International Journal of Engineering Sciences & Research Technology

(A Peer Reviewed Online Journal)
Impact Factor: 5.164

IJESRT

RESEARCHERID
THOMSON REUTERS

[Suman, *et al.*, 9(2): February, 2020] ISSN: 2277-9655
IC™ Value: 3.00 Impact Factor: 5.164
CODEN: IJESS7

IJESRT

INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

A REVIEW ON COMPARATIVE THERMODYNAMIC PERFORMANCE ANALYSIS OF A CASCADE SYSTEM USING DIFFERENT REFRIGERANT COUPLES

Sourav Suman, Sujeet Kumar Singh
[1]M.Tech Scholar, Department of Mechanical Engineering, PCST, Bhopal
[2]Prof., Department of Mechanical Engineering, PCST, Bhopal

DOI: 10.5281/zenodo.3653473

ABSTRACT

As a result of environmental problems related to global warming and depletion of the ozone layer caused by the use of synthetic refrigerants (CFC's, HCFC's and HFC's) experienced over the last decades, the return to the use of natural substances for refrigeration purposes appears to be sound practice. It must be a better solution to use naturally existing and environmentally harmless substances as alternatives refrigerants in refrigeration systems. Cascade refrigeration system is the combination of two refrigeration cycle for maximum refrigeration effect can be obtained. This system is developed to achieve temperature up to -40 to -80°C for the applications like cold storage in malls and stores and in blood banks. These fluids are harmless to environment and GWP and ODP is negligible and do not violate the Kyoto protocol. COP, work done, Refrigeration effect are the parameters studied from the system. The concept is that the cooling produced in first cycle evaporator is used to cool the condenser of second cycle, which reduces the cooling capacity in condenser and enables to produce very low temperature for various cold storage applications.

KEYWORDS: Cascade refrigeration system, low temperature circuit (LTC), high temperature circuit (HTC), coefficient of performance (COP), global warming potential (GWP), ozone depletion potential (ODP).

1. INTRODUCTION

Many industrial applications require low temperature refrigeration such as quick freezing biomedical preservations, manufacturing of dry ice, liquefaction of petroleum vapors, pharmaceutical reactions etc. where evaporating temperature requires between -40ºC to- 80ºC. Condensing temperature is governed by temperature of cooling tower water which is about 35 ºC. Thus, system has to work for wide range of temperature. Single stage vapor compression system is not feasible for such application and its performance decreases below -35 ºC. Multistage or compound systems can be useful but no refrigerants available to work efficiently for high temperature lift. Also, it will be difficult to balance the oil level in compressor because of large difference in suction pressures of low stage and higher stage compressors. Cascade refrigeration system has two different stages which permits appropriate selection refrigerants to maximise system performance. Synthetic refrigerants prominently used in till now due to their excellent thermodynamic properties but owing to higher ODP (Ozone Depletion Potential), GWP (Global worming Potential) they are contributor to ozone depletion and global warming. Cascade refrigeration system is the combination of two single stage vapor compression system together, condenser of LTC and evaporator of HTC is cascaded and forms the heat exchanger where evaporator cascade absorbs the heat from the condenser cascade which further leads to better refrigeration effect.

Amongst the natural refrigerants, Lorentzen and Petterson [1] suggested the use of carbon dioxide (CO2) and seems to be the most promising one especially as the natural refrigerant [1-6]. The key advantages of CO_2 include the fact that is not explosive, non-toxic, easily available, environmental friendly and has excellent thermo-physical properties. On the other hand, researches in Norway in 1993 showed that the refrigerant leakages coming from the commercial sector were 30% of the annual total [7]. In this research, the use of a cascade system using CO2 in the low temperature stage and NH_3 in the high temperature stage turned out to be an excellent alternative for cooling applications at very low temperatures [8-10]. Researches from Eggen and Aflekt [11], Pearson and Cable [12] and Van Riessen [13] show practical examples of the use of a cascade system of CO2/NH3 for cooling in supermarkets. Eggen and Aflekt [11] developed research based on a

