Thermal Analysis on Thrust Pad Bearing with Non-Newtonian Lubricant

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Abstract **--- Hydrodynamic pad thrust bearings are widely used, due to their low friction, good load carrying capacity and high damping characteristics, in high speed rotating machines, such as pumps, compressors, turbines, turbo generators. However, the need for high load bearing capabilities and compactness of the thrust pad bearings has attracted the attention of engineers. The design of such thrust pad bearings involves selection of bearing materials, lubricants and operating conditions. As the performance of lubricants plays a vital role in the life cycle of bearings, thus the present work examines the thermophysical properties of non-Newtonian surrogate lubricants. The lubricant properties at different temperatures were extracted from NIST-Supertrapp® and a correlation is developed which is further used in the computational analysis of thrust pad bearing. A steady state thermal analysis is done on the thrust pad bearings which are modeled and meshed in ANSYS® 14.5. It was observed that the temperature variation on the outer surface to be varying linearly whereas a non-linear variation has been identified at inner surface of a pad in a thrust pad bearing initiating thermal stresses. Moreover, these thermal stresses may contribute finally to the reduction in performance with respect to wearing of pads. The present work also focuses on temperature dependent thermophysical properties on the temperature distribution of thrust pad bearings.**

Keywords --- Thermophysical properties; Thrust pad bearings; non-Newtonian fluids.

I. INTRODUCTION

Thrust bearing finds its application in almost all the engineering services, where there are high speed motions are concerned, to control vibrational adverse effects. In order to minimize the friction between the two mating surfaces, generally lubricating oils are used whose properties decide the heat transfer and flow characteristics which further a function of mode of heat transfer and surface roughness. In general, there are three different types of lubricants by which lubrication can be achieved namely solid, liquid and gaseous lubricants. However, the application of each depends upon the nature of practical situation, environmental conditions, physical and chemical properties of the lubricants, material composition, temperature and the properties of mating parts at the interface. It is expected from a lubricant that it can handle both static and dynamic friction between the mating surfaces. Mostly, liquid lubricants are used in order to minimize the frictional losses due to their excellent properties which are essential to handle lubrication load and heat dissipation capabilities. Additives are also used in order to enhance certain properties of the lubricating oil which depends upon the type of application. However, lubricant properties are robustly depending upon the base oils or on the blends of base oils. The important individuality of a diversity of base oils can be seen in TABLE I [1]. It has been found from the observations that mineral oils show excellent character and are cost effective also. Some property values of several type of lubricating oils used in various applications have been tabulated in the TABLE II [1]. Extensive study on the mineral oils is available in literature and can be found anywhere in [2-6]. The critical property of the lubricating oils is kinematic viscosity which after all varies with respect to temperature. The reliance of kinematic viscosity on temperature can be indicated over a significant range of temperatures by the ASTM D 341 viscosity-temperature equation also known as MacCoull-Walther equation [7]:

$$\log\log(cSt + 0.7) = A - B(\log T) \tag{1}$$

Where A and B are constants and T is absolute temperature measured in Kelvin. It has been stated that the constant value 0.7 is applicable for the viscosities ranging from $2*10^7$ to 2cSt and this value increases as kinematic viscosity decreases below the latter value. For other information about the ASTM equations individual can find the same in [8]. It has been found from literature that after a pressure of 10MPa, the increase in viscosity as a function of pressure becomes appreciable for the mineral oils and can be expressed by Barus equation [1]. :

$$\eta_{t,P} = \eta_{t,0} \exp\,(\alpha P) \tag{2}$$

Where $\eta_{t,P}$ is dynamic viscosity at temperature t and gage pressure P, $\eta_{t,0}$ is dynamic viscosity at temperature t and atmospheric pressure and α is viscosity-pressure coefficient. Information regarding the lubricant properties can be found anywhere in [1, 4, 5, and 9].

A. *Scope of study*

Based on the literature reviewed, the following points have been noticed that authors haven't considered non-linear temperature dependant variations of thermophysical properties as a function of non-Newtonian lubricants. However, in practice, the operation of thrust pad bearings involves variation of viscosity as a function of temperature.

