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Energy and Exergy Analysis of R600a as a Substitute for R134a in Automotive Air Conditioning System

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ABSTRACT

Until now, R134a is still used as a working fluid in automotive air conditioning (A/C) even though it has a very high global warming potential (GWP), which is 1430. Refrigerant R600a is an alternative working fluid as a substitute for R134a in automotive (A/C). This environmentally friendly substitute refrigerant is also expected to produce a better system performance, for which it is necessary to analyse energy and exergy. During work, each AC component generates friction, heat loss, and pressure drop which causes irreversibility in each component. The irreversible quantity of each component is calculated by exergy analysis. Because automotive A/C is driven by engine rotation, its performance is also affected by engine rotation. In this study, the engine rotation to be evaluated is 1000, 1500, 2000, 2500, and 3000 rpm. The evaporating and condensing temperatures of automotive A/C in this study were 5°C and 45°C, respectively. Based on the energy analysis it was found that replacing R134a with R600 enhanced COP, for example at 2000 rpm for R134a and R600a respectively were 3.59 and 3.69, or an increase in COP of about 3%. Based on the exergy analysis, the greatest irreversibility occurred in the compressor, namely 72.1% and 78.6% for R134a and R600a, respectively, for 2000 rpm. This means that there is a potential to enhance the COP improvement using R600a by reducing the irreversibility on the compressor.

1. Introduction

Until now, the refrigerant used in automotive air conditioning (A/C) in Asian countries was still R134a. In the 1990s, this refrigerant started to replace R12 in automobile air conditioning [1]. This refrigerant has a high global warming potential (GWP) of 1430 even though it does not destroy the ozone layer [2,3]. The use of hydrocarbons as refrigerants has not grown to be a significant concern in Asian nations, in contrast to Europe, where the topic has received extensive attention [4-6]. Because hydrocarbons (HC) have a relatively low greenhouse gas potential (GWP of around 3) they can be used as working fluids in refrigeration systems, which can help reduce greenhouse gas

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emissions from the refrigeration industry [7,8]. Using HC will not only result in a very low GWP but also lower power usage in the refrigeration system [9-11]. As a result, the refrigeration industry's contribution to global warming will also decline. Dupont *et al.,* [12] estimate that the worldwide refrigeration industry contributes about 7.8% of global warming. As to the findings of Cabello *et al.,* [13], the refrigeration industry can be directly or indirectly responsible for 37% and 63% of global warming, respectively.

Automotive A/C is more likely to leak when in operation due to vibrations than building A/C. As a result, there is a considerable chance that R134a will leak from an automobile's air conditioning system, which would greatly increase global warming. The refrigeration industry will continue to contribute more to global warming if R134a is not stopped from being used as a working fluid in automobile air conditioning systems. Refrigerant R600a is an excellent substitute for R134a because it has a very low GWP of only 3 and an ODP (ozone depletion potential) of 0 [9,10].

The vapor compression cycle, which consists of the compressor, condenser, expansion device, and evaporator as its four primary components, is the basis for automotive air conditioning. Each component experiences irreversibility when the A/C is operating, making the cycle less than optimal. Heat transfer, pressure drop, friction, and other irreversibilities are examples of these. The Second Law of Thermodynamics' equations are utilized to determine the irreversibility quantity for each component [14,15]. System performance will be enhanced if each component's irreversibility can be decreased [16-18]. In the meantime, the First Law of Thermodynamics is applied to examine the system's performance [18].

Based on the references, the author has not found an exergy analysis of replacing R134a with R600a in automotive A/C. Research whose topic is close to this research was carried out by Joybari *et al.,* [19]. An exergy analysis of replacing R134a with R600a in domestic refrigerators has been conducted by Joybari *et al.,* [19]. They reported that the largest and smallest irreversibility that occurs in the four main components are in the compressor and condenser, which are 47.59%, and 13.39%, respectively. The difference between Joybari's study and this study is not only regarding the compressor capacity used but also the evaporating temperature. In the research of Joybari *et al.,* [19], the compressor capacity is only about 150 W, while the capacity of an automotive A/C compressor can vary, from about 500 W to 5 kW, depending on engine rotation. The evaporating temperature of domestic refrigerators using R134a is about -20^{o}C, while the evaporating temperature of car air conditioners using R134a is about 5^{o}C. As a result, in terms of COP, automotive A/Cs will be greater than refrigerators, because the COP of vapor compression refrigeration engines decreases with decreasing evaporating temperature [20,21]. The input power in building A/C comes from a power source with relatively constant power, while the input power of automotive A/C comes from engine rotation. As a result, when the engine rotates, so does the compressor's input power and the evaporator's cooling capacity [22-24]. The cooling capacity decreases with low engine rotation, and the cooling capacity generated by the evaporator increases with high engine rotation. Put another way, the car's intended cabin temperature is reached more quickly with high engine rotation.

