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Thermodynamic and Heat Transfer Properties of Al_2O_3 Nanolubricants

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ABSTRACT

In vapor compression cycles, a small portion of the oil circulates with the refrigerant throughout the system components, while most of the oil stays in the compressors. In heat exchangers, the lubricant in excess penalizes the heat transfer and increases the pressure losses: both effects are highly undesired but yet unavoidable. Nanoparticles dispersed in the excess lubricant are expected to provide enhancements in heat transfer. While solubility and miscibility of refrigerants in polyolesters (POE) lubricant are well established knowledge there is a lack of information regarding if and how nanoparticles dispersed in the lubricant affect these two properties.

This paper presents experimental data of solubility and miscibility of three types of Al_2O_3 nanolubricants with refrigerant R-410A. The nanoparticles were dispersed in POE lubricant by using different surfactants and dispersion methods. The nanolubricants appeared to have slightly lower solubility than that of R-410A but actually the solid nanoparticles did not really interfere with the POE oil solubility characteristics. High viscosity suspensions are expected to stabilize the nanoparticles and avoid clustering. This aspect was verified in the present paper for the Al_2O_3 nanolubricants and long term stability and the degree of agglomeration, when present, were measured. The data identified optimum combinations of surfactants to achieve stable and uniform nanolubricant dispersions for several months. Surfactants affected slightly the thermal conductivity, specific heat, viscosity, and solubility properties of the nanolubricants. The specific heats of the nanolubricants were lower than that of POE oil at temperatures from 0° to 20°C while they were similar at 40°C. Thermal conductivity ranged from 1.1 times higher at 5°C to 1.4 times higher at 40°C than that of POE lubricant. The viscosity at nanoparticle concentration of 10 wt. % was 30 to 40 percent higher than that of POE oil. The thermal and viscosity data for three nanolubricants provided in this paper advance the basic understanding of nanoparticles interaction with R-410A refrigerant and POE lubricant mixtures.

1. INTRODUCTION

Energy consumption for heating and air conditioning of buildings and for refrigeration systems is a large contributor of the total energy consumption in United States (EIA, 2009). Nanolubricants -- a lubricant with dispersed nano-size particles -- have the potential to be a cost-effective technology for reducing the energy consumption of chillers that cools large buildings, of air conditioners used in residential homes, and of refrigeration systems for supermarket refrigeration. In these applications, vapor compression cycles provide heating and cooling and the working fluid is a refrigerant and oil mixture. A small amount of oil is needed to lubricate and to seal the moving parts inside the compressors. In heat exchangers the lubricant in excess penalizes the heat transfer exchange and increases the flow losses: both effects are highly undesired but yet unavoidable. Nanolubricants are of great interest because their unprecedented thermal transport phenomena surpass the fundamental limits of conventional macroscopic theories of multiphase flow and of in-tube heat transfer (Choi, 2009). Several researchers postulated that the magnitude of the heat transfer enhancement is much higher than the gain in the liquid thermal conductivity and that the nano-scale interactions between the nanoparticles and the refrigerant/oil liquid layers are responsible for the heat transfer intensification. Enhancements were observed in pool boiling (Wen and Ding, 2004, 2005b, Kedzierski, 2009a, 2009b, Peng et al., 2010) and in one experimental work for flow boiling in an horizontal tube (Bartelt et al., 2008). Work on nanolubriant is still in its infancy and this paper aims to provide new experimental data of fundamental thermal and transport properties for refrigerant R-410A and nanolubricant mixtures. Experiments were conducted to measure if sedimentation and agglomeration of the nanoparticles occurred. These are cited as operational challenges associated with the storage and usage of nanolubricants in vapor compression systems. Tests were also conducted to measure the thermal conductivity and specific heat of the nanolubricants at various nanoparticles concentrations in the polyolester (POE) lubricant. In addition, the solubility and miscibility of refrigerant R-410A with two types of nanolubricants that had the same Al_2O_3 nanoparticles but different surfactants and dispersion methods, were investigated.

2. LITERATURE REVIEW

Abundant literature exist on refrigerant and lubricant mixture properties and on water based nanofluids and a review of these topics is beyond the scope of the present paper. Instead the emphasis is on studies in the literature that focused on nanoparticles dispersed in high viscosity suspensions. To the authors' best knowledge, there is very limited information on the thermodynamic, thermal, and transport properties of nanoparticles in polyolesters (POE) lubricants and studies on their solubility and miscibility are basically missing in the open domain literature. Previous work in the literature for the properties investigated in this paper is briefly summarized next.

