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# Thermodynamic performance evaluation of vapour compression refrigeration systems using low GWP & Zero ODO new generation refrigerants

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## Abstract

The second law of thermodynamics infers the concept of exergy, a powerful tool for analyzing both the quantity and quality of energy utilization. It is defined as the maximum amount of work obtainable when the stream of matter is brought from its initial state to the dead state by the processes during which the stream may interact only with the environment. The exergy balance is similar to an energy balance but has the fundamental difference that, while the energy balance is a statement of a law of conservation of energy, the exergy may be looked upon as a statement of law of degradation of energy. In this paper, a comparison was considered about some characteristics of new generation low GWP value gases most of which are at the trial stage. Hydro fluoro-olefin (HFO) based refrigerants having low GWP value were investigated as alternatives to different four refrigerants used commonly in refrigerating and air conditioning systems. In the study, R1234yf and R1234ze gases were used instead of R134a; R404A; R410A were used as alternatives to R22. Refrigerants were compared in terms of their thermodynamic performances.



Keywords: HFO Refrigerants, Low GW, Fourth Generation refrigerants, Energy-Exergy analysis

### 1. Introduction

There is a universal agreement that the next generation of refrigerants needs to have zero ozone depletion and low global warming potential. This agreement is also supported by proposed legislation in various countries to enforce a shift to refrigerants with a reduced environmental impact and more energy efficient [1]. The Clean Air Act Amendments were passed by the U.S. Congress in 1990 following the Montreal Protocol in 1987. The main motivation was the development the ozone depleting potential of the chlorofluorocarbons (CFCs) and hydro- chlorofluorocarbons (HCFCs) frequently used in refrigeration systems leading to the phasing out of CFC12 .This outcomes in the effective development and implementation of HFC134a in domestic refrigeration systems and mobile air conditioning system, having similar vapour pressure and performance as that of CFC12. However, next serious global environmental problem is regarding the refrigerant is the global warming problem. In 1997, United Nations Framework Convention on Climate Change (UNFCCC), held in Kyoto, proposed 'Kyoto Protocol' to control emission of greenhouse gases including HFC's. The HFC-134a was identified as having a high global warming potential (GWP) of 1,400 and hence needs to be replaced by HFO environmentally friendly refrigerants.
To meet its global warming responsibilities and emissions reduction targets, a new legislation was passed by the EU requiring both automotive Original equipment manufacturers (OEMs) and suppliers to accept an alternative refrigerants with a GWP of 150 or less by the year 2012. The European Union's F-gas Regulation No842/2006 became law on 4 July 2006 and many of the requirements came into force on 4th July 2007. The F-Gas regulations will phase out the use of HFC-134a in automotive air conditioning systems for all new models beginning in 2011. The extensive research is being carried out to develop new low global warming potential ecofriendly refrigerants HFO-1234yf & HFO-1234ze to sustenance the refrigeration and air- conditioning industry, which has a 100 year GWP of 4 as compared to that of CO2 could be used as a "near drop-in replacement" for HFC134a, which means that the automobile manufacturers would not require to make significant alterations in the vehicle system designs

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## 2. Environmental impacts

### *2.1 Ozone Depletion Potential*

The greatest environmental effect is the destruction of the ozone layer by the chemical gases. Decrease or removal of this layer which functions as a filter against harmful ultra violet rays can damage life on earth profoundly. After the exploration of the damage caused on the ozone layer by chlorine based gases, removal of this type of gases has been planned with Montreal Protocol. ODP of R11 gas, which is in CFC group, has been accepted as 1 and used as a reference value. ODP of R22 gas, which is in HCFC group, is 0.055 [1].

