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Investigation Of Automotive Air Conditioning Using Eco-Friendly R600a As An Alternative Refrigerant To R134a

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Abstract

One of the main reasons for replacing R134a with R600a is the impact of global warming. In this study, a numerical approach was applied to investigate changes in Automotive Air Conditioning (AAC) performance due to the replacement of R134a with R600a. A thermodynamic evaluation was carried out with evaporating and condensing temperatures of 5°C and 45°C, respectively. The study simulates AAC performance at five engine rotation speeds: 1000, 2000, 3000, 4000 and 5000 rpms. The results show that replacing R134a with R600a reduces the cooling capacity and input power by 45.42% and 47.02%, respectively. However, due to the dominant decrease in input power as compared to the decrease in cooling capacity, the Coefficient of Performance(COP) of AAC increases by 2.93%. Although the increment in COP is relatively small, this replacement greatly contributes to the reduction of greenhouse gas emissions that causes the problem of global warming due to the lower GWP of R600a as compared to R134a.

Keywords:

Automotive air conditioning, R600a, R134a,eco-friendly refrigerant, global warming potential.

1 Introduction

R134a is widely used as working fluid in Automotive Air Conditioning (AAC). R134a is used as an alternative refrigerant to R12 since the early 1990s due to high Ozone Depletion Potential (ODP) of R12 that harmful to the ozone layer [1]–[4]. After the 2000s, almost all AACs used R134a as a working fluid [5], [6]. Although R134a does not damage the ozone layer (zero ODP), it still has a relatively high Global Warming Potential (GWP), which is 1430 [7]–[10]. Due to the increase in global warming awareness around the world, several refrigerants were proposed as alternatives to R134a in AAC, namely R152a, R1234yf, R1234ze(e), CO₂, R290 and R600a [6], [11]–[14].

An experimental study of the substitution of R134a with R600a (safety class A3) in a domestic refrigerator has been performed [15]. It was reported that at optimum refrigerant mass charging, the energy consumption was reduced by approximately 18.7%. They also reported that replacing R134a with R600a in domestic refrigerators can reduce the potential for global warming in the atmosphere by about 21%. A numerical study of the replacement of R134a with R600a in AAC was carried out [16]. The results of his study reported that replacing R134a with R600a

increased Coefficient of Performance(COP) by approximately 3%, at evaporating and condensing temperatures of 7.2°C and 55°C, respectively. The more recent experimental study was carried out in a mini thermoelectric refrigerator by replacing R134a with R600a [17]. It was reported that the COP of mini thermoelectric refrigerators increased up to 19%. To enhance the COP improvement of the AAC, replacements of R134a with a mixture of R600a and R290 have been carried out [18]. In this experiment, the indoor and outdoor temperatures were set at 27°C and 35°C, respectively. The test results reported that the mixture of R600a and R290 increased cooling capacity by 5.95% and Energy Efficiency Ratio (EER) by 8.12%.

Even though R134a has a very high GWP, Indonesia and other Southeast Asian countries, until now they still use R134a as a working fluid. Meanwhile, in several European countries, R152a has been applied as a working fluid in AAC [19], [20]. Compared to R134a, the GWP of R152a is much lower, which is 124 [10]. However, when compared to R600a, the GWP of R152a is much higher, because the GWP of R600a is only 3, as shown in Table 1. It can also be seen that the GWP of R600a is the smallest among the three refrigerants.

Table 1. The properties of R134a and R600a [10], [21].

Refrigerant	Chemical formula	GWP (20-yr)	GWP (100-yr)
R134a	C ₂ H ₂ F ₄	3830	1430
R152a	C ₂ H ₄ F ₂	437	124
R600a	C ₄ H ₁₀	3	3

As an effort to reduce greenhouse gas emissions from the refrigeration sector, the purpose of this study is to investigate changes in AAC performance due to the replacement of R134a with an environmentally friendly refrigerant R600a, for various engine rotation speeds. The most important performance here is the cooling capacity which has never been discussed in previous publications. The results of this study are also expected to be taken into consideration by those who have authority in mitigating global warming.

2 Research Methods

To obtain the performance of the air conditioner, in terms of COP of the refrigerant side, the following steps are accomplished. The first step is determining its refrigerating effect, i.e., the enthalpy difference of refrigerant at the outlet and inlet of the evaporator. The second step is determining the specific work of compression. The next steps are the calculation of cooling capacity and the input power to the compressor. Then, the COP can be calculated from the ratio of cooling capacity and input power.

