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Performance Characteristics of Automotive Air Conditioning System with Refrigerant R134a and Its Alternatives

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Abstract: In this paper, the thermal performance characteristics of automotive air conditioning are carried out. Experimental analysis of R134a automotive air conditioning system with variable speed compressor is investigated. The purpose is to present a clear view on the effect of compressor speed, and condensing temperature on the thermal characteristics of automotive air conditioning. This study is extended theoritcally to cover more alternatives of the current R134a due to its impact of the Global Warming Potential GWP. The possibility of using low-GWP refrigerants of R152a, R1234yf, and R1234ze as alternatives to R134a in automotive air conditioning has been assessed. The refrigerants are investigated over a wide range of condensing temperature, evaporating temperature and refrigerant mass flow rate. The assessment is accomplished with cooling capacity, compressor power, coefficient of performance, pressure ratio, and condenser load. The results indicated that, the refrigerant R1234yf is much more environmentally accepted and has the best thermal performance among all investigated refrigerants.

Keywords: Automotive Air Conditioning, Variable Speed Compressor, R134a Alternatives

1. Introduction

Although the automotive industry has been using HFC134a (R134a) as a standard replacement for CFC12 since 1994 for its zero ozone depletion potential (ODP), this refrigerant has a very high Global Warming Potential (GWP = 1430). HFC134a contributes to global warming because of its fluorine content. Ozone depletion and total climate change depends on both global warming potential and ozone depletion potential. So, there is a need to find out alternatives of R134a under Kyoto protocol and Montreal protocol. The European Union issued a directive requiring for all car manufacturers to begin using a new refrigerant with a global warming potential (GWP) of less than 150 on all cars built for sale in the European Union by 2017, all cars assembled for sale in the European Union must be charged with an alternative refrigerant of R134a.

Over the last several years, much research and development effort has been focused on potential refrigerants possessing low Global Warming Potentials (GWPs). The evaluation of an automotive air conditioning system of R134a with a variable capacity compressor was studied by

J.M. Saiz Jabardo, et al,[1]. They developed a computer simulation model which includes a variable capacity compressor and a thermostatic expansion valve in addition to the evaporator and micro channel parallel flow condenser. Effects of design parameters on system performance of compressor speed, return air to the evaporator and condensing air temperatures have been experimentally simulated by means of developed model.

Comparative performance of an automotive air conditioning system of R134a using fixed and variable capacity compressors was studied by *Alpaslan Alkan, and Murat Hosoz,*[2]. They concluded that the operation with the variable speed compressor usually yields a higher COP than the operation with the fixed speed compressor in expense of a lower cooling capacity.

Jitendra Verma et al, [3] carried out a review of alternative to R134a refrigerant. They stated that, R152a is almost a straight drop-in substitute for R134a. The molecule is similar to R134a except that two hydrogen atoms are substituted for two fluorine atoms. It has similar operating characteristics to R134a but cools even better. An environmental benefit of R152a is that it has a global warming rating of 10 times less

than R134a. *Ghodbane,* [4] simulated the performance of automotive air conditioning systems with several hydrocarbons. He determined that the systems with R152a and R270 yield a better performance than the one with R134a. In addition, a comparative assessment of the performance of a secondary loop system using these refrigerants was provided

E. Navarro, et al, [5] presented a comparative study between R1234yf, R134a and R290 for an open piston compressor of automotive air conditioning at different operating conditions. The test matrix comprised two compressor speeds, evaporation temperatures and condensation temperatures. They concluded that R290 has shown a significant improvement in compressor and volumetric efficiencies while R1234yf improves its efficiencies compared to R134a for pressure ratios higher than 8.

J. Navarro-Esbrı, et al, [6] carried out an experimental analysis of R1234yf as a drop-in replacement for R134a in a vapor compression system. The experimental tests were carried out varying the condensing temperature, the evaporating temperature, the superheating degree, the compressor speed, and the internal heat exchanger use. Comparisons are made taking refrigerant R134a as baseline and the results show that the cooling capacity obtained with R1234yf is about 9% lower than that obtained with R134a. *Claudio Zilio, et al,* [7] studied experimentally an automotive air conditioning system equipped with variable displacement compressor. They concluded that, the R1234yf systems present lower performance than the R134a system at a given cooling capacity. *Yohan Lee and Dongsoo Jung*, [8] carried out a brief performance comparison of R1234yf and R134a in a bench tester for automobile applications. They concluded that the coefficient of performance and cooling capacity of R1234yf were 2.7% and 4.0% lower than that of R134a respectively.

Gustavo Pottker, and Pega Hrnjak, [9] studied the effect of condenser subcooling on the performance of an air conditioning system operating with R134a and R1234yf. It was concluded that the COP of the system operating with R1234yf can benefit more from the condenser subcooling than that with R134a due differences in thermodynamic properties.

In the present study, the thermal performance of R134a automotive air conditioning is carried out experimentally and theoretically. The study is assessed over wider range of compressor speed, condensing temperature and evaporating temperature. This study is extended to cover possible alternatives of R134a with low GWP of 150 or less according to Europe union recommendation. The low Global Warming Potential GWP refrigerants of hydrofluorocarbon- HFC-152a (R152a), and a very low GWP refrigerant of hydrofluoro-olefins of HFO-1234yf (R1234yf) and HFO-1234ze (R1234ze) are concerned in this investigation. The properties

of these Refrigerants are listed in table (1). The possibility of using R152a, R1234yf, and R1234ze, as alternatives to R134a in automotive air conditioning has been investigated using Engineering Equation Solver (EES, 2013). This investigation is done with standard parameters such as cooling capacity, compressor power, coefficient of performance (COP), pressure ratio and condenser heat load.

