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EXPERIMENTAL ANALYSIS OF VAPOR COMPRESSION REFRIGERATION SYSTEM USING NANO-REFRIGERANT

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ABSTRACT

In today's world refrigeration systems play a vital role to fulfill the human needs and a continuous research is being carried out by many researchers in order to improve the performance of these systems. Here, an attempt has been made to improve the performance of such system. Experimental investigation of vapor compression refrigeration system performance using Nano-refrigerant is presented in this work. Nano-refrigerant was prepared in current work by mixing of Al_2O_3 nanoparticles with Polyolester lubrication oil (POE) and added to the compressor of the refrigeration system to be mixed with pure refrigerant R404a during its circulation through refrigeration system. Three different concentrations of Al_2O_3 (0.02%, 0.04% and 0.06%) has been taken to mix with R404a refrigerant. Nanorefrigerant are used to study the performance of the deep freezer test rig and to investigate the effect of using Nano-refrigerant (Al_2O_3) as a working fluid compared with pure refrigerant R404a. The results showed that, the increasing in concentration of Al_2O_3 nanoparticles in the Nano-refrigerant will significantly enhance the performance of the refrigeration system, as adding nanoparticles will increase the thermal conductivity, heat transfer and improve the thermo-physical properties of Nano-refrigerant. Investigation of performance parameters for refrigeration system using Nano-refrigerant with 0.04% concentration compared with that for pure refrigerant R404a shows that, Nanorefrigerant has reflect higher performance in range of 50% increase in COP refrigeration

system. It can be concluded that, Nano-refrigerants can be efficiently and economically feasible to be used in the vapor compression refrigeration systems.

KEYWORDS: Aluminum Oxide, Nanoparticles, Nanorefrigerant, Thermal Conductivity, COP, Energy Consumption, vapor compression cycle.

Nomenclature

Rcon: Nano-refrigerant concentration ratio,

mn = Mass of nanoparticles (g),

mr = Mass of refrigerant (g).

RE = Refrigeration effect (RE)

qe = Heat transfer rate of the evaporator

qc = Heat transfer rate of the condenser

h = Enthalpy (kJ/kg)

