Effect Of Engine Speed On The Performance Of Automotive Air Conditioning System Using R134a And R152a As Refrigerants

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Abstract. This paper presents a numerical approach in the investigation on the effect of engine speed on the performances of automotive air conditioning system using R134a and R152a as refrigerants. In the near future, R152a refrigerant is projected to replace R134a as working fluid in vehicle air conditioning systems. In this study, four engine rotations, i.e., 1000, 2000, 3000 and 4000 rpm that represent: idle, city, medium speed and high speed conditions, respectively, were investigated. In the modeling, the evaporating and condensing temperatures were assumed constant at 5°C and 45°C, respectively. The results showed that coefficient of performances (COPs) of the automotive air conditioning using R152a were higher than that of R134a for all engine speeds. The COP improvement of R152a increased with the increase in engine speed. At engine rotation of 4000 rpm, the COP improvement was by as much as 6.4%. The disadvantage of R152a compared to R134a was in its high discharge temperature. This condition is anticipated to affect the reliability of the compressor in the long run.

1. Introduction
The compressor of a residential air conditioning (A/C) unit is designed for fixed rotation. Consequently, the cooling capacity of the residential A/C unit also generates fixed cooling capacity. The cooling capacity only slightly increases or decreases when the outdoor temperature rise or drop. The cooling capacity of automotive A/C unit is influenced by the engine speed. The higher engine speed the higher the cooling capacity. However, the increase of engine speed will also lead to the increase in the input power of the compressor. Naturally the increase in the input power results in increase in the fuel consumption.

Nowadays, R134a is widely used as working fluid in automotive A/C. This refrigerant is as the substitute to R12 and was in used since 1990s, as R134a is said to be more environmentally friendly than R12. Researchers have found out that the R12 has higher ODP (ozone depletion potential) and
GWP (global warming potential). Meanwhile, R134 has zero ODP and much lower GWP compared to R12 [1,2]. However, due to global warming issue, many have reported that R134a still has high GWP and has to be replaced with more environmentally friendly refrigerants. One of alternative and promising refrigerants is R152a. This refrigerant has very low GWP and many of its properties are very close to the R134a. The properties of R12, R134a and R152 are shown in Table 1, where the normal boiling point (boiling temperature at pressure of 1 atmosphere) of R12, R134a and R152 are almost similar, i.e., -29.8°C, -26.1°C and -24.0°C. This indicates that the suction pressure (low pressure) for these refrigerants are similar when are applied in a refrigerator or in an air conditioner. The table also shows that although R134a has zero ODP (ozone depletion potential), its GWP is 1300, much higher than that of R152a, that is 138. As R134a has high GWP, European countries will ban it in all vehicles A/Cs from 2017 [3]. The European Union issued a regulation that the GWP of refrigerants in the vehicle A/Cs must be below 150. Due to this development, the automotive manufactures was the first industries that considered R152a as an alternative to R134a as refrigerant in passenger car air conditioning systems.

Table 1. Refrigerant properties [1,2].

| Refrigerant | Chemical Formula | Normal Boiling Point (°C) | ODP  | GWP (100-year) |
|-------------|-----------------|--------------------------|------|--------------|
| R12         | CCl₂F₂          | -29.8                    | 0.82 | 8,100        |
| R134a       | CH₂FCF₃         | -26.1                    | 0    | 1300         |
| R152a       | C₂H₄F₂          | -24.0                    | 0    | 138          |

The correlation between the saturation temperature and the pressure of R134a and R152a is shown in Figure 1 [2]. Here, the working temperature and working pressure of refrigerants when applied in the refrigeration system can be predicted. Also from the figure, the working pressure of these refrigerants for the low pressure (evaporating temperature) is almost the same. However, for high pressure (condensing temperature), the pressure of R152a is slightly lower than that of R134a. In other words, for similar evaporating and condensing temperatures, the compression ratio of R134a is slightly higher than that of R152a.

