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EXPERIMENTAL STUDY ON THE REPLACEMENT OF HFC-R134A BY HYDROCARBONS MIXTURE IN AUTOMOTIVE AIR CONDITIONER

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ABSTRACT
Performance characteristics of the current automotive air conditioning system have been evaluated in this experimental study which will evaluate the power consumption, cabin temperature and coefficient of performance (COP) at various internal heat loads and engine speeds using hydro-chlorofluorocarbons refrigerant (HFC-R134a) and automotive hydrocarbon mixture refrigerant (AHCR) as the working fluid of the compressor. Both refrigerants will be tested on the experimental rig which simulated the actual cars as an internal cabin complete with a cooling system component of the actual car including the blower, evaporator, condenser, radiator, electric motor, compressor and alternator. The electric motor acts as a vehicle engine, and then it will drive the compressor using a belt and pulley system, as well as being connected to the alternator to recharge the battery. The rig also is equipped with a simulation room acting as the passenger compartment. The tests have been performed by varying the motor speed; 1000, 1500, 2000, 2500 and 3000 rpm, temperature set-point; 21, 22 and 23^{0}C, and internal heat loads; 0, 500, 700 and 1000 W. As for the results, the performance characteristics of the AHCR indicate the positive improvement of the system compared to HFC-R134a.

Keywords: Air conditioning; Automotive; Energy saving; HCR-134a; Performance.

1. INTRODUCTION
The heating, ventilation and air conditioning (HVAC) of the automotive system is designed to provide thermal comfort level of the driver and passengers. Thermal comfort is one of the crucial things to be fulfilled. Human thermal comfort is defined by the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) as the state of mind that expresses satisfaction with the surrounding environment (ASHRAE Standard 55, 2008).The function of an air conditioning (A/C) control system is to modulate the A/C system capacity to match the design condition, load variation and climate change, in order to maintain the indoor environment within desirable limits at optimum energy use levels during the entire drive duration. Automotive A/C

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components have been going through a steady evolution since the introduction of A/C in cars in 1940. From the early days to today, A/C was a very expensive option in luxury cars while now it is standard equipment in many models and many different types of systems have been used and developed (Birch, 2000).

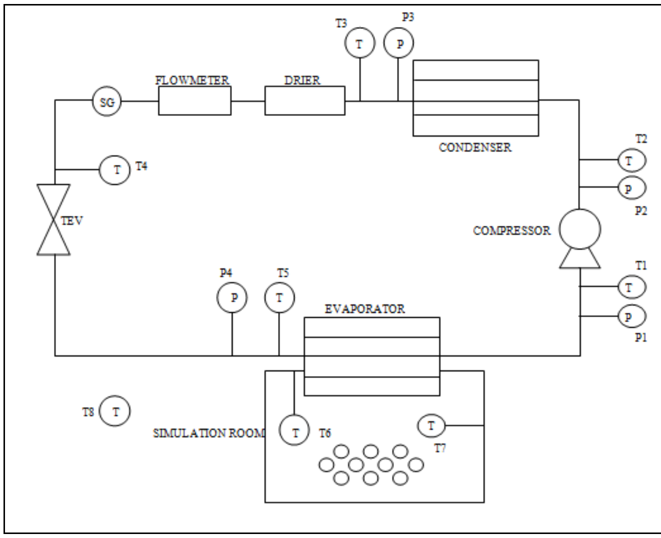
Hydrocarbon (HC) is among the new findings for refrigerants by the experts to replace the current HFC-R134a as the refrigerant for A/C system. HC was used as a refrigerant gas at an early stage of development, which was acceptable before the emergence of CFCs (chlorofluorocarbons) and HCFCs (hydrochlorofluorocarbons). After a long period of time, HC refrigerant was no longer in use because of its flammability characteristics. Thus, CFCs and HCFCs are being used instead of using HC refrigerant, which is flammable, not practical and harmful to users (Granryd, 2001). However, several studies have shown that the use of hydrocarbons in A/C system would improve the performance of the system (Jung and Kim, 2000; Mani and Selladurai, 2008). Some applications of the HC can be found in aerosol fillers, the heating fuels in gas ovens, etc. The HC used in the A/Cs and freezers as a working fluid is not yet in common use.

The research work will undertake experimental studies on HC mixtures as an alternative refrigerant to the automotive A/C system in Malaysia. HC mixture used for this work contains propane (R290), butane (R600), and isobutane (R600a). The formula is known as automotive hydrocarbon mixture refrigerant (AHCR) and Wongwises et al., 2006, Wongwises and Chimres, 2005, Ghodbane, 1999, and Tashtoush et al., 2002, are among the researchers that are involved in the development of automotive HC A/C systems. Table 1 shows the properties of the refrigerant used in this experimental work (Wongwises et al., 2006; REFPROP, 1998).

The HC refrigerant is generally considered as being environmental friendly and it has been used for its noticeable value in relation to Global Warming Potential (GWP) and zero Ozone Depletion Potential (ODP).

