A Study of Nanoparticle Additives On The Performance Of The AH-64 Intermediate Gearbox Lubricant to Achieve CBM Objectives

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Abstract— **Nano-Particle additives are thoroughly investigated due to their promising attributes for lubrication improvement in the Intermediate Gearbox of the AH-64. This paper discusses the evaluation of the effective thermal conductivity and effective dynamic viscosity for nano-composite enhanced transmission Mobile AGL Oil. Experimental results using a unique transient method and viscometer showed significant thermal and rheological improvements of the Oil respectively due to the nano-particle additives. To capture the transport phenomena effectively, two new models based on the effective approach method [14] have been developed to describe non-spherical particles. These continuum models take into account the effects of particle size, particle shape, temperature, layering at the liquid-solid interface and thermo- hydrodynamic effects. The theoretical predictions from the effective thermal conductivity model and effective viscosity model agreed with the experimental data. In order to validate the versatility and goodness of the proposed models, different experimental data and models taken from literature are compared against model results from the current work and confirm that the presented model closely agrees.**

Keywords—Nano-Particles, Oil, thermal conductivity, gear, viscosity, CBM

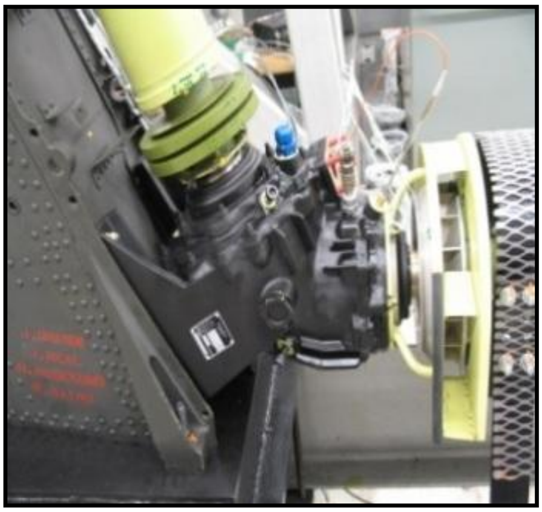
I. INTRODUCTION

Background

Since 1998,, the University of South Carolina (USC) has been strongly collaborating with the South Carolina Army National Guard (SCARNG). Combined efforts between two parties led to a fully developed CBM Research Center within the USC Department of Mechanical Engineering that hosts several aircraft component test stands in support of CBM objectives. At the USC facility, various AH-64 tail rotor drive train (TRDT) components are tested to provide a scientific understanding of various failure modes and other parameters. The work in this paper addresses lubrication improvement for the Intermediate Gearbox (IGB) of the TRDT (Figure 1) of the AH-64 drive train. Upon the addition of a lubricant in the gearbox, a fluid film is formed between the side surfaces that protect against friction, wear, vibration and noise. For the fully developed elastohydrodynamic lubrication regime in the gearbox, operational characteristics of the lubricant always play a major role in protecting the surfaces through shearing and sliding [1].

Early lubrication and friction research studied the impact of viscosity-temperature effects on lubrication in elestohydrodynamic contacts using Newtonian liquids. Crook al. [2] reported the importance of viscosity and temperature in a lubricant film of a Newtonian fluid rubbing between two surfaces. Dyson et al. [3] studied the frictional traction of a Newtonian fluid in the elastohydrodynamic contacts. He concluded the importance of temperature and viscosity variations in reducing friction at high speeds.

(a)



(b)

Figure 1. (a) IGB on an AH-64 Helicopter and (b) IGB on USC Tail Rotor Drive Train test stand

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The work of Petrov was the key turning point in the history of lubrication that revealed the importance of the lubricant's viscosity in protecting surfaces from friction, noise and temperatures. Goodman et al. [4] performed a series of experiments at the USC-CBM test stand on AH-64 tail rotor gearbox (TRGB) to study the leakage of grease lubricant through seeded fault testing. Major findings and discoveries resulted in new condition indicators (CIs) of thermal and vibration signatures. These CIs are model based parameters derived from condition monitoring algorithms and reflect physical phenomenon like gear mesh frequencies, amplitude, ball spin frequency, etc. Results demonstrated that the change in rheological features of the lubricant's viscosity significantly impacted vibration signals and CIs [4, 5].

