Comparative Assessment of Environment-Friendly Alternative to R134a in Vapour Compression Refrigeration System using Exergy Destruction

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ABSTRACT

The goal of this research is to compare the performance of a vapour compression refrigeration system using R-600a to a similar system having R-134a as a refrigerant. Both refrigerants have no potential to deplete the ozone layer. However, because R-134a is an HCF, its global warming potential is rather strong, whereas R-600a's is nearly none. The two refrigerants' desirable properties are compared. R-600a is a better refrigerant for a vapour compression refrigeration system, according to this comparison. The average values of the required parameters are then presented once a number of trials have been completed. To compare the refrigerants, the coefficient of performance, refrigeration effect, Carnot COP, and second law efficiency were calculated. The findings show that R-600a is a superior refrigerant. The system's primary components' exergy destruction has also been calculated. It demonstrates that the compressor has depleted its maximal exergy. R-600a is a strong alternative to R-134a, which is currently utilized in household refrigerators, according to the analysis.

Key words: Refrigeration; Exergy; Refrigerants; Coefficient of performance; Global warming; Ozone layer.

INTRODUCTION

Refrigeration is a process in which the temperature of a body is reduced and maintained below the surrounding temperature. This can be done using various natural and artificial heat transfer methods. To obtain the refrigeration effect continuously and for different capacities several refrigeration systems have been developed and still this development continues. A refrigerator is a device that works on a cycle and transfers heat from low-temperature source to high-temperature sink. According to the Clausius statement of the second law of thermodynamics, this heat transfer is not natural and some external aid is needed to carry out this heat transfer. Vapour compression refrigeration systems are the most popular refrigeration systems as on date due to the high COP in comparison to the other contemporary refrigeration systems. The main components of a vapour compression refrigeration system are the compressor, condenser, expansion device, and evaporator. The compressor is provided a work input to absorb heat in a low-temperature evaporator and reject heat in the high-temperature condenser. To obtain this cooling effect in evaporator a working substance which is called refrigerant circulates in the entire system. The refrigerant used in a particular system has a very significant role in deciding the performance. Therefore the selection of a refrigerant cannot be arbitrary and must be done based on established scientific principles.

The heat absorption and heat rejection processes taking place in the cycle are due to finite temperature difference which causes irreversibility. Generally, first law analysis is done to determine the performance of a system but that is not sufficient to assess how much energy has been degraded in different parts of the system. Second law analysis, based upon exergy destruction is a powerful tool to evaluate the performance of a system. The amount of exergy destruction at different components provides a clear direction for improvement. The Exergy of a system is the maximum useful work that can be obtained from that system until it reaches the dead state i.e. equilibrium with its environment (Dincer, I. 2017).

