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Rheological Insights and Optimization of Bio Nano Lubricants in Tribological Systems

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The Friction being an important tribological properties for lubrication studies. Fundamental feature of the lubricant is to reduce friction between the two surfaces and hence the life of the material. This research focuses on studying the advantage of utilizing the naturally available Pongamia oil that being the bio lubricant as an alternative lubricant engine oil. Commercial oil although available in plenty they have contributed to environmental hazards in one way or the other. And more over these Pongamia trees and seeds are available in plenty in India. The main intension of this research was utilizing the naturally available resources. Nano additives have been added to enhance the bio lubricant properties and to improve the efficiency in the system. Rheometer is an equipment which is used to analyze the viscosity of the samples and their response with respect to shear stress and strain. The different variations of the sample have been incorporated for the studies. The Samples viscosity are empirically considered in the temperature range of 20 to 30∘ C.

Keywords: Nanomaterials, Pongamia oil, Rheometer, Viscosity, Taguchi, optimization.

1. Introduction

The most important of any lubrication system is reduce friction and hence wear rate which can be achieved by constantly dispense the oil the moving components. The impact of lubricant oil on an Automotive engine is to reduce the heat generated and to seize the vehicle quickly. Although the filter is a part of the system whose primary objective is to eliminate pollutant and dust particles and to ensure smooth flow across the system. The Lubricant oil is prone to lubricate the camshaft bearings. The surplus oil in the Machine is then made to drains back to the sump. The importance aspect of any engine lubrication system is to minimize the overall loss, reduce wear and tear, to imbibe a good cooling system, to protect its component parts and to ensure tight fit that is radiating inside the cylinder.

The process of lubricating internal combustion engines is in which a pump forces oil into the engines, pistons shafts and bearings. The Society of Automotive Engineer [5][6] has identified SAE viscosity number for lubricating oils. The viscosity number is determined by the range of viscosities within it fall at the given temperature. And has recommended for winter use as 5W,10W,20W and for normal use 20,30,40. The four main types of lubrication systems Petroil System, Splash System, Pressure system and Dry-Sump System. The different components of an engine that are closely to be monitored with respect to lubrication are Oil Sump, Engine oil filter, Piston cooling nozzles, Oil Pump, Oil Galleries and Oil Cooler.

2. Experimentation and Methodology

2.1 Identification of raw materials:

In this research work Bio lubricant such as Pongamia oil was used along with nano materials such as zinc oxide was used.[9] The nano compound used was ZnO and the combination of ZnO along with the bio lubricant Pongamia oil exhibited superior friction reducing and wear resistance properties [10]. Pongamia is obtained from the tree Pongammia pinnata commonly called as Honge oil, which is a probable source for renewable fuels in wide-ranging and sustainable fuel [9][12]. The Pongamia seeds is available in excess in India and is not effetely used. The intension behind the research was to effectively utilizing the naturally available resources to the fullest extent. The zinc oxide was chosen as it was Non-toxic and environmentally friendly and it had large surface area to their size. It also provided a good surface finish along the surface of the machine [9]. The required raw material that is Pongamia oil and nano zinc oxide are shown in figure 1

Figure 1

2.2 Preparation of Samples:

Nano-Bio lubricating oils sample 1(S1), Sample 2 (S2) and Sample (S3) were considered as sample oils. The sample S1 comprised of 250gms of Pongammia oil and 5gms nano zinc oxide, the sample S2 consist of 250gms of Pongammia oil and 10gms of zinc oxide and the sample 3 was composed of 250gms of Pongammia oil and 15gms of zinc oxide [2][6]. The nano compound was blended well with the bio lubricant by using magnetic stirrer for about 20 min each as shown in figure 2.

Figure 2

2.3 Studying rheological properties of this Bio-nano lubricant.

These samples S1, S2 and S3 were tested in rheometer, it is a latest device which measures viscosity, that is how the lubricant responds to the forces applied, it is basically used to ration the rheology of the fluid. Two types of rheometers can be used to test the sample, they are shear rheometers and extensional rheometers. The samples have tested under the shear rheometer which is also called as rotational rheometer that is located at Reva institute of technology, Yelahanka, Bangalore. The temperature was steadily maintained between 23^{o} C and Viscosity, shear stress, shear rate, and torque were measured using Rheometer MCR302 as shown in figure 3, SN000000, ID 80963516 from Anton Paar. Measuring system PP25/PE-SN25125 (d = 0.4 mm) with accessory TUI = P-PTD200-SN 81183777 was used. The samples were considered under two cases. In the first case the raw samples under the blended condition were examined and tested under the rheometer and in the second case the samples were made to run for 40 hrs, that is 5 days for abouts 8 hrs. on two-wheeler Stationary as shown in figure 4. Each sample were run for about 40 hrs. to check the variations in viscosity as per the general sampling recommendation. And then they were again tested under the rheometer with the same parameters. The Viscosity of the samples S1, S2, and S3 samples were compared before and after the running condition.