W_c= Isentropic compression work

P = Pressure

T = Temperature

η_{isen} = The isentropic efficiency

COP = Coefficient of Performance

ρ_{nr} = Density of a mixture of nanoparticles

ρ_{br} = Density of base fluid or refrigerant

Φ= Mass fraction of nano particle

C_p = Specific heat

K = Thermal conductivity

μ = Viscosity

1. INTRODUCTION

In cooling and heating applications, thermo–physical properties of matter play a great role. It has been observed that the performance of any system mainly depends on the thermal conductivity, viscosity, specific heat and density of gasses and liquids which are used in system. Conventional fluids have poor heat transfer capacity and low thermal conductivity which limits its performance. Due to this, there is always a need to develop effective & efficient fluids capable to deal with high heat transfer rate. Small solid additives usually in micrometer are good option to enhance the thermal properties of fluids, but it has been found that these small solid additives poses number of problems like particle sedimentation, particle clogging, large pressure drop in the system, corrosion of components, etc (Maxwell et al., 1873). Investigations show that use of nanoparticles in conventional fluids is a good option and it also reduces the number of other problems because at nanometer the material behaves like colloidal solutions. Modern nanotechnology offers us many routes to prepare nanometer sized particles. It is possible to break down the limits of conventional solid particle suspensions by conceiving the concept of nanoparticle-fluid suspensions. These nanoparticles-fluid suspensions are termed nanofluids, obtained by mixing nanometer sized particles in a base fluid like, water, oil etc. Jwo C.S et al. (2009) had mixed mineral lubricant with Al_2O_3 nanoparticles to improve the lubrication and heat-transfer performance. This study showed that R134a + 0.1 wt % Al_2O_3 nanoparticles were optimal for best performance. Under these conditions, the power consumption was reduced by about 2.4%, and the coefficient of performance was increased by 4.4%. Loaiza J.C.V et al. (2010) studied the use of nanofluids as secondary coolants in vapor compression refrigeration systems numerically with a simulation model for a liquid-to-water heat pump, using reciprocating compressor and double-tube condenser and evaporator. The simulation program was run for a small capacity system operating with four different water-based nanofluids, Cu, Al_2O_3, CuO and TiO_2 and volume fraction ranged from 1% to 5% and particle size from 10 to 50 nm. It was observed that greatest reductions in evaporator area were obtained with Cu+H_2O nanofluids, flowing with large volume fractions and lower particle diameters followed by TiO_2 and Al_2O_3 results increase in COP of the system. N. Subramani et al. (2011) done experimental studies on a vapour compression system using nano-refrigerants. It was found that, the R134a refrigerant and mineral oil mixture with nanoparticles worked normally. Sendil Kumar et al. (2012) have found that addition of nano Al_2O_3 in to the refrigerant shows improvement in the performance of the refrigeration system. Nano Al_2O_3-PAG oil was used as nano refrigerant in R134a vapour compression refrigeration system and usage for Nano refrigerant reduces the length of capillary tube and cost effective. The system performance was investigated using energy consumption test and freeze capacity test. Clancy E.V. et al. (2012) proposed a new design, where the heat transfer of a vapor compression system was increased by increasing the thermal heat transfer properties of the refrigerant using nanoparticles. Nanoparticles were mixed with refrigerant at inlet of the condenser and removed at outlet of condenser, so by this means heat transfer rate was accelerated in condenser. This research recommended a less than 10% (wt.) of nanoparticles in the fluid. Moreover, the condenser efficiency can be enhanced to improve the performance of the system. Kumar R.R et al. (2013) investigated the effect of aluminum oxide based nano-lubricant on the COP of the system and freezing capacity of the system. The experimental set up was build as per Indian standards. Refrigerants like R12, R22, R600, R600a and R404a were used as a refrigerant. The performance of the system depends upon the thermo-physical properties of the refrigerant. The addition of nanoparticles to the refrigerant results in improvement in the thermo-physical properties thereby improving the performance of the refrigeration system. The experimental studies indicate that the refrigeration system with nanorefrigerant works normally. There was increase in the COP of the system by 19.6%. Mineral oil with alumina nanoparticles oil mixture was investigated and it was found that there is an increase in freezing capacity and reduction in power consumption by 11.5% as compared to polyester. Aluminum oxide based nano-lubricant in refrigeration system was