# EVALUATION OF SOME THERMOPHYSICAL PROPERTIES OF SN500 LUBRICATION OIL BLENDED WITH SiO2, Al2O3 AND TiO2 NANO-ADDITIVES, USING FUZZY LOGIC

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**Abstract:** Nano-additives are generally blended with the base lubricant oil, to enhance the lubricant characteristics such as wear, coefficient of friction (CoF), thermal conductivity, density, and flash and fire points of the lubricant. In this research, nano-additives of SiO2, Al2O3 and TiO2 are blended with the base SN500 oil with different proportions of mixture. When these three nanoparticles are used together in base oil, they enhance most of the desirable properties of a lubricant; 27 samples with three different levels of a mixture of nano-additives are identified using factorial design of experiments. The experimental outcomes for the selected three characteristics of interest of density, flash point and fire point are determined. Conducting experiments for 'n' number of samples with different proportions of mixture of nano-additives is a cumbersome, expensive and time-consuming process, in order to determine the optimum mix of nano-additives for the desirable level of characteristics of interest. In this research, attempt has been made to apply fuzzy logic to simulate a greater number of samples with different proportions of a mixture of three nano-additives with the respective outcomes of characteristics of three thermophysical properties. Out of the numerous samples simulated using fuzzy logic, the sample with the optimum mix of three nano-additives of SiO2, Al2O3 and TiO2 blended with the base oil is identified for the desirable level of characteristics of interest of density, flash point and fire point. The values of the identified sample are found to be at the desirable level of 0.9008 gm/ml, 231°C and 252°C, respectively.

**Key words:** nano-additives, density, flash and fire points, fuzzy logic.

## 1. INTRODUCTION

Nano-additives have captured the attention of researchers as a newly emerged and evolved technology for use due to their special thermophysical characteristics, in lubrication and heat transfer systems. Classified as a new category of fluids, the stability of nano-additives and their performance in various scenarios, including extreme temperatures, are vital focal points in expanding our knowledge of lubrication and heating systems and creating a useful nano lubricant [1-2]. Recent literature recommends using base oil blended with nano-additives for enhancing lubricating properties. Studies have examined the impact of SiO2, Al2O3 and TiO2 nano-additives on the wear rate and coefficient of friction (CoF). The best combination of SiO2, Al2O3 and TiO2 nano-additives in SN500 base oil was examined by Sankar et al [3]. When polyolester oil is combined with SiO2 nano-additive by up to 0.15%, this leads to improved rheological characteristics. The maximum increase in flash point and fire point is observed at 7% and 5.9%, respectively, for the 0.2% SiO2/POE nanolubricant [4]. Flash and fire points are found to be increasing due to the addition of SiO2 nanoparticles in the base oil [5]. By adding SiO2 nano-additives, in a step by step manner at 0.3 wt.% in SAE20W40 engine oil, the flash and fire points become minimum at 0.6 wt.%, and by increasing further from 0.6 wt.% to 1.5 wt.%, the flash and fire points increase [6]. Flashpoint enhancement percentages of 5.042%, 6.612%, 8.502% and 10.67% are achieved for SiO2 nano-additive concentrations of 0.25%, 0.5%, 0.75% and 1 wt.%, respectively. Similarly, Al2O3 nano-additives result in enhancement of 4.237%, 5.04%, 7% and 9.63% for the respective concentrations [7]. In concentrations of 0.2% and 1%, SiO2 has a higher flash and fire point than Al2O3. So it is recommended to add SiO2 in a higher proportion than Al2O3, since it notably increases the operating temperatures [8]. In the case of Al2O3 nanoparticle, which was introduced into two base lubricants, Marula oil and Mineral oil, within the range of 0–2 wt.%, the trend is consistent in both lubricants, where the flash and fire points increase with the addition of Al2O3 nanoparticles, peaking at 0.75 wt.%. Beyond this concentration, these points gradually decrease. Consequently, the optimal Al2O3 amount exhibits an increase in both flash and fire points [9]. The addition of 100 ppm of Al2O3 to diesel significantly raises the flash point from 66°C to 69°C. Even slight increments in the nano-additives content contribute to this enhancement [10]. The addition of Al2O3 nanoparticles in N10, P20 and T30 has shown an increase in their respective flash points than pure base oils [11]. Adding Al2O3 nanoparticles in Servo SAE 20W-40 flash point increases slightly till the value of 0.02% concentration and then decreases with respect to further increase in nanoparticles [12]. The addition of Al2O3 nano-additive at 0.25 wt.%, 0.65 wt.%, 1.05 wt.%, 1.45 wt.% and 1.85 wt.% drastically increased the flash point by 1.33%, 3.54%, 5.75%, 7.52% and 9.73% respectively, which increased the flashpoint from 228°C to 249°C in the lube oil stock-60 [13]. Addition of Al2O3 nano-additive shows an increase in flash and fire points with the base local Iraqi lubricant oil of 20W-50 [14]. Conversely, the flash point decreases with inclusion of TiO2 nanoparticles, with no further variation observed beyond a concentration of 0.6% [15]. The flashpoint rate increases by adding TiO2 nano-additives at different concentrations: 0.1 wt.%, 0.2 wt.%, 0.5 wt.% and 1 wt.%, resulting in flash point increases of 4.54%, 9.45%, 11.81% and 13.63%, respectively, relative to the base fluid. Notably, changes in higher concentrations are less pronounced compared with those in lower concentrations [16]. By the addition of TiO2 nano-additive, there is an enhancement of flash and fire points of castor oil [17]. Kumar [15] investigated the physicochemical and tribological properties of TiO2 nano lubricant oil at different concentrations; 0.2% of TiO2 in SAE 20 W40 exhibits the higher value of flash and fire points while compared with base oil SAE 20 W40. Both flash and fire points are directly proportional to the size of the nanoparticle and the base engine oils the surface modifying behaviour [18]. In the case of nano-lubricating oil made of TiO2 nanoparticles, the flashpoint increased by 9.3% [19].