The working principle of AAC is the vapor compression refrigeration cycle, as shown in Fig. 1. Points 1 and 2 represent the refrigerant condition in the suction line and discharge line, respectively. Meanwhile, points 3 and 4 represent the refrigerant condition leaving the condenser and entering the evaporator, respectively. Based on the figure, the performances of the AAC, i.e., the Refrigeration Effect (RE), the Compressor Work (CW), Cooling Capacity (CC), Input Power (IP) and Coefficient of Performance (COP) are able to be determined. REFPROP is used to determine the properties of the refrigerant at each point in Fig. 1 [22].

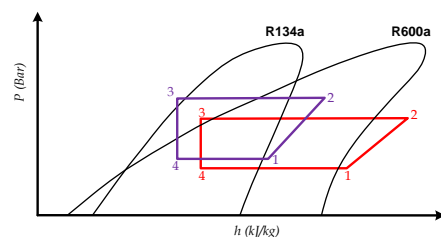


Fig. 1. Refrigerant cycles in automotive air conditioning system using R134a and R600a.

Because the AAC is driven by engine rotation, the performance will depend on the engine rotation. In this study, there are five engine rotation speeds under investigation, i.e., 1000, 2000, 3000, 4000 and 5000 rpms which will be investigated for their effect on AAC performance. These engine rotations represent idle, low, medium, high and very high speeds of the car. Before investigating the effect of changing engine rotation on AAC performance, several assumptions were applied in the numerical approach:

1. The evaporating and condensing temperatures are 5°C and 45°C, respectively;
2. The superheating and subcooling is 10 and 7 K for all engine rotation speeds;
3. The compressor isentropic efficiency is 0.70, 0.65, 0.60, 0.55 and 0.55 for 1000, 2000, 3000, 4000 and 5000 rpms, respectively;
4. The compressor volumetric efficiency is 0.70, 0.65, 0.60, 0.55 and 0.55 for 1000, 2000, 3000, and 4000 rpms, respectively;
5. The compressor has a constant displacement, that is $120 \times 10^{-6} \text{ m}^3 \cdot \text{rev}^{-1}$.

The Refrigeration Effect (RE), the Compressor Work (CW), the Cooling Capacity (CC), the Input Power (IP) and the Coefficient of Performance (COP) are determined using Eq. 1 – Eq. 5, respectively.

$$RE = h_1 - h_4 \quad (1)$$

$$CW = h_2 - h_1 \quad (2)$$

$$CC = \dot{m} \cdot (h_1 - h_4) \quad (3)$$

$$IP = \dot{m} \cdot (h_2 - h_1) \quad (4)$$

$$COP = \frac{CC}{IP} = \frac{(h_1 - h_4)}{(h_2 - h_1)} \quad (5)$$

where:

- h_1 = enthalpy of refrigerant at inlet compressor
- h_2 = enthalpy of refrigerant at outlet compressor
- h_4 = enthalpy of refrigerant at inlet evaporator
- \dot{m} = refrigerant mass flow rate

Furthermore, the mass flow rate (\dot{m}) of refrigerant in Eq. 3 and Eq. 4 are calculated using Eq. 6.

$$\dot{m} = \frac{rpm}{60} \cdot Disp_{comp} \cdot \rho_{suc} \cdot \eta_{vol} \quad (6)$$

The cooling capacity reduction, input power reduction, and system performance improvement due to retrofit from R134a to R600a are calculated using Eq. 7 – Eq. 9, respectively.

$$CC_{red} = \frac{CC_{R134a} - CC_{R600a}}{CC_{R134a}} \quad (7)$$

$$IP_{red} = \frac{IP_{R134a} - IP_{R600a}}{IP_{R134a}} \quad (8)$$

$$COP_{imp} = \frac{COP_{R600a} - COP_{R134a}}{COP_{R600a}} \quad (9)$$

3 Results and Discussion

There are five parameters under investigation in this comparative study, i.e. the Refrigeration Effect (RE), the Compressor Work (CW), Cooling Capacity (CC), Input Power (IP) and COP. Based on the comparison, the disadvantages and advantages of replacing refrigerant R134a with R600a in the AAC will be identified and discussed.

By using Eq. 1, the RE of R134a and R600a for various engine rotation speeds are shown in Fig. 2. The figure shows that the RE of R134a and R600a are constant for all engine rotation speeds. Because according to Fig. 1, the enthalpies at points 1 and 4 do not change during AAC operation, it can be seen that the RE of R600a is higher than that of R134a. The high RE value of R600a is due to higher latent heat of vaporization, as compared to R134a [22]. As a result, AAC using R600a produces a higher cooling capacity (Eq. 3) compared to R134a at constant evaporating temperature and the same refrigerant mass flow rate.

