC), m-Xylene was used. For the mid-temperature circuit (MTC), trans- 2-butane, n-heptane, n-butane, cis-2-butane were used. To assess the performance of TCRS, energy analysis and exergy analysis were conducted, and analyzed. The results show that 1-butene/heptane/m-Xylene pair gives the best performance in terms of 1st law efficiency (COP) and 2nd law efficiency (exergy destruction) for low-temperature applications (lower than -100°C). The results obtained from the simulation model suggests that exergy destruction mainly occurs at the condenser, hence further studies can be carried out on the condenser to increase the overall COP. Further experimental studies can be carried out to assess the feasibility of utilizing the proposed refrigerants pair for low-temperature applications

Keywords—Cascade refrigeration system; Low-temperature application; Hydrocarbon refriger- ants.

.INTRODUCTION

Achieving temperature lower than the atmosphere is done by employing refrigera- tion system. Among traditional refrigeration systems like vapor compression system are widely used for household refrigeration systems and different storages such as food, medicine, cryogenic products etc. Ideally, Using simple single stage vapor com- pression refrigeration system lowest evaporation temperature that can be achieved is around -25°C. This temperature is a bit higher in actual system due to irreversibility. Which can be achieved using refrigerant having normal boiling point temperature around this range. Kilicarslan et al. [32] states that single stage vapor compres- sion systems are not suitable for low temperature applications due to difficulty in compression process of the refrigerant in between large pressure ratio and solidifi- cation temperature of refrigerants. Johnson et al. [27] listed two major limitations of single stage vapor compression refrigeration system . Firstly, if pressure goes below certain limit, the compression process becomes too expensive and secondly, after compression the refrigerant must have pressure below its critical pressure to ensure two-phase condensation process. In industrial processes like natural gas liq- uefaction, preservation of complex medicine and vaccine [e.g. COVID-19 vaccine preservation needs around -70°C], cryogenic process and other very low temperature applications employing single stage vapor compression refrigeration system is not a feasible option thermodynamically or economically. This problem calls for a need of different approach to achieve the desired level of cooling effect at very low tem- perature. Widely used refrigeration technologies for low temperature application can be separated in the two major category based on working fluid types used [59] which are the systems using pure working fluids and systems using mixed working fluids which is generally the combination of different organic compounds. Systems that employ single refrigerant as working fluid are either simple vapor compression system or another innovative system that uses multiple stages of vapor compression systems or combination of absorption system and vapor compression system on top of another named ‘Cascade Refrigeration System’. The system which has several refrigeration cycles above each other, each cycle ranging in different temperature and pressure level, exchanging heat through a common heat exchanger in between, generating a huge cooling effect at very low temperature is defined as the cascade refrigeration system. The first usage of cascade refrigeration system is found in 1877 which was built by Cailletet and Pictet [52] who used ethylene and SO_2/CO_2 separately to build the system. Then later on, in 1908 helium was liquefied using precooling by cascade refrigeration cycles with air and hydrogen [52]. Since then, a trend of using one refrigeration cycle above another was introduced. This is where the term 'Cascade Refrigeration System' first occurred

Literature review

In the past, ice was used for preservation purposes, which was not enough to store larger amounts, and ice does not last long, leading to inventing devices that can hold larger storage and sustain longer. That led the scientists to research and devel- opment of refrigerators. Refrigeration systems seen today had to go through many research and developments to reach this point. However, further possibilities of im- provements leading researchers to conduct studies and innovate new systems.

A refrigerator with or without a freezer is a major appliance designed for cool- ing and preserving foods. One of the essential advancements toward the invention of the refrigerator came when the refrigerated coil was invented by Ibn Sina [30] in the 11th century. But the first research that can be found about the refrigera- tion system was back in 17th century by Sir F. Bacon. Later on more researches were done during the 18th century by M. Lomonoso [32]. The Vapor Compression Refrigeration system we know now was first attempted to be built by W. Cullen

[33] in 1755. But the term 'Refrigerator' was mentioned later on in 19th century. Around 1800 American engineer, T. Moore made a box insulated with rabbit fur, filled with ice, surrounded by a sheet metal container. In 1834 the first patent of vapor compression refrigeration (VCR) was obtained by J. Perkins. The vapor ab- sorption type refrigeration we know now was first introduced by E. Carre who used water and sulphuric acid in 1850 [33]. Nine years later his brother F Carre built the first NH_3/H_2O based absorption type refrigeration system[12]. Around the same time, the first commercial refrigerator in the world was built by J. Gorrie and patent was granted in 1851. This field kept on improving from the first introduction till today and will continue to improve.

