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Thermodynamic study of R134a in Vapour Compression Refrigeration System in Summer Climate

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Abstract

Thermodynamic analysis of an ideal vapour compression refrigeration system is done using refrigerants R134a.This Energy-Exergy analysis is carried out by developed mathematical model. Various parameters are numerically computed are first law efficiency in terms of coefficient of performance (COP) of the system both ideal case and actual experimental and exergetic efficiency and exergy destruction ratio have been computed . The eco-friendly R134a refrigerant gives lower COP than R22. Comparing with R22, R134a takes more compressor power and second law efficiency (exergetic efficiency) of VCRS is also lower than using R22. Due to higher GWP and ODP of R22, R134a can be used for domestic / commercial and industrial applications.

Keywords: Hydrofluorocarbon refrigerants, ozone-friendly, performance characteristics, ODP, GWP,

1. Introduction

Refrigerant is a substance which is used as a working substance in refrigeration system to move heat from lower temperature to higher temperature to get cooling effect. Midgley discovered halogenated hydrocarbon refrigerants having favourable thermodynamic properties. But these halogenated hydrocarbon refrigerants attack the atmospheric stratosphere and destroy ozone layer. With the discovery of ozone hole in stratosphere as stated by Molina and Rowland et al [1] and the Montreal protocols (Paul, *et al* [2]), the CFC and HCFC refrigerants are to be phased out due to their higher global worming potential (GWP) and higher ozone depletion potential (ODP). For these reasons, recently ODP and GWP plays a vital role in the development of new environment friendly alternative refrigerants other than CFC and HCFC refrigerants for their higher ODP and GWP. So, develop countries stopped production of CFC and HCFC refrigerants and looking for alternative environment friendly refrigerants. So, HC and HFC refrigerants with zero ODP and low GWP are considered for long term purpose. Although the ODP of some HFCs is zero, their GWP related to the greenhouse investigated on domestic refrigerator using propane and iso-butane as a refrigerant mixture and found that mass effect is large. On the other hand, HC refrigerants have a flammability issue, which restricts the usage in existing systems. However this flammability issue can be avoided by blending HC refrigerants with HFC refrigerants. It is also found that an HC/HFC mixture makes a very good solution with mineral oil and contribution to global warming of HC/HFC mixture is very low due to very lowGWP (about one third of HFC) and hence R134a is found to be most suitable alternative refrigerant for R12. Refrigerant R134a has very similar thermodynamic properties such as molecular weight, critical temperature, boiling point as R12, with zero ODP and less GWP as compared to CFC12 are shown in table 1 (Calm and Hourahan, et al [3]). This gave confidence to the researchers to consider R134a as a suitable replacement to R12 for short term basis. Hammad and Alsaad et al [4] investigated on domestic refrigerator using LPG (24.4% propane, 56.4% butane and 17.2 % iso-butane) as refrigerant. They concluded that this is the environment friendly refrigerant mixture and that can replace R12 in domestic refrigerator. Jung et al. (Jung, *et al*, 1996)
fraction range of 0.2 to 0.6 of propane increase the COP up to 2.3% compared to R12. Mani and Selladurai (Mani and

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Selladurai, 2008) experimented on vapour compression refrigeration system using new refrigerant mixture of propane and iso-butane for substitution of R12 and R134a. They found that this mixture had a refrigeration capacity 19.9% to 50.1 % higher than R12 and 28.6% to 87.2% higher than R134a and COP improved by 3.9% to 25.1% than R12 at lower evaporator temperature and 11.8% to 17.6% at higher temperature. Chen and Prasad (Chen and Prasad, 1999) theoretically analysed vapour compression refrigeration system using R134a and R12 as refrigerants and reported that the COP for R134a is slightly (3%) lower than the R12.Richardson and Butterworth (Richardson and Butterworth, 1995) experimentally investigated the performance of hydrocarbon refrigerants in a hermetic vapour compression refrigeration system and came to the conclusion that propane and propane/isobutene mixtures can be used in an unmodified R12 system and can achieved better COPs than R12 under the same operating conditions. They found that around 50% propane and 50% isobutene mixture not only just give the similar saturation characteristics but also gives a better COP when proportion of propane is increased. They also mentioned that hydrocarbon refrigerants have a flammability issue, they can be safely used in hermetic vapour compression refrigeration

