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THERMO ECONOMIC ANALYSIS OF ENVIRONMENTAL FRIENDLY REFRIGERANT MIXTURES FOR REPLACEMENT OF R134A

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ABSTRACT

For the last few decades, the vast research on new environmentally friendly alternative refrigerant is going on. However, the limited work is for energy saves and safety aspects using refrigerant HFO1234yf and HC600a. Refrigerant R1234yf is an ecofriendly refrigerant which has lower GWP value of 4 but it is costly and COP is found to be slightly lower than R134a. Refrigerant, R600a (GWP less than 20) has lower power consumption than R134a and average power consumption for refrigerants R1234yf is higher than R134a. In the present work, various relevant mixtures of refrigerants have been experimentally tested to establish relationship between energy consumption, COP and cooling capacity. Thermo economical and flammability issues of refrigerants have been addressed.

Keywords: global warming potential, alternate refrigerants, flammability.

1. INTRODUCTION

The development of suitable refrigerants is one of the main parameters in defining the success of vapour compression refrigeration systems. They have zero ODP (ozone depleting potential) and very low GWP (global warming potential), but some of them are mildly flammable and vast research is going on to overcome this problem as they are anticipated as next generation refrigerants. Lots of research work has been done for replacing "old" refrigerants with "new" refrigerants with the aim of reducing GWP and maintaining energy efficiency. The high value of the COP was not important at the time of low energy prices. Overall energy prices are considerably higher than during the last refrigerant change and COP is affecting indirect GWP. COP is the ratio of refrigeration effect to the net work input given to the system and COP of the system can be improved either by increasing the refrigeration effect or by reducing work input given to the system. A replacement for R134a (high GWP) is needed and its replacement with the low GWP R1234yf and R600a and relevant mixtures is discussed in the present work. Recently, R1234yf (2, 3, 3, 3-Tetrafluoropropene) having the chemical formula CH2=CFCF3 has been proposed as a possible alternative refrigerant for HFC134a. Refrigerant R1234yf has zero ODP, GWP of 4 and excellent life cycle climate performance (LCCP) as compared to HFC134a. HFO-1234yf has the lowest switching cost for automakers among the currently proposed alternatives, although the initial cost of the product is much higher than that of R-134a. Esbr *et al*., 2013 suggested that the search for better alternative refrigerant which have zero ozone depletion potential (ODP) and zero or lower GWP, is still on. R1234yf is a new refrigerant which has lower global warming potential than R134a. The value of GWP for R1234yf is 4 which is lower than the GWP value of 150, so it satisfies MAC Directive passed in July 2006. R1234yf has nearly similar value of the molecular weight and the normal boiling point, making R1234yf a good replacement of R134a. Li *et al.,* 2012 investigated that R1234yf may be used in mobile air-conditioners due to its low GWP and performance comparable to that of R134a. However, its performance is inferior to that of R410a. Ahamed *et al*., 2010 observed that in a domestic refrigerator with R600a and R134a as refrigerants, compressor had the highest exergy destruction with R600a and it is followed by the other equipments. One can deduce from ref. 4 that the total exergy destruction in optimum condition with R600a was 45.05% of the base refrigerator. R600a claimed better energy efficiency than R134a, but it is flammable [5]. Linde, 2017 observed that more environmentally friendly refrigerant used by manufacturers is R600a (isobutane). Therefore, its use and handling requires adequate safety measures. Leighton, 2011 investigated that a slight decrease in system efficiency would occur when replacing R134a with R1234yf, but in both cases the difference was less than 2%. This indicates that R1234yf is an excellent direct substitute for R134a with minor system modifications but R1234yf is flammable. Ansari *et al*., 2013 conducted a theoretical exergy analysis of HFO-1234yf and HFO-1234ze in simple vapour compression refrigeration system and indicated that HFO-1234yf and HFO-1234ze is a good replacement of R-134a. Keerthi *et al*., 2016 suggested that the refrigerator, bed plays a vital role by supporting all the components majorly the compressor. To remove these extra materials, optimization is carried out with unwanted materials removed. Mitishita *et al.*, 2012 suggested a thermo economic design methodology for frost-free refrigerators with two compartments using simulation models. If the optimization is aimed at cost savings, a variable-speed compressor is feasible only if its overall cost does not surpass 20% of that observed for a single-speed compressor with the same displacement. Vincent and Heun, 2006 suggested a cost model for the compressor with Energy Efficiency Ratings ranging between 0.60 and 1.8. Subiantoro *et al*., 2014 suggested that a temperature lift between the evaporating and the condensing temperatures of around 40°C is created, which corresponds to about 9 bars of pressure difference that the compressor has to provide in both the R134a and R1234yf systems. Hasanuzzaman *et al*., 2008 investigated the effect