TABLE I. BASE OIL CHARACTERISTICS [1]

Property	Base oil type										
	Mineral oil	Olefin oil	Alkyl aromatic	Polyphenyl ether	Dibasic acid ester	Neopentyl polyester	Poly-alkylene glycol	Phosphate ester	Silicone	Silicate ester	Fluoro-carbon
Liquid Range	Moderate	Good	Good	Poor	Very good	Very good	Good	Moderate	Excellent	Poor	Poor
Viscosity-temperature	Moderate	Good	Moderate	Poor	Excellent	Very good	Good	Poor	Excellent	Excellent	Moderate
Low-temperature flow	Poor	Good	Good	Poor	Good	Good	Good	Moderate	Good	Moderate	Good
Oxidation stability inhibited	Moderate	Very good	Moderate	Very good	Very good	Moderate	Poor	Good	Very good	Very good	Excellent
Hydrolytic stability	Excellent	Excellent	Excellent	Excellent	Moderate	Moderate	Good	Moderate	Good	Poor	Very Good
Thermal stability	Moderate	Moderate	Moderate	Excellent	Good	Good	Good	Moderate	Very good	Good	Very Good
Solvency, mineral oil	…	Excellent	Excellent	Good	Good	Moderate	Poor	Moderate	Poor	Moderate	Poor
Solvency, additives	Excellent	Good	Excellent	…	Very good	Very good	Moderate	Good	Poor	…	…
Solvency, varnish and paint	Excellent	Excellent	Excellent	Moderate	Good	Moderate	Moderate	Poor	Good	Moderate	Good
Volatility	Moderate	Good	Good	Good	Excellent	Excellent	Good	Good	Good	Good	Moderate
Antirust, inhibited	Excellent	Excellent	Excellent	…	Moderate	Moderate	Good	Moderate	Good	…	…
Boundary lubrication	Good	Good	Good	Excellent	Very good	Very good	Good	Excellent	Moderate	Moderate	Excellent
Fire resistance	Poor	Poor	Poor	Moderate	Moderate	Moderate	Moderate	Excellent	Moderate	Moderate	Excellent
Elastomer swell, Buna	Low	None	Low	Low	Medium	High	Low	High	Low	Low	Medium

Hence, temperature dependent thermophysical properties are to be taken into account in accurate modeling of thrust pad bearings. As lubricating oils are the mixtures of a large number of hydrocarbons, so it becomes much complicated to investigate the composition of the individual. Therefore, to avoid such complexities, a novel concept has been introduced in this study. The concept is related with the use of surrogate oils for the liquid lubricants which consists of similar properties as that of the practical lubricating oil. In the present work, an attempt has been made to match the kinematic viscosity of the liquid lubricant surrogate (LLS) oil as that of VG220 or SAE50 which is taken as reference lubricating oil. Also, temperature dependant thermophysical properties such as density, viscosity, thermal conductivity, kinematic viscosity and specific heat have been studied for 6 different LLSs and also an attempt has been to correlate kinematic viscosity as a function of temperature with a statistical formula. Finally, steady state thermal analysis has been done by considering the properties as a function of temperature and certain observations are made.

II. RESEARCH METHODOLOGY

A. *Selection of Thermophysical Properties*

Temperature dependant properties for the LLSs have been extracted from NIST software package SUPERTRAPP$^{®}$ [10] at a constant pressure 0.2MPa, as liquids are generally incompressible in nature therefore property variation with respect to pressure becomes insignificant. A surrogate mixture containing component of n-alkanes, cyclo-alkanes and aromatic hydrocarbons is chosen in order to match the requirements of practical lubricant oil (VG 220). Mixture includes n-hexatricontane (C36), cis-decalin (c-decalin) and xylene (ortho, meta and para). All three possible arrangements of aromatic compound (xylene) have been considered in the present study in order to see the effect of changing the location of substitution group. Basically six possible combinations have been chosen as given in TABLE III.

. The thermophysical properties such as density, viscosity, kinematic viscosity, specific heat and thermal conductivity of liquid lubricants have been studied at 0.2MPa pressure and from a range of 20 to 140°C temperature.

B. *Design Problem Description of Thrust Pad Bearing*

Pads of a thrust pad bearing are shown in Fig- 1 and modeled in ANSYS$^{®}$ [11]. A single pad of the thrust pad bearing is considered for thermal analysis. The data of the thrust pad bearing has been taken from [12]. Thermal analysis on this thrust pad bearing is done by considering the temperature dependent thermophysical properties of the lubricant. Moreover, it is assumed that there exists a thermal equilibrium between the lubricant and surface of the bearing. In addition, the operating temperature of thrust pad is considered to be in the range of 298K to 398K due to its hydrodynamic operation where an increase in the temperature is evident.

