



Experimental Study on Transport Properties of Sustainable Refrigeration Oils–Refrigerant Mixtures

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Abstract. The present study analysed the heat transfer and pressure-viscous behaviour of sustainable refrigeration oil/green refrigerant for domestic refrigeration systems. The sustainable refrigeration oil was synthesised from pentaerythritol esters (PE) using the uninterrupted transesterification process. Then the polyol ester-based sustainable refrigeration oil (BIO) was added with synthetic refrigeration oil (POE68) in the fraction of 50% by volume. A high-pressure equilibrium cell/mixing chamber was used for the preparation of a sustainable refrigeration oil/green refrigerant mixture. In this study, the thermal conductivity and piezo-viscosity coefficient of the refrigeration oil/refrigerant blends were also investigated. The results indicate that the BIO50/R600a showed higher thermal conductivity of 8.96% as compared to POE68/R134a. BIO50/R600a exhibits the higher piezo-viscosity coefficient as compared to other refrigeration oil/refrigerant blends, showing the better elastohydrodynamic lubrication (EHL) performance. The usage of a sustainable refrigeration oil/green refrigerant combination in the refrigeration systems will play a substantial role in diminishing the energy demand and environmental effect of high global warming potential refrigerants/fossil energy sources.

Keywords: Pentaerythritol ester, Sustainable Refrigeration oil, Natural Refrigerant, Thermal behaviour, piezo-viscosity coefficient, Domestic refrigeration system.

1. Introduction

In recent years, the refrigeration industry gives more attention to sustainable refrigeration oils and refrigerants in concern of global warming and greenhouse emissions and increasing demand for mineral-based lubricants [1]. Thus, it is essential to employ an alternative source of crude oil-based lubricants for the refrigeration systems. Akhavan Behabadi et al. [2] have assessed the influence of CuO nanoparticles on boiling and the two-phase phenomenon of POE oil/ R-600a mixture. They have observed that a 1.5% mass fraction of CuO in the POE oil/ R-600a mixture showed an improved heat transfer rate of 63% as compared with pure POE oil/ R-600a mixture. Ahamed et al. [3] have investigated the energy and exergy performances of a household refrigeration system using natural refrigerants such as butane and isobutane and compared with HFC refrigerant R-134a and have concluded that the coefficient of performance of isobutane is 50% greater than that of R-134a and have observed minimal exergy losses for isobutane refrigerant in the refrigeration components. The refrigeration oil should need to generate the lubrication film which shields the surface of contact from wear which possess required viscosity which decreased by the dissolved refrigerant. This viscosity reduction had led to effect in increasing compressor bearing wear. A pressure-viscosity (piezo viscosity) coefficient of refrigeration oil and refrigerant mixture is intended to compute the piezo-viscous reaction of lubricants at the low-pressure property of the elastohydrodynamic lubrication (EHL) inlet zone. Numerous studies have been carried to assess the lubrication film thickness in EHL contacts lubricated with oil-refrigerant combinations. Jonsson [4] analysed the impact of HFC refrigerants on the pressure-viscosity coefficient/viscosity of polyolester oil compressor lubricants from 0 % to 30 % dilution of refrigerant concentration and reported that that refrigerant dilution significantly reduces viscosity and pressure-viscosity coefficient. Hauleitner and Morales-Espejel [5] examined the quality of roller bearings of compressor with POE68 and R134a and emphasizes the uncertainty in piezo-viscosity of mixtures affecting film thickness. Vishal Singh and Arvind Rajput [6] have investigated the lubrication effect of pressure-viscous/velocity slip on journal bearing of refrigeration compressors and revealed that pressure-viscosity coefficient severely influenced the load capacity, pressure distribution and oil film pressure. Vergne et al. [7] examined and modelled the quantitative elastohydrodynamic method for estimating the thickness of EHL film and revealed that the refrigeration compressor bearing oil film

thickness depends on pressure-viscosity coefficient and density of refrigeration oil and refrigerant mixture.

More research studies were carried out using biolubricants for various applications as lubricant alternative. Sandesh Suresh et al. [8] reported that rapeseed methyl ester exhibits good cold flow properties, such as a cloud point of -3°C to -1°C and a pour point of -9°C to -7°C , compared to palm oil methyl ester, whose higher saturated fat content results in poorer cold flow characteristics. In the current scenario of the refrigeration field, more attention is given to the analysis of lubricants with green refrigerants. Pradip Kailas Rishi et al. [9] have studied the thermophysical properties of POE oil mixed with green refrigerant R600a and graphene oxide/TiO₂ nanoparticles. They have observed that the viscosity and refrigerant concentration affect system performance. The present study experimentally investigated the transport properties of biodegradable refrigeration oil/environmentally friendly refrigerant for a vapour compression refrigeration system.

