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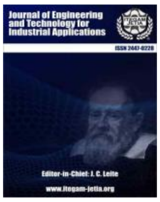

RESEARCH ARTICLEOPEN ACCESS

INFLUENCE OF THE LUBRICANT TEMPERATURE OF SPLASHED LUBRICATED WORM GEARBOX ON CHURNING POWER LOSSES

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ABSTRACT

The primary goal of lubricating a worm gearbox is to encourage sliding between teeth, which lowers the coefficient of friction and regulates the temperature rise brought on by rolling and sliding friction. Due to both non-load-dependent and load-dependent power losses, the worm gearbox has a relatively poor efficiency. Nonetheless, to meet the needs, there is now a greater need for more efficient worm gearboxes. Lowering churning power losses, can be accomplished. Bearing friction losses and gear friction losses make up the load-dependent losses. The non-load dependent losses are the bearing churning losses, gear windage losses, gear churning losses and oil seal losses. Numerous factors, including speed, direction of rotation, oil amount, and immersion depth, affect the non-load dependent losses. Only the impact of lubricant temperature and its relationship to non-load-dependent losses will be the focus of this study. A thorough experimental investigation was conducted utilizing the direct torque measuring method. A brand-new test rig was created, assembled, and placed into service to gauge input torque in the absence of load. We kept an eye on the fluctuating impacts of lubricant temperature on churning power loss.

I. INTRODUCTION

Because of its high torque, large reduction ratios, and inexpensive cost of manufacture, worm gears are extensively utilized in technological systems [1]. A worm gear is more metal-efficient and smaller than a parallel axis gear with the same gear ratio [2]. The most important parts of this gear are the worm and worm wheel, which are normally constructed of hardening steel and bronze, respectively [3]. Worm gear produces excessive heat, which needs to be cooled with the right lubricant. Lubrication not only keeps metal components from corroding and wearing out, but it also acts as a coolant to dissipate heat produced by friction between the gears and inside the bearings during regular operation [4]. A gearbox that is not properly lubricated will not function well, overheat, and finally fail. Power loss is the primary reason for the worm gearbox's reduced efficiency [5]. Gears have two types of power losses: load-dependent (mechanical) and load-independent (spin) power losses from oil windage, oil sealing and oil churning from gear and bearing oil [6–8]. Reducing the input torque can improve both power losses. The input torque is contingent upon several variables, including lubricant temperature, the kind of worm gear, the gear's orientation, rotational direction, geometry, and tribologicalfactors. There will be increased sliding/rolling friction and wear due to the high lubricant temperature since the lubricants will be thinner and the gears and bearing parts will not "hydroplane" on one another as readily [9-10]. Similar to this, low lubricant temperatures -especially in the winter—will cause the oils to thicken and make it harder for the bearing elements and gears to mix, increasing fluid friction and uneven lubrication. A gearbox failure can result from either situation. The spiral bevel gear's frictional heat production was studied by [11]. The finite element method was used to investigate it. The churning power loss of a bevel gear was predicted by [12], the use of computational fluid dynamics (CFD). Using a CFD technique, [13], simulated the planetary gear set model. After researching the different gear properties, they produced a finite-volume computational fluid dynamics (CFD) model of a dip-lubricated planetary test gearbox. The impact of lubricant temperature on churning power loss is demonstrated in this article. A test rig built on the premise of the direct torque measuring technique is used to measure the influence of temperature.

II. MATERIALS AND METHODS

The input torque may be measured in a variety of ways when there is no load. Since the direct torque measurement method is more straightforward and harmonious with the gear pair, it was chosen to measure the worm gear pair's input torque. The churning power loss for the bevel gear and parallel axis of the gear was also examined using this technique [14-19]. A torque-measuring test machine that was specifically constructed was used for the experimental investigations. Figure 1 shows the test machine that was developed. The test apparatus consists of a motor, torque sensor, temperature sensor, variable frequency drive (VFD), bearing, shaft, test bed, couplings, and data collector. To permit the modification in rotational speed, the test stand is constructed with an electric motor that is controlled by a variable frequency drive. Via the shaft, torque sensor, and couplings, the motor is linked to the gearbox housing the test gear pair.

