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Heat transfer enhancement in domestic refrigerator using R600a/mineral oil/nano-Al_2O_3 as working fluid

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ABSTRACT

The experimental apparatus was build according to the national standards of India.. The performance of the refrigeration system depends upon the heat transfer capacity of the refrigerant. Normally R12, R22, R600, R600a and 134a are used as a refrigerant. This refrigerant heat transfer capacity is not so good and increase power consumption. Due to these limitation nanofluids are enhanced with the normal lubricant and increases the heat transfer capacity and reduces the power consumption. Aluminium oxide nanofluid is used for enhancing the heat transfer capacity of the refrigerant in the refrigeration System. In this experiment heat transfer enhancement was investigated numerically on the surface of a refrigerator by using Al2O3 nano-refrigerants, where nanofluids could be a significant factor in maintaining the surface temperature within a required range. The addition of nanoparticles to the refrigerant results in improvements in the thermophysical properties and heat transfer characteristics of the refrigerant, thereby improving the performance of the refrigeration system. Stable nanolubricant has been prepared for the study. The experimental studies indicate that the refrigeration system with nano-refrigerant works normally. It is found that the freezing capacity is higher and the power consumption reduces by 11.5 % when POE oil is replaced by a mixture of mineral oil and Aluminium oxide nanoparticles. Thus using Aluminium oxide nanolubricant in refrigeration system is feasible.

Key words: *Aluminium oxide nanoparticle, nano-refrigerant, Thermal conductivity, freezing capacity COP, Energy consumption.*

List of symbols

Symbol	Description	Unit
Nomenclature		
A	Cross sectional area	m^2
C_p	Specific heat	J/Kg k
D	Diameter	m
h	Enthalpy	KJ/Kg
h_{fg}	Latent heat of vapourisation	w/m k
K	Thermal conductivity	w/m k
m	Mass flow rate	Kg/s
T	Temperature	° C
v	Velocity	m/s
Greek symbols		
σ	Surface tension	N/m
ρ	Density	Kg/m^3
μ	Dynamic viscosity	Kg/ms
ω	Nanoparticle concentration in the nanoparticle oil suspension	
ψ	Volume fraction of nanoparticle in the nanoparticle/oil suspension	
Subscripts		
f	liquid	
g	gas	

n	nanoparticle
o	oil
r	refrigerant
n,o	nanoparticle and oil
r,o	refrigerant and oil
r,n,o	refrigerant, nanoparticle and oil
Abbreviation	
HTC	Heat transfer coefficient
TR	Tonne of refrigeration
COP	Coefficient of performance
HRF	Heat rejection factor
COP	Coefficient of performance
TR	Tonne of refrigeration

I. INTRODUCTION

It is true that rapid industrialization has led to unprecedented growth, development and technological advancement across the globe. It has also given rise to several new concerns. Today global warming and ozone layer depletion on the one hand and spiraling oil prices on the other hand have become main challenges. Excessive use of fossil fuels is leading to their sharp diminution and nuclear energy is not out of harm's way. In the face of imminent energy resource crunch there is need for developing thermal systems which are energy efficient. Thermal systems like refrigerators and air conditioners consume large amount of electric power. So avenues of developing energy efficient refrigeration and air conditioning systems with nature friendly refrigerants need to be explored The rapid advances in nanotechnology have lead to emerging of new generation heat transfer fluids called nanofluids.

Nanofluids are prepared by suspending nano sized particles (1-100nm) in conventional fluids and have higher thermal conductivity than the base fluids. Nanofluids have the following characteristics compared to the normal solid liquid suspensions. i) higher heat transfer between the particles and fluids due to the high surface area of the particles ii) better dispersion stability with predominant Brownian motion iii) reduces particle clogging iv) reduced pumping power as compared to base fluid to obtain equivalent heat transfer. Based on the applications, nanoparticles are currently made out of a very wide variety of materials, the most common of the new generation of nanoparticles being ceramics, which are best split into metal oxide ceramics, such as titanium, zinc, aluminum and iron oxides, to name a prominent few and silicate nanoparticles, generally in the form of nanoscale flakes of clay. Addition of nanoparticles changes the boiling characteristics of the base fluids. Nanoparticles can be used in refrigeration systems because of its remarkable improvement in thermophysical and heat transfer capabilities to enhance the performance of refrigeration systems. In a vapour compression refrigeration system the nanoparticles can be added to the lubricant (compressor oil). When the refrigerant is circulated through the compressor it carries traces of lubricant + nanoparticles mixture (nanolubricants) so that the other parts of the system will have nanolubricant -refrigerant mixture.

