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Experimental Investigation on Churning Power Loss of Splash Lubricated Worm Gear

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Abstract

Churning power losses are a complex phenomenon that produces critical power losses when considering the splash lubrication of gear units. This article describes the method to investigate the churning power loss in a worm gearbox. A particular test rig was designed and fabricated to experiment on single start worm gear incompletely submerged in an oil bath. The direct torque measurement technique was used to determine the churning power losses. Experiments have been conducted to determine the impact of a variety of operating conditions on churning power losses, including worm speeds, gear immersion depth, lubricant temperatures, and lubricant type (mineral and synthetic). It was found that the churning losses were significantly affected by the worm shaft orientation, speed of gear, and the depth of immersion (static head). The lubricant's temperature is more essential than the type of lubricant in terms of churning power loss.

Keywords

worm gear, churning power loss, efficiency, power loss, non-load dependent losses

1 Introduction

Worm gears are widely used in technical systems both due to the possibility of achieving high reduction ratios, high torque and due to the low cost of production [1]. However, with the same gear ratio, the worm gear is more compact than parallel axis gear and requires less metal [2]. The most important part of this gear is the worm and worm wheel which are generally made of hardening steel and bronze respectively [3]. The meshing of the worm and the worm wheel is a blend of sliding and rolling activities, yet sliding contact overwhelms at high reduction ratios. This sliding activity causes friction and heat, which reduces the efficiency of worm gears. Worm gear generates too much heat which has to be cooled by using proper lubrication because the lubricant is not only for friction but also for dissipating the heat created by the gearbox when it is in use [4]. The power losses in gear are split into two categories:

- load-dependent (mechanical);
- load-independent (spin) power losses due to windage losses, oil churning losses, and gear and bearing oil sealing losses [5].

Churning power losses occur when gears drag in splash oil, while windage power losses occur when gears drag in the air. Gear churning power losses are divided into two categories:

- drag losses caused by oil churning along with the side faces and periphery of gears, and
- pocketing losses in the meshing zone.

The majority of distributed gear efficiency research has focused on estimating or forecasting frictional losses [6].

Von Karman [7] analyzed the simplest example of churning power loss by experimenting on a small disc rotating in the fluid. Daily and Nece [8] experimented on enclosures and bladed discs. Boness [9] looked into the churning power losses in dip-lubricated gear transmissions under a variety of operating circumstances and developed the empirical formulas. Using the direct torque measurement technique, types of research have been conducted to develop empirical connections to investigate churning losses [10, 11]. Luke and Olver [12] found certain discrepancies between the results

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of Terekhov and Boness. Michaelis and Höhn [13] experimented on cylindrical gear and discovered that the churning power loss depends mainly on the viscosity of the lubricant not on the type of lubricant. Changenet and Velex [14] examined the influence of housing dimensions on churning loss. Kolekar et al. [15] investigated the churning power loss of single gear by using the Inertia rundown technique.

The literature survey above uncovers that most of experimental studies on gear efficiency are centered on parallel axis of gear and out of that majority of experimental studied devoted to examining churning power losses were constrained either to disc or a single gear. It shows that no experimental information concerning churning power losses produced by worm gears.

2 Materials and methodology

In dip lubrication, there are three methods for determining churning power losses of gears and gear pairs: inertia rundown approach, direct torque measurement via a torque sensor, and heat dissipation measurement [16]. The direct torque measurement technique was used for the work described in this paper. The working model of the test rig is given in Fig. 1. An electric motor drives the worm gear using a flexible coupling through a torque sensor. The foot-mounted bearings are placed on both sides to reduce the vibration of the torque sensor. The resisting torque is directly estimated by the rotational torque sensor of precision ±0.01 N m. For measurement and regulate the speed of the worm, a variable frequency drive (VFD) has been used. The temperature of the housing and the temperature of the lubricant were both measured using a temperature sensor.