2.1 Nanoparticle sedimentation and agglomeration in large clusters

Two critical factors that must be characterized when developing nanolubricants for heat transfer enhancement are the potential for agglomeration of the nanoparticles in large clusters and for sedimentation of the nanoparticles on the heat transfer surfaces. The sedimentation due to clustering and agglomeration of nanoparticles was observed for some nanofluids (Wen and Ding, 2004). Agglomeration and sedimentation of nanoparticles in the lubricant might interfere with the heat transfer process (Das et al., 2003). Enhanced heat transfer surfaces increase heat transfer by using internal micro- and nano-grooves to augment turbulence near the tube wall (Cieslinski and Targanski, 2007). Nanoparticles that are immersed in the heat transfer fluid might deposit in the grooves creating a smoother surface (Bang, 2004). According to Das *et al.* (2003) the resulting smoother surfaces can cause a considerable deterioration of the heat transfer coefficient. From previous studies, it was observed that stable suspensions of nanoparticles had minimum sedimentation. To develop such stable suspensions, the base fluid had high viscosity such as the case with POE oils. The addition of dispersants and surfactants could prevent clustering and findings the correct combination of surfactants and dispersion methods often required a trial and error approach. The size of nanoparticles in suspensions is commonly measured by using a dynamic light scattering (DLS) method, also referred to as quasi-elastic light scattering technique.

2.2 Specific heat of nanolubricants

To authors' best knowledge there are very limited studies that provided data for the specific heat of nanoparticles dispersed in POE lubricant. Model for water based nanofluids are often used to predict the specific heat of nanolubricants but their accuracy was seldom verified. Nanofluids have lower specific heat than their base fluids and it can be estimated according to eq. (1), which valid for an ideal liquid-solid particle mixture:

$$c_{p(nl)} = \phi \cdot c_{p(p)} + (1 - \phi) \cdot c_{p(f)} \quad (1)$$

In several experiments, it was observed that the specific heat decreased if the volume concentration of nanoparticles, ϕ, increased. Specific heat also increased with increase in temperatures (Vajjha and Das, 2009). Experiments conducted by Murshed et al. (2008) used a double hot-wire technique to measure the effective specific heat of different types of nanofluids. Their study concluded that fluids with nanoparticles had lower specific heat than their base fluids, and that the values for specific heat decreased with increasing volume fraction of the nanoparticles. Puliti et al. (2011) presented a comprehensive literature review of nanofluids proprieties. For specific heat, most studies reported in Puliti et al. paper showed that nanofluids have lower specific heats than their base fluids. However some studies were also presented where the specific heat was higher than the base fluids.

2.3 Solubility and miscibility of refrigerant R-410A with nanolubricants

Solubility and miscibility of oil-refrigerant mixtures affects the density, viscosity, specific heat, and thermal conductivity of the liquid phase of the mixture. Studies conducted by Cremaschi et al. (2005) suggested that poor solubility and miscibility between oil and refrigerant, can cause a high amount of oil retention in evaporators and condensers. For oil-refrigerant mixtures, solubility and miscibility are well established knowledge and they depend on the temperature and pressure of the mixture. Solubility of refrigerant in oil can be determined by measuring the weight fraction of refrigerant present in the oil equilibrated at particular temperature and pressure conditions. Data for R-410A and ISO 32 acid POE oil solubility can be found in the ASHRAE Refrigeration Handbook (ASHRAE, 2010). It is unclear if nanoparticles dispersed in POE oil and the surfactants alter the degree of solubility of the refrigerant in the POE oil but some results for R134a and POE nanolubricants indicated slight variation (Bobbo et al., 2010).

2.4 Thermal conductivity and viscosity of nanolubricants

The increase of thermal conductivity of nanofluids due to the addition of nanoparticles was investigated by numerous researchers and a comprehensive review can be found in a paper by Buongiorno et al. (2009) and in a paper by Ozerinc et al. (2009). Nanofluids have often higher thermal conductivity than that predicted by the macroscopic theory. Venerus and Jiang (2011) pointed out that for systems composed of larger diameter nanoparticles (~30nm), there was a good agreement between the measured thermal conductivity enhancement and the one predicted by the classical

Maxwell-Garnett model. The thermal conductivity of nanolubricants was estimated in the literature by using Eq. (2) (Wen and Ding, 2005a, Cremaschi, 2012). Several existing models can be used to predict the thermal conductivity of the nanolubricant (Phillips et al., 1992, Buongiorno et al., 2009, Jain et al., 2009), and their viscosity (Venerus et al., 2010). An example for the viscosity of the nanolubricant and liquid refrigerant mixture is given in eq. (3) (Batchelor, 1977) where k_1 was 2.5 and k_2 was 6.2 and they were modified by Wen and Ding to account for the addition of nanoparticles in the base fluid (Wen and Ding, 2005a). Eq. (3) applies to suspensions of non-interacting particles with a concentration smaller than about 5% by volume. $\mu_{mix,liq}$ is the dynamic viscosity of the nanolubricant and liquid refrigerant mixture and it accounted for the nanolubricant solubility of the refrigerant at given saturation temperatures. Effects of metal oxide nanoparticles dispersed in oil suggest that both thermal conductivity and viscosity increase with the presence of nanoparticles but with different magnitude that depends on temperature range, volume fraction, and particle type (Cremaschi, 2012).

$$\frac{k_{nl}}{k_{POE}} = \frac{(1-\phi)\cdot\left(k_p + 2k_f\right) + 3\cdot\phi\cdot k_p}{(1-\phi)\cdot\left(k_p + 2k_f\right) + 3\cdot\phi\cdot k_f} \tag{2}$$

$$\mu/\mu_{mix,liq} = 1 + k_1\cdot\phi + k_2\cdot\phi^2 \tag{3}$$

3. EQUIPMENT AND INSTRUMENTATION

The nanolubricant samples were diluted in house with the equipment described next and the thermal and transport properties were measured with the instrumentation described in the following section.

