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Research Article

Exergy Performance Investigation of Eco-Friendly Refrigerant Mixtures as an Alternative to R134a in a Domestic Refrigerator

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In this paper, various eco-friendly refrigerant mixtures R430A, R436A, R436B, R435A, and R510A used in vapour compression refrigeration systems are considered for this study. All of them have zero ODP and very low GWP. On the basis of exergy features, the efficiency of various working fluids in vapour compression refrigeration cycles was compared. The exergy efficiency of mixtures is evaluated for various evaporating temperatures ranging from -40°C to -5°C at a constant condensation temperature of 45°C. The variation of exergy is also analyzed for various condensation temperatures ranging from 25°C to 60°C at a constant evaporating temperature of -10°C. The exergy losses in various components are computed and presented in Grassmann diagrams for a cooling load of 1 kW. The results indicate that all the investigated alternative refrigerant mixtures have higher exergy efficiency than R134A. The maximum exergy performance is 39.72% observed for the mixture R435A at an evaporation temperature of -30°C, and this value is 9.89% higher than that of R134a.The results also show that the highest and lowest exergy losses have occurred in the compressor and evaporator.

1. Introduction

In response to the phase-out of CFCs, which have a significant ODP, R134a has been created and is now being used in home refrigerators [1]. When comparing the global warming capability of R134a to that of CO_2, the latter has 1370 [2]. As per Kyoto [3], it is considered a greenhouse gas, and hence, the production and use of the same will be completed in a few years. Hence, it is to be replaced by eco-friendly refrigerants [3, 4]. Now, it is imperative to identify the alternative refrigerant with low GWP in accordance with the limit fixed by EU regulations [5]. Park and Jung [7] conducted an investigation of the energy efficiency of R430A in a domestic water purifier as a potential choice refrigerant to R134a. They found that the energy consumption is 12% lower than that of R134a with 50% less charge mass, and also the operating temperatures are similar to this optimum charge. R430A is a nearly azeotropic compound made of 76 percent R152a and 24 percent R600a by mass, with a temperature swing of about less than 0.10°C. It is composed of 76 percent R152a and 24 percent R600a by the group. It does not have an ODP and has a comparatively low GWP of 110.

Baskaran et al. [8–13] investigated the first and second law efficiency of a vapour compression refrigeration system using a variety of refrigerant mixtures, including HFC152a, HC290, HC600a, and RE170, and compared their findings to those obtained with R134a, which was considered a potential alternative replacement.

Mohanraj [14] conducted a theoretical study of the energy effectiveness of a domestic refrigerator with R430A as a potential choice refrigerant to R134a. The results are better in COP, energy efficiency, total equivalent global warming impact, and VCC. Choedaeseong and Jung (2010) reported the results of an experimental investigation on the use of R435A (a blend of DME and R152a) to substitute HFC134a in residential water purifiers, which they conducted. According to the findings of the tests, the energy usage and discharge temperature were 12.7 percent and 3.7 degrees Celsius lower than those of HFC134a, respectively [15]. Park et al. explored the possibility of replacing HFC134a, which is utilized in the refrigeration system of residential water purifiers, using both experimental and numerical methods. Results of tests found that energy usage and compressor discharge temperature of R510A are 22.3 percent and 3.70 degrees Celsius lower than those of HFC134a with 50% of the refrigerant charge, respectively. HFC134a is a tremendous long substitute for R510A, which necessitates slight alteration to the refrigeration system of household water purifiers compared to HFC134a [16].