The torque sensor (with an accuracy of 0.01) is used to detect the torque at the test gear's input shaft. Temperature sensors (with an accuracy of 0.01) and pressure gauges (with an accuracy of 0.01), respectively, can be used to detect the temperature of the oil inside the gearbox and the air pressure inside the gearbox.

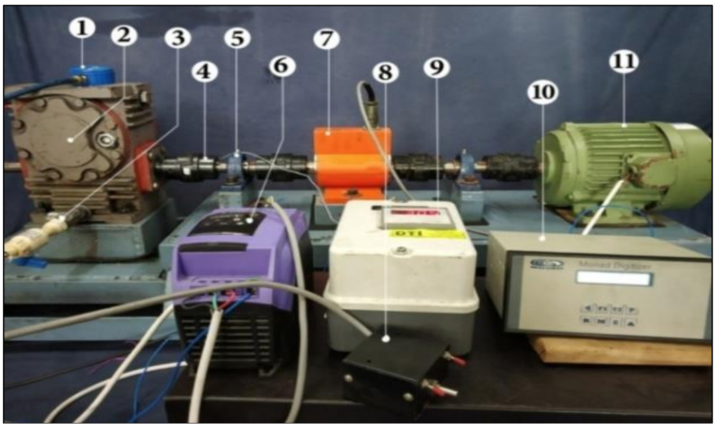


Figure 1: Test rig to investigate churning power loss of worm gear.
Source: Authors, (2024).

1-Pressure Gauge, 2-Worm gearbox, 3-Provision for oil level indicator, 4-Jaw type coupling, 5-Foot mounted bearing,6-Variable frequency drive (VFD), 7-Torque sensor, 8-VFD regulator, 9-Temperature indicator, 10-Digital controller for Torque sensor, 11-3-phase AC motor

Table 1: The geometric properties of the worm gear.

Reduction ratio	30:1	
Outer dia. (mm)	132	40
Center distance (mm)	75	
Pressure angle	20	
Module (mm)	3	
Material	CuSn12	16MnCr5
No. Of teeth	30	Single start
Gear	Worm Wheel	Worm Shaft

Source: Authors, (2024).

The test rig made it possible to study the effects of different working conditions, such as worm speeds, gear orientation (worm at the top and bottom), gear reduction ratio, temperatures, types of lubricant (mineral and synthetic), and immersion depth of the gear (lubricant volume), on input torque. The geometrical measurements and composition of a worm wheel and a single start worm are displayed in Table 1. It should be mentioned that just one geometry was chosen to examine the impact of rotational direction.

Table 2: Lubricant properties.

Sr. No	Name of oil	Kinematic Viscosity (cSt)@ 40 ºC	Kinematic Viscosity(cSt) @ 100 ºC	Viscosity Index	Density (Kg/m3) @ 15 ºC
Oil-A	Mineral oil	312	33	95	880
Oil-B	Synthetic oil	330	35.50	162	790

Source: Authors, (2024).

Table 3: Experimental parameters with their levels.

Control factors	Unit	Level 1	Level 2	Level 3
(A) Oil temperature	(ºC)	30	40	50
(B) Speed (Revolutions) of worm	(rpm)	1000	1200	1400
(C) Oil Volume	(lit)	1.5	2.1	2.7

Source: Authors, (2024).

Lubricating oil is the blood of any rotating component [20]. The worm gear may be lubricated in several ways, but splash lubrication was employed in this experiment to measure input torque. Two distinct oils were utilized as lubricants, and Table 2 summarizes their properties. The 180mm x 180mm x 280mm test gearbox's volume remained unchanged. The lubricant was added to the gearbox and it spun at a specific speed, following the test matrix shown in Table 3. The input torque was measured by the lubricant temperature and level stated.