3.1 Equipment used for diluting the nanoparticles in the base POE lubricant

Concentrated samples of nanolubricants were provided by the manufacturer and an ultrasonic mixer was used for diluting the concentrated samples to the desired solution of Al_2O_3 nanoparticles dispersed in the base POE oil. The net power output of the ultrasonic mixer was 750 Watts, at a frequency of 20 kHz. Different probes were used with this mixer based on the amount of nanolubricant prepared. For the processing of smaller samples, a ½ inch (13mm) diameter probe was used with a griffin beaker while for the processing of larger volumes of nanolubricants a graduated cylinder was used with a 1 inch (25 mm) diameter probe. The time of sonication varied from 8 hours up to 24 hours, depending on the amount of the nanolubricant that was diluted. The sonication was pulsed in cycle of 30 seconds on and 30 seconds off. The concentration of the Al_2O_3 nanoparticles in the POE oil, $w_{\%NL}$, was defined as weight percent of the nanoparticles in the total mixture, as shown in eq (4) below.

$$w_{\%NL}(wt.\%) = \frac{w_{Al_2O_3,solid\ nanoparticles}(g)}{w_{Al_2O_3,solid\ nanoparticles}(g) + w_{POE,oil}(g)} \times 100 \tag{4}$$

3.2 Equipment for measuring the nanoparticle sizes in dispersion in base POE lubricant

A DLS nanosizer was used for measuring the size of the nanoparticles when they were in suspension in the POE lubricant. The device was capable of measuring particles size ranging from 4 nm to 10 µm diameter. The temperature of the samples was close to room temperature for all the particle size measurements of the present work. The DLS nanosizer used an electrophoretic light scattering technique with a He-Ne laser of 633 nm wavelength. An interface software of the nanosizer was used to correlate the back scattering reflection intensity of the laser to the mean particle size in the liquid sample. The nanoparticle diameter can be estimated once the modal distribution of the nanoparticles in the liquid sample is known and by assuming nanoparticles of spherical shape. It should be noted that the nanolubricant was further diluted with POE oil to concentration of less than 1 wt.% before measuring the particles size. This improved the repeatability and accuracy of the measurments by using the nanosizer. The dilution of the nanolubricants with POE oil was conducted very slowly in order to not affect the size of the nanoparticles in the original sample.

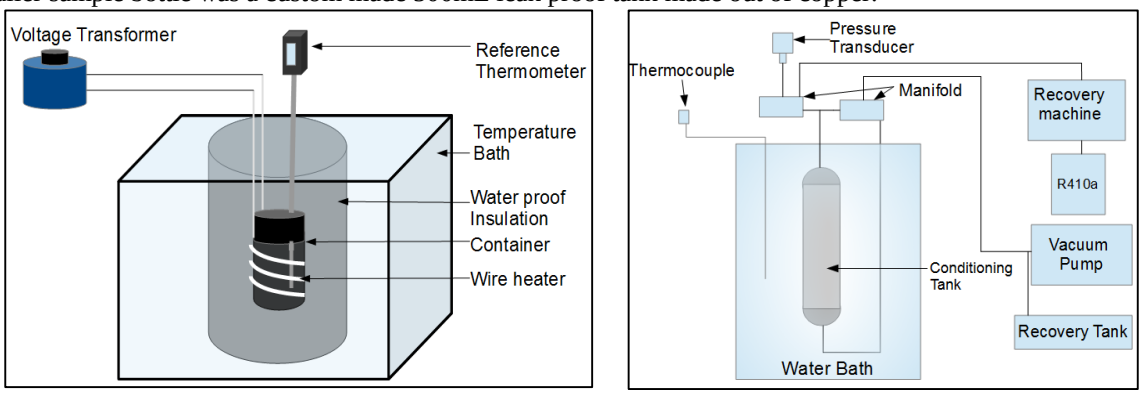
3.3 Equipment for measuring the specific heat of nanolubricants

The equipment for measuring the specific heat of the nanolubricant was custom built in the present work and it is shown schematically in Figure 1a. It consisted of three main components: a temperature bath, a small steel container for the nanolubricant, and an electric heater. A custom made cylindrical stainless steel container of 150 mL of internal volume was used to store the nanolubricant during the experiments. The temperature bath controlled the boundary temperature conditions around the insulated steel container. A wire heater rated 60 W at 120V AC provided heat to the small steel container and a variable voltage transformer regulated the power to the electric heater that was firmly

wrapped around the walls of the steel container. A precision multi meter measured voltage, current, and resistance across the heater. Temperature measurements were made by using a precision thermometer with a resolution of 0.01°C and an accuracy of ±0.06°C. The probe was immersed in the center of the nanolubricant container. Adiabatic conditions around the small steel container were obtained by insulating the container with about 2 cm thick layer of rubber flexible foam insulation and by immersing the container in the water temperature bath. A plastic water jacket was installed around the insulation to avoid water ingress into the insulation.