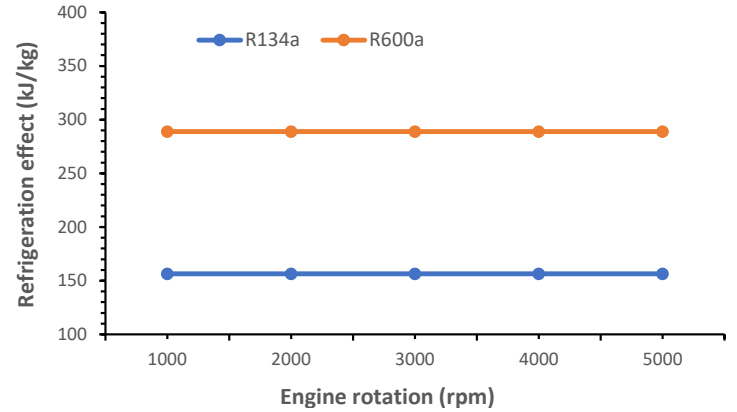


Fig. 2. Refrigeration effect vs engine rotation speed for R134a and R600.

Fig. 3 illustrates the CW of R134a and R600a for various engine rotation speeds. The CW values in the figure are calculated using Eq. 2. In contrast to the RE, the CW increases with the increase of engine rotation. This is because the enthalpy at point 2 increases while enthalpy at point 1 does not change with increasing of engine rotation speed. Furthermore, similar to the RE, the CW of R600a is higher than that of R134a. As a result, for the same refrigerant mass flow rate, R600a requires more input power.

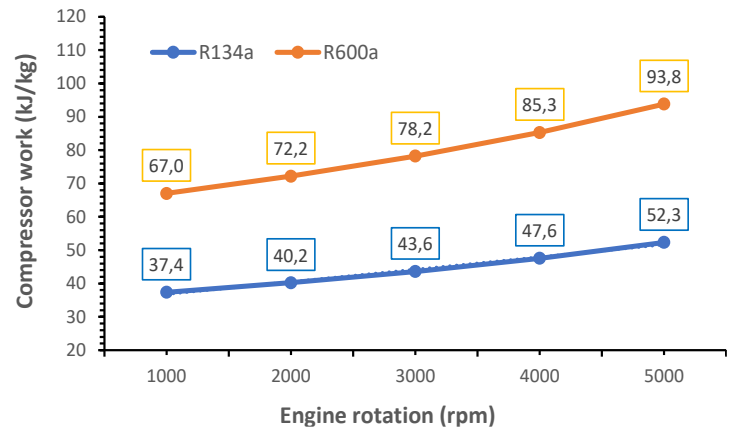


Fig. 3. Compressor work vs engine rotation speed for R134a and R600.

The cooling capacity is the expected output of an air conditioner. The higher the CC, the faster the cabin temperature set point is achieved. Eq. 3 is used to determine CC, while the mass flow rate of refrigerant is determined using Eq. 6. Fig. 4 shows the CC of R134a and R600a for various engine rotation speeds. It can be seen that the CC of both refrigerants increases with an increase in engine rotation speed. The CC of R134a is always higher than that of R600a for all engine rotation speeds. In other words, the CC of AAC will decrease if the refrigerant is replaced from R134a with R600a. This is because the mass flow rate of R134a is higher than that of R600a, as shown in Fig. 5.

The increase in CC for R134a and R600a are nearly linear with gradients of 2.29 and 1.25, respectively. This means that the increase in CC R134a due to the increase in engine rotation speed

is higher than that of R600a. The high of CC results in the cabin temperature being reached more quickly.

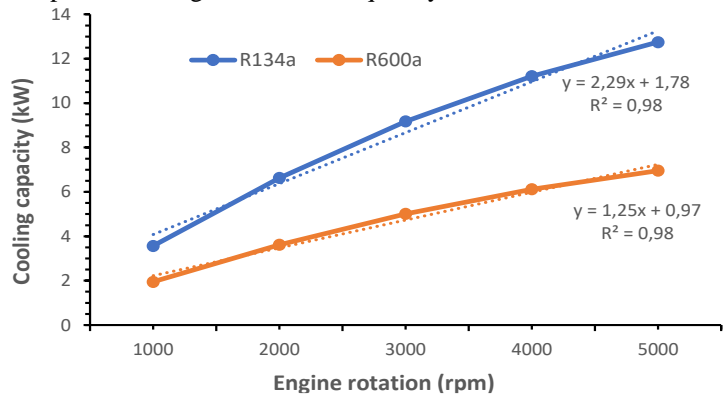


Fig. 4. Cooling capacity vs engine rotation speed for R134a and R600a.