Table 1 Properties of refrigerant

Code	Chemical Formula	Boiling Point at 101.325 kPa (°C)	Latent Heat (kJ/kg)	ODP	GWP
12	CCl_2F_2	-29.8	165.24	0.82	8100
134a	CH_2FCF_3	-26.1	216.87	0	1300
50	CH_4/ methane	-161.5	510.54	0	20
170	C_2H_6/ ethane	-88.8	487.03	0	20
290	C_3H_8/ propane	-42.07	423.33	0	20
600	C_4H_{10}/ butane	-0.5	385.77	0	20
600a	C_4H_{10}/ isobutane	-11.73	364.25	0	20



Caption:

1. Inlet compressor temperature, T1 (°C)
2. Exit compressor temperature, T2 (°C)
3. Exit condenser temperature, T3 (°C)
4. Inlet TEV temperature, T4 (°C)
5. Inlet evaporator temperature, T5 (°C)
6. Supply air temperature, T6 (°C)
7. Cabin temperature, T7 (°C)
8. Ambient temperature, T8 (°C)
9. Inlet compressor pressure, P1 (MPa)
10. Exit compressor pressure, P2 (MPa)
11. Exit condenser pressure, P3 (MPa)
12. Inlet evaporator pressure. P4 (MPa)

Figure 1 Automotive A/C system diagram

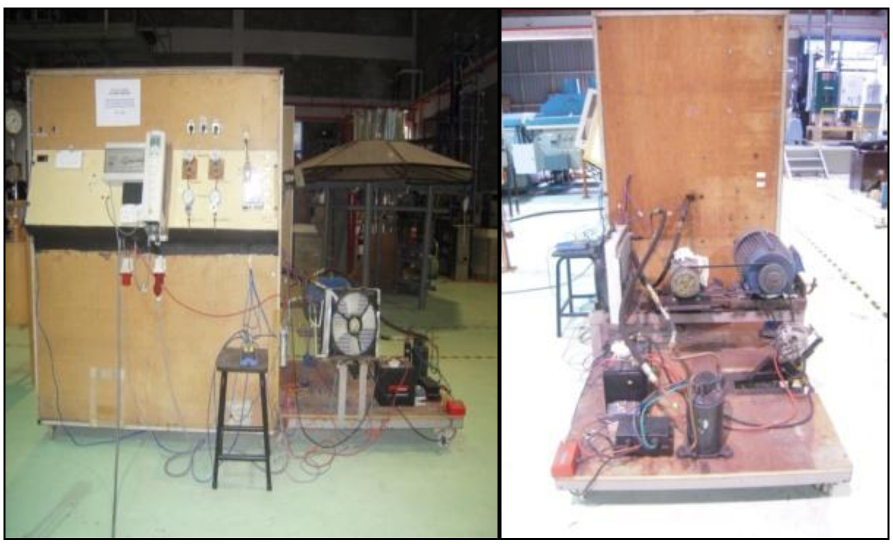


Figure 2 Experimental test rig

2. EXPERIMENTAL APPARATUS AND PROCEDURE

In this research work, the performance characteristics of the automotive A/C system have been conducted via experimental analysis. The tests are performed ons an automotive A/C experimental rig in order to evaluate the power consumption, cabin temperature and coefficient of performance (COP). The refrigerants used are HFC-R134a and AHCR as the working fluids of the compressor. The test is done at various internal heat loads, temperature settings and engine speeds. Figure 1 illustrates the schematic diagram of automotive A/C system that has been used in this work.

Figure 2 shows the experimental rig which simulated the actual cars as an internal cabin complete with an A/C system component of the actual car including the blower, evaporator, condenser, radiator and compressor.

Table 2 Varied parameters

Parameter	Range of variation
Motor speed, N (rpm)	1000, 1500, 2000, 2500 and 3000
Cabin temperature (°C)	21, 22 and 23
Type of refrigerants	HFC-R134a and HC-R134a
Internal heat load (W)	0, 500, 700 and 1000

Other components involved in this work are the electric motor and alternator. The electric motor works as a vehicle engine, and then it will drive the compressor using a belt and pulley system, as well as being connected to the alternator to recharge the battery. The compressor is run by 12 volt original car battery which is continuously charged by the alternator to ensure the whole range of rotating speeds is like the actual car speed. The rig also is equipped with a simulation room acting as the passenger compartment.

The temperatures and pressures parameters were measured by the type T thermocouple fitting (accuracy ±0.1^{o}C) and a flow meter (with an accuracy of ±1 gr/s) respectively, at several locations as shown in Figure 1. Then, the current and voltage of the electric system were measured in order to obtain the compressor energy consumption. The accuracy of the current meter reading is ±1%, and the voltage meter reading accuracy is ±1.5%. 120 experiments have been performed during this stage of the work by varying the motor speed, internal heat load and cabin temperature using HFC-R134a and AHCR simultaneously, as the refrigerant formula for the A/C system. Varied parameters are listed and shown in Table 2.

The experiment was carried out according to the following procedures:

2.1 The A/C system was evacuated using a vacuum pump.
2.2 Refrigerant R134a was charged into the system.
2.3 The A/C system was started and the system was left running for 15 minutes.
2.4 The cabin temperature was set at 21°C.
2.5 The speed of the motor was set at 1000 rpm.
2.6 The internal heat load was set by switching on the bulb with 0, 500, 700 and 1000W simultaneously. Each data was collected after 15 minutes of the A/C system run.
2.7 Procedure 2.6 was repeated with the motor speeds of 1500, 2000, 2500 and 3000 rpm simultaneously.
2.8 Procedures 2.4-2.7 were repeated with the cabin temperature of 22 and 23°C simultaneously.
2.9 Procedures 2.1-2.8 were repeated with the refrigerant of AHCR.