2 Methodology

2.1 Formulation of sustainable refrigeration oil/Blend

The synthesis of sustainable refrigeration oil from pentaerythritol (PE) esters was carried out by using the uninterrupted transesterification process [10]. The formulation process involves in the two-step transesterification of plant-derived oil-based polyol ester. Raw rapeseed oil is selected as a base for biodegradable refrigeration oil. Methanol, sodium hydroxide (NaOH), pentaerythritol (99.9%), xylene and para-toluene sulphonic acid (p-TSA) are the chemicals required for synthesis. For 1 litres of raw rapeseed oil, 0.44 litre of methanol, and 4.32g of NaOH a catalyst will be mixed and stirred well for an hour at a reaction temperature of $55\text{--}60^{\circ}\text{C}$. Then the rapeseed oil methyl ester was added to the p-TSA catalyst of 22.37g, pentaerythritol of 47.54g, and xylene, a solvent. This mixture was heated under elevated temperatures of $150\text{--}160^{\circ}\text{C}$ for five hours. The resulting pentaerythritol esters are then purified to eliminate residual acids and catalysts and labelled as sustainable/biodegradable refrigeration oil (BIO) [11]. A commonly used synthetic refrigeration oil in domestic cooling systems is selected as the base fluid. The rapeseed oil-based sustainable refrigeration oil was further blended with POE68 in a 50% by volume fraction which is labelled as BIO50. Fig. 1 depicts the rheological properties of refrigeration oils.

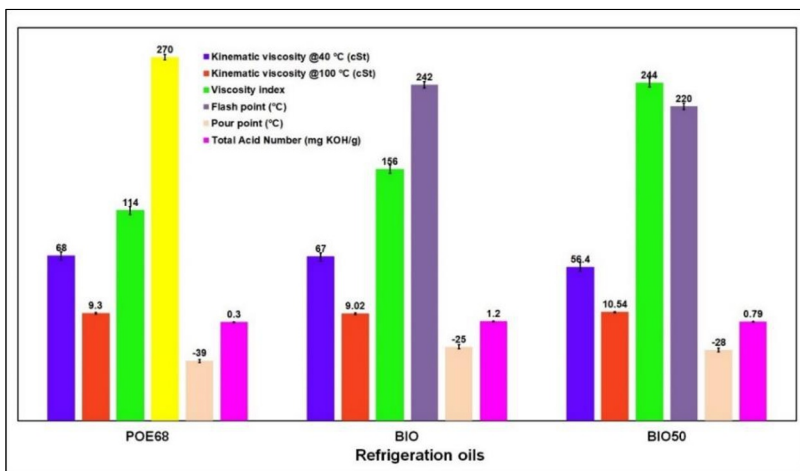


Fig. 1 Rheological Properties of refrigeration oils

2.2 Preparation of sustainable refrigeration oil/green refrigerant mixture

The preparation of a sustainable refrigeration oil/green refrigerant mixture is a critical step in experimental studies such as viscosity, density, and piezo-viscosity coefficient analysis because the

mixture must be accurate, homogeneous, and contamination-free. A High-pressure equilibrium cell /mixing chamber endowed with vacuum pump, charging manifold, pressure gauge is used for mixing the refrigeration oil and refrigerant. The mixing chamber is evacuated to deep vacuum for removing air and moisture. Inject the 240 ml of POE68/ biodegradable refrigeration oil and charge 10% refrigerant R134a/R600 (10% of the weight of lubricant by volume) into the equilibrium cell. Maintain the desired saturation pressure of approximately 0.2-0.5 Mpa and allow sufficient time 5 -15 hours for formation of oil-refrigerant mixture [1].

2.3 Thermal conduction coefficient measurement

The thermal conduction coefficient of the refrigeration oil and refrigerant mixture was measured by using KD2 PRO thermal property analyzer (Decagon Devices INC, USA). The measurement of the refrigeration oil and refrigerant mixtures through ASTM D5334-14 standard. The thermal conductivity of the refrigeration oils under the R134a and R600a atmosphere was studied from a temperature of 40°C to 100°C. The thermal conduction coefficient data were accounted for with the average value of three measurements for reducing the error developed.