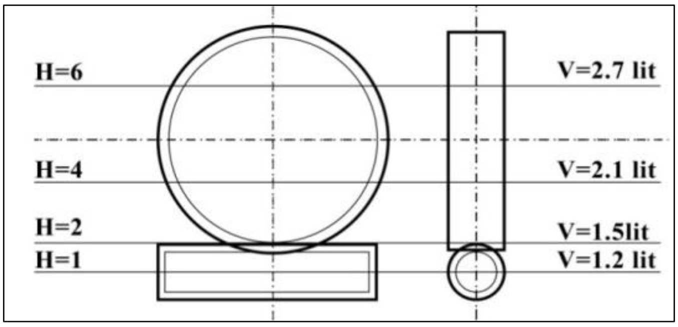


Figure 2: Static head of worm gearbox
Source: Authors, (2024).

The worm wheel and worm shaft levels cannot be explained in terms of a parallel-axis gearbox. Thus, for worms oriented at the bottom, as in Fig. 2, the static level of both is described from the base of the worm shaft; for worms oriented at the top, the same level is measured from the base of the worm wheel.

$$\text{Static Oil level } H = \frac{h}{r} \quad (4)$$

where h is the height of the oil level as measured from the worm shaft's base. where r is the worm shaft's outer (major) radius.

III. RESULT & DISCUSSION

The experiment was run at a temperature that was at least 5° C above the test's fundamental beginning point. The test had no time limit and continued until the target temperature was reached. To find out how rotation affected torque, the full test was conducted under particular setup and operating conditions.As seen in Table 4, the worm speed, lubricant (oil) temperature and lubricant (oil) volume, inside the gearbox were all varied during the trials.With the aid of the torque sensor, the response variable was the input torque, which was measured.In order to measure the churning power loss, the input torque and lubricant heating rate (time) were monitored for each experiment. Every time the temperature rose by 5ºC, the input torque was monitored for a more precise study. The churning torque was determined using the input torque as a guide.

$$T_{ch} = T_{total} - T_{no-oil} \tag{2}$$

T_{ch} = Churning torque,

T_{total} =Input torque with lubricant,

$T_{no\ oil}$ =Input torque without oil.

Equation (2) can be used to determine the churning power loss based on the input torque (response variable).

$$P_c = \frac{2\pi N T_{ch}}{60} \tag{3}$$

P_c= Churning power loss

N=Worm speed

This churning power loss can be normalized by using one (maximum) reference power loss (P_{ref}) and the normalized churning power loss is given in equation (3).

$$\overline{\mathrm{P}} = \frac{P_c}{P_{ref}} \tag{4}$$

III.1 REPEATABILITY EXPERIMENTS

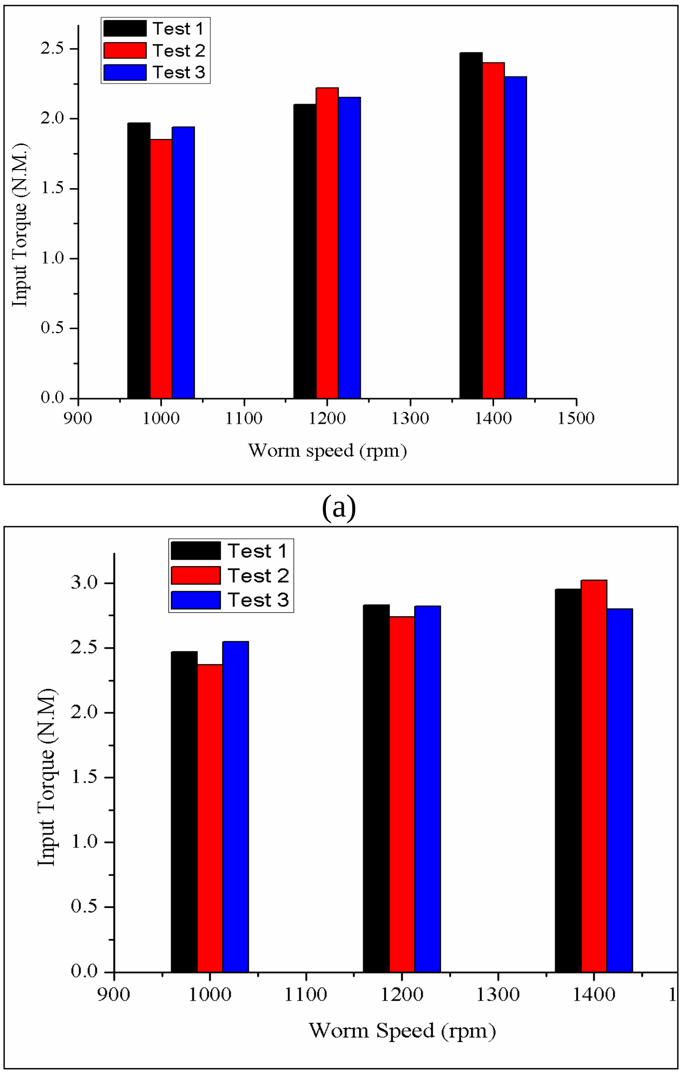
Two sets were chosen at various worm speeds in order to illustrate the measurement's reproducibility, as seen in Table 4. The repeatability of dip-lubricating the worm gearbox has been investigated through three separate trials conducted at various times for each set.

