JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

"THERMAL MODELING OF TWO STAGE VAPOUR COMPRESSION CASCADE REFRIGERATION SYSTEM USING R41/R290 & R41/R404A"

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ABSTRACT

The choice of refrigerants for the High Temperature Circuit and the Low Temperature Circuit is the most important part of the design of a Cascade Refrigeration System (CRS). My research project's goal is to look at two different Cascade Refrigeration Systems that use two different sets of refrigerant, R41/R290 and R41/R404A. Thermodynamic analysis is done on the performance of Cascade Refrigeration System with R41/R290 refrigerant pair and R41/R404A refrigerant pair. This is done with the help of a mathematical model. Mathematical modeling is done with the help of the EES-Engineering Equation Solver software. Under different operating conditions like T_{EVA}, T_{CON}, and T_{CASLTC}, the performance of a Cascade Refrigeration System was looked at in terms of Coefficient of Performance, total exergy destruction, total work and exergetic efficiency. The results indicate that the Coefficient of Performance of the refrigerant pair R41/R290 used in a Cascade Refrigeration System is higher than the Coefficient of Performance of the refrigerant pair R41/R404A used in the same operating conditions.

KEYWORDS: EES, CRS, Coefficient of Performance, Thermal Modeling

1. **Introduction**

We can't imagine what life would be like without fridges and air conditioners. Refrigeration and air conditioning make it easier for us to go about our daily lives. It's important in every part of our daily lives, like keeping fresh veggies, dairy products, and eggs fresh, preserving food, making ice and ice cream, cooling rooms, etc. It is also used in important ways in the medical and business fields. In the medical field, it can be used to store blood, drugs and vaccines, parts for donation, blood cells, etc. Due to the COVID19 world outbreak, vaccines need to be kept at a very low temperature, which can only be done with a cooling system. There are a lot of ways that refrigeration and air conditioning are used in industry. It is not just the goods industry; it also includes the process industry. Some examples are power plants, drug companies, and chemical businesses.

2. **Cascade Refrigeration System**

There are two circuits in a cascade refrigeration system. One is HTC and the other is LTC. HTC stands for "high temperature circuit," and LTC stands for "low temperature circuit." Both circuits are run at different temperatures and use different substances to cool. The LTC and HTC sides of a cascade cooling system are linked by a heat exchanger. The LTC, MTC, and HTC sides of a three-stage cascade liquid refrigeration system are connected by two heat exchangers. MTC stands for middle temperature circuit. HTC works at a high evaporating temperature, while LTC works at a low evaporating temperature and has a cooling effect. A heat exchanger is used as a cascade condenser in a two-stage cascade vapour cooling device. This cascade condenser works as an evaporator for HTC and as a condenser for LTC. The high temperature circuit uses refrigerants with a higher boiling point and a higher critical point, and the low temperature circuit uses refrigerants with a lower boiling point. The cascade refrigeration system is made up of two or more than two VCRS.

3. Criteria for Choosing Refrigerants in the Cascade System

The choice of refrigerants for the high temperature circuit and the low temperature circuit is the most important part of the design of a cascade vapour refrigeration system. When choosing the refrigerants for the Cascade Refrigeration System, you should think about the following things:

I. Because air, water, and land pollution is getting worse around the world, scientists are working on making new refrigerants that are safe for nature and good for the environment. These coolants have a very low GWP and no ODP. Due to the kyoto protocol, the montreal protocol, and the kigali amendment, refrigerants that are bad for the environment are being phased out and their use is being cut down. This helps cut down on green house gas emissions. This will help keep the world safe. Choose the pairs of refrigerants for a cascade system that have a very low GWP and no ODP and are safe for the environment.

II. Because they are better for the earth, natural refrigerants should be chosen for a cascade refrigeration system.

III.The boiling point, the critical point, and the freezing point are the key features of refrigerants that can help you choose the right ones for a cascade system. The refrigerant in a low-temperature circuit should have a low freezing point and a low boiling point. The temperature to be reached should be less than the point at which the refrigerant freezes. In a high temperature circuit, the boiling point of the refrigerant should be higher than in a low temperature circuit. Both the refrigerant's critical pressure and temperature should be high. The boiling point is closely related to how much cooling is needed. As low as possible should be good.