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of the ambient temperature, door openings, thermostat settings and food loading on energy consumption. As an energy-intensive mainstream product, residential refrigerators offer a significant opportunity to reduce electricity consumption through energy-efficiency improvements. For the last few decades, the vast research on new environmentally friendly alternative refrigerant is going on. However, the limited work is for energy saves and safety aspects using low GWP refrigerant like R1234yf and HC R600a and their mixtures. Present work analyses the thermo economic sustainability of low GWP refrigerant mixture for replacing R134a in domestic refrigerator.

2. MATERIAL AND METHODS

A conventional one door one chamber household refrigerator with internal cabin volume 190 L has been used for the present study, which was originally designed for R134a refrigerant with 95g charge. Joybari *et al*., 2013 illustrated that total exergy destruction in optimum condition with R600a was 45.05% of the base refrigeration R134a. Therefore, 43g of R600a is selected. It is also important to note that if R1234yf is used as a direct drop-in, the system will perform adequately without modification to any of the R134a baseline components and the system pressures will stay within acceptable limits and hence the same quantity of refrigerant as selected for R134a is taken for experimentation. Economically fixed cost of refrigerant R600a as obtained from Table-1 is Rs. 27.95 and it is lowest among the entire three refrigerants. Its ODP value is zero and GWP value is very less. All experiments are conducted in a test room, under standard conditions (32^0C ambient temperature and 50% relative humidity). Temperatures in 08 arbitrary points of the refrigerator are monitored and recorded continuously. Time was measured from the stop watch and energy consumption is monitored and measured by energy meter. In addition, the consumed voltage, current, working time and ON time of the compressor are recorded.

Table-1. General comparison of R134a, R600a and R1234yf.

	R1234yf	R600a	R134a
Quantity (g) for 190 L Refrigerator	**95**	**43**	**95**
Price Rs. per Kg	15500	650	450
Charge Cost (Rs. / Refrigerator)	1472.5	27.95	42.75
ODP	0	0	0
GWP	4	10	1430

3. RESULTS AND DISCUSSIONS

As it was predicted, at the zero time (when the compressor starts) the power consumption for all three refrigerants was high but soon it starts decreasing. When interior cabin reaches around a preset temperature, the compressor is turned OFF and compressor stops. The average power consumption during the compressor ON time, determine refrigerator energy consumption. As shown in Table-2, R600a had the longest compressor ON time period, whereas R1234yf has the shortest ON period. Refrigerant R600a power consumption is 21.75 % lower than R134a and it is revealed by lesser surface area under the curves for R600a (Figure-1). Average power consumption for refrigerants R1234yf is 1.59 % higher than R134a. It may be concluded that R600a is thermo economical refrigerant among the selected three refrigerants but it is flammable. Over the range of operational conditions tested, the maximum difference in terms of cooling capacity and COP is less than 3% of R1234yf as compared to R134a. It was revealed that for the same compressor work, the cooling capacity of R1234yf decreases because R1234yf has about 25% more density as compared to R134a. However, this 25% more mass indicated by the R1234yf did not produce an equivalent increase in cooling capacity because the latent heat of vaporization of R1234yf is about 18% lower than that of the R134a (Table 3). R1234yf is used as a direct drop-in, the system will perform adequately without modification to any of the R134a baseline components and the system pressures will stay within acceptable limits.

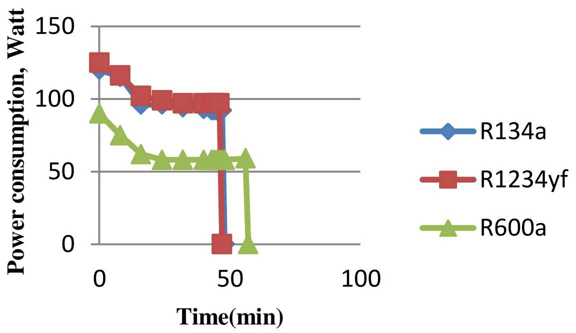

Figure-1. Power consumption for refrigerant R134a, R1234yf and R600a.