found working satisfactorily. Satnam Singh et al. (2013) represented a review on behavior of Nano- refrigerant in vapour compression cycle with different concentration of Nano-particles. The experimental studies revealed that the performance of such systems gets improved by using Nano refrigerants. It is observed that using a Nano-refrigerant with higher concentration is not always true. Kuljeet Singh et al. (2014) carried out an investigation into the performance of a Nano refrigerant (R134a+Al_2O_3) based refrigeration system. It has been found out that the improvement in coefficient of performance (COP) is maximum (7.2 to 8.5%) with 0.5% Al_2O_3 (% wt.) nanoparticles. When the mass fraction of nanoparticles increased to 1% in refrigerant COP is found to be lower than even from pure R134a. Further, increased mass fraction of Al_2O_3 (1%), lowers down the pressure and temperature after expansion of the Nano refrigerant in the expansion valve. In addition to this the specific heat of refrigerant gets decreased. So, both of these factors will result in decrease in the refrigeration effect, hence COP. Improvement is found to be maximum by using Nano-refrigerant R134a+0.5% Al_2O_3 keeping refrigerant flow rate as 6.5 LPH. Omer A. Alawi et al. (2014) presented a comprehensive review of fundamentals, preparation and applications of nanorefrigerants and concluded that adding nanoparticles to the refrigerant enhanced the heat transfer and that the heat transfer coefficient increased with increased nanoparticle mass fraction. From the literatures, it has been found that the thermal conductivities of Nano refrigerants are higher than pure refrigerants. The power consumption was reduced by about 2.4%, and the coefficient of performance was increased by 4.4%. The refrigerator's performance was found 26.1% better with 0.1% mass fraction of TiO_2 nanoparticles compared to a refrigerator's performance with the HFC134a and POE oil system. R. S. Mishra et al. (2015) studied thermo physical properties by addition of different nanoparticle mixed with ecofriendly refrigerant are analyzed and their effects on the coefficient of performance (C.O.P.). The experimental results are indicating the thermal conductivity, dynamic viscosity and density of Nano-refrigerant (different nanoparticle i.e. Cu, Al_2O_3, CuO and TiO_2 with ecofriendly refrigerant R134a, R407c and R404a) increased about 15 to 94%, 20% and 12 to 34% respectively compared to base refrigerant on the other hand specific heat of Nano refrigerant is slightly lower that the base refrigerant. Moreover Al_2O_3/R134a Nano refrigerant shows highest C.O.P. of 35%. R404A and R407 with different nanoparticle show enhancement in C.O.P. about 3 to 14% and 3 to 12% respectively. T. Srinivas and A. Venu Vinod (2015), have investigated the thermal performance of a shell and helical coiled heat exchanger using CuO/water nanofluid at different weight concentrations. They have found the enhancement in heat transfer in the heat exchanger with nano fluid. Over 185% increase in tube side heat transfer coefficient allows reduction of heat exchanger length and fluid velocity and thereby pressure drop up to 94%. The total cost of the optimized heat exchanger was reduced by 55.19% as compared with that designed by conventional methods. In conclusion, the shell and tube exchanger in the presence of nanofluid provides less pressure drop, higher heat transfer coefficients, lower heat transfer surface area and lower investment and operational costs as compared with the exchanger designed by conventional methods. **Ravinder Kumar and Jagdev Singh (2017) worked on** an experimental study on vapour compression refrigeration system using R290/ R600a refrigerant with zinc oxide nanoparticles. The refrigerant R290/R600a and mineral oil with zinc oxide nanoparticles worked efficiently and normally in refrigeration system. The compressor suction and discharge pressures were reduced by 17 and 21% respectively by using (0.2–1.0) wt% nanoparticles in the system. The compressor suction and discharge temperatures were reduced by 37 and 28% respectively by using (0.2–1.0) wt% nanoparticles in the system. The condenser outlet temperature was dropped by 25% by using nanoparticles in the system. The 1.0 wt% nanoparticle concentration has no effect in the system. M. Anish, et al., (2018), have conducted an experimental study with the blend of R22 and the mixture containing 0.05% volume of nanoparticles (copper oxide) in the refrigerant shows increased heat transfer rates. The nanorefrigerant has further reduced the work of the compressor, which led to reduction in power consumption. Time taken for 10 revolutions of disc in energy meter varies positively from the default conventional refrigerant. The output conditioned air has temperature and humidity regulated perfectly, which does not get altered due to the change in refrigerant. Only power consumption and heat transfer rate have changed to desirable values.