TABLE II. LUBRICANT PROPERTIES [1]

Lubricant	**Pour point**		**API gravity**	**Flash point**		**Kinematic viscosity, mm2/ s.cSt**		**Viscosity Index**	**Reolands, Z**	**Ash. %**	**Neutrality No.**
	°C	***°F***		***°C***	***°F***	***At 40°C (105°F)***	***At 100°C (212°F)***				
Jet engine oil, polyol ester, type II, MIL-L-23699B	-54	-65	10	254	489	28	5.10	…	0.61	…	…
ISO VG 32 refrigeration oil	-48	-55	27.2	168	334	30	4.7	54	0.76	…	0.03 TAN
ISO VG 32 R&O turbine oil	-32	-26	32.2	199	390	30.9	5.48	104	0.68	0.002	…
Automatic transmission fluid, Dexron-II, Mercon, Allison C-3, Caterpillar TO-2	-46.0	-51.0	31.0	204.0	399.0	36.2	7.4	176.0	0.5	0.26	…
ISO VG 46 antiwear hydraulic fluid, AGMA No. 1	-32.0	-26.0	30.2	210.0	410.0	45.0	6.8	103.0	0.7	…	…
5W-30 motor oil, SG/CD, energy conserving II, ILSAC, CCMC	-39.0	-38.0	30.0	216.0	421.0	67.8	11.5	165.0	0.5	1.00	…
10W-30 motor oil, SG/CD, ILSAC, energy conserving II, CCMC	-34.0	-29.0	29.0	221.0	430.0	75.0	11.5	146.0	0.5	1.00	…
75W-90 synthetic hydrocarbon gear oil, GL-5, MIL-L-2105C, limited slip	-46.0	-51.0	28.0	163.0	325.0	106.0	15.2	149.0	0.6	…	…
15W-40 motor oil, CE/SG, CD-II, MIL-L-2104E, MIL-L-46152D, Caterpillar TO-2, Allison C-4	-29.0	-20.0	28.2	232.0	450.0	112.0	14.8	136.0	0.5	1.00	7TBN
15W-40 motor oil, CE/SF, CD-II, MIL-L-2104E, MIL-L-46152D, Caterpillar TO-2, Allison C-3	-31.0	-24.0	28.0	226.0	439.0	110.0	14.7	136.0	0.5	1.50	11TBN
SAE 40 motor oil, CE/SG, CD-II, MIL-L-2104E, MIL-L-46152D, Caterpillar TO-2, Allison C-4	-23.0	-9.0	26.1	243.0	470.0	157.0	15.1	96.0	0.6	1.00	7TBN
Polyglycol industrial oil	-30.0	-22.0	…	280.0	536.0	161.0	22.4	173.0	0.5	…	…
SAE 40 motor oil, CC/SF, MIL-L-2104B, MIL-L-46152B	-12.0	10.0	26.4	228.0	442.0	169.0	15.5	93.0	0.6	0.86	6TBN
ISO VG 220 circulating oil, AGMA R&O No. 4	-9.0	16.0	28.7	241.0	466.0	138.0	13.3	89.0	0.6	…	…
ISO VG 220 industrial gear oil, AGMA 4EP, U.S. Steel 224	-12.0	10.0	26.8	213.0	415.0	139.0	14.6	105.0	0.6	…	…
Trunk-type diesel engine oil, CD	15.0	60.0	25.6	238.0	460.0	140.0	14.2	92.0	0.6	3.60	32TBN
Diesel cylinder oil	-12.0	10.0	19.5	243.0	469.0	203.0	17.2	90.0	62.0	9.30	77TBN
ISO VG 460 industrial gear oil, AGMA 7EP, U.S. Steel 224	-12.0	10.0	25.0	>254	489.0	480.0	30.4	90.0	0.6	…	…
ISO VG 460 cylinder oil, AGMA 7 comp.	-7.0	19.0	24.5	280.0	536.0	460.0	30.5	96.0	0.6	…	…

TABLE III. COMPOSITION OF LUBRICANTS NAMED AS L1, L2, L3, L4, L5 AND L6

Lubricant	**Composition (in moles)**				
	C36	***c-Decalin***	***o-Xylene***	***m-Xylene***	***p-Xylene***
L1	0.4	0.25	0.35	-	-
L2	0.4	0.2	0.4	-	-
L3	0.4	0.25	-	0.35	-
L4	0.4	0.2	-	0.4	-
L5	0.4	0.25	-	-	0.35
L6	0.4	0.2	-	-	0.4

