

Exergetic analysis of low gram nano-refrigerant charge for transport application

Luke Onyekwere Ajuka ^{1,*} and Kamilu Moradeyo Odunfa ²

¹ Department of Automotive Engineering, University of Ibadan, University of Ibadan, Ibadan, Nigeria.

² Department of Mechanical Engineering, University of Ibadan, University of Ibadan, Ibadan, Nigeria.

Global Journal of Engineering and Technology Advances, 2022, 12(03), 016–024

Publication history: Received on 25 July 2022; revised on 07 September 2022; accepted on 09 September 2022

Article DOI: <https://doi.org/10.30574/gjeta.2022.12.3.0128>

Abstract

Limited gram charge is beneficial in transport refrigeration by sustenance of flammability limits for safety. Herein, an experimental investigation of 0.11 vol. % of titanium IV oxide doped with 30 g each of R600a and LPG as R_{600aAl2O3} and LPG_{Al2O3} nano-refrigerants were retrofitted into a 102g R134a vapour compression refrigerating system. At steady state, the performance of the system using unblended R134a, R600a, LPG refrigerants, R_{600aAl2O3} and LPG_{Al2O3} nano-refrigerants were examined as a function air evaporator temperature and compressor characteristics; discharge pressure, power consumption, compressor exergetic defect, coefficient of performance and exergetic efficiency. At 80g charge, R600a, LPG, R_{600aAl2O3} and LPG_{Al2O3} had higher COP; Exergetic efficiency; but lower Total exergetic defect of 2.9, 11.3, 9.7 and 14.1%; 19.4, 22.1, 31.8 and 29.4%; and 34.1, 43.6, 56.3 and 58.6% than R134a. R134a has higher discharge pressure of 0.25, 0.12, 0.77 and 0.84 Psia/ 0.77, 0.12, 0.84 and 0.25 Psia; higher power consumption of 14.79, 12.23, 27.83 and 26.51 Watts; higher compressor exergetic defect of 0.03, 0.03, 0.06 and 0.04 Joule, lower coefficient of performance of 0.06, 0.23, 0.71 and 1.18; and lower exergetic efficiency of 0.012, 0.008, 0.056, 0.062 Joule than R600a, LPG, R_{600aAl2O3}, LPG_{Al2O3}. motor compression work of unblended R134a refrigerant is higher than unblended R600a, unblended LPG_{Al2O3} blended in R600a and LPG by 15.28%, 16.08%, 37.73% and 40.43. All the selected refrigerants met the chill compartment temperature, ISO 8187 compartment standard of $-2 \leq t_{cc} \text{ min}$, $\text{max} \leq +3$, while R_{600aAl2O3} and LPG_{Al2O3} nano-refrigerants showed improved compressor characteristics.

Keywords: Transport refrigeration; Flammability limits; Nano-refrigerants; Discharge temperature; Power consumption; Coefficient of performance

1. Introduction

Transport refrigeration exists across refrigerated trucks and vans to refrigerated containers and reefers (refrigerated cargo ships for temperature-sensitive goods), comprising condenser, compressor, expansion valve. Optimal refrigeration cycle is achievable by minimization of irreversibility in system components by the use of exergy method. Exergy analysis gives information on how, where and how much system performance is degraded and the potential for improvement unlike the energy analysis. Several studies on the use of nanoparticles in conventional lubricant and refrigerant enhancements have been conducted, and some are reported. The concept of blending conventional fluids with nanoparticles has been reported to possess great benefits [1]. These includes enhanced solubility of the lubricant and the refrigerant, improvement in the heat transfer characteristics of the refrigerant/lubricant, and reduction in the frictional coefficient and wear rate of the nano-lubricant. Several researches have been conducted on the use of nanoparticle in to improve performance of refrigeration [2], and some of them includes Wang et al. [3] investigated the solubility of appended N- Al₂O₃ in a mineral lubricant using R134a in refrigerating system. They reported that the mineral oil appended with Al₂O₃ nanoparticle returned more lubricant oil back to the compressor indicating better solubility, and had similar performance compared to systems of polyol-ester lubricant and R134a. Examination of the