In collecting the data, the thermostat was set to the maximum cool position. Data was collected when the A/C system was considered to be stable after it ran for 15 minutes for each test condition. Thermodynamic properties of the HFC-R134a and AHCR used were taken from the REFPROP database, 1998, and from the thermodynamic properties.

3. RESULTS AND DISCUSSIONS

The data from the experiment was analyzed by varying two parameters and holding constant two other parameters. The analysis was done on measured parameters in order to obtain the performance levels of the A/C system. The parameters are the coefficient of performance (COP), the power consumption consumed by the compressor and the compression ratio (C_r). COP of the system is a relationship between the energy released from the evaporator (the refrigerating effect (Q_e)) and the energy required by the compressor (W_c). COP was calculated by using Eq. (1) (Cengel and Boles, 2007):

$$COP = Q_e/W_c = (h_1-h_4)/(h_2-h_1) \quad (1)$$

where,
Q_e = Cooling capacity of evaporator, (kJ/kg)
W_c = Compressor power, (kJ/kg)
h_1 = Enthalpy on suction compressor, (kJ/kg)
h_2 = Enthalpy on discharge compressor, (kJ/kg)
h_3 = Enthalpy on condenser exit, (kJ/kg)
h_4 = Enthalpy on evaporator inlet. (kJ/kg)
In order to get the enthalpy through REFPROP software, refrigeration cycles are necessary to be illustrated on the P-h (pressure vs. enthalpy) diagram as shown in Figure 3 (Nasution et al., 2012).

3.1. Cabin Temperature of System

Figures 4(a), 4(b) and 4(c) show the graphs of cabin temperature against the internal heat load (0, 500, 700 and 1000W) at the compressor speeds of 1000, 1500, 2000, 2500 and 3000 rpm respectively and at the set-point temperatures of 21, 22 and 23˚C for AHCR and HFC-R134a. From the figures above, the temperature distribution of AHCR is always lower (up to 5%) than HFC-R134a. This is because the cooling capacity of the AHCR is set higher than HFC-R134a. At an average all temperature set-point, the AHCR is nearer to the set-point temperature at compressor speeds of 1000, 1500 and 2000 rpm respectively. This will indicate that the use of AHCR is better than HFC-R134a because the cooler air is distributed faster to all compartments of the cabin.

3.1 Coefficient of Performance (COP)

Table 3 shows the COP statistically analysis and Figures 5(a), 5(b) and 5(c) exhibits the graph of

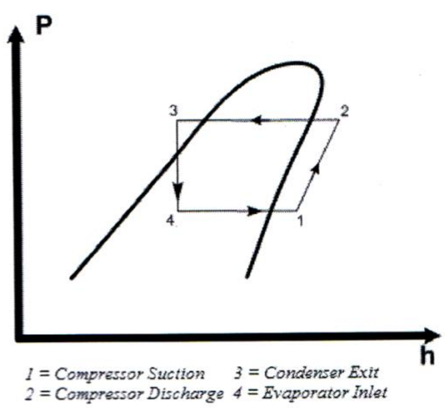


Figure 3 P-h diagram of refrigeration system

Table 3 COP statistically data

Temperature setting (°c)	Load, Watt (W)	Compressor Speed														
		1000 rpm			1500 rpm			2000 rpm			2500 rpm			3000 rpm		
		COP HFC134a	COP AHCR	Difference	COP HFC134a	COP AHCR	Difference	COP HFC134a	COP AHCR	Difference	COP HFC134a	COP AHCR	Difference	COP HFC134a	COP AHCR	Difference
21	0	5.08	6.12	20.4162	4.55	5.10	12.0616	4.87	4.69	-3.59589	4.05	4.22	4.19525	3.69	4.01	8.725136
	500	5.30	5.40	1.71764	4.37	4.76	9.00763	4.12	4.22	2.34628	3.50	4.05	15.9279	3.45	3.84	11.43317
	700	4.75	5.10	7.27485	4.31	4.63	7.44258	4.02	4.21	4.67662	3.43	4.04	17.8821	3.37	3.82	13.53497
	1000	4.36	4.87	11.7168	4.80	4.62	-3.7994	3.96	4.50	13.4893	3.86	4.22	9.32884	3.69	3.75	1.57804
		Average		10.2814	Average		6.1781	Average		4.22908	Average		11.8335	Average		8.81783
22	0	5.90	7.51	27.3472	4.61	5.03	9.14445	4.37	4.68	6.9889	4.10	4.06	-1.0801	3.92	3.88	-1.12933
	500	4.82	6.57	36.2529	4.39	4.80	9.33941	4.18	4.53	8.50838	3.93	3.96	0.90549	3.74	3.75	0.296824
	700	4.54	6.26	38.0729	4.38	4.76	8.58919	4.14	4.64	12.0107	3.98	3.95	-0.8654	3.48	3.75	8.024297
	1000	4.28	5.44	27.1124	4.44	4.41	-0.66017	4.11	4.58	11.5202	3.91	3.91	0.02845	3.38	3.50	3.652517
		Average		32.1964	Average		6.60322	Average		9.75704	Average		-0.2529	Average		2.711078
23	0	5.58	7.78	39.4619	4.73	5.80	22.5493	4.56	4.62	1.24752	4.25	4.34	1.92075	3.97	4.04	1.754134
	500	4.99	6.24	25.0814	4.49	5.14	14.6321	4.29	4.64	8.13261	4.03	4.32	7.10078	3.86	3.85	-0.30675
	700	4.21	5.95	41.3721	3.68	4.67	27.0393	4.11	4.57	11.3799	3.78	4.01	6.23346	3.41	3.82	12.09651
	1000	4.43	5.63	27.1741	4.51	4.61	2.29617	3.34	4.52	35.0898	3.64	3.98	9.28244	3.39	3.73	10.03937
		Average		33.2724	Average		16.6292	Average		13.9624	Average		6.13436	Average		5.895817