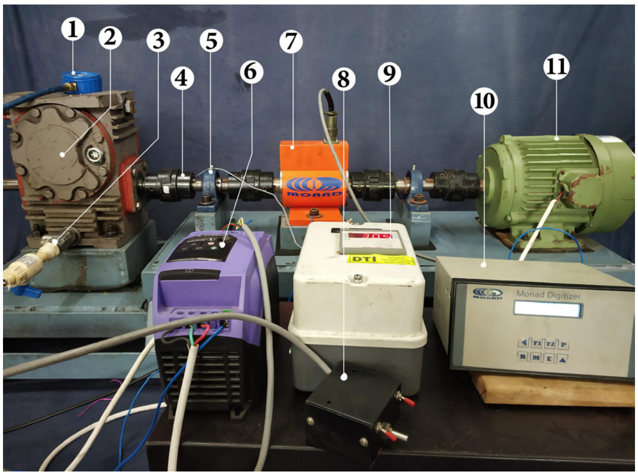

Fig. 1 Test rig to investigate churning power loss of worm gear; 1: Pressure Gauge; 2: Worm gearbox, 3: Provision for oil level indicator; 4: Jaw type coupling; 5: Foot mounted bearing; 6: Variable frequency drive (VFD); 7: Torque sensor; 8: VFD regulator; 9: Temperature indicator; 10: Digital controller for Torque sensor; 11: phase AC motor

The oil level can be measured by an oil level indicator. The pressure of the air inside the gearbox was measured using a gauge mounted on the top of the gearbox. The non-return air valves were arranged at top of the gearbox to reduce or diminish the effect of windage loss. The volume of the test gearbox was kept constant (180 mm × 180 mm × 280 mm). The gearbox was filled with oil according to the test matrix. To calculate the input power $P_{(Immersed)}$, the torque and speed were measured with the help of a torque sensor and variable frequency drive respectively. Before conducting another set of measurements, the gearbox oil temperature was allowed to cool to room temperature. When the worm and worm wheel was not submerged in oil, the power loss $P_{(Non\ immersed)}$ was calculated at the same speed as in the immersed situation. A little amount of oil was provided to the gear work area and the bearing area for the non-immersed condition. Assuming that, if the friction power loss estimates for both (immersed and non-immersed) the circumstances were about comparable [17]:

$$P_{(Immersed)} = P_{wf} + P_{wc} + P_{bf} + P_{bc} + P_s, \tag{1}$$

$$P_{(Non\ immersed)} = P_{wf} + P_{bf} + P_s, \tag{2}$$

where P_{wf} is the friction power loss of worm gear, P_{wc} is the churning power loss of worm gear, P_{bf} is the friction power loss of the bearings, P_{bc} is the churning power loss of the bearings, and P_s is the power loss of the seals. The difference in power loss between the two lubrication conditions ('Immersed' and 'Non immersed') was due to the gears and bearings churning [6, 18]:

$$P_c = P_{(Immersed)} - P_{(Non\ immersed)}, \tag{3}$$

where P_c gearbox's churning power loss.

When using a gearbox with a minimum appropriate shaft diameter in both immersed and non-immersed bearing conditions, the measured torque loss is mostly due to shaft viscous bearing losses and drag losses. The drag loss of the shaft was neglected because of its very small diameter. This setup was utilized to calculate the input shaft bearing's churning power losses (P_{bc}). The churning loss of the bearings (P_{bc}) was quite minor in this test compared to the worm and worm wheel churning loss (P_{wc}). As a result, the relationship stated in Eq. (4) can be taken into account:

$$P_c \approx P_{wc}. \tag{4}$$

During the test, the oil temperature was measured using a temperature sensor., as indicated in Fig. 2 and the geometry of the selected single start worm and worm wheel is

