Thermodynamic Analysis of Cascade Refrigeration System Using R12-R13, R290-R23 and R404A-R23

A. D. Parekh, P. R. Tailor

***Abstract*—**The Montreal protocol and Kyoto protocol underlined the need of substitution of CFC's and HCFC's due to their adverse impact on atmospheric ozone layer which protects earth from U.V rays. The CFCs have been entirely ruled out since 1995 and a long-term basis HCFCs must be replaced by 2020. All this events motivated HFC refrigerants which are harmless to ozone layer. In this paper thermodynamic analysis of cascade refrigeration system has been done using three different refrigerant pairs R13-R12, R290-R23, and R404A-R23. Effect of various operating parameters i.e. evaporator temperature, condenser temperature, temperature difference in cascade condenser and low temperature cycle condenser temperature on performance parameters viz. COP, exergetic efficiency and refrigerant mass flow ratio have been studied. 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.

***Keywords*—**Thermodynamic analysis, cascade refrigeration system, COP, exergetic efficiency.

I. Introduction

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 [1]. A lot of research work is going on to analyze the performance of cascade refrigeration system using alternate refrigerants. J. Alberto Dopazo et al. [2] carried Theoretical analysis of a CO_2–NH_3 cascade refrigeration system for cooling applications at low temperatures; they concluded that COP increases 70% when the T_E varies from -55°C to -30°C. The COP diminishes 45% when the T_C increases from 25°C to 50°C. The system COP diminishes 9% when ΔT_{CC} varies from 3°C to 6°C. The exergetic efficiency decreases 45% and 9% with the increases indicated above in T_C and ΔT_{CC}. H.M. Getu and P.K. Bansal [3] carried Thermodynamic analysis of an R744–R717 cascade Refrigeration system, they showed that an increase in condensing temperature resulted in a decrease in COP and an increase in refrigerant mass flow ratios. An increase in evaporating temperature increased COP of the system and decreased mass flow ratios. An increase in temperature difference in cascade condenser reduced both COP and mass flow ratios. D. Pyasi and R. C. Gupta [4] carried work on Performance analysis of R404A-R508b Cascade Refrigeration cycle for low temperature, they concluded that System overall performance (COP) and Exergetic efficiency gets increased by 0.88 to 1.19 and 0.60 to 0.626 as the evaporator temperature is varied from (-90^{0}C to-70^{0}C) while other parameters are kept constant, The system COP decreases by 1.06 to 0.61 and exergetic efficiency deteriorates by 0.65 to 0.43 when condenser temperature of high stage is varied from 30°C to 50°C keeping other parameter constant, System COP deteriorates by 0.95 to 0.84 and Exergy by 0.60 to 0.53 when temperature difference of cascade condenser is varied from 2°C to 10°C. Mass flow ratio is decreased from (1.84 to 1.34) when low stage condenser temperature is varied from -45°C to -20°C keeping various other parameter constant.

In present study the thermodynamic analysis of cascade refrigeration system has been done with three refrigerant pairs R12-R13, R290-R23 and R404A-R23. The effect of various operating parameters is studied on performance parameters. Thermodynamic analysis is carried out by developing computational model in Engineering Equation solver (EES).

II. Cascade Refrigeration System

Fig. 1 shows cascade refrigeration system with its components. It consists of two stages lower temperature (pressure) cycle and higher temperature (pressure) cycle which is connected by cascade condenser. The main components of cascade system are: Low temperature compressor, High temperature compressor, Condenser, Evaporator, Cascade Condenser and Throttling devices for Low temperature cycle and High temperature cycle.

During process 1-2 the low temperature cycle refrigerant is compressed isentropically. It is then passes through cascade condenser where it gives heat to refrigerant of higher

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temperature cycle (process 2-3). It is expands in throttling device (process 3-4) and further passes to evaporator (process 4-1) to produce necessary refrigerating effect. In higher stage refrigerant is compressed in high temperature cycle compressor (process 5-6), then it passed through condenser where it rejects heat (process 6-7). It expands isentropically in throttling device (process 7-8) further passes to cascade condenser where heat transfer between two refrigerants takes place.