Table 4: Experiment set for repeatability.

Set	Lubricant	Temperature of lubricant (ºC)	Volume of lubricant (lit.)
1	Oil-A	50	2.1
2	Oil-B	40	2.7

Source: Authors, (2024).

The values obtained from three separate experiments at varying input speeds and lubricant characteristics are compared in Figures 2(a) and (b). The data provide an average variation of just 5% about the mean value for Oil B under specific conditions with an appropriate degree of repeatability, as shown in Figure 2(b), and 6.8% about the mean value for Oil A throughout the complete speed range, as shown in Figure 2(a). It demonstrates that the testing conditions and time had no effect on the experiments.



(a)

(b)

Figure2: Repeatability experiment for worm gear pair at (a) Set 1 as per Table 4 (b) Set 2 as per Table 4.

Source: Authors, (2024).

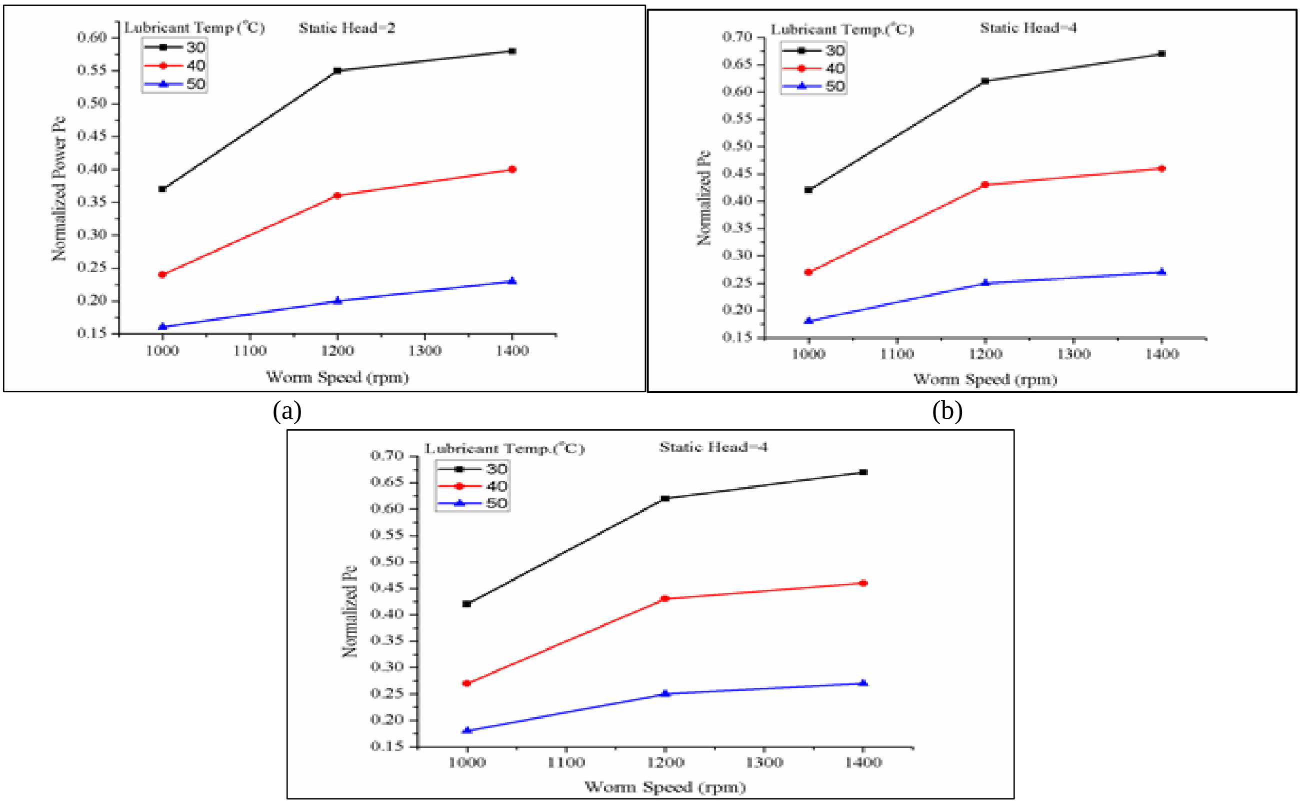
III.2 Influence of Direction of Rotation

