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SIMULATION OF OPTIMAL MIX OF SiO_2-TiO_2-Al_2O_3 NANO ADDITIVES FOR THE MINIMAL WEAR AND COEFFICIENT OF FRICTION OF LUBRICANT USING FUZZY LOGIC

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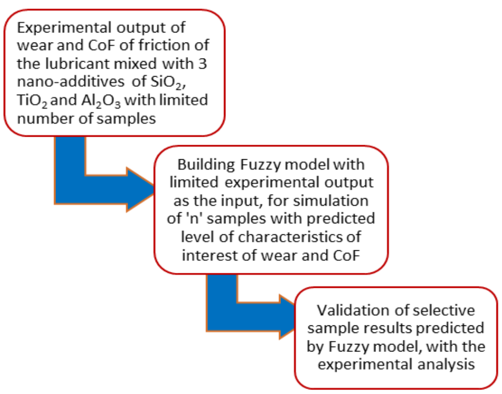
Graphical abstract



Abstract

Nano-particles of oxides of various metals are typically added with the base lubricants for enhancing the tribological properties, especially the wear and coefficient of friction of the lubricants. However, it is required to determine the optimum proportion of mix of the nano-additives in order to obtain the desirable characteristics gained through the addition of various oxides of metals mixed with the lubricants. This paper deals with the application of fuzzy logic to simulate the various proportions of a mix of three nano-additives of SiO2, Al2O3 and TiO2 with the corresponding predicted values of tribological characteristics of wear and coefficient of friction. The limited number of outcomes obtained from a full factorial design of experiments carried out with these three nano-additives at three different levels of mixing, are used as inputs to the fuzzy logic simulation. This approach facilitates simulating as many combinations of nano-additives as possible with the base lubricant oil along with the predicted output of characteristics of interest, which otherwise will be cumbersome to carry out the experiments for all the combinations of mix of additives.

Keywords: Wear, friction, nanoparticle, lubricant, fuzzy logic

1.0 INTRODUCTION

Lubricants with a variety of characteristics are designed and synthesized for use in a variety of mechanical systems and processes. Because the proper formulation of hydrocarbon blends for lubricants is a difficult process, emerging technologies have intensive and varied expectations from lubricants. A variety of base oils and necessary additions make up novel lubricants. Base oil plays many important tasks, but its primary function is to detach the surfaces of moving parts [1]. It also eliminates heat and worn out particles from the system in addition to reducing friction. By incorporating unique additive species into the base stock, several lubricating characteristics are enhanced and created. To fully increase the lubrication properties, lubricant additives are added to the base stock at a rate of a few weight percent. However, proper proportion of the mixture of lubricant additives influences the attainment of desired level of characteristics of interest. It is practically difficult to identify the proper proportion of the mixture of lubricants through numerous trials of experiments as it is time consuming and expensive. In the contemporary era of digital transformation in manufacturing industries [2], the simulation of behavior of any product under the expected environmental studies is found feasible and economical. Hence, an attempt has made is this research to simulate the lubricant characteristics of a base oil for the different proportion of mix of nano additives of SiO_2, TiO_2 and Al_2O_3,

The capacity to enter contact asperities with the right size, thermal stability, a wide range of particle chemistries, and a reaction rate with the surface are some benefits of employing nano-additives [3]. Numerous studies from the past few decades have shown that adding nanoparticles to lubricants can reduce wear and friction [4]. These nanoparticles include metal [5], metal oxide [6], metal sulphides and carbonate [7], borate, carbon materials [8], organic material, and rare-earth compounds. The specific characteristics of the nanoparticles, such as their size, shape, and physicochemical makeup, promote the friction-reduction and anti-wear behaviours [9]. Additives include deposition control additives, viscosity control additives, film forming additives, extreme pressure additives, and antiwear additives [10]. The role of nanoparticles in lubricant oil has been described using a variety of lubrication mechanisms, including the mending effect [5], the rolling effect [9], the polishing effect [11], and protective film [12]. Although nanoparticles have been shown to improve lubricant characteristics, compatibility is currently a problem, according to Gulzar [13]. Nanoparticles tend to sediment with time, causing the lubricant to lose its uniformity. As a result, creating a stable suspension is a critical problem in nano-lubrication since, under static conditions, less stable suspension will cause silt and agglomerates to accumulate over time [14]. There have been some investigations on the tribological effects of adding SiO_2 nanoparticles to lubricating oil. The tribological behavior of mineral 20W-50 and semi-synthetic 15W-50 oils dispersed by various amounts (0.5 and 1 % wt. oil) of SiO_2 nanoparticles was investigated by Rashed and Nabhan [15]. On a tribometer test rig operating under normal load and a range of temperatures between 40°C and 100°C, experiments were conducted. The coefficient of friction (CoF) had not been significantly decreased by SiO_2 addition to engine fluids. In ST5W/30 mobile oil, Li et al [16] ultrasonically dispersed 0.3 weight percent of SiO_2 nanoparticles. In comparison to pure ST5W/30 gas mobile oil, the CoF decreased as a result. According to Peng et al. [17], the tribological behaviour of diamond nanoparticles in liquid paraffin and SiO_2 nanoparticles distributed in oleic acid was identical.