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

prototype of a cooling system built in Norway. Pearson and Cable [12] showed data from a cooling system used in a Scottish supermarket line, (ASDA), and Van Riessen [13] carried out technical energy and economic research of a cooling system used in a Dutch supermarket. In the same way, different researches about the performance of different cooling systems involving CO2 have been carried out together with its reuse as a refrigerant fluid. Lorentzen and Petterson [1] evaluated the possibility of the use of a heat exchanger in a CO2 transcritical system. Hwang et al. [6] showed experimental results and simulation research including expansors and double stage cycles. Groll et al. [14] carried out a numerical analysis of a double stage cycle changing the compression ratio of each compression stage. It is well-known that cascade refrigeration system (CRS) is usually adopted to meet the low-temperature cooling requirement in many commercial and industrial applications where single-stage or multistage systems are insufficient. There are two cycles in a cascade refrigeration system: the high-temperature cycle (HTC) is used to absorbed the energy released by the low-temperature cycle (LTC) during the condensation process [1]. In this way, CRS can satisfy the low-temperature cooling requirement range from -30°C to -55°C [2]. Regarding energy shortage problems, much attention has been devoted to the optimization of CRS performance. One of the research topics is the selection of refrigerant couples [3]. A suitable refrigerant couple is able to provide a large temperature lift while improving system performance [2]. The HTC of a CRS can normally be charged as an intermediate-temperature refrigerant with a normal boiling point ranging from 0 °C to -60°C, such as R22 [4], R404A [5], R290, NH_3(R717), propylene (R1270), R12, R134a, and R410a, whereas the normal boiling points of low-temperature refrigerants such as R23, carbon dioxide (R744) and N2O are usually lower than -70°C.

2. NEED OF CASCADE SYSTEM

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 of substitution of CFC's and HCFC's regarding their bad impact on atmospheric ozone layer which protects earth from U.V rays.

For many industrial and medical applications, very low temperatures are required. Thus the temperatures of the order of -80ºC are required to freeze and store blood and for precipitation hardening of special alloy steels, temperatures as low as -90ºC are required. To obtain such low temperature by conventional system as mentioned earlier becomes difficult because of extremely low evaporator pressures. Thus even with a high pressure refrigerant like R-22, the evaporator pressure is 0.105 bar at -80ºC evaporator temperature. For R-12, the pressure is still lower. Operation at such low pressure becomes difficult both because of sealing problem as well as high displacement volume. Only R-13 can be safely used at such lower temperature as its saturation temperature pressure is 1.12 bar at -80ºC. However its critical temperature (28.8ºC) is very low and direct or stage compression up to condensing pressures is ruled out. Therefore, it is no alternative except cascading which consists of using two different vapour compression plants operating with different refrigerants and coupled together so that the condensing of low temperature stage vapour is achieved by evaporation of high temperature stage liquid. The maximum low temperature achieved by compound compression system is also controlled by the freezing point temperature of the refrigerant used. This difficulty can be solved by using cascade system in which two or more refrigerants can be used separately, and combining the operating cycle of one with other [1].

3. 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]. 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

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

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 and 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.

