Environmental Sustainability of Automobile AIR-Conditioning System with Refrigerant R1234YF

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Abstract
Air- conditioning refrigerant R134a has value of global warming potential (GWP) 1300, which is much higher than MAC Directive (GWP below 150) passed in July 2006. This prompted a search for alternative eco-friendly refrigerant with GWP value less than 150. R1234yf is a new refrigerant which has lower GWP value of 4. Effect of blower speed in car air-conditioning has been compared and flammability issue of R1234yf has been addressed. Cooling time and relative humidity of car air-conditioning system using refrigerant R134a and R1234yf has also been discussed. The paper discusses various aspects for the replacement and provides a long term substitute of presently used refrigerant R134a in automobile air-conditioning for sustainable environment.

1. Introduction

R134a refrigerant is widely used in mobile air-conditioning and causes global warming with a global warming potential (GWP) of 1300. This means that the emission of 1 kg of R134a is equivalent to 1300 kg of CO2. R134a is stable in atmosphere for long time and has atmospheric life time of 13 years. Many investigations have been conducted in the research into substitutes for R134a. Table 1 shows the characteristics of R134a and R1234yf.

Table: 1. Characteristic of R134a and R1234f [1]

Characteristics	R134a	R1234yf
Chemical Formula	CF3CH2F	CH2=CFCF3
Molecular weight	102.03	114.04
Ozone Depletion Potential (ODP)	0	0
Global warming Potential (GWP)	1300	4
Atmospheric Life Time	13(Years)	11(days)

There is a need for better alternatives which have zero ozone depletion potential (ODP) and zero or lower global warming potential. R1234yf is a new refrigerant which has lower global warming potential than R134a. R1234yf has global warming potential of 4, so it satisfy MAC Directive (GWP below 150) passed in July 2006.

Lots of research work has been done for replacing “old” refrigerants with “new” refrigerants with the aim of reducing GWP and maintaining energy efficiency. Maintaining high COP was not as important at the time, because energy prices were relatively low. Today, high COP is much more important for two reasons: overall energy prices are considerably higher than during the last refrigerant change and COP reduces with lower GWP refrigerants in many cases. COP is the ratio of refrigeration effect to the net work input given to the system. The COP of vapour compression refrigeration system can be improved either by increasing refrigeration effect or by reducing work input given to the system. It is found that almost all the vehicles equipped with an air-conditioning system use R134a as a refrigerant. Due to the European community’s motor vehicle directive (EU 2006) refrigerants with a GWP higher than 150, are not allowed from January 1, 2017 in new passenger cars for environmental sustainability. Thus, a replacement for R134a is needed. Proposed substitute refrigerant is R1234yf, which has similar thermodynamic properties and a reasonable retrofit replacement for R134a with modification in expansion valve [2]. An experimental analysis using refrigerants R134a and R1234yf, with and without the presence of internal heat exchanger under a wide range working condition has been studied. The results showed that reduction in cooling capacity and COP have been observed between 6 and 13% when R134a is replaced by R1234yf, although in the presence of internal heat exchanger reduction is between 2 and 6% [3]. R1234yf has nearly similar value of molecular weight and normal boiling point, making R1234yf a good replacement of R134a. It can be realized that R1234yf has been proposed for mobile air-conditioners due to its low GWP and performance comparable to that of R134a. However, its performance is inferior to that of R410a [4]. This makes it difficult to be applied to residential air-conditioners stated that air conditioning is integral for modern cars, particularly in high-temperature regions like the tropics [5]. Automotive AC regulates air as per condition in the cabin, particularly the temperature and humidity. This is not only to provide comfort, but also for health and safety reasons because a driver’s concentration level changes with the air condition in the cabin. With the urgent need to make cars more energy efficient due to increasing fuel prices and the harmful effects of greenhouse gases, it is important to reduce the energy consumption of automotive ACs. The optimum operating condition with compressor and blower speed along with refrigerant charge level has been identified for car air-conditioning system [6]. The steady state performance of the system has been investigated for three independent variables, namely the refrigerant charge level, the compressor speed and the speed of the evaporator fan as they are the only variable parameters for a running car. A systematic energy and exergy analysis of the air conditioning systems employing the mixture of outdoor and

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return air was studied by various researchers. The effects of the incoming air dry bulb temperature to the coil, relative humidity, leaving air dry bulb temperature from the coil on the heat transfer and exergy destruction are investigated by means of a computer code developed [7].