* Corresponding author: Luke Onyekwere Ajuka
Department of Automotive Engineering/Faculty of Technology, University of Ibadan, Ibadan, Nigeria.

viscosity effect of TiO_2 and Al_2O_3 blended into capella mineral oil and ethylene glycol lubricant was examined by Ajuka et al., [4]. They noted that at 0.0025g/ml, both TiO_2 and Al_2O_3 nanoparticle blends in capella mineral oil were less viscous by 9.7 and 2.98%, while the nanoparticle blends were less viscous by 14.1 and 7.1% than unblended ethylene glycol. Thermal conductivity measurement and modeling of carbon nanotube (CNT) R113 nano-refrigerants by Jiang et al. [4], reported an improved 82%, 104%, 43% and 50% on the measured thermal conductivities of four sets of 1.0 vol.% of the CNT-R113 nano-refrigerants. The boiling heat transfer characteristics experimental examination of Al_2O_3 nanoparticles dispersed in R22 refrigerant as reported by Wang et al. Wang et al. [6] showed a reduction in bubble size and its rapid move towards the heat transfer surface. They concluded that nanoparticles can enhance heat transfer characteristic of the refrigerants. The pool boiling heat transfer of the R11 refrigerant blended with Al_2O_3 -nanoparticles at particle loading up to 0.01 g/L was investigated by Wu et al. [7]. They reported that the heat transfer enhancement was up to 20%. The migrated mass characteristics of nanoparticles in the pool boiling process of both nano-refrigerant and nano-refrigerant– oil mixture was examined by Ding et al. [8]. They reported that the nanoparticle migrated mass and nano-refrigerant migration ratios were larger than the nano-refrigerant–oil mixture. The dispersion behavior, thermal conductivity and flow boiling heat transfer of Al_2O_3 -R134a nano-refrigerant in a domestic refrigerator was conducted by Bi and Shi [9]. They reported to have added nanoparticles to lubricant to form nano-lubricant, and then added the mixture in the compressor as lubricant. In another experimental investigation, Bi and Shi reported to have blended nanoparticles and refrigerants together simultaneously to have nano-refrigerant [10]. They reported that both concept of nanoparticle addition gave better performance in the refrigerator. An energy and exergy analysis of a refrigeration system with vapor injection using reciprocating piston compressor was carried out by Tang et al. [11]. They modified a reciprocating piston compressor by building a vapor injection device and reported that the intermediate injection system can minimize exergy loss in the system and expand the application range of reciprocating piston compressor. The study by Bi et al. [12] on the performance of Al_2O_3 -R600a nano-refrigerant considered Al_2O_3 -R600a nano-refrigerant in a household refrigerator with no system reproduction. They reported that the coefficient of performance was higher to the unblended R600a-based system, with 9.6% less energy utilized with 0.5 g/L Al_2O_3 -R600a nano-refrigerant. They inferred that the consequences of the energy utilization and the freeze limit test demonstrate that Al_2O_3 -R600a nano-refrigerants worked typically and securely in the fridge, subsequently, idealized that the utilization of Al_2O_3 -R600a nano-refrigerant in residential refrigerator is practicable. Considering the various researches that has been mentioned, none to the best of the authors knowledge has considered the exergetic effect of limited refrigerant charge with emphasis on compressor parametric performance using Al_2O_3 nanoparticles.

1.1. Statement of problem

Refrigeration of vehicles in motion needs to consider possibilities of cutting down on refrigerant charge percentage (limited charges) especially for flammable refrigerants like hydrocarbons, while hoping to achieve expected refrigerating rational (exergetic) efficiency, low volume hydrocarbon (HC) charge far less than 0.1kgm^{-3} of HC lower flammability limit (LFL) erases the potential of flammability particularly when there are no leaks, according to ASHRAE Standard 34 and ISO 817. There are no reports from literature establishing the limits within which a low charged compressor gives unique acceptable performance before standard refrigerant recharge.