Figure 3 Figure 4

3. Analysis using the Taguchi method

The Taguchi method Using an L9 Orthogonal Array in Minitab for Lubrication Studies was considered. An L9 orthogonal array is a type of fractional factorial design used in experimental studies, particularly in the field of Design of Experiments (DoE). It is often employed when there are multiple factors to test. The L9 array allows for efficient experimentation with 9 trials while examining up to 3 factors at 3 levels each. When it comes to lubrication studies, the L9 orthogonal array was used to optimize different lubrication parameters, such as Shear rate, Shear stress, Viscosity and Torque

Steps to Use the L9 Orthogonal Array in Lubrication Studies:

1. Identify Key Factors: First, you need to identify the key factors that influence lubrication performance. The factors to optimise the lubricant three levels for each factor are chosen. They are lubricant variant such as sample 1, sample 2 and sample 3, Time are 6 sec, 150 s and 300 s and Operating Temperature are of 23.1, 23.2 and 23.4 were considered

2. Set Up the L9 Orthogonal Array: The L9 orthogonal array allows you to test 3 factors at 3 levels in 9 trials. The standard format of an L9 array looks like this for the analysis are shown in table 5 and table 6 table 5 is considered for before run setup and table 6 is considered for after run set up.

3. Assign the levels defined for each factor to the array as Lubricant variant, Time and Operating Temperature

4. Conduct the Experiments: Perform the 9 experiments, each corresponding to one trial in the array. For each trial, vary the levels of the factors according to the design matrix. Measure the performance outcomes for lubrication, which are Shear rate, Shear stress, Viscosity and Torque

5. Analyse the Results: Once the experiments are completed, analyse the results to determine which factors have the most significant impact on lubrication performance. The methods of analysis used was Signal-to-Noise Ratio (S/N Ratio) as it helps identify which factor combinations optimize performance while minimizing variability. Which has been discussed in results and discussions.

4. Results and discussion

Shear Rate:

The shear rate plays a vital role in determining the performance and stability of lubrication systems. The shear rate of three samples before run and after run were considered and a graph was plotted for analysis the analysis shows that by optimizing the shear rate, it is possible to enhance the longevity of mechanical systems, improve energy efficiency, and minimize wear. Consequently, understanding and controlling shear rate is essential for the design of effective lubrication strategies in a wide range of industrial applications. From the table 1 and the graph 1 indicates that shear rate remains same for all values

Table 1

Point No.	Time	Sample 1 Before run S1	After Run S1	Sample 2 Before run S2	After Run S2	Sample 3 Before run S3	After Run S3
1	6	1	1	1	1	1	1
5	30	9.08	9.08	9.08	9.08	9.08	9.08
10	60	19.2	19.2	19.2	19.2	19.2	19.2
15	90	29.3	29.3	29.3	29.3	29.3	29.3
20	120	39.4	39.4	39.4	39.4	39.4	39.4
25	150	49.5	49.5	49.5	49.5	49.5	49.5
30	180	59.6	59.6	59.6	59.6	59.6	59.6
35	210	69.7	69.7	69.7	69.7	69.7	69.7
40	240	79.8	79.8	79.8	79.8	79.8	79.8
45	270	89.9	89.9	89.9	89.9	89.9	89.9
50	300	100	100	100	100	100	100

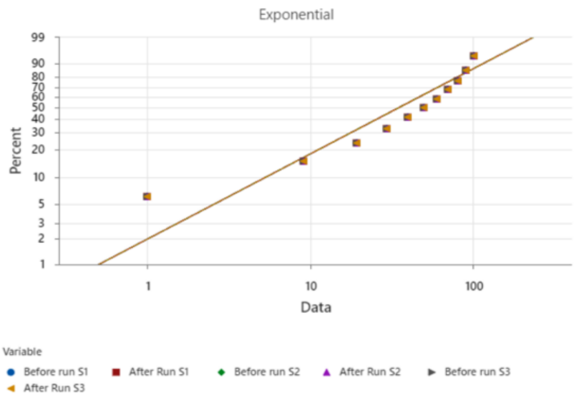

Fig 1

Shear Stress:

Shear stress is the amount of a force applied to the material. The formula for calculating the shear stress is as follows $\boldsymbol{\tau}$ = F/A. The shear stress is said to vary according to thickness of the fluid. It is observed from the table 2 the shear stress of the sample (S1) is found to range between 0.5 Pa to 42.2 Pa, the shear stress for the sample (S2) is observed between 0.9 Pa to 67.4 Pa and the shear stress for the sample (S3) is found to be between 1.1 Pa to 51.8 Pa [16]. It almost shows linearly and the variation of the nano lubricant added does contribute to drastic variation in the function, which suggests that this lubricant can be used as alternative lubricant with dual properties. The interval and data points were collected between 1 to 50. The temperature was maintained around 23^{o} C. The sample 1 sample 2 and the sample shear stress tabulated have been plotted in the graph using Minitab and values shown favorable to the shear stress when compared with SAE 40 lube oil that is widely used.

Table 2

Point No.	Time	Sample 1 Before run S1	After Run S1	Sample 2 Before run S2	After Run S2	Sample 3 Before run S3	After Run S3
	[s]	[Pa]		[Pa]		[Pa]	
1	6	0.5	0.7	0.9	1.1	1.1	1.0
5	30	3.0	4.8	3.7	6.7	4.2	5.2

10	60	6.3	9.1	7.2	13.6	8.2	10.6
15	90	9.5	13.1	10.7	20.5	12.2	15.8
20	120	12.6	17.0	14.2	27.6	16.2	20.9
25	150	15.6	21.3	17.6	34.0	20.1	26.0
30	180	18.8	25.6	21.0	40.8	23.9	31.2
35	210	21.7	29.8	24.4	47.5	27.7	36.6
40	240	24.7	33.8	27.6	54.0	31.5	41.5
45	270	27.6	38.2	31.0	60.7	35.3	46.7
50	300	30.5	42.2	34.1	67.4	39.2	51.8

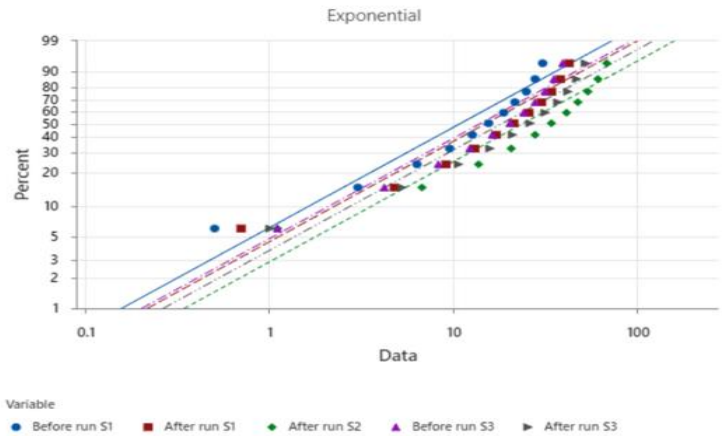

Fig 2

Viscosity:

Viscosity is an important aspect in an any machine as it determines the amount of energy required to pump the lubricant. The unit of viscosity is taken as mPa s. viscosity is of two types dynamic viscosity and absolute viscosity. The standard viscosity for machine oil ranges between 250-310 at 30^{o}C. But the sample 1 (S1) is somewhere between 454 and 422 mPa s, sample 2 (S2) is around 470 and 674 mPa s and sample 3 (S3) values are between 496 and 518 mPa. Although the values of the sample shown in the table 2 and the figure 3 represents the graph of the viscosity levels of the samples 1, samples 2, and samples 3. The graphs shown in the figure 3 does not show much variation when compared to the samples before and after running. But still since viscosity is high it can be used as cylinder oil where the standard values of viscosity is range from 500- 800 mPas [14][16]. But for machine lubrication there is small hinderance as the standard is required somewhere between 256.