By incorporating various amounts of hBN nanoparticles Abdullah et al [18] into standard diesel engine oil, CoF and wear considerably decreased. The studies also revealed that the wear was reduced to 10-7 mm^3/Nm with the addition of 80 nm Al_2O_3 nanoparticles at 5 weight% concentrations as opposed to the wear of poly-tetra-fluoro-ethylene, which is around 10-3 mm^3/Nm [19]. Al_2O_3 nanoparticles were utilized with lubricating oil, SAE 20W40, and Mohan et al [20] examined the impact on the tribological characteristics of an engine. The concentrations of Al_2O_3 nanoparticles were 0.25, 0.50, and 0.75 weight % with a grain size of 20 nm. The obtained results showed that under flooded lubrication circumstances, Al_2O_3 nanoparticles at a concentration of 0.5 weight percent showed the best tribological performance. Under starved conditions, the CoF decreased by 49.1% and 21.6%, respectively, in comparison to the base oil, and the wear depth decreased by 20.1% and 31.1%, respectively. However, under flooded lubrication situation, a concentration of 0.25 weight % of nanoparticles produced the highest wear reduction result, dropping it by 47.1% in comparison to that of the base oil. The absorbed nanoparticles could cause rolling between mating surfaces, changing the nature of friction from sliding to rolling. As a result, the CoF reduced [21]. It is also used as a grating substance or material in a variety of applications, and because of its high dissolving point, it is also used as an unmanageable material in a variety of applications.

Shashikant [22] had attempted to explain the effect of tribological properties of Al_2O_3 nanoparticles added in SN500 base oil. The experimental trials on wear and friction were carried on the pin on disc tribo tester by varying the concentration of nano fluids and varying the loads. The optimum concentration for wear was 0.5wt% and the CoF reduced 52% at concentration 1wt% when compared to virgin SN500 base oil. Frank [23] had a research paper highlighting the enhancement effect of the use of gallic esters with a TiO_2 nano additive. Without the ester, even though the addition of nanoparticles helps improve system lubrication, the formation of sediments has an undesirable effect and hinders their implementation, especially in systems like engine lubrication systems. He engineered TiO_2 nanoparticles with ODG (2-octyldodecyl gallate) which is a polyphenol derivative, which introduces polyphenol tribal-chemical reactions which helps undercut or eradicate the effect of sedimentation.

Busse [24] presents another and elective strategy for decreasing disintegration while gliding on different sorts of substrates by including hard alumina or silica nanostructures on the elastomer surface. The preparation of Al_2O_3 or SiO_2 is done using an in-situ sol-gel process where alumina is dissipated as a silica liquid polymer. De-Xing [25] presented a paper titled size impacts of SiO_2 nanoparticles as oil added substances on tribology of grease. The tribological properties of SiO_2 nanoparticles as added substances in fluid paraffin were presented in his paper. Patil [26] explained about the tribological qualities of SiO_2 nanochips mixed with SN-500 virgin oil. The conduct with SiO_2 nanoparticles surfaces adjusted with oleic corrosive when included into SN500 base oil showed against wear properties, great grinding decrease and furthermore diminished the coefficient of contact by 61% when contrasted with standard SN500 oil without SiO_2 nanoparticles. The tests were performed under various loads on a pin on a circle tribotester. The geography of worn surfaces was examined utilizing Scanning Electron Microscope.