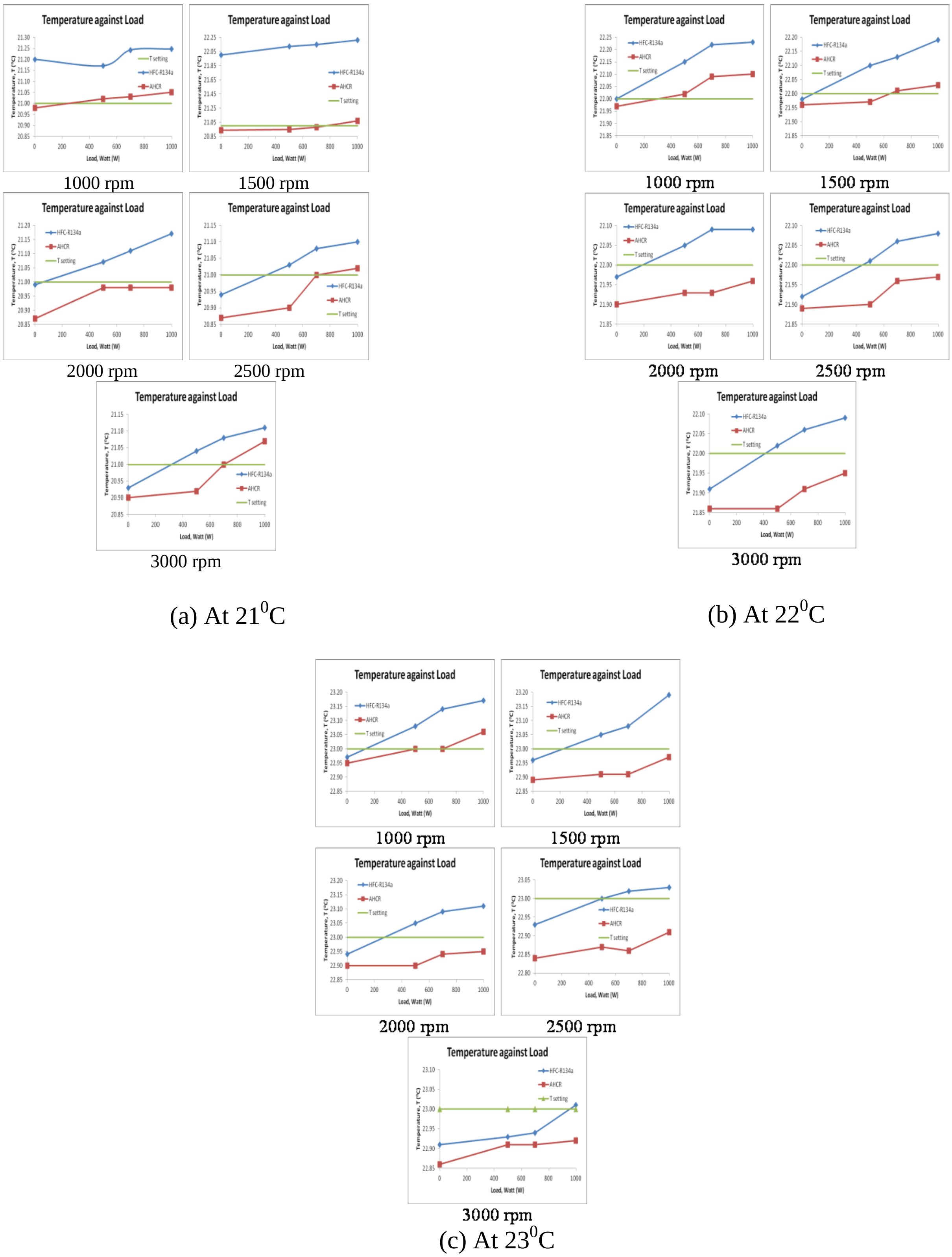
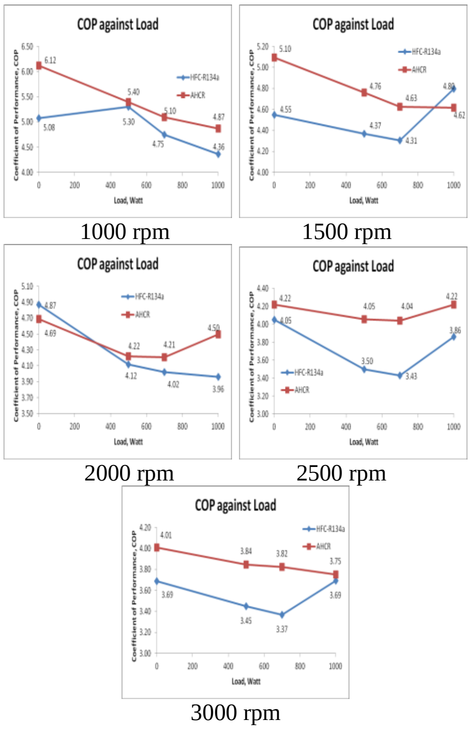
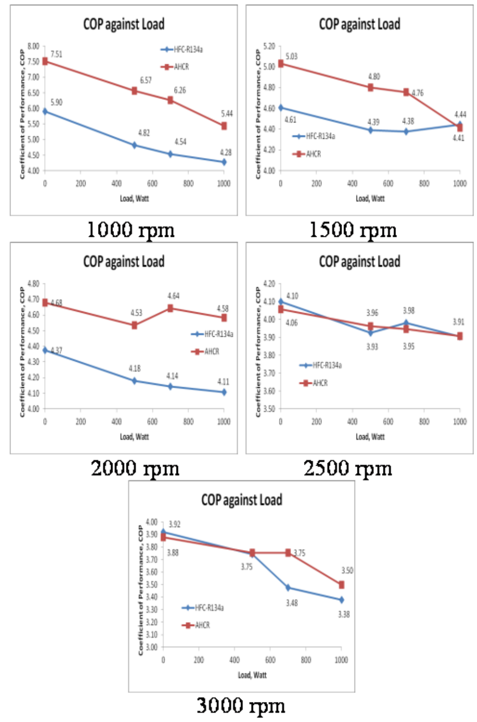