2.4 Piezo-viscous coefficient study of Sustainable Refrigeration oil/green refrigerant mixture

The rheological properties of the refrigeration oil are modified by the existence of refrigerant in the refrigeration oil/refrigerant mixture. The film thickness values of the refrigeration oil/refrigerant mixtures were directly related the piezo-viscosity values of the mixture. A prescribed experimental apparatus will be used for measurement of the rheological characteristics of refrigeration oil/refrigerant combinations. A pressure-viscosity (piezo viscosity) coefficient of refrigeration oil and refrigerant mixture is intended to compute the piezo-viscous reaction of lubricants at the low-pressure property of the elastohydrodynamic lubrication (EHL) inlet zone. R600 which has good solubility with sustainable refrigeration oil will be used as a green refrigerant. To exemplify the relation between viscosity and the piezo-viscosity coefficient of the refrigeration oil /refrigerant mixtures, the Eyring equation [12] was used as provided in Eq. (1), and (2).

$$\alpha_{mix} = \frac{m s_{ref} (\alpha_{ref} - \alpha_{lub})}{s_{ref}^{(m-1)+1}} + \alpha_{lub} \dots\dots\dots (1)$$

$$\alpha = 0.1122 \frac{v_0^{0.163}}{10^4} \dots\dots\dots (2)$$

Where, $m = \frac{M_{lub}}{M_{ref}}$, component molecular weight, M_{lub} and M_{ref} are the molecular weight of the refrigeration oil and refrigerant respectively; α_{lub} and α_{ref} are the piezoviscosity of the refrigeration oil and refrigerant respectively; s - fraction content of refrigerant in the mixture; v_0 - kinematic viscosity. The value of m for different refrigeration oil/refrigerant mixture are listed in Table 1.

Table 1. Value of m for different refrigeration oil/refrigerant mixture

m	R134a	R600a
POE68	7.6	13.34
BIO	7.12	12.51
BIO50	6.97	12.24

3. Results and Discussions

3.1 Thermal conduction coefficient analysis

The thermal conduction coefficient of the refrigeration oil and refrigerant mixture was determined with a temperature ranging from 40°C to 100°C. Fig. 2 depicted the thermal conduction coefficient of the refrigeration oils under the R134a and R600a atmosphere. It was noticed from Fig. 2, that the thermal conductivity of all the experimented refrigeration oils/refrigerant mixture decreases when the temperature increases. This is for the reason when the oil is heated, the liquid expands and the molecules move apart may result in a reduced collision [13].

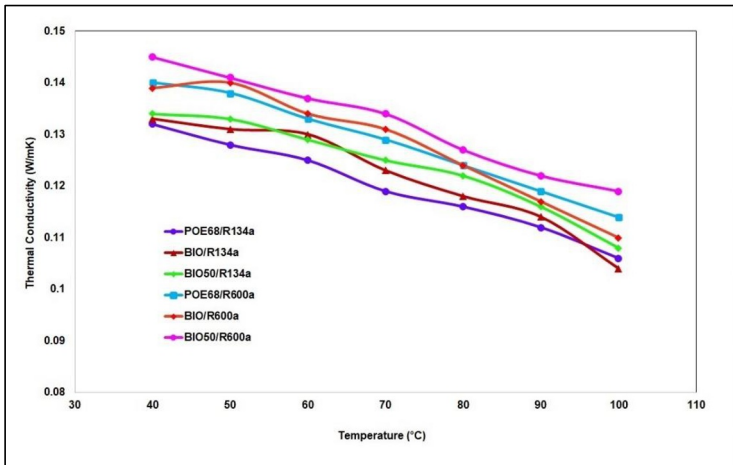


Fig.2 Thermal conductivity of refrigeration oils/refrigerant mixtures

For BIO50/R134a the thermal conductivity at 40 °C is raised by about 0.134 W/mK as compared to BIO/R134a and POE68/R134a for which the thermal conduction coefficient is 0.128 W/mK and 0.127 W/mK respectively. From Fig.2 it is observed that the BIO50/R600a exhibits a higher thermal conductivity of about 0.145 W/m K as compared to BIO/R600a and POE68/R600a for which the thermal conduction coefficient is 0.139 W/mK and 0.141 W/mK respectively. Among all the experimented refrigeration oils/refrigerants tested, BIO50/R600a showed higher thermal conductivity for the reason that a higher collision rate increases the energy exchange among molecules [14]. The thermal conductivity of BIO50/R600a was increased by about 8.96%, 8.27%, 7.59%, 3.44%, and 4.14% respectively as compared to POE68/R134a, BIO/R134a, BIO50/R134a, POE68/R600a, and BIO/R600a.