Haiyan [27] in his research focused on the fabrication of SiO_2 nano capsules wrapped in polystyrene for self-lubricating system setup. The lubrication is done by the pickering polymerization mechanism. The SiO_2 particles helped in emulsification of the nano capsules. The stability of the same was also determined. Then, they are characterized by the use of SEM, Thermo gravimetric analysis and a Fourier Transformation Spectrum. The thermo gravimetric test displayed a thermal decay temperature of 250˚C.

2.0 METHODOLOGY

To provide the fuzzy logic simulation, the inputs of outcome values of desirable characteristics of wear rate and CoF with a limited number of combinations of the chosen three different nano-additives of SiO2, Al_2O_3, and TiO_2, a full factorial design of experiments with the three additives at three different levels has been adopted [28] in this research. In the process of preparing the nanofluid, the selected three different additives of SiO_2, Al_2O_3, and TiO_2 are mixed at three different proportions of 0.05%, 0.5% and 1% in the base oil of SN500. The particle size is selected as 35.9 nm, 32.9 nm and 50.56 nm for the three nano-additives of SiO_2, Al_2O_3, and TiO_2. The hot plate magnetic stirrer is used to stir the mixture at 100˚C at 300 RPM using the magnetic capsule for 30 min. The mixture is further processed at 60 ˚C for 30 min in an ultrasonic cleaner, to ensure the uniform settlement of nanoparticles in the oil. For the full factorial design of experiments with three additives with three different levels, 27 samples are prepared with different proportions of mix of additives.

The majority of tribometer test applications evaluate wear by contrasting the mass or surfaces of test objects before and after testing. The wear out was assessed through SEM. The tribometer plays a crucial role to study how the virgin oil's alteration affected the amount of stress, load, speeds, and wear. The disc material used was EN8 stainless steel and the pin material was varied between three samples of brass, stainless steel, aluminium and the wear was observed. The dimensions of the pins were kept constant of 7 mm diameter and 30 mm length. 27 samples are tested on the pin-on-disc apparatus and the results of wear and CoF obtained are shown in Table 1.

Table 1 Average wear and CoF values for 27 samples

Sample No.	Nanoparticle concentration(wt. %)			Average wear (microns)	CoF
	SiO_2	TiO_2	Al_2O_3		
1	0.05	0.05	0.05	92	0.129760
2	0.5	0.5	0.5	174	0.120054
3	1	1	1	157	0.078257
4	0.05	0.05	0.5	190	0.136205
5	0.05	0.05	1	197	0.116346
6	0.5	0.05	0.05	162	0.141951
7	0.5	0.05	0.5	178	0.130290
8	0.5	0.05	1	203	0.138504
9	1	0.05	0.05	228	0.141697
10	1	0.05	0.5	55	0.120837
11	1	0.05	1	196	0.123081
12	0.05	0.5	0.05	170	0.120146
13	0.05	0.5	0.5	341	0.140628
14	0.05	0.5	1	250	0.140645
15	0.5	0.5	0.05	107	0.122041
16	0.5	0.5	1	257	0.117987
17	1	0.5	0.05	187	0.107105
18	1	0.5	0.5	136	0.093745
19	1	0.5	1	154	0.073371
20	0.05	1	0.05	195	0.049826
21	0.05	1	0.5	241	0.117478
22	0.05	1	1	148	0.108307
23	0.5	1	0.05	166	0.098312
24	0.5	1	0.5	302	0.126930
25	0.5	1	1	272	0.107384
26	1	1	0.05	147	0.132103
27	1	1	0.5	107	0.116356

These values are fed as inputs in the fuzzy logic approach to simulate a greater number of combinations with predicted behavior of the lubricant, which is discussed in the following section.

This study has tried to simulate the outcome performance of tribological characteristics of wear and CoF for the several assumed combinations of mix of the three different additives SiO_2, TiO_2 and Al_2O_3 at various levels of mix, with the inputs obtained from the experimental results of 27 samples take for the experiment. In a fuzzy model, the given value undergoes fuzzification and the degree of membership is calculated based on the relevancy of the event to that variable.