The readings taken from the experiments are given in Table no-5. Which shows the churning power loss and normalized power loss for synthetic lubricant and worm position at bottom. In this way the readings were taken for worm shaft at top position and also for mineral lubricants

Table 5: Experiment results of churning power loss for churning power loss with oil-B, Worm at the bottom position.

Sr. No	**Factors**			**Response Variable**	**Calculated Responses**		
	Worm Speed (rpm)	**Lubricant Volume (Lit.)**	**Lubricant Temperature (C)**	**Input Torque (N.M)**	**Churning Torque (N.M)**	**Churning Power loss**	**Normalized Power loss**
1	1000	1.5	30	2.70	1.25	130.90	0.37
2	1000	1.5	40	2.24	0.79	82.73	0.24
3	1000	1.5	50	1.99	0.54	56.55	0.16
4	1000	2.1	30	2.85	1.4	146.61	0.42
5	1000	2.1	40	2.36	0.91	95.29	0.27
6	1000	2.1	50	2.06	0.61	63.88	0.18
7	1000	2.7	30	2.90	1.45	151.84	0.43
8	1000	2.7	40	2.47	1.02	106.81	0.31
9	1000	2.7	50	2.19	0.74	77.49	0.22
10	1200	1.5	30	3.04	1.52	191.01	0.55
11	1200	1.5	40	2.53	1.01	126.92	0.36
12	1200	1.5	50	2.09	0.57	71.63	0.20
13	1200	2.1	30	3.24	1.72	216.14	0.62
14	1200	2.1	40	2.72	1.2	150.80	0.43
15	1200	2.1	50	2.21	0.69	86.71	0.25
16	1200	2.7	30	3.29	1.77	222.42	0.64
17	1200	2.7	40	2.83	1.31	164.62	0.47
18	1200	2.7	50	2.37	0.85	106.81	0.31
19	1400	1.5	30	3.06	1.39	203.78	0.58
20	1400	1.5	40	2.63	0.96	140.74	0.40
21	1400	1.5	50	2.21	0.54	79.17	0.23
22	1400	2.1	30	3.27	1.6	234.57	0.67
23	1400	2.1	40	2.78	1.11	162.73	0.46
24	1400	2.1	50	2.32	0.65	95.29	0.27
25	1400	2.7	30	3.38	1.71	250.70	0.72
26	1400	2.7	40	2.87	1.2	175.93	0.50
27	1400	2.7	50	2.43	0.76	111.42	0.32

Source: Authors, (2024).



