Thermodynamic Performance Analysis of Cascade Refrigeration System - A Review

Jigar A. Solanki

Department of Mechanical Engineering, ADIT College, New Vallabh Vidyanagar - 388121, Gujarat, India

Abstract: ***Cascade refrigeration system is the solution of one of the stable refrigeration systems operating at very low temperatures. It employs multiple refrigerants and so that a suitable pair of refrigerants can be chosen for a given application so that better system performance can be achieved. In the applications of liquefaction of petroleum vapours, liquefaction of industrial gases, manufacturing of dry ice, deep-freezing, etc. cascade refrigeration system is very useful. The performance evaluation of cascade refrigeration system enhances to understand the thermal behaviour of the system and so that modifications can be done to improve the COP of the system. Such evaluation can be helpful in optimization of various components in the cascade refrigeration system and so proper refrigerant pairs can be selected for suitable applications.***

Keywords: Cascade refrigeration system, Coefficient of Performance, Thermodynamic effectiveness, Cascade heat exchanger

1. Introduction

Refrigeration is a dominant part for both industrial and domestic needs and various types of refrigeration cycles and systems are developed for serving various purposes. In such processes heat is normally rejected or absorbed by a working substance at constant pressure. There are two possible scenarios: either temperature of the substance changes and the substance remains in single phase or the temperature of substance remains unchanged but phase change occurs. If without phase change heat transfer occurs resulting in change of temperature is called sensible heat and heat transferred resulting in phase change at constant temperature is called latent heat.

A refrigeration process resulting in low temperature production involves processes like throttling expansion of liquid with flashing, a gas undergoing reversible adiabatic expansion, irreversible adiabatic expansion of a real gas, thermoelectric cooling and adiabatic demagnetization. To establish a refrigerant's thermodynamic properties some of the minimum data required are saturation pressure, saturation temperature, equation of state of gaseous phase, liquid density, specific volume and liquid specific heat. For any refrigeration system to attain maximum efficiency the value Coefficient of Performance (COP) should be maximum possible. To obtain maximum COP the cold body temperature should be as high as possible and hot body temperature should be as low as possible. So, selection of operating temperatures plays an important part in a refrigeration system.

1.1 Methods of Refrigeration

Methods of refrigeration may be non-cyclic, cyclic, thermoelectric and magnetic. Non-cyclic refrigeration method reduces temperature of a contained area by melting ice, or by sublimating dry ice. Normal ice can maintain temperatures near, but not below the freezing point, unless salt is used to cool the ice down. Dry ice can reliably bring the temperature well below freezing.

Cyclic refrigeration consists of a refrigeration cycle, where heat is removed from a low temperature space or source and rejected to a high temperature sink with the help of external work, and its inverse, the thermodynamic power cycle. In the power cycle, heat is supplied from a high-temperature source to the engine, part of the heat being used to produce work and the rest being rejected to a low-temperature sink. This satisfies the second law of thermodynamics.

A refrigeration cycle describes the changes that take place in the refrigerant as it alternately absorbs and rejects heat as it circulates through a refrigerator. It is also applied to heating, ventilation, and air conditioning work. Work is applied to cool a living space or storage volume by pumping heat from a lower temperature heat source into a higher temperature heat sink. Insulation is used to reduce the work and energy needed to achieve and maintain a lower temperature in the cooled space. The working principle of the refrigeration system was described mathematically by Sadi Carnot in 1824 as a heat engine.

Generally most types of refrigeration systems use the reverse Rankine vapour compression refrigeration cycle, although absorption heat pumps are used in a minority of applications. Cyclic refrigeration can be classified as vapour cycle and gas cycle. Vapour cycle refrigeration can further be classified as:

1) Vapour compression refrigeration
2) Vapour absorption refrigeration

Other refrigeration types include thermoacoustic refrigerator, thermoelectric refrigeration and electromagnetic refrigeration.