The degree of membership will infer how strongly the values represent the particular attribute. For example, the attribute may be a weight, concentration, hotness, efficiency. In this study, the inputs of experimental work into fuzzy values according to the weight percentage of three nano additives of SiO_2, TiO_2 and Al_2O_3 which are considered as degree of membership. The final output also is represented in the membership functions. In the fuzzy model, there are various types of membership functions which include S function, Gaussian function, trapezoidal function and triangular function. In this study, the triangular membership function has been used as shown in Figure 1 and Figure 2.

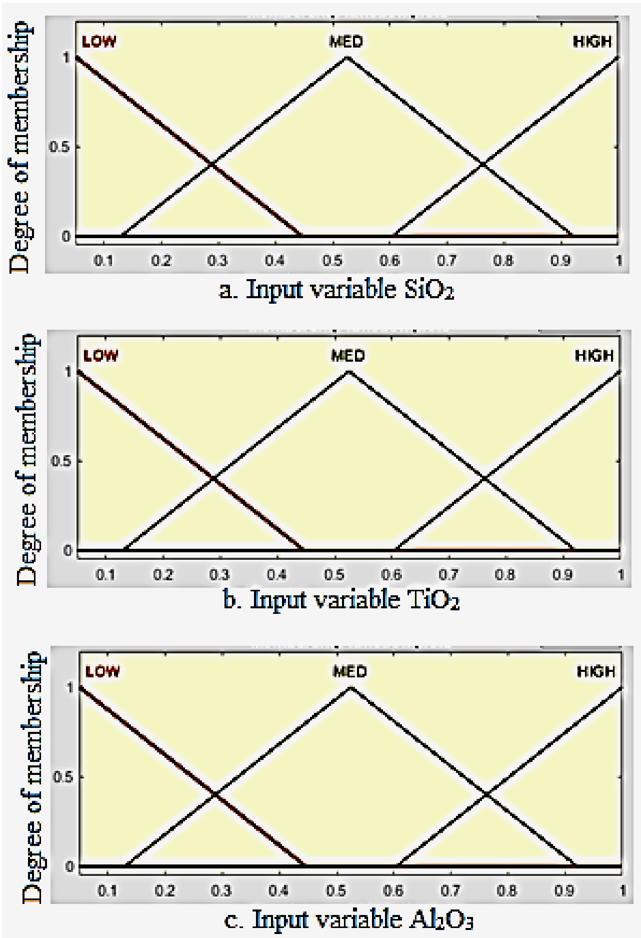


Figure 1 Membership function for variable of inputs

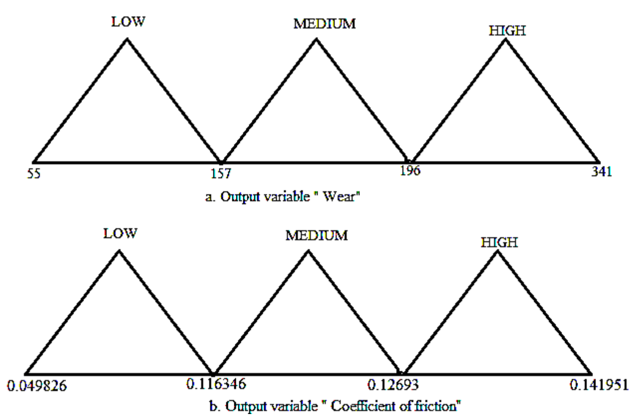


Figure 2 Membership function for the output variable of wear and CoF

In the process of creating fuzzy rules, the antecedent part will contain one or more conditions joined by the fuzzy operator and the consequent part will contain the output for the given conditions. For example, when the HIGH values are set for the three additives, the wear will take the LOW value. So, the experimental results are studied using Mamdani fuzzy logic and the fuzzy rules are created accordingly. In the defuzzification process, the fuzzy output calculated is converted into constant value or crisp value. Defuzzification can be done using many methods like centroid, center of sums, and mean of maximum. The result greatly depends on the method we choose for the defuzzification which influences the speed and the accuracy. This study employs the centroid method which is found to be more efficient [29,30] compared with the other alternative defuzzification methods of Mean of maximum and Weighted average. Centroid method determines the centre of area of fuzzy set and returns the corresponding crisp value quickly and precisely.

