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Theoretical comparison analysis of R134a, R1234yf, R452A and R454C refrigerants used in automobile, trailer, commercial and industrial cooling systems

Alpaslan Alkan[1*]

[1]Mechanical Engineering Department, Faculty of Technology, Sakarya of Applied Sciences University, Türkiye

Orcid: A. Alkan (0000-0001-8117-8545)

Abstract: The release of artificial substances into the environment in recent years has been the main cause of environmental disasters. Artificial refrigerants used in cooling systems have significantly contributed to the depletion of the ozone layer and global warming. In this study, theoretical performance comparisons were performed between R1234yf, which is a substitute for R134a used in automobile air conditioning (AAC) systems, and R452A, R454C refrigerants, which are used as alternative refrigerants in industrial, commercial, and trailer cooling systems. Thus, the performances of alternative refrigerants used in different cooling systems under similar conditions were comparatively evaluated. Performance analyses were carried out according to different condenser and evaporator temperatures. Analysis results are given depending on the condenser/evaporator pressure ratio, mass flow rate, compressor power, cooling effect coefficient (COP) and compressor outlet temperature. According to the study results, it was observed that the COP increased with the increase in evaporator temperature, while the compressor inlet-outlet pressure ratio, refrigerant mass flow rate, compressor power and refrigerant compressor outlet temperature decreased. According to the study, the refrigerant with the highest compressor power and mass flow rate was R452A, followed by R1234yf, R454C, and R134a. The average COP of R134a was found to be approximately 5.4%, 8.6%, and 0.6% higher than R1234yf, R452A, and R454C, respectively. The compressor powers of R134a, R1234yf, R452A, and R454C were in the range of 1.01–3.28 kW, 1.03–3.62 kW, 1.02–3.88 kW, and 0.98–3.36 kW, respectively, according to the theoretical analysis conditions.

Keywords: Automobile, Refrigeration, GWP, Energy, Theoretical, Cooling cycle.

1. Introduction

Over the last century, environmental problems in our world have increased significantly. Sudden temperature changes, solar radiation reaching the atmosphere without filtering, and large-scale pollution of the atmosphere have increased environmental problems. It is also becoming increasingly obvious how expensive and scarce energy is, especially from fossil fuels. The use of gasoline in urban automobiles and environmental pollutants have been primarily associated with gasoline consumption. Besides, vehicle air conditioning systems, also found in private and commercial vehicles, have a major impact on greenhouse gas emissions and the world's oil consumption. [1-4]. Refrigerants containing chlorofluorocarbons (CFC) and hydrochlorofluorocarbons (HCFC) interact with the ozone layer in the atmosphere and have the potential to deplete the ozone layer. This effect is called the ozone depletion potential (ODP). Chlorine atoms contained in these compounds break down ozone molecules, causing the ozone layer to weaken. Due to the ozone layer's thinning, the sun's destructive radiation reached Earth, causing environmental problems. At the same time, increasing global warming has triggered sudden meteorological events and caused the world to become even warmer. Refrigerants with high global warming potentials (GWP), when released into the environment, significantly contribute to global warming by trapping heat in the atmosphere. Efforts have been made to prevent these two situations through international agreements [5,6]. Artificial ingredients used in cooling systems can contribute to both the ozone layer and global warming. Refrigerants containing fluorine atoms are limited and prohibited to prevent ozone depletion. With the agreements taken against global warming, especially in European Union (EU) member countries, the usage of refrigerants with a GWP value of more than 150 in automobile air conditioning (AAC) systems is limited [7]. In addition to AAC systems, cooling systems are utilised in