3.4 Equipment for measuring the solubility of refrigerant R-410A in nanolubricants

The equipment for measuring the solubility of refrigerant in nanolubricant was custom build in the present work and it is schematically shown in Figure 1b. It consisted of mainly four components: a temperature bath, a large reservoir, a smaller sample bottle, and a pressure transducer. A vacuum pump was used for depressurization of the large reservoir. A precision scale with an accuracy of ±0.2g measured the weights. The large reservoir was a stainless steel tank with a working pressure of 1800 psig (12410 kPa) and with a 1 gallon (0.0037 m^3) volumetric capacity. The smaller sample bottle was a custom made 500mL leak proof tank made out of copper.



(a) (b)

Figure 1: Experimental setups for measuring specific heat (a) and solubility (b) of nanolubricants

3.5 Instrumentation for measuring the thermal conductivity of nanolubricants

The instrumentation for measuring the thermal conductivity of the nanolubricant included a thermal conductivity probe and a temperature bath. The thermal conductivity probe had a build-in controller and it measured the thermal conductivity of the nanolubricant based on a double hot-wire technique. The accuracy of the probe was ±0.01 W/(m-K) for a range of thermal conductivity from 0.02 to 0.2 W/(m-K).

4. EXPERIMENTAL METHODOLOGY

4.1 Procedure for measuring the nanoparticle sedimentation and agglomeration

The procedure for conducting the sedimentation tests included the preparation of the nanolubricant samples, the storage of the samples, and the measurements of samples with few droplets of the nanolubricant taken from the bottom of the containers and from the top of the containers used to store the nanolubricant test specimens. The measurements of particle size was performed using the nanosizer. Each type of nanolubricant was tested at two nanoparticle concentration of 0.5 wt% and 1 wt% and each sample was about 80 mL in volume. A 100mL beaker was used, and the dry weight of the beaker was measured first. The mass of POE oil required was added into the beaker using a 10 mL syringe. The concentrated solution of nanolubricant was then added to the POE oil in order to achieve the required concentration according to eq. (4). Ultrasonic mixing was conducted for 24 hours with pulse on/off cycle of 30 seconds. Small droplets of nanolubricant were taken from the top and from the bottom of the 100mL container by using a micro syringe. The particles size were measured every 2 weeks for a period of six months.

4.2 Procedure to measure the specific heat of the nanolubricants

Limiting the heat loss was crucial for the measurements of the specific heats of the nanolubricants. The container with the nanolubricant was sealed and a thermometer was fixed in the container by using an air tight sealing putty. This container was insulated and immersed in the thermal bath. Then the heater was switched on and timed. The voltage transducer was dialed up to 60 Volts and the fluid temperature increased. Four different temperature ranges were taken, from 2 to 12°C, from 12 to 22°C, from 22 to 32°C, and from 32 to 42°C. After each final temperature was

reached, the heater was turned off, the time was stopped and the entire system was allowed to come to thermal equilibrium. The water was stirred slightly in order to promote even temperature distribution on the nanolubricant sample. For each temperature range, the temperature of the bath was set at the initial temperature of the range. This ensured repeatability of the experiments and limited the heat losses from the container.

4.3 Procedure to measure the solubility of refrigerant R-410A in the nanolubricants

The solubility tests were conducted by measuring the weight of refrigerant in solution with the nanolubricant. A tank was submersed in a large water bath and the temperature of the water was controlled. The tank was depressurized to approximately 1.5 psia (10.34 kPa) by using a vacuum pump. 200mL of nanolubricant was introduced in the tank through a Schrader valve located at the bottom. Refrigerant R-410A was also introduced into the tank through the bottom valve of the tank until the required pressure was achieved. The mixture was allowed to reach thermal equilibrium and the temperature of the bath was monitored by using a T-type thermocouple, and the pressure was monitored by using an absolute pressure transducer. A recovery tank was then depressurized to a pressure of about 1 psia (6.8 kPa) and the tare weight of the recovery tank was measured and recorded. A sample of the refrigerant-nanolubricant mixture was extracted from the main tank into the recovery tank and the weight of the mixture inside the recovery tank was recorded. Then, the refrigerant was slowly removed until the pressure in the recovery tank was approximately 1 psia (6.8 kPa). The remaining weight of the nanolubricant inside the recovery tank was measured and recorded. The weight of the refrigerant removed out of the recovery tank divided by the weight of the refrigerant and nanolubricant mixture inside the recovery tank is defined as the weight percent of refrigerant R-410A in the nanolubricant sample, as shown in Eq.5.

$$w_{\%ref}(\,wt.\%\,) = \frac{w_{ref}(g)}{w_{NL}(g) + w_{ref}\,(g)} \times 100 \tag{5}$$

4.4 Procedure to measure the thermal conductivity of the nanolubricants

The nanolubricant liquid sample was placed in a small container provided by the manufacturer of the thermal conductivity probe. The container was immersed in a thermal bath in order to control the sample temperature. For each measurement the temperature bath was switched off immediately before immersing the thermal conductivity probe in the nanolubricant sample. Also the container was placed far away from any air diffuser of the room. All efforts were made to limit forced convection effects due to the vibrations and air movement. Thermal conductivity was measured by immersing the probe in the nanolubricant sample. Each measurement took few minutes for achieving thermal equilibrium of the nanolubricant with the probe and each measurement was repeated at least 3 times.