C. Solution Methodology

The solution methodology involves choosing of relevant element type such SOLID90 which has the capability to perform the thermal analysis. Non-linear material properties (temperature dependent thermophysical properties) are to be specified for the chosen element (SOLID90) as the material properties considering the thrust pad as isotropic material. Steady state thermal analysis is performed, considering

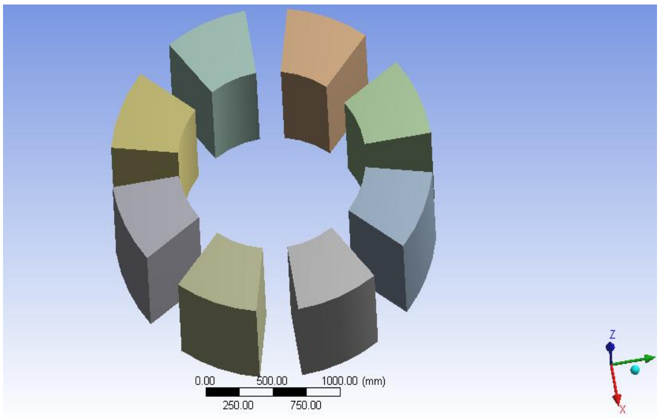


Fig- 1 Computer aided model of pads of thrust pad bearing

III. STUDY OF THERMOPHYSICAL PROPERTIES OF LUBRICANTS

The primary function of liquid lubricants is to control friction, wear, and surface damage over the anticipated life of a system that contains machine elements, such as gears and bearings. Wear and surface damage occur under boundary or partial boundary lubrication conditions. Secondary functions are to prevent corrosion and to scavenge heat, dirt, and wear wreckage. Lubricants can also transfer either force or energy, as occurs in hydraulic systems.

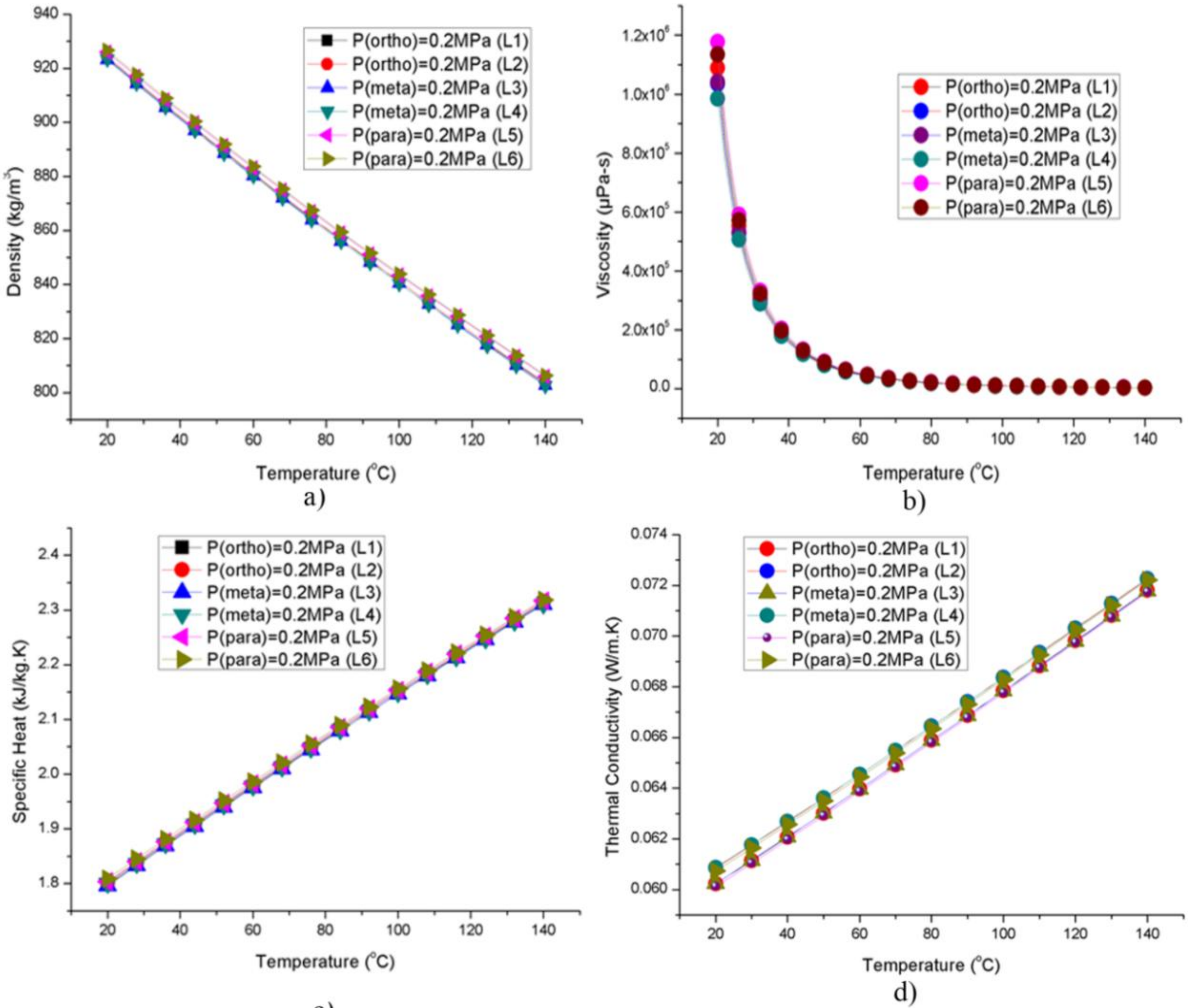
Thus, in order to implement lubricants in the respective applications for what they are meant to be, the knowledge regarding their property variations with respect to the operating variables becomes necessary to discover the potential of the lubricant to work in rough conditions. Because of incompressible nature of liquid lubricants, pressure does not affect the properties too much and it is only the temperature that play an important role while the selection of lubricant as per application requirement. Therefore, it becomes essential to know the behaviour of liquid lubricant properties as a function of temperature. In this section, five thermophysical properties of a liquid lubricant surrogates (LLSs) have been studied.