The main goal of the refrigeration system is to lower the temperature of substances below atmospheric temperature. A refrigeration system is used in different applica- tions e.g. preserving the food, medicine, blood bank etc. Also, in gas liquefaction and air conditioning systems. They might be used in different complex systems like chemical processing and refining industries, separation of chemical components of a mixture by condensation, and other processes. Different systems need different cooling requirements.

The simple vapor compression cycle is the most widely used refrigeration cycle. Due to its simplicity, it is suitable for household use. However, for larger industrial appli- cations, the main goal is to get higher efficiency and varying cooling loads according to need, so new modification is frequently done on the related cycles. The new indus- tries have cooling requirements different than typical applications. liquefaction of LNG, LPG, air, and component separation from a mixture need lower temperature than -100oC. Especially in cryogenic engineering, the temperature needed is around

-233^{o}C [25] which is not achievable by conventional refrigeration systems. To over- come this challenge, cascade refrigeration system was introduced. The first usage of cascade refrigeration system is found in 1877 which was built by Cailletet and Pictet

[52] who used ethylene and SO_2/CO_2 separately to build the system. Then later on, in 1908 helium was liquefied using pre-cooling by cascade refrigeration cycles with air and hydrogen. Since then, a trend of using one refrigeration cycle on top of another like electrical series connection was introduced. This is where the term 'Cascade Refrigeration System' first occurred. So, in a way we can define cascade refrigeration system as, the system which has several refrigeration cycles above each other, each cycles operating in different temperature and pressure level, exchanging heat through a common heat exchanger in between, generating a huge cooling effect is called a cascade refrigeration system.

METHODOLOGY

When a very low-temperature (e.g. -40^{o}C to -150^{o}C) system needs to be handled, the pressure ratio becomes very high. This pressure ratio is challenging to handle using single or double refrigeration stages. Also, sequential cooling of refrigerant is needed to achieve this kind of range of temperature. Among different alternatives found in the literature, the triple cascade refrigeration system is the most suitable. The three compression stages can handle a vast pressure ratio and reach below - 140^{o}C.

A triple cascade refrigeration system is a three-stage vapor compression system combined by two cascade heat exchangers. This specific type of refrigeration system is mostly applicable to achieve extremely low evaporation temperature (e.g. -40^{o}C to -150^{o}C). This system combines three VCR systems to achieve high COP for the low-temperature application rather than a single-stage VCR to achieve the same cooling using lower COP. This system is a complex refrigeration system in which two cascade heat exchangers play the most vital roles.

Designing a cycle from a thermodynamic perspective includes evaluating all the points of the working fluids. Two independent parameters are needed to determine all the necessary properties of each state to simulate a thermodynamic analysis. The simulation code for the TCRS was conducted in Python 3.0. Thermodynamic prop- erties of the refrigerants were taken from CoolProp 6.4. CoolProp [5] can be easily integrated to Python using a function provided in the official website of CoolProp to make it easy to determine the thermodynamic properties of each state by calling the refrigerant's name.

The parameters considered to simulate the cycle is summarised below.

Parameters	Values	Parameters	Values
Qe (kW)	10	T_{lc} (°C)	-80 to -45
ΔT (°C)	5	T_{mc} (°C)	-40 to -0
T_a (°C)	25	Superheating at HTC (°C)	5

T_k (°C)	40	Superheating at MTC (°C)	12
T_e (°C)	-100	Superheating at HTC (°C)	12

Table 3.2: Basic parameter values of simulation model

Cooling load for the refrigeration was considered 10 kW, evaporation temperature was taken -100°C and cascade temperature difference was 5K. A flow chart is shown in Fig. 3.3 to show the steps of the simulation.