5. CALIBRATION, BASELINE TEST RESULTS, AND UNCERTAINTY ANALYSIS

For specific heat and solubility tests, in which newly developed test apparatuses were used, preliminary experiments were conducted by using water and by using POE oil in order to calibrate the instrumentation and refine the test procedures. A completely adiabatic system was never achieved during the specific heat tests of this work and three sets of calibration tests were performed to estimate the heat losses from the container of the POE oil inside the temperature bath and to confirm the repeatability of the tests. The calibration experiments showed that the heat losses were small (but not negligible!), measurable, and fairly constant. Using a heat loss correction factor, the specific heat of POE lubricant was measured and the data in this work were within 3% agreement when compared to values predicted from correlations in the literature (Thome, 1995). Similarly, preliminary tests were conducted to estimate the solubility of refrigerant R-410A in POE lubricant by using the developed test apparatus. After few refinements of the mixing and sampling procedures, the data of solubility from the present work for refrigerant R-410A and POE lubricant were within 5% agreement with respect to the Cavestiri's relations (ASHRAE, 2010). The uncertainty in the measurements was estimated according to uncertainty propagation analysis (Taylor and Kuyatt, 1994) and the uncertainties calculated for each measurement type are given in Table 1. Uncertainty bars are reported in each figure of the result and discussion section for representative data points.

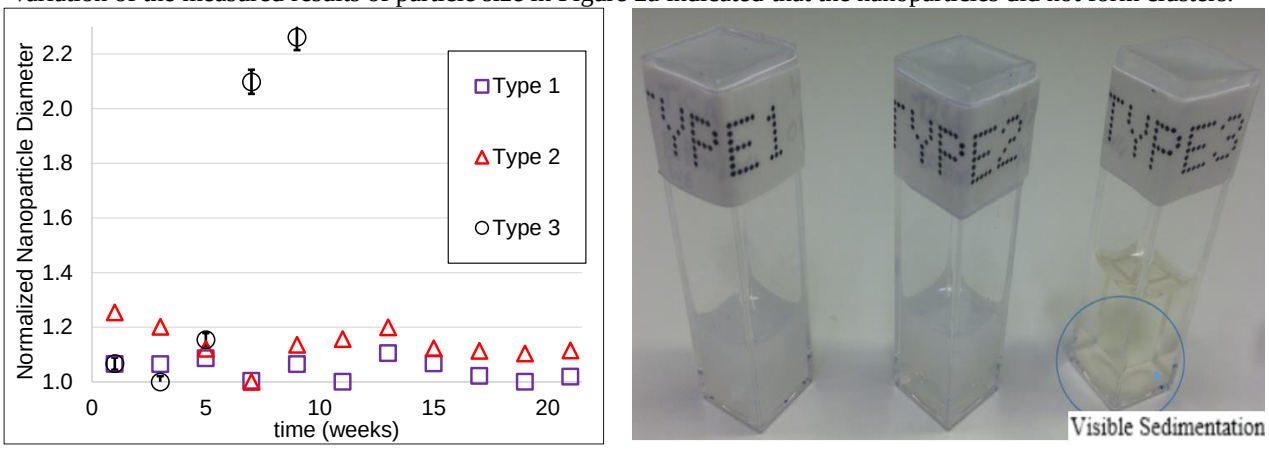
Table 1: Uncertainty of the experimental measurements of the nanolubricants proprieties

Test	Measurement objective	Max Uncertainty
Sedimentation	Nanoparticle size	±2%
Solubility	Weight percent of refrigerant in the nanolubricant	±1.2%
Specific Heat	Specific heat of the nanolubricant	±2.3%
Thermal Conductivity	Thermal conductivity of the nanolubricant	±7.2%

6. RESULTS AND DISCUSSION

6.1 Sedimentation and agglomeration test results

Sedimentation and agglomeration tests were conducted for three types of nanolubricants (type 1, type 2, and type 3) that shared the same solid nanoparticles but had three different type of surfactants and dispersants. The nanoparticle agglomeration tests results are shown in Figure 2a. The x-axis represents the time in weeks and the y-axis shows the nanoparticle mean diameter, which was normalized with respect to the minimum mean diameter measured for each type of nanolubricant during the entire test period. The variation of normalized diameter between 1 and 1.2 in Figure 2a was due to the statistical distribution of the nanoparticle sizes in the sample placed inside the nanosizer and due to the laser interference created by the polymer material of the transparent cuvette inside the nanosizer. Thus, this variation of the measured results of particle size in Figure 2a indicated that the nanoparticles did not form clusters.