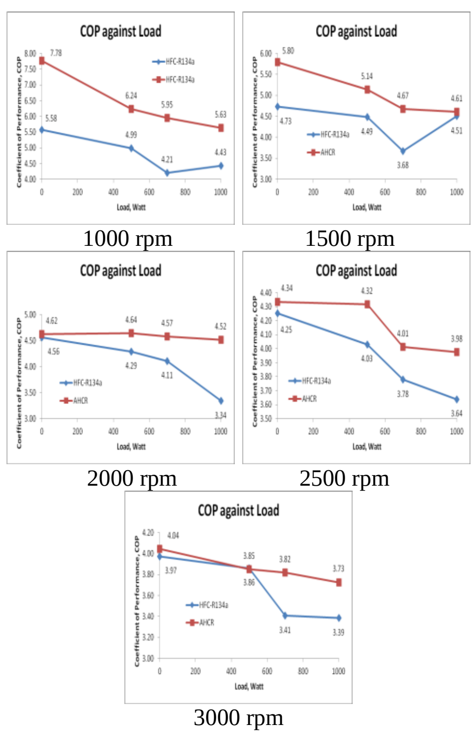
Figure 4 Graph of temperature distribution against load (at compressor speed of 1000 – 3000 rpm).



(a) At 21^0C



(b) At 22^0C



(c) At 23^0C

Figure 5 Graph of COP against load (at compressor speed of 1000 – 3000 rpm).

COP against the load at variable compressor speed of 1000 - 3000 rpm with the refrigerants HFC-R134 and AHCR. The COP of AHCR is higher than HFC-R134a, which is up to a level of 40%. This is a positive improvement because the AHCR produces a high COP which is indicative of better performance than HFC-R134a.

When the compressor speed increases with the increments of internal heat load and compressor speed, the COP will decrease. Thus COP will decrease when compressor work increases at the level of the constant condition of evaporator heat absorption.

There is also a relationship between COP of the different temperature set-points and an internal heat load at a compressor speed of 1000 rpm. It can be observed from the figures in the above illustration that when the temperature set-point increases, the COP will increase. Therefore, COP will be high when compressor work is constant, but the evaporator heat absorption will be lower.

3.2 Compression Ratio (C_r)

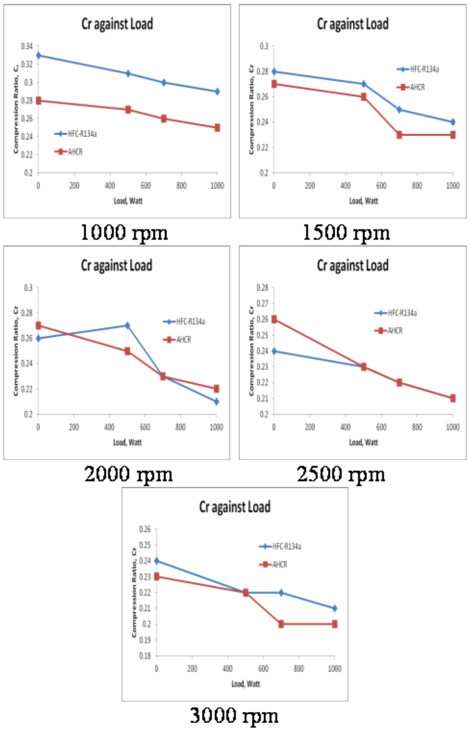
Table 4 shows the statistical data for the compression ratio and Figures 6(a), 6(b) and 6(c) illustrate the graph of the compression ratio set against the internal heat load which shows that C_r decreases with an increase of the internal heat load. And as the temperature set-point increases, the compression ratio will decrease. This shows that the compression ratio of AHCR is better than for HFC-R134a. This is an encouraging improvement as the compression increases then less energy is needed to cool the same set-point temperature. The compression ratio will affect the energy required to run the compressor.