It has been found that titanium oxide and aluminium oxide nanoparticles are the most effective thermal enhancers [20]. Based on the statistical performance indicators acquired, designing the model and estimate using the ANFIS technique can be done with a high degree of dependability [21]. The accuracy of prediction is determined by calculating statistical data from the values of experimental and predicted models [22]. The model's performance in the experiment is assessed using R2 and RMSE values [23]. These observations suggest that the ANFIS model demonstrates greater resilience in predicting values when compared with the RSM model [24]. Based on the statistical performance indicators acquired, designing the model and estimate using the ANFIS technique can be done with a high degree of dependability [25].

John Shelton et al. [26] recently examined the rheological properties of Al2O3-TiO2/MO hybrid nanofluids, focusing on temperature, particle concentration, ratio and composition. The results show more Newtonian flow behaviour compared with conventional nanofluids, with higher TiO2 ratios affecting the properties. Kia et al. [27] also examined the heat transfer and pressure drop characteristics of Al2O3 and SiO2/base oil nanofluid flow in a helical tube, revealing that nanofluid enhances heat transfer factor and pressure drop, with the highest rate at 0.5% mass concentrations.

Every nanoparticle blending with the base oil enhances the property of a lubricant in a distinct manner [28]. From the literature, it is found that mixing of SiO2 with base oil induces the ball bearing effect and hence reduces the friction between rubbing surfaces. Similarly, Al2O3 improves the thermal conductivity of a lubricant and hence disseminates the heat considerably away from the rubbing surfaces and thus improves the lubricant action. TiO2 reduces the wear rate considerably. In this research, attempt has been made to blend optimally all these three nanoparticles together with the base oil SN500, in order to enhance the selected properties of the lubricant to its respective desirable level.

## 2. METHODOLOGY

The chosen three additives, SiO2, Al2O3 and TiO2, are blended with the SN500 base oil in three distinct ratios of 0.05%, 0.5% and 1% during the nanofluid preparation process. The three nano-additives of SiO2, Al2O3 and TiO2 are chosen with particle size of 35.9 nm, 32.9 nm and 50.56 nm respectively. The specifications of the nanoparticles used in this research are given in Tab. 1.

**Tab. 1.** Specifications of nanoparticles used

| Molecular formula | $TiO_2$ | $SiO_2$ | $Al_2O_3$ |
|---|---|---|---|
| Purity (%) | 99 | 99 | 99 |
| Average particle size (nm) | <100 | <100 | <100 |
| Molecular weight (g/mol) | 79.8658 | 231.533 | 101.96 |
| Colour | White | White | White |
| Surface area ($m^2$/g) | 150 | 220 | 110 |
| Bulk density (g/$cm^3$) | 0.9 | 0.3 | 0.6 |

Courtesy: Ad Nano Technologies, India.

Recycled base oil SN500-distilled is suitable for use in high-temperature applications due to its low volatility, or its inability to evaporate quickly. This product is less likely to ignite or catch fire because of its high flash point. Tab. 2 describes the properties of the base lubricant oil SN500 used in the experimental work.