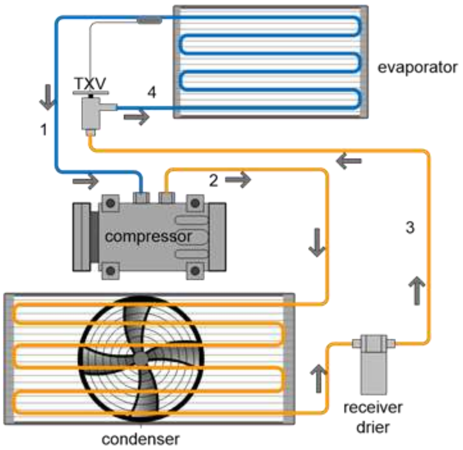
This study aims to examine how different engine rotations affect the performance of automobile A/C using R134a and R600a. Additionally, an exergy analysis for different engine rotations, starting from idle, low, and high rotations, will be conducted as part of this study to ascertain the irreversibility of each vehicle A/C component. Based on the findings of the exergy study, attempts are made to enhance the system's performance by understanding the irreversibility of each automotive A/C component.

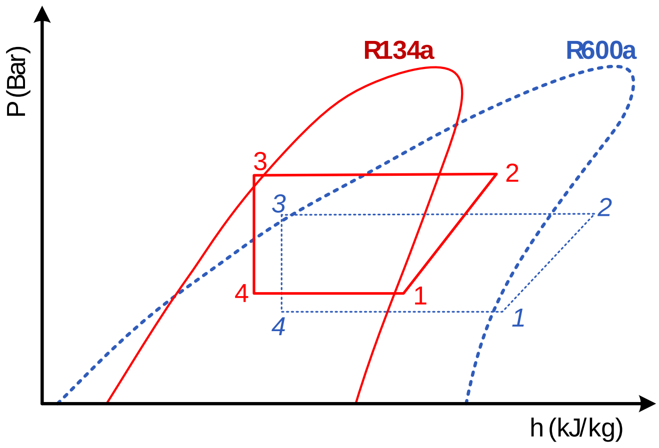
2. System and Configuration

2.1 Energy Analysis

Figure 1(a) and Figure 1(b) illustrate schematic and P-h (pressure vs. enthalpy) diagrams of the automotive A/C. In Figure 1(b), the refrigeration cycle using R134a in the Ph diagram is shown by the red-solid line, while the cycle using R600a is depicted by the blue-dashed line. Before conducting energy and exergy analysis, it is necessary to make several assumptions on the automotive A/C system. These assumptions are shown in Table 1. The table shows that the five engine rotations to be analysed are 1000, 1500, 2000, 2500, and 3000, at which the isentropic and volumetric efficiencies are 0.70, 0.65, 0.60, 0.55, and 0.50, respectively.

Based on Figure 1(b) and the assumptions in Table 1, the energy and exergy analysis of the A/C system will be calculated. The parameters for energy analysis are cooling capacity (Q), input power (W), and coefficient of performance (COP). The three parameters are calculated with Eq. (1), Eq. (2), and Eq. (4). Meanwhile, to calculate the COP improvement due to the replacement of refrigerant from R134a with R600a, Eq. (5) is used.