II. LITERATURE SURVAY

Recently, some investigators have conducted studies on vapour compression refrigeration systems, to study the effect of nanoparticle in the refrigerant/lubricant on its performance.[1] Pawel et al. (2005) conducted studies on nanofluids and found that there is the significant increase in the thermal conductivity of nanofluid compared to the base fluid. They also found that addition of nanoparticles results in significant increase in the critical heat flux. [2]Bi et al. (2007) conducted studies on a domestic refrigerator using nanorefrigerants. In their studies R134a was used the refrigerant, and a mixture of mineral oil TiO_2 was used as the lubricant. They found that the refrigeration system with the nanorefrigerant worked normally and efficiently and the energy consumption reduces by 21.2%. When compared with R134a/POE oil system. Later, [3]Bi et al. (2008) found that there is remarkable reduction in the power consumption and significant improvement in freezing capacity. They pointed out the improvement in the system performance is due to better thermo physical properties of mineral oil and the presence of nanoparticles in the refrigerant.

[4]Jwo et al. (2009) conducted studies on a refrigeration system replacing R-134a refrigerant and polyester lubricant with a hydrocarbon refrigerant and mineral lubricant. The mineral lubricant included added Al_2O_3 nanoparticles to improve the lubrication and heat-transfer performance. Their studies show that the 60% R-134a and 0.1 wt % Al_2O_3 nanoparticles were optimal.

Under these conditions, the power consumption was reduced by about 2.4%, and the coefficient of performance was increased by 4.4%. [5]Peng et al. (2010) conducted experimental on the nucleate pool boiling heat transfer characteristics of refrigerant/oil mixture with diamond nano particles. The refrigerant used was R113 and the oil was VG68. They found out that the nucleate pool boiling heat transfer coefficient of R113/oil mixture with diamond nanoparticles is larger than the R113/oil mixture. They also proposed a general correlation for predicting the nucleate pool boiling heat transfer coefficient of refrigerant/oil mixture with nanoparticles, which well satisfies their experimental results.

[6]Henderson et al. (2010) conducted an experimental analysis on the flow boiling heat transfer of R134a based nanofluids in a horizontal tube. They found excellent dispersion of CuO nanoparticle with R134a and POE oil and the heat transfer coefficient increases more than 100% over baseline R134a/POE oil results. [7]Bobbo et al. (2010) conducted a study on the influence of dispersion of single wall carbon nanohorns (SWCNH) and TiO_2 on the tribological properties of POE oil together with the effects on the solubility of R134a at different temperatures. They showed that the tribological behaviour of the base lubricant can be either improved or worsen by adding nanoparticles. On the other hand the nanoparticle dispersion did not affect significantly the solubility. [8]Bi et al. (2011) conducted an experimental study on the performance of a domestic refrigerator using TiO_2-R600a nanorefrigerant as working fluid. They showed that the TiO_2-R600a system worked normally and efficiently in the refrigerator and an energy saving of 9.6%. They too cited that the freezing velocity of nano refrigerating system was more than that with pure R600a system. The purpose of this article is to report the results obtained from the experimental studies on a vapour compression system.

Lee et al. [9] investigated the friction coefficient of the mineral oil mixed with 0.1 vol.% fullerene nanoparticles, and the results indicated that the friction coefficient decreased by 90% in comparison with raw lubricant, which lead us to the conclusion that nanoparticles can improve the efficiency and reliability of the compressor. Wang and Xie [10] found that TiO_2 nanoparticles could be used as additives to enhance the solubility between mineral oil and hydrofluorocarbon (HFC) refrigerant. The refrigeration systems using the mixture of R134a and mineral oil appended with nanoparticles TiO2, appeared to give better performance by returning more lubricant oil back to the compressor, and had the similar performance compared to the systems using polyol-ester (POE) and R134a. In the present study the refrigerant selected is R600a and the nanoparticle is alumina. Isobutane (R600a) is more widely adopted in domestic refrigerator because of its better environmental and energy performances. In this paper, a new refrigerator test system was built up according to the National Standard of India. A domestic R600a refrigerator was selected. Al_2O_3-R600a nano-refrigerant was prepared and used as working fluid. The energy consumption test and freeze capacity test were conducted to compare the performance of the refrigerator with nano-refrigerant and pure refrigerant so as to provide the basic data for the application of the nanoparticles in the refrigeration system..