(a) (b)

(c)

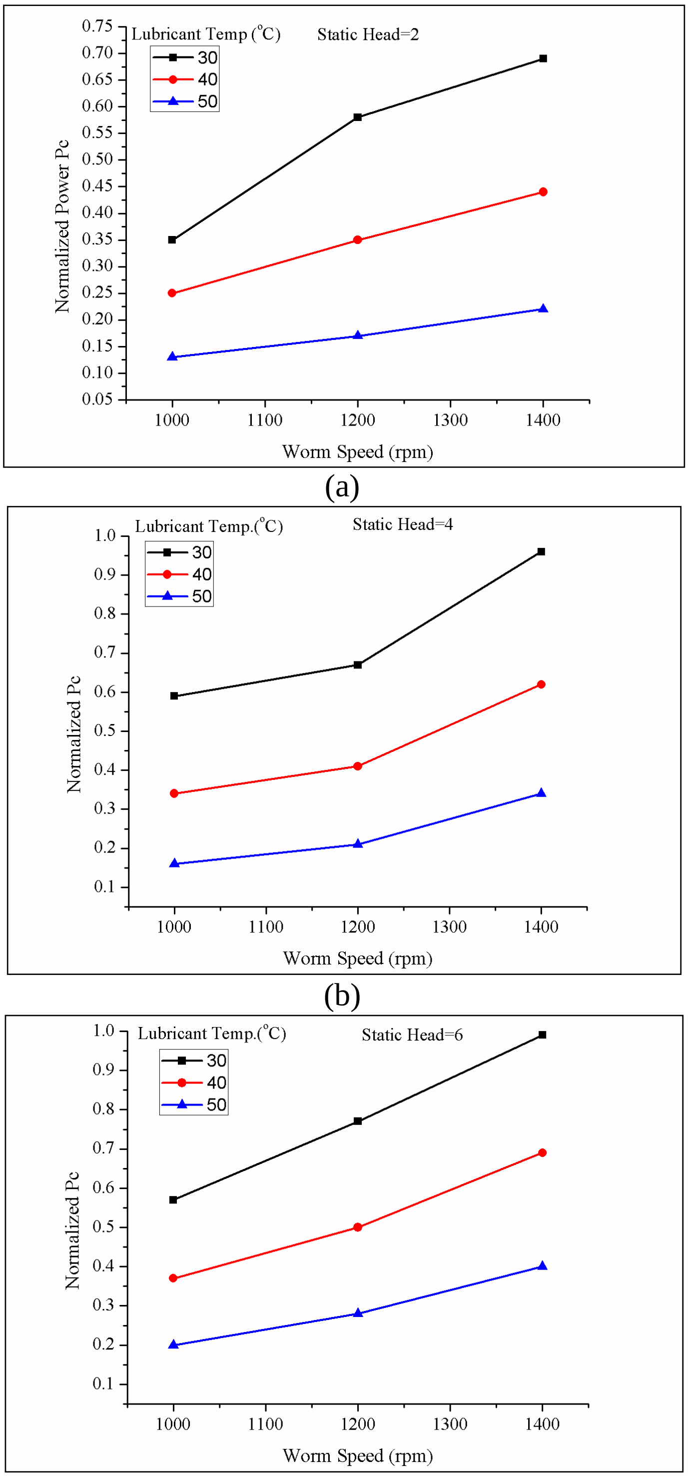
Figure 4: Influence of temperature on churning power loss with oil-B, Worm at the bottom position and gear pair-1 (a) Static Head=2 (b) Static Head=4 & (c) Static Head=6.

Source: Authors, (2024).