2. MATERIALS AND METHODS

2.1 Experimental Setup

This section provides a detailed description on the facilities developed for conducting the experimental work on a fabricated vapor compression deep freezer. The technique used for charging nanoparticles and evacuation of the system is also discussed here. A detailed report on this facility development is as follows.

The temperature of the refrigerant at inlet/outlet of each component of the refrigerator is measured with thermometers. Temperature measurement is necessary across each component of the system in order to investigate the performance. Similarly pressure measurements are also taken across different components of the refrigeration system. The Pressure gauges are fitted at the inlet and outlet of the compressor and expansion valve. The pressure gauges are fitted with the T-joint and then brazed with the tube to measure the pressure at desired compressor and heater to measure the power and energy consumption. Firstly, performance of the system is investigated with pure refrigerant R404a. Then nanoparticles are injected in the refrigerator through charging line for the refrigerant. Then performance is investigated with the Al2O3 nanoparticles. Volumetric concentration of nanoparticles, mass flow rate of refrigerant are the key parameters which varied during experimentation.

Figure 3: Actual Test Setup of Vapour Compression Refrigeration Deep Freezer.

Figure 3 shows the actual setup for vapor compression deep freezer in which R404a refrigerant is used as working fluid along with the nanoparticles (Al_2O_3).

2.2 Thermodynamic analysis

Generally, the system of vapor-compression refrigeration consists of a condenser, an expansion valve, an evaporator, and a compressor as shown in figure 1. The vapor-compression refrigeration cycle consists of four processes:

(1-2) compressing refrigerant in compressor isentropically,

(2-3) condensation at constant pressure,

(3-4) adiabatic expansion in the expansion valve,

(4-1) evaporation at constant pressure.

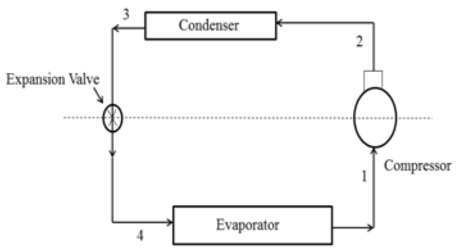

Figure 1: Vapour compression system.

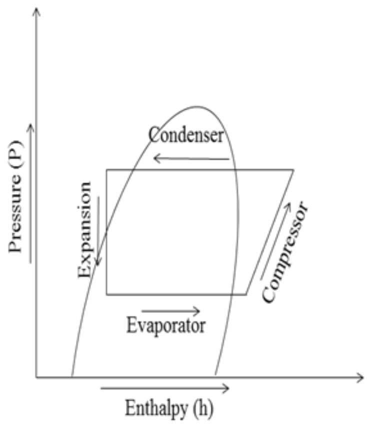

Figure 2: Pressure Enthalpy representations.

The pressure-enthalpy diagrams of vapour compression refrigeration cycle are shown in figure 2. The refrigerant at the inlet of the evaporator is vaporized by removing heat from the area desired to cool. Saturated vapor at point 1 goes into the compressor at low pressure and is exposed to a reversible adiabatic compression during the process from 1 to 2 in Figure 2. During process (2-3), while the heat is rejected in the condenser at a constant pressure, the working fluid changes to a saturated liquid when exiting the condenser. Refrigerant at point 1 in Figure 2 is saturated vapor at the evaporator temperature and at point 3 is saturated liquid at the condenser temperature. The working fluid at the exit of the expansion valve enters the evaporator, and the cycle is completed. Completely vaporized refrigerant enters the compressor, and its pressure and temperature increase during the compressing process. The working fluid at the condenser outlet should be completely liquid, which is achieved by using superheating/subcooling instead of the nonsuperheating/ subcooling arrangement.

2.3 Thermodynamic Analysis

The refrigeration effect (RE) or heat transfer rate of the evaporator (qe) is calculated as follows:

$$q_e = h_1 - h_4 \qquad (1)$$

The heat transfer rate of the condenser (qc) is calculated as follows:

$$q_c = h_2 - h_3 \qquad (2)$$

The isentropic compression work of the compressor W_c is expressed as follows:

$$W_c = h_2 - h_1 \qquad (3)$$

The isentropic efficiency of the compressor is calculated as follows:

$$\eta_{isen} = \frac{\text{Isentropic compressor work}}{\text{Actual compressor work}}$$

$$\eta_{isen} = \frac{h_{2s} - h_1}{h_{2a} - h_1} \qquad (4)$$

The performance of refrigerators is determined in terms of the COP. COP is defined as follows:

$$COP = \frac{q_e}{W_c} \qquad (5)$$

$$COP = \frac{h_1 - h_4}{h_2 - h_1} \qquad (6)$$

3. Calculation of thermophysical properties of nano lubricant

3.1 Density of nano fluid

The density of a mixture of nanoparticles ρ_{nr} and the base fluid ρ_{br} and the density of the base fluid can be determined based on Xuan and Roetzel; however, it should be noted that the original equation is modified by using mass fraction instead of volume fraction in this study. The base fluid is R404a refrigerant. The density of the nano fluid (R404a and Al_2O_3 nano particles) for different concentration of Al_2O_3 nano particles is developed by Pak and Cho;

$$\rho_{nr} = \Phi\rho_{np} + (1-\Phi)\rho_{br} \qquad (7)$$

3.2 Isobaric specific heat of nano fluid

Specific heat is the amount of heat required to raise the temperature of one gram of nano fluids by one degree centigrade.