Table 3

Point No.	Time	Sample 1 Before run S1	After Run S1	Sample 2 Before run S2	After Run S2	Sample 3 Before run S3	After Run S3
	[s]	[mPa·s]		[mPa·s]		[mPa·s]	
1	6	454.1	742.3	470.1	760.4	496.6	515.3
5	30	332.7	532.6	405	733.4	467.2	577.5

10	60	329.8	473.1	373.5	710.8	429.4	552.6
15	90	323.3	448.5	365.3	701.3	416.9	538.9
20	120	318.6	432.1	360.4	700.5	411.5	531.7
25	150	316.1	430.3	355.1	687.3	405.7	524.7
30	180	315.1	429	352	684.7	401.8	523.5
35	210	312	428.2	349.4	681.4	397.8	525.3
40	240	309.8	423.8	346.4	677.3	395.1	519.8
45	270	307.5	424.7	344.7	675.3	392.5	519.2
50	300	304.8	422.4	340.7	674.3	391.7	518.4

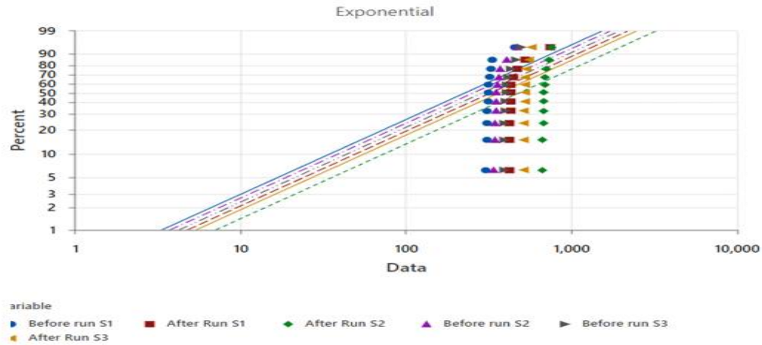

Fig 3

Torque:

The relationship between torque and lubrication is integral to the efficiency of mechanical systems. By selecting the right lubricant, controlling viscosity, and using friction-reducing additives, engineers can minimize the torque needed to operate machinery, improving performance and extending the life of components. Torques values observed from the table 4 and fig 4 for all the three samples are in close proximity with the standard oil SAE 40. Optimizing lubrication not only reduces mechanical strain but also contributes to energy savings, making it a key factor in the overall efficiency of a system. The sample values observed are crucial for reducing energy consumption, preventing overheating, and minimizing wear in mechanical systems.

Table 4

Point No.	Time	Sample 1 Before run S1	After Run S1	Sample 2 Before run S2	After Run S2	Sample 3 Before run S3	After Run S3
1	6	0.001	0.002	0.002	0.003	0.003	0.002
5	30	0.007	0.011	0.009	0.016	0.010	0.012
10	60	0.015	0.021	0.017	0.032	0.019	0.025
15	90	0.022	0.031	0.025	0.048	0.029	0.037
20	120	0.029	0.040	0.033	0.065	0.038	0.049
25	150	0.037	0.050	0.041	0.080	0.047	0.061
30	180	0.044	0.060	0.049	0.095	0.056	0.073
35	210	0.051	0.070	0.057	0.111	0.065	0.086
40	240	0.058	0.079	0.065	0.126	0.074	0.097
45	270	0.065	0.089	0.072	0.142	0.083	0.109
50	300	0.071	0.099	0.080	0.158	0.092	0.121

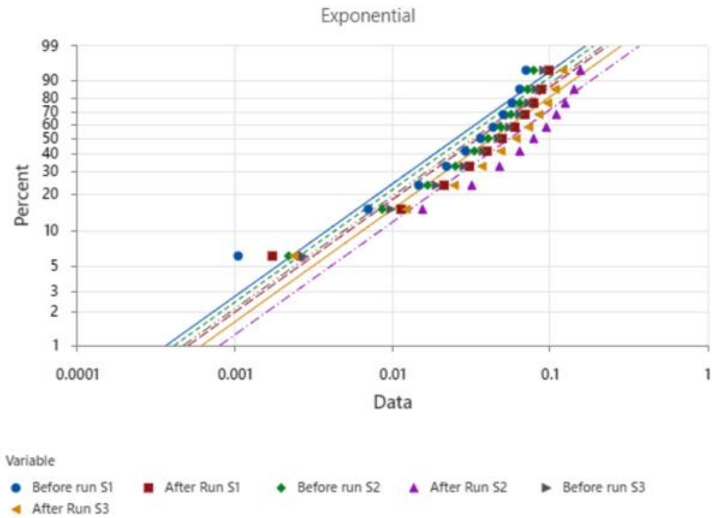

FIG 4

Taguchi Analysis using Minitab software

The experiments were analysed and optimised using Taguchi method using Minitab software. The components of the Graph are Y-Axis represents Mean of SN Ratios that is the y-axis represents the mean of SN ratios, a measure used to determine the performance of a system. And the x axis resents factors such as the plot analyses three factors: Variant, Time, and Temperature. Each factor has multiple levels that represent the experimental conditions for that variable (e.g., different variants, different times, and different temperature values).