An exergy study is typically performed in order to establish the highest efficiency of the system and to describe the locations where exergy is destroyed. It is possible to undertake an exergy analysis of a complicated system by studying each of the system's components individually. Finding the primary sources of exergy destruction indicates the route in which potential enhancements might be made [17]. As a result, exergy analysis estimates the margin accessible to design highly efficient energy systems by lowering inefficiencies. Numerous limitations of conventional energy analysis can be eliminated with exergy analysis. Exergy analysis is conducted on data in order to establish the sources, locations, and intensities of system inefficiencies. However, there has been minimal exploration into the exergy of vapour compression refrigeration utilizing these refrigerant mixes, despite the fact that these refrigerants have been determined to be acceptable refrigerants as a replacement for R134a in numerous investigations. Using two environmentally friendly refrigerants, R134a and R152a, as alternatives to R12, Bolaji [18] performed an exploratory study on the exergetic effectiveness of a domestic refrigerator. The findings acquired indicate that the overall COP of R152a had been very near to that of R12 with only 1.4 percent reduction, while the average COP of R134a was an 18.2 percent reduction when compared to that of R12—using R600 and R600a as refrigerants [18]. Ahamed et al. made a comparative analysis of the thermodynamic performance of the two refrigerants. This study demonstrates that the exergy efficiency of butane is higher than that of isobutene and R134a as a refrigerant when compared to the other two [19].

Studies on the exergy assessment of a vapour compression refrigeration system employing these refrigerant combinations have only been carried out in a limited number of cases. It is discovered that these refrigerants have a better advantage in terms of energy efficiency as well as other global impacts than other refrigerants. The research work is based on the investigation of R134a substitution and exergetic analysis. Therefore, in this research work, the exergy performances of five non-ozone-depleting and very low global warming potential refrigerants (R430A, R435A, R436A, R436B, and R510A) were investigated theoretically and compared with that of the baseline refrigerant R134a.

2. Materials and Methods

For basic vapour compression cooling cycles, energy and exergy evaluations require fundamental mathematical formulations. External energy (power) is delivered to the compressor; also, heat is supplied to the system in the evaporator, yet in the condenser, heat loss is generated from the system. Heat rejection and heat add-ons are modified for several coolants, which generate a variance in refrigerants' energy performance. Exergy emissions are never the same in several components of the system. The ambient temperature and pressure are, respectively, indicated by T_0 and P_0. Exergy is eaten or lost because of entropy caused by the associated activities (Sahinet al., 2005).

Figure 1 illustrates the photographic view of the domestic refrigerator of Kelvinator made with 185-litre capacity with a testing facility designed to work with R134a. It is comprised of an evaporator, a wire mesh wind cooled condenser, and a reciprocating compressor that is hermetically sealed. A total of four pressure gauges have been mounted at the compressor air intake and outlet as well as the condenser outlet and the evaporator inlet. All these pressure gauges were fitted on a wooden panel to avoid vibration during testing. The thermocouple wire was linked to the thermocouple analyzer at all 10 of its locations, which was a first. A thermocouple analyzer is a device that reads the temperatures that have been measured. It was decided to install 10 calibrated temperature sensors at the evaporator inlet and outlet, compressor intake and outlet, compressor outlet, and condenser inlet as well as the freezer section and refrigerator cabin. Furthermore, the voltage and current that were spent were recorded. Additionally, the flow meter, which also has been connected to the tubing running between both the condenser and the capillary tube, was permanently attached to the wooden panel. All of the data were captured using digital storage equipment for the Human Machine Interface (HMI), which was set to record data periodically each 10 seconds. To check the quality of condensed liquid flow, a sight glass is provided.

An energy meter of the Select MFM384 model with a capability of 100-500 V was connected to the compressor in order to assess the power and electricity consumption. Service ports were built on the upper face of the compressor to allow for the charging and recovery of refrigerant while the compressor was in operation. Initially, the service port was used to facilitate the removal of moisture from the system. This has now changed. The device was cleansed with nitrogen gas in order to remove any air, contaminants, moisture, or other things that may have accumulated inside the system and could have negatively impacted its operation. To charge the system, we used a charging system. The system was vacuumed with the assistance of just a vacuum pump to pressure with -30 mm of mercury.

Figure 1: The photographic view of the domestic refrigerator in the experimental setup.

3. Test Procedure

As per the guidelines given by ASHRAE Handbook 2010, the energy consumption test and no-load pull-down test were conducted with the following system parameters.

