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Comparative performance study of vapour compression refrigeration system with 22/R134a/M09/R410a/R407c/R290/M50

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ABSTRACT

This paper presents the thermodynamic analysis of various refrigerants using vapour compression refrigeration cycle. Various refrigerants are now coming up as substitutes to replace R22 and R134a. R134a is extensively used in refrigeration industry these days. This HFC is inflammable but contributes to global warming a lot. Besides this environmental issue, R134a is not compatible with mineral oil. Therefore, in case of retrofitting, oil change is going to be a major issue. In the present work, a theoretical analysis has been done on various refrigerants which include R134a, R22, R290, R410a, R407c, MO9 (mixture of R134a/R290/R600a). Coefficient of performance of these refrigerants has been compared. Thermodynamic properties of these refrigerants are taken from REFPROP software (NIST, 2007) .In present study M09 is found out to be a suitable substitute for R134a for new systems as well as for retrofitting.

Keywords: Refrigeration system, Compression system, COP, Retrofitting, R134a, M09

Nomenclature

COP coefficient of performance (non- dimensional)
GWP global warming potential
h specific enthalpy (kJ/ kg)
HCs hydrocarbons
HFCs hydro fluorocarbons
m mass flow rate (kg/min)
ODP ozone depletion potential
P pressure (MPa)
QH rate of heat transfer in condenser (kW)
RE refrigerating effect, kJ/ kg
s specific entropy (kJ/ kg/ K)
T temperature (K)
W work rate (kW)

Subscripts

cod condensing/condenser
evap evaporating/evaporator
comp compressor

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1. INTRODUCTION

Chlorofluorocarbons (CFC) and hydro chlorofluorocarbons (HCFC) composites were introduced in 1930 and since then, they have been the important refrigerants for the majority of the applications in the refrigeration industry. But because of their contribution to ozone depletion potential and green house effect they are being gradually eliminated. Therefore the CFC's and HCFC's need to be replaced by the more eco-friendly refrigerants. HFC's having zero ozone depletion potential are considered to be the promising refrigerants. But the major problem that HFC's have is high global warming potential. Refrigeration process has become important in everyday applications like building cooling, transportation and automobiles. The refrigeration industry dependence on these refrigerants has deferred the elimination of their consumption. Some countries congregated in 1985 in the Convention of Vienna and started an agreement that was firmed up in 1987 in Canada, the Protocol of Montreal. This protocol determined the elimination of the CFCs until 1996 and the HCFCs until 2030 in the

Table 1
Environmental impacts of various refrigerants

Refrigerant	Chemical formula	GWP	ODP
R600a	C_4H_{10}	Less than 20	0
R290	C_3H_8	Less than 20	0
R134a	CH_2FCF_3	1300	0
R22	$CHClF_2$	1700	0.05

Table 2
COP of various refrigerants for evaporator temperature ranging from -20 ^{0}C to 10 ^{0}C and condenser temperature 40 ^{0}C

Evaporator Temperature (^{0}C)	R22	R134a	M09	R410A	R407C	R290	M50
-20	3.15	3.063	2.766	2.93	2.975	3.02	2.86
-15	3.59	3.501	3.149	3.33	3.39	3.44	3.2856
-10	4.11	4.027	3.619	3.83	3.94	3.96	3.79
-5	4.75	4.679	4.19	4.43	4.5	4.603	4.429
0	5.042	5.49	4.917	5.19	5.28	5.40	5.21
5	6.59	6.55	5.84	6.18	6.28	6.42	6.248
10	7.98	7.95	7.09	7.5	7.62	7.8	7.6225

Table 3
Refrigeration effect (kJ/min) of various refrigerants at different evaporator temperatures with mass flow rate of refrigerant m= 1kg/min

Evaporator Temp (K)	R22	R134a	M09	R407c	R290	M50	R410a
253	147.55	130.27	153.24	148.96	245.25	143.33	153.27
258	149.55	133.35	154.88	151.11	251.04	146.34	155.27
263	151.69	136.38	156.57	153.19	256.77	150.15	157.06
268	153.65	139.38	158.29	155.2	262.43	153.95	158.7
273	155.54	142.33	160.03	157.12	267.99	157.73	160.19
278	157.35	145.22	161.77	158.94	273.45	161.48	161.5
283	159.06	148.04	163.49	167.56	278.8	165.21	162.61