2. Experimental Test Rig

The experimental setup of automotive air conditioning system is shown in Figs. (1-a, 1-b) which is consists of R134a refrigeration system with variable speed compressor, condenser, thermostatic expansion valve and evaporator. The compressor is belt driven by a three-phase 1.5 kW electric motor energized through a frequency inverter, which allows the operation of the compressors at the required speed. It contains auxiliary equipment of a liquid receiver/filter-drier, flowmeter, and thermostat.

The experimental system contains two air ducts in which the evaporator and condenser have been inserted. The duct containing the evaporator has a cross-section area of 0.0504 m^2 and a length of 1.2 m. This duct has an axial fan driven by a DC motor and an electric heater with a maximum capacity of 1.8 kW. The air flow rate passing through the evaporator can be maintained at the required value by varying the voltage across the fan motor via a voltage regulator. Furthermore, the required air temperature at the evaporator inlet can be achieved by varying the voltage across the heater via another voltage regulator. On the other hand, the duct containing the condenser has a cross-section area of 0.187 m^2 and a length of 1.2 m. This duct contains a condenser axial fan driven by DC motors and another electric heater with a maximum capacity of 3 kW. The condenser air flow rate can be varied by adjusting the voltage across the fan motors. Moreover, the temperature of the air stream entering the condenser can be kept at the required value by varying the voltage across the heater. The reading of the measuring instruments of temperature, air velocity, refrigerant flow rate are recorded after the experiment reach steady state condition which in most cases takes time about 45 minutes.

Table 1. *Details of refrigerants properties.*

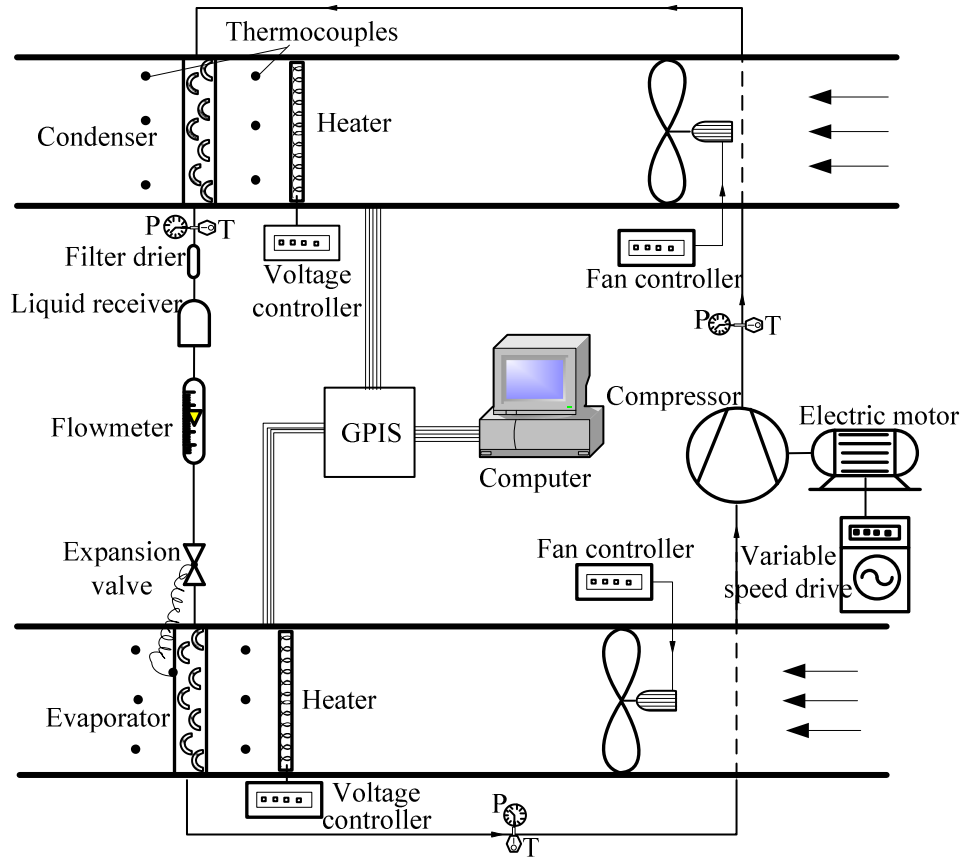| Item	R134a	R152a	R1234yf	R1234ze
Chemical formula	$C_2H_2F_4$	$C_2H_4F_2$	$C_3H_2F_4$	$C_3H_2F_4$
Molecular weight (kg/kmol)	102	66	114	114
ASHRAE safety classification	A1	A2	A2L	A2L
ODP	0	0	0	0
100-year GWP	1430	140	4	6
Critical temperature (k)	374.21	386.26	367.85	382.51
Critical pressure (kPa)	4059	4580	3382	3636
Boiling point (ºC)	-26.1	-24.0	-30	−19

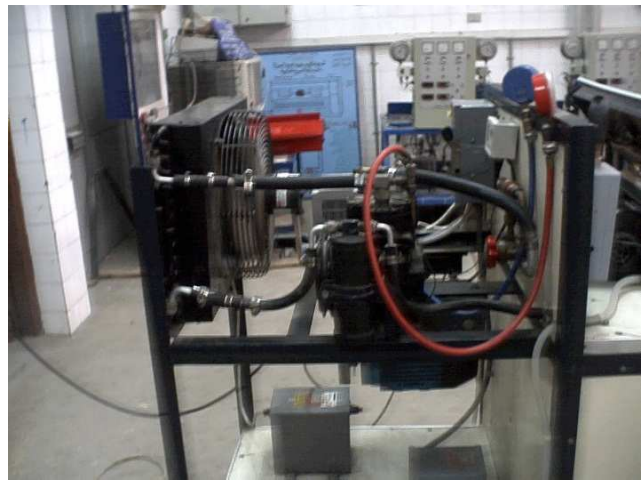**Fig. (1a).** *Schematic of experimental test rig.*