RESULTS AND DISCCUSION

COP indicates the performance of a refrigeration system. It is the most important parameter to find out effectiveness of the system with respect to the input provided. However, evaluating COP of an TCRS system is dependent on multiple parameters in which T_{lc} and T_{mc} are the most important ones. In addition to that, T_{lc} and T_{mc} are also dependent on each other. For a certain range of T_{lc} optimum T_{mc} is different for each pair of refrigerants. Fig 4.1 shows optimum T_{mc} for a certain range of Tlc. Fig 4.1 represents that, for each stated pair of refrigerant optimum T_{mc} will be different and this optimum T_{mc} will give optimum COP of a TCRS. From Fig 4.1, it is clear that 1-butene/toluene/mXylene has the highest optimum Tmc temperature which eventually leads this pair to have the lowest COP among the stated pairs as the TCRS will work for a larger temperature range in the MTC. This phenomenon causes the MTC to have lower COP, leading to a lower overall COP for the pair.

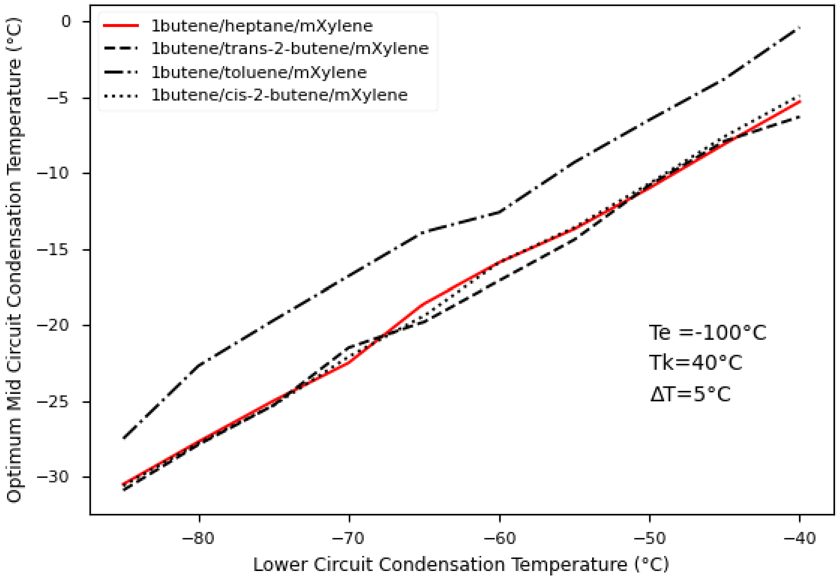

Figure 4.1: Relation between optimum T_{mc} and T_{lc}.

T_{lc} (°C)	-85	-80	-75	-70	-65	-60	-55	-50	-45	-40
t_{mc} (°C)	-30.5	-27.7	-25	-22.5	-18.6	-15.9	-13.7	-11	-8.1	-5.3

Table 4.1: Change of T_{mc} with T_{lc} at evaporation temperature of -100°C.

Table 4.1 shows the optimum T_{mc} of 1-butene/Heptane/mXylene pair for T_{lc} temperature. Based on this table, Fig 4.2 represents the behavior of the TCRS in terms of performance. From Fig 4.2, it is seen that, with the increase of T_{lc}, COP_L decreases but COP_M and COP_H increases. This is justified because increasing T_{lc} causes LTC to work for a higher temperature range from evaporation to condensation while MTC and HTC start to work for a smaller temperature range. This leads LTC to work in between higher-pressure ratio and MTC and HTC to work in smaller pressure ratio. Hence, increasing the lower circuit condensation temperature has opposite effects on LTC with respect to MTC and HTC. This phenomenon causes overall COP of a TCRS to increase with the increase of T_{lc} up to a certain point of T_{lc} temperature but starts to decrease after reaching maximum point (also shown in Fig 4.3).