Figure 4 shows direct comparisons between the results at 30°C and 50°C to show how the lubricant temperature affects the churning power losses of the worm gear pair. One important factor that affects every aspect of power loss is the lubricant's viscosity. It has been demonstrated that reducing oil viscosity reduces gear churning power losses [13,17]. The viscosity of the lubricant decreases with temperature, making it a low-viscosity lubricant. Likewise, the lubricant is thought to have a higher viscosity at a lower temperature. Oil pushed upwards would return to the oil bath at the bottom in the direction of the gear's tangential velocity, when the H<2flow of fluid was such that a working oil level could be determined at a lower height than the static oil level. In the meantime, for H>2 where fluid forms a vortex—a full, continuous circulation channel inside the test gearbox. The temperature of the bulk lubricant inside the test gearbox increased when a vortex was present. Figure 4(a) shows that the influence of lubricant temperature on the churning power loss of a worm gear pair at lower speed is insignificant for low immersion levels (static head H≤ 2).As seen in Figures 4(b) and 4(c), the oil temperature (i.e., kinematic viscosity) becomes increasingly significant for static head H> 2. The churning power loss is more impacted up to 1200 rpm at lubricant temperatures below 50 ºC (temperature < 50 ºC), and above that point, the normalized power loss increases at a steady rate. When the lubricant temperature is below 40ºC, the power loss during churning remains very modest, even at 1200 rpm, compared to lower temperatures. The churning torques for the worm gear pair with the worm in the bottom, the speed of worm shaft at 1400 rpm, and the lubricant temperatures at 30°C, 40°C, and 50°C are 1.39, 0.96, and 0.54 N.m., respectively, and the corresponding power loss is 203.78, 140.14, and 79.17 watts when the churning torques are measured for lower static head H=2 (Volume=1.5 liter).

Similarly, for greater static head H=6 (Volume=2.7 liter), the corresponding power loss at 30ºC, 4º0C, and 50ºC is 250.70, 175.93, and 111.42 watts, respectively, for the same torque. A 30% increase in churning power loss on average occurs when oil temperature is lowered from 50°C to 30°C at lower static head (H≤ 2). When oil temperature drops from 50°C to 30°C, there is an average 33% rise in Pc at higher static head (H>2).

The noteworthy aspect is that the churning losses resulting from the lubricant at a lower temperature were not consistently greater than those resulting from the lubricant at a higher temperature. It was discovered that the churning power loss of lower static head and lower lubricant temperature for the oil-B, worm position at the bottom, was 22% smaller than the churning power loss of higher static head and higher lubricant temperature.



(a)

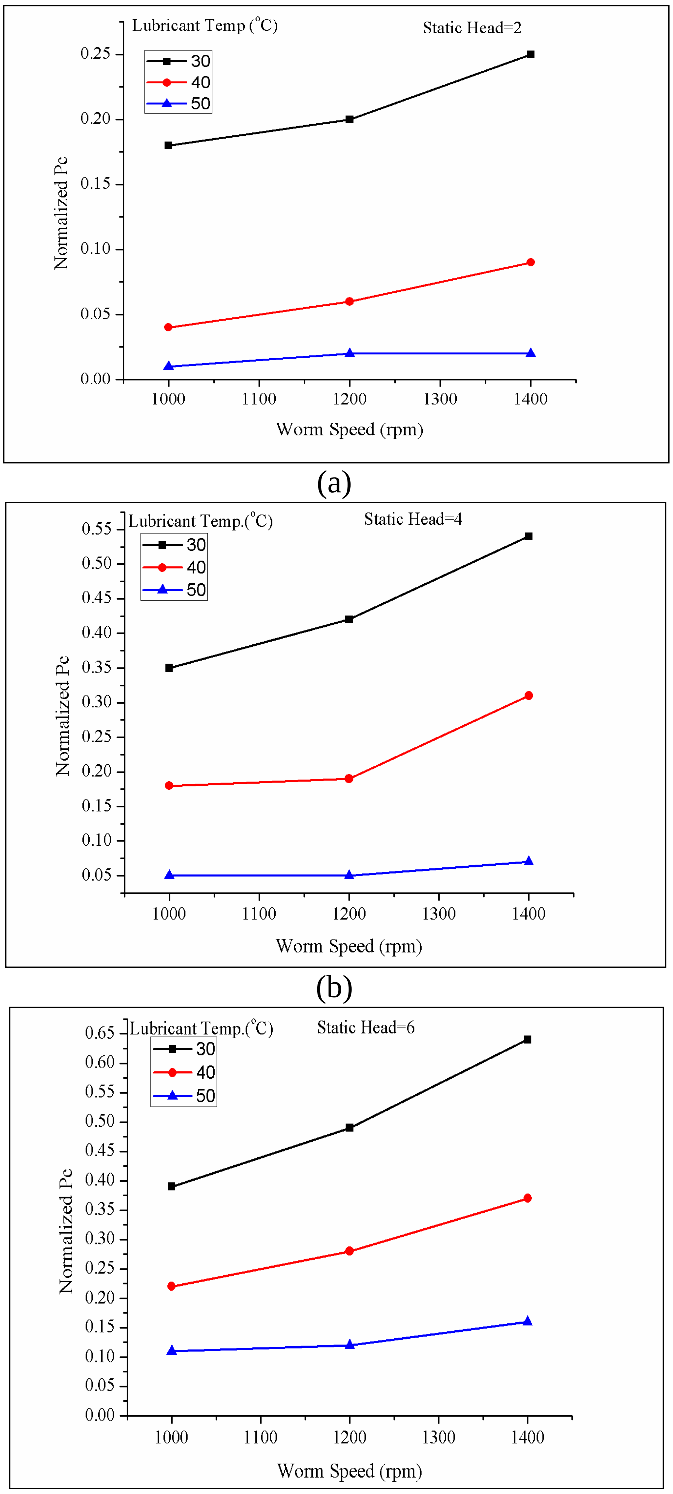
(b)