1.2 Cascade Refrigeration System

Cascade refrigeration system consists of two separate vapour compression refrigeration system circuits, each using a different refrigerant appropriate for its temperature range. Cascade refrigeration system is used when the difference between the condenser temperature and evaporating temperature is so large that a single refrigerant with vapour compression refrigeration system is not suitable be used because of low COP and high compressor discharge temperature. Cascade refrigeration system effectively uses the operating range of individual refrigerants for better thermodynamic effectiveness and also permits each compressor to take a share of the total pressure ratio between the low-temperature evaporator and the condenser of high temperature circuit.

A schematic diagram of simple cascade refrigeration system is as shown below:

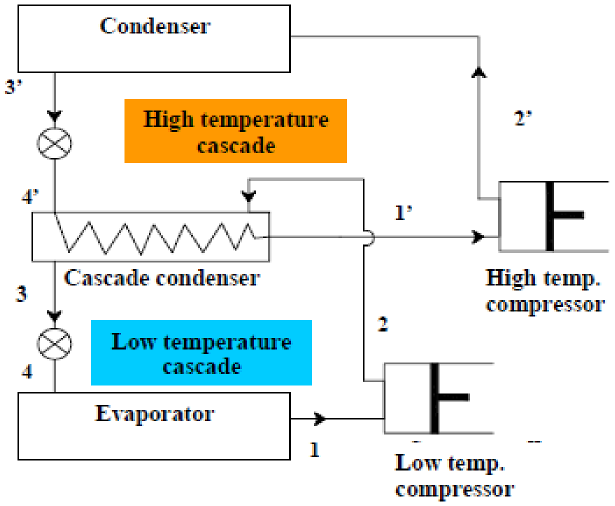

Figure 1.2.1: Two stage cascade refrigeration system

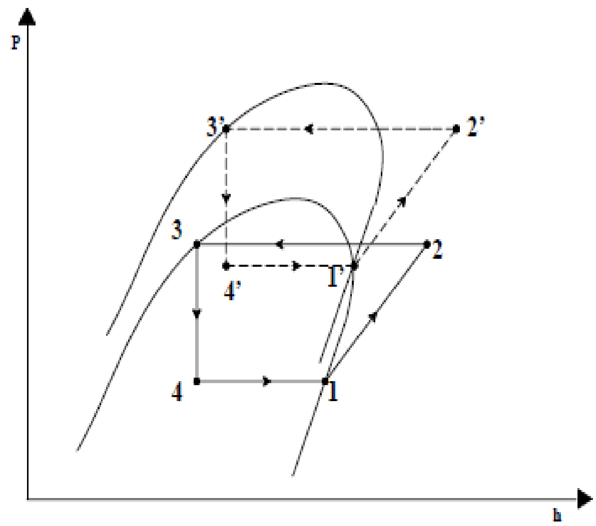

Figure 1.2.2: Schematic P-h diagram of two-stage cascade refrigeration system

In practice, matching of loads in the cascade condenser is difficult, especially during the system pull-down. Hence, the cascade condensers are normally oversized. In addition, in actual systems a temperature difference between the condensing and evaporating refrigerants has to be provided in the cascade condenser, which leads to loss of efficiency. In addition, it is found that at low temperatures, superheating is detrimental from volumetric refrigeration effect point-of-view, hence in cascade systems, the superheat should be just enough to prevent the entry of liquid into compressor, and no more for all refrigerants.

2. Literature Survey

Parekh and Tailor (2011) had done thermodynamic analysis of cascade refrigeration system using ozone friendly refrigerants pair R507A and R23. R507A is a zeotropic mixture made by HFC refrigerants R125/ R143a (50%/50%wt.). R23 is HFC refrigerant used as replacement to CFC refrigerant R13 in low temperature applications. These refrigerants have zero ozone depletion potential and are non-flammable and as R507A, an azeotropic mixture there is no problem of temperature glide. This study thermodynamically analyzedR507A-R23 cascade refrigeration system to optimize the design and operating parameters of the system. The design and operational parameters are condensing, evaporating, superheating and sub-cooling temperatures in the high temperature circuit, temperature difference in the cascade heat exchanger, condensing, evaporating, subcooling and superheating temperatures in the low temperature circuit. The COP of the system increased from 0.7851 to 1.232 as low temperature circuit evaporator temperature is varied from -80°C to -50°C keeping others parameters constant. The COP of system reduced from 0.9274 to 0.5486 when high temperature circuit condenser temperature is increased from 25°C to 50°C keeping other parameters constant. The COP of system reduced by about 17.10 % when temperature difference in cascade condenser was increased from 2.5°C to 12.5°C.