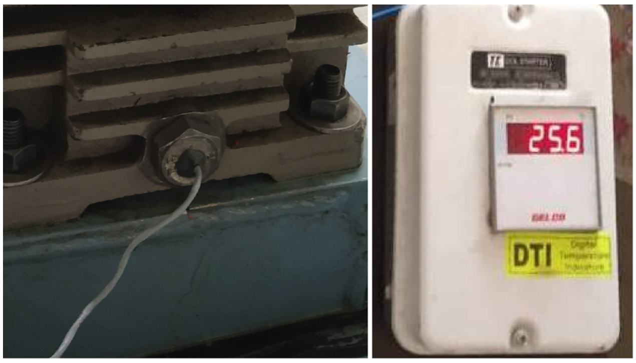

Fig. 2 Temperature sensor and its arrangement

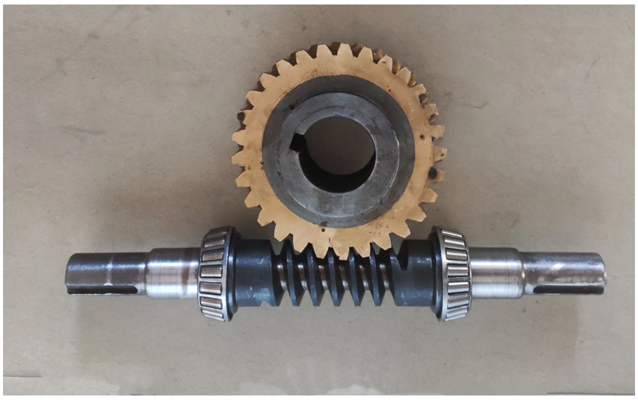

Fig. 3 Single start worm and worm wheel

shown in Fig. 3. Table 1 shows the geometrical dimensions and material of a single start worm and a worm wheel. It can be noted that single geometry was selected to study the effect of orientation. There are several techniques to lubricate the worm gear, however, for this experiment; splash lubrication was used to assess churning power loss. In terms of lubricants, two different oils were used, with their characteristics summarized in Table 2 [19].

2.1 Test matrix

Table 3 shows the test matrix for the full factorial design. Pilot studies on the same test setup were used to determine the acceptable ranges for these variables. Theoretically, a gearbox's churning power loss P_c is the sum of gear drag losses and gear pocketing losses.

The level of worm shaft and worm wheel can't be described as per parallel axis gearbox. So static level of both is described from the base of worm shaft for worm at bottom orientation as shown in Fig. 4 and for worm at top position same level measured from the base of the worm wheel:

$$\text{Static Oil level}: H = \frac{h}{r}, \tag{5}$$

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

When the worm is at the bottom condition, H = 0 implies that oil is not in touch with the worm shaft. H = 1 when the worm is half-immersed in oil, and H = 2 when the static oil level is at the worm's top, submerging the entire worm in oil or up to meshing.

Table 1 The geometric properties of the worm gear [19]

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

Table 2 Lubricant properties [19]

Sr. No	Name of oil	Kinematic viscosity (cSt) @ 40 °C	Kinematic viscosity (cSt) @ 100 °C	Viscosity index	Density (kg/m^3) @ 15 °C
Oil-A	Mineral oil	312	33	95	880
Oil-B	Synthetic oil	330	35.50	162	790

Table 3 Test matrix

Control factors	Unit	Values
Speed of worm	rpm	1000, 1200, 1400
Static Oil Level (H)	–	2, 4, 6
Temperature	°C	30, 40, 50
Orientation of worm	–	Worm at the top Worm at the bottom
Lubricant	–	Oil-A, Oil-B

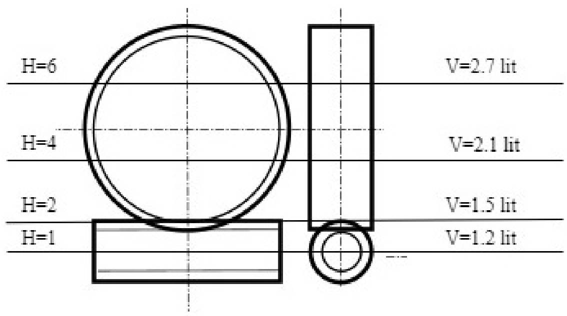

Fig. 4 Static head of worm gearbox

3 Results and discussion

Each test at a given arrangement and designed operating conditions were run for at least 20 minutes to determine the torque loss at various parameters.