**Tab. 2.** Specifications of SN500 base oil

| Property | Test method | Typical result of SN500 base oil |
|---|---|---|
| Density @15°C, kg/$m^3$ | ASTM D 1298 | 880 |
| Viscosity @100˚C,cSt | ASTM D 445 | 9.4 |
| Viscosity index | ASTM D 2270 | 92 |
| Flash point °C | ASTM D 92 | 225 |
| Pour point °C | ASTM D 97 | –3 |
| Colour | ASTM D 150 | 2 |

# https://tnzoil.com/wp-content/uploads/2020/11/Base-Oil-SN500

The optimal settings for the independent variables may be estimated using a full factorial design of experiments which also determines the main effects and the effects of interactions on the response variable. A three-level factorial design is used in this research. This means that k factors are considered, each at three levels which are also referred to as low, intermediate and high levels. In this research, 27 samples (treatments) are created for the complete factorial design of experiments with three different additives selected at three distinct levels. The experimental values of density, flash and fire points are determined for all the selected 27 samples. Using a proper weight proportion of three nano-additives along with Span 80 surfactant are blended with the SN500 base oil. Using the magnetic capsule, the mixture is stirred for 30 min at 300 RPM at 100°C using a hot plate magnetic stirrer. In order to ensure that the nanoparticles settle uniformly in the oil, the mixture is further treated in an ultrasonic cleaner for 30 min at 60°C.

Cleveland open cup tester is used to measure the flash and fire points in accordance with ASTM D92 standards. The experimental values are obtained for the 27 samples which are used as inputs in the fuzzy logic program later to determine the optimum mix of three nano-additives for all the three characteristics of interest of density, flash and fire points of lubricant at their desirable levels.

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**Tab. 3.** Density (gm/ml), Flash point and Fire point (°C)

| Sample number | Nano-additives concentration (wt.%) | | | Density (gm/ml) | Flash point (°C) | Fire point (°C) |
|---|---|---|---|---|---|---|
| | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | | | |
| 1 | 0.05 | 0.05 | 0.05 | 0.88 | 230 | 261 |
| 2 | 0.5 | 0.5 | 0.5 | 0.8906 | 220 | 226 |
| 3 | 1 | 1 | 1 | 0.9008 | 231 | 252 |
| 4 | 0.05 | 0.05 | 0.5 | 0.8929 | 224 | 240 |
| 5 | 0.05 | 0.05 | 1 | 0.8927 | 228 | 242 |
| 6 | 0.5 | 0.05 | 0.05 | 0.8904 | 215 | 232 |
| 7 | 0.5 | 0.05 | 0.5 | 0.8916 | 224 | 251 |
| 8 | 0.5 | 0.05 | 1 | 0.8911 | 220 | 250 |
| 9 | 1 | 0.05 | 0.05 | 0.8909 | 232 | 252 |
| 10 | 1 | 0.05 | 0.5 | 0.8911 | 230 | 260 |
| 11 | 1 | 0.05 | 1 | 0.8934 | 210 | 241 |
| 12 | 0.05 | 0.5 | 0.05 | 0.8884 | 192 | 218 |
| 13 | 0.05 | 0.5 | 0.5 | 0.8905 | 183 | 221 |
| 14 | 0.05 | 0.5 | 1 | 0.8924 | 197 | 225 |
| 15 | 0.5 | 0.5 | 0.05 | 0.8944 | 180 | 206 |
| 16 | 0.5 | 0.5 | 1 | 0.8913 | 189 | 223 |
| 17 | 1 | 0.5 | 0.05 | 0.8928 | 141 | 162 |
| 18 | 1 | 0.5 | 0.5 | 0.8886 | 194 | 228 |
| 19 | 1 | 0.5 | 1 | 0.8924 | 212 | 236 |
| 20 | 0.05 | 1 | 0.05 | 0.8872 | 185 | 215 |
| 21 | 0.05 | 1 | 0.5 | 0.8933 | 190 | 210 |
| 22 | 0.05 | 1 | 1 | 0.8968 | 196 | 227 |
| 23 | 0.5 | 1 | 0.05 | 0.8913 | 180 | 210 |
| 24 | 0.5 | 1 | 0.5 | 0.894 | 191 | 229 |
| 25 | 0.5 | 1 | 1 | 0.8905 | 195 | 220 |
| 26 | 1 | 1 | 0.05 | 0.8924 | 205 | 235 |
| 27 | 1 | 1 | 0.5 | 0.891 | 210 | 240 |

From Tab. 3, it is observed that the three different samples of 1, 3 and 9 possess the desirable high values of density, flash and fire points, respectively. However, it is required to determine a single sample that possesses the closely desirable level of characteristics of density, flash and fire points. In this study, attempt has been made to apply fuzzy logic to find a sample with an optimum mix of three nano-additives of SiO2, Al2O3 and TiO2, which possess the desirable characteristics of density, flash and fire points.