1.2. Aim and Objectives

The aim of this paper is to investigate the chill compartment temperature (tcc) performance of selected low volumetric charge of Alumina hydrocarbon and compressor associated exergy performance of nano-refrigerant against $-2 \leq \text{tcc} \leq +3$ ISO standard as can be applied in transport refrigeration. The specific objectives are to utilize R600a, LPG, $\text{R600a}_{\text{Al}_2\text{O}_3}$, $\text{LPG}_{\text{Al}_2\text{O}_3}$ and R134a refrigerant to evaluate the

- Power consumption
- Discharge pressures
- COP, Exergetic defects and Efficiencies

Of the vapour compression refrigeration system.

2. Material and methods

A typical domestic refrigerator running on capella oil was used in this study.

2.1. Rig set-up and Experimentation

In this study, a 48 Litre refrigerator test rig with a single door, evaporator cabinet, compressor, condenser, expansion valve and a capillary tube at no load condition using R134a was retrofitted with 30 g mass charges of LPG and R600a

refrigerants in Al_2O_3 nano-lubricant. Using the two-step method, the 0.11 vol.% nano-lubricant (mixture of nanoparticle and capella oil) was thoroughly homogenized with an ultrasonic vibrator (Branson M2800H) and the mixture was observed for 48 hours to examine coagulation or sedimentation before experimentation. As shown in the Figure 1, the temperatures and pressures at state points 1- 4 as T_1, T_2, T_3, T_4 and T_{air} were measured according to ISO 8187 chill compartment temperature standard of $-2 \leq tcc \text{ min, max} \leq +3$ using type K thermocouples as well as the suction and discharge pressures P_1 and P_2 using pressure gauges and recorded. The test was carried out using 30 g charge for each refrigerant: unblended R134a, R600a, LPG (50/50 Propane-Butane), $R600a_{Al_2O_3}$, $LPG_{Al_2O_3}$. The system compressor was flushed with unblended capella oil after each test to avoid leftover nanoparticle interaction while sigma B-42: ¼ HP Vacuum pump was utilised in the extraction of pent refrigerant after each trial. The schematic and pictorial diagrams of the system and materials are given in Figures 1 and 2, the specifications of the test unit, measurement ranges and the uncertainty of the measuring instrument are shown in the Table 1 below;

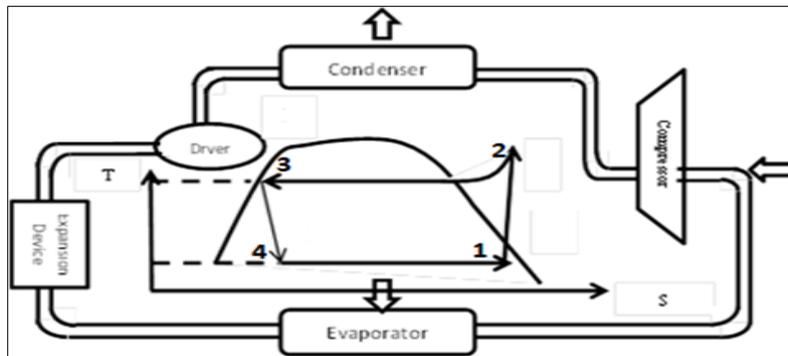


Figure 1 The schematic temperature-entropy embedded in a schematic diagram for a vapour compression refrigerating system