Freezer compartment: -18°C to -15°C

Food compartment: 3°C to 5°C

Steady ambient temperature: 25°C to 32°C

Furthermore, certain randomized experiments were conducted to establish the reproducibility of the data. When the system was left to function, measurements were taken of the temperatures, pressure, and energy consumed, and the amount of refrigerant flow was collected once in every ten seconds till the steady-state operating conditions were reached. The observed temperatures, pressures, mass flow rate, electric power, and energy were utilized to calculate the operation characteristics of the refrigeration system. Variables are pull downtime, coefficient of performance, compressor power, discharge temperature, refrigerating capacity, and energy consumption.

A thermodynamic study is required to explain the exergy losses and destruction in the system. The main assumptions are made in this investigation:

1. In all components, steady-state parameters exist
2. Pressure losses are ignored in the pipelines
3. Heat addition and heat loss from the system or to the system are not considered
4. Kinetic, potential energy, and exergy losses are not considered

The following is an example of how a mathematical equation of exergy analysis in distinct components can be organized:

Specific exergy in any state:

$$\begin{aligned} \psi &= (h - h_0) - T_0(s - s_0), \\ Q_{\mathrm{ev}} &= m(h_1 - h_4). \end{aligned} \tag{1}$$

Evaporator exergy loss:

$$\begin{aligned} I_{\mathrm{ev}} &= \mathrm{m}(\psi_4 - \psi_1) + Q\left(1 - \frac{T_0}{T_{\mathrm{ev}}}\right) \\ &= m[(h_4 - h_1) - T_0(s_4 - s_1)] + Q\left(1 - \frac{T_0}{T_{\mathrm{ev}}}\right). \end{aligned} \tag{2}$$

Compressor exergy loss:

$$\begin{aligned} I_{\mathrm{comp}} &= m(\psi_1 - \psi_2) + W_{\mathrm{el}} = m[(h_1 - h_2) - T_0(s_1 - s_2)] + W_{\mathrm{el}}, \\ Q_{\mathrm{cond}} &= m(h_2 - h_3). \end{aligned} \tag{3}$$

Condenser exergy loss:

$$\begin{aligned} I_{\mathrm{cond}} &= m(\psi_2 - \psi_3) - Q_{\mathrm{cond}}\left(1 - \frac{T_0}{T_{\mathrm{cond}}}\right) \\ &= m[(h_2 - h_3) - T_0(s_2 - s_3)] - Q_{\mathrm{cond}}\left(1 - \frac{T_0}{T_{\mathrm{cond}}}\right). \end{aligned} \tag{4}$$

Expansion valve exergy loss:

$$I_{\mathrm{exp}} = m(\psi_4 - \psi_3) = m(s_4 - s_3)[\text{Thortling}, h_4 = h_3]. \tag{5}$$

Coefficient of performance:

$$\mathrm{COP} = \left(\frac{Q_{\mathrm{e}}}{W_{\mathrm{el}}}\right). \tag{6}$$

Total destruction:

$$\begin{aligned} I_{\mathrm{total}} &= I_{\mathrm{cond}} + I_{\mathrm{exp}} + I_{\mathrm{comp}} + I_{\mathrm{ev}}, \\ \eta_{\mathrm{x}} &= \left(\left(\frac{T_{\mathrm{o}}}{T_{\mathrm{s}}}\right) - 1\right) * \frac{Q_{\mathrm{ev}}}{W_{\mathrm{el}}}, \\ \eta_{\mathrm{x}} &= \left(\left(\frac{T_{\mathrm{o}}}{T_{\mathrm{s}}}\right) - 1\right) * \mathrm{COP}. \end{aligned} \tag{7}$$

The main goal of this research is to determine the impact of different operating parameters of the refrigeration system on the exergy performance and exergy losses of the system's various components.

In order to generate exergy efficiency diagrams, it is necessary to make the assumptions listed below:

$$\begin{gathered} \text{Environmental temperature } (T_{\mathrm{O}}) = 25^{\circ}\mathrm{C} \\ \text{Isentropic compression efficiency} = 0.75 \\ \text{Compressor motor efficiency} = 1.0 \end{gathered} \tag{8}$$

All the enthalpy and entropy values needed for the analysis are obtained from the software REFPROP 9.0 [20].