The aim of this study is to investigate the performance of vapour compression refrigeration systems using R12, R125, R134a, R143a and R152a as refrigerants based on energy and exergy concept. Various parameters like COP, refrigerating capacity, compressor work, cycle efficiency, exergy efficiency are computed and compared in this work.

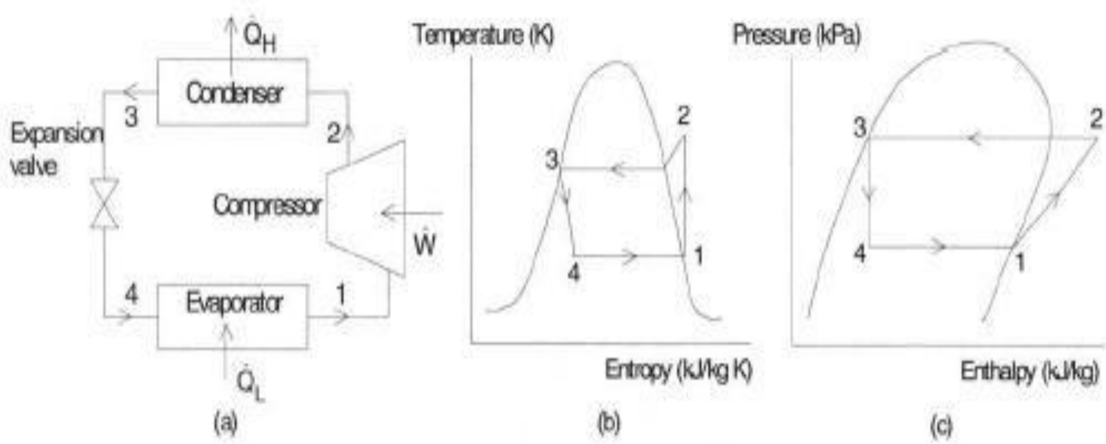

Figure 1 (a) A basic Vapor Compression refrigeration Cycle. (b) T-S diagram (c) its P-H diagram. [1]

Vapor compression refrigeration cycle on p-h diagram. The p-h diagram is frequently used in the analysis of vapor compression refrigeration cycle and usually consists of the four processes.

Process 1-2 is the compression.
Process 2-3 is the Condensation.
Process 3-4 is the expansion.
Process 4-1 is the evaporation.

T_1 and T_2 are the suction and discharge temperatures.
P_e and P_c are the evaporating and condensing pressures.
The different enthalpies involved in the cycle are,
h_1: enthalpy of suction pipe or end of evaporation.
h_2: end of suction pipe or end of compressor.
h_3: inlet of throttling valve or end on heat exchanger.
h_4: inlet of evaporation or end of expansion.

1.1 Thermal Analysis of Vapour Compression Refrigeration System

Figure 1 shows the p-h diagram of a complete ideal vapour compression refrigeration system. Various calculations are done based on this system using different refrigerants. COP of vapour compression refrigeration system is a very important criterion for performance analysis. It represents the refrigeration effect per unit compressor work.

COP_{VCRS} = Refrigeration Effect/ Compressor Work= R_E/W

Where R_E is the refrigeration effect and W is the compressor work.