* Corresponding author.
Email: aalkan@subu.edu.tr

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the transportation, commercial, and industrial sectors. R404A refrigerant is used as broadcast in these cooling systems. The fact that R404A refrigerant has a GWP value of 3943 necessitated the use of an alternative refrigerant. The EU has limited the use of refrigerants with GWP values above 2500 in fixed facilities in 2020 [8]. However, the use of R404A refrigerant is allowed until 2030 under certain rules. Refrigerant R452A is increasingly being used as a replacement for R404A in trailer and pickup truck cooling systems. In recent years, there has been a shift towards using R454C refrigerant as a replacement for R404A refrigerant in commercial and industrial cooling systems. [9]. At first, R12 refrigerant was used in the AAC system. However, since it was harmful to the ozone layer, R134a refrigerant was chosen. In this case, with the understanding that R134a refrigerant has a high contribution to global warming, a widespread switch has been made to R1234yf refrigerant with a low GWP value. Some automobile companies have preferred carbon dioxide (R744) refrigerant in some of their vehicles [10].

Daviran et al. [11] simulated the cooling cycle of an AAC system with R134a and made a comparative analysis of the use of R1234yf. They stated that the cooling efficiency coefficient (COP) of the R1234yf system is 1.3 - 5% less than that of R134a at a given cooling load, and 18% higher than that of R134a at a given refrigerant mass flow rate. Zilio et al. [12] tested using R1234yf instead of R134a in an AAC system. According to their findings, R1234yf has a lower cooling capacity and COP compared to R134a. Direk and Yüksel [13] investigated the use of R1234ze(E), R152a and R444a as alternatives to R134a in an automobile heat pump system. They mentioned that R152a has a higher heating capacity than R134a, R444a, and R1234ze(E). Additionally, they noted that the heating capacity of R1234ze(E) can be increased by increasing the total compressor volume. Cho and Park [14] compared the performance of R1234yf with R134a by adding an internal heat exchanger to an AAC system. They showed that R1234yf has a lower cooling capacity in the range of 4.0–7.0% and more COP in the range of 3.6–4.5% compared to R134a. They also revealed that R1234yf had higher total exergy destruction than R134a, in the range of 0.5–3.3%. Golzari et al. [15] used a computer program to compare R134a and R1234yf and stated that R1234yf led to high exergy efficiency. Mostafa et al. [16] conducted an empirical investigation to evaluate the efficiency of R404 and R454C refrigerants in the cooling system of a cold storage facility. The experimental studies were conducted under varying outdoor and indoor air conditions, specifically considering the product's thermal load and cooling water temperature. According to their findings, R404A achieves the target temperature in the warehouse 23.1% faster than R454C, thanks to its superior cooling capability. It was discovered that R454C had a 10.8% greater COP than R404A, but its energy consumption was 20.6% higher. Aral et al. [17] compared R134a and R1234yf in an AAC system that can also operate as a heat pump. They stated that R134a has 5.8% more cooling capacity and 0.2% less heating capacity than R1234yf. Alkan and M.S İnan [18] experimentally carried out the performance analysis of R134a refrigerant and its alternative R1234yf refrigerant in an AAC system with a variable-capacity compressor. They reported that the COP of R1234yf refrigerant decreased as compressor speed increased, except at low airflow inlet temperatures. At high airflow inlet temperatures, R134a had a COP value 20% higher than R1234yf, and at low airflow inlet temperatures, R134a had a COP value 2% higher than R1234yf. Alkan and M. S. İnan [19] conducted an experimental study to investigate the performance of R1234yf in an AAC system with variable and fixed capacity compressors. Their study showed that the COP value of the AAC system with R1234yf is 13.6% and 20.1% less than that of the variable and fixed capacity R134a system, respectively. Devecioğlu and Oruç [20] made comparisons of R404A and R452A refrigerants in a basic vapour compression refrigeration cycle according to different evaporator and condenser temperatures. They revealed that when R452A was used instead of R404A in the cooling cycle, the COP value was higher, but the power consumption of the system was less. According to them, R452A is a suitable substitute for R404A when it comes to commercial cooling applications. In another study, Devecioğlu and Oruç [21] investigated the use of R454C instead of R404A. On average, R454C's COP was 10% higher and its power consumption was 15% less than R404A. Khatoon and Karimi [22] conducted a theoretical analysis of a vapour compression system that uses two evaporators to eliminate the need for separate refrigeration and air conditioning units. They carried out energy and exergy performance evaluations, considering the changes in condenser and evaporator temperatures. They compared low-GWP refrigerants such as R1234yf, R1336mzz(Z), R513A and R450A to high-GWP refrigerants such as R134a and R452A. They found that R1336mzz(Z) had the highest exergy efficiency and COP values (31.50 and 2.47%, respectively). They also mentioned that it has the lowest compressor power. They revealed that R1336mzz(Z) was the best-performing refrigerant, while R452A exhibited the poorest thermodynamic performance.