Fig. (1b). *Photographs of the experimental test rig.*

3. Measuring Techniques

The temperatures of the air side are measured using pre-calibrated K-type thermocouples. Two points of the K-type thermocouple probes with accuracy of 0.5 ^{o}C are placed on the upstream air and four thermocouples probes are placed on downstream of the test section to measure the air temperatures for both the evaporator and condenser respectively. All thermocouples are connected via a data acquisition system with accuracy of ± 0.1%. The relative humidity of the air upstream and downstream is measured by a humidity meter with accuracy of ± 1%. The air velocity profile through the duct section is identified according to ASHRAE recommendations by hot wire anemometer with an accuracy of ± 0. 1% of full scale. The refrigerant flow rate is measured by using refrigerant flow meter with an accuracy of ± 1%. Refrigerant pressure gauges with an accuracy of ± 0.5 % are fixed on high pressure and low pressure sides to measure the pressure before and after of the evaporator and condenser respectively.

4. Measurements Uncertainties

The experimental error analysis indicates the implication of error of the measured parameters on the uncertainty of the results. The uncertainty analysis of the various calculated parameters are estimated according to Holman JP, [10]. Given $W_1, W_2, W_3, ..., W_n$ uncertainties in the independent variables $(X_1, X_2, X_3, ...X_n)$ and W_R is the uncertainty in the result at the same odds. Then the uncertainty in the result can be given as;

$$W_R = \left[\left(\frac{\partial R}{\partial X_1} W_1 \right)^2 + \left(\frac{\partial R}{\partial X_2} W_2 \right)^2 + \left(\frac{\partial R}{\partial X_3} W_3 \right)^2 + ... + \left(\frac{\partial R}{\partial X_n} W_n \right)^2 \right]^{\frac{1}{2}} \qquad (1)$$

The uncertainties of the calculated experimental parameters are given in Table 2.

Table 2. *Range of uncertainties of calculated parameters.*

	Q_{eva} (%)	Q_{cond} (%)	W (%)	COP (%)
Minimum uncertainty	± 2	± 2.1	± 2.4	± 4
Maximum uncertainty	±3.6	± 3.8	± 4.9	± 6.5

5. Data Reduction

The refrigeration pressure-enthalpy diagram of the automotive air conditioning cycle is illustrated in Fig. (2). Thermodynamically, The cooling capacity (Q_{eva}) is given by,[11]

$$Q_{eva} = \dot{m}_{ref} \left(h_1 - h_4 \right) \qquad (2)$$

The power required to drive the compressor is given by:

$$W_{com} = \dot{m}_{ref} \left(h_2 - h_1 \right) \qquad (3)$$

Actual specific enthalpy of the superheated vapor refrigerant at the compressor outlet (h_2) can be calculated as follows:

$$h_2 = h_1 + \frac{(h_{2,is} - h_1)}{\eta_{is,com}} \qquad (4)$$

The isentropic compressor efficiency ($\eta_{is,com}$) is taken as 0.65, M. Fatouh, et al [12].
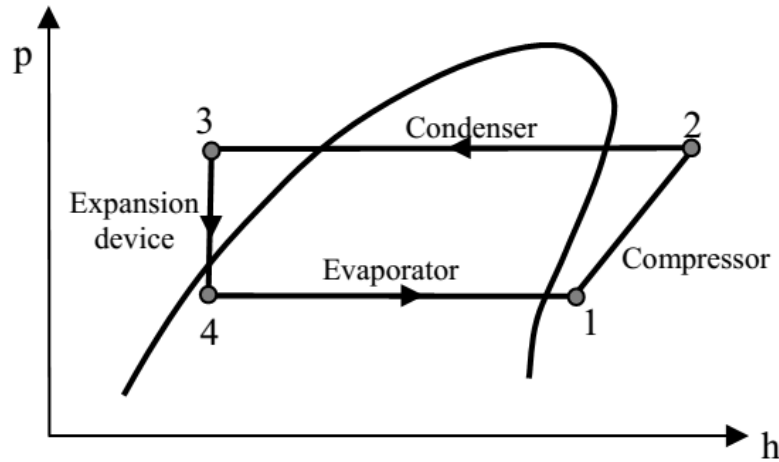

Fig. (2). *Pressure-enthalpy diagram of the air conditioning refrigeration cycle.*

Condenser heat load can be written as;

$$Q_{con} = \dot{m}_{ref} \left(h_2 - h_3 \right) \qquad (5)$$

The coefficient of performance (COP) is defined as the ratio of the cooling capacity to the compressor power, i.e.

$$COP = \frac{Q_{eva}}{W} \qquad (6)$$

Pressure ratio (*PR*) is defined as the ratio between condenser and evaporator pressures in which they depend mainly on the condensation and evaporation temperatures, respectively,

$$PR = \frac{P_{con}}{P_{eva}} \qquad (7)$$

The pervious equations are used to develop a computer program using Engineering Equation Solver (EES, 2013), [13]. Input parameters are refrigerant type, evaporating temperature, condensing temperature, refrigerant mass flow rate, evaporator specifications and condenser specifications. Output data are pressure ratio, refrigerant cooling capacity, condenser heat load, input power and coefficient of performance, for the existing system.

6. Results and Discussion

In this investigation, the results are comprised in two categories, the performance of R134a system with variable speed compressor and the performance of low global warming potential refrigerants as an alternative of R134a in automotive air conditioning.