3.3 Compressor Power Consumption

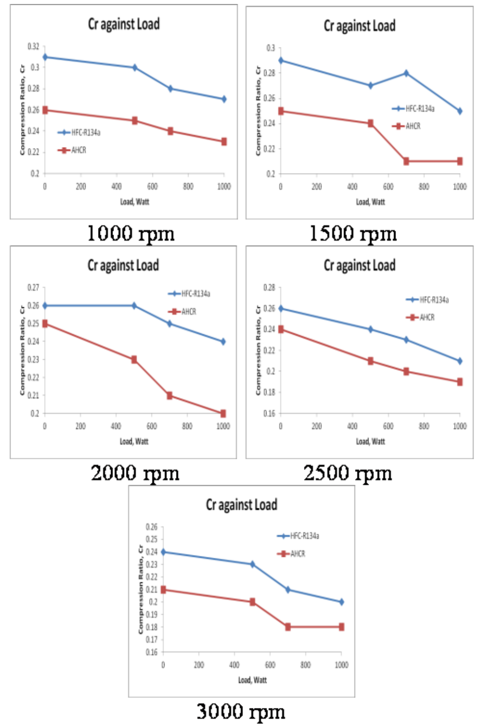
Table 5 exhibits power consumption (kWh) statistical data and Figures 7(a), 7(b) and 7(c) show the relationship between power consumption and internal heat load at various speeds of compressor

Table 4 Compression ratio statistically data.

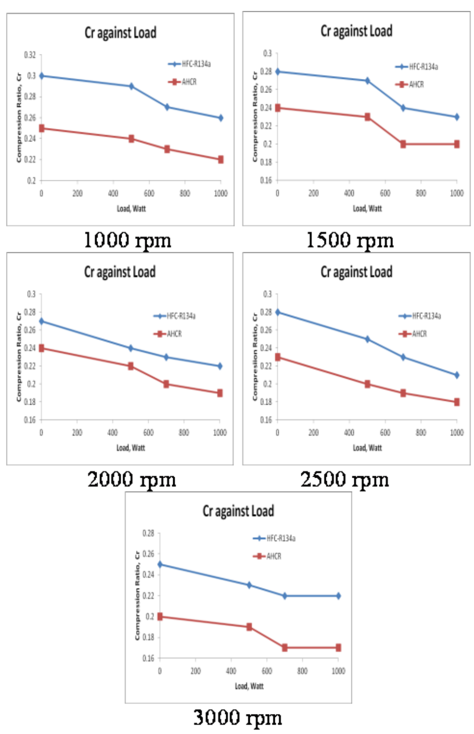
Temperature setting (^{0}C)	Load, Watt (W)	Compressor Speed														
		1000 rpm			1500 rpm			2000 rpm			2500 rpm			3000 rpm		
		Cr HFC134a	Cr AHCR	Difference	Cr HFC134a	Cr AHCR	Difference	Cr HFC134a	Cr AHCR	Difference	Cr HFC134a	Cr AHCR	Difference	Cr HFC134a	Cr AHCR	Difference
21	0	0.33	0.28	15.15	0.28	0.27	3.57	0.26	0.27	-3.85	0.24	0.26	-8.33	0.24	0.23	4.17
	500	0.31	0.27	12.90	0.27	0.26	3.70	0.27	0.25	7.41	0.23	0.23	0.00	0.22	0.22	0.00
	700	0.3	0.26	13.33	0.25	0.23	8.00	0.23	0.23	0.00	0.22	0.22	0.00	0.22	0.2	9.09
	1000	0.29	0.25	13.79	0.24	0.23	4.17	0.21	0.22	-4.76	0.21	0.21	0.00	0.21	0.2	4.76
		Average		13.80	Average		4.86	Average		-0.30	Average		-2.08	Average		4.50
22	0	0.31	0.26	16.13	0.29	0.25	13.79	0.26	0.25	3.85	0.26	0.24	7.69	0.24	0.21	12.50
	500	0.3	0.25	16.67	0.27	0.24	11.11	0.26	0.23	11.54	0.24	0.21	12.50	0.23	0.2	13.04
	700	0.28	0.24	14.29	0.28	0.21	25.00	0.25	0.21	16.00	0.23	0.2	13.04	0.21	0.18	14.29
	1000	0.27	0.23	14.81	0.25	0.21	16.00	0.24	0.2	16.67	0.21	0.19	9.52	0.2	0.18	10.00
		Average		15.47	Average		16.48	Average		12.01	Average		10.69	Average		12.46
23	0	0.3	0.25	16.67	0.28	0.24	14.29	0.27	0.24	11.11	0.28	0.23	17.86	0.25	0.2	20.00
	500	0.29	0.24	17.24	0.27	0.23	14.81	0.24	0.22	8.33	0.25	0.2	20.00	0.23	0.19	17.39
	700	0.27	0.23	14.81	0.24	0.2	16.67	0.23	0.2	13.04	0.23	0.19	17.39	0.22	0.17	22.73
	1000	0.26	0.22	15.38	0.23	0.2	13.04	0.22	0.19	13.64	0.21	0.18	14.29	0.22	0.17	22.73
		Average		16.03	Average		14.70	Average		11.53	Average		17.38	Average		20.71



(a) At 21^{0}C



(b) At 22^{0}C



(c) At 23^{0}C

Figure 6 Graph of compression ratio against load (at compressor speed of 1000 – 3000 rpm).