Exergy efficiency plots are presented for the investigated refrigerants with the following conditions.

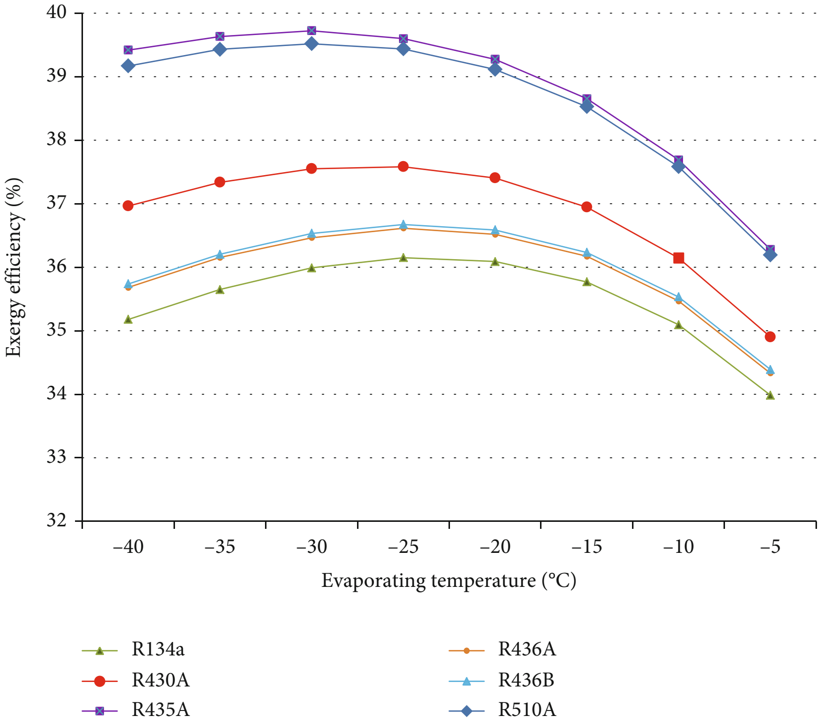

Figure 2: Exergy efficiency variation of refrigerant mixtures with R134a for various evaporating temperatures.

Table 1: Properties of the investigated refrigerants.

S. no	Refrigerant mixture	Composition (% mass f.)	NBP (C)	GWP	Molecular mass	Critical temperature	Critical pressure
1	R430A	R152a/R600a (76/24)	-27.6	107	63.96	107	4.09
2	R436A	R290/R600a (56/44)	-34.3	3	49.33	115.9	4.27
3	R436B	R290/R600a (52/48)	-33.4	3	49.87	117.4	4.25
4	R435A	DME/R152a (80/20)	-26.1	<31	49.04	125.2	5.39
5	R510A	DME/R600a (88/12)	-25.2	<3	47.24	127.9	5.33

(i) Variation with condensing temperature (25–60°C) for a constant evaporating temperature of -10°C

(ii) Variation with evaporating temperature (-40°C to -5°C) for a constant condensing temperature of 45°C

4. Result and Discussions

4.1. Exergy Efficiency at Constant Condensation Temperature ($T_{cond} = 45°C$). Figure 2 depicts the variation in exergy efficiency as a function of evaporator temperature for R134a and a few selected combinations. Exergy efficiency rises in all circumstances up to a specific point and then falls as the temperature of the evaporator is raised over that point. This is due to an enhancement in the irreversibility of the components as the temperature of the evaporator rises. The rising and lowering of exergy efficiency are dependent on the amount of exergy available for use and the compressor work needed by the compressor W_{el}. The cumulative effect of these two elements increases exergy efficiency until the optimum evaporator temperature is reached, after which it decreases. The thermo-physical and environmental properties of investigated refrigerants are shown in Table 1 [6].