In this study, theoretical comparisons were made between R1234yf, an alternative to R134a in AAC systems, and R452A, an alternative to R404A refrigerant in trailer-type cooling systems, and R454C refrigerants, which are used as an alternative in industrial and commercial-type cooling systems. Performance comparisons were performed for different evaporator and condenser temperatures to reveal the performance of alternatives for R134a and R404A refrigerants.

2. Theoretical Analysis

Theoretical analysis investigated the fundamental elements of the cooling cycle utilized in various systems, including AAC, trailers, industrial, and commercial cooling systems. The basic components of a cooling cycle are the compressor, condenser, evaporator, and expansion valve. A schematic view of basic cooling cycle elements is given in Figure 1.

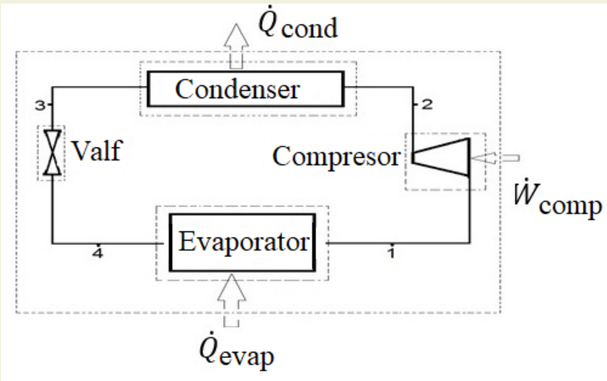

Figure 1. Basic refrigeration cycle elements

The cooling cycle in both AAC systems, trailer, industrial and commercial type cooling systems works according to the vapour compression cooling cycle. In the cycle, the element that compresses the refrigerant fluid and turns it from superheated vapour at low pressure to superheated vapour at high pressure is the compressor. In Figure 1, the refrigerant, which is in the form of superheated vapour at low pressure at point 1, is subjected to compression in the compressor and becomes superheated vapour at high pressure at point 2. There are various types of compressors used in refrigeration cycles. The condenser is the element where the refrigerant, which is in the form of superheated vapour at high pressure, turns into saturated vapour, liquid/vapour and saturated liquid by losing heat. Condensers are classified based on the type of heat rejection medium and their fin and tube types. In Figure 1, the refrigerant, which is in the form of superheated vapour at high pressure at point 2, releases heat to the environment in the condenser and becomes a saturated liquid at point 3. In the actual cooling cycle, the refrigerant in the condenser is ensured to exit at a lower temperature than the saturation temperature consistent with the condenser pressure. This difference is referred to as subcooling. Thus, the refrigerant is prevented from evaporating again by gaining heat in the liquid line. The element that lowers the saturation temperature by decreasing the pressure on the refrigerant is the expansion element. Figure 1 illustrates the transformation of the refrigerant from a high-pressure liquid state at point 3 to a low-pressure liquid/vapour state at point 4 through the reduction of pressure via the expansion valve. There are different types of expansion elements. Various accessories are used in the cooling cycle depending on the type used. The refrigerant, whose pressure drops, tries to evaporate by gaining heat. The heat exchanger element where this situation occurs is the evaporator. In Figure 1, at point 4, the refrigerant in the liquid/vapour state at low pressure draws heat from the environment in the evaporator and becomes saturated vapour at low pressure at point 1. In the real cycle, the refrigerant is required to leave the evaporator saturation temperature slightly warmer than the evaporator saturation temperature to shed heat in the suction line and condense again. This situation is called superheat. Thus, the refrigerant returns to the compressor as superheated steam at low pressure. Thus, the vapour compression refrigeration cycle is completed.