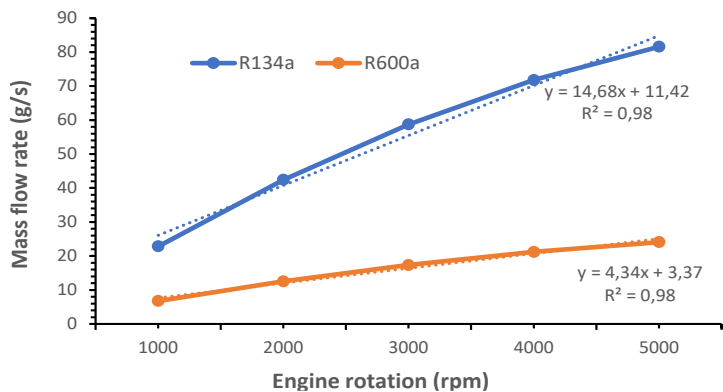


Fig. 5. The mass flow rate vs engine rotation speed for R134a and R600 in AAC.

Fig. 5 depicts the mass flow rate in AAC using R134a and R600a. It can be seen that the mass flow rate of R134a is higher than that of R600a for all engine rotation speeds. This is because the density of R134a (16.3 kg/m^3) at suction is almost four times as compared to R600a (4.8 kg/m^3). Consequently, the CC of R134a is higher than that of R600a, although the RE of R134a is lower than that of R600a. The increase in the mass flow rate of R134a and R600a in AAC is almost linear, with gradients of 16.68 and 4.34 for R134a and R600a, respectively. It means that the increase in the mass flow rate of R134a is higher than that of R600a for all engine rotation speeds.

The high density of R134a at suction also leads to higher IP, as compared to R600a for all variations of engine rotation speed, even though the CW of R134a is lower than that of R600a, as shown in Fig. 6. The figure illustrates that the IP increment of R134a and R600a due to engine rotation speed are linear with gradients of 0.9 and 0.5 for R134a and R600a, respectively. The gradient of R134a is higher than that of R600a, similar to the mass flow rate. The high IP causes an increase in car fuel consumption as the AAC compressor requires higher IP from the engine. In other words, for the same CC, the AAC using R134a will consume more fuel when the air conditioner is operated.

Fig. 7 depicts the COP of R134a and R600a of AAC for five engine rotation speeds. The figure shows that the COP of R600a is higher than that of R134a for all engine rotation speeds. The COP for two refrigerants decreases with the increase in engine rotation speed. In this case, linear decrement in COP for both refrigerants with the same gradient of -0.3 for higher engine rotation speeds is shown in Fig. 7.

The increase in COP due to the substitution of R134a with R600a indicates that the working fluid of R600a in AAC will produce the more efficient system. Although the increment in COP is not significant, however, in terms of environmental pollution, replacing R134a with R600a will greatly reduce greenhouse gas emissions. It is based on the fact that the GWP of

R134a is very high, that is 1430, while the GWP of R600a is only 3.

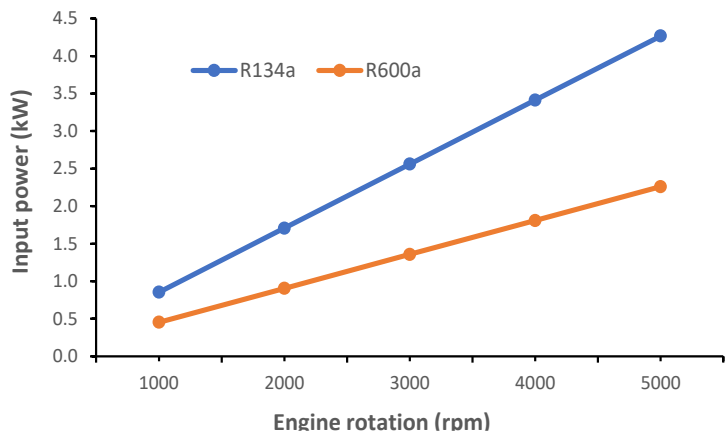


Fig. 6. The input power vs engine rotation speed for R134a and R600.