4. Literature Review

ENRIQUE ÁNGELRODRÍGUEZ-JARA et.al [1] [2022] current study offers two adjustments to the auto-cascade system by adding an ejector mechanism to increase the coefficient of performance (COP). In the first alteration, the ejector serves as an expansion device at the phase-output, separators whereas in the second, it serves as a pre-compression stage. As an alternative to traditional refrigerants with a very high GWP, a combination of the hydrocarbons iso-butane (R600a) & ethylene (R1150) was used. The current analysis finds that ethylene and iso butane are a reasonable mix for auto-cascade cycles and the ejector may be applied to increase the COP without adding undue complexity or expense.

JIARUI LIU et al. [2] [2022] research proposed a new of auto-cascade refrigeration cycle. The ejector not only substitutes one expansion valve in the innovative cycle to reclaim partial expansion work, but it also significantly minimizes the throttling loss of the additional expansion valve linked to the evaporator. The energy and exergy analysis methodologies are utilized to analyze and compare the performance of the NEARC employing R290/R170 with the conventional auto-cascade refrigeration cycle (CARC) and the previously suggested ejector-enhanced auto-cascade refrigeration cycle (EARC). The simulation findings reveal that the COP & exergy efficiency of NEARC are better to those of CARC under all given operating circumstances, but not necessarily better to those of EARC.

MINGZHANG PAN et al. [3] (2020) is looked at the cascade refrigeration system (CRS). It is an important system that can reach an evaporating temperature as low as -170 ^{0}C and expands the range of temperatures that conventional refrigeration systems can handle.

BARIS YILMAZ et al. [4] (2020) examined natural and synthetic refrigerants used in cascade refrigeration systems operating at very low temperatures. In this study, natural refrigerants R1270–R170 and synthetic refrigerants R404 (A)–R508 (B) were used. He analyzed both pairs of refrigerants in terms of their COP and environmental impact to determine which was superior. Using Engineering Equation Solver software, the performance of the refrigerant combinations under certain operating circumstances is compared. Natural refrigerants R1270-R170 have a higher coefficient of performance (COP) than synthetic refrigerants R404 (A)-R508 (B). The TEWI for synthetic refrigerants R404 (A)-R508 (B) is just twice that of natural refrigerants R1270-R170. The performance of natural refrigerants is superior to that of synthetic refrigerants.

YIJIAN HE et al. [5] (2020) created a cascade system that employs 45-600°C heat. He creates a two-stage compression cascade absorption system. In compression, R1234yf and R1234ze (E) refrigerants are used, whereas the Li Br/H2O refrigerant combination is chosen for absorption. This system reaches 70 degrees Celsius. The COP input value is raised. If the evaporating temperature at the sub-cooler for condensation rises, the net COP will likewise rise. This technology has tremendous potential to use 45-600C heat.

5. Simulation Model

A simulation model is a combination of several numerical conditions that uses computers to get an approximation of the solution to the underlying genuine problem. To aid in the analysis of design issues, it is essential to comprehend the Physical model inside a numerical model.

Consequently, this section controls simulation modeling in two areas:

i. **CASCADE REFRIGERATION SYSTEM -R41/R290**

ii. **CASCADE REFRIGERATION SYSTEM -R41/R404A**

Two vapour compression refrigeration systems are combined to form the cascade refrigeration system. A heat exchanger links the two VCRS. Due to its low NBP, R41 is employed in LTC-Low Temperature Circuit. In the suggested cascade system, this refrigerant provides the needed cooling effect. In the HTC -High Temperature Circuit, the R290 refrigerant is used to condense the R41 of the LTC.

With LTC, R41 refrigerant in the evaporator at the associated evaporating temperature TEVA preserves the cooling obligation QevaR41 from atmospheric cooling at T_F temperature. It is then compressed using a compressor (R41).This compressed refrigerant then enters the cascade heat exchanger, in which it is condensed at a condenser temperature of TconR41 and then sent to the evaporator from where it was applied.

With HTC, QconR290 in the condenser rejects R290 refrigerant heat at a condensing temperature of Tcon R290 to the condensing medium at temperature T_0. The refrigerant is now expanded in the expansion valve and then enters the cascade heat exchanger, where it is evaporated at TevaR290 evaporating temperature, and finally compressed in the compressor. Once again, it is released into the condenser.