$$C_{pnr} = \Phi C_{np} + (1-\Phi)C_{pbr} \qquad (8)$$

3.3 Thermal Conductivity of Nano fluid

The equation for calculating thermal conductivity is given below. It is developed by Hamilton and Crosser (1962);

$$K_{nr} = K_{br}\left[\frac{\left(K_{np}+2K_{br}-2\Phi\left(K_{br}-K_{np}\right)\right)}{\left(K_{np}+2K_{br}+\Phi\left(K_{br}-K_{np}\right)\right)}\right] \qquad (9)$$

3.4 Viscosity of Nano fluid

The equation for calculating the viscosity of the nano fluid given by Brinkman 1952 is given below,

$$\mu_{nr} = \mu_{br}\left[\frac{1}{(1-\Phi)^{2.5}}\right] \qquad (10)$$

3.5 Preparation of Nano particles–Lubricating Oil Suspension

To achieve uniform dispersion of nanoparticles with working fluid, Al_2O_3 nanoparticles (brought from laboratory materials suppliers) was mixed with Polyolester lubrication oil (POE) which is compatible with refrigerant R404a at three different mass fractions and added to the system compressor to be mixed with refrigerant R404a during its circulation through refrigeration system due to the difficulty of preparing Nano-refrigerant Al_2O_3-R404a directly. The nanoparticles-lubrication oil suspension was prepared with three concentrations using, 4 digits electronic balance, magnetic stirrer and ultrasonic vibrator (shaker) in the engineering materials Lab as shown in figure (3). The nanoparticles-oil suspension was at first kept vibrated on magnetic stirrer for 2 hours to obtain proper homogenization and then kept vibrated in the ultrasonic vibrator for 1hour to maintain the suspension with uniform dispersion and to prevent nanoparticles sediments. The nanoparticles-lubrication oil suspension was then added to compressor to form Nano-refrigerant Al_2O_3-R404a with three concentrations 0.01%, 0.04%, and 0.06% when circulated through components of the refrigeration system.

The different concentrations of Nano-refrigerant are determined using the following relation:

Rcon $= mn/mn+mr$ (11)

Figure 3: Preparation of Nano refrigerants in laboratory.

4. RESULTS AND DISCUSSION

The density of a nanorefrigerant can be a parameter to obtain the enthalpy of working fluid. Mollier charts of pure refrigerant can be used to obtain enthalpy values corresponding to the density and temperature or pressure at cycle point, so there is no chart or correlation to predict the properties of nanorefrigerants. The density of Al_2O_3 was accepted to be equal to 3,690 kg/m^3.[11] It should be noted that the enthalpy of point 3 is estimated as follows. First, temperature (T_3) and saturation pressure (P_3) corresponding to T_3 are specified at 20.5^{0}C and 10.68 bar, respectively. Then density is read from the Mollier chart of R404a. Density of nanorefrigerant (ρ_{nr}) is calculated by replacing nanoparticle mass fraction in nanorefrigerant (Φ), ρ_{np} and ρ_{pr} in (7). Then saturation temperature and pressure and enthalpy of nanorefrigerant are read from chart R404a for point 3. Similar to the determination of enthalpy of nanorefrigerant at point 3, enthalpy of nanorefrigerant at point 1 can be found. Temperature (T_1) and saturation pressure (P_1) corresponding to T_1 is specified at 5.6^{0}C and 1.732 bar, respectively. Then density is read from the chart of R404a. The density of nanorefrigerant (ρ_{nr}) is calculated by replacing nanoparticle mass fraction in nanorefrigerant (Φ), ρ_{np}, and ρ_{pr} in (7). Then saturation temperature and pressure and the enthalpy of the nanorefrigerant are read from chart R404a for point 1.