(a) (b)

Fig. 1. (a) Schematic diagram of automotive A/C; (b) Refrigeration cycle on P-h diagram of automotive A/C

Table 1
Assumption in the numerical approach

No.	Parameter	Unit	Quantity
1	Engine rotation	rpm	1000, 1500, 2000, 2500 and 3000
2	Isentropic & volumetric efficiencies	%	70, 65, 60, 55 and 50
3	Compressor displacement	m^3/rev.	120 x10^{-6}
4	Subcooling	K	7
5	Superheating	K	10
6	Evaporating temperature	°C	5
7	Condensing temperature	°C	45

$$Q_{evap} = \dot{m} \cdot (h_1 - h_4) \quad (1)$$

$$W_{comp} = \dot{m} \cdot (h_2 - h_1) \quad (2)$$

$$\dot{m} = \frac{rpm}{60} \cdot Comp_{dis} \cdot \rho_{suct} \cdot \eta_{vol} \quad (3)$$

$$COP = \frac{Q_{evap}}{W_{comp}} = \frac{(h_1 - h_3)}{(h_2 - h_1)} \tag{4}$$

$$COP_{imp} = \frac{COP_{R600a} - COP_{R134a}}{COP_{R134a}} \cdot 100\% \tag{5}$$

where,

Q_{evap} = cooling capacity
W_{comp} = power input
$\dot{m}$ = mass flow rate of refrigerant
$Comp_{dis}$ = compressor displacement
ρ_{suct} = refrigerant density at suction
η_{vol} = compressor volumetric efficiency
h_1 = specific enthalpy at point 1
h_2 = specific enthalpy at point 2
h_4 = specific enthalpy at point 4

2.1 Exergy Analysis

As mentioned above, the exergy analysis was carried out using the Second Law of Thermodynamics. Based on Figure 1, the exergy analysis of each component of the automotive A/C is carried out by using Eq. (6) to Eq. (10) [19,25,26].

Irreversibility in the evaporator:

$$I_{evap} = \dot{m} \cdot (h_3 - T_o \cdot s_3) + Q_{evap} \cdot \left(1 - \frac{To}{T_{cabin}}\right) - \dot{m} \cdot (h_1 - T_o \cdot s_1) \tag{6}$$

Irreversibility in the compressor:

$$I_{comp} = \dot{m} \cdot (h_1 - T_o \cdot s_1) + \dot{m} \cdot (h_2 - T_o \cdot s_2) \tag{7}$$

Irreversibility in the condenser:

$$I_{cond} = \dot{m} \cdot (h_2 - T_o \cdot s_2) + \dot{m} \cdot (h_3 - T_o \cdot s_3) - Q_{cond} \cdot (1 - \frac{To}{T_{cond}}) \tag{8}$$

Irreversibility in the expansion:

$$I_{exp} = \dot{m} \cdot T_o \cdot (s_4 - s_3) \tag{9}$$

The total irreversibility is,

$$I_{Total} = I_{comp} + I_{cond} + I_{exp} + I_{evap} \tag{10}$$

The second law efficiency is,

$$\eta_{sec.} = (1 - \frac{I_{Total}}{W_{comp}}) \quad (11)$$

where,

T_o = ambient temperature
T_{cond} = condensing temperature
T_{cabin} = cabin temperature
s_1 = specific enthalpy at point 1
s_2 = specific enthalpy at point 2
s_3 = specific enthalpy at point 3
s_4 = specific enthalpy at point 4
Q_{cond} = condenser capacity

3. Results and Discussion
3.1 Energy Analysis

Based on Figure 1(b) and Table 1, the cooling capacity of automotive A/C for various engine rotations using R134a and R600a was calculated by using Eq. (1) and Eq. (3) and the results are depicted in Figure 2. From the figure, the cooling capacity increases with increasing engine rotation. It is also evident from the figure that the cooling capacity with R134a is always higher than that with R600a. The correlation between the increase in cooling capacity with R134a and R600a against engine rotation is almost linear, with the linear equation shown in Figure 2.

In Figure 2, the lowest cooling capacities for R134a and R600a are 3.6 and 1.9 kW, respectively, at 1000 rpm engine rotation. While at 5000 rpm, the cooling capacity of the automotive A/C reaches its highest for both R134a and R600a at 7.7 and 4.2 kW, respectively. The figure also shows that the cooling capacity of R600a is only about 55% of that of R134a for the same engine rotation. This means that when using R600a in car A/C, the cabin temperature is slower to reach the desired temperature compared to using R134a. One effort to make the cooling capacity of R600a equivalent to R134a for the same engine rotation is to increase the compressor displacement.