III. PHYSICAL PROPERTIES OF NANOFLUIDS

3.1. Thermophysical properties of base refrigerant.

Its numerical designation is R600a or Isobutane. Its chemical formula $(CH3)_3$ CH.

Normal boiling point	=	260-264 °K at atm pressure
Critical Temperature	=	135°C
Critical pressurer	=	3.65 MPa
Vapour pressure	=	204.8 KPa at 21°C
Specific heat of liquid	=	2.38 KJ/Kg°C at 25°C
Molar mass	=	58.12 g mol^{-1}
Density	=	2.51 kg/m^3, gas (15 °C, 1atm) 593.4 kg/m^3, liquid
Melting point	=	-159.6 °C, 114 K, -255 °F
Boiling point	=	-11.7 °C, 261 K, 11 °F
Solubility in water	=	Insoluble
Ozone depletion potential (ODP)	=	0
Global warming potential (GWP)	=	3
Flash point	=	Flammable gas
Latent heat of evaporation	=	362.6 KJ/Kg at atm pressure
Specific Heat Ratio Cp/Cv	=	1.091(atm, 25°C).
Assigned colour code	=	Colorless gas

3.2. Thermophysical properties of nanoparticles.

Its molecular formula is Al_2O_3.

Melting Point	=	2072°C
Boiling Point	=	2977°C
Flash Point	=	non-flammable
Colour	=	Ivory / White
Density	=	0.26 g/cm^3
Specific heat.	=	880 J/KgK
Thermal conductivity	=	30 W/mK
Molecular mass	=	101.96 g/mol
Specific Surface Area	=	0.5- 50 m2/g
Average Primary Particle size	=	50nm
Appearance	=	White powder
PH	=	7-9

Properties

It is insoluble in water.
Stable under normal, temperature and pressures.
It is odorless
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3.3. Thermophysical properties of nanofluid.

In order to estimate the heat transfer coefficient in the refrigerant side of the evaporator the thermophysical properties of the nanorefrigerant have to be calculated. The thermophysical properties of the nanorefrigerant are calculated in two steps.

Firstly thermophysical properties of the nanoparticles oil mixture is calculated and this data is used to calculate the properties of nanorefrigerant.

3.3.1. Calculation of thermophysical properties of nanolubricant

The following correlations are used to calculate the thermophysical properties of nanolubricant [11,12,13] Specific heat of nanolubricant $Cp_{,n,o} = (1-\psi_n)\, Cp_o + \psi_n\, C_{pn}$

(1)Thermal conductivity nanolubricant, $K_{n,o} = K_o[(K_n+2K_o- 2\psi_n(K_o-K_n)) / (K_n+2K_o+ \psi_n (K_o-K_n))]$ (2)

Viscosity of nanolubricant , $\mu_{n,o} = \mu_o\, [1 / (1- \psi_n)\, 2.5]$ (3)

Density of nanolubricant, $\rho_{\,n,o} = (1- \psi_n)\, \rho_o + \psi_n\, \rho_n$, (4)

Volume fraction of nanoparticle in the nanoparticle-oil suspension,

$\psi_n = \omega_n\, \rho_o / [\omega_n\rho_o + (1-\omega_n)\rho_n]$ (5)

Mass fraction in the nanoparticle oil suspension, $\omega_n = m_n / (m_n+m_o)$ (6)

3.3.2.Calculation of thermophysical properties nanorefrigerant

The following correlations are used to calculate the thermophysical properties of nanorefrigerant [14,15,16]

Specific heat of the nanorefrigerants $Cp_{,r,n,o,f} = (1-X_{n,o})\, Cp_{,r,f} + X_{n,o}Cp_{,n,o}$, (7)

Viscosity of the nanorefrigerants $\mu r,n,o,f = \exp\, (Xn,o\ \ln\mu n,o + (1-Xn,o)\ln\mu r,f)$, (8)