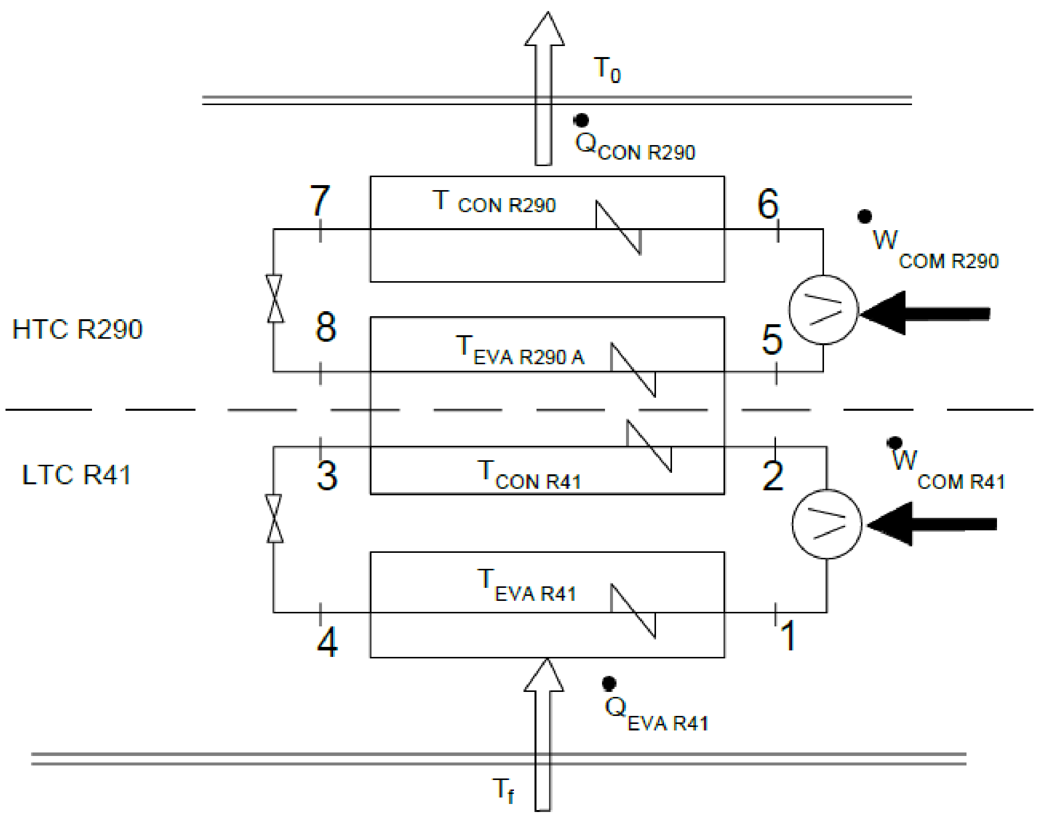

FIG 1 LINE DIAGRAM OF CRS -R41/R290

6. Assumptions for Cascade Refrigeration System -R41/R290

i. All segments are believed to represent steady state steady flow measurements. Minor variations in the potential and kinetic energies of the components are disregarded.

ii. At the outlets of the evaporator, condenser, and heat exchanger, the refrigerant is assumed to be in a saturated condition.

iii. Compressor used in the LTC of a cascade system with isentropic compression. 0.6 is the isentropic efficiency of the Compressor.

iv. Isenthalpic expansion devices are used in cascade systems.

v. It is considered that framework components of the system neither contribute nor reject heat. Also, pressure is believed to be negligible in the system.

vi. Equilibrium state temperature & pressure are t_O= 260C & p_O = 1.01325 bar.

vii. Temperature difference for cascade condenser is 4^0C.

7. **Mass & Energy Equilibrium**

The relationship shown below is used to calculate the COP of a refrigeration system

$$COP = Q_L/W_r$$

Where Wr = Total Work Required for the Refrigeration System

Q_L = Heat Extraction from Cold Body.