## 3. FUZZY LOGIC APPROACH

A fuzzy system describes the inputs and outputs using fuzzy sets and membership functions. The surface response graph is a three-dimensional graph that visually represents the output varying with changes in input variables. It is determined by the fuzzy rules and inference mechanisms used. Higher regions indicate stronger output responses, while lower regions indicate weaker responses. The surface response graph can help optimise the system by identifying suboptimal output regions and adjusting fuzzy rules or membership functions accordingly. It can also be used for system validation by comparing the predicted output with the actual responses and refining and validating the model. The surface response graph's shape indicates how the fuzzy system responds to different input values. The rules are developed using the relationships between the measured parameters of density, flash point and fire point, with different nano lubrication concentration of SiO2, TiO2 and Al2O3 nano-additives. Three membership functions are employed for the input (nano lubrication concentration of SiO2, TiO2 and Al2O3 nanoparticles) and output variables (density, flash point and fire point) to categorise them in different response levels as Low, Medium and High, used for the input variables to categorise them in different set-up levels, as shown in Tab. 4.

**Tab. 4.** Fuzzy linguistic variables used for each parameter

| **Input parameter** | **Linguistic variables** | **Range of parameter** |
|---|---|---|
| $SiO_2$ | L, M, H | 0.05 wt.%, 0.5 wt.% and 1 wt.% |
| $TiO_2$ | L, M, H | 0.05 wt.%, 0.5 wt.% and 1 wt.% |
| $Al_2O_3$ | L, M, H | 0.05 wt.%, 0.5 wt.% and 1 wt.% |
| Output parameter | Linguistic variables | Range of parameters |
| Density (gm/ml) | L, M, H | 0.88–0.8909, 0.891–0.8924 and 0.8927–0.9008 |
| Flash point °C | L, M, H | 141–192°C, 194–215°C and 220–232°C |
| Fire point °C | L, M, H | 162–223°C, 225–240°C and 241–261°C |

where L = Low, M = Medium, H = High.

Tab. 3 is rewritten with the above linguistic variables, as shown in Tab.5.

The fuzzy linguistic variables are high for density, flash point and fire point in Samples 3 and 5. High-density lubricants typically have higher viscosity and better load-carrying capacity. They can provide better film strength and protection against surface wear and contact fatigue in high-load applications. So, it leads to better thermal stability, which means they can withstand higher operating temperatures without breaking down. High-density lubricants are generally more resistant to oxidation, preventing the formation of harmful deposits and sludge. However, in order to get an optimum mix of the three nano-additives even with concentrations other than 0.05 wt.%, 0.5 wt.% and 1 wt.%, a fuzzy logic approach is used in this study.

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**Tab. 5.** Fuzzy linguistic variables used for experimental values

| S. No. | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | Density (gm/ml) | Flash point (°C) | FIRE point (°C) |
|---|---|---|---|---|---|---|
| 1 | L | L | L | L | H | H |
| 2 | M | M | M | L | H | M |
| 3 | H | H | H | H | H | H |
| 4 | L | L | M | H | H | M |
| - | - | - | - | - | - | - |
| - | - | - | - | - | - | - |
| 26 | H | H | L | M | M | M |
| 27 | H | H | M | M | M | M |

The proposed model demonstrates that the type of membership function utilised during fuzzification relies on the relevant event. Fig. 1 illustrates the properties of the FIS. In this specific scenario, the input variables are partitioned based on the range of experimental parameters.