Numerical analysis on the switching from R134a to R152a in a car A/C system was done by Ghodbane [4]. He reported that COP of the A/C using R152a was higher than that of R134a. The COP improvements were 11% and 15% for idle and road conditions, respectively. An experimental investigation on automotive A/C system using a swash-plate open-type compressor was carried out by Kim et al. [5]. In the experiments, they tested the A/C system performances using R134a and R152a as refrigerants. Based on the experimental data, they reported that the COP of R152a was 20% higher than of R134a. Another experiment on automotive A/C system using R134a and R152a as working fluids was made by Bryson et al. [6]. Their experimental data also revealed an improvement in cooling capacity and COP of 2% and 9%, respectively. Furthermore, an experiment using a hermetic compressor with R134a and R152a as refrigerants was carried out by Cabello et al. [3]. Substitution refrigerant from R134a to R152a was performed by a conventional drop-in, without changing compressor lubricant. According to the experimental data, the cooling capacity of R152a decreased by 10% and COP increased by 13%. The outcomes indicate that the decrease in input power using R152a is more than the decrease in the cooling capacity (10%), because the COP is the ratio of the cooling capacity to the input power.
2. System Description And Modeling

2.1 System Cycle

Vapor compression refrigeration cycle (VCRC) is widely used in the automotive A/C system, as shown in Figure 2. The figure shows that the compressor is coupled to the car engine. Because the increase in cooling capacity and input power due to engine speed are not linear, as a result, the COP of the automotive A/C also is not constant.

The cycle of VCRC in P-h (pressure vs. enthalpy) diagram for R134a and R152a as refrigerants is shown in Figure 3. Based on the thermodynamic properties of R134a and R152a, the saturated lines of R152a lies on the right of R134a [2]. The refrigerating effect is represented by \((h_1 - h_4)\), whereas the compressor work is calculated by \((h_2 - h_1)\). In this simple cycle, points 1 and 3 lie on the saturated vapor and saturated liquid lines, respectively, whereas point 2 and 4 represent enthalpies of the compressor discharge and expansion device outlet, respectively. However, in the actual system, the points 1 and 3 lie in the superheated and subcooled regions, respectively.
2.2 Modeling Procedure

In normal operation, a car engine rotates from low to high speed depending on the driving condition. In this study, four engine speeds, i.e., 1000, 2000, 3000 and 4000 rpm were selected for the modeling. They represent idle, in the city, medium and in high speed conditions, respectively. Refprop NIST software [2] is used to determine the refrigerant properties. There are some assumptions applied in the modeling process and they are:

- The superheating at the evaporator is similar to subcooling in the condenser (as shown in Figure 3).
- The superheating is 1, 2, 3 and 4 K for 1000, 2000, 3000 and 4000 rpm, respectively, because the higher the engine speed, the higher the superheating, due to the higher heat absorbed by the evaporator.
- The superheating in the evaporator is not calculated as the cooling capacity, because it occurs at the outside of the evaporator.
- The volumetric efficiency ($\eta_{vol}$) and isentropic efficiency ($\eta_{ise}$) of the compressor are the same, namely 0.75, 0.65, 0.55 and 0.50 for 1000, 2000, 3000 and 4000 rpm, respectively [7].
- The compressor has a constant displacement of is $120 \times 10^{-6}$ m³.rev⁻¹.
- The expansion process is isenthalpic and enthalpy of entering refrigerant to the evaporator is on saturated liquid condition.
- The pressure drops in all of the components are ignored.

Based on the above assumptions, the refrigerant properties at each point in Figure 3 can be determined; and furthermore the performances of automotive A/C can be calculated. The flow chart for simulating the performance of system is shown in Figure 4. Four parameters of car A/C, namely the cooling capacity ($Q_{evap}$), the input power ($P_{comp}$), the COP and the discharge temperature ($T_{disc}$) will be presented.

In order to evaluate the A/C performances due to engine speed, some equations are used. The equations of mass flow rate ($\dot{m}$), the cooling capacity ($Q_{evap}$), the input power ($P_{comp}$) and the COP are calculated using Eqs. (1), (2), (3) and (4), respectively.