A. *Density*

Fig- 2(a) shows the variation in density of six different LLSs as a function of temperature at a constant pressure of 0.2MPa. It can be noted from the plot that as temperature increases, the density of surrogates decreases linearly. Also to be noted that for all LLSs, the density drop found to be approximately identical. Means there is no significant effect of concentration on density of lubricant.

B. *Viscosity*

Fig- 2(b) shows the variation in viscosity of six different LLSs as a function of temperature at a constant pressure of 0.2MPa. It can be noted that as temperature increases, there is a sudden drop in viscosity in the range of 20-40^{o}C temperature and then following by gradual decrease up to 140^{o}C temperature. Also to be noted that there is no significant effect on viscosity of LLSs as the concentration and the location of substitute group changes.



a)

b)

c)

d)

Fig- 2 Temperature dependent property variations of surrogate lubricants

C. Specific Heat

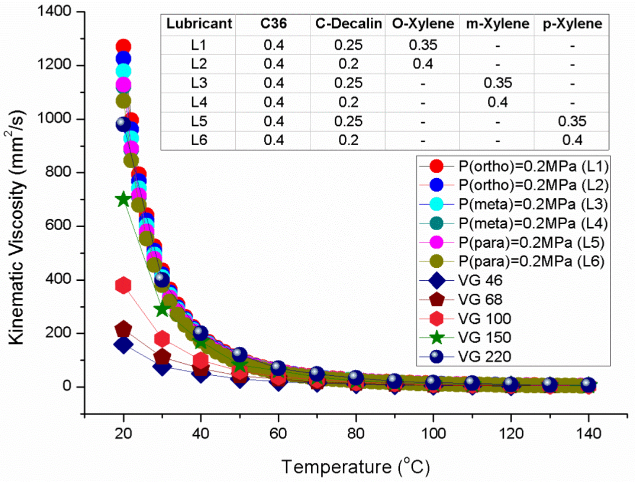
Fig- 2(c) shows the variation of specific heat for all LLSs as a function of temperature at a constant pressure 0.2MPa. It can be found that as temperature increases, the specific heat of LLSs will also tends to increase in linear fashion. Also there is no significant variation in specific heat with respect to change in concentration of cyclo-alkanes and aromatic hydrocarbons.

D. Thermal Conductivity

Fig- 2(d) shows the variation of thermal conductivity for all LLSs as a function of temperature at a constant pressure 0.2MPa. It can be found that as temperature increases, the thermal conductivity of LLSs will also tends to increase linearly. Also there is no significant variation in thermal conductivity with respect to change in concentration of cyclo-alkanes and aromatic hydrocarbons.