$$\text{Churning power loss}: P_c = \frac{2\pi NT}{60}, \tag{6}$$

$$\text{Normalized Churning Power loss}: P_{ch} = \frac{P_c}{P_{ref}}, \tag{7}$$

where T is churning torque in N m, N is the worm speed in rpm, and P_{ref} is the reference value. It is noted here that the equivalent P_{ref} was utilized all through this examination so each data can be compared to others.

3.1 Influence of various parameters on churning power loss

To demonstrate the repeatability of the measurements, two sets were selected at different worm speeds as shown in the following Table 4. Three experiments per set have been taken at a different time to investigate the repeatability of dip lubricated the worm gearbox.

Fig. 5 and Fig. 6 compares the values measured through three different tests at various input speed and lubricant properties. At a given condition with a suitable level of repeatability, the statistics show an average variation of only 5%

Table 4 Experiment set for repeatability

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

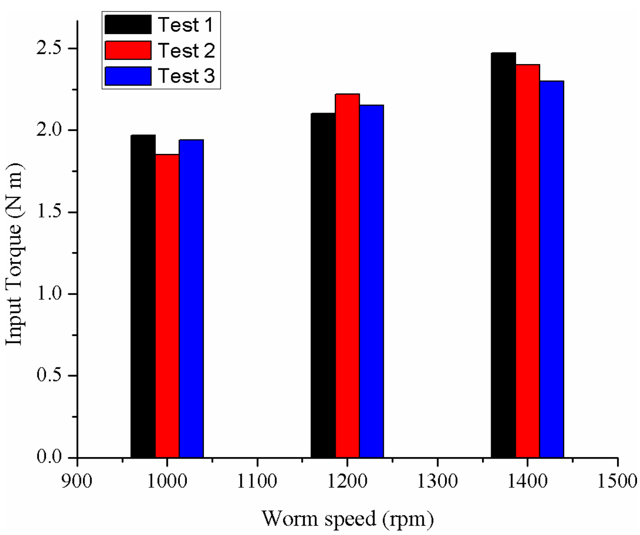

Fig. 5 Repeatability of churning loss measurement for worm gear pair for Set 1 as per Table 4

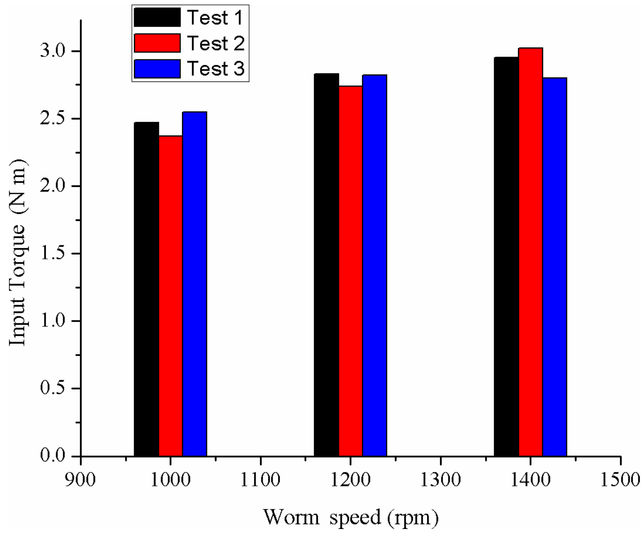

Fig. 6 Repeatability of churning loss measurement for worm gear pair for Set 2 as per Table 4

variation about mean value for Oil-B as shown in Fig. 6 and 6.8% variation about mean value for Oil-A over the whole speed range as shown in Fig. 5. It shows that the experiments are not affected by the testing time and environment.