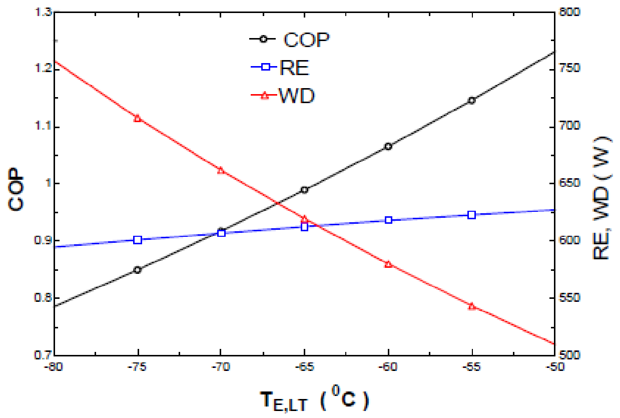

Figure 2.1: Effect of low temperature stage evaporator temperature on COP (Parekh et al., 2011)

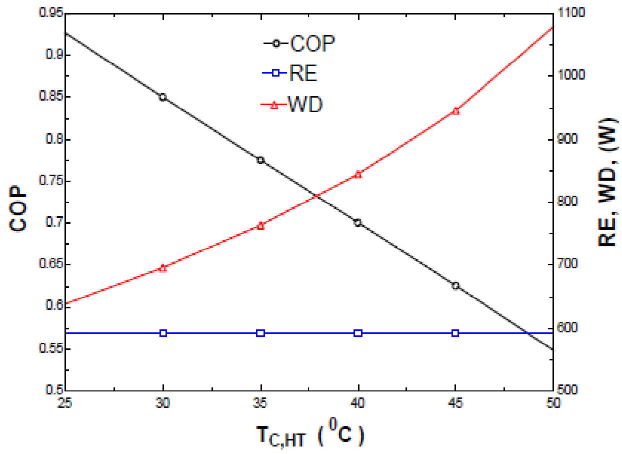

Figure 2.2: Effect of high temperature stage condensing temperature on COP (Parekh et al., 2011)

Dopazo et al. (2009) analyzed cascade refrigeration system with CO_2 and NH_3 as working fluids in the low and high temperature stages, respectively. Results of COP and exergetic efficiency versus operating and design parameters have been obtained. The compressor isentropic efficiency influence on the optimum system COP has been demonstrated. The results show that the COP increases 70% when the Evaporating temperature of low temperature cycle varies from -55°C to -30°C. As Evaporating temperature of low temperature cycle increases, the influence of the other parameters on the COP also increases. The COP diminishes 45% when the condenser temperature of high temperature cycle increases from 25°C to 50°C. The system COP diminishes 9% when cascade condenser temperature difference varies from 3°C to 6°C. The exergetic efficiency decreases around 45% and 9% with the increases indicated above in condenser temperature and cascade condenser temperature difference respectively.

Gholamian et al. (2018) performed exergy analysis of carbon dioxide ammonia cascade refrigeration system. Engineering Equation Solver (EES) as a potential tool is used for the simulation purpose. In order to validate the simulation code, the exergy destruction and COP is compared with an experimental data from the literature. In addition, advanced exergy analysis is applied to the system in order to determine exergy destruction rates. The conventional exergy analysis demonstrates that the highest exergy destruction rate occurs in NH_3-condenser, CO_2-throttling valve, and CO_2 compressor, respectively and indicate that the improvement priority should be given these components while the advanced exergy analysis indicates that the focus of system improvements should be on the CO_2-throttleing valve, CO_2compressor and cascade heat exchanger, respectively.