When operating at higher evaporator temperatures, the R134a refrigerant has significantly lower exergy efficiency than any other mixes. All the investigated refrigerants have a higher value of exergy efficiency than R134a. The maximum exergy performance is 39.72% observed for the combination of R435A at an evaporation temperature of -30°C, and this value is 9.89% higher than that of R134a. The results of exergy performance at varying evaporating temperatures (-40°C to -5°C) are listed in Table 2.

The exergy performance results of refrigerant mixtures when compared with R134a at evaporating temperature (-40°C to -5°C) for a constant condensing temperature of 45°C are interpreted as shown in Table 2.

It is found through Figure 2 that the exergy efficiency of the R435A combination is greater than that of R134a between 6.33 and 10.76 percent for the investigated range of evaporator temperatures. Exergy performance of 35.09 percent and 37.69 percent was recorded for R134a and R435A, respectively, at an evaporator temperature of -10°C.

TABLE 2: Results of exergy performance at varying evaporating temperatures (-40°C to -5°C).

S. no	Refrigerant	Exergy efficiency improvement (%)	Exergy efficiency (%) at -10°C evaporating temperature
1	R134a	—	35.09
2	R430A	2.63 to 4.83	36.14
3	R435A	6.33 to 10.76	37.69
4	R436A	1.01 to 1.41	35.47
5	R436B	1.17 to 1.56	35.53
6	R510A	6.09 to 10.19	37.58

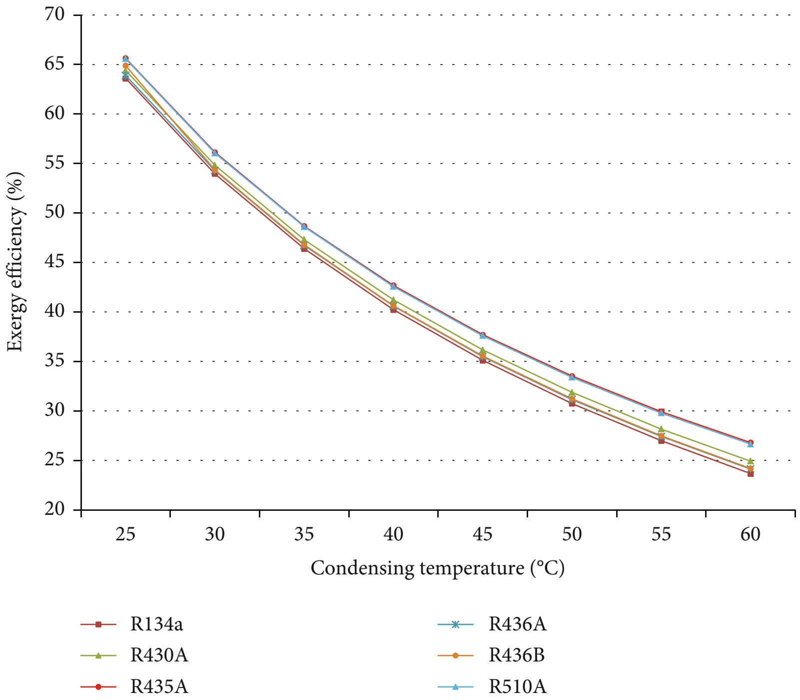

FIGURE 3: Exergy efficiency variation of refrigerant mixtures with R134a for various condensing temperatures.

4.2. Variation of Exergy Efficiency between Refrigerant Mixtures and R134a at a Condensing Temperature of 45°C

4.2.1. Exergy Efficiency at Constant Evaporation Temperature ($T_e = -10°C$). Figure 3 demonstrates the variance in exergy effectiveness as a consequence of condensation temperature utilizing R134a and selected combinations. In all of the cases investigated, the exergy efficiency decreases as the condensation temperature rises. The coefficient of performance (COP) falls as the level of effort needed for compression rises as the condensation temperature rises. As a result, the exergy effectiveness is predicted to fall. All the investigated refrigerants have a higher value of exergy efficiency than R134a. The maximum exergy performance is 65.62% noticed for the mixture R435A and 65.57% for the mixture R510A at a condensation temperature of 25°C. A big divergence is observed in the alternative refrigerants R435A and R510A, particularly at higher condensing temperatures. For certain temperatures, the difference between R435A and R134a can even approach 13.3 percent.