3.2 Influence of static head

To investigate the effect of the static head at various temperatures, various speeds, various lubricants, and three static heads were considered H = 2, H = 4, and H = 6. However, these static heads were equivalent to the volume of 1.5 liters, the volume of 2.1 liters, and volume 2.7 liters respectively as shown in Fig. 4.

Fig. 7 shows the churning power loss increased with increase of static head. Higher static head cause higher churning power loss. At lower static head (H = 2) churning power loss is gradually increase with speed because at lower static head (H = 2), the worm shaft was fully immersed in lubricant and the worm wheel was not immersed in lubricant as shown in Fig. 4. At higher static head (H = 6) the increasing rate of churning power loss is higher with speed because at this condition worm shaft was fully immersed and worm wheel was also 75% immersed in lubricant as shown in Fig. 4. The effect of the static head on churning power loss based on the various temperature of lubricant is shown in Fig. 8. It shows that the churning power loss is gradually decreased when operating temperature is increased.

3.3 Influence of temperature

To illustrate the influence of the lubricant temperature on the churning power losses of the worm gear pair, direct comparisons between the measurements at 30 °C to 50 °C

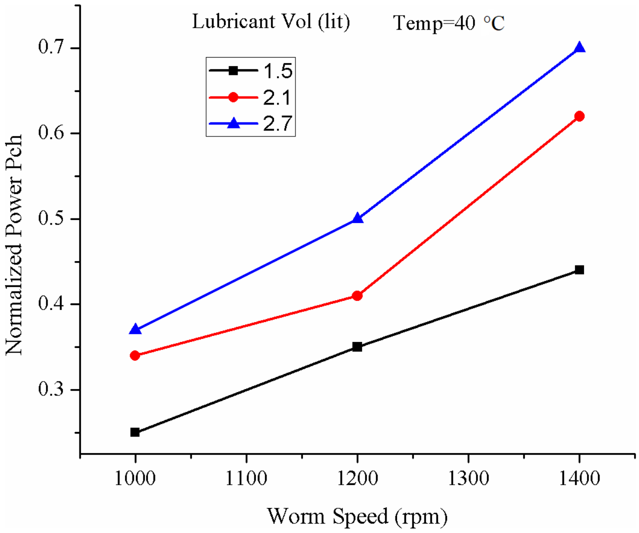

Fig. 7 P_{ch} vs Worm speed @ 40 °C

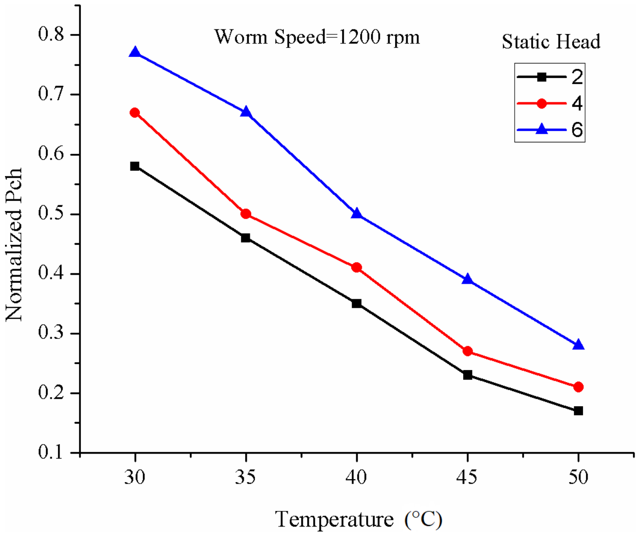

Fig. 8 P_{ch} vs temperature of lubricant @ 1200 rpm

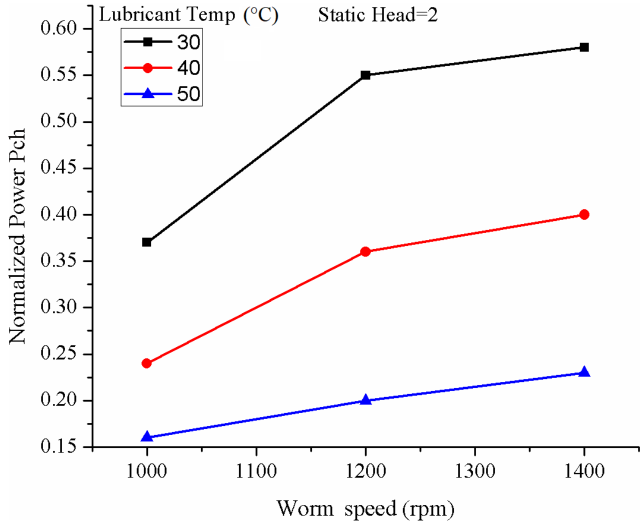

Fig. 9 Influence of temperature for worm at the bottom and Oil-B for H = 2

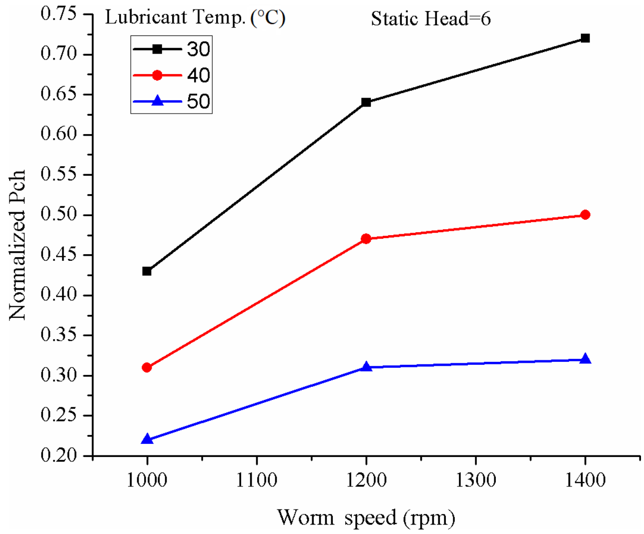