Thermal conductivity of the nanorefrigerants

$K_{r,n,o,f} = K_{r,f}(1-X_{n,o}) + (K_{n,o}X_{n,o)} – (0.72X_{n,o}\, (1- X_{n,o})(K_{n,o\text{-}}K_{r,f}))$, (9)

Density of the nanorefrigerants $\rho_{r,n,o,f} = [(X_{n,o}/\rho_{n,o}) + ((1-X_{n,o})/\ \rho_{r,f})]$ -1 (10)

Nanoparticle/oil suspension concentration, $X_{n,o} = m_{n,o} / (m_{n,o} + m_r)$ (11)

The theoretical C.O.P is calculated using the equation C.O.Pth= (h1 – h4) / (h2 – h1) (12)

h1– enthalpy of refrigerant at the inlet of the compressor
h2 – enthalpy of refrigerant at the outlet of the compressor
h4 – enthalpy of refrigerant at the inlet of the evaporator
the values of the enthalpy are taken from refrigerant tables.

The actual C.O.P is calculated using relation C.O.P act = cooling load / power input (13)

IV. EXPERIMENTAL SETUP AND TEST PROCEDURE

This section provides a description of the facilities developed for conduction experimental work on a refrigerator. The technique of charging and evacuation of the system is also discussed here.

4.1. Experimental methodology

The temperature of the refrigerant inlet/outlet of each component of the refrigerator was measured with copper – constantan thermocouples (T type). The thermocouple sensors fitted at inlet and outlet of the compressor, condenser, and thermocouples/temperature sensors were interfaced with a HP data logger via a PC through the GPIB cable for data storage. Temperature measurement is necessary to find out the enthalpy in and out of each component of the system to, investigate the performance. The inlet and outlet pressure of refrigerant for each of the component is also necessary to find out their enthalpy at corresponding state.

The pressure transducer was fitted at the inlet and outlet of the compressor and expansion valve as shown in Fig.1. The pressure transducers were fitted with the T-joint and then brazed with the tube to measure the pressure at desired position. The range of the pressure transducer is -1 to + 39 bars. The pressure transducers also been interfaced with computer via data logger to store data. A service port was installed at the inlet of expansion valve and compressor for charging and recovering the refrigerant. The location of the service port is shown in Fig. 1. The evacuation has also been carried out through this service port. A power meter was connected with compressor to measure the power and energy consumption.

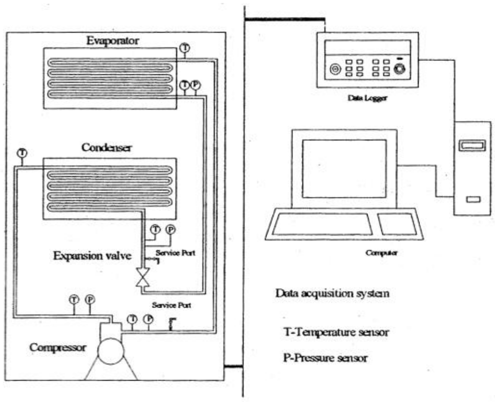

Fig. 1. Experimental apparatus

4.2. Preparation of nanolubricants

Preparation of nanolubricants is the first step in the experimental studies on nanorefrigerants. Nanofluids are not simply liquid solid mixtures. Special requirements are even, stable and durable suspension, negligible agglomeration of particles, and no chemical change of the fluid. Nanofluids can be prepared using single step or two step methods. In the present study two step procedure is used. Commercially available nanoparticles of aluminium oxide (manufactured by Sigma Aldrich) with average size <50nm and having density 0.26 g/cc were used for the preparation of nanolubricant. Mass fraction of nanoparticles in the nanoparticle–lubricant mixtures is 0.06%. An ultrasonic vibrator (Micro clean 102, Oscar Ultrasonics) was used for the uniform dispersion of the nanoparticles and it took about 24 hours of agitation to achieve the same. Experimental observation shows that the stable dispersion of alumina nanoparticles can be kept for more than 3 days without coagulation or deposition.