As with R134a, the suction line heat exchanger (SLHX) is very important for system energy efficiency of R600a. Here the SLHX receives the condensate as hot fluid at 40^0 C and subcools to 30^0C at constant pressure by exchanging heat to the vapour from the evaporator at -20^0C. Cooling capacity was higher by 15.2%, 17.6% and 25.7% to the refrigerant R134a, R1234yf and R600a respectively. It is well known that cooling capacity increases with SLHX but large increase in cooling effect for R 600a was also caused by a high vapour heat capacity (Table-4).

Figure-2 shows a vapour compression refrigeration system (VCRS) between a suction line heat exchanger (SLHX) as condensate sub-cooler and evaporator outlet as a vapour super heater.

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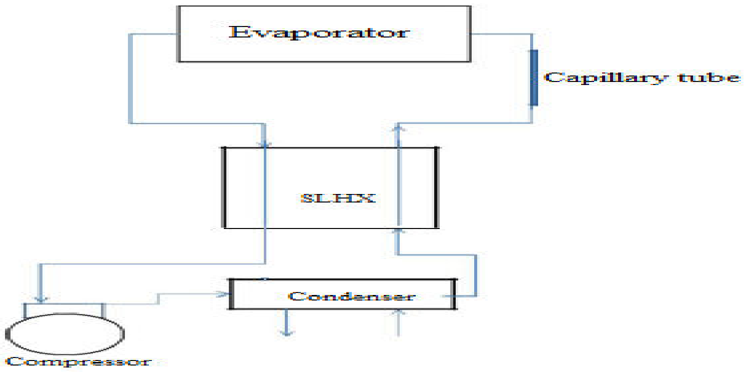

Figure-2. Positions of installation of SLHX & capillary tube in VCRS

Table-2. Average energy consumption.

S. No.	Refrigerant	ON time period (min)	Improvement in cooling capacity due to SLHX	COP	Average energy consumption (Wh)	% change relative to R134a
1	R134a	47	15.2%	2.04	75.70	-
2	R1234yf	46	17.6%	1.98	76.90	1.59
3	R600a	56	23.7%	2.28	59.23	-21.75

Table-3. General properties of R134a and R1234yf refrigerants.

Property	R134a	R1234yf	[R134a-R1234yf] /[R134a] *100
Sat. vapour density (kg/m^3) at -10.6^{0}C	9.816	12.296	-25.26%
Latent heat of vaporisation (kJ/kg) at -10.6^{0}C	206.40	169.81	+17.73%
Saturated pressure @-10.6°C (kPa)	195.90	216.92	-10.73 %
Saturated pressure @54.4^{0}C (kPa)	1469.8	1444.5	+1.72 %
Sat. vapour density(kg/m^3) at -10.6^{0}C	9.816	12.296	-25.26%
Latent heat of vaporisation (kJ/kg) at -10.6^{0}C	206.40	169.81	+17.73%

Table-4. General properties of R600a and R134a.

S. No.	Refrigerant	R 600a	R 134a
1	Critical temperature (^{0}C)	135	101
2	Normal boiling point (^{0}C)	-11.6	-26.5
3	Pressure at -25 °C in bar (absolute)	0.58	1.07
4	Liquid density at -25 ° C in kg/l	0.60	1.37
5	Vapour density at t_o -25/+32 °C in kg/m³	1.3	4.4
6	Enthalpy of vaporisation at -25 °C in J/kg	376	216
7	Pressure at +20 °C in bar (absolute)	3.0	5.7

The refrigerant R600a has additional advantages of a low saturated range of pressure between evaporator and condenser than other refrigerants and hence the compression work requirement for same refrigeration capacity becomes lower and it improves the COP of the refrigerator (Table-2).

3.1 Thermo economic refrigerant mixture

This study is carried out with the objective of reducing costs, flammability, improving thermal properties and reducing energy consumption using refrigerant mixtures. This research work explores the feasibility of the R134a/HC blend in an existing R134a refrigerator. Kim *et al.*, 1994 worked on a compatible mixture for the refrigerants R134a/R600a/R290 (91/4.93/4.07 mass percentage). The mixture becomes miscible with the conventional mineral oil because of hydrocarbon presence and it also enhances the thermo-physical properties of R-134a. This blend has proved to be a better retrofit refrigerant and improves the thermo-physical properties of R134a. Agarwal experimentally, 1998 evaluated the HC mixture of R134a/R600a and found that the R600a/R134a exhibits higher system capacity than R134a.