### *2.2 Global Warming Potential*

Another environmental impact is high GWP value which is used to measure greenhouse effect of a gas based on its radiative properties relative to CO2 in a given time frame. The GWP of CO2 is 1 [1].Refrigerants having high GWP are not preferred since they stimulate sera gas formation and increasing global warming [13]. The GWP depends on the infrared radiation absorption of the refrigerants, gas lifetime in the atmosphere, and the selected time frame. Thus, the same gas can have different GWP for different time frames with 100 years normally used as the standard time frame Comparison of GWP values of the refrigerants used[1].

## 3. Utility of Ecofriendly HFO Refrigerants

Many factors are considered in refrigerating fluid selection. Removal of chloride and fluoride containing gases is aimed with Montreal Protocol due to ozone depletion potential (ODP). Usage of some refrigerating fluids is limited with Kyoto Protocol [1] due to their contribution to sera gas formation. However, owing to some regulations and limitations in the recent years, tendency to refrigerants having low global warming potential (GWP) has increased. Along with EU F-gas regulation, usage of gases lower than 150 GWP value has become mandatory for the vehicle air conditioning systems [2]. Obligation of low GWP value refrigerating fluid using has increased new gas search for different systems (refrigeration, air conditioning, cryogenic, etc.). In addition to low GWP value, enabling of the desired capacity with lower gas charge is important in terms of environmental effect. Despite of the production of low GWP gases for different systems, most of them are at the trial stage. Major manufacturers collaborate in this matter. The phase out process for the CFC and HCFC gases has been started due to the adverse effect of those refrigerants on the ozone layer and global warming. It is not sufficient to use gases having low GWP and ODP of zero value for decreasing sera gases. Several ecofriendly refrigerants are widely used in vapor compression refrigeration systems. Although each gas is used for different processes, R134a gas is used in small capacity refrigerators and chiller equipment generally, R404A is used in cool-store equipment, R410A is used in air conditioning equipment (cooling and heating), and R22 is used in both refrigerating and air conditioning devices. The properties of four main refrigerating fluids according to different application fields and the alternative refrigerants with low GWP values are given in Table 1. When critical temperatures and pressures of main refrigerant and alternative gases are reviewed, it is clear that the values are similar. It is seen that some of the candidate gases are mildly flammable. This property will be limiting for usage in some applications. The literature survey emphasizes that HFO-1234yf and HFO-1234ze can be a promising alternative to HFC-134a.Secondly, it has been observed that in most of the studies referred above, the analysis of the systems is based on first law of thermodynamics i.e. estimating coefficient of performance. In this study a more comprehensive exergy approach is followed, based on both first and second laws of thermodynamics. It is a powerful tool in the design and performance evaluation of the systems and allows an explicit presentation of thermodynamic processes by quantifying the effect of irreversibility occurring during the processes. Exergy balance applied to processes tells us how much of the exergy input to the system has been consumed by the system in terms of irreversibly lost. This analysis takes into account all the losses appearing in the refrigeration system, for calculating exergetic efficiency. The various parameters calculated are COP, exergetic efficiency, exergy destruction and efficiency defects. Effects of degree of sub-cooling, liquid vapour heat exchanger effectiveness and dead state temperature are also computed. At the same time, in the selection of refrigerating fluid, refrigerants with thermodynamic properties such as high vaporizing temperature and high gas density should be preferred for capacity improving and low energy consumption. Otherwise, an increase in sera gas amount can be caused indirectly as a result of high energy consumption. Considering the studies in which utilization of refrigerating fluid with low GWP value instead of available refrigerants. B.O. Bolaji and Z. Huan [2] presented natural refrigerants as the ideal, environmentally friendly refrigerants and the ultimate solution to the problems of