4.3. System Evacuation

Moisture combines in varying degree with most of the commonly used refrigerants and reacts with the lubricating oil and with other materials in the system, producing highly corrosive compound. The resulting chemical reaction often produces pitting and other damage on the valves seals, cylinder wall and other polished surface of the system. It may cause the deterioration of the lubricating oil and the formation of sludge that can gum up valves, clog oil passages, score bearing surface and produce other effect that reduce the life of the system. Moisture in the system may exist in solution or as free water. Free water can freeze into the ice crystals inside the metering device and in the evaporator tubes of system that operate below the freezing point of the water. This reaction is called freeze up. When freeze up occurs, the formation of ice within the orifice of the metering device temporarily stops the flow of the liquid refrigerant .To get rid of the detrimental effect of moisture Yellow jacket 4cfm vacuum pump was used to evacuate the system. This system evacuates fast and better which is deep enough to get rid of contaminant that could cause system failure. The evacuation system consists of a vacuum pump, a pressure gauge and hoses. The hoses were connected with the service port to remove the moisture from the system. When the pump is turned on the internal the pressure gauge shows the pressure inside the refrigerator system.

4.4. System Charging

Yellow jacket digital electronic charging scale has been used to charges R600a into the system. This is an automatic digital charging system that can charge the desired amount accurately and automatically. The charging system consists of a platform, an LCD, an electronic controlled valve and charging hose. The refrigerant cylinder was placed on the platform which measures the weight of the cylinder. The LCD displays the weight and also acts as a control panel. One charging hose was connected with the outlet of the cylinder and inlet of the electronic valve and another one was connected with the outlet of electronic valve and inlet of the service port. Using this charging system refrigerants were charged into the system according to desired amount.

4.5. Test Procedure:

The system was evacuated with the help of vacuum pump to remove the moisture and charged with the help of charging system. The pressure transducers and thermocouples fitted with the system were connected with the data logger. The data logger was interfaced with the computer and software has been installed to operate the data logger from the computer and to store the data. The data logger was set to scan the data from the temperature sensor and pressure sensor at an interval of 5 minutes. A power meter was connected with the refrigerator and interfaced with the computer and power meter software was installed. The power meter stores the instantaneous power and cumulative energy consumption of the refrigerator and cumulative energy consumption of the refrigerator. The pressures and temperatures of the refrigerants from the data logger were used to determine the enthalpy of the refrigerant. All equipments and test unit was installed inside the environment control chamber where the temperature and humidity was controlled. The dehumidifier has been used to maintain desired level of humidity at the control chamber. The experiment has been conducted of the refrigeration test rig.

V. RESULTS AND DISCUSSION

In the present experimental study, three cases have been considered. The hermetic compressor filled with i) pure POE oil ii) mineral oil and iii) mineral oil + alumina nanoparticles as lubricant. The mass fraction of the nanoparticles in the nanolubricant is 0.06 %.