4.3. Variation of Exergy Efficiency between Refrigerant Mixtures and R134a at Evaporating Temperature of -10°C. The exergy performance results of the refrigerant mix, when compared with R134a at condensing temperature (25°C to 60°C) for a constant evaporating temperature of 50°C, are interpreted as follows. The results of exergy performance at varying condensing temperature (25°C to 60°C) are listed in Table 3.

Figure 3 shows that the exergy effectiveness of the R435A mix is greater for the investigated temperature range than that of R134a, between 3.20 and 13.28 percent. Exergy performance of 30.74 and 33.51% was obtained at 50°C for R134a and R435A condenser temperatures, respectively.

4.4. Grassman Diagrams. Figures 4 and 5 show Grassmann plots created using the identical basic assumptions as those used in exergy efficiency diagrams; these assumptions are shown in the previous section. The evaporation temperature has been set to -10 degrees Celsius, the compressor motor performance has been set to 0.80, and the cooling load has

Table 3: Results of exergy performance at varying condensing temperatures (25°C to 60°C).

S. no	Refrigerant	Exergy efficiency improvement (%)	Exergy efficiency (%) at 50°C condensing temperature
1	R134a	—	30.74
2	R430A	1.26 to 5.35	31.86
3	R435A	3.20 to 13.28	33.51
4	R436A	0.5 to 1.98	31.14
5	R436B	2.05 to 2.25	31.21
6	R510A	3.11 to 12.61	33.38

