R1234yf/R134a Based Refrigerant Mixture for Automobile Air Conditioning Systems: A Thermodynamic Approach

Rajendran Prabakaran¹*, P Somasundaram¹, Shaji Sidney², K Sanjeev¹, Fasil Mohamed¹, and VM Subathran¹

¹Department of Automobile Engineering, Kongu Engineering College, Perundurai, Erode – 630 060, India.
²Department of Energy and Environmental Engineering, Saveetha School of Engineering, Saveetha Nagar, Thandalam - Perambakkam -Thakkolam Rd, Tamil Nadu – 602 105, India.

*Email: praba.auto@gmail.com

Abstract. The environmental protocols lead to analysing various refrigerants minimum global warming potential (GWP) to substitute high GWP R134a in an automobile air conditioning (AAC) system. The present study deals with the thermodynamic analysis of the AAC unit using R1234yf/R134a refrigerant mixtures under three-vehicle speed conditions such as idling (L-900 rpm), city limit (M-1800 rpm), and high speed (H-2700 rpm). The mass fractions of R1234yf/R134a such as 0:1, 1:0, 0.9:0.1, 0.8:0.2, 0.7:0.3, 0.6:0.4 and 0.5:0.5 were considered in this analysis. The cooling capacity and coefficient of performance (COP) of R1234yf were observed to be poorer than that of the existing R134a by up to 10.4% and 8.3%. The addition of R134a in R1234yf reduced the performance gap between the existing R134a system under all the speed conditions. There was an increase cooling capacity and COP of the AAC by up to 6.4% and 4.9% was found with the addition of 0.5 mass fraction of R134a in R1234yf. However, the GWP of the refrigerant mixture was increased with rise in R134a mass fraction of which causes more direct CO₂ emission from the AAC system. This study prevailed that the use of R1234yf/R134a mixture (0.5:0.5 by a mass fraction) performed very much similar to that of R134a in the AAC unit. Further, the R1234yf/R134a mixture (0.9:0.1 by a mass fraction) is suggested to use in the AAC system to satisfy the environmental protocols (GWP < 150).

1. Introduction

The use of refrigerants with high global warming potential (GWP) needs to be replaced soon because of the environmental protocols [1]. In this context, many researchers were trying to replace the existing R134a because of its GWP as 1430 in automobile air conditioning (AAC) systems [2]. The AAC system played a crucial role in fuel consumption also because it used 12 – 20% of engine power for running its compressor [3]. It is very important to consider thermo-physical, environmental, toxicity, and flammability properties for the selection of new refrigerant to replace R134a [4]. The properties of thermo-physical namely, latent heat of condensation and evaporation, thermal conductivity, viscosity, density, and pressure-temperature characteristics are played a significant role in the refrigerant performance [4]. Many refrigerants such as R152a, R1234ze(E), R1234yf, R744, R290, R600a, R430A, R444A, and R445A, etc were used in the AAC system for R134a replacement [5 – 11]. Out which, R1234yf attracts many researchers because of its comparable pressure-
temperature characteristics with R134a and also had slightly poor performance. The technologies like suction line heat exchanger [12, 13], mini channel heat evaporator/condenser [14], high capacity compressor [15], TXV modification [16] were employed for enhancing R1234yf performance. Instead of using system/component modification, Meng et al. [17] proposed a refrigerant mixture of R1234yf/R134a (89:11 by mass) for heating and cooling in AAC application. They observed that the mixture had lower COP in both heating and cooling modes by up 16% and 9% respectively and it is also found that the adding of 11% of R134a eliminates the flammability issues in R1234yf. Similarly, Lee [18] also used three different mass fractions of R134a (5, 10, and 15%) in R1234yf for achieving better performance with negligible flammability. Later Shin et al. [19] experimentally analysed the R134a/R1234yf mixture with mass fractions of 90:10, 80:20, and 70:30 for AAC unit under different outdoor temperatures. From their results, it is suggested to use the mixture R134a/R1234yf (70:30 by mass) in the place of R134a because it had only 5% lesser COP than that of R134a.