The correlations between the input parameters - Nanoparticle Concentration (wt %) of SiO_2, TiO_2 and Al_2O_3 - and the mechanical output parameters - Average wear (microns) and CoF for pin on disc machine mechanical output parameter were used to develop the rules. Each input and output parameter has three membership functions, according to this paradigm. The input variables were categorized into several setup levels using the membership functions Low, Medium, and High. From the literature review, the minimum and maximum weight percentage of nanoparticles mixed in the base oil were observed in the range of 0.05-1.0 with the interval period of 0.05. Accordingly, for the 20 intervals between 0.05 to 1 with the interval period of 0.05, the 7 values from 0.05 to 0.35 are given LOW grade, the other 7 values from 0.4 to 0.7 are given MEDIUM grade and the remaining 6 values from 0.75 to 1 are given as HIGH grade as shown in Table 2.

Table 2 Range of weight % and the respective linguistic variable

0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
L	L	L	L	L	L	L	M	M	M
0.55	0.6	0.65	0.7	0.75	0.8	0.85	0.9	0.95	1
M	M	M	M	H	H	H	H	H	H

L – Low, M – Medium, H - High

Experimental results of wear for 27 samples are arranged in ascending order for the range of 55 to 341 microns. The output wear values are classified into LOW, MEDIUM and HIGH grade as mentioned below.

For the characteristic of interest of wear,
LOW is set for the wear of 55, 92, 107, 107, 136, 147, 148, 154, 157 microns, MEDIUM is set for the values of 162, 166, 170, 174, 178, 187, 190, 195, 196 microns and HIGH is set for the values of 197, 203, 228, 241, 250, 257, 272, 302, 341 microns. Similarly,

For the characteristic of interest of CoF,
LOW is set for the CoF values of 0.049826, 0.073371, 0.078257, 0.093745, 0.098312, 0.107105, 0.107384, 0.108307, 0.116346. MEDIUM is set for 0.116356,

0.117478, 0.117987, 0.120054, 0.120146, 0.120837, 0.122041, 0.123081, 0.12693 and HIGH is set for 0.12976, 0.13029, 0.132103, 0.136205, 0.138504, 0.140628, 0.140645, 0.141697, 0.141951.

In Table.3, the linguistic variables and the range value for each of the 3 input parameters and 2 outputs are tabulated. The linguistic variables are taken as LOW, MEDIUM and HIGH for SiO_2, TiO_2, and Al_2O_3, and their range is taken between 0.05 wt.% and 1 wt.%. For output parameters such as wear and CoF, the linguistic variables are taken as LOW, MEDIUM and HIGH and the range is taken to between 55 and 341 microns for wear and 0.049826 and 0.141951 for the CoF.

Table 3 Fuzzy linguistic variables and range

INPUT PARAMETER	**LINGUISTIC VARIABLES**	**RANGE**
SiO2	L, M & H	0.05 Wt.% to 1 Wt.%
TiO2	L, M & H	0.05 Wt.% to 1 Wt.%
Al2O3	L, M & H	0.05 Wt.% to 1 Wt.%
OUTPUT PARAMETER	LINGUISTIC VARIABLES	RANGE
Wear	L, M & H	55 to 341
CoF	L, M & H	0.049826 to 0.141951

L – Low, M – Medium, H - High

The three input weight percentage values of nanoparticles of SiO_2, TiO_2, and Al_2O_3 and the corresponding out values of average wear and CoF are converted into respective linguistic variables such LOW, MEDIUM and HIGH for all the 27 experimental samples and tabulated as shown in Table 4.

Table 4 Tribology parameters changed into LOW, MEDIUM and HIGH grades

Sample No.	**Nanoparticle concentration (wt. %)**			**Average wear**	**CoF**
	SiO_2	**TiO_2**	**Al_2O_3**		
1	L	L	L	L	H
2	M	M	M	M	M
3	H	H	H	L	L
4	L	L	M	M	H
5	L	L	H	H	L
6	M	L	L	M	H
7	M	L	M	M	H
8	M	L	H	H	H
9	H	L	L	H	H
10	H	L	M	L	M
11	H	L	H	M	M
12	L	M	L	M	M
13	L	M	M	H	H
14	L	M	H	H	H
15	M	M	L	L	M
16	M	M	H	H	M
17	H	M	L	M	L
18	H	M	M	L	L
19	H	M	H	L	L
20	L	H	L	M	L
21	L	H	M	H	M
22	L	H	H	L	L
23	M	H	L	M	L
24	M	H	M	H	M
25	M	H	H	H	L
26	H	H	L	L	H
27	H	H	M	L	M

L – Low, M – Medium, H - High

After converting all the values into linguistic variables, the nanofluid values with the optimum lower values of wear and CoF are identified and tabulated in Table 5.