5.1. The cooling load temperature – time chart

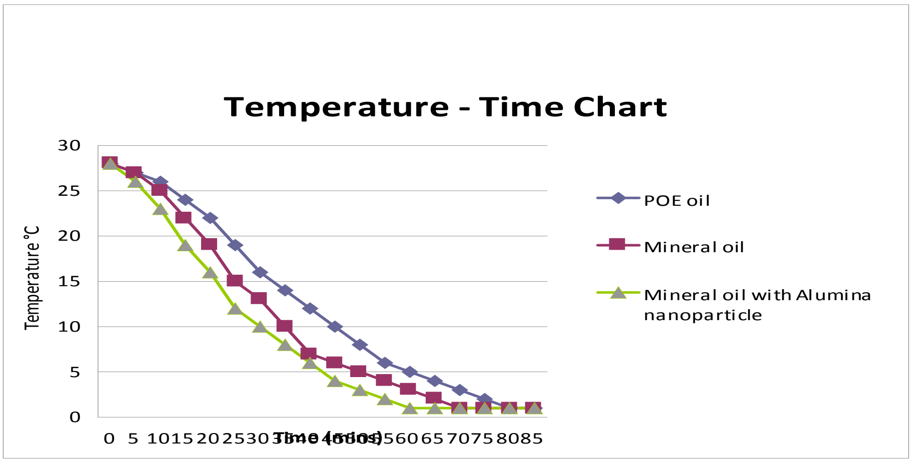

Fig.2. Temperature - Time chart

The cooling load temperature – time history is shown in figure.2 and the freezing capacity for the three cases is shown in Figure.3. In all the cases the condenser pressure is 5.6 bar and the evaporator pressure is 0.58 bar. No appreciable pressure drops due to friction were observed in the condenser and evaporator. From the figure it is clear that, the time required for reducing cooling load temperature is less for the mineral oil + alumina nanoparticle mixture. For example, with mineral oil + alumina nanoparticle, the time required to bring the cooling load temperature from 28°C to 5°C is 42 minutes where as that with mineral oil and POE oil is 50 and 60 minutes respectively. It is clear that, the freezing capacity of the mineral oil + Alumina nanoparticle mixture is higher when compared with the other two cases The time taken to reduce the temperature of the cooling load from 28°C to 1 °C with POE oil is 85 minutes and it reduces by 29 % if mineral oil + alumina nanoparticle is used. This is due to the fact the nanoparticles present in the refrigerant enhances the heat transfer rate in the refrigerant side of the evaporator

5.2. Effect of nanoparticle on the freezing capacity

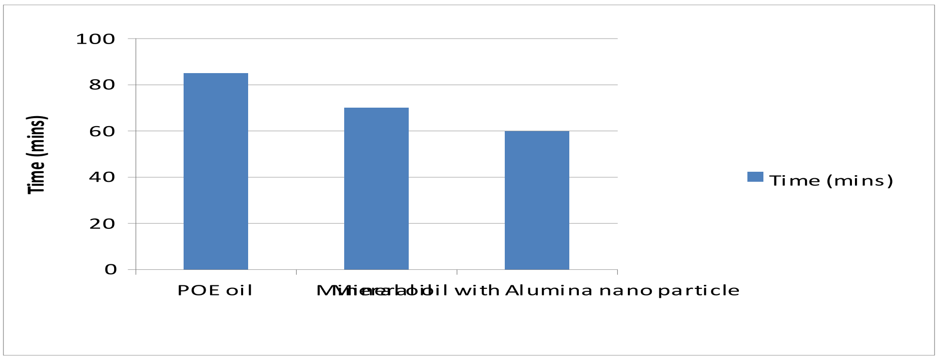

Fig.3 Effect of nanoparticle on the freezing capacity

5.3. Reduction in refrigerant temperature while passing through the condenser

Figure 4 shows drop in the refrigerant temperature in the condenser of the refrigeration system. Temperature drop of the refrigerant is high with nanorefrigerant when compared with the other cases. The temperature of the refrigerant at the inlet of the condenser is in the range 69 – 65°C. The saturation temperature of R600a corresponding to the condenser pressure of 5.6 bar is 42°C. In the case of mineral oil nanoparticle mixture the temperature at the exit of the condenser is 39°C and the subcooling obtained is 3 °C. In fact there is no subcooling when POE oil is used as the lubricant. The enhanced heat transfer rate in the condenser is due to the presence of nanoparticles in the refrigerant.

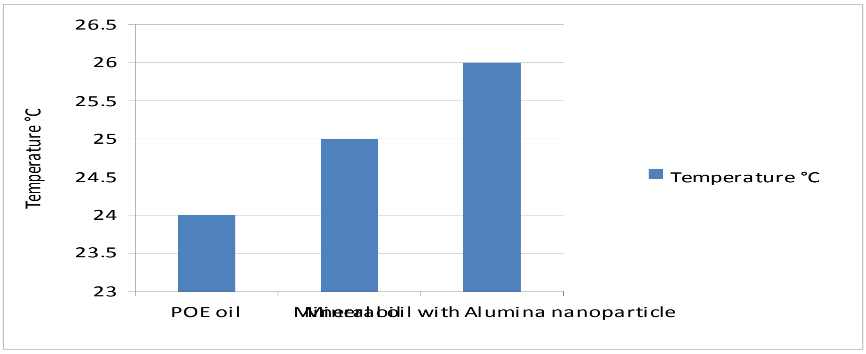

Fig.4. Reduction in refrigerant temperature while passing through the condenser

5.4. Energy Consumption By The Compressor

Table. 1. Energy consumption results

	POE oil	Mineral oil	Mineral oil with Alumina nanoparticle
Energy consumption kw hr	0.635	0.614	0.572
Energy saving %	-	6.0	11.5