E. Kinematic Viscosity

Fig- 3 shows the variation of kinematic viscosity as a function of temperature at constant pressure for our selected LLSs and the lubricants used in practical applications. The data for the lubricants used in applications have been taken from ASM Handbook [1]. It can be seen that the rate at which kinematic viscosity drops is higher in the temperature range of 20-40^{o}C than 40-140^{o}C. It can also to be noted that the kinematic viscosity of all selected LLSs is found to be higher than the lubricants such as VG46, VG68, VG100, VG150 and VG220.



Lubricant	C36	C-Decalin	O-Xylene	m-Xylene	p-Xylene
L1	0.4	0.25	0.35	-	-
L2	0.4	0.2	0.4	-	-
L3	0.4	0.25	-	0.35	-
L4	0.4	0.2	-	0.4	-
L5	0.4	0.25	-	-	0.35
L6	0.4	0.2	-	-	0.4

Fig- 3 Kinematic viscosity-temperature relation of surrogate lubricant in comparison with standard lubricants

Development of Correlation for viscosity as a function of temperature for surrogate Lubricant

The behavior of kinematic viscosity for various surrogates such as L1, L2,….L6, have been studied with respect to temperature (20-140°C) at constant pressure (0.2MPa) with the help of SUPERTRAPP [10]. All that data, an equation has been developed for all combinations of the surrogate lubricant which favors the behavior of the fluid with more than 99.9%as indicated by the R-square value as shown in TABLE IV.

$$\log_{10} \nu = a - b \log_{10} T \tag{3}$$

Where; 'a' and 'b' are the correlation coefficients as given in the TABLE IV. 'ν'is the kinematic viscosity in mm^2/sec. and T is the temperature of the lubricant in °C.

TABLE IV. CORRELATION COEFFICIENTS FOR SURROGATE LUBRICANTS

Lubricant	**Correlation Coefficients**		**R-Square Value**
	a	***b***	
L1	6.64961	2.72068	0.99961
L2	6.624	2.71312	0.99956
L3	6.57653	2.68916	0.99954
L4	6.53871	2.67658	0.99948
L5	6.52543	2.66441	0.9995
L6	6.48228	2.64937	0.99943

IV. THERMAL ANALYSIS ON A PAD OF THRUST PAD BEARING

The modeling of a pad of pad thrust bearing and its analysis has been designed in ANSYS [11]. Fig- 4 shows the temperature distribution on a single pad of thrust pad bearing. It can be observed that the temperature is varying linearly from 298K to 323K (25^{0}C to 50^{0}C) and which is due to isotropic properties assumed for this problem. Fig- 5(a) and Fig- 5(b) show the thermal flux variation along the x and y-direction of the thrust pad bearing respectively. Fig- 5(c) and Fig- 5(d) show the variation of thermal gradient along x and y-direction of the thrust pad bearing respectively. Large thermal gradients would result into higher heat transfer rates in the region.

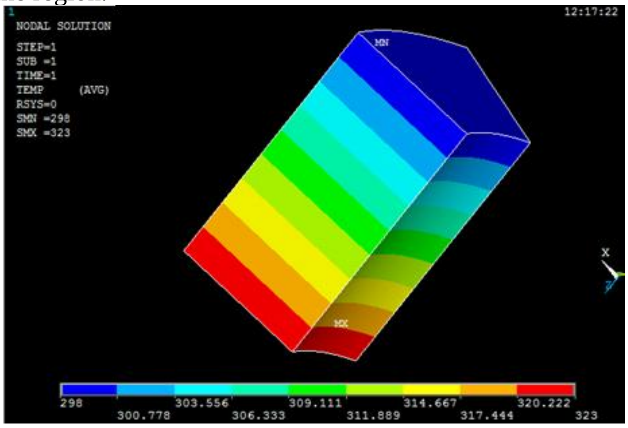
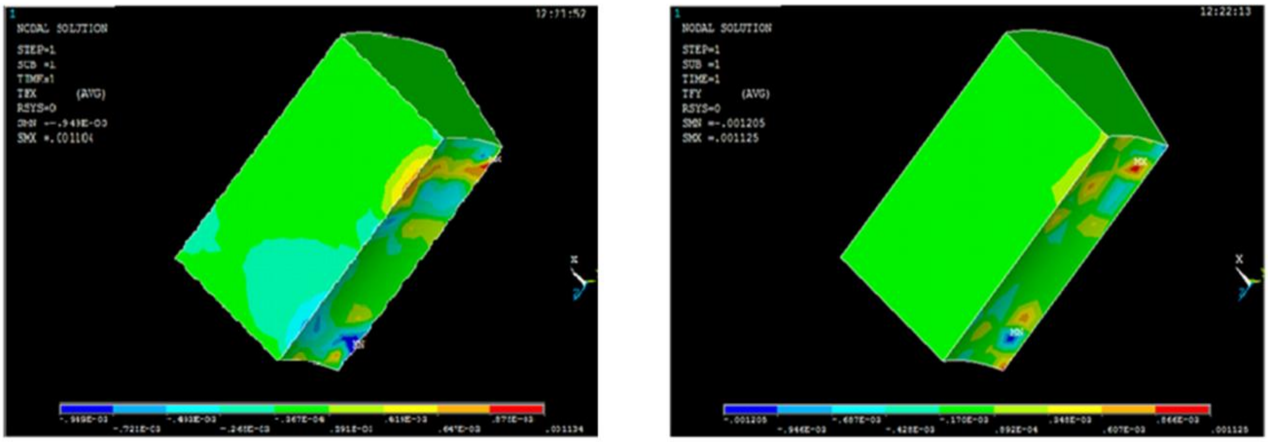