Table 5 LOW grade values of wear and CoF identified

Sample No.	Nanoparticle Concentration (wt. %)			Average wear (microns)	CoF
	SiO_2	TiO_2	Al_2O_3		
3	H	H	H	L	L
18	H	M	M	L	L
19	H	M	H	L	L
22	L	H	H	L	L

L – Low, M – Medium, H - High

The original values of weight percentage of the three nano-additives along with the respective wear and CoF values for the linguistic variables mentioned in table 5 are shown in Table 6.

Table 6 Linguistic variables converted into original values

Sample No.	**Nanoparticle Concentration (wt. %)**			**Average wear (microns)**	**CoF**
	SiO_2	**TiO_2**	**Al_2O_3**		
3	1	1	1	157	0.078257
18	1	0.5	0.5	136	0.093745
19	1	0.5	1	154	0.073371
22	0.05	1	1	148	0.108307

3.0 RESULTS AND DISCUSSION

The pairs of two nano-additives of SiO_2, TiO_2 and Al_2O_3 are taken simultaneously in the fuzzy model and the characteristics of interest of wear and CoF are analysed with respect to these nano-additives as shown in Figures from 3 to 8.

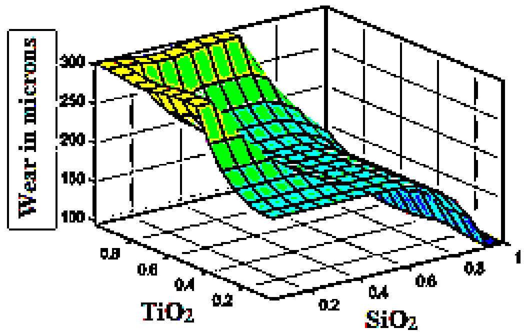


Figure 3 Wear in relation to SiO_2 and TiO_2 concentration

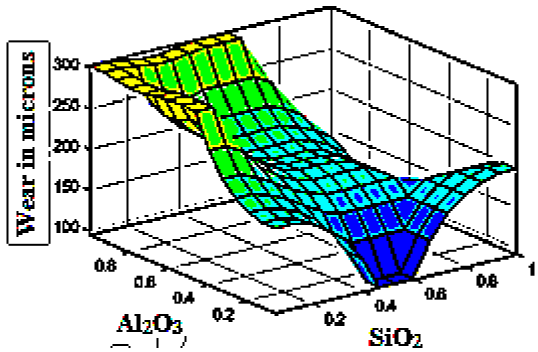


Figure 4 Wear in relation to SiO_2 and Al_2O_3 concentration

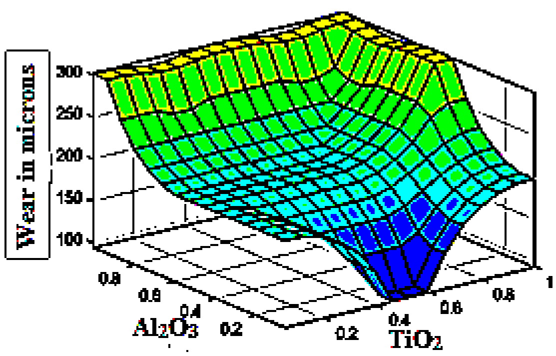


Figure 5 Wear in relation to TiO_2 and Al_2O_3 concentration

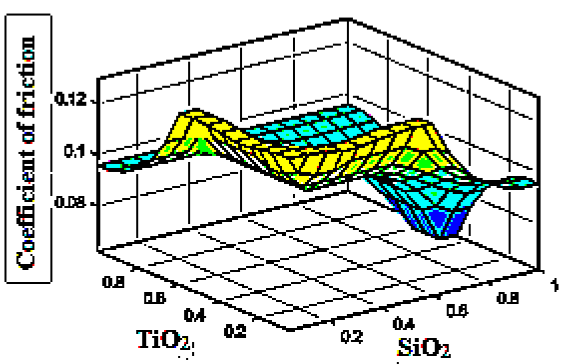


Figure 6 CoF in relation to SiO_2 and TiO_2 concentration

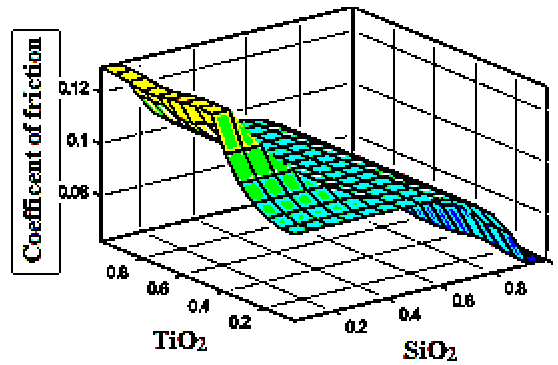


Figure 7 CoF in relation to SiO_2 and Al_2O_3 concentration

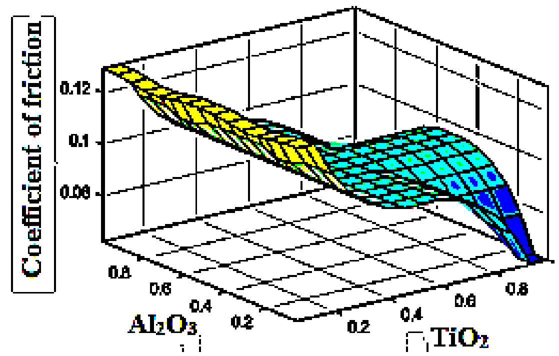


Figure 8 CoF in relation to TiO_2 and Al_2O_3 concentration

The simulated values are tabulated in table 7 for the selected 125 different combinations of nano-additives. The 27 experimental sample number whose wear and CoF values are matching with that of simulation are indicated in the last column.

Table 7 Values simulated by Fuzzy logic

Nanoparticle Concentration (wt. %)			Average wear (in microns)	CoF	Experimental sample number
SiO2	TiO2	Al2O3			
0.2500	1.0000	1.0000	201.5602	0.1079	
---	---	---	---	---	
---	---	---	---	---	