3.2 Piezo-viscosity coefficient analysis

The piezo-viscosity coefficient directly correlated to the solubility and viscosity of refrigerant in the mixture. Laesecke and Bair [15] reported that the lower piezo-viscosity value of refrigerants which do not help to produce the thick lubrication film. Normally, the refrigerant dissolved in the refrigeration oil was varied between 0 to 40% approximately in most of the refrigeration systems. The piezo-viscosity coefficient of the various concentrations was calculated with the use of mixture laws proposed by [16] when the value of m is known. The piezo-viscosity coefficient values of the refrigeration oil/refrigerant mixture from 0 to 100% as shown in Fig. 3. Considering the results of Fig.3, the predictions of Eq. (1) were agreed with the results of Bair [17]. It is noticed from Figure.3, among all the blends, BIO/R134a was showed the lower piezo-viscosity coefficient from 10 to 100%. Meanwhile, BIO50/R600a exhibit the comparable piezo-viscosity coefficient and better agreement for all of refrigerant dilution with refrigeration oil with POE68/R600a. In the context of BIO with POE68, the molecular asymmetry linked with their phase behaviour could be a reason for substantial deviations from the ideal solution behaviour agreed with the statement of Quinones et al [18]. For BIO50/R600a and POE68/R600a, the justification for the higher piezo-viscosity coefficient is due to the collective influence of the profound effect in the mixture transport properties and better binary interaction. This assessment of the mixture properties is a significant transitional step of film thickness in EHL contacts and result ensured that the piezo viscosity and viscosity of refrigeration oil/refrigerant mixtures which influence the trend of frictional behaviour.

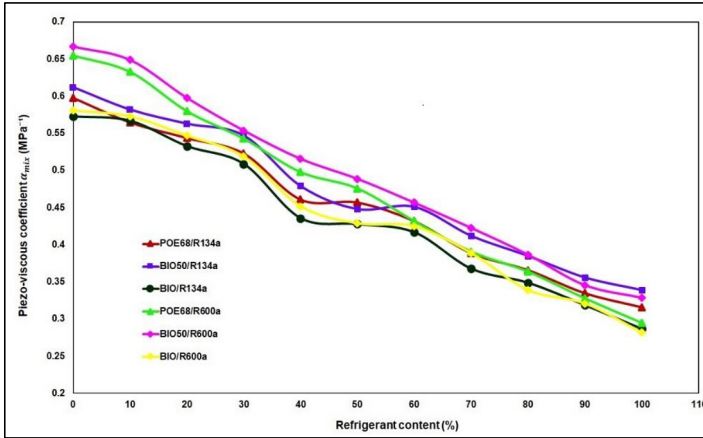


Figure. 3 Variation of piezo-viscosity coefficient and refrigerant dilution in refrigeration oils/refrigerant mixtures

3.3 Compressor operating conditions analysis

Fig.4 demonstrates the compressor inlet pressure of all tested refrigeration oils/refrigerants. The suction pressure of refrigeration oil/refrigerant mixture at the initial state increases gradually with time but after some time (say 40-50 min) the suction pressure stabilizes with time. It was observed from Fig.5, the lowest suction pressure was measured at BIO50/R600a. This is because of the superior thermal conduction coefficient of BIO50/R600a than the other combinations which enhance the refrigerant sub-cooling rate/superheating at the exit of condenser and evaporator. Figs. 5 and 6 show the discharge/delivery pressure and temperature of the refrigeration compressor for the experimented refrigeration oil/refrigerant combinations. At the beginning of the refrigeration cycle, both discharge pressure and temperature slightly increased for all the refrigeration oil/refrigerant blends and later stabilize and reach the steady-state. It was observed from Fig.5, BIO50/R600a showed reductions in compressor discharge pressure of 0.37 MPa and 4.5 °C as compared to all other refrigeration oil/refrigerant blends [19]. The reason behind the trend is that the higher thermal conduction coefficient conductivity of BIO50/R600a considerably augments the heat transfer characteristics in both condenser and evaporator.