TABLE 1 MASS AND ENERGY EQUILIBRIUM EQUATIONS – R41/R290

COMPONENT	MASS EQUI.	ENERGY EQUI.
ltc (Compressor)	$m_2=m_1$	$W_{(comp)}R41=m_1*(h_{2s}-h_1)$
htc(Compressor)	$m_6=m_5$	$W_{(comp)}R290=m_5*(h_{6s}-h_5)$
ltc thrott. Device	$m_4=m_3$	$h_4=h_3$
htc thrott. Device	$m_8=m_7$	$h_8=h_7$
ltc Evap.	$m_1=m_4$	$Q_{(evap)}R41=m_1*(h_1-h_4)$
htc Condenser	$m_7=m_6$	$Q_{(cond)}R290= m_5*(h_7-h_6)$
C.H.E	$m_3=m_2,m_5=m_8$	$m_1*(h_3-h_2)=m_5*(h_5-h_8)$

8. Results & Discussion

To evaluate the efficiency of CRS systems for R41/R290 & R41/R404A refrigerant couples, a Numerical Model was developed in my study using engineering equation solver software. Both refrigerant couples' performance in a cascade refrigeration system is evaluated thermodynamically to determine which pair performs better. COP expresses the performance of a cascade vapour refrigeration system. The primary objective of my research is to determine the optimal operating conditions, including optimal condenser temperature, optimal evaporator temperature, etc. In order to evaluate the performance of the CRS system, a parametric model was developed.

This analysis's findings are essentially divided into two categories-

i. **THE EFFICACY OF THE R41/R290 REFRIGERANT COUPLE IN THE CRS SYSTEM.**
ii. **THE EFFICACY OF THE R41/R404A REFRIGERANT COUPLE IN THE CRS SYSTEM**

a. THE EFFECTS OF CHANGING T_{EVA}

The effect of varying T_{EVA} -T_1 on performance parameters such as COP of an R41/R290 and R41/R404A refrigerant pairs in the CRS system is showing in the graph. T_{EVA} ranges between -60 and -24^{0}C.

Other design constants are as follows-

i. Temperature of the condenser T_{CON} = 27^{0}C

ii. ΔT = 4°C(Temperature difference in C.H.E)