Figure 2 Pictorial view of experimental materials

Table 1 Characteristics of the refrigerating system

S/N	Characteristics	Specifications/Units	Uncertainty
1	Evaporator volume	48 Litres	
2	Refrigerant/ Lubricant type	R600a, LPG, R134a/Capella oil	
3	Compressor (220-240, 60Hz)	Reciprocating type	
4	Evaporator	Cross flow fin heat exchanger	
5	Condenser	Air cooled	
6	Expansion Device	Capillary tube	
7	Power (Digital watt-hour meter)	0 -5000w	±0.1%

8	Pressure (Pressure Gauge)	0 – 2500Kpa	±0.1%
9	Temperature (Thermocouple)	-50- (100) °C	±0.1%
10	Lubricant: ISO Viscosity Grade	68	
11	Density at 15oCkg/L	0.91	
12	Flash point	-36 °C	
13	Kinematic viscosity (mm2/s) at 40oC	68	
14	Kinematic viscosity (mm2/s) at 100oC	6.8	
15	Viscosity index	22	
16	Nanoparticle: Titanium dioxide	15nm, 99.7% purity (TiO ₂)	
17	Density	0.26g/cm ³	
18	Molecular weight	79.87 gmol ⁻¹	

2.2. Experimental Analysis

The thermodynamic properties of the selected refrigerants which were recorded were determined using NIST REFProp 9.1 according to Lemmon et al. [13]. The results were then used to determine the intended performance characteristics which equations are given below:

Volume fraction of nanoparticle in nano-lubricant is given by Φ_n ;

$$\Phi_n = \frac{m_n / \rho_o}{m_n / \rho_n + m_n / \rho_o} \dots\dots\dots (1)$$

Where m_n, ρ_n, ρ_o are the nanoparticle mass, density and oil density.

Electrical Power;

$$W_{el} = \frac{W_c}{\eta_{mech} \times \eta_{el}} \dots\dots\dots (2)$$

An expression of mass, energy and exergy is given by [14]:

$$\sum Ex_{in} - \sum Ex_{out} = \sum Ex_{def} \dots\dots\dots (3)$$

Exergy of refrigerant at any state:

$$E_{x, ref} = (h - h_0) - T_a \times (S - S_0) \dots\dots\dots (4)$$

Compressor Exergy defect (net):

$$C.M.E.D/Ex, d, com = m_r \times (h_2 - h_2) - T_a \times (S_1 - S_2) + W_{el} \dots\dots\dots (5)$$

Exergy defect due to air-cooled compressor motor [15]:

$$E_{motor} = P_{comp} \times \left[\frac{(1 - \eta_{motor})}{\eta_{motor}} \right] \dots\dots\dots (6)$$

Evaporator Exergy defect:

$$E_{x, d, ev} = m_r \times [(h_4 - h_1)T_a \times (s_4 - s_1)] + Q_{ev} \left(1 - \frac{T_a}{T_r} \right) \dots\dots\dots (7)$$

Condenser Exergy defect:

$$E_{x,d,con} = m_r \times [(h_2 - h_3) + T_a \times (S_2 - S_3)] + Q_{ev} \left(1 - \frac{T_a}{T_{con}}\right) \dots\dots\dots (8)$$

Exergy defect within (net) Capillary tube:

$$E_{x,d,cap} = m_r \times T_a (S_2 - S_3) \dots\dots\dots (9)$$

Total Exergetic defect within the system (Ex, tol, d):

$$Ex, tol, d = E_{x,d,com} + E_{x,d,ev} + E_{x,d,con} + E_{x,d,cap} \dots\dots\dots (10)$$

Exergetic Efficiency of the system:

$$E_{,eff} = 1 - \frac{E_{x,tol,d}}{W_{el}} \dots\dots\dots(11)$$

Where E_{in} , E_{out} , W_{el} , W_c , η_{motor} , Φ_n , T_a , com , con , ev , cap represents exergy in, exergy out, electrical work, compressor work, motor efficiency, volumetric percentage, ambient temperature, compressor, condenser, evaporator, capillary tube, respectively.