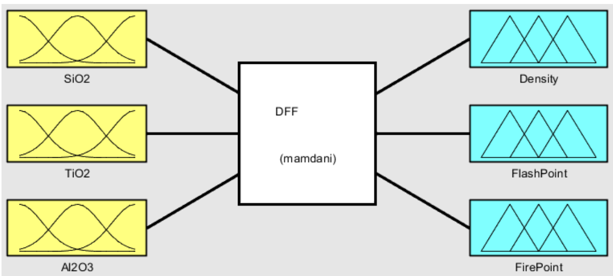


**Fig. 1.** FIS properties

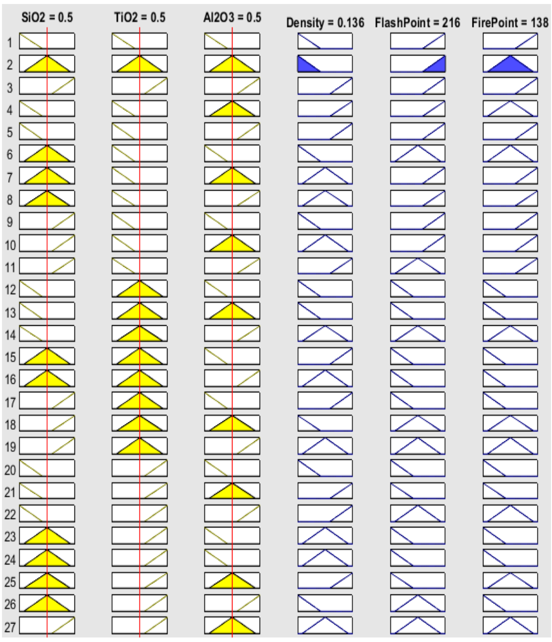


**Fig. 2.** Rules used in fuzzy logic approach

The surface response is determined by system-defined fuzzy rules and an inference mechanism, with each point on the surface associated with input values and output values determined by fuzzy inference.

Using SiO2, TiO2 and Al2O3 nanosuspension lubricant, a total of 27 rules for density, flash point and fire point are developed using the experimental data, as shown in Fig. 2. The experiment's findings are then examined utilising Mamdani Fuzzy Logic through the MATLAB software.

A fuzzy system describes the inputs and outputs using fuzzy sets and membership functions, which represent the degree to which a particular input or output belongs to a fuzzy set.

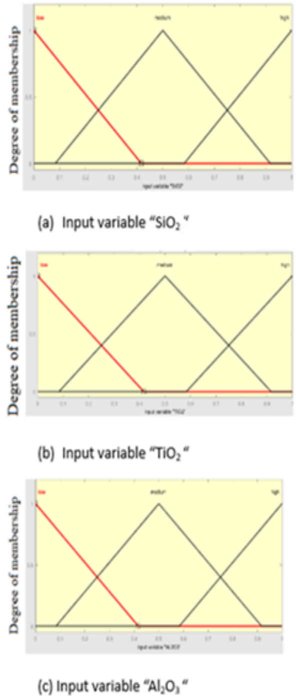


**Fig. 3.** Input variables in the membership function (a) SiO2 (b) TiO2 (c) Al2O3

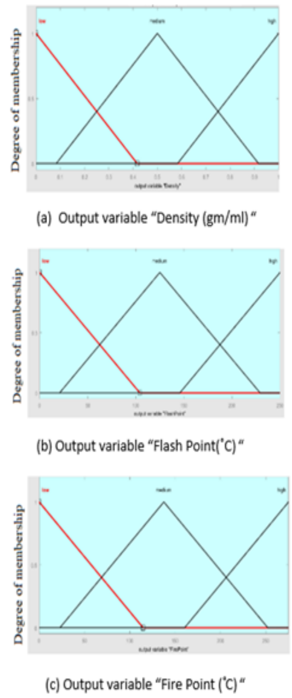


**Fig. 4.** Output variables in the membership function (a) density (b) flash point (c) fire point

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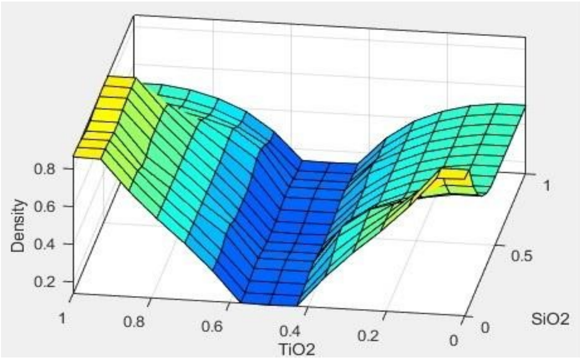
## 4. RESULTS AND DISCUSSION

The surface response graph is a three-dimensional visualisation that shows how the output of a fuzzy system changes with changes in multiple input variables, illustrating the smooth variation of the output as input variables change. The relationship between the amount of nanoparticles added and the changes in the properties are represented here using the surface graphs. In the surface graph, with increase in the altitude of the surface and property of the nano-additives combination, the colour of the surface changes from blue to yellow, where the blue represents lower values and yellow represents the higher values. Also, in between the blue and yellow there is a transition of middle values represented from conversion of blue into yellow colour.