Through a lot of work had been done on energy and exergy analysis of automobile air-conditioning and to find substitute of R134a which has GWP value of 1300 but its alternate refrigerant with low GWP finds limited practical applications. Present work is a systematic analysis of its alternate refrigerant R1234yf for actual car practical applications. In air-conditioning of car, the refrigerant must be safe even during accidents and therefore, safety aspects have been addressed in this paper. This paper mainly deals with the various aspects of replacement of R134a of GWP value 1300 with R1234yf of GWP value of 4 in air-conditioning of car to meet MAC Directive (GWP below 150) passed in July 2006.

2. Materials and Methods

2.1 Compressor

In a car, the environment to be cooled is the cabin and the heat is transferred to the outside air through condenser. R134a is the mostly used refrigerant in motor vehicle air-conditioning system at present. The refrigeration cycle consists of four stages evaporation, compression, condensation and expansion. Car uses swash plate type five cylinder reciprocating compressor. Swash plate compressor (Fig.1) is widely used in automotive air conditioning systems and its parts are the swash plate and the piston cylinder arrangement. Same quantity of both refrigerants (by volume) was charged in turn in the refrigeration system of the car. Each refrigerant was charged in turn in the air-conditioning system of the car. A valve was fitted for charging the refrigerant and then releasing for storing in the cylinder. Many tests were conducted on the material compatibility exposures using R1234yf, with seals and polymers, which included elastomers, flat gaskets, polymeric materials and motor materials; it was suggested that many of the seal and structural polymer materials currently used are suitable for use with next generation low GWP refrigerants R1234yf [5 and 8].

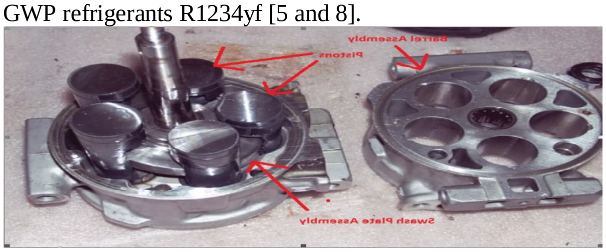

Fig: 1. Five cylinder swash plate reciprocating compressor

Compression ratio being absolute output (head) pressure divided by the absolute input (suction) pressure

$$\text{Compression Ratio} = \frac{\text{Head Pressure}}{\text{Suction Pressure}} \qquad (1)$$

Reduced condenser air flow can also cause this ratio to increase. Excessive condenser temperature causes head pressure to rise. This causes more refrigerant to be squeezed into that efficiency-reducing clearance space at the top of the cylinder, and lowers compressor efficiency. A dirty evaporator plus a dirty condenser can lead to compression ratios of 10-14 resulting in long compressor run times, increased energy expenditure, and the potential for compressor damage. In general, operating with the highest suction pressure and lowest head pressure that meets your refrigeration needs will maximize both compressor life and compressor efficiency.

2.2 Evaporator and condenser temperature

A certain temperature difference is required between the refrigerant in the heat exchanger and the surrounding air to allow for heat exchange to occur. In the benchmark system, this difference is 5°C between the evaporating and the dew point temperatures at the evaporator; and 20°C between the condensing and the outdoor temperature at the condenser. This results in a temperature lift of around 40°C between the evaporating and the condensing temperatures, which corresponds to about 9 bar of pressure difference that the compressor has to provide in both the R134a and R1234yf systems.