The refrigerating effect, RE can be expressed as

$R_E = \dot{m}\,(h_1 - h_4)$

The compressor work, W can be expressed as

$W = \dot{m}\,(h_2 - h_1)$

Where $(h_2 - h_1)$ is the difference of enthalpy which includes the effect of compressor efficiency and $\dot{m}$is the mass flow rate of the refrigerants which can be expressed as

$\dot{m}$ = RE/ (h_1– h_4)
Where (h_1–h_4) is the difference of enthalpy in the cycle. The exergetic efficiency, η_{II} is computed in terms of second law efficiency , which is a the ratio of COP of VCRS to the COP of Carnot cycle, then

$$\eta_{II} = COP_{VCRS}/ COP_{Carnot} = \frac{\frac{R_E}{W}}{\frac{T_e}{T_c - T_e}}$$

and $COP_{Carnot} = \frac{T_e}{T_c - T_e}$
Where T_e is evaporator temperature and Tc is condenser temperature

(The COP of Carnot refrigeration cycle is a function of evaporator and condenser temperatures only and is independent of the nature of the working substance. The Carnot COP sets an upper limit for refrigeration systems operating between two constant temperature thermal reservoirs (heat source and sink). From Carnot's theorems, for the same heat source and sink temperatures, no irreversible cycle can have COP higher than that of Carnot COP.)
The cycle efficiency (also called as second law efficiency) is a good indication of the deviation of the standard VCRS cycle from Carnot cycle. Unlike Carnot COP, the cycle efficiency depends very much on the shape of T s diagram, which in turn depends on the nature of the working fluid.
Exergy or availability of a system is the maximum obtainable work output from the system. So exergy loss is the very important criterion to evaluate the thermodynamic performance of the vapour compression refrigeration system. System performance improved if exergy loss is less. For that reason it is our aim to minimize the exergy loss to improve the system thermodynamically. The exergy can be expressed following Chen and Prasad (Chen and Prasad, 1999) as
$e = (h-h_0) - (s-s_0)$
where kinetic and potential energy are excluded.
The exergy loss can be calculated by calculating exergy loss in each component of the system. Exergy loss in compressor can be expressed as
$\Delta e_w = (h_1-h_2)+T_0(s_2-s_1)+W$

Exergy loss in condenser can be expressed as
$\Delta e_c = (h_2-h_3)+T_0(s_3-s_2)$

Exergy loss in expansion valve can be expressed as
$\Delta e_v = (h_3-h_4)+T_0(s_4-s_3)$
Exergy loss in evaporator can be expressed as
$\Delta e_w = (h_4-h_1)(T_0/T_r)+T_0(s_1-s_4)$

And the total exergy loss can be expressed as
$\Delta E = \dot{m}(\Delta e_w + \Delta e_c + \Delta e_v + \Delta e_w)$

Exergetic efficiency can be expressed as

$$\eta_x = \frac{RE\left|\left(1 - \frac{To}{Tr}\right)\right|}{W}$$

1.2 Properties and Environmental Impacts of Selected Alternative Refrigerants

The vapour compression refrigeration system operates on refrigerant R12 which is most important CFC refrigerant identified for phase out in the country by HFC refrigerant. The institute has been one of the few institutes selected for funding for research work under World Bank project TEQIP. A research work was undertaken for finding the most suitable ozone-friendly Hydrofluorocarbon refrigerant for replacing ozone depleting refrigerant R12. Then most suitable refrigerant has been selected for replacing harmful refrigerant. Four non-ozone depleting HFC refrigerants (R125, R134a, R143a and R152a) were selected from methane and ethane derivatives and their performances in vapour compression refrigeration system were investigated. Properties and environmental impacts of selected zero ozone-depleting refrigerants used as substitutes in the refrigeration systems are listed in the Table (1a) to Table-1(c) [3-6] respectively.

Table-1(a) : Some properties and environmental impacts of selected alternative refrigerants.[3][5][6]

Refrigerants	Chemical formula	Molecular mass	Freezing point (°C)
R12	CF_2CL2	121	-157.5
R125	$C_2 HF_5$	120	-102.99
R134a	$C_2H_2F_4$	102	-96.67
R143a	$C_2H_3F_4$	84	-111

Table-1(b) : Some properties and environmental impacts of selected alternative refrigerants.[3][5][6]

Refrigerants	Chemical formula	Boiling point (ºC)	Critical point (°C)
R12	CF_2CL2	-29.8	112
R125	$C_2 HF_5$	-48.1	66.18
R134a	$C_2H_2F_4$	-26.1	101.06
R143a	$C_2H_3F_4$	-47.2	72.89
R152a	$C_2H_4F_2$	-24.0	113.26

Table-1(c): Some environmental properties of selected alternative refrigerants [3][5][6.