(a) (b)

Figure 2: (a) Sedimentation test results for three types of nanolubricants and (b) visual observation of sedimentation for type 3 nanolubricant

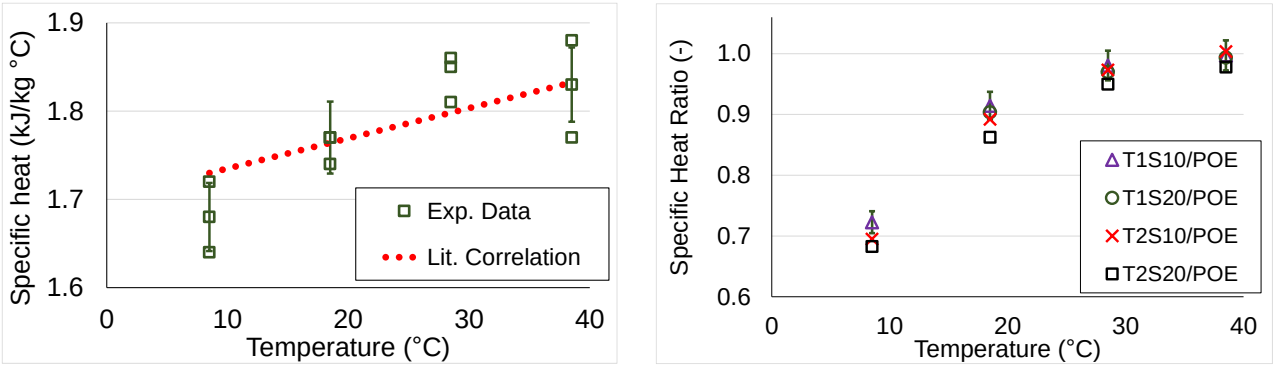
The concentration of the nanolubricant samples for the sedimentation and agglomeration tests reported in Figure 2a was 1 wt. % but similar results were obtained for nanoparticle concentration of 0.5 wt%. These samples represented the least viscous nanolubricants and thus, they were the worst case scenario for testing if sedimentation and agglomeration of the nanoparticles could occur in POE oil. Type 1 and type 2 nanolubricant samples, which had the same Al_2O_3 nanoparticles but different surfactants, showed that the nanoparticle diameter did not increase over a 22 week period. Because the nanoparticle diameter was similar for both top and bottom regions of each container storing type 1 and type 2 nanolubricants, we also concluded that there was not any agglomeration of the nanoparticles in large clusters. Visual confirmation of these results are shown in Figure 2(b) in which the suspensions appears uniform in color and in consistency everywhere. Type 3 nanolubricant, which had same Al_2O_3 nanoparticles but used a different surfactant, showed some agglomeration as reported in Figure 2a for the round data points. Sedimentation was also observed as shown in Figure 2b type 3 within the blue solid circle at the bottom of the transparent cuvette. The particle sizes for type 3 increased with time; it started from a size ratio of about 1 and increased gradually up to about 2.3 over 8 weeks period. These measurements indicated that the particles agglomerated and sedimentation occurred for type 3 nanolubricant. The samples for type 3 were taken from the bottom of the container where the largest concentration was measured due to sedimentation effects. The top of the container for type 3 nanolubricant was basically POE oil only and appeared transparent and POE liquid like.

It should be noted that the nominal Al_2O_3 nanoparticle size in the dry state conditions was about 40 nm according TEM measurements provided by the manufacturer. However, the DLS nanosizer measured particle sizes of 170 to 200 nm for the type1 and type 2 nanolubricant samples and particle size of about 800 to 2000 nm for the type 3 nanolubricant sample. These measurements of the particle size by using a nanosizer were also confirmed by the manufacturer when similar DLS technique was adopted to characterize the particle size.

6.2 Specific heat test results

The specific heat of POE oil is showed in Figure 3a and the measured data (square points) and the literature values (Thome, 1995) (dashed line) are plotted for a temperature range from 10 to 40 °C. The ratio of the specific heat of the nanolubricants type 1 and type 2 at concentration of 10 and 20 weight percent over the specific heat of POE oil at the same temperature are given in Figure 3b. The specific heat of the nanolubricants were lower than that of POE oil

and the difference was greater at temperatures of about 10°C. When the temperatures were closer to 40°C the nanolubricants had similar specific heat as to the one of the POE lubricant. Increasing the concentration of the nanoparticles in the lubricant decreased the specific heat slightly and the difference was within the experimental uncertainty of the test apparatus.

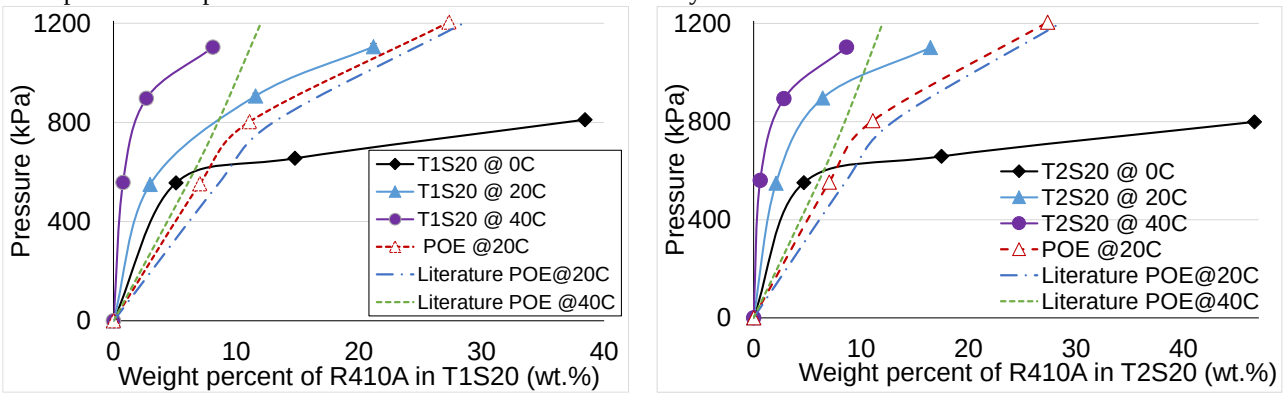


(a) (b)