The temperature difference between the condensing and the outdoor temperature is reduced to only 100C-15°C which reduces the corresponding temperature lift is by 100C-15°C. This is because the reduction of the temperature lift to 30°C from 400C across the evaporator and condenser reduces the pressure difference to only about 6-7 bar, as compared to 9 bars in the benchmark system. However, the size of condenser is to be increased because temperature difference is lesser. In comparison to plate type heat exchangers, the mini-channel heat transfer rate showed higher than that of the laminated evaporator in all operating conditions in automotive vehicles. The mini-channel evaporators have further advantages of 33% more compactness, lower power consumption of compressor and 20% lighter weight than that of currently used laminated evaporator [9]. Mini-channel heat exchangers have shorter operating time and lower power consumption of compressor. Similarly, advance design of mini-channel heat exchangers on condenser side can be used to have compactness, lower power consumption of compressor and for the purpose of weight reduction.

3. Results and Discussion

3.1 Effect of blower speed

A stationary test has been performed for the investigation of steady state and dynamic performance of a car air conditioning system. The car body effective area was 2.5 m2. Compressor displacement is 117 cc. Air conditioner compressors run by direct connection with the engine crank shaft by a groove type pulley and belt. In general, automobile air-conditioner consumes power as per ambient temperature, cabin cooling load, and type of refrigerant, air volume and heat absorbed by various parts of cabin in a car. The experiments are carried out with varying blower speed. Blower speed was changed by knob in the automobile vahicle. Its speed was measured by non contact type tachometer.The swash plate compressor runs at different speeds as it is driven by the engine in the car but in the present analysis, the car was parked in a garage and it was not exposed to sunlight. The engine was running at constant speed and supplying constant power to the compressor through pulley and belt arrangement. The temperature of surrounding and cabin was recorded to 320C. There was only one person in the vehicle to note down temperature reading by Sling psychomotor, time taken for cooling by stop watch and velocity of air by anemometer. The one set of reading was taken with R134a (Table 2) and another set of reading was taken with R1234yf (Table 3). It may be observed that cooling time decreases with increase in blower speed for both the refrigerants. Similarly, the increased air flow rate at higher blower speed reduces the RH when the cabin temperature changes from 320C to 240C. Cooling time was found to be lesser in case of refrigerant R1234yf as compared to R134a and decreases in the range between 4% to 6%. There is negligible change for the effect of blower speed on relative humidity (RH) of R1234yf over R134a.

Table: 2. Effect of blower speed on refrigerating effect of R134a

Sr. No.	Blower speed (rpm)	Time taken for cooling the cabin from 32^0C to 24^0C, seconds	RH (%)
1	1400	525	57.98
2	1740	411	56.01
3	2250	319	54.70
4	2656	293	52.13

Table: 3. Effect of blower speed on refrigerating effect of R1234yf

Sr. No.	Blower speed (rpm)	Time taken for cooling the cabin from 32^0C to 24^0C, seconds	Relative decrease in time taken for cooling (%) [(R1234yf – R134a)/ (R134a)]* 100	RH (%)
1	1400	503	4.19	57.91
2	1740	387	5.83	55.98
3	2250	303	5.01	54.30
4	2656	280	4.4	52.07

It was revealed that for the same compressor work, the cooling time of R1234yf decreases up to 6% because R1234yf has about 25% more mass than R134a. However this 25% more mass indicated by the R1234yf did not produces an equivalent increase in cooling capacity because the latent heat of vaporization of R1234yf is about 18% lower than that of the R134a, as shown in (Table 4).

Table: 4 General properties of R134a and R1234yf refrigerants

Property	R134a	R1234yf	[R134a-R1234yf]/[R134a]* 100
Sat. vapour density(kg/m^3) at -10.60°C	9.816	12.296	-25.26%
Latent heat of vaporisation(kJ/kg) at -10.60°C	206.4	169.81	17.73%
Saturated pressure @-10.6°C (kPa)	195.9	216.92	-10.73%
Saturated pressure @54.4^{0}C (kPa)	1469.8	1444.5	1.72%
Boiling point at 1 atm pressure	-26.1	-29.2	11.80%
Critical Temperature (^{0}C)	101.06	94.8	6.10%