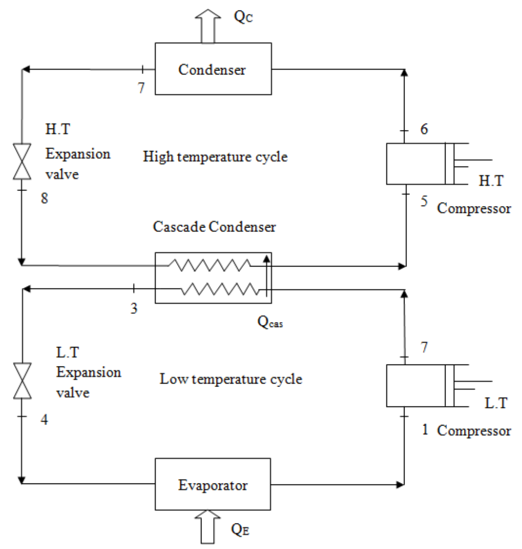

Fig. 1 Cascade refrigeration system

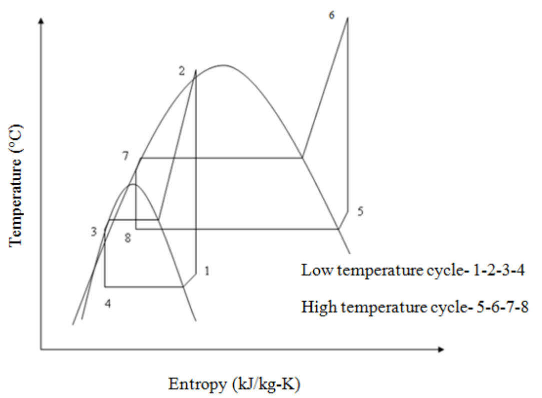

Fig. 2 Temperature-Entropy diagram of cascade refrigeration system

III. Thermodynamic Modeling

The thermodynamic analysis of the two-stage cascade refrigeration system was performed based on the following general assumptions:

- Negligible pressure and heat losses or gains in the pipe networks or system components.
- The dead state is T_0=25°C and P_0=1 atm
- Negligible changes in kinetic and potential energy.
- Isenthalpic expansion of refrigerants in expansion valves.

The capacity of the evaporator is calculated by the equation (RE):

$$RE = m_L(h_1 - h_4) \tag{1}$$

Power consumed by HT cycle compressor is calculated by equation (W_H):

$$W_H = m_H(h_6 - h_5) \tag{2}$$

Power consumed by LT compressor is calculated by the equation (W_L):

$$W_L = m_L(h_2 - h_1) \tag{3}$$

Exchange of heat by refrigerants in cascade condenser is calculated by the equation (Q_{cas}):

$$Q_{cas} = m_L(h_2 - h_3) = m_H(h_5 - h_8) \tag{4}$$

Refrigerant mass flow ratio is calculated by the equation (m_H/m_L):

$$\frac{m_H}{m_L} = \frac{(h_2 - h_3)}{(h_3 - h_8)} \tag{5}$$

Heat rejected by condenser calculated by the equation (Q_C):

$$Q_C = m_H(h_6 - h_7) \tag{6}$$

Coefficient of performance of system is calculated by equation [5]

$$COP = \frac{Q_E}{W_L + W_H} \tag{7}$$

Exergetic efficiency of system is calculated by the equation [6]

$$\eta_{exe} = \frac{W_{rev}}{W_{act}} \tag{8}$$

Reversible work input of system is calculated by the equation [7]

$$W_{rev} = m_L(h_1 - h_4)\left[\frac{T_0}{T_1} - 1\right] \tag{9}$$

These all above equations are used for thermodynamic modeling of cascade refrigeration system.

IV. Results and Discussions

Computational model has been developed in EES to find effect of various design and operating parameters on the on the performance parameters which are coefficient of performance (COP), exergetic efficiency (η_{exe}) and refrigerant mass flow ratio (m_H/m_L). The different operating parameters which are varied during thermodynamic analysis and their effect on the performance parameter are listed in this section. The parameters which are varied explained here.