iii. Temperature on the Low Temperature Circuit side of the C.H.E

T_{CASLTC} = -7^{0}C

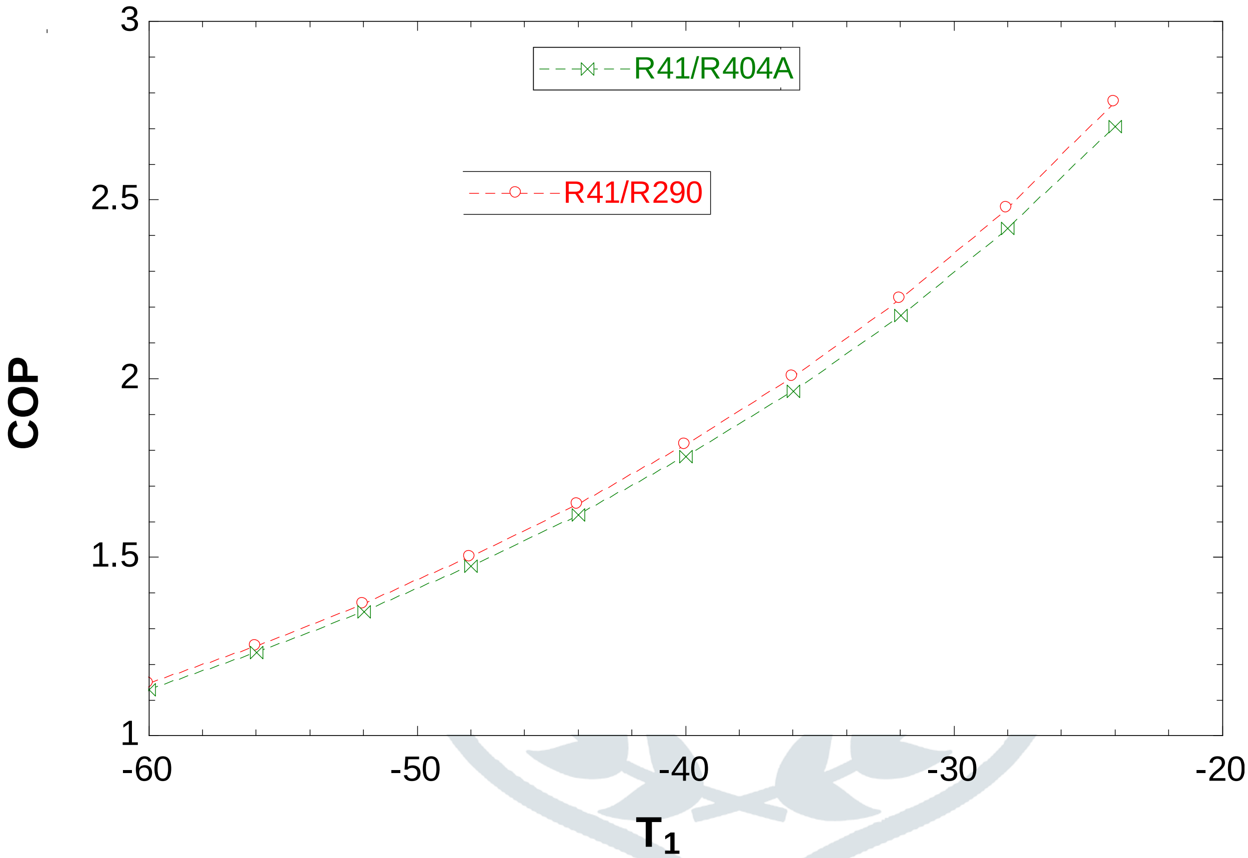

Fig 2 Effect OF Differing T_{EVA} ON COP OF R41/R290&R41/R404A REFRIGERANT PAIRS

Figure 2 shows that if the T_{EVA} goes up, the COP of the system as a whole also go up. T_{EVA} belongs between -60^{0}C and -24^{0}C. For calculations, the temperature here changes by 4^{0}C. The COP for the R41/R404A refrigerant couple is going up from 1.129 to 2.705, and the COP for the R41/R290 refrigerant couple is going up from 1.145 to 2.775. Both sets of refrigerants work at the same temperature in the evaporator. In a CRS, the R41/R290 refrigerant pair works better than the R41/R404A refrigerant pair.

b. THE EFFECTS OF CHANGING T_{CON}

The effect of varying T_{CON} –T_6 on performance parameters such as COP of an R41/R290 and R41/R404A refrigerant pairs in the CRS system is showing in the graph. T_{CON} ranges between 27 and 45^{0}C.

Other design constants are as follows:

i. Evaporator temperature T_{EVA}=-60^{0}C

ii. T = 4°C(Temperature difference in C.H.E)