2.3. Data presentation

The result of coefficient of performance (COP), exergetic efficiency (Ex. Eff.) and total exergetic defect (T.E.D) using 80 g charge of LPG, $LPG_{Al_2O_3}$, R600a, $R600_{Al_2O_3}$ and R134a are given in the Table 2 below. It can be inferred that R134a had the least COP and Ex. Eff. But highest T.E.D. value. Total exergetic defect is the sum total of exergetic defects in the compressor, condenser, expansion device and the evaporator. The effect of titania nanoparticle is also seen.

Table 2 Exergetic Performance of 80 g charge

Sr. No.	Refrigerants (80g)	COP	Ex. Eff.	T.E.D
1	LPG	2.5395	0.2769	0.4235
2	$LPG_{Al_2O_3}$	2.6217	0.3055	0.38356
3	R600a	2.3196	0.2675	0.4536
4	$R600_{Al_2O_3}$	2.4929	0.3164	0.3893
5	R134a	2.2519	0.2157	0.6083

3. Discussion of findings

The result of the experiment investigating the compressor associated exergy performance using unblended LPG, R600a and blend of Al_2O_3 on each ($R600a_{Al_2O_3}$ and $LPG_{Al_2O_3}$) are discussed below;

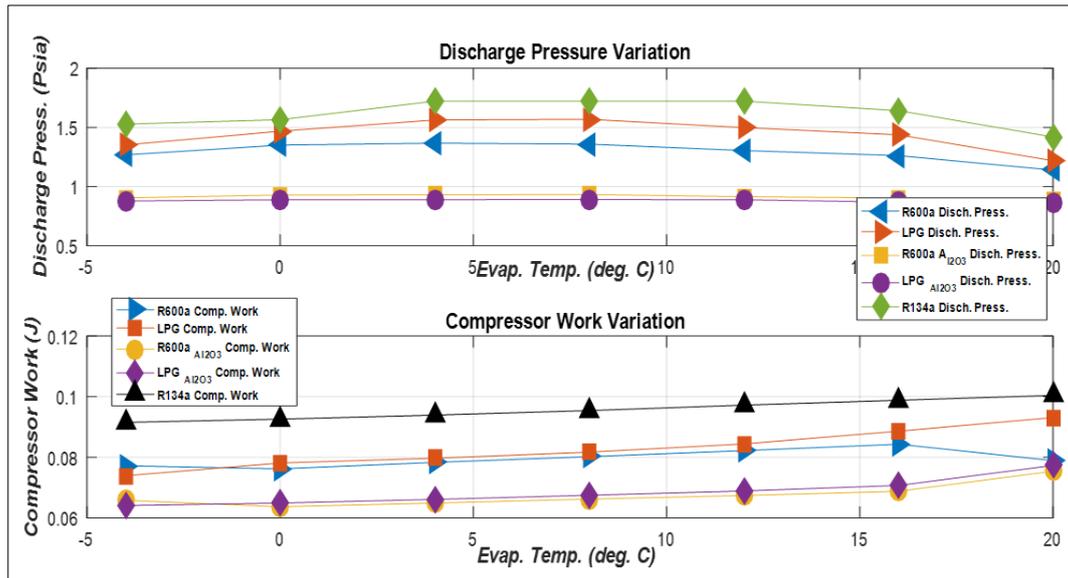


Figure 3 Variations of Discharge Pressure and Compressor Work with Temperature

3.1. Discharge Pressure

Compressor discharge pressure is a function of the performance of the refrigerating system’s mean temperature difference. In the discharge pressure variation graphical illustration shown in Figure 3, the discharge pressure of unblended R134a (baseline) refrigerant is 3.0%, 3.0%, 6.01% and 4.2% higher than that of unblended R600a, unblended LPG, R600a_{A1203}, LPG_{A1203}. Since the size of the discharge line is unchanged for all the refrigerants, it can be concluded that at low volume of refrigerants, there was lower percentage variation in the baseline discharge pressure and the selected refrigerants.