Applying the principle of conservation of energy allows us to calculate the load on the evaporator.,

$$\dot{Q}_{evap} = \dot{m}_r(h_1 - h_4) \tag{1}$$

Here, the refrigerant's enthalpy is denoted by h, and its mass flow rate by $\dot{m}_r$.

If the evaporator load is known, then the refrigerant mass flow rate can be calculated using the following formula:

$$\dot{m}_r = \frac{\dot{Q}_{evap}}{(h_1 - h_4)} \tag{2}$$

According to the principle of conservation of energy, the inlet and outlet enthalpy will be equal in the expansion valve as there is no heat and work transfer;

$$h_3 = h_4 \tag{3}$$

Assuming that compression in the compressor is adiabatic, the power delivered to the refrigerant by the compressor is expressed as:

$$\dot{W}_{comp} = \dot{m}_r(h_2 - h_1) \tag{4}$$

The efficiency of the cooling system is as the ratio of evaporator load to compressor power;

$$\mathrm{COP} = \frac{\dot{Q}_{evap}}{\dot{W}_{comp}} \tag{5}$$

Compressor outlet-inlet pressure ratio is defined as:

$$P_{ratio} = \frac{P_{cond}}{P_{evap}} \tag{6}$$

Compressor discharge temperature was obtained using the refrigerant superheated steam tables in the REFPROP 9.1 [23] program as a function of the condenser saturation pressure and the enthalpy values of the refrigerant at point 2.

$$T_{dis} = f(P_{cond}, h_2) \tag{7}$$

Thermodynamic properties of R134a, R1234yf, R454C and R452A refrigerants are given in Table 1. R134a and R1234yf refrigerants are pure fluids. It consists of a mixture of R32-R125-R1234yf refrigerants with R452A refrigerant and 11%-59%-30% by weight, respectively. It contains a blend of R32-R1234yf refrigerants with R454C refrigerant and 21.5%-78.5% by weight, respectively.

The comparison parameter values of the vapour compression refrigeration cycle are given in Table 2. Evaluations are based on condenser temperatures of 40 and 60 °C and evaporator temperatures increased by 5 °C between -10 and 10 °C. The superheat of the evaporator outlet refrigerants in the cooling cycle is assumed to be 6°C,

Table 1. Properties of refrigerants [8, 19, 23, 24]

ASHRAE Number	R452A	R454C	R1234yf	R134a
Molecular Mass (g mol^{-1})	103,5	90,78	114,0	102,0
Boiling Point (°C) at 1 atm	-47,0	-45,6	-29,4	-26,1
Liquid Density at 21.1°C (kg m^{-3})	1148,8	1042,4	1100	1,206
ASHRAE Class	A1	A2L	A2L	A1
Critical Temperature (°C)	74,9	85,7	94,7	101,1
Critical Pressure (bar)	40,02	43,188	33,81	40,67
GWP	2140	146	4	1430

and the subcooling temperature of the condenser outlet refrigerants is assumed to be 6°C. In addition, the compressor isentropic efficiency is supposed to be 70%, and the evaporator load is assumed to be 6 kW. Thermodynamic properties of the refrigerants to be used for evaluation in the study were found by using the REFPROP 9.1 program [23]. R134a, R1234yf, R454C and R452A refrigerants were compared depending on condenser and evaporator pressure ratio, mass flow rate, compressor power, cooling effect coefficients, and compressor outlet temperatures.