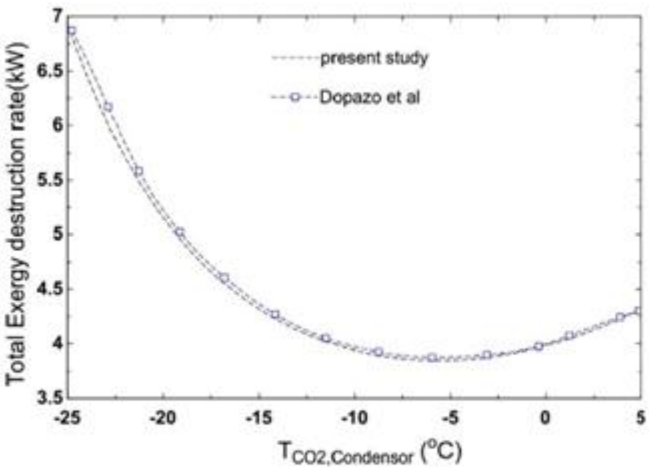

Figure 2.3: Comparison of condenser temperature for the total exergy destruction rate (Gholamian et al., 2018)

Messineo (2012) analyzed cascade refrigeration system using refrigerant carbon dioxide in low-temperature circuit and ammonia in high-temperature circuit. The operating parameters considered include condensing, evaporating, superheating and subcooling temperatures in the ammonia (R717) high temperature circuit and in the carbon dioxide (R744) low-temperature circuit. Diagrams of COP versus operating parameters have been obtained. In addition, values for R744-R717 cascade refrigeration system are compared with the values obtained for a partial injection two-stage refrigeration system using the synthetic refrigerant R404A, a nearly azeotropic blend, specially used for commercial refrigeration systems. Results show that a carbon dioxide-ammonia cascade refrigeration system is an interesting alternative to R404A two-stage refrigeration system for low evaporating temperatures (–30°C to –50°C) in commercial refrigeration for energy, security and environmental reasons. A decrease of the COP as the condensing temperature increases from 30°C to 45°C, with zero degree of subcooling and for T_E= –35°C. The decrease is by 27% for the cascade cycle and by 37% for the R404A two-stage cycle, respectively. In the case of subcooling equal to 10°C, these decreases amount to 27% and 34%, respectively. On the other hand, it was noticed an increase of the COP as the evaporating temperature rises from -50°C to-30°C, with zero degree of subcooling and for T_C = 35°C. The increase is by 50% for the cascade cycle and by 53% for the two-stage cycle, respectively; in the case of subcooling equal to 10°C these increases change to 48% and 50%, respectively.

Kilicarslan and Hosoz (2010) done energy and irreversibility analysis of a cascade refrigeration system employing various refrigerant couples, namely R152a–R23, R290–R23, R507–R23, R234a–R23, R717–R23 and R404a–R23, using a computer code developed for this aim. It is assumed that the refrigeration load is 1 kW, the refrigerated space temperature is -40°C, and the environment temperature is 300 K, while the degrees of condenser subcooling and evaporator superheat are 5°C and 7°C, respectively, for all cases. Furthermore, the polytropic efficiencies of the compressors are assumed equal. It has been determined that the COP of the cascade refrigeration system increases and the irreversibility decreases with rising evaporator temperature and polytropic efficiency for all studied refrigerant couples. On the other hand, the COP of the cascade refrigeration system decreases and the irreversibility increases on increasing the condenser temperature and the difference between the saturation temperatures of the lower and higher temperature systems in the heat exchanger (ΔT). In all cases, the refrigerant couple R717–R23 has the highest COP and lowest irreversibility except for the limited ranges of polytropic efficiency (50–60%) and ΔT (13K–16 K), while R507–R23 has the lowest COP and highest irreversibility. The refrigerant couple R152a–R23 has been found to be an alternative couple to R717–R23 for the above mentioned ranges of polytropic efficiency and ΔT. The refrigerant couples R134a–R23 and R290–R23 have placed in the middle range, and R404a–R23 can be considered as a replacement couple for R507–R23 in all cases.