3.2. Compressor Work

The compressor work for the refrigerants as a function of evaporator air temperature is given in Figure 3. The compressor work of unblended R134a is higher than unblended R600a, unblended LPG, R600a_{A1203}, LPG_{A1203} by 18.3%, 15.6%, 41.9% and 39.7%, respectively. There is a slight increase in compressor work with increase in Evaporator air temperature.

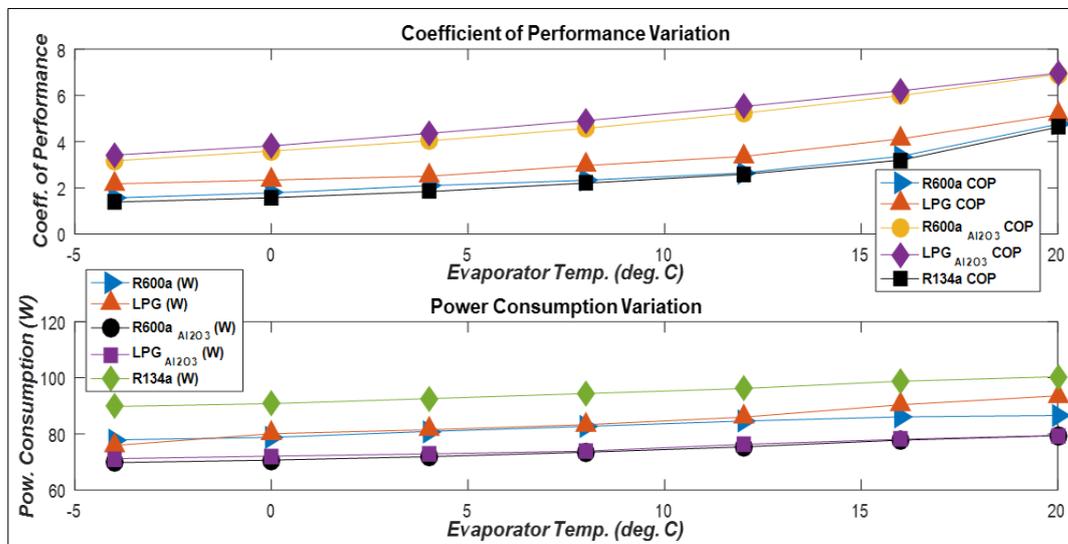


Figure 4 Variations of Coefficient of Performance and Power Consumption with Temperature

3.3. Coefficient of Performance (COP)

Coefficient of Performance of R134a refrigerant was lower than unblended R600a, unblended LPG, Al₂O₃ blended in R600a and LPG by 6.01%, 12.04%, 48.02% and 50.5% as shown in the Figure 4 with varied evaporator air temperature. The entire selected refrigerant had similar trend as the figure shows that COP increased with increase in evaporator temperature.

3.4. Power Consumption (P_{con})

Figure 4 also gives the mean power consumption of R600a, unblended LPG, R600a_{Al2O3}, LPG_{Al2O3} and R134a are 82.5W, 84.4W, 74.1W and 74.9W. These shows that the power consumption by R134a was higher than unblended R600a, unblended LPG, R600a_{Al2O3}, LPG_{Al2O3} by 14.79%, 12.23%, 27.83% and 26.51%, respectively. The power consumption increased with increasing evaporator air temperature.