Table 5

BEFORE RUN

variant	Time	temp	Shear Rate	Shear Stress	Viscosity	Torque
s1	6	23.1	1.00	0.45	454.10	0.00
s1	150	23.2	49.50	15.64	316.10	0.04
s1	300	23.4	100.00	30.48	304.80	0.07
s2	6	23.2	1.00	0.94	944.10	0.00
s2	150	23.4	49.50	17.57	355.10	0.04
s2	300	23.1	100.00	34.07	340.70	0.08
s3	6	23.4	1.00	1.15	1146.60	0.00
s3	150	23.1	49.50	20.08	405.70	0.05
s3	300	23.2	100.00	39.17	391.70	0.09

Table 7

Response Table for Signal to Noise Ratios

	Variant	Time	Temp
1	-3.951	-5.993	-4.136
2	-4.086	-4.019	-4.126
3	-4.234	-2.259	-4.009
Delta	0.284	3.735	0.128
Rank	2	1	3

Table 8

Response Table for Means

Level	Variant	Time	Temp
1	106	212.5	117.1
2	153.6	106.6	154.9
3	179.6	120.1	167.2
Delta	73.6	106	50
Rank	2	1	3

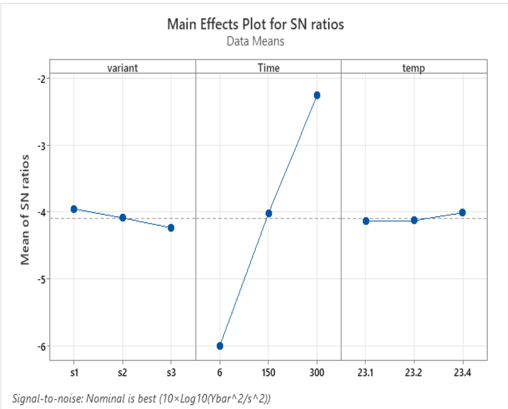

FIG 5

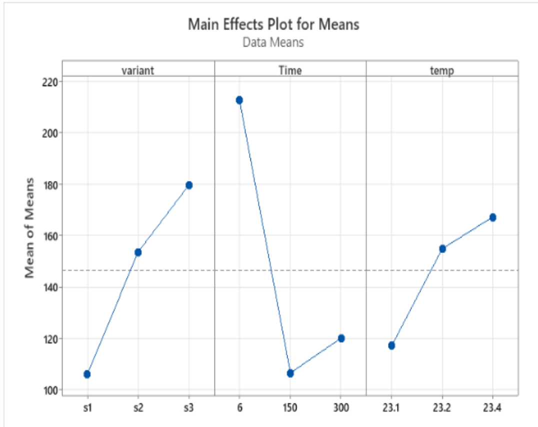

FIG 6

Table 6

After Run

Variant	TIME	TEMP	Shear Rate	Shear stress	Viscosity	Torque
S1	6	23.1	1	1.1224	1122.4	0.002626
S1	150	23,2	49.5	34.015	687.3	0.079577
S1	300	23.4	100	67.428	674.3	0.15775
S2	6	23,2	1	1.0154	1015.3	0.002376
S2	150	23.4	49.5	34.015	687.3	0.079577
S2	300	23.1	100	67.428	674.3	0.15775
S3	6	23.4	1	1.0154	1015.3	0.002376
S3	150	23.1	49.5	25.97	524.7	0.060755
S3	300	23,2	100	51.844	518.4	0.12129

Table 9

Response Table for Signal to Noise Ratios

Level	Variant	Time	Temp
1	-52.14	-54.4	-51.37
2	-51.85	-49.98	-51.11
3	-50.34	-49.95	-51.85
Delta	1.81	4.45	0.74
Rank	2	1	3

Table 10

Response Table for Means

Level	Variant	Time	Temp
1	228.1	263.3	213.9
2	219.2	178.5	204.9
3	190.7	196.2	219.2
Delta	37.4	84.8	14.3
Rank	2	1	3

FIG 7

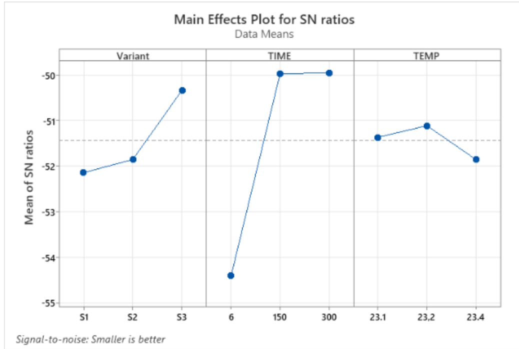

FIG 8

5. Conclusion:

The benefits of using Bio Nano Lubricant in a 2-stroke engine was investigated experimentally the main conclusions are listed below