Refrigerants	Ozone Depletion Potential (ODP)	Global Warming Potential (GWP)
R12	1	8100
R125	0	2800
R134a	0	1300
R143a	0	3800
R152a	0	140

2. Results and Discussions

Experiment was conducted in the laboratory for obtaining thermal performance using eco-friendly R134a, refrigerant. The following data have been recorded.
Atmospheric pressure: 1 bar
Atmospheric temperature: T_0 =30°C =303 K
Condenser pressure: 135psi
Evaporator pressure: 8psi
Compressor delivery temperature: 61.9°C
Compressor suction temperature: -12.7°C
Ref. leaving condenser temperature: 29.6°C
Evaporator inlet temperature:-16.7°C
Mass flow rate: 5 kg/min
Evaporator volts: V_e/V = 196
Evaporator AMPS: I_e/n =2.24
Motor volts: V_m/V =198
Motor amps I_m/A =2.892
Motor compressor speed: 2800rpm
The Enthalpy and Entropy have been computed on above state temperature data as shown in the table-2.

Table-2 Enthalpy and Entropy of various components of VCRS

States	***Temperature in ^0C***	***Enthalpy in KJ/Kg***	***Entropy in KJ/Kg-K***
Outlet of evaporator-1	-12.7	391	1.7355
Compressor outlet-2	61.9	427	1.7011
Condenser outlet-3	29.6	240	1.1437
Evaporator Inlet-4	-16.7	178.6	0.9179

- Coefficient of performance
COP $_{\text{ideal cycle}}$ = $(h_1-h_4)/((h_2-h_1)/0.8)$ = 4.719
(Assuming 80% volumetric efficiency of compressor)
COP $_{\text{Actual}}$ =Q_e/Power =V×I/Power= V×I/(Motor volts ×Motor amps×Cos∅) =0.983

$\eta_{\text{IItheoritical}}$ = (COP $_{\text{Actual}}$ / COP $_{\text{ideal cycle}}$) = 0.2083

- Exergy loss in each component of the system
Exergy loss in compressor
$\Delta e_w = (h_1-h_2) + T_0 (s_2-s_1) + W$
Δe_w=133.5768 KJ/KG

Exergy loss in condenser
$\Delta e_c = (h_2-h_3)+T_0(s_3-s_2)$
Δe_c= 18.1078 KJ/KG

Exergy loss in expansion valve
$\Delta e_v = (h_3-h_4)+T_0(s_4-s_3)$
Δe_v=-7.0274KJ/KG

Exergy loss in evaporator
$\Delta e_w = (h_4-h_1)(T_0/T_2)+T_0(s_1-s_4)$
Δe_w=-3.3565KJ/KG

And the total exergy loss
$\Delta E = \dot{m}(\Delta e_w + \Delta e_c + \Delta e_v + \Delta e_w)$
ΔE = 706.5035 KJ/KG

- Exergectic Efficiency (η_x)

$$\eta_x = \frac{RE\left|\left(1-\frac{To}{T2}\right)\right|}{W}$$

$\eta_{\text{II\_exp}}$=0.1791= 17.91%

3. Conclusion

The experimental work presented in this paper on vapour compression refrigeration system, the following conclusions were made.

1. The eco-friendly R134a refrigerant gives lower COP than R22.
2. Comparing with R22, R134a takes more compressor power.
3. Second law efficiency (Exergetic efficiency of VCRS is also lower than using R22.
4. Due to higher GWP and ODP of R22, R134a can be used for domestic / commercial and industrial applications.

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