Another experiment performed by Goodman on a seeded fault IGB was tested and has shown critical over temperature signals above the cut off threshold of 295 deg. F [5]. Nooli et al. [6] studied the drastic rheological changes on the grease lubricant to identify its functional properties during the operation of the system. His work concluded that changes in the rheological features of the non-Newtonian lubricant used in the IGB and TGB are due to the shear-viscosity properties rather than the temperature effects. Bayoumi et al. investigated the feasibility of Oil in the IGB instead of the traditionally used grease. The work was originally devised through The Aviation Engineering Directorate (AED) that had found multiple faults in the field that led to 169 maintenance actions and five IGB removals [8]. Results showed grease dissipating less heat and led to higher temperatures as well as significant drops in viscosity compared to Oil. The work concluded the importance of additional studies to be conducted to show the potential of Oil lubricant in the IGB.

Problem Definition

The detection of lubricant leaks and loss of operational characteristics such as viscosity in a gearbox of the AH-64 drive train gearboxes is a major problem that can lead to emergency landing of the entire aircraft for a thorough inspection on the component. Historically this is one of the most common maintenance faults for these particular drive train gearboxes that negatively impact CBM practices and airworthiness [4]. Lubricant leaks in the gearbox can lead to the rupture of the film between meshing gears and eventually more friction induced vibration, higher CIs, higher temperature performance and power loss. The works presented in the literature [4-7] discuss the impact of the operational characteristics of the lubricant on vibration, friction, CIs and temperature, but does not attempt to improve the lubricant properties through nano-particle (NP) additives. Ultimately, the thermo-physical properties of the lubricant have to improve for better performance of the gearbox.

The objective of this paper is a novel approach to study the effect of utilizing conductive NP additives incorporated in a selected IGB lubricant Oil, Mobile AGL. Lubricants that contain NP are known as nano-fluids, which are colloidal suspension of particles in the neighborhood of 10-100 nm. The mechanisms of the interaction of the particles in a solution are liquid layering at the interface and hydrodynamic effects. These are the main reason for the improved thermal conductivity and viscosity of the lubricant [9]. In the gearbox, the nano-fluids are expected to lower the temperatures due to friction at a given heat flux and protect against wear, friction and vibration

II. EXPERIMENTAL

In this work, a new lubricant for Apache drivetrain gearboxes with different NP concentrations is studied. The thermal conductivity and viscosity of nano-composite transmission AGL Oil are evaluated experimentally and theoretically.

Materials

Mobile AGL are a group of synthesized oils that are extensively used as lubricants and coolants in various military and aerospace applications. Seven Different concentrations of NP samples dispersed in Mobile AGL were analyzed by means of two different experiments for the purpose of determining the effectiveness of the nano-fluid. Both base Oil and Oil containing NPs are tested and compared against each other.

Thermal conductivity

A unique transient technique is developed to evaluate the thermal conductivity of the nano-samples under static conditions. The experimental set up consists of a test tube heated in constant temperature bath at 40 deg. C. An Oil sample is injected at the center of the test tube (Figure 2). The Oil is gradually heated and temperature at the center will be measured and recorded with time, until it reaches equilibrium with the bath temperature. The thermal conductivity at the center is calculated from time-temperature profile.

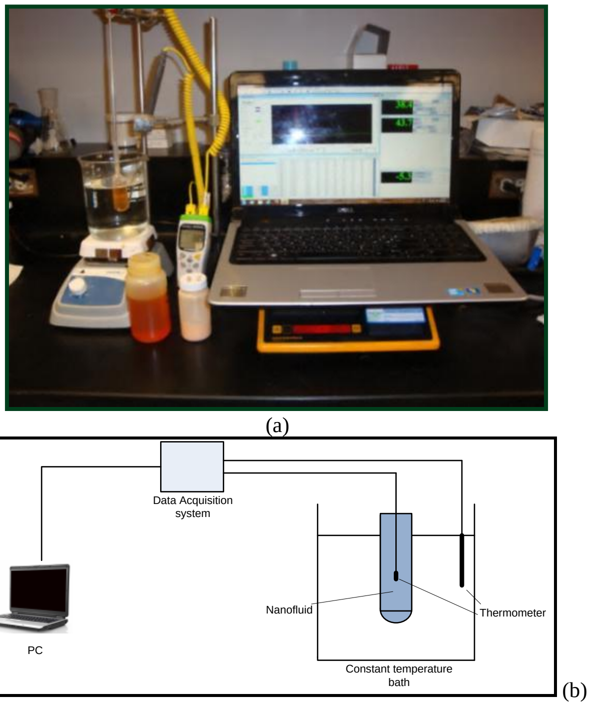


Figure 2. (a) Experimental set up and (b) Schematic representation for thermal conductivity experiment