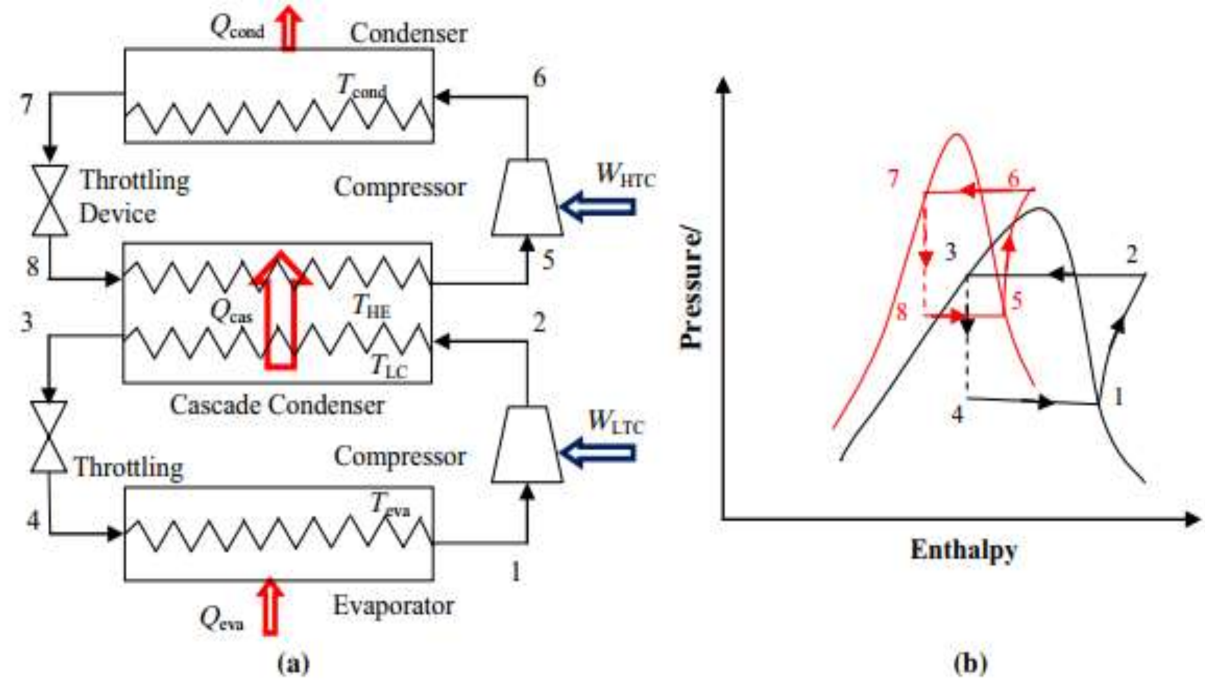

Fig. 1: Two stage cascade refrigeration system and P-H chart

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

In Asia and Pacific regions, economic growth in the last few years has propelled the use of air-conditioning for space cooling along with the use of refrigeration system for year round space conditioning. This has led the increasing power demand and the requirement of efficient energy use for air –conditioning and refrigeration systems specifically in hot summer season. In India the energy consumption patterns in the use of refrigeration and air conditioning are fast growing as per Table- 1.

Table 1: Projected Power Consumption by Cooling Appliances (2006-2031)

Heating Cooling	Year	2006	2011	2016	2021	2026	2031
Fans	Operating GWh /Yr	22,724	34,100	49,310	67,521	84,441	100,185
Air -cooler	Operating GWh /Yr	8,091	13,373	21,186	31,828	43,626	55,975
Air - conditioning	Operating GWh /Yr	2,298	5,084	10,783	20,966	34,675	49,913
Total energy consumption	Total GWh/yr	2,308	5,099	10,806	21,005	34,737	50,000
% Increase	from previous yr	NIL	46	47	51	60	96

Key reasons attributing to this increasing power consumption include:

- Growth in population
- Greater demand for building services
- Need for better comfort levels
- Longer duration of occupants spent time inside buildings

Energy consumption in Asia and Pacific regions has recently expanded rapidly compared with the rate of worldwide expansion.

4. Review of Past Studies

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. **Yilmaz & Selbas (2019)** had done a comparative thermodynamic performance analysis of cascade system (CCS) for cooling and heating applications is presented and compared for different refrigerant couples. The CCS consists of the low-temperature cycle (LTC) and high-temperature cycle (HTC). The CO_2 was used as working fluid in LTC, whereas the HFE 7000, R134a, R152a, R32, R1234yf, and R365mfc refrigerants were used in HTC. The heating and cooling coefficients of performance (COPht, COPcl) and exergy efficiency of CCS are investigated parametrically according to various factors such as the evaporator, condenser, and reference temperatures. After thermodynamic analyses are completed, the COPcl of CCS is obtained as 1.802, 1.806, 1.826, 1.769, 1.777, and 1.835 for CO2-HFE7000, CO2-R134a, CO2-R152a, CO2-R32, CO2-R1234yf, and CO2-365mfc refrigerant couples, respectively. Furthermore, the heat exchanger has the highest exergy destruction rate, whereas the expansion valves have the lowest of exergy destruction rate. In **Canan Cimsit (2018)** study, the absorption part has been designed to improve the performance of absorption – vapour compression cascade cycle as serial flow double effect. The detailed 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. Also the thermal energy consumption in the cascade cycle is 38% lower than the single effect absorption–vapour compression cascade refrigeration cycle. It is found that the minimum & maximum exergy efficiency occurs in the cooling set & low pressure generator (LPG) as 21.85% & 99.58% respectively. **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. **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. **R.S. 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. The utility of R1234ze and R1234yf and in the high temperature circuits and new eco-friendly refrigerants in the intermediates circuits and R134a or R404a in the low temperature cascade circuit have been optimized. It was observed that in the low temperature (between -50ºC to -100ºC) applications. It was observed that the best combination in terms of R1234ze-R134a-R404a gives better thermal performance than using R1234yf-R134a-R404a. Similarly other combination in terms of R1234ze-R134a-R404a gives better thermal performance than using R1234ze-R1234yf-R404a. **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. **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. **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. **Kushwaha et. al. (2016)** introduces a new concept of Two Stage Vapour Compression-Absorption Cascade Refrigeration System (TSVCACRS) for achieving low temperature Industrial Cooling. The system comprises of Two Stage Vapour Compression System having flash intercooler integrated with single stage vapour absorption refrigeration system, thermally coupled by means of cascade condenser heat exchanger. That proposed TSVCACRS system would minimize the compressor works up to 28%, compared to existing installed TSVCACRS. **Gami et.al. (2014)** reported a thermodynamic energy and exergy analysis cascade refrigeration system using refrigerants pairs R134a R23and R290-R23 is presented in this paper to optimize the operating parameters of the system. The results show that COP and exergetic efficiency decreases when degree of superheating increases in LT system and increases when degree of superheating increases in HT system and remain constant when degree of superheating increases in HT and LT system. The results show that COP and exergetic efficiency increases when degree of sub cooling increases in all three cases as discussed above. **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. **Messineo et.al. (2012)** the thermodynamic analysis of a cascade refrigeration system working at T_E=-35°c and T_C= 35°c is reported. In particular, six different refrigerants were analyzed in the HTC, of which three were natural refrigerants (R717, R290 and R600), and three were synthetic refrigerants (R404A, R410A and R134a). In the Low temperature circuit, carbon dioxide was considered exclusively. In conclusion, the results obtained show that a cascade refrigeration system using natural refrigerants is an interesting alternative to systems using synthetic refrigerants for energetic, security and environmental reasons. **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.