Figure 3: (a) Specific heat vs. temperature for POE oil and (b) Specific heat ratio vs. temperature for the nanolubricants

6.3 Solubility test results

Figure 4 shows the solubility test results obtained for the nanolubricants with refrigerant R-410A. The weight percent of R-410A in nanolubricant is plotted on the x-axis and pressure on the y-axis. Each line represents a specific temperature and the symbols show the actual data points taken in the present work. The dashed lines represent the literature correlations (ASHRAE, 2010) and the triangular data symbols represent the baseline series of experiments conducted in the present work. These baseline series were used to compare the behavior of the nanolubricants at same temperature and pressure conditions with the POE oil solubility characteristics.



(a) (b)

Figure 4: Pressure vs. refrigerant concentration in wt. % of R-410A in (a) T1S20 and in (b) T2S20 nanolubricants

Both type 1 and type 2 nanolubricants had lower solubility than that of POE oil with no nanoparticles (and with no surfactants). For example, at 400 kPa and 20°C the solubility of R-410A in nanolubricant type 1 was less than 2% while the solubility of R-410A in POE oil was close to 5%. The solid particles seemed not to interfere with the refrigerant dissolving process in the POE oil. The remaining weight of the material inside the recovery tank at the end of the refrigerant recovery process was higher with nanolubricants because of the solid nanoparticles dispersed in the oil. As a result, the solubility of the nanolubricant calculated according to Eq. 5 appeared to be slightly lower than that of POE oil but actually the solid particles did not really interfere with the POE oil solubility characteristics. T1S20 had R-410A solubility up to 38.5% at approximately 0°C and 800kPa. T2S20 showed lower solubility at 20°C relative to T1S20 and both nanolubricants showed about the same solubility characteristics at 40°C.

6.4 Thermal Conductivity test results

The thermal conductivity of POE lubricant is shown in Figure 5(a) and the ratio of thermal conductivity of each nanolubricant over that of POE oil at the same temperature is shown in Figure 5(b). Although there are scattered data in Figure 5(a), it appears that the POE oil thermal conductivity decreased slightly if the temperature increased from 5

to 30°C. Figure 5(b) shows that the highest thermal conductivity was measured for the T2S20 nanolubricant sample followed by T1S20 sample. These samples had the highest concentration of Al_2O_3 nanoparticles of 20 wt. % and their thermal conductivity ranged from 1.1 times higher at 5 °C to 1.4 times higher at 40 °C than the thermal conductivity of POE oil at similar temperature. The sample T2S10 showed a higher thermal conductivity relative to T1S10 and both had the 10 wt.% percent Al_2O_3 nanoparticles concentration. It appears that the surfactant that was used to stabilize the nanoparticles had an effect on the thermal conductivity of the nanolubricant. This is evident from the T2S20 and T2S10 data, which had higher thermal conductivity in both 10 and 20 weight percent concentrations when compared their Type 1 sample counterparts.

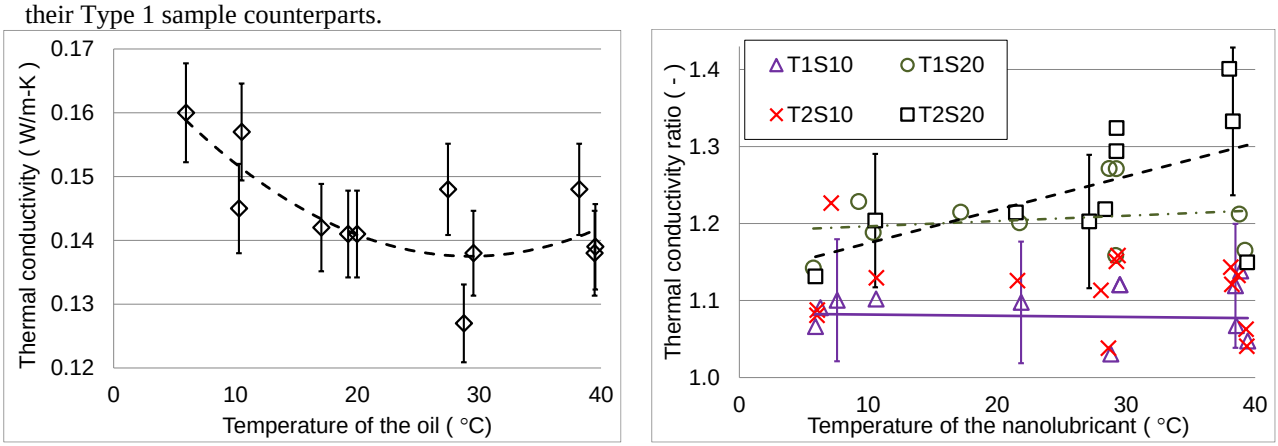


Figure 5: (a) Thermal conductivity vs. Temperature for POE oil and (b) Nanolubricant-POE thermal conductivity ratio