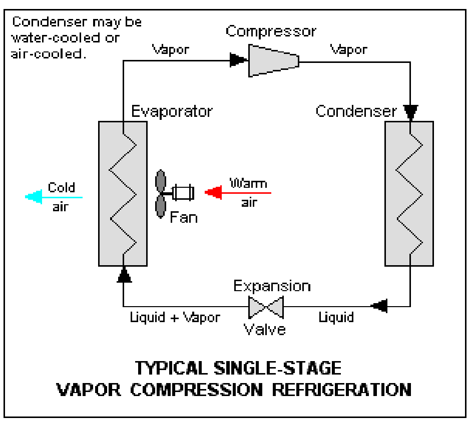

Figure 1
A typical single-stage Vapour Compression Refrigeration system

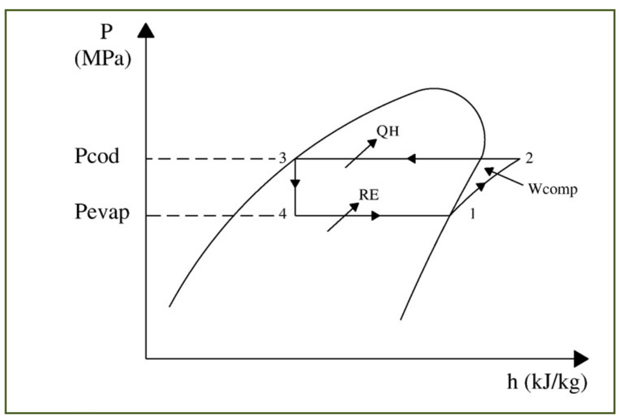

Figure 2
Traditional vapour-compression refrigeration cycle used in the analysis for the case of non-superheating/sub cooling

developed countries and a lag of 10 years in the developing countries. These compounds besides having chlorine content which are mainly responsible for ozone layer depletion also have greater stability which makes them exist in the atmosphere for very long time. Therefore the substitution of CFC R12, HCFC R22 and HFC R134a is considered to be a topic of concern from environmental point of view. Environmental impacts of various refrigerants are shown in Table 1. The hydrocarbons have various advantages like good compatibility with mineral oil, zero depletion potential, good compatibility with materials used in refrigeration system and non-toxicity. But hydrocarbons have the disadvantage of high flammability. However, if safety measures are taken to prevent the leakage of the refrigerants, then a flammable refrigerant could be as safe as other refrigerants. Hence the refrigerant M09 can be used as a potential retrofit.

2. LITERATURE REVIEW

An experimental performance study on a vapour compression refrigeration system with the new R290/R600a refrigerant mixture as drop-in replacement was conducted and compared with CFC12 and HFC134a by Mani et al. (2008). Their work showed that the mixture R290/R600a has higher refrigeration capacity and COP than R12 and R134a. A theoretical development of the thermodynamic properties of two mixtures of hydro fluorocarbon i.e. R407C and R410A, was carried out by Monte (2002). Arora and Kaushik (2008) did the theoretical analysis of a vapour compression refrigeration system with R502, R404A and R507A.Their work represents a detailed exergy analysis of an actual vapour compression refrigeration cycle. The efficiency defect in condenser was highest, and the lowest in liquid vapour heat exchanger for the refrigerants considered. Improved energy efficiency for CFC domestic refrigerators retrofitted with ozone friendly HFC134a/HC refrigerant mixture study was done by Shekhar et al. (2004). Their study represents the detailed study of retrofitting existing R12 system with the mixture of HFC134a/HC blends. They conducted a test on 165l CFC12 household refrigerator and found useful results in favour of the new mixture.

3. COMPARATIVE PERFORMANCE OF REFRIGERANTS

3.1. Simulation conditions

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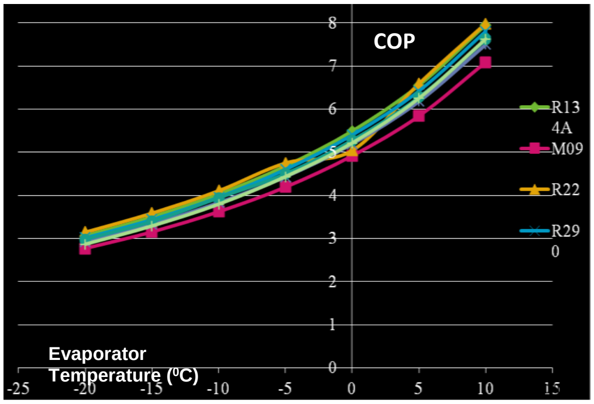

Figure 3

Plot showing comparison of COP of various refrigerants at evaporator temperature ranging from -20 ⁰C to 10 ⁰C and condenser temperature 40⁰C