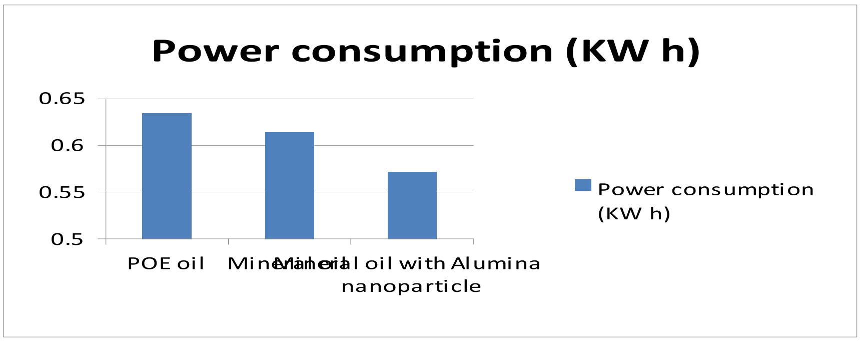

Fig.5. Comparison of power consumption

Figure 5 shows the comparison of power consumption of the compressor . The reduction in power consumption is 6 % if the mineral oil is used instead of POE Oil and a reduction of 11.5 % is observed when mineral oil is mixed nanoparticles. [8]Shengshan B (2010) reported that for a refrigeration system using R600a as refrigerant the power consumption can be reduced by 9.6 % if mineral oil with TiO2 nanoparticle is used instead of POE oil.

5.5. Temperature of salient points

Table 2. Temperature of salient points

Quantity	POE oil °C	Mineral oil	Mineral oil with Al2O3 nanoparticle
Temperature at inlet of the compressor	20	19	17
Temperature at inlet of the condenser	69	67	65
Temperature at outlet of the condenser	45	42	39
Temperature at outlet of the expansion valve	-20	-20	-21
Temperature at inlet of the evaporator	-19	-19	-20

5.6. Comparison of Coefficient of performance

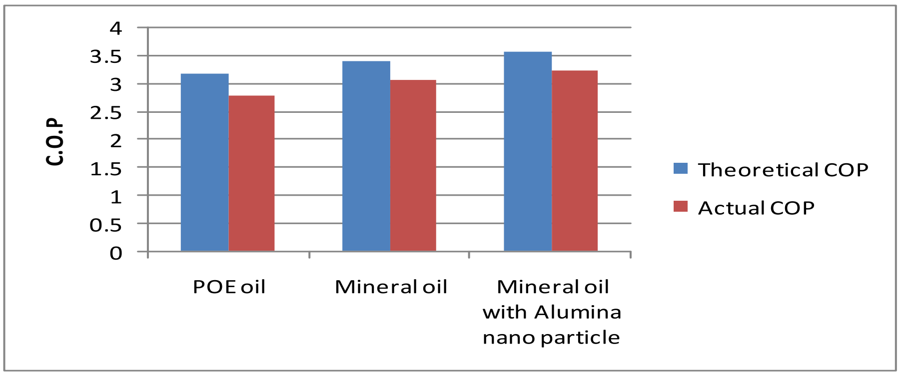

Fig. 6. Comparison of Coefficient of performance of the three cases

Figure 6 shows the coefficient of performance (COP) calculated using the experimental data. The actual COP is calculated using the cooling load and the power input. The theoretical values are also shown for comparison. In all cases the actual COP is less than the theoretical COP. The condenser pressure is 5.6 bar and the evaporator pressure is 0.58bar. The temperatures at the salient points of the refrigeration system are shown in Table 2. It is very much clear from the histogram shown below that the mineral oil + alumina nanoparticle mixture has the highest COP when compared with the other cases. The advantages of adding nanoparticle to the lubricant is manifold. It reduces the power consumption of the compressor and there is sub cooling of the nano-refrigerant in the condenser which in turn increases the COP. The Actual COP is calculated using the energy meter reading and the cooling load. For the calculation of theoretical COP the enthalpy values at the salient points are taken from P-h chart for R600a.

VI. CONCLSION

Extensive experimental studies have been conducted to evaluate the performance parameters of a vapour compression refrigeration system with different lubricants including nanolubricants. The conclusions derived out of the present study are (i) The R600a refrigerant and mineral oil mixture with nanoparticles worked normally

(ii) Freezing capacity of the refrigeration system is higher with mineral oil + alumina nanoparticles oil mixture compared the system with POE oil

(iii) The power consumption of the compressor reduces by 11.5% when the nanolubricant is used instead of conventional POE oil (iv) The coefficient of performance of the refrigeration system also increases by 19.6 % when the conventional POE oil is replaced with nanorefrigerant

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