ozone depletion and global warming. HFC refrigerants are currently the leading replacement for CFC and HCFC refrigerants in refrigeration and air-conditioning systems. However, they are equally foreign to nature like CFCs and HCFCs, consequently, strong basis for the need to embrace the use of natural refrigerants as replacement for the halocarbon refrigerants. They analyzed the potentials of various natural refrigerants and their areas of application in refrigeration and air-conditioning systems. Natural refrigerants especially hydrocarbons and their mixtures are miscible with both mineral oil used in R12 and poly-ol-ester oils used in R134a systems. With exception of ammonia, they are fully compatible with all materials traditionally used in refrigeration systems and revealed that natural refrigerants are the most suitable long time alternatives in refrigeration and air-conditioning systems. Atilla G Devecioglu Vedat Oruc [2] studied a method for enhancing the energy parameters of the refrigeration systems operating with R134a which generally presents low performance of the units. Hence, R134a was experimentally compared with HFO-based refrigerants of R1234yf and R1234ze (E) having low-GWP. Additionally, plate-type liquid to suction heat exchanger (LSHX) was utilized in order to determine its effect on the system's energy performances. The evaporation temperatures were −9, −4.5 and 0 °C while the condenser temperatures were 40, 45, and 50 °C in the experimental work. The cooling capacity and power consumption of R1234ze (E) were noticed lower, however its COP was higher compared to R1234yf. It was also figured out that COP of the system with LSHX using R1234ze (E) was better about by 3% than that without LSHX which operated with R134a. The results of the present study indicated that the presence of LSHX caused improved COP and lower power consumption of the refrigeration system. Mota-Babiloni et al. [3] theoretically investigated the efficiency values of HFO based new gases such as L40, DR-7 and R448A for the different refrigeration systems. They have stated that according to the simple transition, DR-7 has a COP value 10% higher than R404A for the evaporation and condensing temperature values of -10°C and 40°C, respectively [3]. One of the major candidates is R1234yf as a substitute for R134a used in the automotive industry. Among HFO derivative gases, it is the refrigerant commercialized first and still in use. Therefore, most of the studies on gases with HFO have focused on R1234yf and R1234ze. Atilla Gencer Devecioğlua, VedatOruça [4] compared the R1234ze (E) with the alternatives R134a. With the same perspective, the specific refrigerating effect of R1234ze (E), observed as much close to R134a and much better than R404A. It is obvious that R1234yf and R1234ze (E), refrigerants having better specific refrigerating effect in comparison to R404A. R1234yf and R513A refrigerants with less need for fluid charge and with lower liquid density can meet cooling capacity compared to R134a. The liquid density values of alternative refrigerants for R134a are also lower another variable which is one of the transport characteristics of refrigerating fluids is liquid viscosity. Low viscosity means low friction and the system can consume less energy. The variation of viscosity with temperature is demonstrated in Figure 4 for the investigated refrigerants. It is seen that the liquid viscosity of R1234yf, is lower than that of R134a. Based on this result, the new refrigerant with low GWP has lower friction in comparison to R134a. The liquid viscosity values of the refrigerants those can be used as alternatives to R404A and R410A are very close to each other. Atilla G Devecioglu Vedat Oruc [5] studied a method for enhancing the energy parameters of the refrigeration systems operating with R134a which generally presents low performance of the system and was experimentally compared R134a with HFO-based refrigerants of R1234yf and R1234ze (E) having low GWP using, plate-type liquid to suction heat exchanger (LSHX) to determine its effect on the system's energy performances. The evaporation temperatures were −9, −4.5 and 0 °C while the condenser temperatures were 40, 45, and 50 °C in the experimental work. The cooling capacity and power consumption of R1234ze (E) were noticed lower, however it's COP was higher compared to R1234yf. It was also figured out that COP of the system with plate-type liquid to suction heat exchanger using R1234ze (E) was better about by 3% than that without LSHX which operated with R134a. The