A Review on Thermodynamic Analysis of Two Stage Cascade Refrigeration System

Anmol Rangare[1] Praveen Mishra[2]
[1]M. Tech. Student [2]Assistant Professor
[1,2]Department of Mechanical Engineering
[1,2]OCT, Bhopal, India

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. Due to the increasing demand of energy primarily for RAC & HP applications (around 26-30%) this leads to degradation of environment, global warming and depletion of ozone layer etc., to overcome these aspects there is urgent need of efficient energy utilization.

Key words: Thermodynamic Analysis, Cascade Refrigeration System, COP, Exergetic Efficiency

I. Introduction

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 is desirable to provide a base for energy conservation and waste heat energy recovery from RAC & HP systems.

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.

II. Cascade Refrigeration System

The first low temperature refrigeration system was primarily developed for solidification of carbon dioxide and liquefaction & subsequent fractional distillation of gases such as air, oxygen, nitrogen, hydrogen and helium Ultra low temperature refrigeration in industrial work has increased tremendously in the last few years [2].

A. Cascade Process

Cascade system is just similar to the binary vapour cycle used for the power plants. In a binary vapour cycle, a condenser for mercury works as boiler for water. Similarly in cascade system condenser of low temperature cycle works as evaporator for the high temperature cycle. In cascade system, a series of refrigerants with progressively lower freezing points are used in a series of single stage unit. The cascade condensing unit used two refrigerating systems or cycles and referred to as cycles A and B. The condenser of cycle B, called the "high stage", is usually fan cooled or in some cases a water supply may be used to cool but air cooling is common. The Evaporator of cycle B is used to cool the condenser of cycle A called the "low stage". The unit that consist of condenser of cycle A and evaporator of cycle B. is often referred to as the "Inter-stage condenser" or "cascade condenser". Thus a cascade condenser serves as an evaporator "for high temperature cascade system (cycle A)". The difference in low temperature cascade condenser temperature and high temperature cascade evaporator temperature is called temperature overlap and is necessary for heat transfer. Cascade system use two different refrigerants in each stage. The reason that two refrigeration systems are used because single stage system cannot economically achieve the high compression ratio necessary to obtain evaporating and condensing temperatures. The high temperature cascade system uses a refrigerant with low boiling temperature such as R-13 or R-13B1. These low boiling temperature refrigerants have extremely high pressure which ensures a smaller compressor displacement in the low temperature cascade system and a higher COP [2].

Another set of refrigerants commonly used for liquefaction of gases in a three stage cascade system is ammonia, ethylene and methane. The additional advantage of a cascade system over multi stage compression is that the lubricating oil from one compressor cannot wander to the other compressors.

Cascade staging incorporates several individual refrigeration systems that use different refrigerants and have closed heat exchangers to achieve low operating temperatures and reasonable condensing pressure. For some industrial applications which require moderately low temp, single stage vapour compression refrigeration cycle and vapour absorption refrigeration cycle become impractical therefore cascade system are employed to obtain high temperature differentials between the heat source & heat sink. These systems are applied for temperature ranging from -70°C to -100° C [3].

Two stage cascade refrigeration system is represented by a P-h diagram in Fig.1.1 and 1.2 respectively. In the system both Low Temperature Cycle (LTC) and High Temperature Cycle (HTC) work with different refrigerants and thermally connected to each other through a heat exchanger which acts as an evaporator for the HTC and a condenser for the LTC. HTC operates with refrigerant having high boiling point and high critical temperature and LTC operates with refrigerant having low boiling point. Properties of refrigerants are given in Table I. Fig.1 shows that the condenser rejects heat QHT from the condenser at condensing temperature of Tc to its condensing medium or environment. The useful refrigerating effect is produce in evaporator of LTC by absorbing the cooling load QLT from the cooling space at the evaporating temperature Te. Heat absorbed by LTC evaporator and work input to LTC compressor equals the heat absorbed by HTC evaporator that is cascade condenser. Tc,cas and Te,cas represent the condensing and evaporating temperatures respectively. The temperature difference between them, ΔT= Tc,cas – Te,cas is called temperature overlap which is necessary for heat transfer.