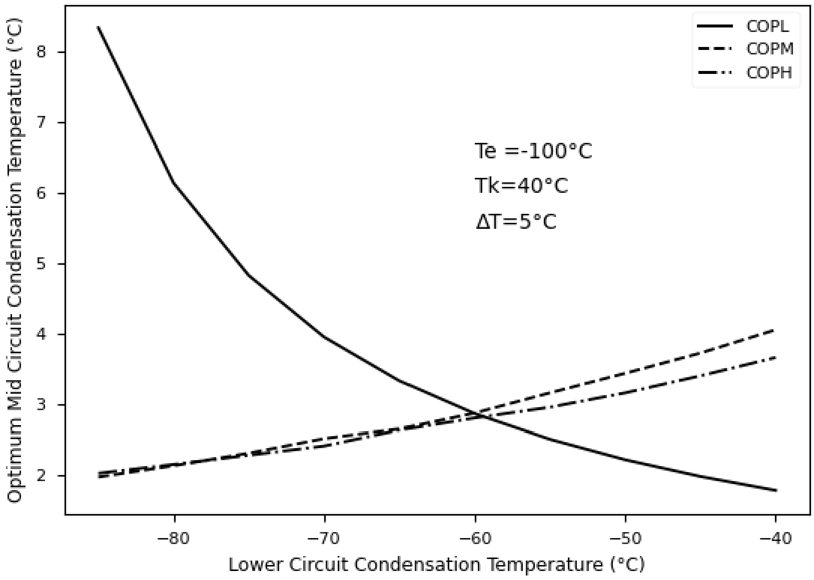

Figure 4.2: Effect lower circuit condensation temperature on circuit COP.

COP of the system is also dependent on the evaporation temperature (T_e). Fig 4.4 shows the relation between T_{lc} and COP, when Te is changed from -150°C to -100°C with a difference of 10°C. From the figure, it is clear that with increase of evaporation temperature, COP increases too.

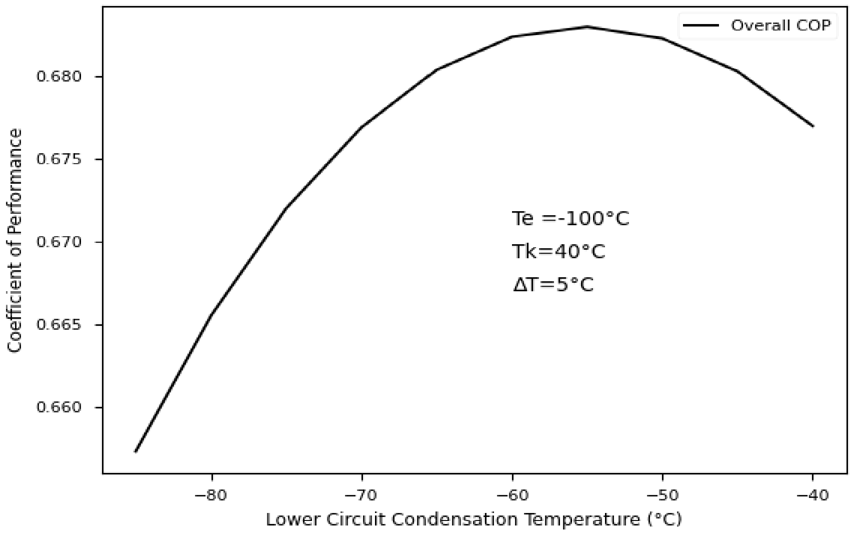

Figure 4.3: Effect of lower circuit condensation temperature on overall COP.

CONCLUSION

In this study, triple cascade refrigeration system was analyzed for low temperature application. Eco-friendly hydrocarbon (HC) refrigerants were used for the triple cascade refrigeration system (TCRS). In this study, TCRS was analyzed for evapo- ration temperature ranging from -100ºC to -150ºC. Different applications of TCRS for this kind of range can be suggested.

1. LNG liquefaction needs evaporation temperature ranging from around -150ºC [29].
2. 5. LPG liquefaction needs below -60ºC [58].
3. Steel alloy treatment needs around -100ºC [15].
4. Military and national defence -80ºC [58].

Different industries (e.g freeze-drying, cooling in pharmaceutical, chemical and

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