LITERATURE REVIEW

An investigation was done in which R-513a which is a blend of 56% of R-1234f and 44% R-134a was used GWP is high for R-134a. The mixture has 50% of GWP in comparison to R-134a. This study shows that the compressor of the system should be redesigned to improve performance and the effect of the condenser is almost nil (Sun, J.et al.,2020).). A cascade vapour absorption refrigeration system and vapor compression refrigeration system has been analyzed for low-temperature cooling application. The lithium-bromide vapour absorption refrigeration system is used at the high-temperature side with vapour compression system at the low-temperature side using R-1234yf. The system can be used to produce quite a low temperature of the range 223.15 K -263.15 K. Parametric investigation has been done. The analysis depicts the effect of generator absorber and evaporator temperature. It is found that COP and second law efficiency are higher for the triple effect cascade system (Agarwal, S. et al., 2019). A model is produced to design a vapor compression refrigeration system for different refrigerants. Volumetric and global efficiency curves have been plotted for commercial systems. An optimization system is also used to reduce the geometric structure of the system. The analysis shows that the system with R-290 gives higher exergy efficiency for a certain range of evaporator and condenser temperatures (de Paula, C. H.et al., 2020). An exergy analysis was performed where R-1234yf and R-1234ze were tried as replacement of R-134a in a two evaporator vapor compression system. Computer code was developed using EES (Engineering Equation Solver) software package system. The effect on exergy destruction and exergy efficiency with evaporator and evaporator temperature were investigated. R-1234yf and R-1234ze were found to be strong replacements of R-134a (Yataganbaba, A. et al., 2015). Laws of thermodynamics and finite time-temperature difference heat transfer theory were applied on a vapor compression system using R-22, R-134a, R-410a, and -717 as refrigerants. Effect of subcooling and superheating was also observed (Yang, M. H., & Yeh, R. H. 2015). A commercial vapor compression system is compared with a vapor compression –absorption integrated refrigeration system using energy, exergy, economic, and environmental principles. The thermo-economic study depicts that the annual cost of the plant is less for an integrated system (Jain, V., Sachdeva, G. and Kachhwaha, S. S. 2015). A theoretical instigation of a multi-stage vapor compression refrigeration has been done. In this work conjugate directions method was used for optimization. Sub-cooling, super-heating, evaporator temperature, and condenser temperature were considered as variables, and COP is maximized. Eight refrigerants were compared and COP was found to be maximum for ammonia and minimum for R-407 (Baakeem, S. S. et al., 2018). Energy analysis to find out the alternatives of R-134a was done. Exergy destruction was calculated for compressor, evaporator, etc. It was found that the maximum exergy destruction takes place in the compressor. R-513a was found to be better than R-134a (Mota-Babiloni, A. et al., 2018). Exergy destruction calculations have been done using entropy generation. It was found that evaporator and condenser temperatures have a significant effect on exergy destruction. The effect of sub-cooling and super-heating was also studied (Arora, A. et al., 2007). An energy and exergy analysis of a vapor compression system was done using hydrocarbons as a refrigerant. Thermodynamic equations have been solved using EES package (Bayrakçi, H. C. and Özgür, A. E. 2009).

OBJECTIVES

The main objectives of the present study are:

1. To compare the properties of refrigerants R-134a and R-600a.
2. To determine the exergy destruction in the prominent components of the vapour compression refrigeration system.

3. To assess the performance measuring parameter, coefficient of performance (COP), and second law efficiency of the vapour compression system.

Table 1 Properties of R-134a and R-600a

Property	**R-134a**	**R-600a**
Chemical formula	CF_3CH_2F	$(CH3)_3CH$
Molar mass	12.03 g/mol	58.12 g/mol
Boiling point	246.8 K at atm pressure	260-264 K at atm pressure
Freezing point	169.8 K at atm pressure	114 K at atm pressure
Crtical point temperature	371.21 K	407.17 K
Crtical point pressure	40.59 bar	36.29 bar
Crtical point density	511.89 kg/m^3	225.5 kg/m^3
Ozone Depletion Level	0	0
Global Warming Potential	1200	3
Latent heat of vaporization	214.8 kJ/kg at atm pressure	362.6 kJ/kg at atm pressure
Specific volume	0.19 m^3/kg at atm pressure	0.353 m^3/kg atm pressure

COMPARISION OF AFOREMENTIONED REFRIGERATNS

There is no ideal refrigerant which can be called the best refrigerant or a refrigerant which is suitable for all refrigeration and air-conditioning applications. Therefore the properties of a refrigerant make it suitable for a particular application. Currently, R-134a is the refrigerant used in domestic refrigerators. Properties of R-600a also make it suitable for the same application. A comparison of the properties of these refrigerants is mentioned in table 1.

The boiling point of a refrigerator should be less at atmospheric pressure. In this comparison R-134a has a low boiling point i.e. 246.8 K. Freezing point of the refrigerant should be much below the evaporator temperature. R-600a has a very low free freezing point i.e. 114 K. The Critical temperature of a refrigerant should be much higher than condensing temperature otherwise the system consumes excessive power. R-600a has 407.1 K critical temperature which is higher than that of R-134a. Both the refrigerants have zero ozone layer depletion potential (ODP). Global warming potential (GWP) is a crucial criterion to select a refrigerant. GWP is almost nil for R-600a. It gives the upper hand to R-600a. The latent heat of vaporization must be high at the evaporator temperature. It results in a higher refrigeration effect per kg. of refrigerant flow per ton of refrigeration. If it is compared at atmospheric pressure, R-600a is found more suitable. Specific volume indicates compressor displacement. R-600a has a high specific volume. Since R-600a (Isobutane) is a hydrocarbon, therefore, it is a flammable substance. Both the refrigerants are non-toxic.