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Douglas *et al*., 1996 proposed that flammable refrigerants can be mixed with non-flammable refrigerants to produce a non-flammable mixture. R1234yf has similar thermodynamic properties to the R134a however, it is expensive. Barroso-Maldonado *et al*., 2015 carried out an energy simulation to replace R134a mixtures with R134a and R1234yf.Finally, the model is carried out to an energy simulation in order to predict the behavior of different mass fractions of R1234yf and used R1234yf with a value of 0.9 so that GWP of the mixture is 150.

Based on a literature survey and in order to lower GWP equal to 150 and thermo economic aspect, the following refrigerant mixtures (Table-5) are tested:

Reco1: Mixture of 90% R1234yf and 10% R134a in mass percentage

Reco2: Mixture of 91% of R600a and 9% R134a in mass percentage

Reco3: Mixture of R134a/R600a/R290 in 91/4.93/4.07 in mass percentage

Table-5. Energy consumed by refrigerants and ON time of the compressor.

Energy consumption (Watt)						
Time (Min)	**R134a**	**R1234yf**	**R600a**	**Reco1**	**Reco2**	**Reco3**
0	120	125	90	121	100	115
8	115	116	75	112	94	110
16	96	102	62	92	77	88
24	96	99	58	92	64	88
32	94	97	58	92	62	87
40	93	97	58	91	62	86
43	92	97	58	90	62	86
44	92	97	58	90	62	86
46	92	97	58	90	62	
47	92	0	58	0	62	
48	0		58		62	
56			59		62	
57			0		60	
58					0	

It may be revealed that energy consumption slightly decreases as compared with R1234yf in case of Reco1 mixture. As R1234yf is costly, therefore, the cost of refrigerant is reduced by the addition of R134a while it maintains GWP mixture less than 150. Energy consumption is higher for Reco2 as compared with R600a. Refrigerant Reco2 has an area under the curve equal to Reco3 which means same energy consumption. Isobutane (R600a) is found to be a viable additive due to its better thermo-physical properties, but its NBP is -11.73^{0}C. In the mixture of R600a and R134a (NBP = -26.15^{0}C), When R600a is added to R134a (NBP = -26.15^{0}C), the more volatile R134a will evaporate first and leave the mineral oil lubricant behind, as it is not miscible and the refrigerant R600a is less volatile in the evaporator.

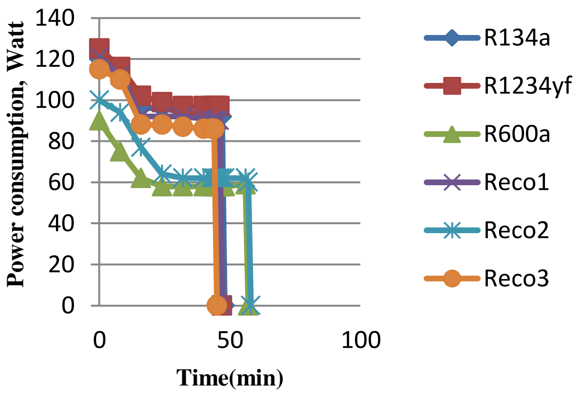

Figure-3. Power consumption for refrigerants and mixtures.

Results and Discussion However, energy consumption of mixture of R134a/R600a/R290 (91/4.93/4.07) in mass percentage is lower than R134a (Table-6). A variation of the COP and improvement in cooling capacity is shown in Figure-4 and Figure-5 respectively.

Table-6. Thermo economic comparison of various mixtures of R134a, R600 and R1234yf.

Property	R134a	Reco3	R1234yf	Reco1	R600a	Reco2
Improvement in cooling capacity due to SLHX	15.2%	18.4%	17.6 %	18.6%	23.7%	20.2%
COP	2.04	2.10	1.98	2.05	2.28	2.12
Energy consumption (Wh)	75.7	65.30	76.90	68.23	59.23	65.35