(c)

Figure 5: Influence of temperature on churning power loss with oil-A, Worm at the bottom position and gear pair-1 (a) Static Head=2 (b) Static Head=4 & (c) Static Head=6
Source: Authors, (2024).

The type of lubricant used also affects how much temperature affects the churning power loss of worm gears. Figure 5 illustrates how temperature affects oil-A and the worm shaft at the bottom. When the oil temperature is lowered from 50°C to 30°C, there is an average 37% increase in churning power loss at lower static head (H≤ 2). At higher static (H>2) head, churning power loss increases by an average of 50%. when oil temperature is lowered from 50°C to 30°C. Similarly, the influence of temperature is determined by the location of the worm shaft in the worm gearbox.

Figure 6(b) and (c)illustrate the average 38% increase in churning power loss at greater static head (H>2) when oil temperature is lowered from 50°C to 30°C.To reduce churning loss (loss that is dependent on no load), it is advantageous to select lubricant with the lowest feasible operating viscosity for practical applications. Higher temperatures cause a decrease in viscosity, which lessens the power loss during churning.



(a)

(b)

(c)

Figure 6: Influence of temperature on churning power loss with oil-B, Worm at Top position and gear pair-1 (a) Static head=2 (b) Static Head=4 & (c) Static Head=6.
Source: Authors, (2024).

IV. CONCLUSION

The purpose of the research was to find out how lubricant temperature affected the churning power loss for worm gears that were dip-lubricated. The lubrication level, worm shaft speed, lubricant temperature, and rotation direction were among the variable operating conditions that influenced the measurement, which relied on the direct torque measuring technique. The temperature of the lubricant has a significant impact on the churning of the worm gear, especially in the case of the deeply submerged state and increased worm speed in the bottom condition. Because viscosity changes with temperature, experiments conducted at lower temperatures consistently produced larger churning power losses than those conducted at higher temperatures. When oil temperature is lowered from 50°C to 30°C, there is an average 33% increase in churning power loss at greater static head (H>2). When the static head and lubricant temperature were lower, the churning power loss was 22% less than when the static head and lubricant temperature were greater. The present study investigated the effect of temperature on churning power loss for the worm gear only, Similerly other parameter effects can be obtained by the same experiments. It is also recommended to investigate the churning power loss for worm gear with jet lubrication. The CFD analysis is also most powerful tool to obtain the windage and churning power losses.

V. AUTHOR'S CONTRIBUTION

Conceptualization. G Chothani.
Methodology: H.G. Chothani
Investigation: D.J. Marsonia&S.H. Zala
Discussion of results: H.G. Chothani
Writing – Original Draft: H.G. Chothani
Supervision: N.N. Jadeja.

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