![Figure 3](image-url)
\[
\dot{m} = \frac{\text{rpm}}{60} \cdot \text{Disp}_{\text{comp}} \cdot \rho_{\text{suct}} \cdot \eta_{\text{vol}} \tag{1}
\]

\[Q_{\text{evap}} = \dot{m} \cdot (h_1 - h_3) \tag{2}\]

\[P_{\text{comp}} = \dot{m} \cdot (h_2 - h_1) \tag{3}\]

\[\text{COP} = \frac{Q_{\text{evap}}}{P_{\text{comp}}} \tag{4}\]

where \(\text{Disp}_{\text{comp}}\) is the compressor displacement (m\(^3\)rev\(^-1\)), \(\rho_{\text{suct}}\) (kg/m\(^3\)) is refrigerant density at suction, \(\eta_{\text{vol}}\) is the compressor volumetric efficiency and \(P_{\text{disc}}\) (MPa) is discharge pressure.

One of the objectives of the refrigerant substitution from R134a to R152a is to improve the cooling capacity and reduce the input power. The increase in cooling capacity and decrease in input power cause the COP improvement. Furthermore, to calculate the cooling capacity improvement \((Q_{\text{evap\_imp}})\), the input power reduction \((P_{\text{comp\_reduc}})\) and the COP improvement \((\text{COP\_imp})\) due to drop-in from R134a to R152a, Eqs. (5), (6) and (7), respectively will be applied.

\[Q_{\text{evap\_imp}} = \frac{Q_{\text{Evap\_R152a}} - Q_{\text{Evap\_R134a}}}{Q_{\text{Evap\_R134a}}} \tag{5}\]

\[P_{\text{comp\_reduc}} = \frac{P_{\text{Comp\_R152a}} - P_{\text{Comp\_R134a}}}{P_{\text{Comp\_R134a}}} \tag{6}\]

\[\text{COP\_imp} = \frac{\text{COP}_{\text{R152a}} - \text{COP}_{\text{R134a}}}{\text{COP}_{\text{R134a}}} \tag{7}\]

The values of Eqs. (5) and (7) may be positive or negative. The positive value indicates that the performance using R152a is better than that of R134a. Conversely, the negative value shows that the system performance of R152a is worse than that of R134a. Meanwhile, according to Eq. (6), when the input power reduction is positive, it implies that the use of R152a in A/C system will reduce fuel consumption compared to R134a in a car.
Determine $T_{\text{evap}}$ and $T_{\text{cond}}$

For ES = 1000 rpm to 4000 rpm
   Step 1000 rpm

- Determine the subcooling and superheating
- Determine $\eta_{\text{vol}}$ and $\eta_{\text{ise}}$
- Calculate the mass flow rate
- Find the enthalpies at points 1, 2, 3 and 4

Calculate the $Q_{\text{evap}}$, $P_{\text{comp}}$, COP and $T_{\text{disc}}$

Figure 4. Flow chart of calculating method for simulating the system performance.

3. Results and Discussion

3.1 Cooling Capacity

The cooling capacity represents the amount of absorbed heat by the evaporator. Figure 5 illustrates the cooling capacity for R134a and R152a for various engine speeds. It can be seen that the cooling capacity of R134a and R152a increases with the increase in the engine speed. In addition, the cooling capacity of R134a was slightly higher than that of R152a. According to Eq. (1), the high of cooling capacity of R134a compared to R152a was caused by the high of mass flow rate of R134a compared to R152a, because the density of R134a is higher than that of R152a.

The cooling capacity improvement is depicted in Figure 6. The figure shows that the values of cooling capacity improvement are negative. It means that there is no the cooling capacity improvement, but rather the cooling capacity reduction in the drop-in from R134a to R152a. The figure shows that the cooling improvement increases with increase in the engine speed. For example, at 4000 rpm, the difference of cooling capacity of R134a and R152a is only 2%. This indicates that at high engine rotation, the amount of cooling capacity that produced by R152a is almost similar to the R134a, that is only a 2% difference. Compared to the experimental results were carried out by Bryson et al. [6], the numerical results were not too far with their experimental data. In the experimental
results, they reported that the cooling capacity improvement on drop-in from R134a to R152a was 2%.

Figure 5. The cooling capacity versus engine speed for R134a and R152a.

Figure 6. The cooling capacity improvement versus engine speed.