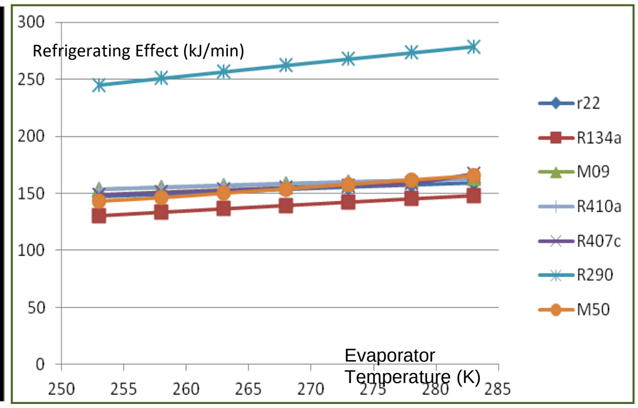

Figure 4

Plot showing comparison of refrigerating effect (kJ/min) of various refrigerants at evaporator temperature ranging from -20 ⁰C to 10⁰C

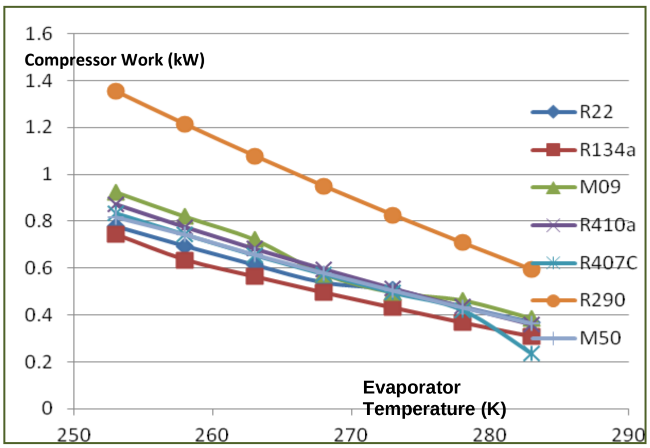

Figure 5

Plot showing comparison of compressor work (kW) of various refrigerants at evaporator temperature ranging from -20⁰C to 10⁰C

For theoretical analysis of various refrigerants the ideal vapour compression refrigeration cycle is used. The evaporator temperature is varied from -20 ⁰C to 10 ⁰C and the condenser temperature is kept constant at 40 ⁰C with corresponding saturation pressures at these temperatures. This temperature range for evaporator and condenser is used keeping in mind the temperatures used in domestic refrigerator. The conditions are very much similar to domestic refrigerator. For the mixtures, these conditions represent the average between bubble and dew point temperatures and the corresponding saturation pressures for these temperatures. R134A, R22 and R290 are pure substances while R410a, R407c, M09 and M50 are mixtures that have been analysed. To be more specific, these are non-azeotropic mixtures which have different boiling points of its components at their saturation temperatures. The temperature glide of non- azeotropes is greater than 10 ⁰C. The properties of pure refrigerants and mixture of refrigerants are taken from REFPROP (NIST) 8.0 program (2007). The superheating at the exit of compressor was considered and sub cooling at the exit of condenser was neglected in this analysis.

3.2. Refrigerant Selection

HC additives with HFC 134a behave like a zeotrope. It has been found that HC600a is less volatile than HFC134a, so when this mixture evaporates inside evaporator tubes, then evaporator liquid becomes rich in HC600a. Due to this the circulation fluid becomes rich with more volatile component HFC143a and the oil will not be removed since mineral oil is not miscible with HFC143a. Hence to improve the oil carrying capacity, an HC additive with more volatility than HFC134a is selected. It is reported that HC290 is more volatile than HFC134a; therefore it is also added to the above mixture. The resulting blend of HC600a, HC290 and HFC134a could be a promising refrigerant. Therefore we selected different percentage of these three refrigerants and analysed them. We selected M09 (HC600a 4.932%, HC290 4.068% and HFC134a 91%). Similarly we also did analysis on M50 (HC600a 25%, HC290 25% and HFC134a 50%). Other refrigerants like R410a and R407c are also analysed since their performance is said to be very close to R22, the most potential refrigerant used in air conditioning.