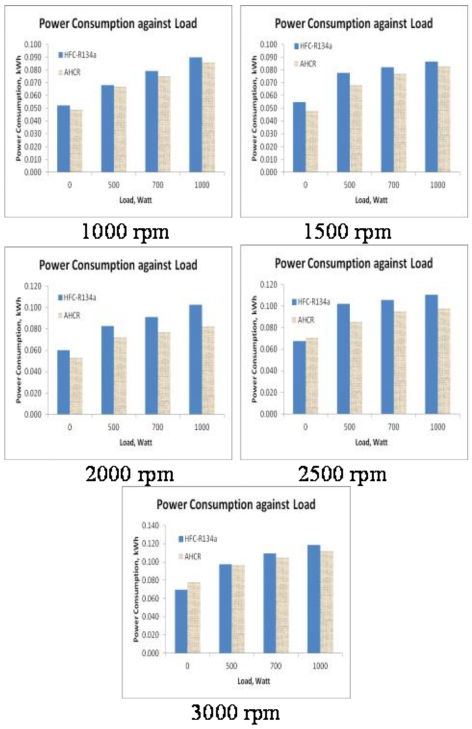
operation (1000 - 3000 rpm). The compressor power consumption increases proportionally with an increase in the internal heat load. At the temperature set-points of 21, 22 and 23°C respectively, the graphs show the same trend of rising internal heat load. At each set-point temperature and with the commensurate increase in internal heat load, the compressor needs to work more often and more power will be consumed. As a result, the compressor uses more power to compress the refrigerant to a higher pressure in order to maintain the temperature in the cabin.
The compressor power consumption of AHCR is lower than HFC-R134a which indicates a positive improvement up to 25% (on average decreasing by 15%).

4. CONCLUSIONS

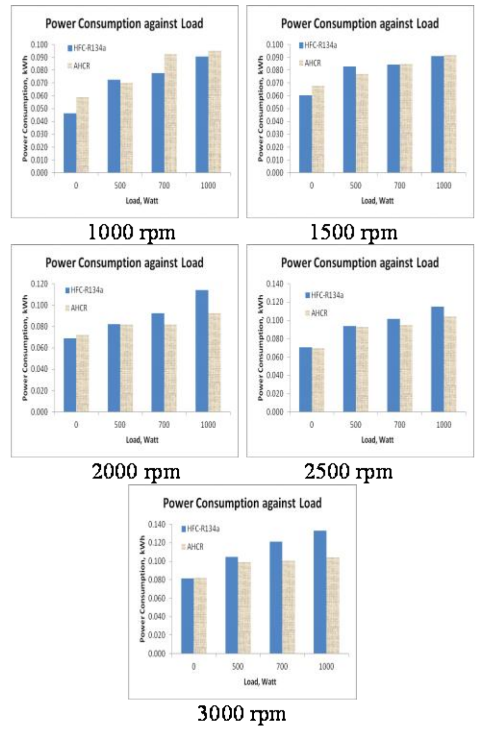
From the discussions above, the AHCR indicates a positive improvement of performance characteristics compared to HFC-R134a in term of COP, temperature distribution and power consumption. Therefore, the HC refrigerant type is suggested to be the replacement for current HFC-R134a used in the automotive industry.
Energy consumption will vary with the changes of the A/C compressor speed. Whilst the compressor speed increases, the room temperature is going to decrease and the COP will decrease as well. As a result, the consumption of energy will increase and a lower level of energy will be saved and vice versa.