Table 2. Comparison parameters.

Input parameters	Values
Evaporator Load (kW)	5.5
Superheated temperature (°C)	8
Evaporator temperature (°C)	-6, 0, 6
Condenser temperature (°C)	40, 45, 50, 55, 60
Isentropic efficiency (%)	75
Subcooling temperature (°C)	6

3. Results and Discussion

Figure 2 depicts the comparative performance graphs of refrigerants based on evaporator temperatures from -10 to 10°C in 5°C increments and condenser temperatures of 40 °C. and 60°C.

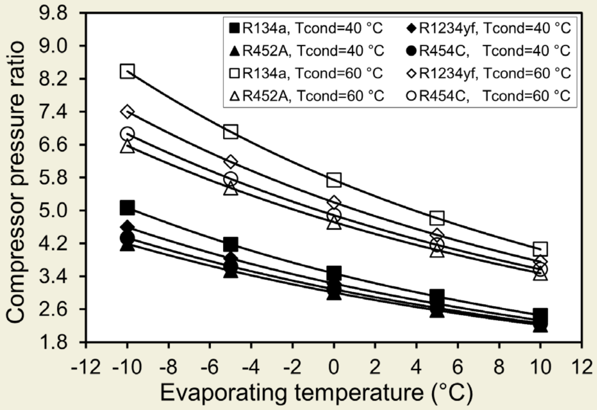

Figure 2. Variation of compressor pressure ratio with evaporator temperature.

The change in condenser and evaporator pressure ratios depending on the evaporator temperature of different refrigerants used in automobile, trailer, commercial and industrial-type cooling systems is illustrated in Figure 2. It was seen that as the evaporator temperature increased from -10°C to 10°C, the R134a, R1234yf, R452A and R454C condenser and evaporator pressure ratios decreased by about 51.6%, 49.3%, 47.2% and 47.9%, respectively. It was observed that as the condenser temperature increased from 40°C to 60°C, the R134a, R1234yf, R452A and R454C condenser and evaporator pressure ratios increased by approximately 65.4%, 61.2%, 56.9% and 58.3%, respectively. It has been observed that R134a has an average of approximately 8.4%, 15.7% and 13.1% higher condenser and evaporator pressure ratios than R1234yf, R452A and R454C, respectively.

Changes in the refrigerant mass flow rate depending on the evaporator temperature of different refrigerants used in automobile, trailer, commercial and industrial-type cooling systems is presented in Figure 3. It is seen that as the evaporator temperature increases from -10°C to 10°C, the refrigerant mass flow rates of R134a, R1234yf, R452A and R454C decrease by approximately 8.4%, 12.0%, 9.7% and 8.1%, respectively. It is understood that as the condenser temperature increases from 40°C to 60°C, the R134a, R1234yf, R452A and R454C refrigerant mass flow rates increase by approximately 24.1%, 32.2%, 37.6% and 27.1%, respectively. The results presented in Figure 3 indicate that R134a has approximately 31.9%, 38.8% and 4.2% less refrigerant mass flow rate than R1234yf, R452A and R454C, respectively.

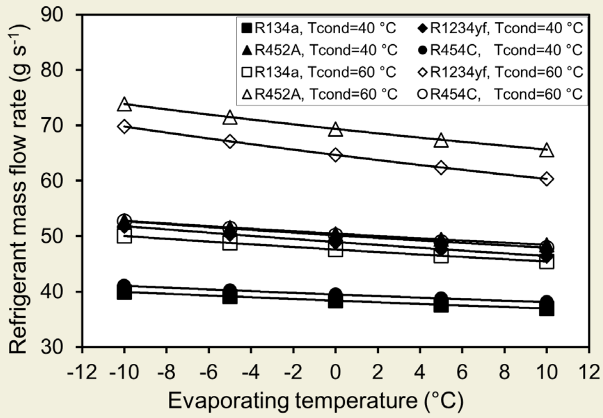

Figure 3. Variation of refrigerant mass flow rate with evaporator temperature.