Experimental results in Table 1 demonstrate the potential of the improved thermal conductivity of the nano-samples for gearbox application, reaching a 30 % increase in K value compared to its base oil.

TABLE I. THERMAL CONDUCTIVITY RESULTS OF SEVEN NANO-SAMPLES

Samples	*K(W/mK)*	*Concent (%)*	*% increase*
Base oil	137.8	0	-
NG-1A	142.8	0.5 %	3.6
CG-1A	145.6	1.5%	5.6
NG-1B	159	1.5 %	15
XG-2A	165.8	1 %	20
XG-1A	173	1 %	25.5
XG-1B	178	1.5 %	29
XG-0A	179.4	0.5 %	30

Dynamic Viscosity

The dynamic viscosity is measured using a viscometer (NDJ-8S) at constant speed of 60 rpm and temperature of 30 deg.C. A single measurement of viscosity is taken every 12 minutes for two hours. This experiment can be very similar to the final step in a gearbox when the lubricant is subjected to a steady shear rate. Viscometer results show improved viscosity compared to base Oil (Figure 3). This can be attributed to the Brownian and hydrodynamic effects [17]. The slight deviation from Newtonian behavior for some of the samples is likely due to the aggregates of particles as clusters and sedimentation.

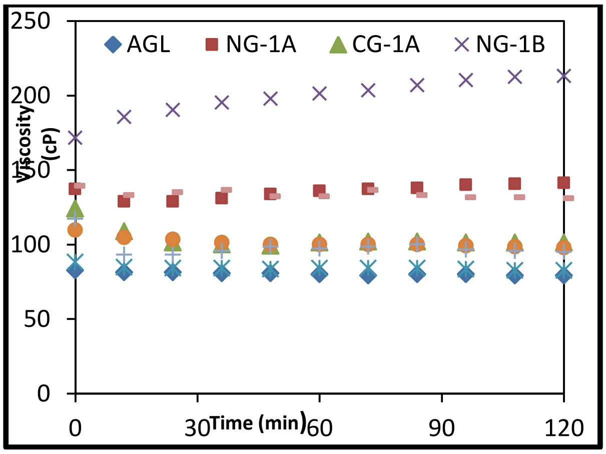


Figure 3. Viscometer results for AGL dispersions

III. Theoretical

Two continuum models are developed for the effective thermal conductivity and effective viscosity. The models take into account the liquid layering and hydrodynamic interactions that are found to be the main reason for improved thermo-physical properties

A modified Hamilton-crosser thermal conductivity model

The classical models for prediction of thermal conductivity of Maxwell and Hamilton derived from the effective medium theory were devised to predict particles thoroughly dispersed in their medium as a function of concentration only [13]. The classical models fail as theoretical predictions for the NPs, and will give poor indication of thermal conductivity and viscosity

The literature reveals that the development of theoretical models for non-spherical NPs is not well understood and still remains elusive due to its complex shape [10]. In this paper, an attempt is made to theoretically describe non-spherical particles through developing a new model for cylindrical shaped NPs [11]. The renovated models for predicting the effective thermal conductivity, consisting of a static part of the Hamilton-Crosser (K_{static}) and a dynamic part ($K_{dynamic}$) that takes into account the Brownian and hydrodynamic motions of the dispersed particles. The effective thermal conductivity model is defined as:

$$K_{eff}=K_{static}+K_{dynamic} \qquad (1)$$

Static Part

A liquid in contact with a particle is more ordered than the bulk liquid and therefore it has a larger thermal conductivity than the bulk [14]. In order to consider liquid layering, an equivalent volume concentration for non-spherical particles is developed as follows:

$$\varphi_e=\varphi(1+\frac{h}{r})^2(1+\frac{2h}{l}) \qquad (2)$$

Where h is the interfacial nano-layer thickness, r is the radius of the particle and l is the length of the particle. Using the above effective volumetric concentration, the equivalent thermal conductivity of [11] is modified as follows for the liquid layer and particle combined is as follows:

$$k_{pe}=\frac{[(n-1)(1-\gamma)+\frac{\varphi_e}{\varphi}(1+(n-1)\gamma)]\gamma}{-(\gamma-1)+\frac{\varphi_e}{\varphi}(1+(n-1)\gamma)}k_p \qquad (3)$$