With this discussion, it found that R-600a do have properties to make it an alternative of R-134a. The thermodynamic analysis further confirms this claim.

THERMODYNAMIC ANALYSIS OF VAPOR COMPRESSION REFRIGERATION SYSTEM

To perform first law and second law analysis of this vapour compression refrigeration system following assumptions have been made.

1. Pressure losses occurring in the pipelines are negligible.
2. Changes in kinetic energy and potential energy are negligible.
3. Power consumptions in the condenser fan and evaporator fan are negligible.
4. Observations have been taken at steady-state conditions.

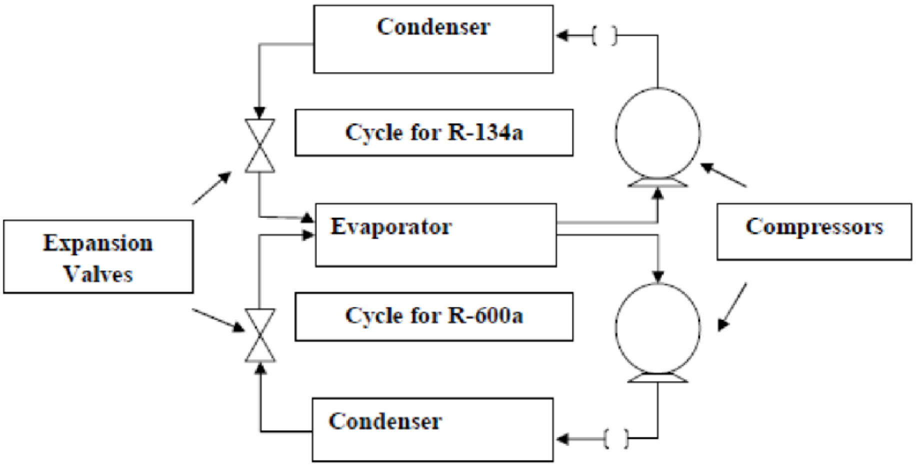

Figure 1 Line diagram of experimental set up.

Fig (1) shows the line diagram of the experimental set up. Subscripts 1, 2, 3, and 4 in the ongoing discussion represent the state of refrigerant at suction to compressor, discharge from compressor, outlet from condenser, and entry to evaporator respectively.

First law analysis using steady flow energy equation:

For compressor, $W_C = h_2 - h_1$

For condenser, $Q_C = h_2 - h_3$

For expansion device, $h_3 = h_4$ (isoenthalpic process)

For evaporator, $Q_R = h_1 - h_4$

Heat absorbed in the evaporator is Refrigeration effect ($RE = Q_R$)

Theoretical Coefficient of Performance, $COP = \frac{RE}{W_C} = \frac{h_1 - h_4}{h_2 - h_1}$

Second law analysis:

Exergy of a flow system can be written as:

$$\psi = (h - h_0) - T_0(s - s_0)$$

Applying this equation for the above mentioned components:

For compressor, $I_{Comp} = \psi_2 - \psi_1 = (h_2 - h_1) - T_0(s_2 - s_1)$, where $s_2 = s_1$

Considering $\eta_{mech} = 0.9$ and $\eta_{elect} = 0.9$

$$I_{Comp} = \frac{h_2 - h_1}{0.9 \times 0.9}$$

For condenser,

$$I_{Cond} = \psi_2 - \psi_3 = (h_2 - h_3) - T_0(s_2 - s_3) - Q_C\left(1 - \frac{T_0}{T_{Cond}}\right)$$

For expansion device,

$I_{Exp} = \psi_3 - \psi_4 = (h_3 - h_4) - T_0(s_3 - s_4)$, where $h_3 - h_4$

For evaporator,

$I_{Evap} = \psi_1 - \psi_4 = (h_1 - h_4) - T_0(s_1 - s_4) + Q_C\left(1 - \frac{T_0}{T_{Evap}}\right)$ Observations taken have been mentioned in table 2 and table 3.