The change in compressor power depending on the evaporator temperature and, changes in COP depending on the evaporator temperature of different refrigerants are shown in Figure 4 and Figure 5 respectively. It is understood that as the evaporator temperature increases from -10°C to 10°C, the compressor power of R134a, R1234yf, R452A and R454C decreases by approximately 44.9%, 44.5%, 47.9% and 46.5%, respectively. It is seen that as the condenser temperature increases from 40°C to 60°C, the compressor power of R134a, R1234yf, R452A and

R454C increases by approximately 76.4%, 85.3%, 96.1% and 80.1%, respectively. Besides, R134a has approximately 5.8%, 9.9% and 0.7% less compressor power on average than R1234yf, R452A and R454C, respectively. It is seen that the compressor powers of R134a, R1234yf, R452A and R454C are in the range of 1.01 - 3.28 kW, 1.03 - 3.62 kW, 1.02 - 3.88 kW and 0.98 - 3.36 kW, respectively, according to the theoretical analysis conditions.

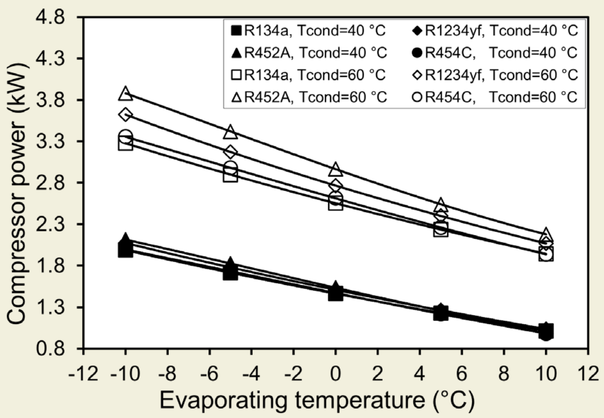

Figure 4. Variation of compressor power with evaporator temperature.

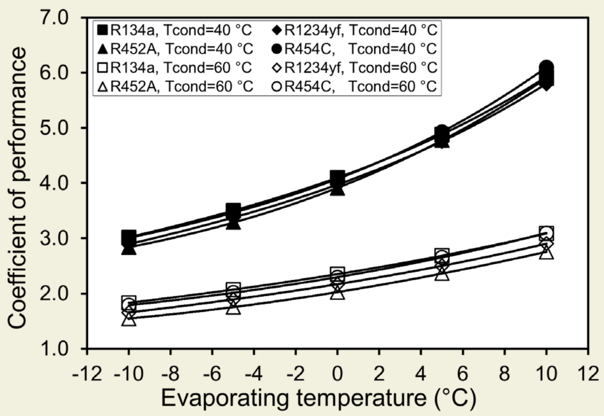

Figure 5. Variation of COP with evaporator temperature.

Changes in COP depending on the evaporator temperature of different refrigerants used in automobile, trailer, commercial and industrial-type cooling systems is given in Figure 5. It is observed that the evaporator temperature rises from -10°C to 10°C, the COP of R134a, R1234yf, R452A and R454C increases by approximately 82.5%, 87.9%, 93.1% and 87.9% as shown in Figure 5, respectively. It is observed that as the condenser temperature increases from 40°C to 60°C, the COP of R134a, R1234yf, R452A and R454C decreases by nearly 43.2%, 45.9%, 48.8% and 44.3%, respectively. R134a appears to have an average of about 5.4%, 8.6% and 0.6% higher COP than R1234yf, R452A and R454C, respectively. The results were found to be compatible with Mostafa et al. [16] and Alkan and M.S İnan [18].