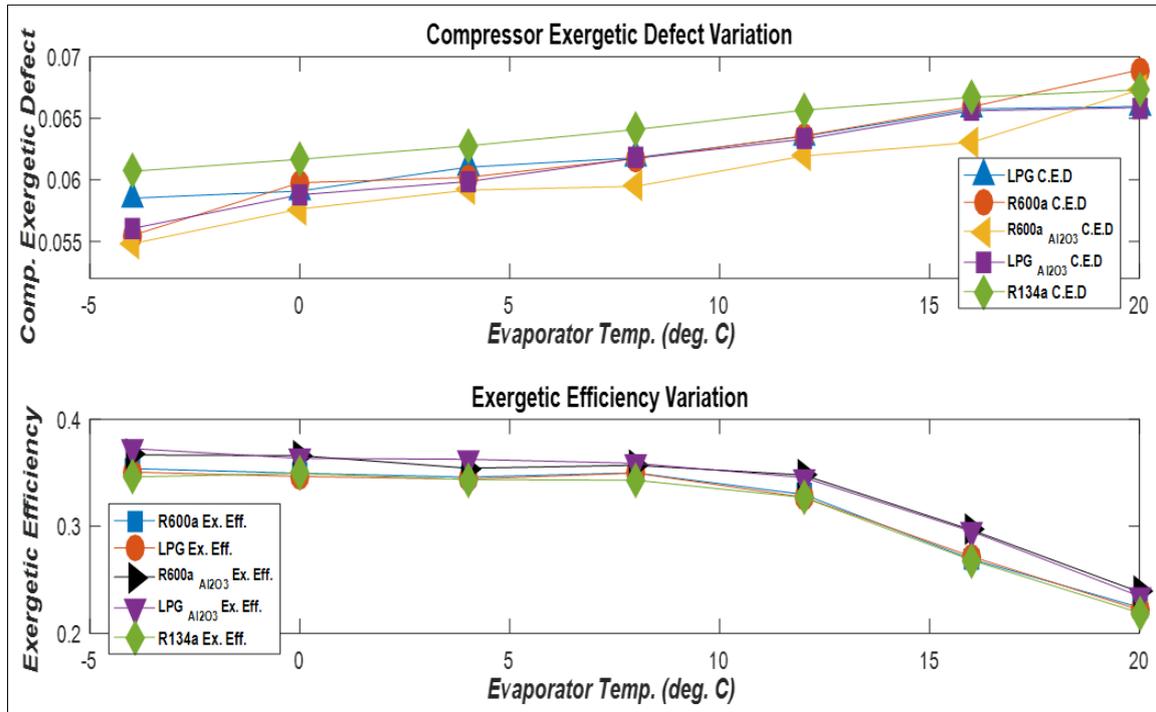


Figure 5 Variations of Compressor Exergetic Defect and Exergetic Efficiency with Temperature

3.5. Compressor Exergetic Defect (C.E.D)

The Figure 5 shows that the Compressor exergetic defect increases as evaporator temperature increases. Unblended R134a showed the highest compressor defect and the least exergetic defects were LPG and R600a blended with Alumina. This may be due to the transport properties nanoparticle.

3.6. Exergetic Efficiency (Ex. Eff.)

Figure 5 also shows the exergetic efficiency of unblended R134a and hydrocarbons were the least and had close value, whereas the effect of alumina nanoparticle was observed in the LPG and R600a blends which had the highest exergetic efficiencies.

3.7. Compressor motor exergy defect (c.m.e.d/ex_{c, motor})

Figure 6 below is a representation of the defect of compression work in the compressor (Ex_{c, motor}) for the refrigerants. It can be inferred that the highest work of compression is done in the system when unblended R134a refrigerant is used and the least work was done with LPG (Al₂O₃) refrigerant. The work of motor compression of unblended R134a refrigerant is higher than unblended R600a, unblended LPG, Al₂O₃ blended in R600a and LPG by 15.28%, 16.08%, 37.73% and 40.43%, respectively. Work of compression decreased with increase in motor efficiency and it can be concluded that the nano-refrigerants reduced the compression work since the unblended refrigerants had higher

associated exergy defect due to work of compression. This may be due to the unique transport properties of the Al_2O_3 nanoparticle.