Fig. 10 Influence of temperature for worm at the bottom and Oil-B for static head H = 6

are made in Figs. 9 and 10. Fig. 10 indicates that at low immersion levels (static head H ≤ 2), the influence lubricant temperature on Churning power loss of worm gear pair at lower speed is negligible.

The oil temperature becomes more influential for static head greater than as shown in Fig. 10 At lubricant temperature less than 50 °C, the churning power loss is more affected up to 1200rpm and above it, the increasing rate of churning power loss is constant. However, the lubricant temperature less than 40 °C, the churning power loss is not too much affected up to speed 1200 rpm as affected in lower temperatures. At lower static head (H less than 2), an average 30% increase in churning power loss when decreasing oil temperature from 50 °C to 30 °C. At higher static head (H greater than 2), an average 33% increase in churning power loss when decreasing oil temperature from 50 °C to 30 °C.

At higher temperature, lubricant viscosity goes down; It can be considered as a low viscous lubricant. Similarly, at a lower temperature, the lubricant is considered a higher viscous lubricant [6]. The low lubricant viscosity reduces the churning power loss because of the low gear movement resistance.

3.4 Influence of worm speed

Gear speed has the largest effect on gear churning losses for the parallel axis of gear and these losses are proportional to 1.7 power of bevel gear speed [12]. Figs. 11 and 12 shows the Influence of worm speed for worm at the bottom, 40 °C, Oil-A and Oil-B respectively at various static heads. According to Fig. 11, the churning power loss is nearly constant up to the speed of 1200 rpm, however,