6.1. Effect of Compressor Speed (RPM)

In automotive air conditioning, the compressors are usually belt-driven by the engine and therefore the compressor speed varies according to crankshaft RPM which led to a varying in mass flow rate through the air conditioning cycle. Experimentally the effect of compressor speed on the cooling capacity of R134a for different condensing temperature is illustrated in Fig. (3). For a certain condensing temperature, the cooling capacity increases as the compressor RPM increases. This is due to the increase of refrigerant mass flow rate with the increase in compressor speed. The ambient air temperature affects directly the cooling capacity. When the condensing temperature increased by 5°C, the cooling capacity decreased by 9%, while the COP decreased by 27% as illustrated in Fig. (4). The lower compressor RPM led to a higher in COP which can revealed that the increasing of compressor speed produce more friction power and hence more heat release at the compressor is occurred. A lower COP means a lower energy efficiency system and hence more global worming potential at a given duty.
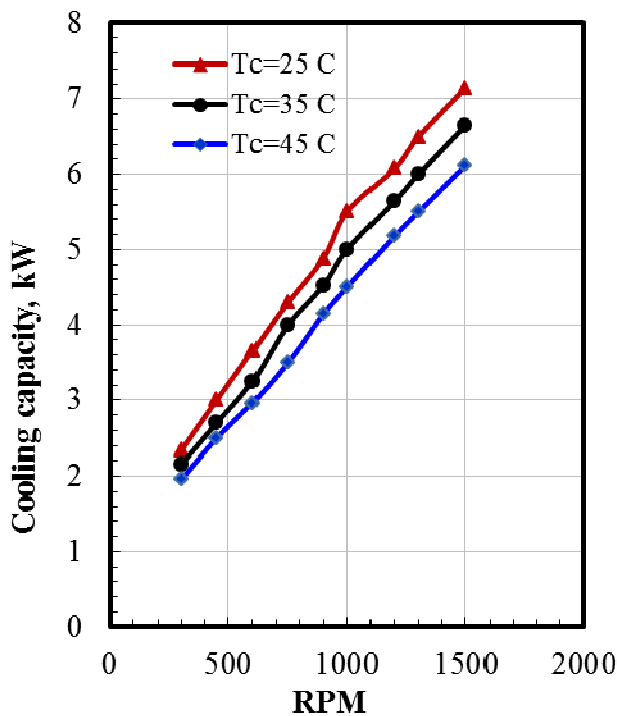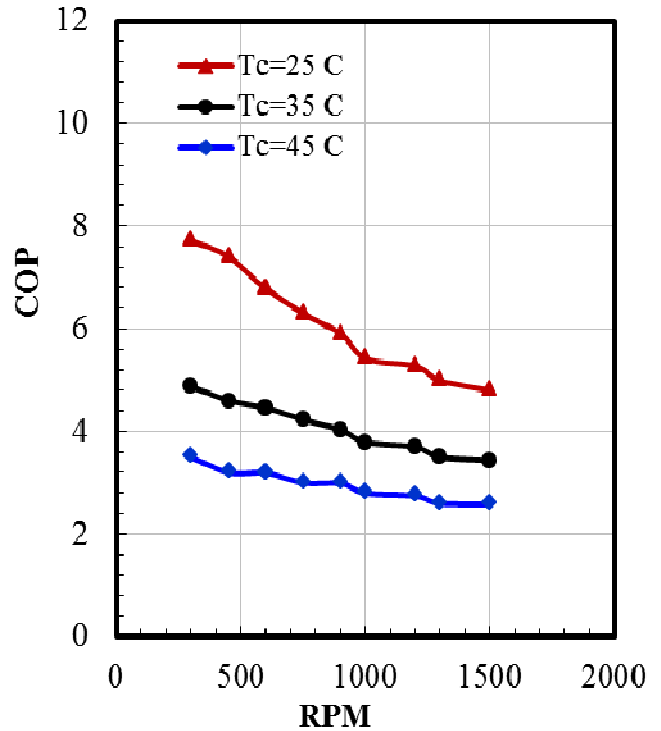

Fig. (4). COP versus RPM of R134a. (Experimental results).
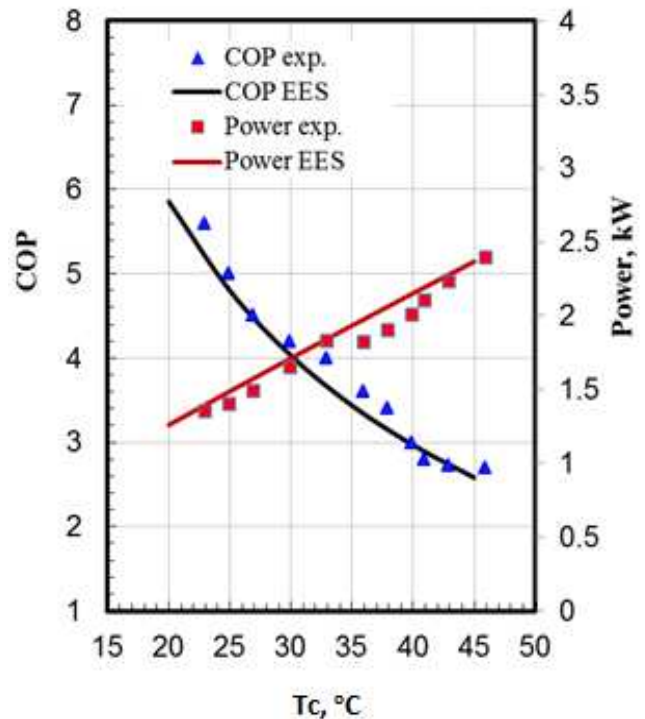
Fig. (5). Validation of experimental and theoretical results of R134a for COP and input power.