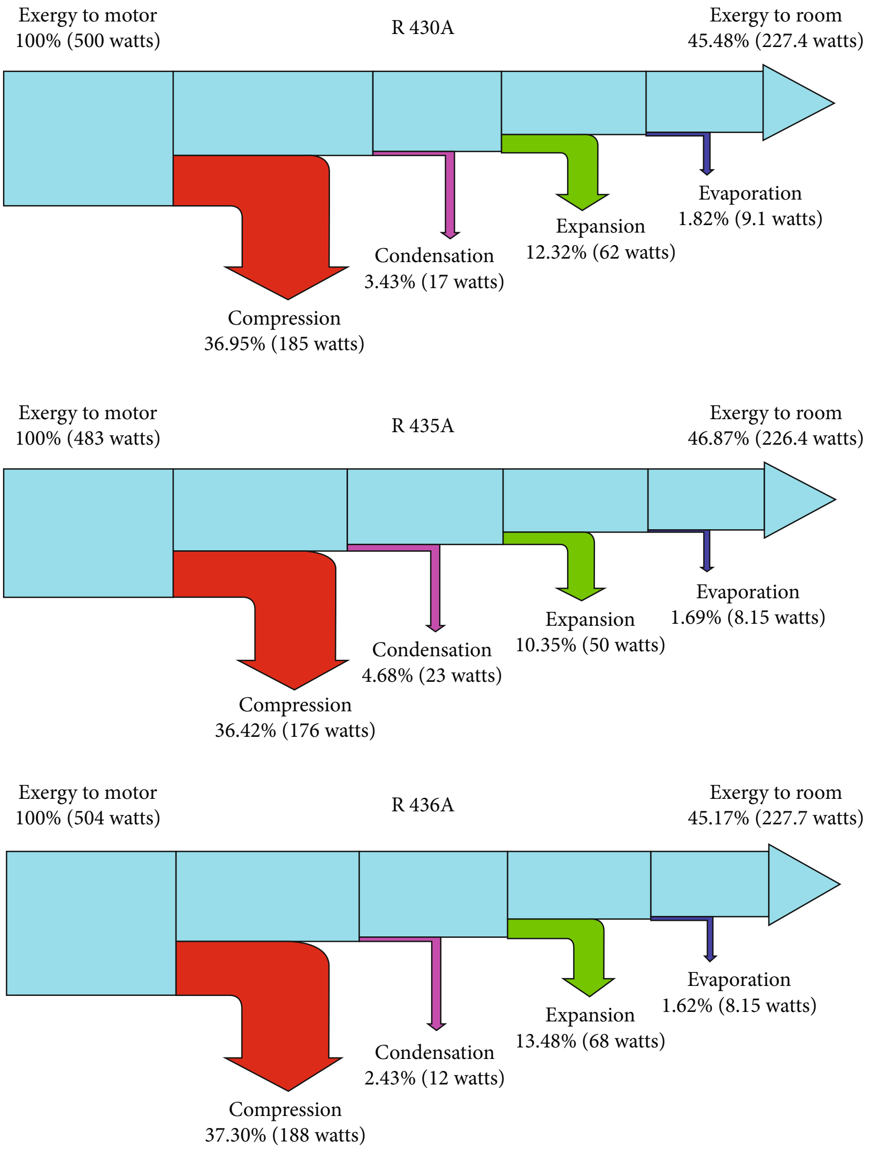

Figure 4: Grassmann diagrams illustrate the exergy losses with the use of R430A, R436A, and R435A.

been set to 1 kilowatt. Grassmann diagram analysis shows that the compression exergy loss is the most substantial, rising from 36.42 percent (for the mixture R435A) to 37.39 percent (for the mixture R435B) as the compression rate increases (for the combination R436B). Expansion losses are accompanied by compression exergy losses, with the latter increasing from 10.35 percent (for the mixture R435A) to 13.48 percent (for the mixture R435B) (for the mixture R436A). Condensation losses are the third most significant source of loss, followed by evaporating losses.

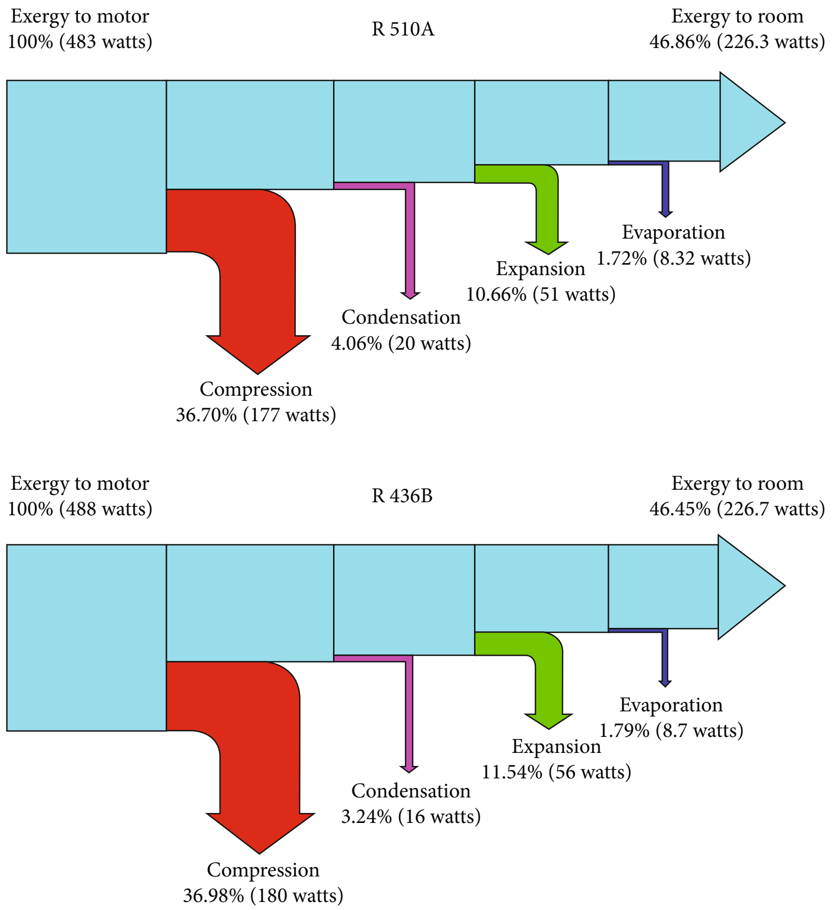

Figure 5: Grassmann diagrams illustrate the exergy losses with the use of R510A and R436B.