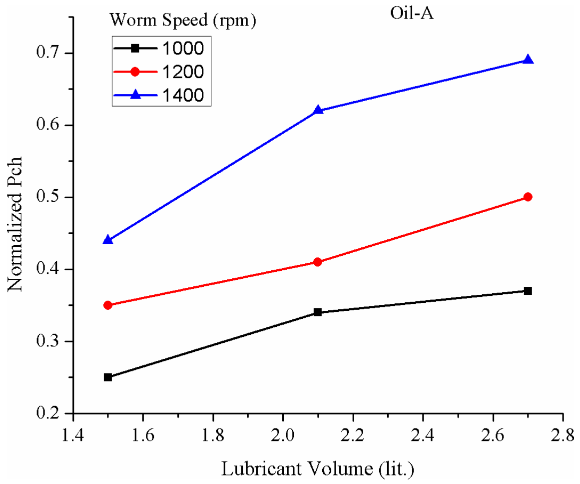

Fig. 11 Influence of worm speed for worm at bottom, 40 °C with Oil-A

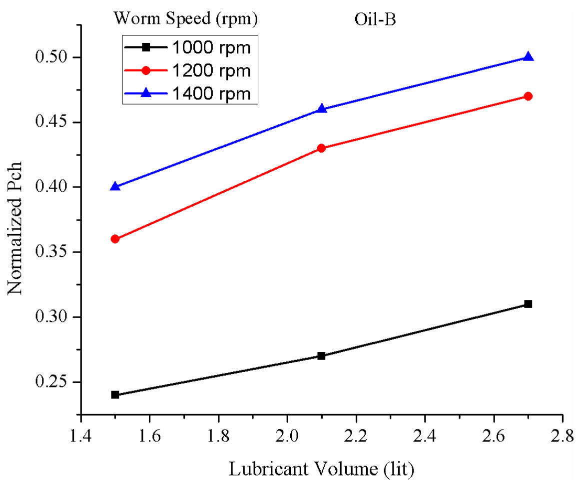

Fig. 12 Influence of worm speed for worm at bottom, 40 °C with Oil-B

above 1200 rpm, the churning power loss goes up rapidly. Similarly, According to Fig. 12, the churning power loss is rapidly increased at worm speed higher than 1000 rpm. At speed below 1000 rpm, churning loss was very small considered as a negligible effect so worm speed was considered from 1000 rpm. At higher speed more friction occurred between oil and surface.

The churning power loss is increased by 47% as worm speed increases from 1000 rpm to 1400rpm for Oil-A. Similarly, for Oil-B the churning power loss is increased by 39% as worm speed increases 1000 rpm to 1400 rpm for the 2.7 liter volume of test gearbox (see Table 5). It is noticed that the churning power losses are proportional to $N^{0.70}$ for the 2.7 liter volume of test gearbox and average churning power losses are proportional to $N^{0.68}$ for the test gearbox (by considering 1.5 liter, 2.1 liter and 2.7 liter volume). At higher speed more friction occurred between oil and surface. At lower speed oil thrown upward in in the direction of tangential velocity of the gear would return back to the oil bath at the bottom while at higher speed oil through in circular path which produces vortex which increases the power loss [20].

3.5 Influence of lubricant type

Mineral oil and synthetic oil are commonly used in industrial worm gears. To examine the effects of the type of oil with nearly the same viscosity, two different gear oils, called Oil-A and Oil-B were considered. Oil-A is the mineral oil and Oil-B is the synthetic oil as discussed in Table 2. These were tested at different temperature levels, static head, and orientation of worm, and speed of worm.

In the beginning there was minor difference between churning power loss for Oil-A and Oil-B was because of slightly higher viscosity however it was reduced with time and after 30 minutes it was the same as shown in Fig. 13. Fig. 14 shows the heating rate of Oil-A and Oil-B which was also almost similar. Synthetic oil plays major role for load dependent losses. Synthetic oil has a much larger load capacity with respect to the temperature limit. Mineral oils have a higher coefficient of friction compared to synthetic oils in the same operating conditions [20]. However, for load non-dependent power losses, and the effect of lubricant type (Mineral and synthetic) are nearly less for nearly similar viscosity.