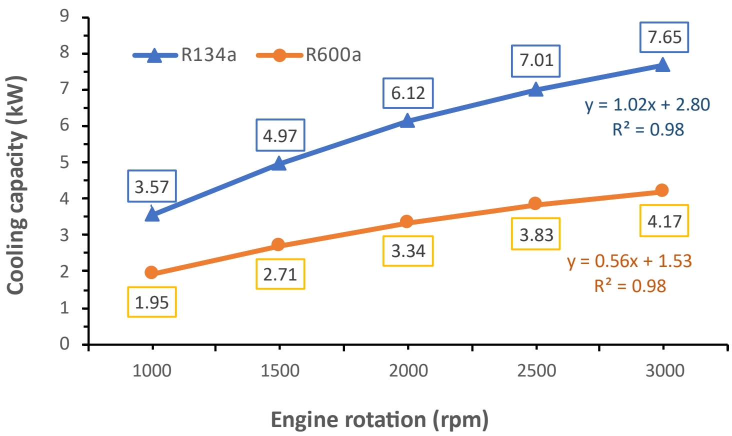


Fig. 2. Cooling capacity of automotive A/C for various engine rotations using R134a and R600a

The input power from the engine rotation for revolutions from 1000 to 5000 rpm transmitted to the compressor is calculated by using Eq. (2) and Eq. (3) and the results of these calculations are shown in Figure 3. From the figure, the relationship between input power and engine rotation for

R134a and R600a is linear with a linear equation as shown in Figure 3. Like the relationship between cooling capacity and engine rotation, input power also increases with increasing engine rotation. The difference is that the cooling capacity of R134a is always higher than that of R600a, while the input power of R134a is always lower than that of R600a. Since the input power with R600a is lower than that with R600a, when the A/C is operated, it will reduce the fuel consumption of the car. This is because the engine rotation power utilized to move the A/C using R600a is smaller than that of R134a.

The smallest input power at 1000 rpm engine rotation is 0.9 and 0.5 kW, respectively. The largest input powers are 2.6 and 1.4 kW for R134a and R600a, respectively, at 5000 rpm. On average, the input power of R600a is only about 53% of that of R134a for the same engine rotation. Lower input power is more advantageous when the A/C is operated, but a small input power will also result in a small cooling capacity.

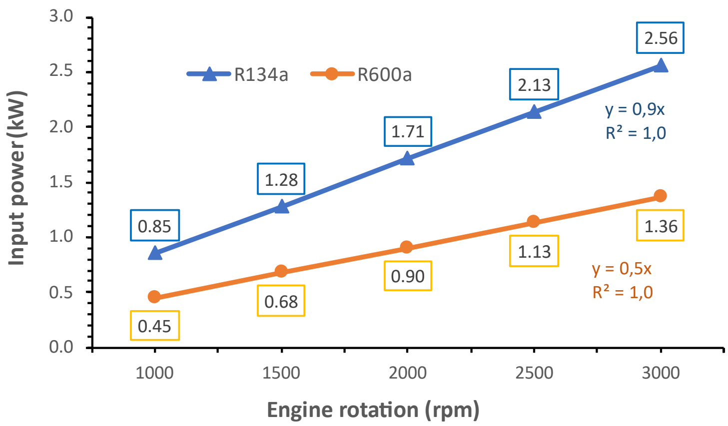


Fig. 3. Input power of automotive A/C for various engine rotations using R134a and R600a

A parameter often used to indicate the performance of an A/C is the COP, as shown in Eq. (4). This equation is the ratio between Eq. (1) and Eq. (2), or the ratio between cooling capacity and input power. The COP values for various engine rotations are shown in Figure 4. An increase in engine rotation will cause a decrease in COP. The relationship of the decrease of COP to engine rotation is linear for both R134a and R600a, with the same gradient of -0.3. The figure also shows that the COP of R600a is slightly greater than that of R134a at the same engine rotation. This means that replacing R134a with R600a can improve the COP of automotive A/C.

