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# Thermodynamic Analysis of a Cascade Refrigeration System Based on Carbon Dioxide and Ammonia

**M.Tech. Scholar Sourabh Kori, Asst. Prof. Shahrukh Khan**
Department of Mechanical Engineering,
Trinity Institute of Technology & Research,
Bhopal

**Abstract- Refrigeration and air conditioning (RAC) play a very important role in modern human life for cooling and heating requirements. This area covers a wide range of applications starting from food preservation to improving the thermal and hence living standards of people. The utilization of these equipment's in homes, buildings, vehicles and industries provides for thermal comfort in living/working environment and hence plays a very important in increased industrial production of any country. In present study the comparison of thermodynamic analysis of cascaderefrigeration system has been done with two refrigerant pairs R23-R600A and R23-R290. In these systems, performance of two stage cascade compression system using above different refrigeration system have been studied and the effect of condenser temperature & evaporator temperature , difference in cascade condenser and low temperature cycle condensertemperature on performance parameteron COP, total compressor work, exergy efficiency and total exergy loss has also been done.Thermodynamic analysis is carried out by developingcomputational model in Engineering Equation solver (EES).**

**Keywords- Refrigeration and air conditioning, refrigeration system, COP, cascade system.**

## I. INTRODUCTION

As energy conservation is becoming an increasingly important aspect/parameter, there is a need to optimize the thermodynamic processes for the minimum consumption of energy. Many parameters affect the performance of a refrigeration cycle. In order to optimize their design, a thorough study based on the second law of thermodynamics (exergy analysis) analysis is required. Although, first law of thermodynamic analysis method is most commonly used, however, this is concerned only with the conservation of energy and therefore it cannot show how or where irreversibility in the system and or a process occurs.

On the other hand, second law based exergy analysis is another well-known method being used to analyse these cycles. Unlike, the first law, second law analysis determine the magnitude of irreversible processes in a system and thereby, provides an indication to point out the directions in which the engineers should concentrate more to improve the performance of thermal system.

In view of shortage of energy and a quest to conserve it in all possible ways energy conservation is becoming a slogan of the present decade and new methods to save energy which is otherwise wasted are being explored. Energy recovery from waste heat and/or to utilize it for useful applications to improve the system efficiency is growing concern in scientific community and hence, is in use for industrial installations now-days. Ever present energy crises have forced the scientists and engineers all over the world to take into account the energy conservation measures in various industries. Reduction of electric power and thermal energy consumption are desirable but unavoidable in view of the fast and competitive industrial growth throughout the world.

Refrigeration and air conditioning systems form a vital component for the industrial growth and affect both the food and energy problem of a country at large. RAC systems are also a major contributor to the energy consumption. Therefore it isdesirable to provide a base for energy conservation and waste heat energy recoveryfrom RAC & HP systems.

A cascade refrigeration system consists of two independently operated single-stage refrigeration systems. A lower system that maintains a lower evaporating temperature and produces a refrigeration effect and a higher system that operates at a higher evaporating temperature.

For some industrial applications that require moderately low temperatures with a considerably large temperature and pressure difference then the single stage vapor-compression refrigeration cycles become impractical. One of the solutions for such cases is to perform the refrigeration in two or more stages which operate in series. These refrigeration cycles are called cascade refrigeration cycles. Therefore, cascade systems are employed to obtain high-temperature differentials between the heat source and heat sink and are applied for temperatures ranging from −70°C to -100°C.

Application of a three-stage vapor compression system for evaporating temperature below −70°C is limited, because of difficulties with refrigerants reaching their freezing temperatures.The Montreal protocol and Kyoto underlined the need ofsubstitution of CFC's and HCFC's regarding their bad impacton atmospheric ozone layer which protects earth from U.Vrays.

## II. LITERATURE REVIEW

In **Cimsit (2018)** study, the absorption part has been designed to improve the performance of absorption – vapour compression cascade cycle as serial flow double effect.Thedetailed thermodynamic analysis has been made of double effect absorption –vapour compression cascade refrigeration cycle. For the novel cycle working fluid used R-134a for vapour compression section & LiBr-$H_2O$ for absorption section.

This cycle has been compared with single effect absorption – vapour compression cascade cycle & one stage vapour compression refrigeration cycle. The results indicate that the electrical energy consumption in the novel cycle is 73% lower than the one stage vapour compression refrigeration cycle.

**Botia (2018)** document presents a combined refrigeration system consisting of two vapour compression refrigeration cycles linked by a heat exchanger that not only reduces the work of the compressor but also increases the amount of heat absorbed by the refrigerated space as a result of the cascade stages & improves the COP of a refrigeration system. **Zhou et al (2018)** find out that waste heat can be utilized in absorption refrigeration systems. In this article, the performance of an auto-cascade absorption refrigeration system using R23/R134a/DMF solutions as the working substance was analyzed. Optimization analysis results showed that to some extent, the COP could be increased when the low pressure of the system decreased.