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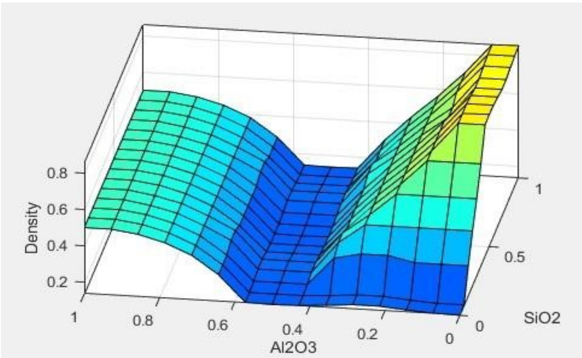


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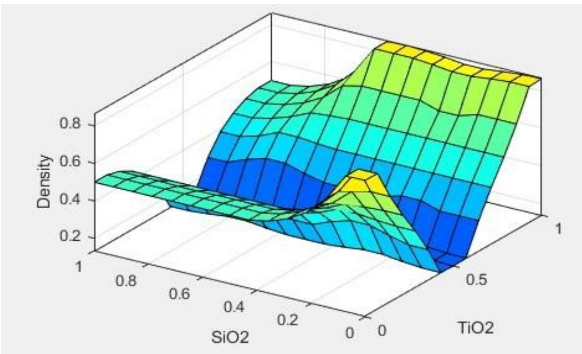


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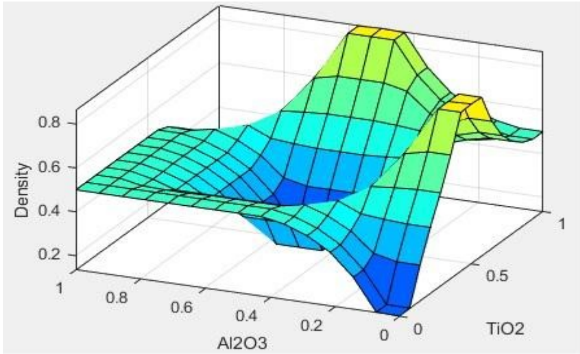


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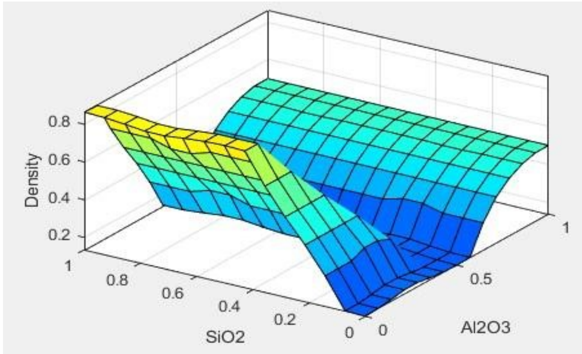


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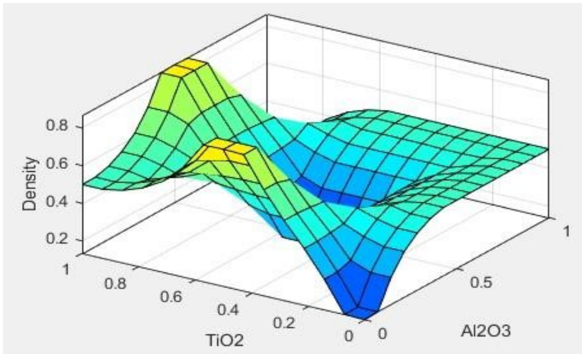


f.

**Fig. 5.** Predicted density by fuzzy logic in relation to SiO2, TiO2 and Al2O3. (a) Density in relation to concentration of SiO2 and TiO2. (b) Density in relation to concentration of SiO2 and Al2O3. (c) Density in relation to concentration of SiO2 and TiO2. (d) Density in relation to concentration of TiO2 and Al2O3.(e) Density in relation to concentration of Al2O3 and SiO2. (f) Density in relation to concentration of Al2O3 and TiO2.

Fig. 5 shows the predicted density using the fuzzy logic for the SiO2, Al2O3 and TiO2 nano-additives as pairs of two nano-additives, in six possible combinations. It is represented as the surface graph where the relation between the nano-additives concentration and density can be clearly observed.