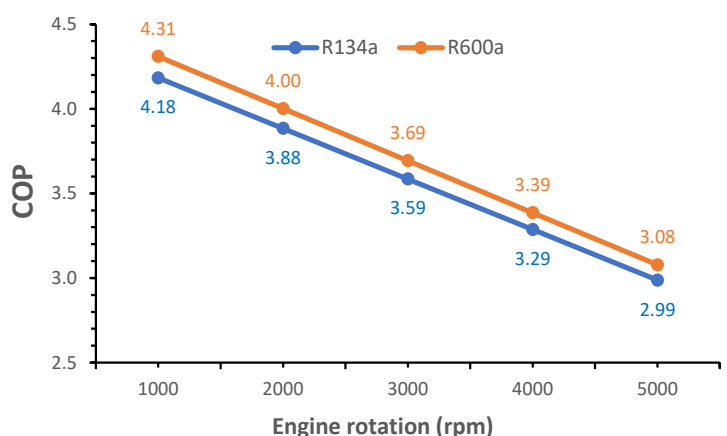


Fig. 7. The COP vs engine rotation speed for R134a and R600.

Further studies to enhance the COP improvement in AAC are still required. Apart from having a positive impact on the environment, replacing R134a with R600a will also have a positive impact on the Indonesia economy. In Indonesia, R600a can be produced from natural gas refining. Meanwhile, R134a is not produced in Indonesia, where it must be imported from foreign countries.

As previously explained, the cooling capacity of AAC will decrease if R134a is substituted by R600a. The decrement percentage in CC is calculated using Eq. 7. Based on Fig. 4, the CC increases with increasing engine rotation speed, but in fact, the decrease in CC is constant at 45.42%. This decrease in CC is due to the reduction in mass of filling R600a into the system because the density of R600a is around 40% of R134a [22]. Generally, in the process of replacing the original refrigerant with the alternative refrigerant, the same volume is used as a reference. Therefore, for the same volume, the mass of R600a is only about 40% that of R134a. A small charging mass will cause the mass flow rate to decrease and will also produce a small cooling capacity, because CC is directly proportional to the mass flow rate of the refrigerant, as shown in Eq. 3.

In addition to a decrease in cooling capacity, the replacement of R134a to R600a will also reduce the IP of the compressor. The decrease in IP is calculated using Eq.8. It can be seen that the decrement percentage in IP is constant with an average of 47.02%. The decrease in IP from this numerical study was higher when compared to the previously performed experiment on domestic refrigerators, which is 18.7% [15]. This is reasonable because, in the numerical approach, the calculation conditions are carried out ideally, while in the experimental study, several conditions in the field are not taken into account in the numerical analysis. In addition, domestic refrigerators use small capacity compressors of less than 0.5 HP and the input power comes from constant

electricity. Meanwhile, AAC uses input power that comes from engine rotation with varying power.

Eq. 9 is used to calculate the increment in COP. The increase in COP is constant at an average of 2.93% even though the engine rotation speed increased. This means that replacing R134a with R600a has an advantage, in terms of AAC performance, albeit relatively small. These results are similar to those previously carried out [16], where the COP improvement is 3%, although the evaporating and condensing temperatures modeling are slightly different from the numerical assessment in this study.

Ideally, substituting refrigerant in the refrigeration system may increase the COP, but if it does not increase the COP, there must be another side that benefits. Like the replacement of R134a with R600a, even though it only slightly increases the COP, the environmental impact is very huge. This is because the GWP of R134a is very high, which is 1430, while the GWP of R600a is only 3. This means that if a refrigerant leak occurs at the AAC, the refrigerant emission that causes greenhouse gas will decrease significantly.

4 Conclusion

The use of R134a for AAC shortly has to be phased out due to high GWP characteristics and strong legislative requirements. The thermodynamic investigation showed that replacing R134a with R600a decreases the refrigeration effect and compressor work. It is observed that the charging mass of R600a is only about 40% as compared to R134a, and this causes the cooling capacity and input power to decrease drastically. However, the decrement in input power is more dominant than that of a decrease in cooling capacity, thus leading to an increase in COP of around 2.93%. The reduction in cooling capacity, however, needs to be taken into account whether it is still sufficient to handle the cooling load in the vehicle cabin. If not, then a larger AAC unit is needed. Apart from producing an increase in COP, the more important aspect of replacing R134a with R600a is efforts to mitigate greenhouse gas emissions originating from R134a. In the other aspect, further detailed research to improve AAC system performance using either R600a or mixed refrigerants which have low GWP is still required before it can be commercialized and becomes a solid alternative to R134a.

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