**Mishra (2017)** deals with thermodynamic analysis of three stages cascade vapour compression refrigeration systems using eco-friendly refrigerants used for low temperature applications. The effect of thermal performance parameters on the first law thermal performances $COP_{system}$ and also in terms of second law efficiency of the cascade system and System exergy destruction ratio have been optimized thermodynamically using entropy generation principle.

**Rajmane (2017)** study is presented a cascade refrigeration system using as refrigerant (R23) in low temperature circuit and R404a in high temperature circuit. The operating parameters considered in this paper include superheating, condensing, evaporating and sub cooling temperatures in the refrigerant (R404a) high temperature circuit and in the refrigerant (R23) low temperature circuit.

**Dixit et al (2016)** study helps to find out the best refrigerants and appropriate operation parameters. It is found in the study that cascade condenser, compressor and refrigerant throttle valve are the major source of exergy destruction. The analysis has been realized by means of mathematical model of the refrigeration system.

## III. RESEARCH METHODOLOGY

**1. System Modeling:**

The cascade refrigeration system is constituted by 2 single stage system connected, by a heat exchanger (cascade heat exchanger). The low temperature system with R23 as refrigerant is used for cooling. The high temp system with R290 as the refrigerant is used to condense the R23 of the low temperature system.

In the evaporator, the R23 at the evaporating temperature absorbs the cooling duty $Q_{evap}$R23 from the cooling space (at $T_f$ temp), then is compressed in the R23 compressor and condensed in the cascade heat exchanger at a condensing temperature of $T_{cond}$R23 and then sent to the from which evaporator is applied.

Inthe condenser, the heat flow $Q_{cond}$R290 is removed from the R290 at condensing temp of $T_{cond}$R290 to condensing medium (at $T_0$ temperature). The R290 is expanded, then evaporated at an evaporating temp of $T_{evap}$R290 in the cascade heat exchanger and then compressed in R290 compressor and discharged into the condenser.

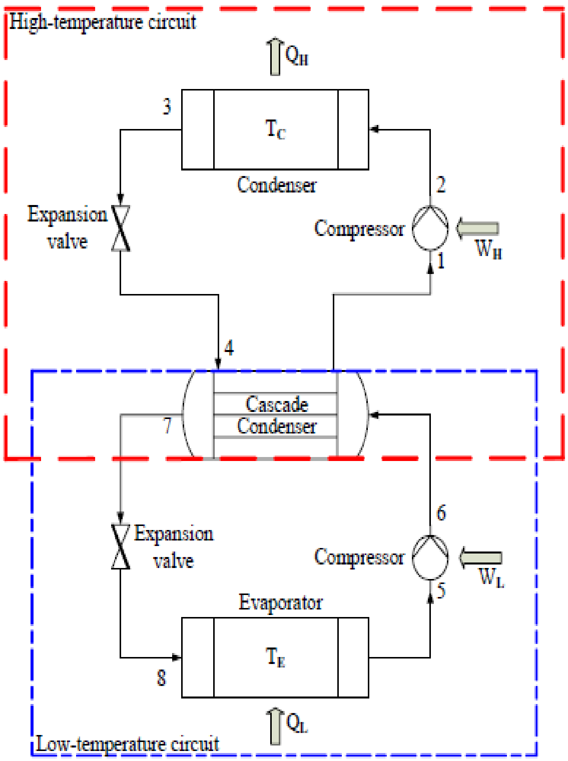


Fig 1. Schematic diagram of the cascade refrigeration system

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### 2. Mass Balance and Energy Balance:

In table 1 specific equation for each system's component are summarized. The system's COP hasbeen calculated by the following equation

$$COP = Q_L / W_{Total}$$

Table 1. Energy and Mass Balance for CO2/NH3 Cascade System.

| Component | Mass | Energy |
|---|---|---|
| R23-Compressor<br>R290-Compressor<br>R23- Exp. Device<br>R290- Exp. Device<br>Evaporator (R23)<br>Condenser (R290)<br>Cascade heat exchanger | $m_2=m_1$<br>$m_6=m_5$<br>$m_4=m_3$<br>$m_8=m_7$<br>$m_1=m_4$<br>$m_7=m_6$<br>$m_3=m_2, m_5=m_8$ | $W_{comp}R23=m_1(h_{2s}-h_1)$<br>$W_{comp}R90=m_5(h_{6s}-h_5)$<br>$h_4=h_3$<br>$h_8=h_7$<br>$Q_{evap}R23=m_1(h_1-h_4)$<br>$Q_{cond}R290= m_5(h_7-h_6)$<br>$m_1(h_3-h_2)=m_5.(h_5-h_8)$ |

### 3. Thermodynamic Analysis:

The thermodynamic analysis of R23-R290and R23-R600A cascade refrigeration system performed based on the following assumptions.