Therefore, previous studies suggested that the use of R1234yf/R134a refrigerant mixture could have lesser difficulty as compared to the system component modification/addition; which in turn reduces the initial cost also. Hence, the presented concentrated on the thermodynamic performance of an AAC using R134a, R1234yf, and R1234yf/R134a mixtures with different mass fractions (as shown in Table 1) under three-vehicle speeds (idling, city limit, and high speed). The properties of the refrigerants (R134a, R1234yf, and R1234yf/R134a mixtures) are calculated using Refprop 8.0 software [20].

| Refrigerants/mixtures | Mass fraction | R134a | R1234yf | GWP  |
|-----------------------|---------------|-------|---------|------|
| R134a                 | 1             | 0     | 0       | 1430 |
| R1234yf               | 0             | 1     | 1       | 4    |
| M01                   | 0.1           | 0.9   | 1       | 146  |
| M02                   | 0.2           | 0.8   | 1       | 289  |
| M03                   | 0.3           | 0.7   | 1       | 432  |
| M04                   | 0.4           | 0.6   | 1       | 574  |
| M05                   | 0.5           | 0.5   | 1       | 717  |

2. Thermodynamic analysis of AAC system

The AAC system works based on the principle of vapour compression refrigeration (VCR) as shown in Figure 1. Major components are compressor, condenser, thermostatic expansion valve, evaporator, and a magnetic clutch. The coefficient of performance (COP) is the term used for evaluating the performance of the VCR system, which is the ratio between cooling capacity (Qe) and power consumed by the compressor as shown in equation 1 [21].

$$\text{COP} = \frac{Q_{\text{evap}}}{W_{\text{ele}}}$$  \hspace{1cm} (1)

$$Q_{\text{evap}} = \dot{m}_{\text{ref}}(h_{\text{evap,in}} - h_{\text{evap,out}})$$  \hspace{1cm} (2)

$$W_{\text{ele}} = \dot{m}_{\text{ref}}(h_{\text{comp,out}} - h_{\text{comp,in}})$$  \hspace{1cm} (3)

Where, \(\dot{m}_{\text{ref}}\) is the mass flow rate of the refrigerant in kg.s\(^{-1}\), \(h_{\text{evap,in}}\) and \(h_{\text{evap,out}}\) are the enthalpies of the refrigerant at evaporator entry and exist in kJ.kg\(^{-1}\) respectively. Further, the mass flow rate of the refrigerant is calculated from the volumetric efficiency (\(\eta_{\text{vol}}\)) of the compressor by using the following equation [22],

$$\eta_{\text{vol}} = \frac{\dot{m}_{\text{ref}} \cdot \theta_{\text{ref,in}}}{CC \times \text{compressor speed}}$$  \hspace{1cm} (4)
The Test conditions for analysis on the performance of a VCR cycle are shown in Table 2. Further, the following assumptions were used during the calculated [23]. There are,

- The degree of superheating (DSH) and subcooling (DSC) at the evaporator outlet and condenser outlet respectively are 5°C.
- The pressure drop in the pipelines, condenser and evaporator are negligible.
- The expansion process in the TXV is assumed to be isenthalpic.
- The compressor displacement volume is same (160 cm³/min).
- The volumetric ($\eta_{vol}$) and isentropic ($\eta_{isen}$) efficiencies of the compressor change.
- The evaporator temperature is constant (0°C) for all the driving condition and the difference between condenser temperature and the atmospheric temperature is maintained as 15°C.

### Table 4.2. MAC system operating conditions for theoretical analysis [23]

| Parameters                               | Operating conditions |
|------------------------------------------|----------------------|
|                                          | Idle speed | City limit speed | High speed |
| Atmospheric temperature (°C)             | 30         | 40              | 45         |
| Vehicle speed (rpm)                      | 900        | 1800            | 2700       |
| Compressor volumetric ($\eta_{vol}$) and isentropic ($\eta_{isen}$) efficiencies | 0.75       | 0.65            | 0.55       |
3. Results and Discussion

In this chapter, the effect of R134a addition on the thermo-physical properties, flammability aspect, and GWP variation in the R1234yf refrigerant mixture is discussed. Then the performance variables namely, refrigerant mass flow, discharge temperature, power consumption cooling capacity, and COP as a function of compressor speeds (L, M, and H) for the pure R134a, R1234yf, and mixtures of R1234yf and R134a are discussed comprehensively.

3.1 Thermo-physical properties of R1234yf/R134a mixture

The variations in saturation pressure and phase change at evaporation (0°C) and condensation (50°C) temperatures as a function of R134a mass fraction are illustrated in Figures 2a and 2b respectively. The discharge pressure and phase change enthalpy during condensation and evaporation of R1234yf are found to be lower than those of R134a by 1.18%, 17.7%, and 19.5% respectively, while suction pressure is 7.8% higher. There is a rise in discharge pressure as well as phase change enthalpies with augmentation in R134a mass fraction, while suction pressure drops slightly. Therefore, the pressure ratio for the constant evaporation and condensation temperatures got increased which indeed required more input power. Overall, the maximum rise in discharge pressure, pressure ratio, latent heat of evaporation, and condensation owing to the addition of 0.5 mass fraction of R134a in R1234yf mixture are 0.78%, 4.4%, 11.8, and 10.6% respectively with a 3.6% reduction in suction pressure.