Fig. (3). Cooling capacity versus RPM of R134a. (Experimental results).
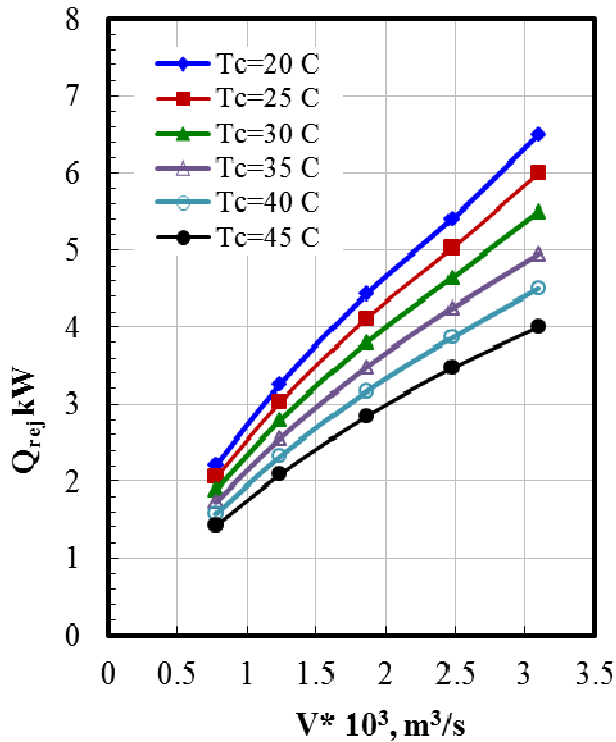
Fig. (6). Condenser heat rejection versus refrigerant flow rate of R134a.

The analysis of the automotive air conditioning refrigeration cycle is extended using Engineering Equation Solver (EES, 2013) in order to study a wide range of design parameters in addition to a study the performance of low Global Warming Potential (GWP) alternatives refrigerants as low as 150 according to EU recommendation. Validation between the experimental and theoretical (EES) results is needed. Figure (5) shows the COP and input power validation of the theoretical EES results with the present experimental results. The results show that simulated EES results are comparable to the experimental results.

6.2. Effect of R134a Condensing Temperature

The effect of condensing temperature on the compressor power and heat rejection from the condenser of R134a system is illustrated in Fig. (6) and Fig (7) respectively. It evident that the increase of condensing temperature is led to increase in compressor consumption power furthermore increase in condenser load at the same refrigerant flow rate. As the refrigerant flow rate increase which is happened as a reason of compressor speed, both the compressor power and condenser load increase on the other hand, the increase in cooling capacity is evidenced. Figure (8) indicates the trend of the COP with the refrigerant flow rate of R134a system at different condensing temperature. For all condensing temperature, the COP increase with the increase of the volume flow rate. It is noted that to obtain enhanced COP, the condensing temperature should maintain as low as possible.
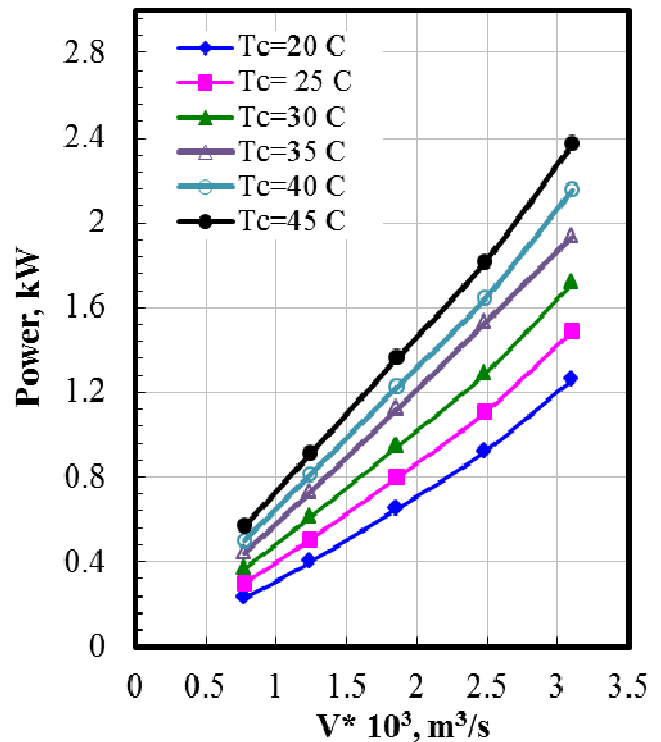

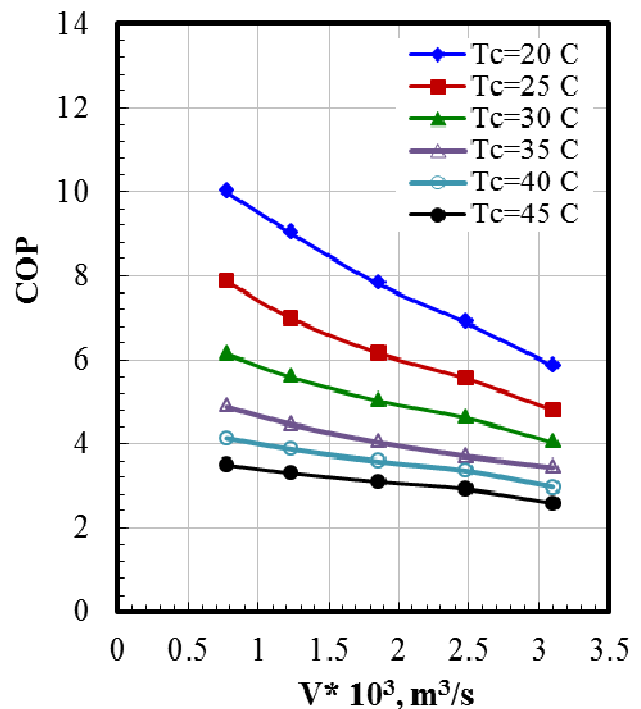*Fig. (7). Compressor power versus refrigerant flow rate of R134a.*

Fig. (8). COP versus refrigerant flow rate of R134a, EES results.