Table 1: Typical Application of Deep Freezer.

Deep Freezer	
R404A Models	KCN418LAL
Nominal Capacity Hard Top (Ltrs.)	550 - 600
Condenser Size (inch) (Length X Height) 3/8*O.D. Tube 13FPl	13 x 12 x 3 ROWS
Condenser Fan Motor	1/36 HP x 1.350 RPM
Condenser Fan	12” DIA
Evaporator Size O.D Tube (inch) x Length (ft)	3/8 x 95
Capilary Tube Bore x Length	0.050” x 8’ x 1 NO.

Table 2: Technical specification of freezer test rig.

component	**specification**
Compressor	Hermetically sealed 0.5 TR, Reciprocating
Condenser	Air- cooled condenser
Capacity	550 Litter
Evaporator	Tubes type
Expansion Device	Capillary Tube
Refrigerant	R-404A
Energy Meter	3200 (constant)
Suction Pressure Gauge	250 Psi
Discharge Pressure Gauge	550 Psi
Temperature Sensors	ST _ 1A digital thermometer manual
Lubricant	Polyolester (POE) oil (380 cm^3) (13.0 Oz) RL 32H
Nanoparticles	AL_2O_3
Drier / Filter	Dry all Make
Refrigeration test rig	Direct expansion coil (Capillary Tube)
Supply	230 VOLTS, 50 HZ, 1 PHASE, AC
Condenser Fan Motor	1/10 HP x 1.350 RPM – 75 W – CAP 2.5 MF

RESULT AND DISCUSSION

4.1 Effect on Coefficient of Performance

Table 1 and table 2 shows the specification of the test rig used in the present analysis.

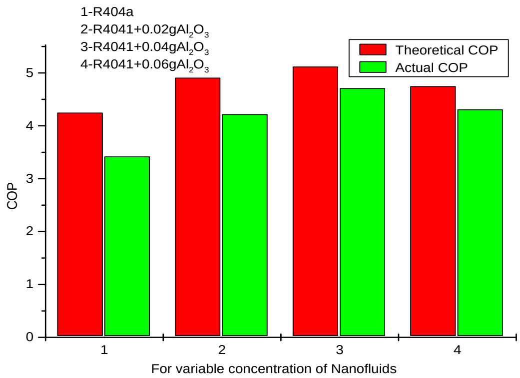

Figure 4.1: Effect on COP with and without Nano Refrigerant.

COP is highly influenced by operating conditions, especially ambient temperature and relative temperatures between sink and system. Here in this experimental study actual COP of refrigeration system has been investigated. COP is the ratio of refrigerating effect and work input. In this study, COP has been calculated with help of experimental data. Refrigeration effect is estimated by means of energy meter connected to heater. Ultimately the heater is supplying heat to evaporator by means of heating water and same amount of heat is removed by refrigerant after achieving steady state. Theoretical COP is evaluated as 4.25 for pure R404a. On the other hand, with R404a+0.02% Al_2O_3 and for R404a+0.04% Al_2O_3 theoretical COP is found to be 4.91 and 5.12 respectively. R404a+0.06% Al_2O_3 decrases in theoretical COP upto 4.75. Actual COP is evaluated as 3.42 for pure R404a. On the other hand, with R404a+0.02% Al_2O_3 and for R404a+0.04% Al_2O_3 actual COP is found to be 4.22 and 4.71 respectively. R404a+0.04% Al_2O_3 shows the improvement in actual COP by 10.40% and R404a+0.06% Al_2O_3 shows the decline in actual COP by around 8.49%.