References

[1] Canan Cimsit, Thermodynamic Performance Analysis of the double effect absorption –vapour compression cascade refrigeration cycle. Journal of Thermal Science and Technology, Vol.13, NO.1 (2018).
[2] Leonardo Arrieta Mondragon, Guimllermo Valencia Ochoa, Gaudy Parda Botia, Computer-Aided Simulation of the Energetic and Exergetic Efficiency of a Two Stage Cascade Cooling Cycle, International Journal of Applied Engineering Research, ISSN: 0973-4562, Volume 13, NO. 13 (2018), pp.11123-11128.
[3] Jinkun Zhou, Shengjian Le, Qin Wang and Dahong Li, Optimization analyses on the performance of an auto-cascade absorption refrigeration system operating with mixed refrigerants, International Journal of Low- Carbon Technologies (2018), 13, 212-217.
[4] Umesh C. Rajmane, Cascade Refrigeration System: R404a-R23 Refrigerant, Asian Journal of Electrical Sciences, Vol.6, NO. 1(2017), pp. 18-22.
[5] R.S.Mishra, Thermal modeling of three stage vapour compression cascade refrigeration system using entropy generation principle for reducing global warming and ozone depletion using ecofriendly refrigerants for semen preservation, International Journal of Engineering and Innovation, vol.1, issue 2 (2017), 22-28.
[6] Umesh C.Rajmane, A Review of Vapour Compression Cascade Refrigeration System, Asian Journal of Engineering and Applied Technology, Vol.5 No.2, (2016), pp.36-39.
[7] Bhavesh Patel, Surendra Singh Kushwaha and Bhumik Modi, Thermodynamic modeling & parametric study of a Two Stage Compression – Absorption Refrigeration System for Ice Cream Hardening Plant. International Conference on recent advancements in Air conditioning & Refrigeration, Bhubaneswar, India, 10-12 Nov (2016).
[8] Manoj Dixit, S.C. Kaushik, Akilesh Arrora, Energy & Exergy Analysis of Absorption – Compression Cascade refrigeration system, Journal of Thermal Engg. 5(2016), pp 995-1006.
[9] J .Alberto Dopazo, Jose Fernandez-Seara-Theoretical analysis of a CO_2-NH_3 Cascade refrigeration system for cooling applications at low temperature, applied thermal engineering 29 (2009) 1577-1583.
[10] J. Fernandez, Vapour compression –absorption cascade refrigeration system, Applied Thermal engineering 26(2006) 502-512.
[11] L .Kauouani, E-Nehdi, Cooling performance and energy saving of a compression – absorption refrigeration system assisted by geothermal energy applied thermal engineering, 26 (2006) 288-294.
[12] T .Lee, C. Liu, T .Chen ,Thermodynamic analysis of optimal condensing temperature of cascade condenser in CO_2/NH_3 Cascade refrigeration system, international journal of refrigeration 29 (2006) 1100-1108.
[13] A. Kilicarlsan, An experimental investigation of a different type vapour compression cascade refrigeration system .Applied Thermal engineering 24 (2004) pp.2611-2626.
[14] G.L. Molenaar use of R22/23 in lieu of R-502/13 in a cascade refrigeration system, in: Proceedings, Annual international journal of Energy Research 26 (8) (2002), 763-774.
[15] Kanoglu, Mehmet, Exergy analysis of multistage cascade refrigeration cycle used for natural gas liquefaction." International Journal of energy Research 26 (2002): 763-74.
[16] Zhili Sun, Youcai Liang, Shengchun Liu, Weichuan Ji, Runqing Zang, Rongzhen Liang, Zhikai Guo, Comparative analysis of thermodynamic performance of a cascade refrigeration system for refrigerant couples R41/R404A and R23/R404A, 184, 19-25, 2016.
[17] A. D. Parekh, P. R. Tailor, Thermodynamic Analysis of Cascade Refrigeration System Using R12-R13, R290-R23 and R404A-R23, International Journal of Mechanical and Mechatronics Engineering, 8(8), 1351-1356.