![Figure 2. Effect of R134a addition on the a) saturation pressure and b) Phase change enthalpy of R1234yf/R134a mixture.](image-url)

The effect of R134a inclusion on the liquid density, vapour density, thermal conductivity, and viscosity of the R1234yf/R134a mixtures are illustrated in Figures 3(a – b). The liquid density, thermal conductivity, and viscosity of R1234yf are found to be 10.15%, 18.2%, and 21.8% lower than those of R134a, though it had 22.3% higher in vapour density. The addition of R134a mass fraction in the refrigerant mixture increases the liquid density, liquid thermal conductivity, and viscosity, while vapour density got decreased. The increased thermal conductivity has a positive impact on the betterment in heat transfer, on the other hand, the rise in viscosity could cause more friction pressure drop in the system. Similarly, the rise in liquid density of the mixture could resulting in more refrigerant inventory for the same volume of the system, while the compressor pumping capacity may be slightly affected because of reduced vapour density (increased vapour volume). Overall, the inclusion of 0.5 mass fraction of R134a in R1234yf had better liquid density, thermal conductivity,
and viscosity by 5.4%, 7.8%, and 13% lower than those of R1234yf with 9.7% reduced vapour density.

![Figure 3](image)

**Figure 3.** Effect of R134a inclusion on thermo-physical properties of R1234yf/R134a mixture a) Liquid density, b) Vapour density, c) Thermal conductivity and d) Viscosity.

From this chapter, it is observed that the addition of R134a in R1234yf had greater advantage in the latent heat of phase change, thermal conductivity with better temperature-pressure characteristics; though it had some drawbacks such as increased viscosity, refrigerant inventory, and GWP. Therefore, it is better to know the system performance for identifying the better R1234yf/R134a refrigerant mixture theoretically by considering all the above-mentioned properties.

### 3.2 Analysis of AAC system using R1234yf/R134a mixture

The influence of R134a mass fraction and vehicle speed on the refrigerant mass flow rate of the R1234yf/R134a mixture is shown in Figure 4. In comparison with pure R134a, pure R1234yf has a 22.7% higher refrigerant mass flow rate at idling speed (L) owing to its higher vapour density at compressor inlet; the difference in mass flow rate further got reduced to 19.7% when the vehicle speed increased to high-speed condition (H). The seeding of R134a in R1234yf is resulting in the reduction of refrigerant mass flow rate which is due to the drop in vapour density of the mixture as shown in Figure 3b. The maximum drop in mass flow is experienced with 0.5 mass fraction of R134a in R1234yf/R134a mixture by up to 9.8% for the considered vehicle speed condition; the same mass flow rate is still 10.5% higher than that of R134a mass flow rate.
The influence of R134a mass fraction and compressor speed on the discharge temperature of the R1234yf/R134a mixture is presented in Figure 5. The lower saturation temperature of R1234yf as compared to R134a at the same pressure resulted in low discharge temperature by 7°C, 8.2°C, and 8.8°C at the idling (L), city (M), and high speed (H) driving conditions respectively. The rise in R134a mass fractions reduced the difference in pressure–temperature characteristics between R134a and R1234yf/R134a mixture. However, it increased the discharge temperature of the R1234yf/R134a
mixture by up to 4.3°C with a 0.5 mass fraction of R134a, and at the same time, it had still lower discharge temperature by up to 4.5°C as compared to pure R134a.

![Figure 6. The variation cooling capacity as a function of R134a mass fraction and compressor speed.](image)

The variation cooling capacity of the R1234yf/R134a mixture as a function of R134a mass fraction and compressor speed is illustrated in Figure 6. There is a rise in cooling capacity with an increase in R134a mass fraction and compressor speed is seen. This could be due to the rise in latent of evaporation due to the addition of R134a mass fraction (seen from Figure 2b), which outweighs the drop in refrigerant mass flow rate (seen from Figure 4); which in turn increased the system cooling capacity by 2.9%, 4.2% and 6.4% at the idling (L), city (M) and high speed (H) driving conditions respectively. Overall, the cooling capacity of the R1234yf/R134a mixture with a 0.5 mass fraction of R134a is slightly lower than that of pure R134a by 1.2 – 4.5% for the considered driving conditions.