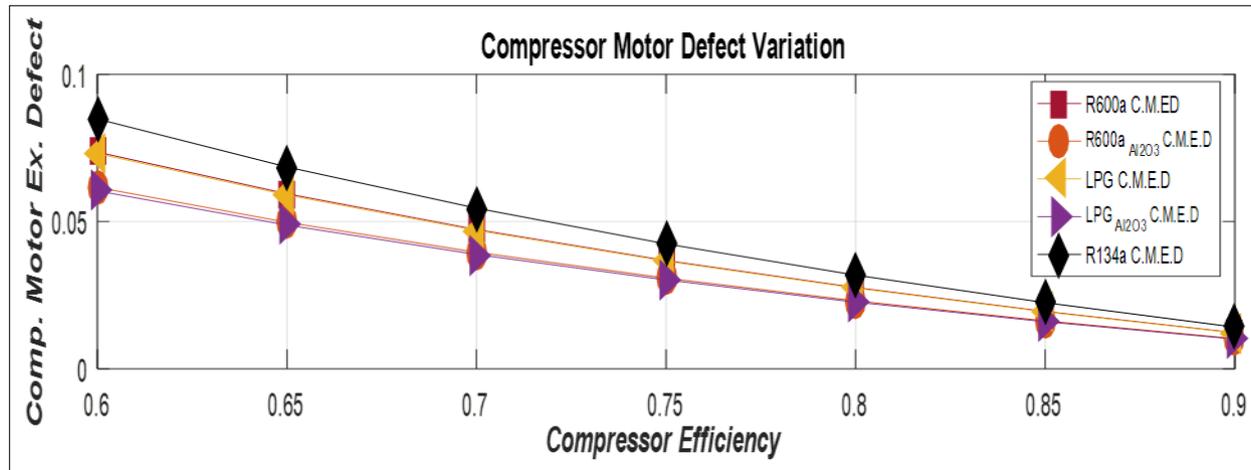


Figure 6 Variations of Compressor Motor Exergetic Defect with Compressor Efficiency

4. Conclusion

Technically, transport refrigeration involves some motion of refrigerant in the compressor during navigation. This puts such vehicles at higher risk when flammable refrigerants are used. Limited refrigerant charges, energy savings and better cooling is essential without affecting the environment. Exergetic investigation of the impact of low volume (30 g) refrigerant charge using capella oil was carried out and the following were deduced:

- The 30 g refrigerant charges worked normally and efficiently in the refrigerating system with all the refrigerants reaching the $-2 \leq \text{tcc min}$, $\text{max} \leq +3$ ISO standard, with higher COP record of 6.1% and 23.3% using unblended R600a and LPG, and 48.02% and 50.5% using R600a_{Al2O3} and LPG_{Al2O3} when compared to the R134a refrigerant.
- There was energy savings within the range 27.8% and 26.5 using R600a_{Al2O3} and LPG_{Al2O3} nano-refrigerants.
- The nano-refrigerants operated at lower discharge pressures compared to unblended R134a which is a benefit for the compressor life.

The COP, exergetic efficiencies and energy savings attributed to the nano-refrigerants may be due to better heat transport of particle/ particle surface area, lesser compressor work from the alumina nanoparticle.

Contributions to knowledge

In light of the study, the following recommendations are suggested:

- Alumina hydrocarbon nano-refrigerants meets ISO standard, even, at lower charge rate.
- Energy savings of alumina nano-refrigerant is not limited to only high charge rates.
- Service life of nano-refrigerant charged compressor should be higher due to lesser discharge pressure.
- R134a low gram charge is not recommended for use in VCRS (Incorrect refrigerant), otherwise;
- Utilizing lower gram charges of R134a: Installation of compound Cut-out to limit the upper and lower pressure limits.

Compliance with ethical standards

Acknowledgments

The authors appreciate the technical staff of the refrigeration and air-conditioning laboratory, faculty of Technology for their efforts.

Disclosure of conflict of interest

There authors will like to state that there is no conflict of interest whatsoever regarding this research manuscript.

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