1. Evaporator temperature (T_E) varied from -80°C to -60°C
2. Condenser temperature (T_C) varied from 25°C to 45°C

3. Temperature difference in cascade condenser (ΔT_{CC}) varied from 2°C to 6°C
4. L.T cycle condenser temperature (T_{casL}) varied from -5°C to -35°C

Standard operating parameters of cascade refrigeration system are taken as below

1. Evaporator temperature (T_E) = -80°C
2. Condenser temperature (T_C) = 25°C
3. Temperature difference in cascade condenser (ΔT_{CC}) = -3°C
4. Low temperature cycle condenser temperature (T_{casL}) = -5°C

A. Effect of Evaporator Temperature (T_E):

The effect on COP, exergetic efficiency and refrigerant mass flow ratio, when evaporator temperature varied from -80°C to -60°C in the interval of 5°C keeping other parameters constant is shown in Figs. 3 (a), (b), and (c) respectively. For a given condensing temperature, the pressure ratio increases as the evaporator temperature decreases.

Fig. 3 (a) shows that as evaporator temperature increases the COP increases. COP varies from 1.147 to 1.764, 1.176 to 1.779, and 1.158 to 1.743 for R12-R13, R290-R23, and R404A-R23 respectively. Among all three pair R12-R13 shows maximum change in COP followed by R290-R23 and R404A-R23.

Figs. 3 (b) and (c) show that as evaporator temperature increases, the exergetic efficiency improves while mass flow rate decreases. Exergetic efficiency varies from 0.6175 to 0.6976, 0.6335 to 0.7033 and 0.6233 to 0.689 for R12-R13, R290-R23 and R404A-R23 respectively. For R12-R13 the variation of exergetic efficiency is highest followed by R290-R23 and R404A-R23.

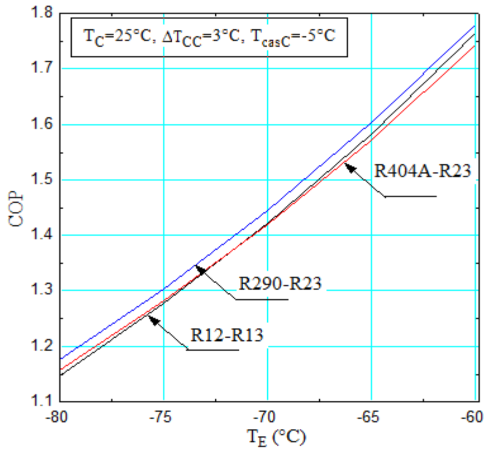

Fig. 3 (a) Effect of evaporator temperature on COP

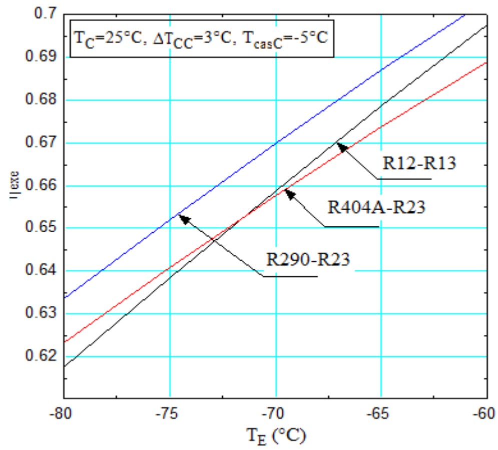

Fig. 3 (b) Effect of evaporator temperature on exergetic efficiency

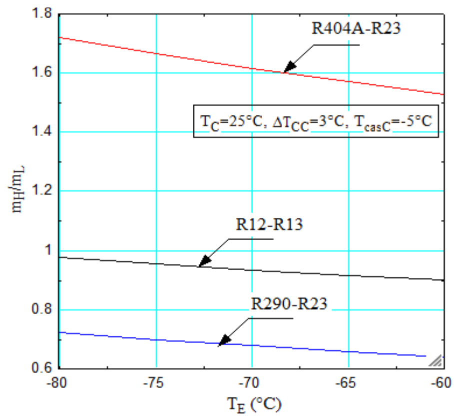

Fig. 3 (c) Effect of evaporator temperature on refrigerant mass flow ratio

B. Effect of Condenser Temperature (T_C):

The condenser temperature is varied from 25°C to 45°C in the interval of 5°C and other parameters are kept constant. The effect on COP, exergetic efficiency and refrigerant mass flow ratio is shown in Figs. 4 (a), (b), and (c) respectively.

Fig. 4 (a) shows that when condensing temperature varied from 25°C to 45°C the COP of system is decreasing and It decreases from 1.147 to 0.9453, 1.176 to 0.9536 and 1.158 to 0.9038 for R12-R13, R290-R23 and R404A-R23 respectively. Out of three refrigerant pairs R404A-R23 shows maximum change followed by R290-R23 and R12-R13.