Figure 6 represent the changes in compressor discharge

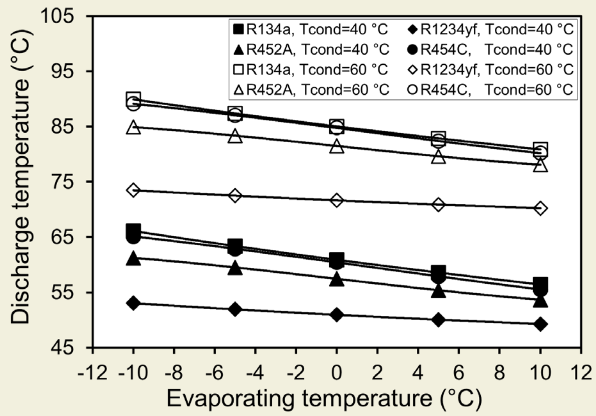

Figure 6. Variation of refrigerant compressor discharge temperature with evaporator temperature.

temperature depending on the evaporator temperature of different refrigerants. It has been determined that as the evaporator temperature increases from -10°C to 10°C, R134a, R1234yf, R452A and R454C refrigerants reduce the compressor discharge temperatures by approximately 12.4%, 5.8%, 10.2% and 12.4%, respectively. It is seen that as the condenser temperature increases from 40°C to 60°C, the compressor discharge temperatures of R134a, R1234yf, R452A and R454C systems increase by approximately 24.1%, 20.7%, 24.1% and 24.3%, respectively. Moreover, the R1234yf system has an average of 13.8% less compressor discharge temperature than the R455A system. It is also observed that R134a has an average of approximately 16.1%, 4.11% and 0.9% less compressor discharge temperature than R1234yf, R452A and R454C, respectively. Based on the theoretical analysis conditions in the study, compressor discharge temperatures of R134a, R1234yf, R452A and R454C are in the range of 56.42 - 89.92 °C, 49.26 - 73.47 °C, 53.67 - 84.91 °C and 55.52 - 89.12 °C, respectively.

4. Conclusions

In this theoretical study, the performances of refrigerants R134a, R1234yf, R452A, and R454C used in automobile, trailer, commercial and industrial cooling systems were compared based on their evaporator and condenser temperatures. Thus, the performances of alternative refrigerants used in different cooling systems under similar conditions were comparatively evaluated. Thermodynamic properties of refrigerants were found using the REFPROP 9.1 program. The main results obtained from the comparative theoretical analysis results of the R134a, R1234yf, R452C and R454C refrigerant systems are given below.

- R134a was found to have on average about 8.4%, 15.7% and 13.1% higher condenser and evaporator pressure ratios than R1234yf, R452A and R454C, respectively.

- It was found that the refrigerant with the highest compressor power and mass flow rate was R452A, followed by R1234yf, R454C and R134a.

- R134a was found to have 31.9%, 38.8% and 4.2% lower mass flow than R1234yf, R452A and R454C, respectively.
- The compressor powers of R134a, R1234yf, R452A and R454C were found to be in the range of 1.01 - 3.28 kW, 1.03 - 3.62 kW, 1.02 - 3.88 kW and 0.98 - 3.36 kW, respectively, according to the theoretical analysis conditions.
- R134a showed an average COP almost 5.4%, 8.6% and 0.6% higher than R1234yf, R452A and R454C, respectively.
- It was observed that the compressor discharge temperatures of R134a, R1234yf, R452A and R454C were in the range of 56.42 – 89.92 °C, 49.26 – 73.47 °C, 53.67 – 84.91 °C and 55.52 – 89.12 °C, respectively, according to theoretical analysis conditions.
- When the temperature of the evaporator increases, the COP increases, while the pressure ratio at the compressor inlet and outlet, the refrigerant mass flow rate, the compressor capacity and the compressor outlet temperature decrease.
- It has been observed that increasing the condenser temperature results in decreasing the compressor inlet-outlet pressure ratio, refrigerant mass flow rate, COP, and compressor power while increasing the compressor discharge temperature.

Conflict of Interest Statement

The author must declare that there is no conflict of interest in the study.

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