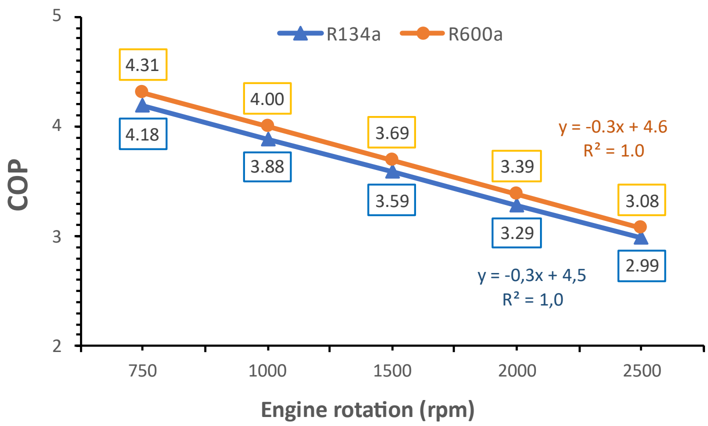


Fig. 4. COP of automotive A/C for various engine rotations using R134a and R600a

The increase in automotive A/C COP due to the replacement of R134a with R600a for various engine rotations is shown in Figure 5. The figure shows that the increase in COP is relatively constant, which is about 3%. The difference in COP improvement for each engine rotation is relatively insignificant, as it is only about 0.01%. In other words, the increase in COP is relatively constant for all engine rotation variations.

Although the increase in COP is only about 3%, the replacement of R134a with R600a will greatly reduce the percentage contribution of refrigerant emissions to global warming, because the GWP of R600a is only 3, while R134a is 1430 [2,3]. This means that the replacement of R134a with R600a is urgent to be implemented immediately if we want to reduce the percentage contribution of refrigerant emissions to global warming.

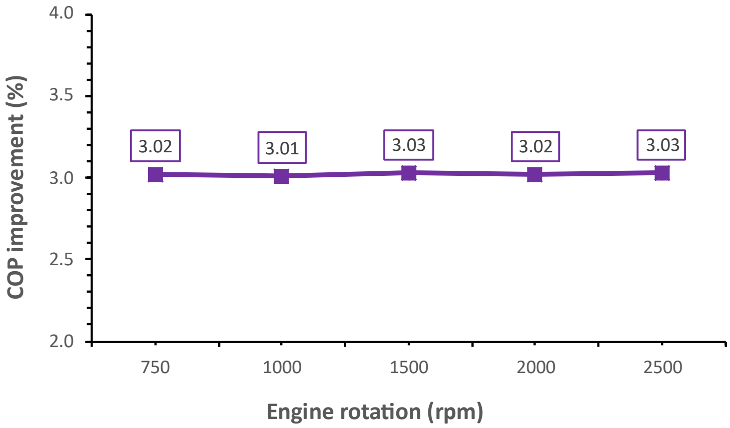


Fig. 5. COP improvement of automotive A/C for various engine rotations using R134a and R600a

3.2 Exergy Analysis

Energy analysis has been carried out in the previous section to investigate changes in automotive A/C performance caused by the replacement of R134a with R600a for several engine rotations. Meanwhile, the exergy analysis is performed to investigate the irreversibility that occurs in each component for various engine rotations. By knowing the quantity of irreversibility in each automotive A/C component, efforts can be made to reduce the quantity of irreversibility.

Based on Figure 1(b) and using Eq. (6), the exergy at the evaporator of automotive A/C for various engine rotations using R134a and R600a is depicted in Figure 6. The irreversibility in the evaporator using R134a is always higher than that of R600a for all engine rotations. Both irreversibilities increase with increasing engine rotation. The increase in irreversibility caused by increased engine rotation in R134a is sharper than the increase in irreversibility in R600a. Compared to R134a, the irreversibility of R600a is low because the mass of R600a refrigerant charge is only about 50% of the mass of R134a charge, and therefore, the mass flow rate of R600a is also lower [19]. Based on Eq. (6), the irreversibility is directly proportional to the refrigerant mass flow rate, because the charging mass of R600a is lower than R134a so the irreversibility is lower than that of R134a.