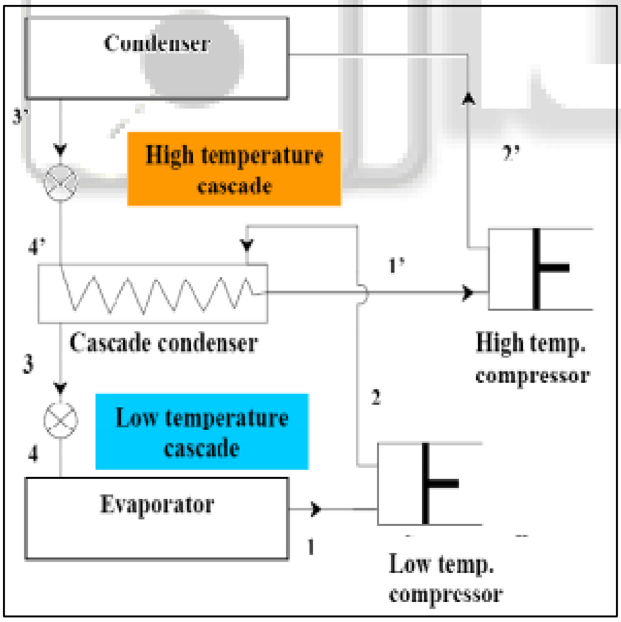

Fig. 1: Two stage cascade refrigeration system

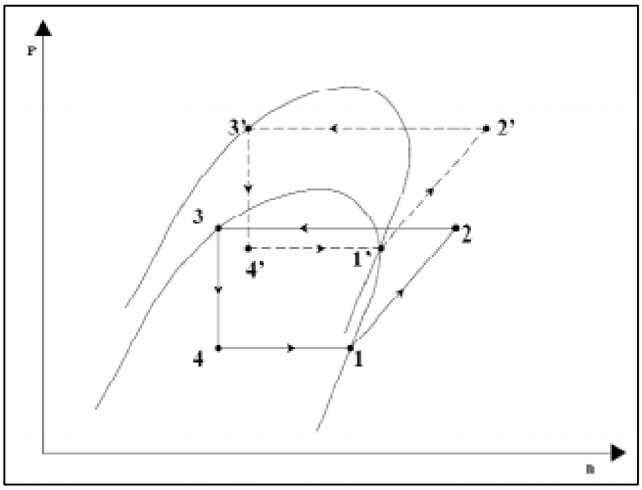

Fig. 2: P-H chart

III. REVIEW OF PAST STUDIES

Kanoglu (2002) developed a thermodynamic model to perform the energy analysis of multistage cascade refrigeration cycle for natural gas liquefaction. He also obtained an expression related to minimum work. Winkler et.al. (2008) discussed on a cascade system simulation algorithm and implemented with the help of a component based modeling tool for vapor compression systems. The low temperature and high temperature vapor compression systems consisted of multiple compressors and the high temperature system utilized two condensers. The simulation tool, despite using simple heat exchanger models, predicted the COP with an average error of 4.4% and a maximum error of 11.3%. Gaudy Prada 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.

Manoj 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. Umesh C. Rajmane (2016) study provides the advantages of vapour compression refrigeration system & also summaries various techniques used in cascade refrigeration system. The operating parameters considered in this study include Condensing , Sub Cooling, Evaporating & Super heating temperatures in high – temperature circuit & temperature difference in Cascade heat exchanger Evaporating, Superheating, condensing & Sub-cooling in the low temperature circuit. Umesh C. 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. Jinkun 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. The reasonable upper limit of the high pressure was the high pressure at the turning point of COP, and the reasonable lower limit of the low pressure was the low pressure at the turning point of COP. The COP of the system monotonously increased with the increase of the mole fraction of R23 in solutions. The low R23 mole fractions were more appropriate. J. Alberto Dopazo (2010) did the experimental evaluation of a cascade refrigeration system prototype with CO_2 & NH_3 for freezing process application .They also compared the experimental results with two common single stage refrigeration systems using NH_3 as refrigerant. A. D. Parekh and P. R. Tailor (2014) thermodynamic analysis of cascade refrigeration system has been done using three different refrigerant pairs R13-R12, R290-R23, and R404A-R2. Thermodynamic analysis shows that out of three refrigerant pairs R12-R13, R290-R23 and R404A-R23 the COP of R290-R23 refrigerant pair is highest.

IV. Conclusion

Continuous efforts have been made by numerous researchers on different types of cascade refrigeration system. Wonder to improve their performance and make them cost effective .Some researchers have developed thermodynamic model for the two stage and cascade refrigeration system. Also various studies provide the advantages of vapour compression refrigeration system & also summaries various techniques used in cascade refrigeration system. The operating parameters considered in this study include Condensing , Sub Cooling, Evaporating & Super heating temperatures in high – temperature circuit & temperature difference in Cascade heat exchanger Evaporating, Superheating, condensing & Sub-cooling in the low temperature circuit.

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