- Compression process is adiabatic with an isentropic efficiency of 0.7 in both HTC and LTC;
- The expansion process is isenthalpic;
- Negligible heat interaction in the cascade heat exchanger with surrounding;
- Negligible changes in kinetic and potential energy;
- The system is at steady state condition. All processes are steady flow processes.
- Temperature difference in the cascade heat exchanger is -3°C.

The thermo-physical properties of R23-R290and R23-R600A specified in this work were calculating using a software package called engineering equation solver (EES). The cycle is modelled by applying mass balance and energy balance equation for each individual process of the cycle.

## IV. RESULTS AND DISCUSSION

### 1. Effect of Evaporator Temperature:

For a given condensing temperature, the pressure ratio increases as the evaporator temperature decreases.As the evaporator temperature increases, the refrigeration effect increases marginally and the required compressors work decrease significantly, therefore the performance of the cascade system increases considerably.

Compression Work required in LTC decreases with increase in evaporator temperature since pressure ratio is decreases. Hence combined work required also reduces.

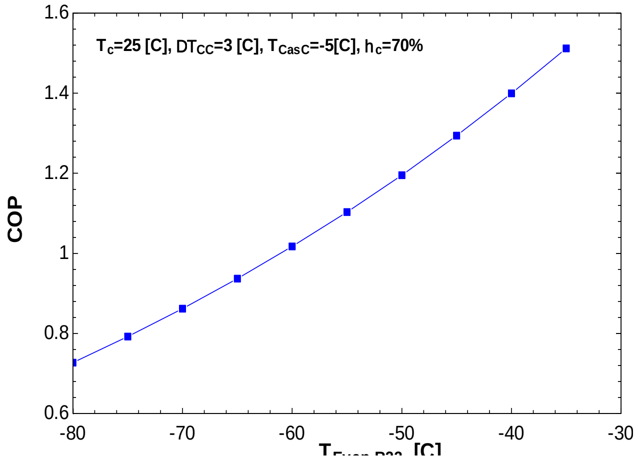


Fig 2. Effect of evaporator temperature on COP.

It is obvious from the graph that as the evaporating temperature $T_E$increases, the COP also increases. In the graph it is shown that when the $\Delta T$ (temperature difference between cascade condenser and cascade evaporator) = 3°C and the evaporating temperature is -80°C and condensing temperature is 25°C, the COP is around 1.05 and after that it is increasing with the increase in evaporating temperature at constant condensing temperature of 25°C. But as the condensing temperature $T_C$ increases the COP decreases. As evaporating temperature $T_E$ =-80°C and $T_C$=25°C, the COP is equal 1.02.

### 2. Effect of Condenser Temperature:

The results are obtained at fixed -35°C evaporator temperature and 15°C coupling temperature. As the evaporator and coupling temperatures are fixed, the refrigeration effect will be constant for entire range of condenser temperature. However required work in HTC increases due to increase in pressure ratio in HTC. Hence combined work required increases, therefore the COP of cascade system decreases.

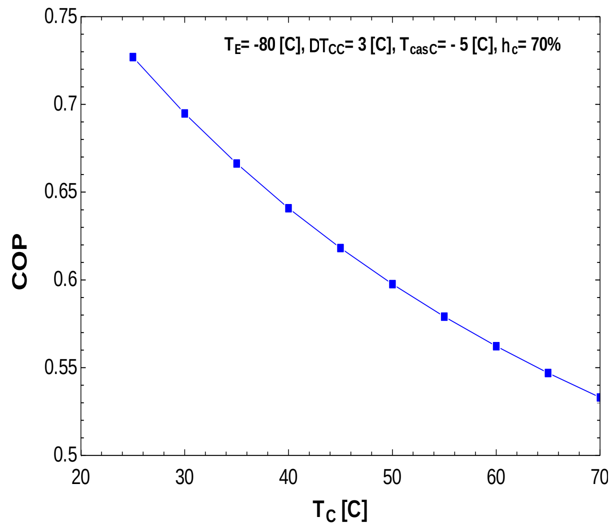


Fig 3. Effect of condenser temperature on COP.

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## V. CONCLUSION

In present work thermodynamic analysis of cascade refrigeration system has been carried out by developingcomputational model in EES to find the effect of variousoperating parameters on the performance parameters.In present work thermodynamic analysis of cascade refrigeration system has been carried out by developingcomputational model in EES to find the effect of variousoperating parameters on the performance parameters.It is observed that as evaporator temperature increases the total exergetic loss decreases.

Among two pair R23-R600A shows maximum change in exergetic efficiency followed by R290-R23.It is observed that as condenser temperature increases the COP decreases. Among two pair R23-R600A shows maximum change in COP followed by R290-R23.It is observed that as condenser temperature increases the total compressor work increases. Among two pair R23-R600A shows minimum change in total compressor work followed by R290-R23.

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