Where the γ is the ratio of thermal conductivity of the liquid layer to that of the particle, n is the shape factor (3 for spheres and 6 for non-spheres). Substituting this equivalent thermal conductivity in Hamilton and Crosser model results in:

$$k_{eff}=\frac{k_{pe}+(n-1)k_l+(n-1)(k_{pe}-k_l)\varphi_e}{k_{pe}+(n-1)k_l-(k_{pe}-k_l)\varphi_e}k_l \qquad (4)$$

Dynamic Part

The random movement of particles in a suspended fluid is known as the Brownian motion. It can produce micro-mixing and improve the thermal conductivity. Koo et al. [12] proposed a new model based on kinetic theory for predicting the effective thermal conductivity of nano-fluids of spherical particles. For the derivation of $K_{dynamic}$, they assumed two NPs with translational time-averaged Brownian motion in two different temperature cells. The Brownian velocity used is independent of the particle volume fraction, but it is more justifiable to employ the Brownian velocity which is also a function of the particle volume fraction. The Brownian motion based on effective diffusion coefficient concept used [13]:

$$V_B = \sqrt{\frac{3kT(1-1.5\varphi_e)}{2\pi\rho_{cp}{r_{cp}}^3}} \qquad (5)$$

Where k is Boltzmann constant, T is the temperature, ρ_{cp} is effective density of particle and liquid layer, and r_{cp} is equivalent radius of particle and liquid layer. Hence, the additional amount of heat by conduction ($q_{dynamic}$) due to the Brownian motion and with regards to (2) and (5), final dynamic model is represented as:

$$k_{Brownian} = P\,\rho_{cp}\varphi_e C_l\sqrt{\frac{kT(1-1.5\varphi_e)}{2\pi\rho_{cp}{r_{ep}}^3}} \qquad (6)$$

Where P is the probability that the particle moves in one direction as Koo indicated. (p=0.197 from [12]) and C_l is the specific heat.

Model parameters

Clearly, as the particles move, a portion of the surrounding fluid is affected resulting in fluid motion and particle-particle interactions. This hydrodynamic movement is one of the major contributors for improved thermal and rheological properties of the Oil. When a NP travels in the fluid it affects a portion of surrounding fluid. Koo [12] estimated this region of influence with 99% criterion of vanishing impact as:

$$V_f = \frac{\pi}{6}a^2 b \qquad (7)$$

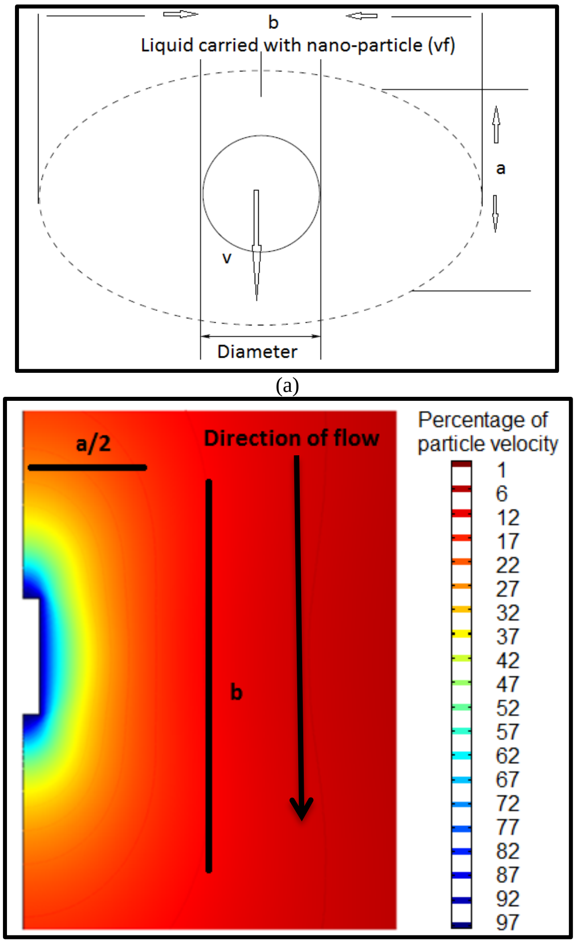
For non-spherical particles, the analytical solution of equation of motion is not available [13]. In this paper, a model of the steady-state movement of a single particle in the fluid is numerically developed to estimate the region of influence. The volume of the surrounding fluid is influenced by a cylindrical particle motion with the assumption of having creep flow (Figure 4). It is worth noting that the small size of the particles, the Reynolds number is very small which makes a creep flow assumption valid. The shape of the influenced volume is an ellipsoid and defined by (7). The dimensions of this ellipsoid (a and b) for non-spherical particles depends on both thickness and diameter of the particles and given by:

$$b = 8.367D + 10.233H - 0.637DH + 35.611 \qquad (8)$$
$$a = 4.317D + 5.275H - 0.325DH + 17.500 \qquad (9)$$

Where D and H are the diameter and thickness of the cylindrical particles respectively. Therefore, (6) turns into:

$$k_{Brownian} = V_f P\beta\,\rho_{cp}\varphi_e C_l\sqrt{\frac{kT(1-1.5\varphi_e)}{2\pi\rho_{cp}{r_{ep}}^3}}\,f\,(T,\varphi_e) \qquad (10)$$

Where V_f is the volume of surrounding fluid around particle, β is the fraction of liquid volume that moves with the particles and f is an added function in the model to account for the particle-particle interaction.



(a)

(b)

Figure 4. (a) Schematic representation of the dynamic model; particle with surronding fluid and (b) Numerical model to estimate the volume of non-spherical particles

Determination of nano-fluid properties (β and f)

In this model, β is added to represent the fraction of the influenced liquid travelling with a particle and f is a function added to consider the interaction between particles. Due to the viscous effects of the moving particles, β will decrease with the volume fraction. Here β is a function of the volume fraction only. For liquid-solid suspensions and because of the small inter-particle distance of the particles, the particle-particle interactions are assumed to be very strong and increase with the volume fraction. Modifying the "f "value of Koo [12], so that it varies continuously with volume fraction and temperature with two fitting parameters such that:

$$f = (C_2\varphi T + C_3 T) \qquad (11)$$

Instead of two model parameters (β and f), one lumped parameter, α is used and given by:

$$\alpha = \beta * f = \varphi^{C_1}(C_2\varphi T + C_3 T) \qquad (12)$$

It is hypothesized that at low volume fraction, Brownian α depends on the volume fraction, temperature, particle shape, and hydrodynamic interactions. The parameters C_1, C_2, and C_3 can be calculated by fitting the experimental data.

Using the same concept of deriving the thermal conductivity model, the dynamic viscosity due to hydrodynamic interactions is derived with a final form of:

$$\mu_{Brownian} = V_f P\beta\, \rho_{cp}\varphi_e \sqrt{\frac{kT(1-1.5\varphi_e)}{2\pi\rho_{cp}{r_{ep}}^3}}\, f\,(T,\varphi_e) \qquad (13)$$

IV. Discussion of Model results

Effective Thermal conductivity Model

The effectiveness of nano-fluid is compared to the effectiveness of their base fluids. The relative thermal conductivity ($K_{relative}$=K_{eff}/K_{bulk}) of the experimental results are compared against the model predictions with an R-squared value of 0.979 (Figure 5). Model results indicate the augmented thermal conductivity of the tested nano-fluids is mainly because of the layering of the flake like particles that lead to thermal diffusion by conduction at the liquid-solid interface rather than the Brownian motion. Nevertheless, the Brownian has some portion of contribution to the enhanced thermal conductivity. Due to the lack of experimental data, it is necessary to validate the goodness of the model proposed. The model is compared against Rohini's experimental data at different temperatures [10]. In Figure 6, the model is a good fit to the experimental data with minimum error and high R-squared values. The model has the capability of predicting effective thermal conductivities at different temperature. This suggests the contribution and impact of the Brownian motion