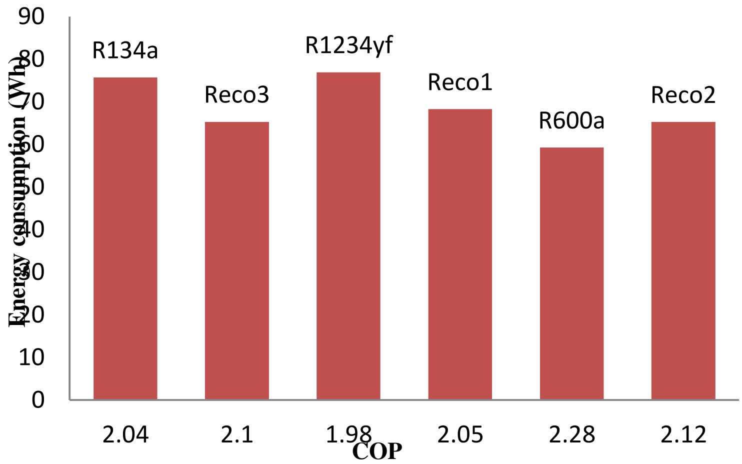

Figure-4. COP vs energy consumption (Wh).

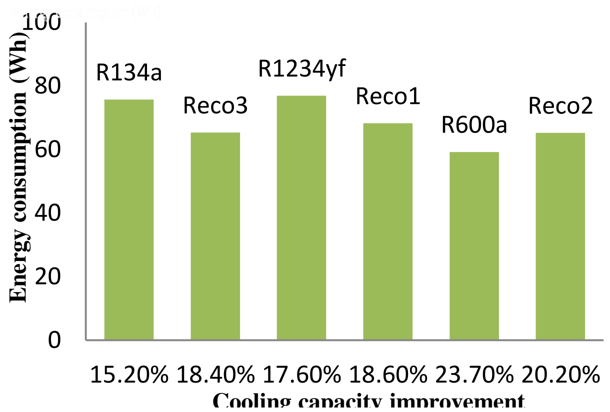

Figure-5. Cooling capacity improvement vs energy consumption (Wh).

4. ENVIRONMENTAL ASPECT

Working fluid selection for the refrigeration and air conditioning applications is based on three factors: flammability and safety, environmental impact (ODP and GWP) and energy efficiency. In this section, environmental impact of fluid shall be discussed along with flammability and safety. As per ANSI/ASHRAE standard, 2015 refrigerants regarding safety and collecting values of ODP and GWP from published paper are given in Table-7.

4.1 Flammability aspects

The Main common starting point is that accidents need to have two essential preconditions. One is the flammable mixture of gas and air and the other is the ignition source of a energy / temperature. As a safety precaution, maximum refrigerant charge is set to be 150 g and ignition risk is very low for approx. 8 g/m^3, for a standard kitchen[5]. R600a is generally used in small quantities in refrigerator (20-50 g); therefore, it may be used with safety precautions. Flammable refrigerants can be mixed with non-flammable refrigerants to reduce the flammability tendency of mixture. If added in very small quantity in non-flammable refrigerant like in Reco3, the mixture is inflammable.

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Table-7. Characteristics of R134a, R1234f and R600a.

Characteristics	R134a	R1234yf	R600a
Flammability	A1, No Flame Propagation	A2L, Mild flammable	A3, Flammable
Ozone Depletion Potential (ODP)	0	0	0
Global Warming Potential (GWP)	1430	4	10

5. CONCLUSIONS

The following conclusions are drawn from the above study on environmental friendly refrigerants and mixtures:

a) Refrigerant R600a is the most thermo economical refrigerant among the selected three refrigerants but it is flammable.

b) The maximum difference in terms of COP and cooling capacity is less than 3% for R1234yf as compared to R134a. Therefore R1234yf is used as a direct drop-in, the system will perform adequately without modification to any of the R134a baseline components and the system pressures will stay within acceptable limits.

c) Refrigerant R600a power consumption is 21.75 % lower than R134a. Average power consumption for refrigerants R1234yf is 1.59 % higher than R134a.

d) Amount of R600a used in refrigerator is less as compared to other alternative refrigerants. So, it may be used in household refrigerator with safety precautions.

e) 5. Cooling capacity was higher by 15.2%, 17.6% and 25.7% to the refrigerant R134a, R1234yf and R600a respectively due to SLHX.

f) It may be revealed that energy consumption slightly decreases as compared with R1234yf in case of Reco1 mixture. As R1234yf is costly, therefore, the cost of refrigerant is reduced by the addition of R134a while it maintains GWP of the mixture equal to 150. Energy consumption is higher for Reco2 as compared with R600a. Refrigerant Reco2 has an area under the curve equal to Reco3 which means same energy consumption. However, energy consumption of mixture of R134a/R600a/R290 (91/4.93/4.07) in mass percentage is lower than R134a.