6.5 Viscosity test results

The viscosity of the nanoubricants was measured by using a Cannon-Fenske type viscometer. The viscosity of both type 1 and type 2 nanolubricants at nanoparticle concentration of 10 wt. % was similar and it was 30 percent higher than that of POE lubricant if the temperature ranged from 20°C to 45°C and 40 percent higher when the temperature was 0°C. The viscosity of nanolubricant type 1 with nanoparticle concentration of 20 wt. % ranged from 1.3 times higher if the temperature was 20°C to 1.6 times higher than that of POE oil when the temperature was 0°C. At similar temperature and nanoparticles concentration of 20 wt. %, the viscosity of nanolubricant type 1 was about 8 to 16% lower than that of nanolubricant type 2. The difference in viscosity between the two types of nanolubricants decreased if the nanoparticle concentration was 10 wt. % or lower. The viscosity of type 3 nanolubricant was about twice of that of nanolubricant type 1. These results showed that the surfactants affect the viscosity of the nanolubricant and their impact of viscosity becomes significant if the nanoparticles concentration was higher than 10 wt. % and the temperature decreased below 20°C.

6.6 Miscibility test results

The refrigerant and nanolubricant mixtures were tested for miscibility at concentrations that ranged from 95/5% to 30/70% and for temperature that ranged from-30°C to 60°C. For type 1 nanolubricant at concentration of 5 wt. % and 10 wt. % of nanoparticles (i.e., T1S5 and T1S10 samples), the results indicated that miscibility was mainly dependent on the temperature. Both samples were miscible at 80/20% for a temperature range of -30 to 50°C but immiscible for temperature of 55 to 60°C. At any other refrigerant/nanolubricant concentration, T1S5 and T1S10 samples were miscible with refrigerant R-410A and the solid nanoparticles remained well dispersed in the solution The nanolubricant T1S20 sample was miscible at a concentration of 60/40% from -30 to 55°C. At a refrigerant/oil concentration of 30/70% the T1S20 samples were miscible for the entire range of temperatures. The type 2 nanolubricant experienced precipitation of the solid nanoparticles when refrigerant was introduced in the nanolubricant samples.

7. CONCLUSIONS

Work on nanolubricant is still in its infancy and this paper aims to provide new experimental data of fundamental thermal and transport properties for refrigerant R-410A and nanolubricants mixtures. Experiments were conducted to measure if sedimentation and agglomeration of the nanoparticles occurred. Tests were also conducted to measure the thermal conductivity, specific heat, and viscosity of the nanolubricants at various nanoparticles concentration and that

shared the same Al_2O_3 nanoparticles but had different surfactants and used different dispersion methods. Solubility and miscibility of refrigerant R-410A and nanolubricants were measured for temperature ranging from 0°C to 40°C. The results showed that surfactants play a critical role in preventing agglomeration and sedimentation of the nanoparticles dispersed in the POE oil. Two out of three surfactants used in the present work were successful to prevent agglomeration in POE oil while one type of surfactant was ineffective and large clusters were observed. The specific heats of the nanolubricants were lower than that of POE oil at temperatures of 0° to 20°C while they were similar at 40°C. Thermal conductivity was 1.1 times higher at 5 °C and increased up to 1.4 times higher at 40 °C than that of POE lubricant. The viscosity at nanoparticle concentration of 10 wt. % was 30 to 40 percent higher than that of POE oil. The surfactants affected the thermal conductivity, viscosity, and the solubility and miscibility. The nanolubricants appeared to have slightly lower solubility than that of R-410A but the solid nanoparticles did not really interfere with the POE oil solubility characteristics. The thermal and viscosity data for three nanolubricants provided in this paper advance the basic understanding of nanoparticles interactions with the refrigerant R-410A and POE lubricant mixtures.

NOMENCLATURE

c_p	:	Specific Heat, (kJ/kg-°C)
k	:	Thermal conductivity, (W/m-°C)
μ	:	Dynamic Viscosity, (Pa-s)
w	:	Weight, (g)
w%	:	Concentration in weight percent, (wt. %)
ϕ	:	Nanoparticle volume fraction (-)
T1S5	:	Type 1 nanolubricant with 5 wt. % conc. of nanoparticles
T1S10	:	Type 1 nanolubricant with 10 wt. % conc. of nanoparticles
T1S20	:	Type 1 nanolubricant with 20 wt. % conc. of nanoparticles
T2S10	:	Type 2 nanolubricant with 10 wt. % conc. of nanoparticles
T2S20	:	Type 2 nanolubricant with 20 wt. % conc. of nanoparticles

Subscripts

Al_2O_3	:	Al_2O_3 Nanoparticles
f	:	Fluid
Mix,liq	:	Liquid mixture
nl	:	Nanolubricant
p	:	Nanoparticle
POE	:	Polyolester Oil
Ref	:	Refrigerant

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