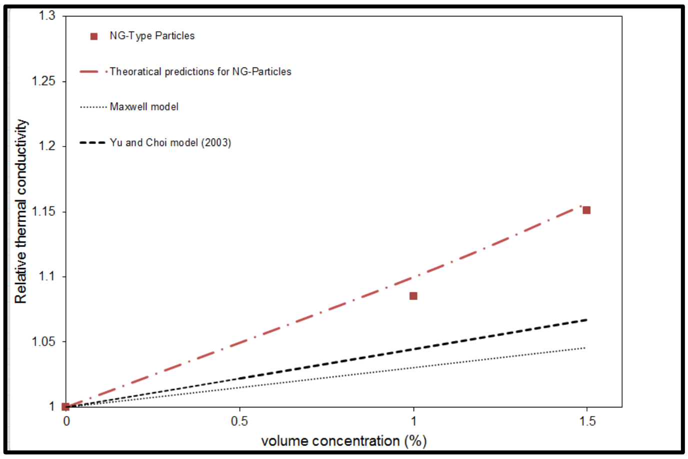


Figure 5. Comparison of model with experimental results of NG-samples

The fitting parameters (C_1, C_2 *and* C_3) are reported in Table II for the current work and compared with literature data

motion and the movement of particles is the dominant dynamic mechanism than the particle-particle interaction (*f*). On the other hand, at high volume fractions particle-particle interactions becomes more significant.

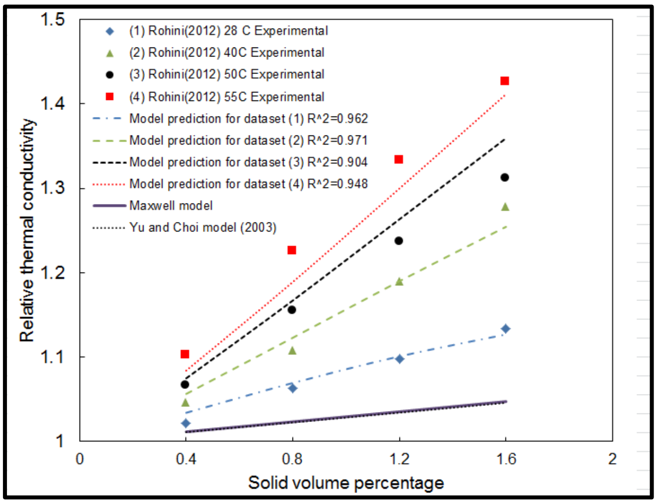


Figure 6. Comparison of model with external experimental data

Effective Viscosity Model

The effective viscosity predictions are limited for the given experimental nano-fluid data, as most samples are deviating from the Newtonian behavior (Figure 3). As a result, model fitting with experimental data was not performed. However, model predictions for external data are in Figure 7. Results indicate the versatility of the proposed model with external data, in general, with high R-squared values (Table III).