3.2 Safety with R1234yf

Indoor set temperature may be increased from 20°C to 24°C; the compressor power requirement can be reduced. It may be noted that the savings are achieved without any major modification to the system. The energy saving is obtained because with a higher indoor temperature, the corresponding dew point temperature is higher. The condensing temperature, on the other hand, remains unaffected and so, the pressure difference that the compressor has to provide is lesser. These results in lesser compressor power requirements and higher COP. When the temperature difference between the condensing and the outdoor temperature is reduced to only 10°C, and cabin set temperature is 24°C instead of 20°C, the compressor power requirement reduces while the COP increases. Increasing indoor set temperature from 20°C to 24°C and smaller air lift is advantageous in reducing flammability of R1234yf because of decrease in compression ratio, reduction in load on the compressor and temperature in the system. It will also reduce the leakage of refrigerant and oil from the system to the environment, thereby, reducing the flammability risk as follows:

The mass flow rate of refrigerant, m:

$$m = \frac{\text{Refrogeration capacity (Q)}}{\text{Refrigeration effect (qe)}} \quad (2)$$

The power input to the compressor is given by:

$$W_c = m.h_c \quad (3)$$

Where h_c is work of compression, W_c is the power input to the compressor.

The COP of the system is defined as: $COP=Q/W_c =q/h_c$ (4)

R1234yf is costlier as compared to R134a at present. Reduced quantity of R1234yf refrigerant (by volume) with lower compression ratio, efficient heat transfer in condenser and evaporator will maintain same COP and refrigerating effect. It will also reduce flammability as the temperature and pressure encountered in the system is lesser.

As per ANSI/ASHRAE standard [10] refrigerants regarding Safety and collecting values of ODP and GWP from published paper are as follows (Table 5):

Table: 5. Characteristics of R152a, R134a and R1234f

Characteristics	R134a	R1234yf	R152a
Flammability	No Flame Propagation(A1)	R1234yf (A2L) has mild flammability and shows lesser flammability concern than R152a.	
Ozone Depletion	0	0	0
Global warming Potential	1300	4	120

Since R152a has higher flammability concern than R1234yf and, therefore, it has not been discussed in the present work.

The same refrigeration system is adapted with limited modification of the expansion valve while replacing R134a by R1234yf. While heat exchanger process and design development appears less critical, the main concern of flammability is with the compressor. Even so R1234yf is announced to be a mild flammable refrigerant with the ASHRAE classification of A2L but still in an accident simulation with rupture of the refrigerant line, leaking of refrigerant, its contact with engines and hot exhaust gas lines, ignition takes place and fire occurs. A key question to be clarified is that if the flammability of the refrigerants can be suppressed by R744. It is known, that R744 (CO2) is a good flame suppressant. Explosion limits have been investigated. Adding R744 as an inert gas can suppress the explosion. One pressurized gas container with R744 may be fitted in vehicle near compressor which will automatically explode in case of accidents or any rupture to supply R744.

There can also be possibility to develop, an indirect system based on R744 as secondary refrigerant to use with R1234yf primary refrigerant for confining the refrigerant (R1234yf) in limited space. But, it may take time to develop such a system and COP of system is expected to be reduced because of heat exchange process. In such a process only R744 will be allowed to enter the cabin cooling coils and system will be safer but costly.

4. Conclusions

The paper concludes that eco-friendly refrigerant R1234yf is substitute of R134a in mobile air-conditioning application with increasing indoor set temperature from 20°C to 24°C and smaller air- lift. This is advantageous in reducing flammability of R1234yf because of decrease in compression ratio, reduction in load and temperature in the system. It will also reduce the leakage of refrigerant and oil from the system to the environment, thereby, reducing the flammability risk. It may be observed that cooling time decreases with increase in blower speed for both the refrigerants. Similarly, the increased air flow rate at higher blower speed reduces the RH when the cabin temperature changes from 320C to 240C. Cooling time was found to be lesser in case of refrigerant R1234yf as compared to R134a and decreases in the range from 4% to 6%. There is no relative change for the effect of blower speed on relative humidity (RH) of R1234yf over R134a. It is known, that R744 (CO2) is a good flame suppressant. Adding R744 as an inert gas can suppress the explosion. One pressurized gas container with R744 may be fitted in vehicle near compressor which will automatically explode in case of accidents or any rupture to supply R744.

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