1. The Pongamia oil that is the bio lubricant along with the nano compound such as zinc oxide could be the natural alternative for SAE 20/30/40 crude lube boil and worked efficiently in a 2-stroke engine

2. The shear rate of the lubricant has not shown much variation after subjecting to several cycles. The shear rates of piston rings can be as high as $2*10^7 s^{-1}$. Hence these sample shears are in the range of 1 to 100 s^{-1}, which signifies it to be an alternative lubricant.

3. Shear stress for the lubricant show a linear graph. And for all the three samples the values are linear. Hence the relationship between shear stress and shear rate are also linear which follows the flow curve.

4. The standard viscosity for machine oil ranges between 250-310 at 30^{o}C. the range of viscosity obtained from the samples are 400 to 577 mPa. The viscosity range of the samples are high for machine oil, but it can be used as cylinder oil as its viscosity range from 500- 800 mPas.

5. The percentage of the bio-Nano lubricant can be modified to provide significant influence on the viscosity that may be permissible to use of Machine oil that can be investigated in future studies.

6. From figure 1, 2,3 and 4 the graphs indicates that AD (Anderson-Darling statistic) and suggests that the data aligns with the with the normal distribution which states that the data fits the distribution closely and the p-value (P) is a measure that helps you determine the statistical significance of your results. A low p-value (usually less than 0.05) suggests that the observed data significantly deviates from what would be expected under the null hypothesis, meaning the result is statistically significant

7. Interpretation using Taguchi method

1. Variant (S1, S2, S3):

- The Variant factor shows a significant effect on the SN ratio.
- As you move from S1 to S3, there is a gradual increase in the SN ratio.
- S3 produces the highest SN ratio, which suggests that S3 is the most favourable variant for minimizing undesirable outcomes.

2. Time (6, 150, 300):

- Time has a strong effect on the SN ratio.
- At 6 (probably the shortest time), the SN ratio is the lowest, meaning this time setting results in the worst performance.
- However, as time increases to 150, there is a sharp increase in the SN ratio, showing improved system performance.
- Beyond 150, the SN ratio remains constant up to 300, indicating that longer time intervals don't further improve the performance significantly.

3. Temperature (23.1, 23.2, 23.4):

- The Temperature factor shows a more subtle effect compared to Variant and Time.
- The SN ratio increases slightly from 23.1 to 23.2, suggesting that 23.2 is an optimal temperature for performance.
- At 23.4, the SN ratio decreases, indicating worse performance at this higher temperature.

8. Overall Analysis for before run from fig 5 and fig 6:

- Variant S3 and Time at 150 or 300 show the best performance based on the "Smaller is better" SN ratio criterion. Using S3 with a time setting of 150 or higher would likely minimize undesirable outcomes or system variability.
- Temperature 23.2 seems to be the most favorable, though temperature has a less significant impact compared to the other factors.

9. Overall Analysis for after run from fig 7 and fig 8:

- The Variant (s3) and Time (6) appear to have the largest positive and negative influences on the response, respectively.
- Temperature has a less pronounced but positive effect, with higher temperatures leading to a higher mean response.
- The dashed line across the plot represents the overall average of the means for each factor.

Using an L9 orthogonal array for lubrication studies is an effective way to optimize multiple factors, such as lubricant type, viscosity, temperature, and load, without conducting a full factorial experiment. By applying this design of experiment technique, you can systematically determine the best combination of parameters to enhance lubrication performance, reduce wear, and improve energy efficiency in mechanical systems.

Hence Optimization in lubrication is essential to achieve the best performance, durability, and efficiency in mechanical systems. By applying systematic optimization techniques, such as Design of Experiments, tribology testing, viscosity control, and numerical modelling, engineers can identify the ideal lubrication parameters for specific applications. Ultimately, optimized lubrication not only reduces friction and wear but also extends the life of machinery, improves energy efficiency, and lowers operational costs

DATA AVAILABILITY

All data that were used to support the conclusion are included in this article.

CITATIONS

All citations in the text are in the reference list

CONFLICTS OF INTEREST

Conflicts of interest the author the authors declare that there are no conflicts of interest

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