Fig. 5 shows the relationship between three input parameters, that is, 0 wt.% to 1 wt.% of SiO2, TiO2 and Al2O3 nanoparticles and their density as the output parameter in a 3-D input–output space. Fig. 5a, c, d and f, shows an increase in the level of wt.% of TiO2 to obtain maximum density, and Fig. 5b and

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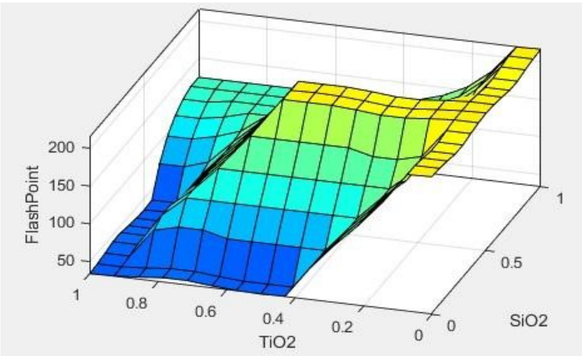
e, shows an increase in the level of wt.% of SiO2 to obtain the maximum density. The influence of the Al2O3 nanoparticle is less than that of the other two nanoparticles.

Fig. 6 shows the predicted flash point (°C) the fuzzy logic for the SiO2, Al2O3 and TiO2 nano-additives as pairs of two nano-additives, in six possible combinations. It is represented as the surface graph where the relation between the nano-additives concentration and flash point (°C) can be clearly observed.

Fig. 6 shows the relationship between three input parameters, that is, 0 wt.% to 1 wt.% of SiO2, TiO2 and Al2O3 and their flash point temperature in °C as the output parameter in a 3-D input–output space. Fig. 6a, c, d and f, shows minimum levels of the wt.% of TiO2 to obtain maximum flash point temperature, and Fig. 5b and e shows an increase in the level of 0.4 wt.% to 0.6 wt.% of SiO2 and Al2O3 to obtain the maximum flash point temperature. The influence of the TiO2 nanoparticle is less than that of the other two nanoparticles.

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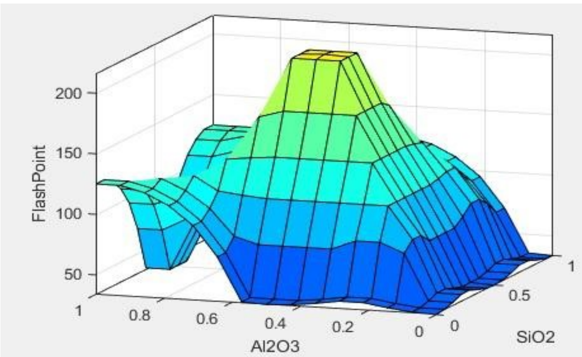


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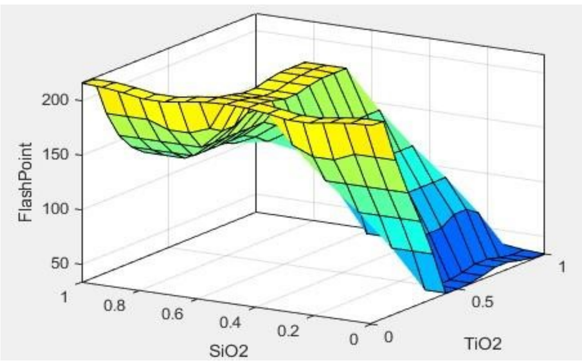


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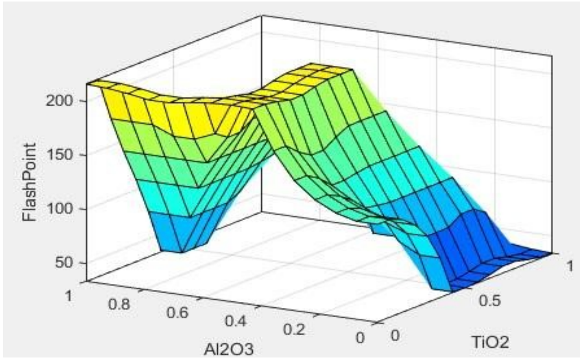


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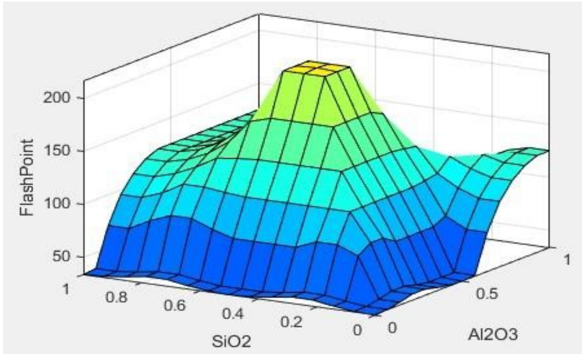