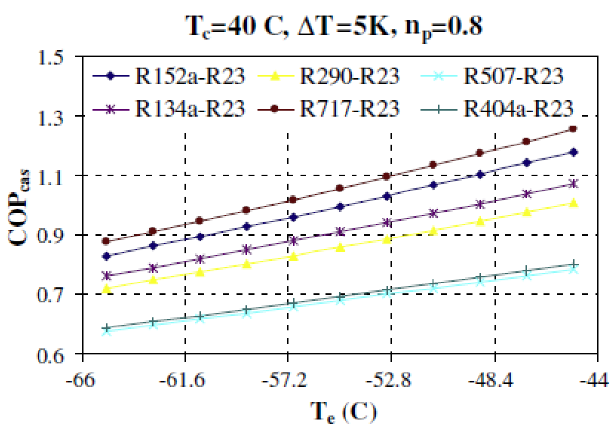

Figure 2.4: COPcas as function of evaporator temperature (Kilicarslan and Hosoz, 2010)

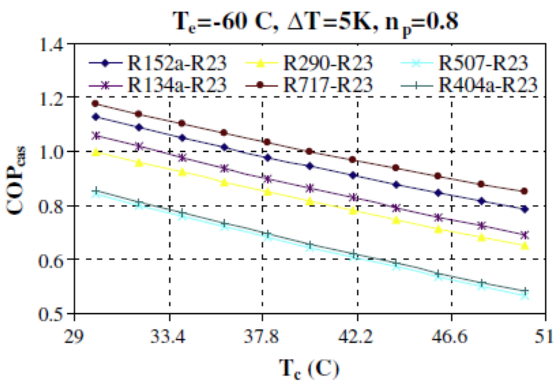

Figure 2.5: COPcas as function of condenser temperature (Kilicarslan and Hosoz,2010)

Sachdeva et al. (2014) studied cascade refrigeration system with various refrigerants. The working fluid in low temperature circuit (LTC) is CO_2 (R744) while Ammonia (R717), Propane (R290), Propylene (R1270), R404A and R12 are the refrigerants in high temperature circuit (HTC). The performance curves of Ammonia, Propane, Propylene, and R404A are compared with R12 to find its nearest substitute. The condenser heat transfer is maximum for R404A and is minimum for Ammonia. The system cost will be more for R404A and will be least for Ammonia. Propane is high capacity and high pressure refrigerant compared to R12. Because of these characteristics; propane air conditioner of same capacity requires a larger displacement compressor, large evaporator, condenser and tubing. Hence, Propane system costs more to build and operate than an equivalent R404A system. Propylene has similar characteristic as Propane; hence propane system can easily be replaced with propylene. R404A is higher pressure refrigerant as compared to R12. It has lower COP and high refrigerant charge as compare to R12 system. So it requires large displacement compressor, evaporator, condenser and tubing. Hence it has high cost. Ammonia is high pressure and high capacity refrigerant than R12.Ammonia is the best high-temperature refrigerant among propane, propylene, R12 and R-404A considered in this study. It gives a theoretical optimum COP of about 1.299 with the lowest mass flow rate of 0.078 kg/s in HTC at a condenser temperature of 52.2°C, an evaporator temperature of –31.28°C, and a cascade heat exchanger approach of 5 K. It also has the lowest optimum operating temperatures and pressures for maximum COP in the cascade heat exchanger.

Sun et al. (2016) carried comparative analysis of thermodynamic performance of cascade refrigeration system for refrigerant pairs R41/R404A and R23/R404A to explore whether R41 is a suitable substitute for R23. The discharge temperature, input power of the compressor, coefficient of performance (COP), exergy efficiency (g) and exergy loss (X) are considered as the objective functions. The operating parameters considered include condensing temperature, evaporating temperature, superheating temperature and subcooling temperature in both high-temperature cycle (HTC) and low temperature cycle (LTC). The results indicate that an optimum condenser temperature exists for LTC at which COP acquires maximum value. Under the same operation condition, the input power of R41/R404A CRS is lower than that of R23/R404A system, and COPopt is higher than that of R23/R404A cascade refrigeration system. The maximum exergy efficiency of R41/R404A and R23/R404A systems are 44.38% and 42.98% respectively. The theoretical analysis indicates that R41/R404A is a more potential refrigerant couple than R23/R404A in cascade refrigeration system.