0.5000	0.0500	0.0500	161.9998	0.1420	sample 06
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---	---	---	---	---	
0.5000	1.0000	0.5000	301.9997	0.1269	sample 24
---	---	---	---	---	
0.0500	1.0000	0.5000	240.9998	0.1175	sample 21
---	---	---	---	---	
0.5000	1.0000	0.0500	165.9998	0.0983	sample 23
---	---	---	---	---	
1.0000	0.5000	1.0000	153.9999	0.0734	sample 19
1.0000	1.0000	0.0500	146.9998	0.1321	sample 26

Nanoparticle Concentration (wt. %)			Average wear (in microns)	CoF	Experimental sample number
SiO2	TiO2	Al2O3			
---	---	---	---	---	
0.5000	1.0000	1.0000	271.9997	0.1074	sample 25
0.0500	0.5000	0.0500	169.9998	0.1201	sample 12
---	---	---	---	---	
1.0000	0.0500	0.0500	227.9997	0.1417	sample 09
0.0500	0.0500	0.0500	91.9999	0.1298	sample 01
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0.0500	0.5000	1.0000	249.9998	0.1406	sample 14
---	---	---	---	---	
0.5000	0.5000	1.0000	256.9998	0.1180	sample 16
0.0500	0.0500	0.5000	189.9998	0.1362	sample 04
---	---	---	---	---	
0.0500	1.0000	1.0000	147.9999	0.1083	sample 22
---	---	---	---	---	
0.5000	0.0500	0.5000	177.9998	0.1303	sample 07
---	---	---	---	---	
1.0000	1.0000	0.5000	106.9999	0.1164	sample 27
---	---	---	---	---	
1.0000	0.5000	0.5000	135.9999	0.0937	sample 18
---	---	---	---	---	
0.0500	0.5000	0.5000	340.9997	0.1406	sample 13
---	---	---	---	---	
0.5000	0.0500	1.0000	202.9998	0.1385	sample 08
---	---	---	---	---	
0.5000	0.5000	0.0500	106.9999	0.1220	sample 15
---	---	---	---	---	
0.0500	0.0500	1.0000	196.9998	0.1163	sample 05
---	---	---	---	---	
1.0000	0.0500	1.0000	195.9998	0.1231	sample 11
---	---	---	---	---	
1.0000	0.5000	0.0500	186.9998	0.1071	sample 17
---	---	---	---	---	
1.0000	1.0000	1.0000	156.9998	0.0783	sample 03
---	---	---	---	---	
0.0500	1.0000	0.0500	194.9998	0.0498	sample 20
1.0000	0.0500	0.5000	55.0000	0.1208	sample 10
0.5000	0.5000	0.5000	173.9998	0.1201	sample 02
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From the above table, the samples with the low values of wear and CoF, lesser than that of experimental values are identified and tabulated in Table 8.