6.3. Performance of Low GWP Refrigerants

The selection of an alternative refrigerant of the automotive air conditioning system receives special significance not only with zero ozone depletion potential but

also with the global warming potential (GWP ≤ 150), furthermore a low energy demand by the system which is seen as an essential criterion. In particular, the refrigerants R152a, R1234yf and R1234ze automotive air conditioning systems are the most possible as an alternative with R134a. An environmental benefit of R152a is that it has a global warming rating of 140, which is 10 times less than R134a. The refrigerant R1234yf (HFO-1234yf) is the first in a new class of refrigerants acquiring a global warming potential (GWP = 4) rating 335 times less than that of R134a. It was developed to meet the European directive that went into effect in 2011 requiring that all new car platforms for sale in Europe use a refrigerant in its air conditioning system with a GWP below 150. The refrigerant R1234ze is a hydrofluoroolefin and it was developed as a "fourth generation" refrigerant to replace R134a in automotive air conditioning which it has zero ozone-depletion potential and a low global warming potential (GWP = 6), [14].

6.4. Effect of Condensing Temperature

Figure (9) shows the cooling capacity of R152a, R124yf and R1234ze with particular reference to R134a for a typical evaporation temperature of 10 ^{o}C and 0.0031 m^3/s refrigerant volume flow rate. The cooling capacity of R134a is higher than that of R152a, R1234yf and R1234ze by 3.5%, 3.8%, and 19% respectively at the same operating condition. The effect of the condensing temperature on the compressor power consumption is illustrated in Fig. (10). The condensing temperature is ranged from 20°C to 45°C which is most practically applicable. This figure indicates that, the compressor power consumption of R134a is higher than that of R152a, R1234yf and R1234ze by 8.5%, 1.6%, and 28% respectively at the same operating condition (T$_e$ = 10°C and V = 0.0031 m^3/s).

Figure (11) shows the COP variation with the condensing temperature of R134a, R152a, R124yf and R1234ze. The COP of R1234yf system is lower than that of R134a by 2.2% this is confirmed with *Yohan Lee and Dongsoo Jung*, [8]. The COP of R1234ze and R152a is higher than that of R134a by 10.8% and 5.6% respectively.

The effect of evaporating temperature on the coefficient of performance of R134a, R152a, R124yf and R1234ze is illustrated if Fig. (12). The evaporating temperature affects the COP positively. It is evident that the coefficient of performance of all investigated refrigerants increases when the evaporating temperature increases. This is due to the increase in cooling effect and the decrease in compressor power. For all evaporating temperature, the COP of R1234ze is the highest among the other refrigerants. It confirmed that the system performance of R1234yf is the most closely to the performance of R134a system in which it is more environmentally sustainable refrigerant for automobiles which has a 99.7% better GWP score than R134a.
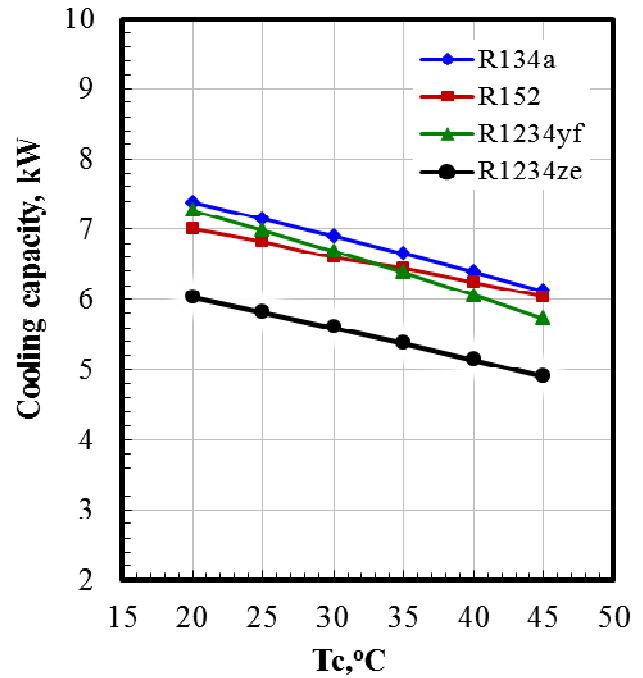

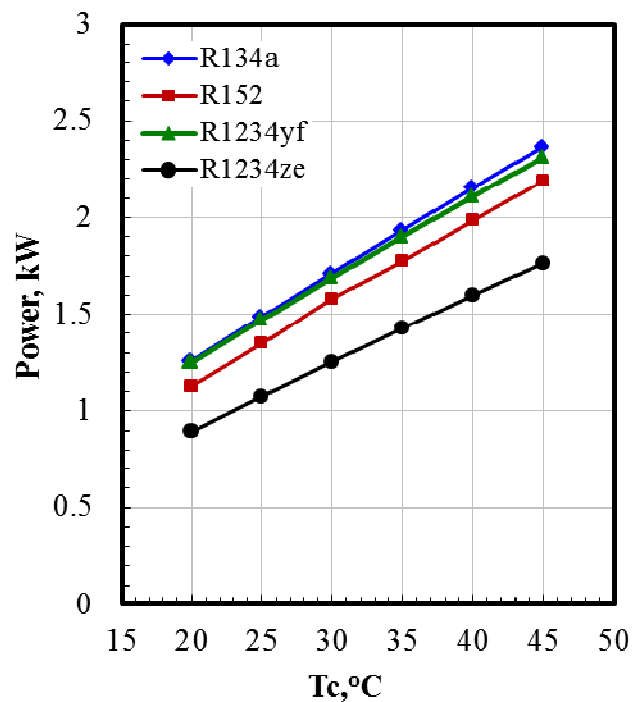**Fig. (9).** *Cooling capacity versus condensing temperature at T$_e$=10°C*

Fig. (10). *Compressor power versus condensing temperature at T$_e$= 10°C.*

6.5. Effect of Refrigerant Mass Flow Rate

The performance of the low GWP refrigerants of R152a, R1234yf and R1234ze are stated in this section in which the representations of cooling capacity, compressor power, pressure ratio, and COP with the refrigerant volume flow rate are shown in Figs. (13 to 16) for a typical evaporation and condensing temperatures of 10°C and 35°C respectively.