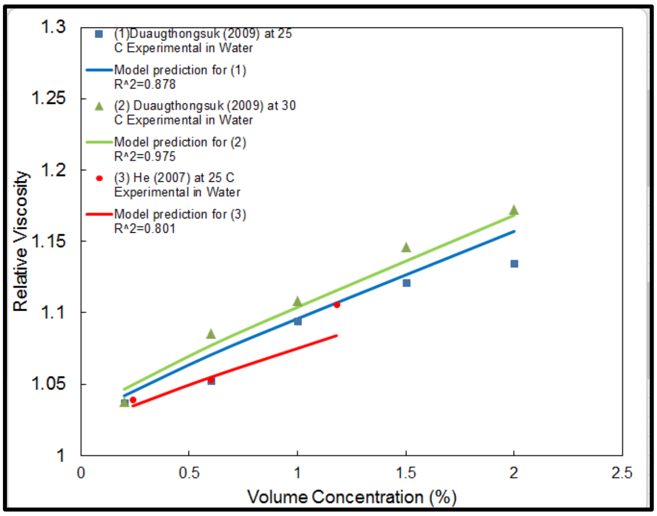


Figure 7. Comparison of effective viscosity model with external data

TABLE II. EFFECTIVE THERMAL CONDUCTIVITY FITTING PARAMETERS FOR THE PROPOSED MODEL USING DIFFERENT EXPERIMENTAL DATA

Fluid	**Particle**	**Volume percentage (%)**	**C1**	**C2**	**C3**	**R^2**	**Reference**
Ethylene	Al2O$_3$	0.5-8	-0.7545	-2.2E-06	1.95E-07	0.986	[17]
Water	Al2O$_3$	0.3-4.3	-0.7545	8.46E-06	-3.6E-08	0.982	[11], [17], [18]
Ethylene	Al	1-5	-0.7546	1.3E-05	3.9E-07	0.911	[17]
Engine oil	Al	1-3	-0.7546	1.3E-05	3.9E-07	0.911	[17]
Ethylene	Al$_2$Cu	0.5	-0.7546	1.92E-05	5.73E-07	0.831	[19]
Water	Al$_2$Cu	0.5	-0.7546	3.75E-05	1.34E-06	0.939	[19]
Ethylene	TiO$_2$	1-5	-0.75462	-1.5E-06	8.4E-08	0.935	[17]
Water	TiO$_2$	0.2-4.3	-0.75462	-5.4E-06	2.41E-07	0.687	[18], [20], [21], [22]
Ethylene	Cu	0.4-2	-0.75462	3.73E-05	1.3E-07	0.984	[23]
Water	Cu	0.05-0.3	-0.75445	0.002844	1.58E-06	0.997	[24]
Ethylene	CuO	0.01-1	-0.75462	-6E-05	2.01E-06	0.942	[15]
Gear Oil	CuO	0.5-2.5	-0.75467	-1.8E-08	9.45E-08	0.828	[25]
water	CuO	0.02-1	-0.75465	8.66E-05	1.08E-06	0.942	[15,16]
Water	CuO	0.4-1.6	-0.89996	0.000489	-1.5E-06	0.921	[10]
Gear Oil	-	0.5-1.5	-0.97954	2.23E-06	-1.7E-08	0.979	Presented work

TABLE III. EFFECTIVE VISCOSITY FITTING PARAMETERS FOR THE PROPOSED MODEL USING DIFFERENT EXPERIMENTAL DATA

Fluid	**Particle**	**Volume percentage**	**C1**	**C2**	**C3**	**R^2**	**Reference**
Ethylene	TiO$_2$	0.1-1.8	-0.7545	-2.2E-06	0.004233	0.983	[26]
Water	TiO$_2$	0.2-2	-0.75429	-0.00361	-0.00366	0.92	[22]
Ethanol	SiO$_2$	1-7	-0.7545	0.000573	-4.1E-06	0.951	[27]
Water	Al	1-8	-0.7545	0.000573	-4.1E-06	0.971	[28]
Propylene	Al$_2$O$_3$	0.5-3	-0.75474	0.002274	2.36E-05	0.832	[29]
Gear Oil	-	0.5-1.5	-0.97955	-0.00371	0.000102	0.979	Presented work

V. Conclusions and future work

Conclusions

In this paper, the fluid properties of the aircraft Oil for the gearbox are determined using different NP additives. A new effective thermal conductivity and effective viscositymodels were developed.

- The static part of liquid layering is the dominant mechanism for augmented thermal conductivity.
- In the model developed, low concentrations indicates the Brownian movement of particles is dominant as the dynamic mechanism of the particles, while with higher concentrations particle-particle interactions take place and this explains the augumented effective viscosity, especially for dense particles.
- The model predicts properties at different temperatures, which is an indication of the importance of hydrodynamic and Brownian effects.
- To improve the accuracy of K_{eff} and μ_{eff} models, more experimental data are needed
- The work in this paper is to select samples for testing in the Intermediate gearbox of the AH-64 based on thermo-physical responses, which is part of a comprehensive study needed to meet CBM objectives through improving lubrication

Future work

After reducing some samples based on the lubricant results, the selected nano-fluids will be further investigated on a no-load test stand for another round of filtering variables before the main testing.

The no-load test stand is simply the IGB as the only component being driven without the remaining components (Figure 8a). The optimum performed nano-fluid samples will then be tested in the full load Tail Rotor Drive Train (TRDT) test stand for a final investigation to meet CBM objectives (Figure 8b).

(a)

(b)

Figure 8. (a) No-Load Test stand and (b) Full Load Test Stand at USC

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