Table 5 Effect of worm speed on churning power loss @ 2.7 liter volume

Sr	Oil type	Gear pair	Oil temperature	Oil volume	Worm speed	P_{churn}
1	Oil-A	Gear-1	40 °C	2.7 liter	1000	129.5
2	Oil-A	Gear-1	40 °C	2.7 liter	1200	175
3	Oil-A	Gear-1	40 °C	2.7 liter	1400	245
4	Oil-B	Gear-1	40 °C	2.7 liter	1000	108.5
5	Oil-B	Gear-1	40 °C	2.7 liter	1200	164.5
6	Oil-B	Gear-1	40 °C	2.7 liter	1400	178.5
7	Oil-C	Gear-1	40 °C	2.7 liter	1000	87.5
8	Oil-C	Gear-1	40 °C	2.7 liter	1200	115.5
9	Oil-C	Gear-1	40 °C	2.7 liter	1400	140

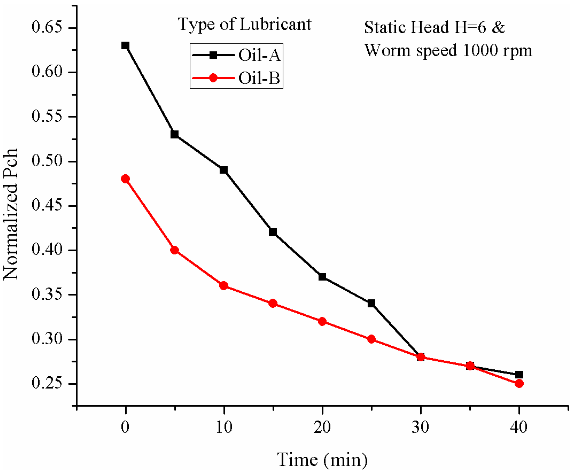

Fig. 13 P_{ch} vs time of run

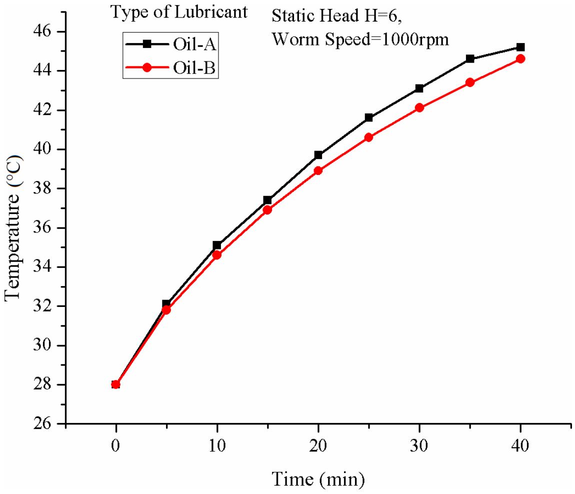

Fig. 14 Temp of lubricant vs time

4 Conclusions

The main objective of this study was to investigate the churning power loss for dip lubricated worm gear. The measurement was based on the direct torque measurement method. The experiments clearly showed that churning power loss present in the worm gear. Based on the results of experiments, the valuable conclusions are given below.

1. The static head is the most dominant factor in the churning power losses in dip lubrication. With dip lubrication, average churning power loss was increased by 30-35% when the static oil level increased three times from reference line of immersion.
2. Lubricant temperature has a valuable effect on worm gear churning, for the heavily immersed condition and higher worm speed only.
3. The churning power loss is increased by 40–50% as worm speed increases from 1000 rpm to 1400 rpm.
4. Types of lubricant (synthetic and mineral) at almost the same viscosity has not been too much dominating on churning power loss of worm gear.

It is summarized that moderate static head (50% immersion of worm wheel), average speed (not produces the vortex) and worm at top position are more preferable for lower churning power loss.

The present study investigated the churning power loss for the worm gear only. Similarly, it can be focused on windage power losses for no-load dependent losses.

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