Furthermore, the condensation exergy losses increase from 2.43 percent (for the combination R436A) to 4.68 percent (for the mixture R435A). In contrast, the evaporating losses rise from 1.62 percent (for the mixture R436A) to 1.82 percent (for the mixture R435A) (R430A). Among the mixtures tested, R435A had the highest exergy efficiency, with a value of 39.6 percent. Despite the fact that this blend has the highest condensation exergy losses (4.68 percent), its high value of exergy effectiveness can be attributed to the fact that, when compared to all other refrigerant blends, it has the lowest compression as well as expansion exergy losses (and thus the highest value of exergy effectiveness). In spite of the fact that it has the fewest condensation and evaporation exergy losses of all, the mixture R436A exhibits the lowest exergy efficiency of all, with a value of 36.61 percent (2.43 percent and 1.62 percent).

5. Conclusions

Using R134a and alternative refrigerant combinations, an exergy analysis was carried out in a vapour compression refrigeration system among the temperatures of evaporation and condensation ranging from -50°C to -40°C and 25°C to 60°C, respectively. Based on exergy analysis on the performance of alternative refrigerant mixtures in the vapour compression refrigeration system, the following conclusions were drawn:

(i) All the investigated refrigerants have a higher value of exergy efficiency than R134a

(ii) The highest and lowest exergy efficiency in the system is 39.6% and 36.61% for the mixtures R435A and R436A, respectively, while R134a has only 36.10%

(iii) The highest exergy efficiency emerges at an evaporation temperature of-25°C for refrigerants R430A, R436A, and R436B and at -30°C for the refrigerants R435A and R510A

(iv) The highest exergy effectiveness is 39.72 percent, which is 9.89 percent higher than that of R134a and R435A at such an evaporation temperature of -30°C

(v) The efficiency of exergy diminishes in all circumstances as the condensation temperature increases. The maximal exergy efficiency for the R435A mixture is 65.62%, and for the R510A, it is 65.57% at a condensation temperature of 25°C

(vi) The lowest and highest compression exergy losses in the system are 36.42% and 37.39% for the mixtures R435A and R436B, respectively

(vii) The lowest and highest expansion exergy losses in the system are 10.35% and 13.48% for the mixtures R435A and R436A, respectively

(viii) The lowest and highest condensation exergy losses in the system are 2.43% and 4.68% for the mixtures R436A and R435A, respectively

(ix) The lowest and highest evaporation exergy losses in the system are 1.62% and 1.82% for the mixtures R436A and R430A, respectively

(x) The total exergy performance of the system operating with the R435A refrigerant combination is consistently superior to the performance of the system operating with any other examined refrigerant. The compressor, capillary tube, and condenser were the three key components that suffered the most damage out of the four major components

(xi) In general, the vapour compression refrigeration system functioned better when the R435A refrigerant combination was used as working fluid rather than when R134a was used

(xii) In conclusion, the R435A combination has the potential to be an ozone-friendly, low global warming potential (GWP), energy-efficient, and secure credible option to R134a with vapour compression refrigeration systems

Nomenclature

COP: Coefficient of performance
I: Exergy destruction rate (kW)
Ψ: Specific exergy
η_{ex}: Exergy efficiency
Q: Heat transfer rate (kW)
m: mass flow rate (kg/sec)
h: Enthalpy (kJ/kg)
S: Entropy (kJ/kg K)
T: Temperature (K)
W_{el}: Electrical power (kW).

Subscripts

comp: Compressor
cond: Condenser
exp: Expansion valve
evap: Evaporator
ev: Evaporator temperature
o: Dead state
s: Space.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

This study was performed as a part of the employment of the authors. The authors declare that there are no conflicts of interest.

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