results show that the presence of plate-type liquid to suction heat exchanger caused improved COP and lower power consumption of the refrigeration system. Calabrese D. Ahri [6] studied the critical point temperatures of R134a and its alternatives are very close to each other. R410A has a lower critical point temperature than that of its alternatives. Another factor affecting the cooling capacity is the mass flow rate of the refrigerant which circulates in the system. The reduction in liquid density will significantly decrease the amount of refrigerating fluid charge. In the present study, thermodynamic performances of new generation refrigerating refrigerants known as hydrofluoro-olefin, and their environmental effects were compared. Sachin Gupta [7] studied that the third-generation refrigerants belonging to hydrofluorocarbons (HFCs) do not contribute to ozone depletion. However, HFCs are listed as greenhouse gases by Kyoto Protocol because of their relatively high global-warming potential (GWP) and also found that refrigerants with zero ozone depletion potential (ODP) and less GWP, are termed as Fourth generation refrigerants. They analyzed the advancement in refrigerants, and presented the different options in choosing a refrigerant with respect to international agreements to curb the stratospheric ozone depletion and global warming. The hydrofluoroolefins (HFOs) i.e., fourth generation refrigerants are available in limited quantities and also their performance is not completely tested in different applications. Therefore they reviewed the performance of fourth generation refrigerants in terms of their mass flow rate requirement and COP for a specified cooling load and compared with the existing third generation refrigerants in use and found that fourth generation refrigerants has low COP and low mass flow rate along with high power requirements and also found that the HFO1234ze (E) can replace R134a as its performance is almost similar to R134a with an added advantage of low GWP. A.S. Dalkilic,S. Wongwises[8] studied theoretical performance on a traditional vapour-compression refrigeration system with refrigerant mixtures based on HFC134a, HFC152a, HFC32, HC290, HC1270, HC600, and HC600a for various ratios and their results are compared with CFC12, CFC22, and HFC134a as possible alternative replacements. The hydro carbon refrigerants' highly flammable characteristics, are used in many applications, Due to safety of the leakage from the system, as other HFC refrigerants in recent years are not related with any effect on the depletion of the ozone layer and increase in global warming. Han et al. [9] studied a new hydrocarbon refrigerant mixture instead of R407C for vapour-compression refrigeration systems experimentally. As a result of the experimental and theoretical analyses, their new ternary non-azeotropic mixture of R32/R125/R161, whose ODP and GWP are zero and lower than R407C respectively, showed better refrigerating capacity and coefficient of performance (COP) than R407C. Wongwises et al. [10] conducted studied on the application of hydrocarbon mixtures to replace HFC134a in automotive air conditioning system. The hydrocarbons investigated are propane (R290), butane (R600), and isobutane (R600a). Wongwises and Chimres [11] experimentally studied on the application of a mixture of propane, butane, and isobutene to replace HFC134a in a domestic refrigerator and found that a 60%/40% propane/butane mixture was the most appropriate alternative refrigerant. Hammad and Alsaad [12] investigated the performance of a domestic refrigerator using LPG (24.4% propane, 56.4% butane, and 17.2% isobutane), which is available locally in many countries, is cheap, and possesses an environmentally friendly nature with no ozone depletion potential (ODP), as an alternative refrigerant to CFC12. Jung et al. [13] used a propane/isobutane (R290/ R600a) mixture to determine their performance for domestic refrigerators. According to their thermodynamic cycle analysis, the propane/isobutane blend in the composition range from 0.2 to 0.6 mass fraction of propane yields an increase in the coefficient of performance (COP) of up to 2.3% compared to CFC12. Granryd [14] studied the possibilities and problems of using hydrocarbons as working fluids in refrigeration equipment. In spite of their flammability specification, it is shown in his paper that alternative refrigerants can be obtained by means of hydrocarbons for energy efficient and environmentally friendly refrigerating equipment and heat pumps. Han et al. [15] studied a new