When the change in car speed is occurred which is due to change of fuel consumption, this led to a change in compressor RPM and hence variation in refrigerant flow rate is achieved. As the refrigerant flow rate increase, the cooling capacity, compressor power and pressure ratio increase also. The pressure ratio of R134a is higher that of R152a, R1234yf, R1234ze by 2%, 7.3%, 4.4% respectively. It can be seen that the R152a has a higher COP and lower values of pressure ratio and compressor input power.

It is evident that the coefficient of performance of all investigated refrigerants decreases when the refrigerant volume flow rate increases. At all values of refrigerant flow rate, the highest coefficient of performance is obtained for R1234ze among all investigated refrigerants. From the environmental and thermal performance point of view, the refrigerant R1234yf has the best thermal performance among all investigated refrigerants and the automakers would not have to make significant modifications in production lines or in automotive system designs to accommodate this refrigerant.
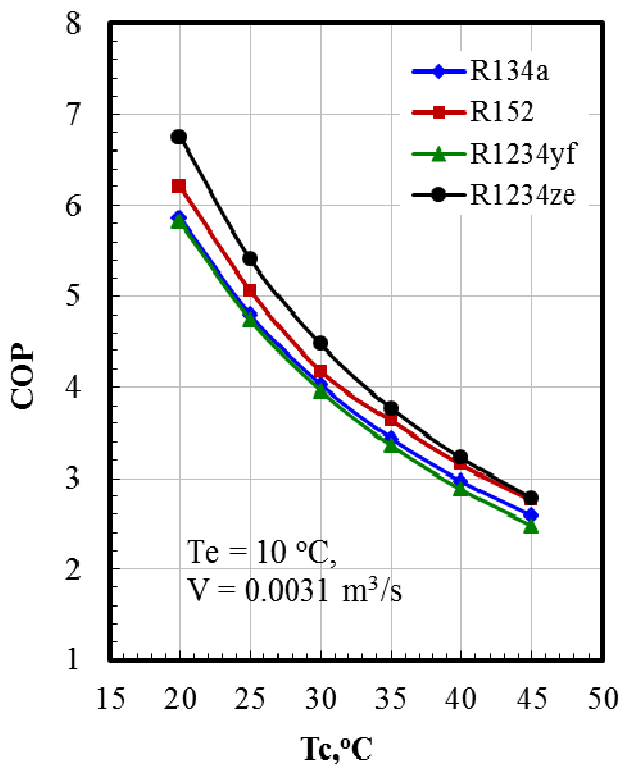

Fig. (12). *COP versus evaporating temperature for Tc = 35ºC and V = 0.0031 m³/s.*

Fig. (11). *COP versus condensing temperature for Te = 10ºC and V = 0.0031 m³/s.*
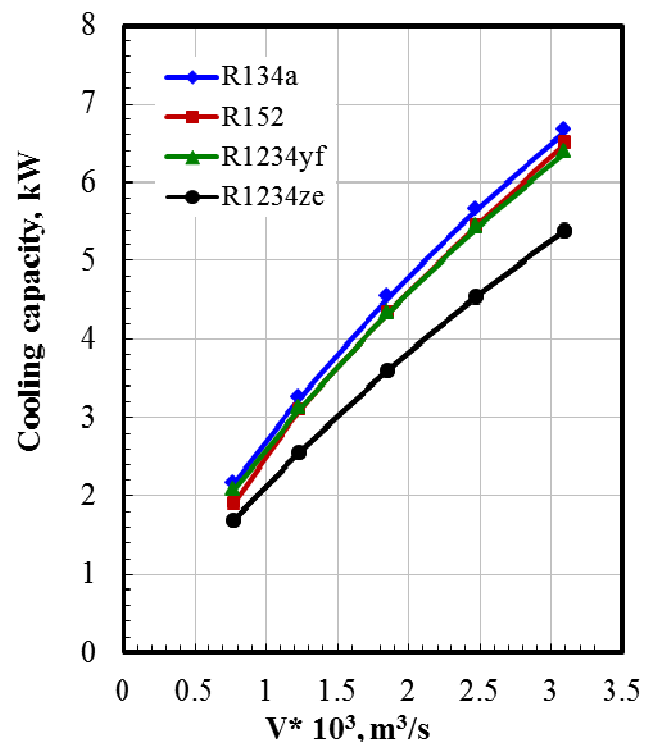
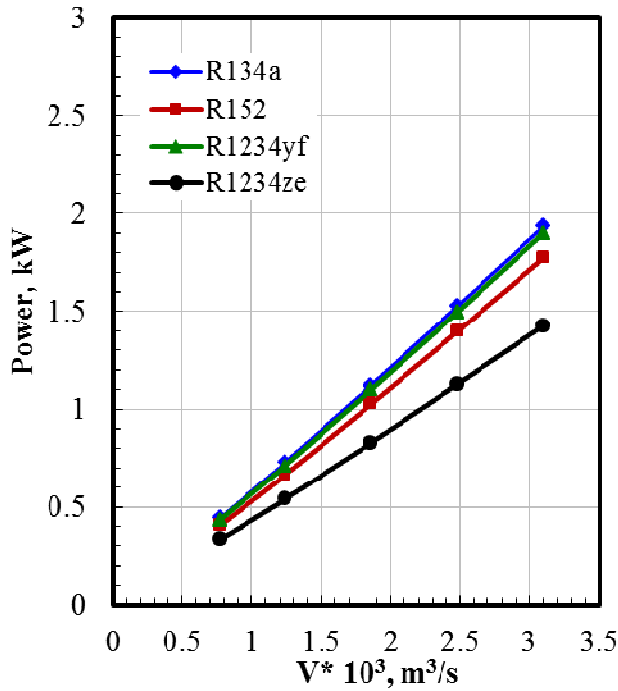**Fig. (13).** *Cooling capacity versus refrigerant flow rate at Tc = 35ºC and Te = 10ºC.*