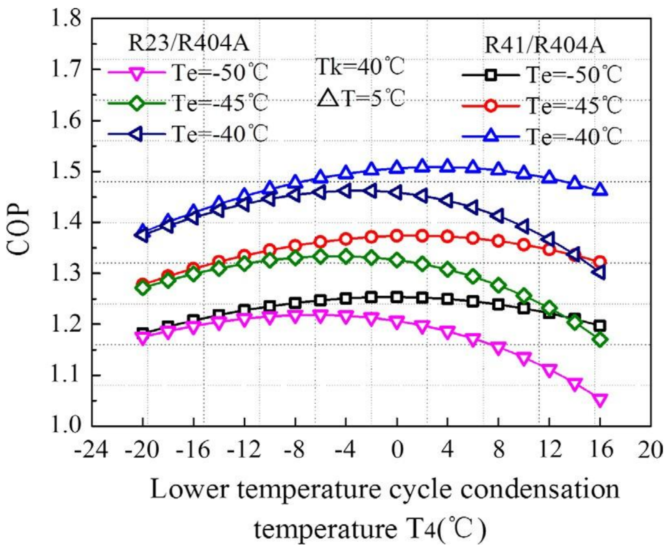

Figure 2.6: Effect of Condensation temperature on COP (Sun et al., 2016)

Getu and Bansal (2008) analyzed carbon dioxide–ammonia (R744–R717) cascade refrigeration system to optimize the design and operating parameters of the system. The design and operating parameters considered in this study include (1) condensing, subcooling, evaporating and superheating temperatures in the ammonia (R717) high-temperature circuit, (2) temperature difference in the cascade heat exchanger, and (3) evaporating, superheating, condensing and subcooling in the carbon dioxide (R744) low-temperature circuit. A multilinear regression analysis was employed in terms of subcooling, superheating, evaporating, condensing, and cascade heat exchanger temperature difference in order to develop mathematical expressions for maximum COP, an optimum evaporating temperature of R717 and an optimum mass flow ratio of R717 to that of R744 in the cascade system.

3. Conclusion

Following are some of the limitations of multi-stage refrigeration systems:

- As only one refrigerant is used int the system, the refrigerant used must have high critical temperature and low freezing point.
- The operating pressures with a single refrigerant may become too high or too low. Usually only R134A, R22 and ammonia systems have been used in multi-stage systems as other conventional working fluids may operate in vacuum at very low evaporator temperatures. Operating in vacuum causes leakages in the system and large compressor displacement because of high specific volume.
- Possibility of migration of lubricating oil from one compressor to other leading to compressor breakdown.

These problems can be overcome by using cascade systems**.**

Following are the advantages of cascade refrigeration system over other refrigeration systems:

1) Since each cascade uses a different refrigerant, it is possible to select a refrigerant that is best suited for that particular temperature range. Very high or very low pressures can be avoided.
2) It allows stable very low temperature operation.
3) Use of cascade system reduces power consumption.
4) Migration of lubricating oil from one compressor to the other is prevented.

Following are the key aspects in thermodynamic performance analysis of cascade refrigeration system utilizing two suitable refrigerants in both low and high temperature cycles:

- Increase in condensing temperature decreases COP and increases refrigerant mass flow ratios.
- Increase in evaporating temperature increased COP and decreased mass flow ratios.
- Increase in temperature difference in cascade condenser reduces both COP and mass flow ratios.
- Increase in isentropic efficiency of compressors increases COP linearly.
- Increase in subcooling increases both COP and mass flow ratio.
- Increase of superheat increases mass flow ratio but reduces COP of the system.
- There exists a maximum COP at optimum condenser temperature of low temperature cycle.

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Author Profile

Jigar Solanki received Bachelor of Engineering degree in Mechanical Engineering and currently pursuing Master of Engineering degree in Thermal Engineering from Gujarat Technological University, Gujarat, India.