In terms of quantity, because the charging mass of R600a into the automotive A/C is lower than that of R134a, it will reduce the percentage of global warming from the refrigeration sector. This means that the replacement of R134a with R600a not only reduces the percentage contribution to global warming due to its very low GWP, but also has the charging mass of R600a, which is no more than 60% of the charging mass of R134a.

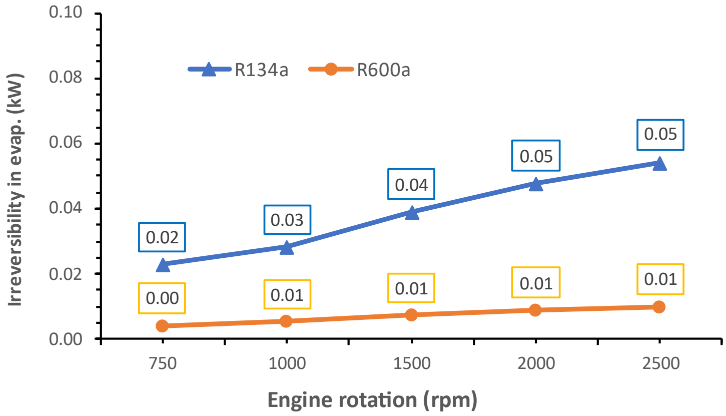


Fig. 6. Irreversibility in the evaporator for various engine rotations using R134a and R600a

Figure 7 illustrates the irreversibility of a compressor using R134a and R600a for various engine rotations. From the figure the irreversibility of R134a is always higher than that of R600a, this is because the filling mass of R600a is much lower than the filling mass of R134a, as explained earlier. The irreversibility in the compressor using R600a is much higher than the irreversibility in the evaporator, for example at 2000 rpm, the irreversibility in the evaporator is 0.01 kW, while the irreversibility in the compressor is 0.34 kW. The high irreversibility in compressor can potentially be reduced by using several methods to improve compressor performance. Improving the performance of the compressor will reduce the input power to the compressor. When the input power decreases, the COP of the automotive will increase.

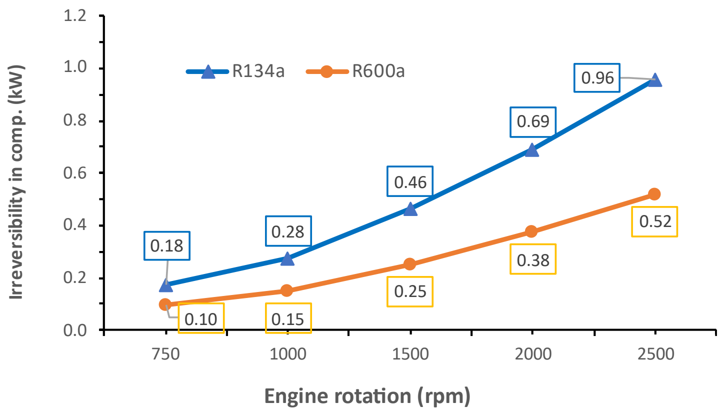


Fig. 7. Irreversibility in the compressor for various engine rotations using R134a and R600a

Figure 8 and Figure 9 show the irreversibility at the condenser and expansion device for R134a and R600a for various engine rotations. Similar to the irreversibility at the evaporator and compressor, the irreversibility at the condenser and expansion device of R600a is always lower than that of R134a. The irreversibility values at the condenser and expansion device are also much smaller than the irreversibility at the compressor. This means that the effort to improve the performance of automotive A/C using R600a is to reduce the irreversibility of the compressor.

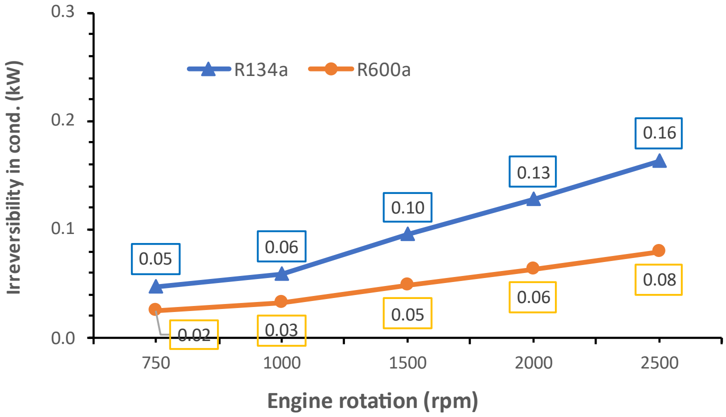


Fig. 8. Irreversibility in the condenser for various engine rotations using R134a and R600a