Fig. (14). *Compressor power versus refrigerant flow rate at T_c = 35ºC, T_e = 10ºC.*
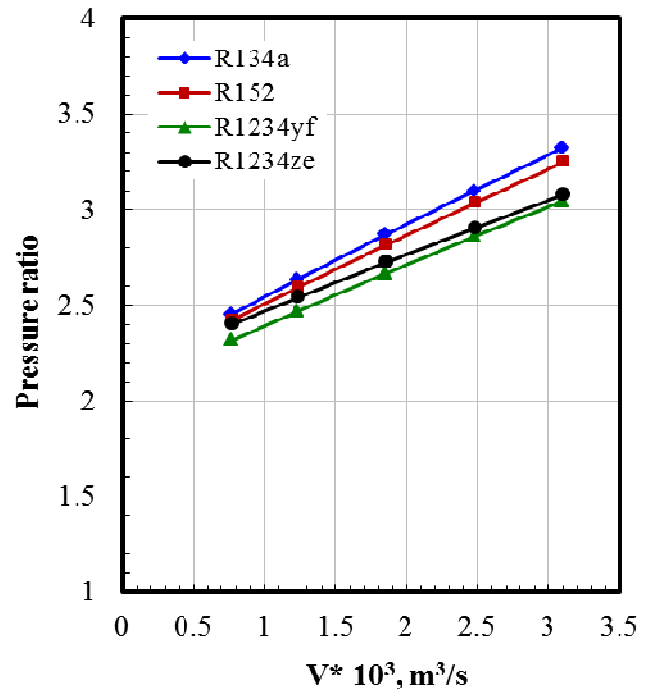
Fig. (16). *Pressure ratio versus refrigerant flow rate at T_c = 35ºC and T_e = 10ºC.*
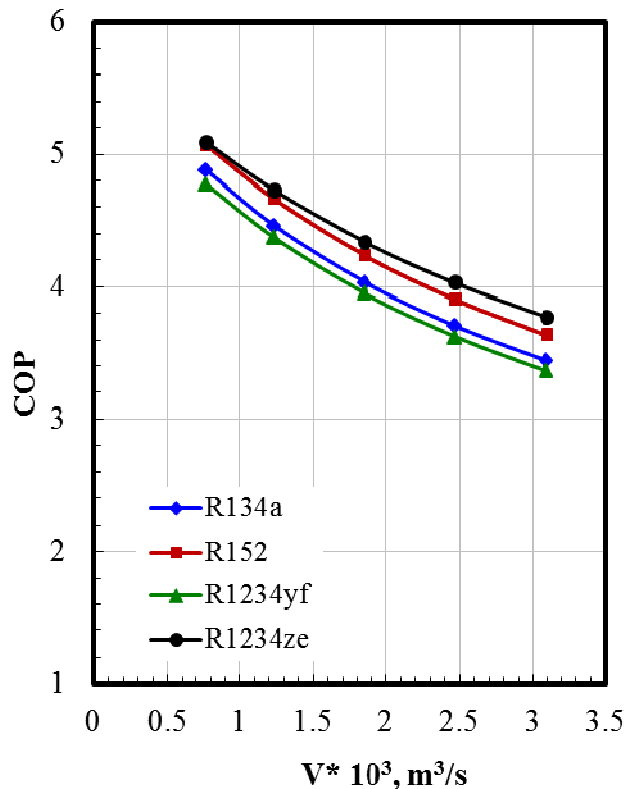
7. Conclusion

The thermal performance of R134a automotive air conditioning is carried out experimentally and theoretically. The performance of R134a alternatives (R152a, R1234yf, and R1234ze) which are characterized by low GWP of less than 150 is presented. The study is assessed over wider range of compressor speed, condensing temperature and evaporating temperature. This investigation is done with standard parameters such as cooling capacity, compressor power, coefficient of performance, pressure ratio and condenser heat load and the main conclusion are;

- The increase in compressor speed (RPM) produces a lower values of COP for all values of condensing temperature.
- When the condensing temperature increased by 5ºC, the cooling capacity decreased by 9%, while the COP decreased by 27%.
- For all values of condensing and evaporating temperature, the highest coefficient of performance is obtained for R1234ze among all investigated refrigerants.
- The performance of refrigerant R1234yf is the most similar to refrigerant R134a in all parameters.
- From the environmental and thermal performance point of view, the refrigerant R1234yf has the best thermal performance among all investigated refrigerants.
- For all investigated refrigerant, the increase of condensing temperature led to increase in compressor consumption power furthermore increase in condenser load at the same refrigerant flow rate.

Fig. (15). COP versus refrigerant flow rate at Tc = 35ºC and Te = 10ºC.

Nomenclature

COP	coefficient of performance	(-)
h	specific enthalpy	(kJ/kg)
$\dot{m}$	mass flow rate	(kg/s)
W	Compressor power	(kW)
RPM	Revolution per minute	(min^{-1})
P	pressure	(N/m^2)
PR	pressure ratio	(-)
Q	heat transfer rate	(kW)
η_{is}	Isentropic efficiency	(-)

Subscripts

eva	Evaporator
com	Compressor
con	Condenser
ref	Refrigerant

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