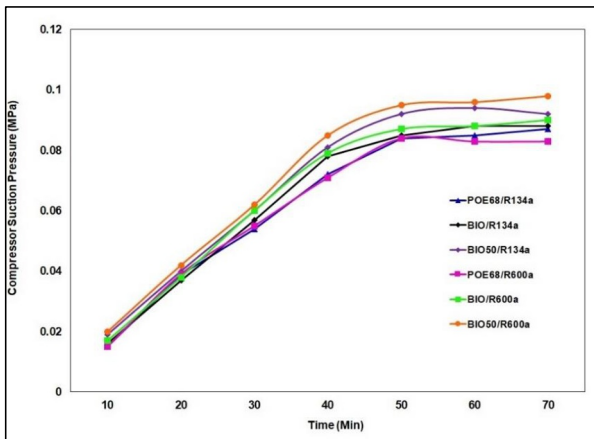


Fig.4. Compressor inlet pressure - time for refrigeration oil/refrigerant blends

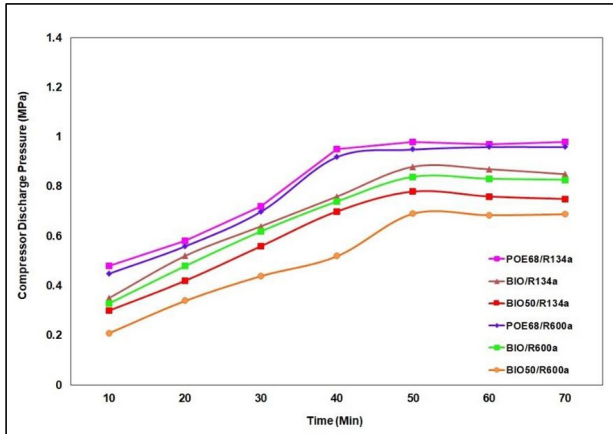


Fig.5. Compressor delivery pressure - time for refrigeration oil/refrigerant blends

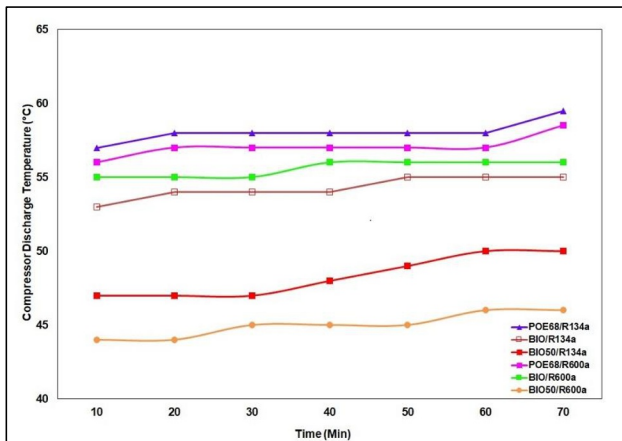


Fig.6. Compressor delivery temperature - time for refrigeration oil/refrigerant blends

It was noticed from Fig.6, BIO50/R600a showed reductions in compressor discharge temperature of 13 °C as compared to all other refrigeration oil/refrigerant blends. These confirmations assure that the lubricant/refrigerant mixture decreases the friction coefficient, leading to a reduction in the compressor discharge temperature, further resulting in improved performance of the refrigeration system [20]. Table.2 depicts the compressor operating conditions.

Table 2. Compressor Operating Conditions

Refrigeration oil/Refrigerant mixture	Suction Pressure (MPa)	Discharge Pressure (MPa)	Discharge Temperature (°C)	Evaporator Air Temperature (°C)
POE68/R134a	0.087	1.063	57	-10
BIO/R134a	0.079	0.854	60	-11
BIO50/R134a	0.092	0.751	48	-13.5
POE68/R600a	0.083	1.172	59	-10.5
BIO/R600a	0.089	0.827	58	-12
BIO50/R600a	0.098	0.689	44	-14.5

4.0 Conclusions

This investigation analysed the heat transfer and pressure-viscous behaviour of biodegradable refrigeration oil/green refrigerant for vapour compression refrigeration system. The thermal conductivity of the refrigeration oil/refrigerant mixture decreases with the intensification of temperature. The maximum thermal conductivity obtained was 0.145 W/m K for BIO50/R600a at 40°C. The thermal conductivity of BIO50/R600a was increased by about 8.96%, 8.27%, 7.59%, 3.44%, and 4.14% respectively as compared to POE68/R134a, BIO/R134a, BIO50/R134a, POE68/R600a, and BIO/R600a. The piezo-viscosity coefficient analysis for refrigeration oil/refrigerant mixture indicated that the refrigerant nature and concentration highly influence the pressure-viscosity behaviour. BIO50/R600a exhibit the higher piezo-viscosity coefficient with all other refrigeration oil/refrigerant mixtures.

Declaration of Conflicts Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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