3.2 Input Power

The compressor of automotive A/C is driven by engine, as a result, when the input power that consumed by this A/C system increases, fuel consumption will also rise. In other words, the lower the input power, the lower the fuel consumption. Figure 7 depicts the input powers of R134a and R152a versus engine speed. The figure shows that the input power for the A/C with R152a is lower than that of R134a for all engine speed. It can also be seen that the difference between input powers R134a and R152a increases with increase in the engine speed.
Figure 8 illustrates the input power reduction due to drop-in from R134a to R152a. The figure shows that the input power reduction is almost constant for all engine speeds. At the speeds of 1000 rpm to 2000 rpm, the input power reduction was 8%, whereas for speeds of 3000 rpm to 4000 rpm raised the input powers of 7.9%. This also implies that the increase in speed has no affect on the input power reduction. As such, it can be said that the use of R152a will result in the input power reduction for all engine rotations, that is about 8%. Consequently, this leads to reduction of fuel consumption of the car filled with such a system.

3.3 Coefficient of Performance (COP)

The COP is the most important parameter in A/C system to indicate the system performance. It is expected that refrigerant replacement from R134a to R152a will increase the COP. As explained in the previous section that the drop-in from R134a to R152a decreased the cooling capacity and input power. Because the COP is the ratio between the cooling capacity and the input power, as a result the COP improvement will be positive if the decrease in cooling capacity is lower than that of the input power. Figure 9 depicts the COP of R134a and R152a. It shows that the COP of R134a is lower than that of R152a for all engine rotations. This indicates that the use of R152a as a substitute refrigerant in A/C system will enhance COP.
Figure 10 illustrates the COP improvement versus engine rotation for R134a and R152a as refrigerant on the car A/C. It has been explained in the previous section that in this study, the decrease in cooling capacity was lower than that of the decrease in input power. As a result, the COP improvement will be positive. The figure shows that the COP improvement increases with increase in the engine rotation. The increase in COP improvement rises significantly at engine rotation of 3000 rpm to 4000 rpm. In this study, the maximum of COP improvement is 6.4%, occurred at engine rotation of 4000 rpm. Compared to the experimental data from Kim et al. [5], the obtained data in this study was much lower than that of the experimental data from Kim et al. [5], namely 6.4% compared to 20%, respectively. However, if compared to experimental results from Bryson [6], the result data in this study was not too different, namely 9% to 6.4%, respectively. The difference might be caused by selection of the compressor isentropic and the compressor volumetric efficiencies in this study.

3.4 Discharge Temperature
The discharge temperature is not directly related to the automotive A/C performance. In normal condition, the discharge temperature is higher than the ambient temperature because during operation, the compressor produces heat. However, too high temperature of the discharge temperature will
decrease compressor isentropic efficiency and overheating on the compressor. The overheating of the compressor leads to premature wear of the compressor’s cylinder and piston ring. In addition, the overheating also may cause lubricant to break down, causing accelerated wear in the compressor [8]. The reliability of the compressor will decrease and failure will soon follow if continues to overheating occur. Figure 11 depicts conditions discharge temperature where R152a is higher than that of R134a for all the engine speeds. It can be seen that the differences in discharge temperature between R134a and R152a increase with the increase in the engine speed. The figure shows that the highest temperature is 93.1°C at 4000 rpm when the A/C system using R152a as refrigerant. At this speed, the discharge temperature is only 74.3°C when R134a is applied as working fluid. It means that direct drop-in from R134a to R152a in automotive is not recommended, because potential overheating will occur in the compressor at a high speed.

Figure 11. The discharge temperature versus engine speed.

4. Conclusions
The evaluation on the performance of automotive A/C system using R134a and R152a as refrigerant for various engine rotations has been investigated. The results showed that the use of R152a as a refrigerant substitute in automotive A/C system could boost the performance. Based on the obtained results, the following conclusions have been made:

The use of R152a decreased the cooling capacity; however the decrease in cooling capacity increases with the increase in the engine speed. The highest cooling capacity reduction was 2% at engine speed of 4000 rpm.

1. The use of R152a decreased the input power. The highest input power reduction was 8% at engine speeds of 1000 rpm and 2000 rpm when R152a was applied as refrigerant. The input power reduction leads to decrease the fuel consumption for automotive A/C application.
2. The COP improvement increased with increase in the engine speed. The highest COP improvement was 6.4%, occurred at engine rotation of 4000 rpm.
3. The use of R152a as working fluid in automotive A/C leads to significant increase the compressor discharge temperature, especially at a high engine speed.

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