3.3. Calculation

A typical single-stage Vapor Compression Refrigeration system is shown in Figure 1.
COP of various refrigerants is calculated using the following steps with the help of Figure 2.
Values of enthalpy and entropy at saturation points i.e. points 1, 4, 3 and 2' are obtained from REFPROP (NIST) 8.0 program (2007). We need to find values of entropy and enthalpy at point 2. For this the following formula is used:

$$\mathbf{s_2 = s_{2'} + c_p \ln (T_2/T_2')} \qquad (1)$$

After finding out the value of T_2, value of enthalpy at point 2 is calculated using formula:

$$\mathbf{h_2 = h_{2'} + c_p (T_2 - T_{2'})} \qquad (2)$$

Now,

$$\mathbf{COP = (h1 - h_{4)} / (h_2 - h_1)} \qquad (3)$$

4. RESULTS AND DISCUSSION

4.1. COP

From Table 1 it is observed that R407c and R410a are very much close to R22 in terms of COP. For lower evaporator temperature the COP of R410a is 6% - 7% lower, and at higher temperature of evaporator it is only 4% lower than

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Table 4
Compressor work (kW) of various refrigerants at different evaporator temperatures with mass flow rate of refrigerant = 1kg/min

TEMP(K)	R22	R134a	M09	R410a	R407C	R290	M50
253	0.778	0.742	0.924	0.872	0.834	1.353	0.817
258	0.694	0.635	0.819	0.775	0.743	1.213	0.742
263	0.614	0.564	0.721	0.683	0.655	1.079	0.657
268	0.539	0.496	0.574	0.596	0.574	0.950	0.579
273	0.508	0.432	0.495	0.514	0.495	0.827	0.503
278	0.436	0.369	0.461	0.435	0.421	0.709	0.431
283	0.369	0.310	0.384	0.361	0.236	0.595	0.363

R22.Similar is the case with R407c; at lower evaporator temperature the COP is 5%-6%lower than R22. M09 COP is 9%-10% less than R134a at the given evaporator temperature range. M50 has COP 6%-7% lower than that of R134a at lower evaporator temperature and at higher evaporator temperature it is 4%-5% lower. The results in Table 2 were used to plot the graph of Figure 3.

4.2. Refrigeration effect

From Table 2 of refrigeration effect, it is observed that refrigeration effect of R407c is 0.95% -1.043% greater than that of R22 in the temperature range of 253K to 278K. Refrigeration effect of R410a is 3.28%-3.87% higher than that of R22 at the lower evaporator temperature, whereas at higher evaporator temperature it is 2.6% to 2.9% higher. Refrigeration effect of M09 and R290 is also greater than that of R134a.For M09 it is 10% to 18% higher in the given range of evaporator temperature. For R290 refrigeration effect values is remarkably high. It is 88% to 88.4% higher than R143a in the given range of temperature. Refrigeration effect of R290 is the greatest of all the refrigerants under analysis. M50 has higher refrigeration effect values in the given temperature range. It is 10% to 12% greater than that of R134a. The results in Table 3 were used to plot the graph of Figure 4.

4.3. Compressor Work

Table 4 shows the compressor work of refrigerants under analysis and following observations are made. In the temperature range of 258K to 273K compressor work for R410a is higher than R22 by 10% to 12% but in the temperature range of 278K to 283K compressor work is lesser by 1% to 3%. For R407c compressor work is higher than that of R22 in the temperature range of 253K to 268K but it becomes less than that of R22 in the higher evaporator temperature range. When compared with R134a, M09 has higher compressor work. It is 20% to 25% greater in the given temperature range. R290 has compressor work values much higher than that of R134a throughout the range of evaporator temperature. The results in Table 4 were used to plot the graph of Figure 5.

5. CONCLUSIONS

The main objective of this work is to present the thermodynamic analysis of various refrigerants. For this MO9, M50, R290 were analysed as substitute for R134a. According to the results, R290 might be a potential substitute for R134a but it cannot be used in industrial application where large amount of refrigerant is charged into the system. This is because large amount of HC might be hazardous owing to its flammable property. Hence R290 could be a better substitute for R134a for domestic purpose only. However, some important advantages presented by the hydrocarbons should be emphasized such as the cost of the refrigerant and the prospects of price reduction due to the increase in the demand. And the other advantages are the possibility to work with cheaper mineral oils and the possibility to work with more compact heat exchangers in function of its higher latent heat. M09 although has lower COP than R134a, is more environmental friendly as far as GWP is considered. Its global warming potential (GWP) is lower than R134a. Besides M09 can be used when retrofitting is required. And M09 can also work with cheaper mineral oil. M50 although having COP greater than M09, has a disadvantage of having hydrocarbons in large amount. 50% of this refrigerant contains mixture of propane (R290) and isobutane (R600a) and this increases its flammability. Therefore it is necessary to study the methods which could tackle the flammability issue with hydrocarbons without affecting the COP of system.

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