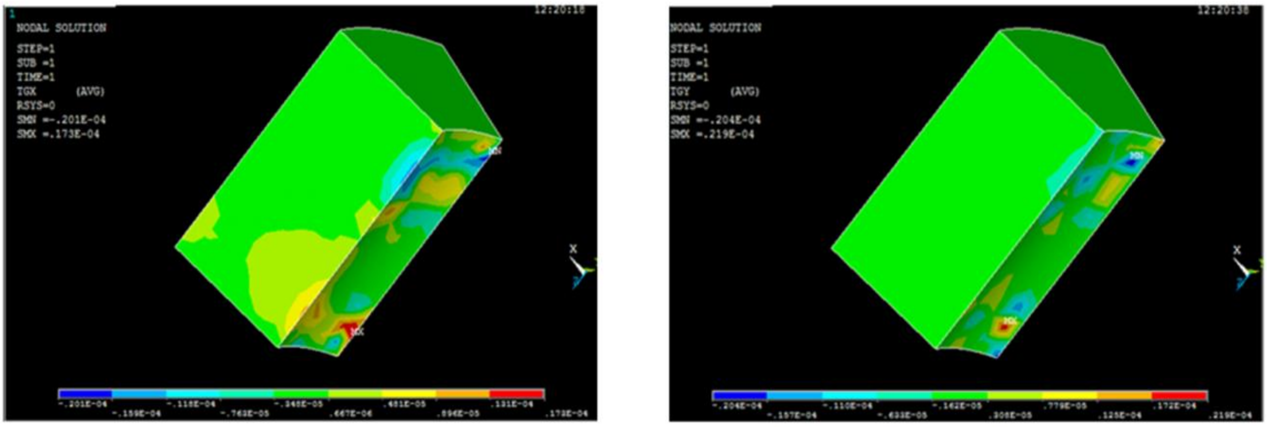
Fig- 4 Temperature distribution in thrust pad bearing at constant properties

Fig- 6 shows the variation of temperature with respect to arc length (longitudinal) at inner and outer edge of the thrust pad bearing. It can observed that the temperature variation on the outer surface to be varying linearly whereas a non-linear variation has been identified at inner surface of a pad in a thrust pad bearing. This in turn infers that the inner surface is vulnerable to higher temperature variations which may initiate thermal stresses. Moreover, these thermal stresses may contribute finally to the reduction in performance in the form of wearing of the thrust pads.