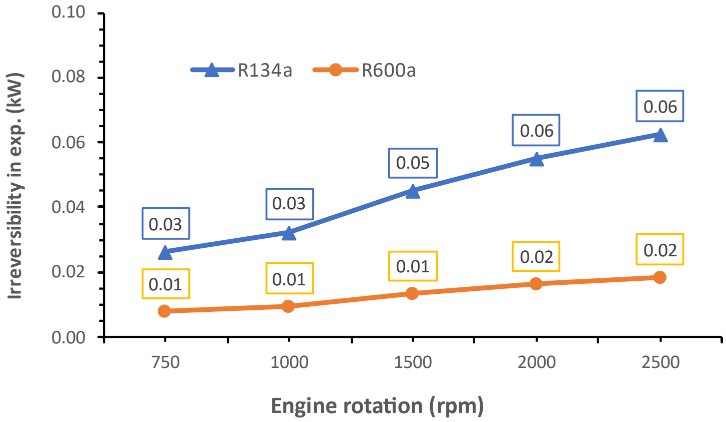


Fig. 9. Irreversibility in the expansion device for various engine rotations using R134a and R600a

The sum of the irreversibility in the four main components, namely in the evaporator, compressor, condenser, and expansion device is the total irreversibility, as shown in Figure 10. The figure shows that the trend of increasing total irreversibility due to increasing engine rotation using R134a is similar to that of R600a. The figure also shows that the total irreversibility of R600a is about 50% of the irreversibility of R134a. This percentage value is similar to the filling mass ratio between R600a and R134a [19].

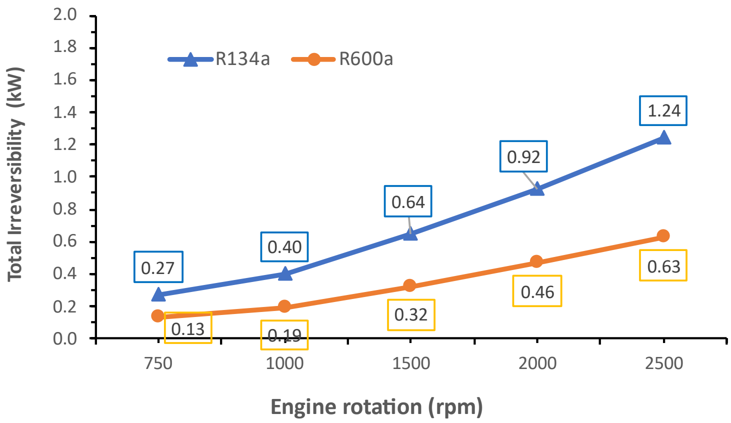


Fig. 10. Total irreversibility in the automotive A/C for various engine rotations using R134a and R600a

Figure 11 displays the irreversibility percentage of the automotive A/C compressor. The irreversibility percentage of the compressor increases with increasing engine rotation. From the figure, it can also be seen that the percentage of irreversibility in the compressor using R600a is higher than that using R134a. From this the potential for improving the performance of automotive A/C is to improve the performance of the compressor so that the irreversibility of the compressor decreases and can lead to a decrease in the input power of the compressor.