4.2 Effect on suction and Discharge Temperatures of compressor

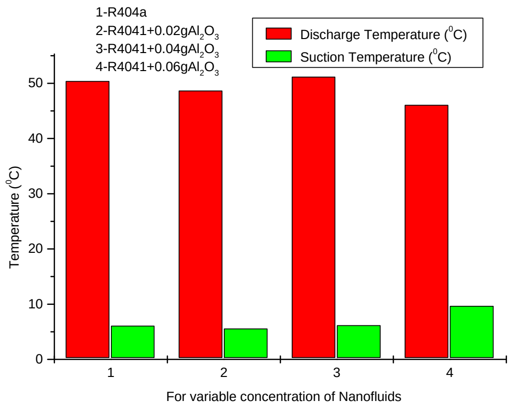

Figure 4: Effect on suction & discharge Temperature of compressor with and without Nano Refrigerant.

The discharge temperature for pure refrigerant R404a is 50.4^{0}C. It reduced to 48.7^{0}C for R404a + 0.02% Al_2O_3. And for R404a+0.04% Al_2O_3 it is increased up to 51.2^{0}C. The suction temperature for pure R404a is 6.1^{0}C. It is decreased by 5.6^{0}C in R404a + 0.02% Al_2O_3. And for R404a+ 0.04% Al_2O_3 it is increases up to 6.2^{0}C.

4.3 Effect on suction & Discharge pressure

For the above experiments the Pressures at suction and discharge have been recorded and are discussed in following section. P1 and P2 refer the Pressure at compressor suction and compressor discharge. Suction pressure shows decrement for R404a + 0.02% Al_2O_3 by 28.94% and for R404a + 0.06% Al_2O_3 by 18.42%. The discharge pressure shows increment. The discharge pressure of R404a + 0.06% Al_2O_3 is increased by 0.005%. Thus there is significant increment for both the mixtures. In actual practice, the discharge pressure (or condenser pressure) increases due to frictional resistance of flow of the refrigerant and the suction pressure (or evaporator pressure) decreases due to the frictional resistance of flow of the refrigerant. An increase in condenser pressure, results in a decrease in the refrigerating capacity and an increase in power consumption.

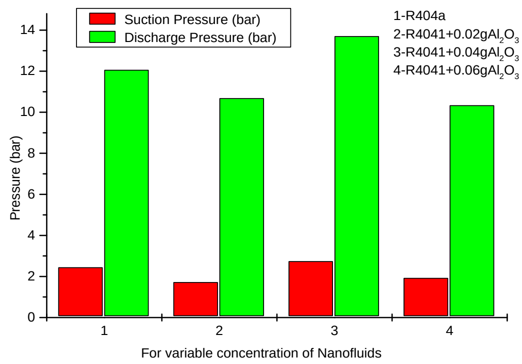

Figure 4.3: Effect on suction & discharge Pressure of compressor with and without Nano Refrigerant.

A high volumetric efficiency means that more of the piston's cylinder volume is being filled with new refrigerant from the suction line and not re-expanded clearance volume gases. The higher the volumetric efficiency, the greater the amount of new refrigerant that will be introduced into the cylinder with each down stroke of the piston, and thus more refrigerant will be circulated with each revolution of the crankshaft.

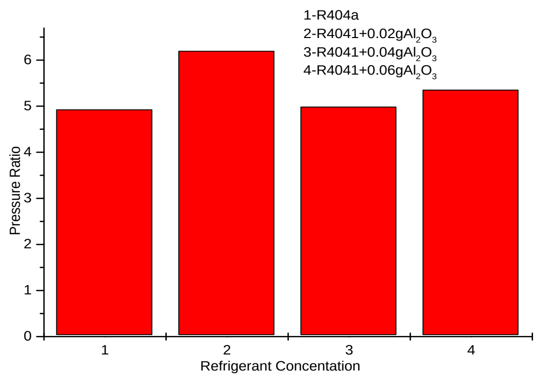

Figure 4.4: Effect on Compression Ratio of system with and without Nano Refrigerant.

5. CONCLUSION

From the above result and discussion it is concluded that, addition of 0.04% of Al_2O_3 Nanoparticles in the base refrigerant will leads to improvement in the overall performance of the deep freezer freezing capacity than that of pure base Refrigerant. However, increase in the percentage of nanoparticles in the base refrigerant will result in decreased system performance.

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