Table 2 Observations R-134a

R-134a	**At comp. suction**	**At comp. discharge**	**At condenser. outlet**	**At evaporator inlet**
Temperature	8.3 ^{0}C	83.3 ^{0}C	44.2 ^{0}C	1.1 ^{0}C

Suction pressure = 1.1 bar

Discharge pressure = 11.37 bar

T_0 = Atmospheric temperature = 293 K

Table 3 Observations R-600a

R-600a	**At comp. suction**	**At comp. discharge**	**At condenser. outlet**	**At evaporator inlet**
Temperature	5.7 ^{0}C	63.4 ^{0}C	36.2 ^{0}C	0.2 ^{0}C

Suction pressure = 1.103 bar

Discharge pressure = 8.75 bar

RESULT & DISCUSSION

To compare R-134a and R-600a number of experiments performed on the test rig using the same mass of both the refrigerants individually i.e. 180 gm. The average values of temperature and pressure are compiled in tables 2 and 3. Using p-h charts for the above two refrigerant work input, refrigeration effect, theoretical COP, Carnot COP, exergy destruction in all major components (Compressor, condenser, evaporator, and capillary tube), and second law efficiency were determined and shown in table 4.

In this experiment, 3 kg of water was kept in the refrigerated space at an initial temperature of 40 ^{0}C. The setup was run for 40 minutes. The final temperature of the water was observed to be 6.8 ^{0}C and 4.2 ^{0}C with R-134a and R-600a respectively. This shows that the heat absorption rate in the evaporator is higher with refrigerant R-600a.

Table 4. Performance parameters

					Exergy destruction (kJ/kg)	

Refrigerant	Work Input (kJ/kg)	Refrigeration Effect (kJ/kg)	COP (Theoritical)	COP (Carnot)	Evaporator	Compressor	Condenser	Exp. Device	η_{II} (%)
R-134a	55	140	2.54	7.83	5.12	20.47	6.82	4.91	32.43
R-600a	90	280	3.11	9.13	8.33	27.62	11.16	13.26	34.07

Thermodynamic calculations show that the energy consumption is higher with R-600a but the refrigeration effect is also higher, which compensates the first observation. Theoretical COP is also higher with R-600a. Exergy destruction has been determined for the evaporator, compressor, condenser, and capillary tube. Exergy destruction is more with R-600a. This calculation shows that maximum exergy destruction takes place in the compressor. Second law efficiency is also higher for R-600a.

CONCLUSION

R-134a is the refrigerant that is currently used in all domestic refrigerators which work on vapour refrigeration systems. A comparison of the two refrigerants based on the desirable properties of a refrigerant shows that R-600a is better than R-134a. To corroborate this outcome, number of experiments were conducted. All important performance measuring parameters like work input, refrigeration effect, theoretical COP, Carnot COP, exergy destruction, and second law efficiency were determined and analyzed. The analysis shows that in all aspects R-600a is a better refrigerant to be used in refrigerators. As the global warming potential of R-600a is almost nil in comparison to R-134a, the former becomes a strong alternative of R-134a. While conducting experiments, it is also observed that the final temperature of water-cooled in the evaporator is lower with R-600a. This observation also gives the upper hand to R-600a. The market cost of R-600a is almost double of R-134a but this initial cost of the refrigerant will be compensated with the operating cost. Therefore it can be concluded that R-600a is a better choice. Exergy destruction for the major components of the system shows that the maximum destruction occurs in the compressor followed by capillary, condenser, and evaporator. The exergy destruction can be determined with variation in evaporator and condenser temperatures in the feasible range. It may help in obtaining the operating conditions in which the device will give the best performance.

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