iii. Temperature on the Low Temperature Circuit side of the C.H.E

$T_{CASLTC} = -7^0C$

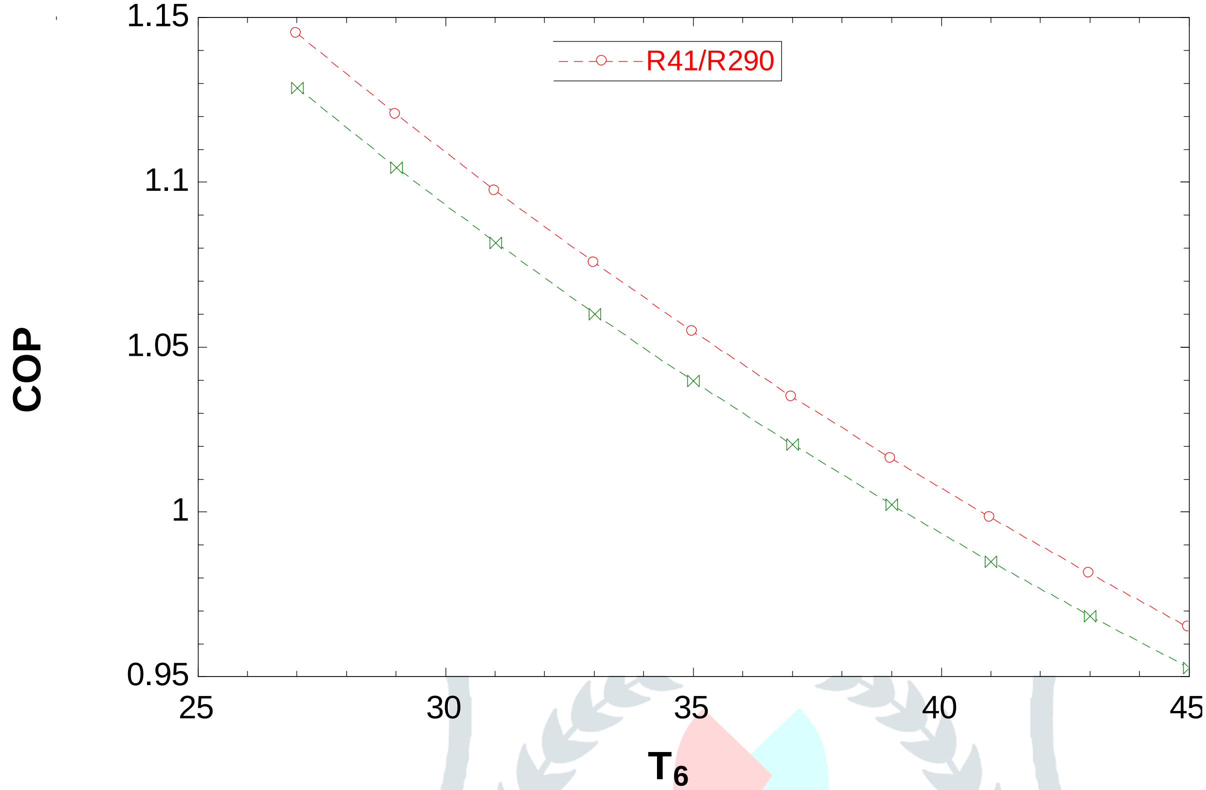

Fig. 3 Effect OF Differing T_{CON} ON COP OF R41/R290&R41/R404A REFRIGERANT PAIRS

c. THE EFFECTS OF CHANGING T_{CASLTC}

The effect of varying T_{CASLTC} –T_3 on performance parameters such as COP of an R41/R290 and R41/R404A refrigerant pairs in the CRS system is showing in the graph. T_{CASLTC} ranges between -30 and -3^0C.

Other design constants are as follows:

i. Evaporator temperature T_{EVA}=-60^0C

ii. ΔT = 4°C (Temperature difference in C.H.E)