Table 5 Power consumption statistical data

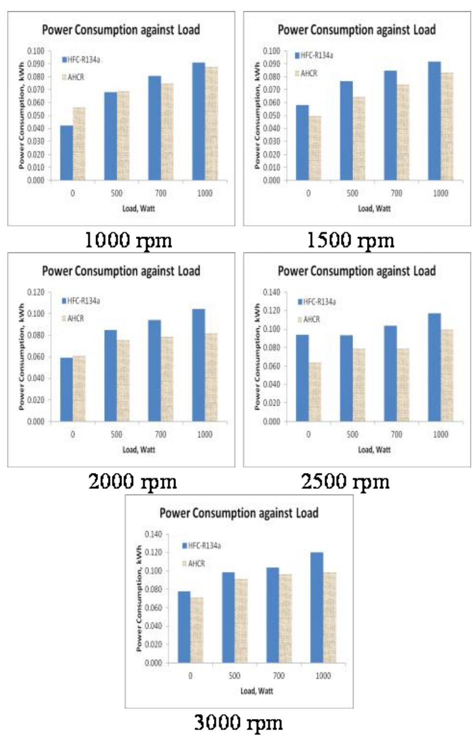
Temperature setting (°C)	Load, Watt (W)	Compressor Speed														
		1000 rpm			1500 rpm			2000 rpm			2500 rpm			3000 rpm		
		kWh HFC134a	kWh AHCR	Difference	kWh HFC134a	kWh AHCR	Difference	kWh HFC134a	kWh AHCR	Difference	kWh HFC134a	kWh AHCR	Difference	kWh HFC134a	kWh AHCR	Difference
21	0	0.052	0.049	-6.4811	0.055	0.048	-12.7273	0.060	0.053	-11.6758	0.068	0.071	4.50023	0.070	0.078	11.98488
	500	0.068	0.067	-1.4706	0.078	0.068	-12.4464	0.083	0.072	-13.0026	0.102	0.085	-16.368	0.097	0.096	-1.1487
	700	0.079	0.075	-5.0633	0.082	0.077	-6.38298	0.091	0.077	-15.3484	0.105	0.095	-9.8328	0.110	0.105	-4.26325
	1000	0.090	0.086	-4.4444	0.087	0.083	-4.2754	0.102	0.082	-19.9389	0.110	0.098	-11.559	0.119	0.112	-5.54218
		Average		-4.3649	Average		-8.958	Average		-14.9914	Average		-8.315	Average		0.257687
22	0	0.046	0.059	27.2198	0.060	0.068	12.2208	0.069	0.072	4.69837	0.071	0.070	-1.287	0.082	0.082	0.310704
	500	0.072	0.070	-3.6752	0.083	0.077	-6.8891	0.082	0.082	-0.40366	0.094	0.093	-1.0508	0.105	0.099	-5.67145
	700	0.078	0.092	19.0381	0.084	0.085	0.29993	0.092	0.082	-11.4534	0.102	0.095	-6.8405	0.121	0.101	-16.8305
	1000	0.091	0.095	4.66776	0.091	0.092	0.87858	0.114	0.092	-18.942	0.115	0.104	-9.6854	0.133	0.104	-21.9659
		Average		11.8126	Average		1.62756	Average		-6.52518	Average		-4.7159	Average		-11.0393
23	0	0.042	0.056	32.8365	0.058	0.050	-14.6812	0.059	0.061	3.07648	0.094	0.064	-31.872	0.078	0.071	-8.84493
	500	0.068	0.069	1.5762	0.077	0.064	-15.8508	0.085	0.075	-11.1265	0.093	0.079	-15.735	0.098	0.091	-7.1969
	700	0.081	0.075	-7.2189	0.085	0.074	-12.5418	0.094	0.079	-16.7064	0.104	0.079	-24.158	0.103	0.096	-7.05636
	1000	0.091	0.088	-3.6391	0.092	0.083	-9.34373	0.104	0.082	-21.6876	0.117	0.100	-14.924	0.120	0.098	-17.8861
		Average		5.88867	Average		-13.1044	Average		-11.611	Average		-21.672	Average		-10.2461



(a) At 21^0C



(b) At 22^0C



(c) At 23^0C

Figure 7 Graph of power consumption against load (at compressor speed of 1000 – 3000 rpm).

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6. REFERENCES

ANSI/ASHRAE Standard 55, *Thermal environmental conditions for human occupancy*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2008.

Birch, T., 2000. *Automotive Heating and Air Conditioning 2nd Edition*, Prentice Hall.

D. Jung and C.B. Kim., 2000. Testing of propane/isobutene mixture in domestic refrigerator. *International Journal Refrigeration*

Ghodbane. M., 1999. An Investigation of R152a and Hydrocarbon Refrigerants in Mobile Air Conditioning, SAE Paper 1999-01-0874

Granryd, E., 2001. Hydrocarbons as refrigerants – an overview. *International Journal Refrigeration,* Volume 24 pp. 15-24

Henry Nasution, et. al., 2012. *Experimental Evaluation of Automotive Air-Conditioning Using HFC-134a and HC-134a.* American Institute of Physics

K. Mani and V. Selladurai, 2008. Experimental Analysis of a new refrigerant mixtures as drop-in replacement for CFC12 and HFC134a. *International Journal of Thermal Sciences*

REFPROP, Thermodynamic properties of refrigerants and refrigerant mixtures, Version 6.1, Gaittherbeurg, MD, National Institute of Standards and Technology, 1998.

Tashtoush, B., Tahat, M., Shudeifat, M.A., 2002. Experimental study of new refrigerant mixtures to replace R12 in domestic refrigerators. *Application Thermal Engineering*, Volume 22 pp. 495-506

Wongwises, S., Chimres, N., 2005.Experimental study of hydrocarbon mixtures to replace HFC-134a in a domestic refrigerator. *Energy Conversion & Management*, Volume 46, pp.85-100

Wongwises, S., Kamboon, A., and Orochon, B., 2006 Experimental investigation of hydrocarbon mixtures to replace HFC-134a in an automotive air conditioning system. *Energy Conversion & Management,* Volume 47, pp.1644-1659

Y.A. Cengel and M.A. Boles., 2007. *Thermodynamics: An engineering Approach (6 ed.)*. McGraw-Hill