The variation compressor power consumption for the R1234yf/R134a mixture as a function of R134a mass fraction and compressor speed is shown in Figure 7. There is an increase in power consumption by the compressor is seen with an increase in compressor speed and R134a mass fraction. The increase in the R134a fraction increased the discharge temperature as well as discharge pressure, which in turn increased the pressure ratio for the constant evaporation and condensation temperatures. This could be the possible reason for the increased power consumption with R134a mass fraction by 0.6%, 1.1%, and 1.4% at the idling (L), city (M), and high speed (H) driving conditions respectively. Overall, the cooling capacity of the R1234yf/R134a mixture with a 0.5 mass fraction of R134a is slightly lower than that of pure R134a by up to 0.8% for the considered driving conditions.

The variation system COP for R1234yf/R134a mixture as a function of R134a mass fraction and compressor speed is demonstrated in Figure 8. In comparison with pure R134a, pure R1234yf had 3.21% lower COP at idling speed (L) owing to its poor cooling capacity; the difference in COP further got increased to 8.3% when the vehicle increased to high-speed condition (H). This could be due to the significant rise in power consumption with an increase in compressor speed as compared to the cooling capacity. There is an increase in system COP is seen with the increase in R134a mass fraction and it decreased with an increase in compressor speed.
The possible reason for the rise in COP is the significant enhancement in the cooling capacity of the R1234yf/R134a mixture due to the seeding of R134a (seen from Figure 6) and it outweighs the increase in power consumption by the compressor (seen from Figure 7). Even though the R1234yf/R134a mixture had better COP than that of R1234yf by 2.2 – 5% with 0.5 mass fraction of R134a, still it had slightly poorer COP than that of the existing R134a by 1.03 – 3.7% for the considered vehicle driving conditions.

![Figure 7. The variation compressor power consumption as a function of R134a mass fraction and compressor speed.](image7)

![Figure 8. The variation system COP as a function of R134a mass fraction and compressor speed.](image8)
From this thermodynamic study, it inferred that the inclusion of R134a mass fraction in the R1234yf refrigerant could be possible way to reduce the performance difference between these refrigerants without modifying the system configurations. However, the seeding of R134a increased GWP of refrigerant mixture and this will lead to increase the direct CO2 emission from the AAC. Therefore, the R1234yf/R134a mixture with 0.5 mass fraction of R134a is suggested in terms of better performance, however in terms of environmental aspects (GWP < 150), R1234yf/R134a mixture with 0.1 mass fraction of R134a is the best option.

4. Conclusion

The thermodynamic performance of AAC was analysed theoretically using R134a, R 1234yf, and R1234yf/R134a mixture for three-vehicle speed conditions such as idling (L-900 rpm), city limit (M-1800 rpm), and high speed (H-2700 rpm). The mass fractions of R134a such as 0, 0.1, 0.2, 0.3, 0.4 and 0.5 were considered in this analysis. Based on this theoretical study, the following conclusions have arrived,

- The inclusion of 0.5 mass fraction of R134a in R1234yf enhanced the liquid density, thermal conductivity, and viscosity by 5.4%, 7.8%, and 13% lower than those of R1234yf with 9.7% reduced vapour density.

- Maximum augmentation in discharge pressure, pressure ratio, latent heat of evaporation, and condensation owing to the addition of 0.5 mass fraction of R134a in R1234yf mixture are found to be 0.78%, 4.4%, 11.8, and 10.6% respectively with a 3.6% reduction in suction pressure.

- The pure R1234yf had poorer performance than that of R134a in terms of cooling capacity and COP by up to 10.4% and 8.3% respectively for the considered vehicle speed condition.

- The maximum drop in mass flow experienced with 0.5 mass fraction of R134a in R1234yf/R134a mixture is 9.8% for the considered vehicle speed condition; the same mass was still 10.5% higher than that of R134a mass flow rate.

- The cooling capacity of the R1234yf/R134a mixture with a 0.5 mass fraction of R134a is slightly lower than that of pure R134a by 1.2 – 4.5% for the considered driving conditions.

- R1234yf/R134a mixture had better COP than that of R1234yf by 2.2 – 5% with 0.5 mass fraction of R134a, still, it had slightly poorer COP than that of the existing R134a by 1.03 – 3.7% for the considered vehicle driving conditions.

This study prevailed that the use of R1234yf/R134a mixture (0.5:0.5 by a mass fraction) performed very much similar to that of R134a in the AAC unit. However, the R1234yf/R134a mixture (0.9:0.1 by a mass fraction) is suggested to use in the AAC system to satisfy the environmental protocols (GWP < 150) without any component modification.

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