iv. Temperature of the condenser T_{CON} = 27^0C

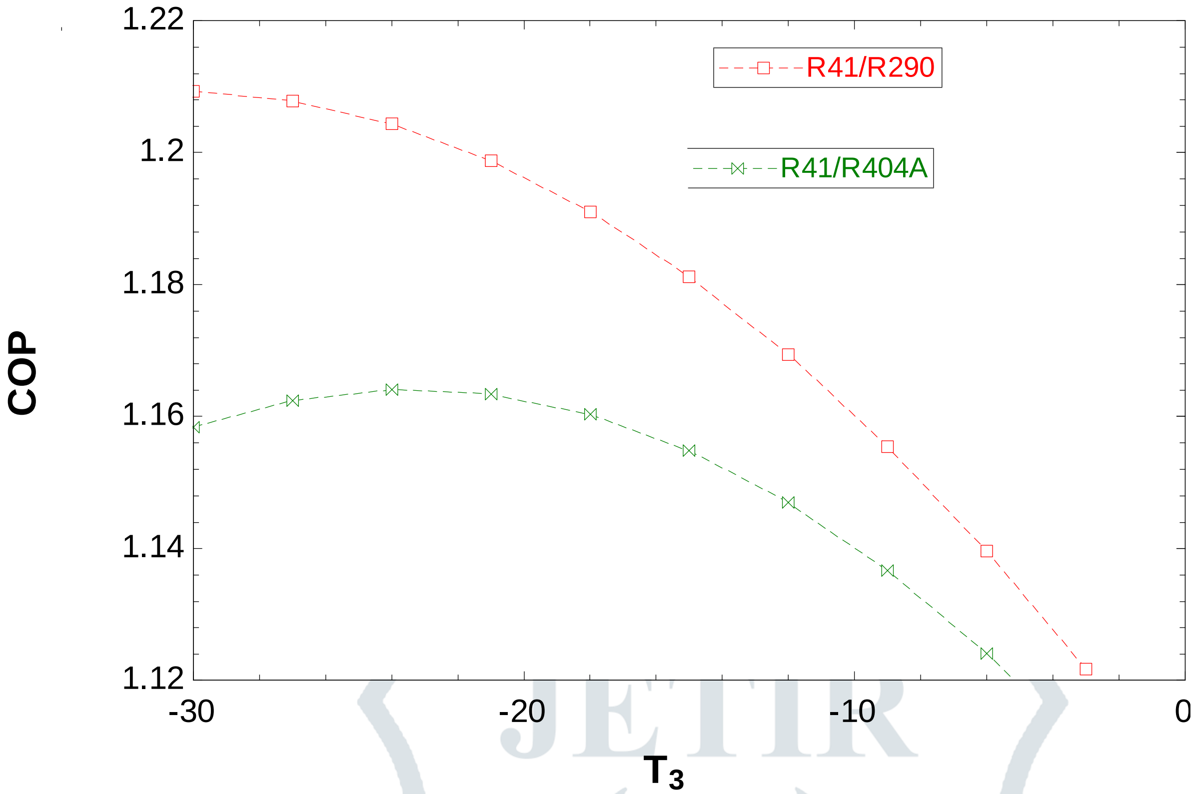

Fig. 4 Effect OF Differing T_{CASLTC} ON COP OF R41/R290&R41/R404A REFRIGERANT PAIRS

9. Conclusion

To evaluate the performance of CRS for R41/R290 & R41/R404A refrigerant pairs, a Numerical Model was developed in my research using EES-engineering equation solver software. Both refrigerant pairs performance in a CRS is compared thermodynamically to determine which pair performs better. COP expresses the performance of a CRS.

Important findings from my research are as follows-

I. On the grounds of thermodynamic research, R41/R290 has superior performance to R41/R404A.

II. R41/R290 refrigerant pair has a higher Coefficient of Performance -COP than R41/R404A refrigerant pair used in CRS.

III. If indeed the evaporator temperature (T_{EVA}) raises, the overall COP of the cascade system rises from 1.129 to 2.705 for the R41/R404A refrigerant pair and from 1.145 to 2.775 for the R41/R290 refrigerant pair. Both refrigerant pairs have the identical evaporator temperature (-60 to -24^{0}C). In a CRS, the R41/R290 refrigerant pair has greater performance efficiency than the R41/R404A refrigerant couple.

IV. If the condenser temperature T_{CON} rises, the overall COP of the cascade system falls from 1.145 to 0.965 for R 41/R290 and from 1.129 to 0.9526 for R 41/R404A. R41/R290 refrigerant pair in cascade vapour refrigeration system has a marginally higher COP than R41/R404A refrigerant pair operating at the same condenser temperature -T_{CON} (27 to 45^{0}C).

V. If the T_{CASLTC} of the Low Temperature Circuit side cascade condenser increases from -30 to -3 degrees Celsius, the overall COP of the cascade system changes both for refrigerant pairs. COP decreases from 1,209 to 1,122 for R41/R290. Maximum COP for R41/R404A is 1.164, whereas maximum COP for R41/R290 is 1.209. R41/R290 refrigerant pair in CRS has a higher COP than R41/R404A refrigerant pair operating at the same T_{CASLTC}.

10. **Future Scope of Work**

The objective of my investigation is to analyze the performance of a CRS using the software Engineering Equation Solver-EES under different operating conditions. As is common knowledge, it is impossible to collect all available information on a specific topic in a brief amount of time. This research uncovers relatively few flaws as well as finds out about them; in the future, a new event will be held to discover and survey new flaws. The present dissertation work is only coordinated for two-stage compression cascade systems. However, there are few additional boundaries that can be altered during in the evaluation and system performance can be evaluated.

I. It is feasible to evaluate numerous alternate combinations of refrigerant couples.
II. A three-stage refrigeration cascade system can be assessed using the same research methodology.
III. In addition to mass & energy balance, entropy balance is expected to be studied in the future.
IV. Sets of identical refrigerants may be subjected to a trial examination with a test arrangement.
V. Other recently developed examination strategies are applicable to the refrigerant pairs utilized in my investigation.

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