Fig. 4 (b) shows that as condensing temperature increases the exergetic efficiency is decreases. The exergetic efficiency decreases from 0.6175 to 0.509, 0.6335 to 0.5135 and 0.6233 to 0.4867 respectively R12-R13, R290-R23 and R404A-R23 respectively. R404A-R23 shows maximum variation for condensing temperature change followed by R290-R23 and R12-R13.

Fig. 4 (c) shows that as condensing temperature increases the refrigerant mass flow ratio increases. The increases are from 0.9769 to 1.157, 0.7217 to 0.883 and 1.719 to 2.28 for R12-R13, R290-R23 and R404A-R23 respectively. The R404A-R23 show maximum variation followed by R12-R13 and R290-R23 respectively.

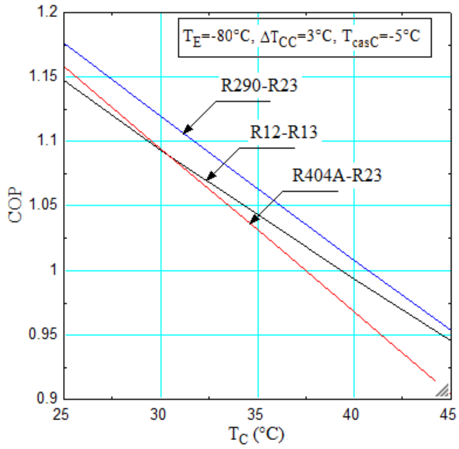

Fig. 4 (a) Effect of condenser temperature on COP

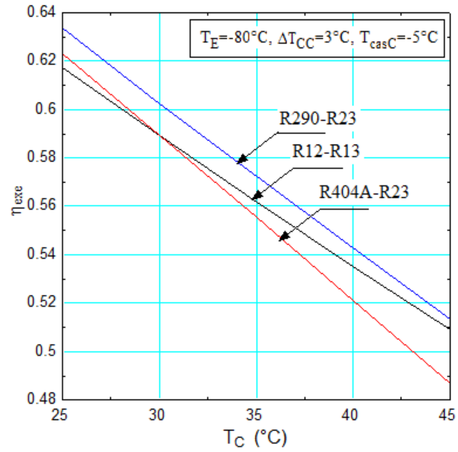

Fig. 4 (b) Effect of condenser temperature on exergetic efficiency

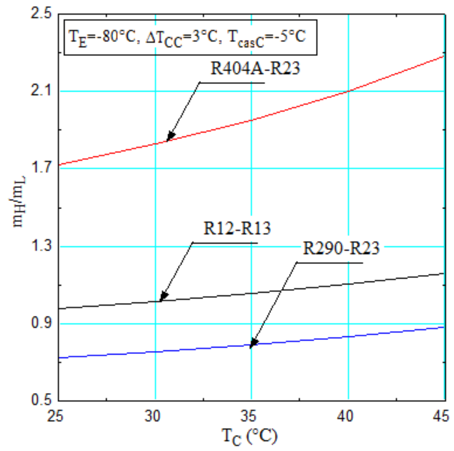

Fig. 4 (c) Effect of condenser temperature on refrigerant mass flow rate

C. Effect of Temperature Difference in Cascade Condenser (ΔT_{CC}):

The temperature difference in cascade heat exchanger is varied from 2°C to 6°C in the interval of 1°C and other parameters are kept constant. The effect of temperature difference in cascade condenser on COP, exergetic efficiency and refrigerant mass flow ratio is shown in Figs. 5 (a), (b) and (c) respectively.

The effect of temperature difference in cascade condenser on COP is shown in Fig. 5 (a), when the temperature difference in cascade condenser increases the COP of system decreases. The COP varies from 1.158 to 1.112, 1.189 to 1.14 and 1.171 to 1.119 for R12-R13, R290-R23 and R404A-R23 respectively. Out of three refrigerant pairs R404A-R23 responds maximum for change in temperature difference in cascade condenser.

The effect of temperature difference in cascade condenser on exergetic efficiency is shown in Fig. 5 (b), when the temperature difference in cascade condenser is increases the exergetic efficiency is decreases. The exergetic efficiency varies from 0.6237 to 0.599, 0.6401 to 0.6137 and 0.6303 to 0.6025 for R12-R13, R290-R23 and R404A-R23 respectively. The R404A-R233 shows maximum variation for change in temperature difference in cascade condenser.