Table 8 Nearest optimum value

Sample No.	Wt. % of SiO_2	Wt. % TiO_2	Wt. % Al_2O_3	Wear in microns	CoF
18	1	0.5	0.5	136	0.093745
19	1	0.5	1	154	0.073371

From Table 8, it is understood that Sample number 18 containing 1Wt. % of SiO_2, 0.5 Wt. % of TiO_2, and 0.5 Wt. % of Al_2O_3 nanoparticles in the lubricant oil, exhibits lower wear of 136 microns. Similarly, Sample number 19 containing 1Wt. % of SiO_2, 0.5 Wt. % TiO_2, and 1 Wt. % Al_2O_3 nanoparticles in the lubricant oil, exhibits lower CoF 0.073371. However, these two samples have higher values compared with each other against another parameter respectively. Also, it is clear that both the samples have the same proportion of 1Wt. % of SiO_2 and 0.5 Wt. % of TiO_2. But they differ in the mix proportion of Al_2O_3. Hence it is evident that there exists a sample with the mix of Al_2O_3 with the proportion between 0.5 and 1 wt %. Using the fuzzy logic rules, a simulation is run with different proportions with the increment of 0.05% between 0.5 and 1 wt % and the following results are obtained as shown in Table 9.

Table 9 Optimal results

Sample No.	Wt. % of SiO_2	Wt. % TiO_2	Wt. % Al_2O_3	Wear in microns	CoF
18	1	0.5	0.5	136	0.093745
	1	0.5	0.75	144.5468	0.0837
19	1	0.5	1	154	0.073371

From Table 9, it found that the sample with the mix of 1Wt. % of SiO_2, 0.5 Wt. % TiO_2 and 0.75 Wt. % Al_2O_3 nanoparticles in the lubricant oil exhibits the lower value for both the wear of 144.5468 microns and CoF of 0.0837 of all the samples simulated using fuzzy logic. This best result could have been obtained using experimental trials also, only if the fourth level of 0.75 weight percentage had been included in the trials. This would have ended up with the requirement of 81 samples instead of 27 samples and thus would have ended up in consumption of more time and cost for carrying out the experiments. This has been avoided using fuzzy logic approach. Table 7 indicates that all the experimental values obtained for the selected 27 samples are found to be closer to the values predicted by fuzzy logic in the set of 125 samples. It validates the predictions of fuzzy logic and hence the outcome of all 125 predicted combinations can well be considered. However, the predicted sample with the optimum results as mentioned in table 9, with the mix of 1Wt. % of SiO_2, 0.5 Wt. % TiO_2 and 0.75 Wt. %

Al_2O_3 has been tested through experiments and the wear and CoF are found to be 143 microns and 0.082781 respectively. It implies that the algorithm used in the fuzzy logic predicts well with the experimental values and can be used for any level of weight percentage of mix of all additives to be tested.

4.0 CONCLUSION

From the study enumerated in this article, it is evident that the optimum values within the experimental trials carried out also may be predicted using a fuzzy logic approach. It is not practically possible to carry out all the numerous trails of experiments to determine the optimum mix of additives when the number of additives (factors) and their levels (weight proportions) increases. This approach [31] provides concrete evidence that the possible outcomes for the various combinations can be easily derived and the suitable sample may be identified and tested for its efficiency.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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