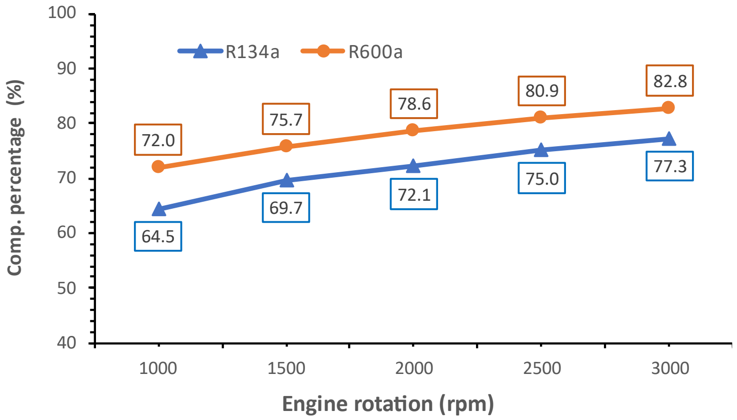
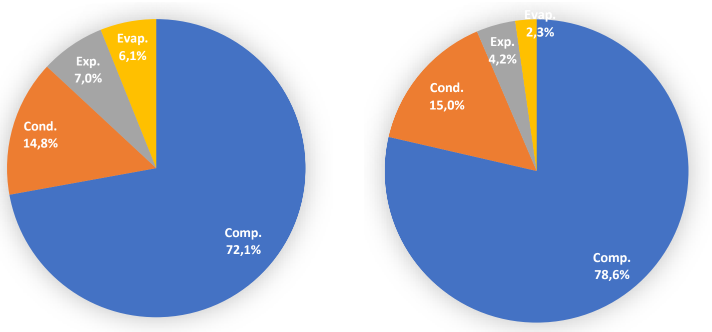


Fig. 11. Irreversibility percentage in the compressor for various engine rotations using R134a and R600a

The irreversibility percentage of the four main components of automotive A/C at 2000 rpm for R134a, and R600a are shown in Figure 12(a) and Figure 12(b), respectively. From the figure, the percentage of irreversibility in the compressor and condenser using R600a is higher than that using R134a. This means that if the performance of automotive A/C is to be improved, it is necessary to improve the performance of these two components, namely the compressor and condenser.



(a) (b)

Fig. 12. Irreversibility percentage in each component of automotive A/C at 2000 rpm: (a) R134a; (b) R600a

Figure 13 illustrates the Second Law efficiency (SLE) of automotive A/C using R134a and R600a for various engine rotations. The SLE values in the figure are calculated using Eq. (11). From the figure, the SLE values decrease with increasing engine rotation. This is because the total irreversibility of A/C increases with increasing engine rotation. It is also seen that the SLE using R600a is higher than R134a for all engine rotations. This means that the use of R600a in automotive A/C will produce better performance than using R134a. From this data in addition to reducing the percentage contribution to global warming, the use of R600a in automotive A/C will also result in improved performance of the system.

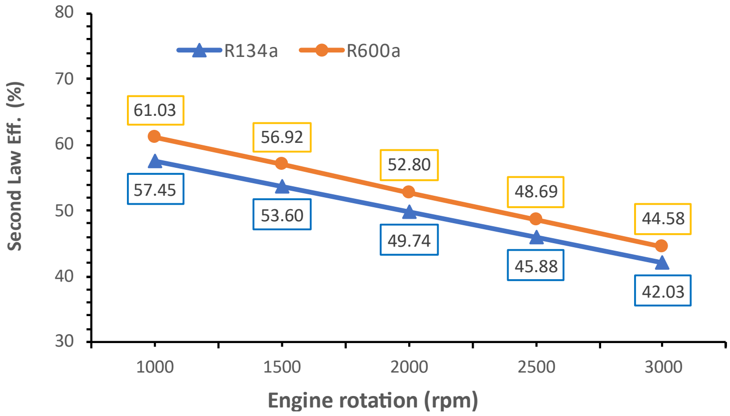


Fig. 13. Second Law efficiency of the automotive A/C for various engine rotations using R134a and R600a

4. Conclusions

The energy analysis shows that replacing R134a with R600a will increase the COP by about 3% for all engine rotations. It is also shown that the SLE of automotive A/C using R600a is also higher than that using R134a. Therefore, in term of efficiency, the use of R600a is quite promising to substitute R134a. Meanwhile, the exergy analysis shows that the percentage of irreversibility in the compressor and condenser using R600a was higher than using R134a. Therefore, to further improve the performance of automotive A/C, the performance improvement of the compressor and condenser are needed. However, the replacement of R134a with R600a in automotive A/C could be done because, thermodynamically, the use of R600a will produce better performance than R134a. In addition, from an environmental perspective the use of R600a as a substitute of R134a will significantly reduce the global warming effects.

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