a) Thermal Flux Distribution along the x-axis of the thrust pad bearing

b) Thermal Flux Distribution along the y-axis of the thrust pad bearing



c) Thermal Gradient Distribution along the x-axis of the thrust pad bearing

d) Thermal Gradient Distribution along the y-axis of the thrust pad bearing

Fig- 5 Thermal flux distribution along the x-axis of the thrust pad bearing

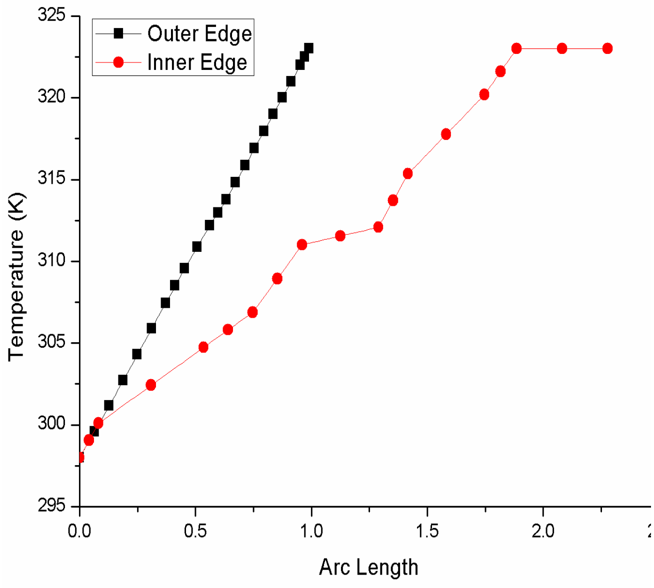


Fig- 6 Temperature dependent thermophysical properties

V. FUTURE SCOPE

The present work discusses the steady state effect of temperature dependent thermophysical properties on the temperature distribution of thrust pad bearings. However, time dependent analysis on thrust pad bearing which entails the opportunity to record the rise in temperature for every second may be helpful in preventing the wear, tear and frictional losses. Moreover, simultaneous effects of nonlinearities in material properties, lubricant properties and governing equations are not studied in the present work. In addition, as the analytical solution for non-Newtonian (rheological) fluid flow is difficult with temperature dependent thermophysical properties being considered, computational methods were chosen in the present work. However, benchmarking of the computational results is still requires further experimentation.

REFERENCES

[1]. "Friction, Lubrication, and Wear Technology" published in 1992 as Volume 18 of the ASM Handbook. The Volume was prepared under the direction of the ASM International Handbook Committee.

[2]. E.R. Booser, Ed., CRC Handbook of Lubrication: Applications and Maintenance,Vol 1, CRC Press, 1983.

[3]. E.R Booser, Ed., CRC Handbook of Lubrication: Theory and Design,Vol 2, CRC Press, 1983.

[4]. D. Klamann, Lubricants and Related Products,Verlag Chemie, Federal Republic of Germany, 1984.

[5]. M.J. Neale, Tribology Handbook,Wiley, 1973.

[6]. J.J. O'Connor and J. Boyd, Standard Handbook of Lubrication Engineering,McGraw-Hill, 1968.

[7]. 1990 Annual Book of ASTM Standards,ASTM, 1990.

[8]. E.E. Klaus and E.J. Tewksbury, CRC Handbook of Lubrication: Theory and Design, Vol II, E.R. Booser, Ed., CRC Press, 1983.

[9]. M. L. Huber, NIST Thermophysical Properties of Hydrocarbon Mixtures Database, SUPERTRAPP-Version 3.2, 2007.

[10]. ANSYS® Academic Research, Release 12.0, Thermal Analysis Guide, ANSYS, Inc.

[11]. Sinha A.N., Athre, K;Biswas, S. 2001 , "Non-linear solution of Reynolds equation for thermo-elasto hydrodynamic analysis of thrust pad bearing", Industrial Lubrication and Tribology, Volume 53, Issue 5, Pages 202-210.

[12]. D. Markin, D.M.C. McCarthy, S.B. Glavatskih, "A FEM approach to simulation of tilting-pad thrust bearing assemblies", Tribology International, Volume 36, November 2003, Pages 807-814.

[13]. Sergei B. Glavatskih, Osten Uusitalo, Daniel J. Spohn, "Simultaneous monitoring of oil film thickness and temperature in fluid film bearings", Tribology International, Volume 34, December 2001, Pages 853-857.

[14]. Y. Shi, I. Minami, M. Grahn, M. Björling, and R. Larsson, "Boundary and elastohydrodynamic lubrication studies of glycerol aqueous solutions as green lubricants", Tribology International, Volume 69, January 2014, Pages 39–45.

[15]. S. H. P. Bettini, M. P. P. de Miranda Josefovich, P. A. R. Muñoz, C. Lotti, and L. H. C. Mattoso, "Effect of lubricant on mechanical and rheological properties of compatibilized PP/sawdust composites", Carbohydr. Polym., Volume 94, Issue 2, May 2013, Pages 800–806.