REFERENCES

[1] J. N. Esbr, F. Mole and A. Barragan-Cervera. 2013. Experimental analysis of the internal heat exchanger influence on a vapour compression system performance working with R1234yf as a drop-in replacement for R134a. Applied Thermal Engineering. 153-161: 59-1:2.

[2] Minxia Li, Chaobin Dang and Eiji Hihara. 2012. Flow boiling heat transfer of HFO1234yf and R32 refrigerant mixtures in a smooth horizontal tube: Part I. Experimental investigation. International Journal of Heat and Mass Transfer. 3437-3446: 55-13:14.

[3] J.U. Ahamed, R. Saidur and H.H. Masjuki. 2010. Thermodynamic performance analysis of R-600 and R-600a as refrigerant. Engineering e-Transaction. 11-18: 5-1.

[4] M. M. Joybari, M. S. Hatamipour, A. Rahimi and F. G. Modarres. 2013. Exergy analysis and optimization of R600a as a replacement of R134a in a domestic refrigerator System. International Journal of Refrigeration. 1233-1242: 36.

[5] Danfoss Technical Information. Practical Application of Refrigerant R600a Isobutane in Domestic Refrigerator Systems. www.danfoss.com/compressors.

[6] Linde. Linde Gases Division. Seitnerstrasse 70, 82049 Pullach, Germany AG 2017, www.linde-gas.com/refrigerants.

[7] 2011. Daniel Thomas Leighton. Investigation of household refrigerator with global warming potential alternative refrigerant. Master of Science, University of Maryland.

[8] N. A. Ansari, B. Yadav and J. Kumar. 2013. Theoretical Exergy Analysis of HFO-1234yf and HFO-1234ze as an Alternative Replacement of HFC-134a in Simple Vapour Compression Refrigeration System. International Journal of Scientific & Engineering Research. 134-144: 4-8.

[9] S. Keerthi, A. yaska, N Sukesh. G. Kumar and Chandana G N. 2016. Topological Optimization of a

Refrigerator Bed. International Journal of Advancements in Technology. 1-6: 7-3.

[10] R. Mitishita, E. Barreira, C. Negrao and C. Hermes. 2012. Simulation-Based Design and Optimization of Frost-Free Refrigerators: A Thermoeconomic Approach. Proc. Int. Conf. International Refrigeration and Air Conditioning, Purdue University. 2102: 1-10.

[11] CE Vincent and MK Heun. 2006. Thermoeconomic Analysis & Design of Domestic Refrigeration Systems. Proc. Domestic Use of Energy Conference, Calvin College, Michigan, USA.

[12] A. Subiantoro, K. T. OOI and U. Stimming. 2014. Energy Saving Measures for Automotive Air Conditioning (AC) System in the Tropics. Proc. Int. Conf. International Refrigeration and Air Conditioning, Purdue University. 2116: 1-8.

[13] M. Hasanuzzaman, R. Saidur and H.H. Masjuki. 2008. Investigation of energy consumption and energy savings of refrigerator-freezer during open and closed door condition. Journal of Applied Sciences. 1822-1831: 8-10.

[14] M. S. Kim, W. J. Mulroy and D. A. Didion. 1994. Performance analysis of two azeotropic refrigerant mixtures of HFC-134a with R290 (Propane) and R600a (Isobutane). Journal of Energy Resource Technology. 148-154: 116.

[15] R. S. Agarwal. 1998. Hydrocarbon blends and blends of HFC-134a-HC600a as drop in refrigerants for small capacity commercial refrigeration appliance - an experimental study. Proc. Int. Conf. International Refrigeration and Air Conditioning, Purdue University. 51-56.

[16] J. D. Douglas, E. A. Groll, J. E. Braun and D. R. Tree. 1996. Evaluation of propane as an alternative to HCFC-22 in residential applications. Proc. Int. Conf. International Refrigeration and Air Conditioning, Purdue University. 13-20.

[17] J. M. Barroso-Maldonado, J. M. Belman-Flores and C. Rubio-Maya. A brief model to evaluate the behaviour of R134a/R1234yf mixtures on a reciprocating Compressor. ASME International Mechanical Engineering Congress and Exposition Volume 2015; V06BT07A013-8 pages: 6B-Energy.

[18] ANSI/ASHRAE. 2015. Classification and safety classification of Refrigerant. Addenda supplement.