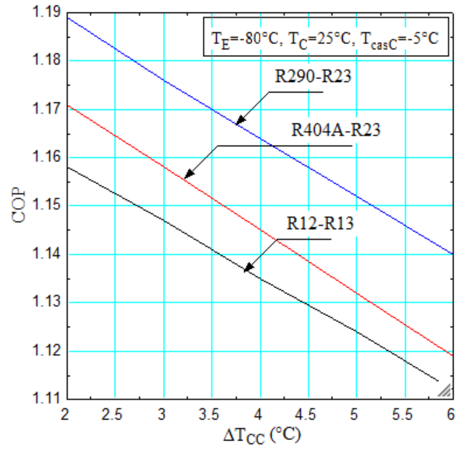

Fig. 5 (a) Effect of temperature difference in cascade condenser on COP

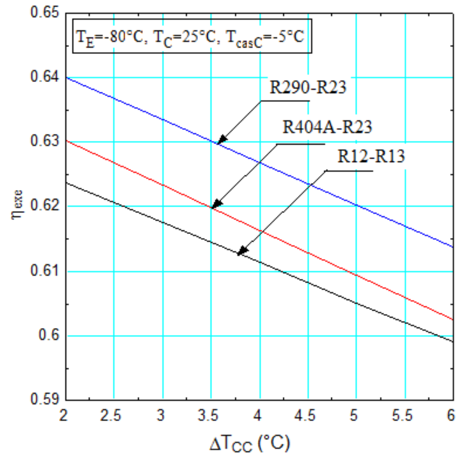

Fig. 5 (b) Effect of temperature difference in cascade condenser on exergetic efficiency

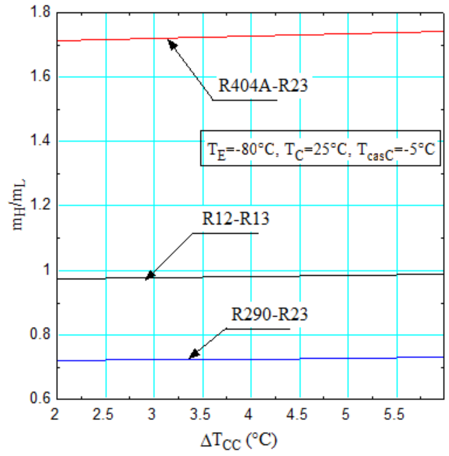

Fig. 5 (c) Effect of temperature difference in cascade condenser on refrigerant mass flow ratio

When the temperature difference in cascade condenser is increases the refrigerant mass flow ratio increases as shown in Fig. 5 (c). The changes in refrigerant mass flow ratio are from 0.9735 to 0.9872, 0.719 to 0.7299 and 1.712 to 1.741 for R12-R13, R290-R23 and R404A-R23 respectively. The R404A-R23 shows maximum variation for temperature difference in cascade condenser.

D. Effect of L.T Cycle Condenser Temperature (T_{casl}):

The low temperature cycle condenser temperature is varied from -35°C to -5°C in the interval of 5°C and the effect on performance parameters is analysed. The effect of low temperature cycle condenser temperature on COP, exergetic efficiency and refrigerant mass flow ratio is shown in Figs. 6 (a), (b), and (c) respectively.

Fig. 6 (a) shows that as low temperature cycle condenser temperature is increases the COP of system decrease. The COP decreases from 1.355 to 1.147, 1.325 to 1.176 and 1.251 to 1.158 for R12-R13, R290-R23 and R404A-R23 respectively. The R12-R13 shows maximum variation in COP followed by R290-R23 and R404A-R23.

Fig. 6 (b) shows that as low temperature cycle condenser temperature increases the exergetic efficiency decreases. The exergetic efficiency decreases from 0.7298 to 0.6175, 0.7136 to 0.6335 and 0.6734 to 0.6233 for R12-R13, R290-R23 and R404A-R23 respectively. The R12-R13 shows maximum variation in exergetic efficiency followed by R290-R23 and R404A-R23.