hydrocarbon refrigerant mixture instead of R407C for vapour-compression refrigeration systems experimentally. As a result of the experimental and theoretical analyses, their new ternary non-azeotropic mixture of R32/R125/R161, whose ODP and GWP are zero and lower than R407C respectively, showed better refrigerating capacity and coefficient of performance (COP) than R407C. Park et al. [16] studied two pure hydrocarbons and seven mixtures composed of propylene, propane, HFC152a, and dimethyl ether as an alternative to HCFC22 in residential air-conditioners and heat pumps. Their experimental results show that the coefficient of performance (COP) of these mixtures is up to 5.7% higher than that of HCFC22. Mani and Selladurai [17] conducted experiments using a vapour-compression refrigeration system with the new R290/ R600a refrigerant mixture as a substitute refrigerant for CFC12 and HFC134a. According to the results of their experiments, the refrigerant R290/R600a had a refrigerating capacity 19.9% to 50.1% higher than that of R12 and 28.6% to 87.2% than that of R134a. The R290/R600a blend's performance coefficient (COP) is improved by 3.9–25.1% compared to that of R12 at lower evaporating temperatures and by 11.8–17.6% at higher evaporating temperatures. The refrigerant R134a had a slightly lower coefficient of performance (COP) than R12. Chen and Yu [18] presented a new refrigeration cycle, introduced as an alternative refrigeration cycle applied in residential air-conditioners, using the binary non-azeotropic refrigerant mixture R32/R134a. As a result of the comparison between the conventional cycle configuration and the new one, the coefficient of performance (COP) increases by 8% to 9% compared to the conventional system, and the volumetric refrigerating capacity is increased 9.5% approximately. Reaser et al. [19] compared the thermophysical properties of HFO-1234yf with HFC-134a and R410a for finding the drop-in replacement potential of HFO-1234yf and concluded that properties were similar to that of HFC-134a and not similar to that of R410a. Zang et al. [20] established the non-azeotropic mixtures composed of HFOs (HFO-1234yf, HFO-1234ze(e), HFO-1234ze(z) and HFO-1234zf) as a replacement of HFC-134a and CFC-114 in air-conditioning system and high temperature heat pump system and investigated theoretical performance and found that COP of mixture of HFO-1234zf/HC-290 (60%/40% in mass) was 1.5% higher than that of HFC-134a, thus a good substitute in air conditioning system. Similarly Leighton et al. [21] theoretically observed that HFO-1234yf had 9% lower COP and 6% less capacity thanHFC-134a and also showed HFO-1234ze had 8% higher COP and 21% lower capacity than HFC-134a. Abdel Aziz et al. [22] experimentally evaluated and compared the performance of HFC-134a to HFO-1234yf and HFO-1234ze, and concluded that HFO-1234yf had 2.7% higher energy consumption than HFC-134a, indicating that HFO-1234yf is a suitable drop-in replacement of HFC-134a in domestic refrigerators. While HFO-1234ze had16% lower energy consumption than HFC-134a, hence to replace HFC-134a with HFO-1234ze lower capacity refrigerators were required, thus HFO-1234ze might not be suitable for drop-in replacement. Esbri, et al. [23] experimentally analysed HFO-1234yf as a drop-in replacement for HFC-134a in a vapour compression system and summarized as, the cooling capacity of HFO-1234yf is about 9% lower than that ofHFC-134a, which diminishes with the use of internal heat exchanger. Volumetric efficiency was about 5% less than that obtained with HFC-134a. Jung, et al. [24] evaluated the performance of HFO-1234yf and HFO-1234yf/HFC-134a mixture in three compositions and drawn the results that COP, capacity and discharge temperature of HFO-1234yf and mixture of refrigerants are similar to those of HFC-134a, with decrement in flammability as the content of HFC-134a increases.

## 4. Conclusion

Following conclusions were drawn from present investigations [25]. In the selection of HFO refrigerants of low GWP consideration, gives better energy characteristics Although they have some differences in terms of energy parameters such as first law efficiency in terms of COP, Second law efficiency in terms of exergetic efficiency and exergy destruction ratio based on exergy of fuel (i.e. total power required to run the compressor) used in the first and second law analysis, it can be stated that R1234yf, and R1234ze refrigerants can be good alternatives to R134a, R404A, R410A and R22, respectively.

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