Fig. 6 (c) shows as the low temperature cycle condensing temperature increases the mass flow ratio is decreases. The mass flow ratio decreases from 1.231 to 0.9769, 0.8631 to 0.7217 and 2.103 to 1.719 for R12-R12, R404A-R23 and R404A-R23 respectively. The R404A-R23 shows maximum variation followed by R12-R13 and R290-R23.

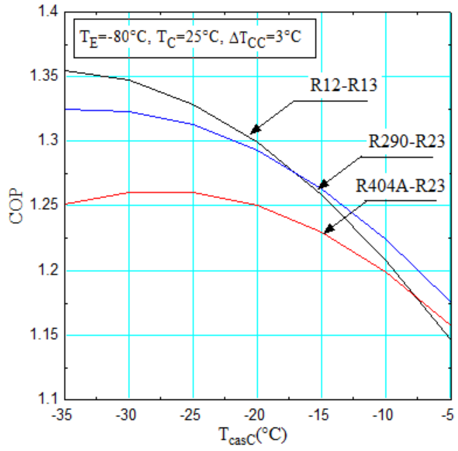

Fig. 6 (a) Effect of LT cycle condenser temperature on COP

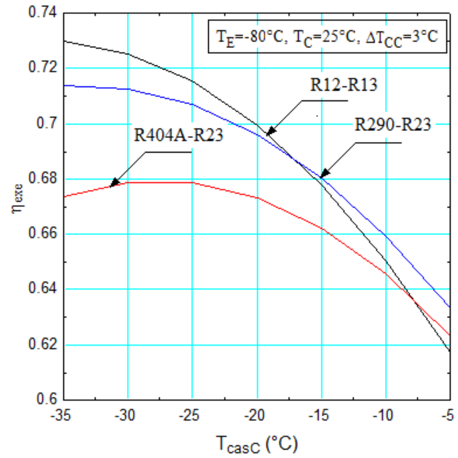

Fig. 6 (b) Effect of LT cycle condenser temperature on exergetic efficiency

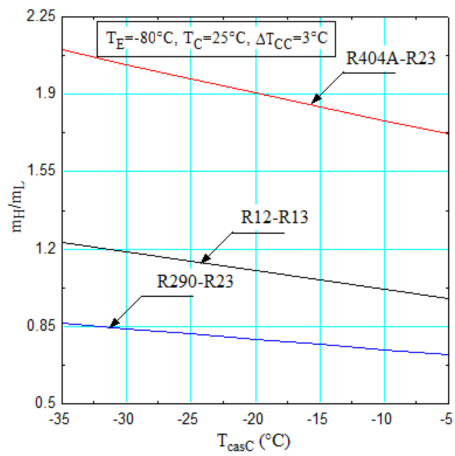

Fig. 6 (c) Effect of LT cycle condenser temperature on refrigerant mass flow ratio

V. Conclusion

In present work thermodynamic analysis of cascade refrigeration system has been carried out by developing computational model in EES to find the effect of various operating parameters on the performance parameters. The following conclusions are drawn from present study.

- 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.
- When the evaporator temperature varied from to -80°C to -60°C the COP increased by 53.8% for R12-R13, 51.2% for R290-R23 and 50.51% for R404A-R23.
- When condenser temperature varied from 25°C to 45°C the COP decreased 17.5% for R12-R13, 18.9% for R290-R23, 21.9% for R404A-R23.
- When Temperature difference in cascade condenser varied from 2°C to 6°C the COP decreased 3.97% for R13-R2, 4.12% for R290-R23, 4.44% for R404A-R23.
- When lower temperature cycle condenser temperature varied from -5°C to -35°C the COP increased by 18.13% for R12-R13, 12.67% for R290-R23, 8.03% for R404A-R23.

NOMENCLATURE

T_E	Evaporator temperature (°C)
T_C	Condenser temperature (°C)
ΔT_{CC}	Temperature difference in cascade condenser (°C)
T_{casC}	Temperature of LT cycle condenser (°C)
RE	Refrigerating effect (kW)
COP	Coefficient of Performance
m_H	Refrigerant mass flow rate of HT cycle (kg/s)
m_L	Refrigerant mass flow rate of LT cycle (kg/s)

Greek Letters

η	Efficiency
ρ	Density
Δ	Change
Δ	Change

Subscript

act	Actual
E	Evaporator
C	Condenser
exe	Exergetic
isen	Isentropic
HT	High Temperature
LT	Low Temperature
rev	Reversible

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