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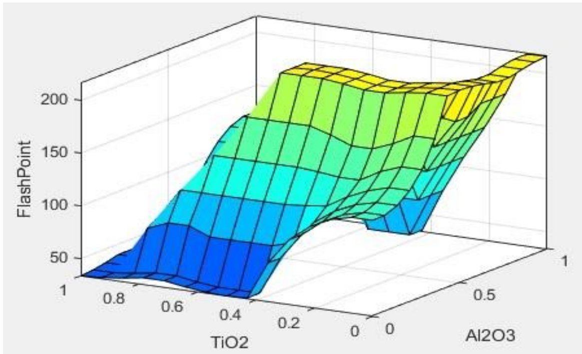


f.

**Fig. 6.** Predicted flash point by fuzzy logic in relation to SiO2,TiO2 and Al2O3. (a) Flash point (°C) in relation to concentration of SiO2 and TiO2. (b) Flash point (°C) in relation to concentration of SiO2 and Al2O3. (c) Flash point (°C) in relation to concentration of TiO2 and SiO2. (d) Flash point (°C) in relation to concentration of TiO2 and Al2O3. (e) Flash point (°C) in relation to concentration of Al2O3 and SiO2. (f) Flash point (°C) in relation to concentration of Al2O3 and TiO2.

Fig. 7 shows the predicted fire point (°C) using the fuzzy logic for the SiO2, Al2O3 and TiO2 nano-additives as pairs of two nano-additives, in six possible combinations. It is represented as the surface graph where the relation between the nano-additives concentration and fire point (°C) can be clearly observed.

Fig. 7 shows the relationship between three input parameters, that is, 0 wt.% to 1 wt.% of SiO2, TiO2 and Al2O3 and their fire point temperature in °C as the output parameter in a 3-D input–output space. Fig. 6a, c, d and f, shows the minimum level of the wt.% of TiO2 to obtain the maximum fire point temperature, and Fig. 5b and e, shows an increase in the level of

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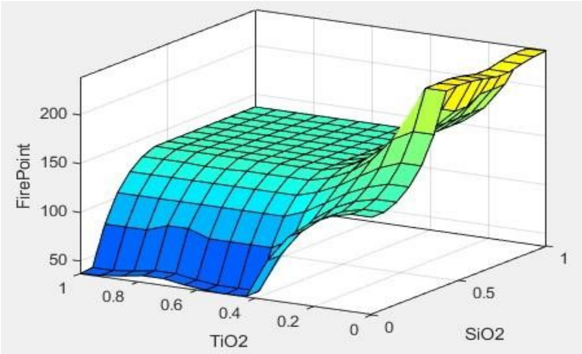
0.4 wt.% to 0.6 wt.% of Al2O3, and 0.6 wt.% to 1 wt.% of SiO2 to obtain the maximum fire point temperature. The influence of the TiO2 nanoparticle is less than that of the other two nanoparticles.

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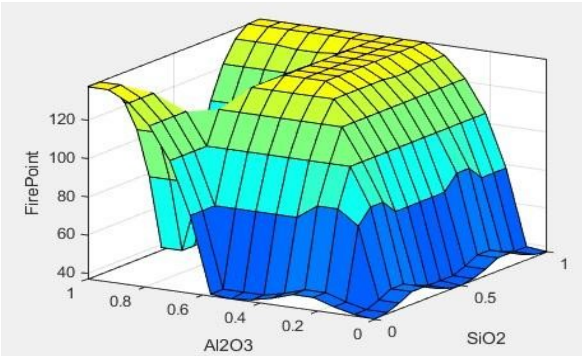


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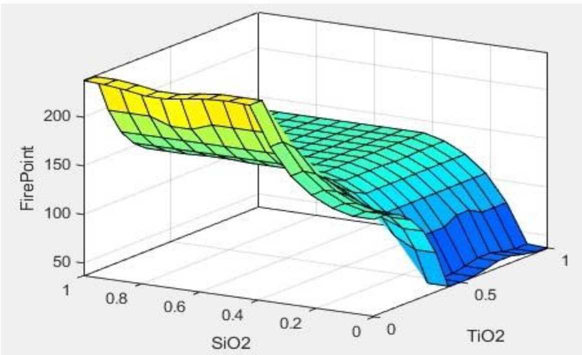
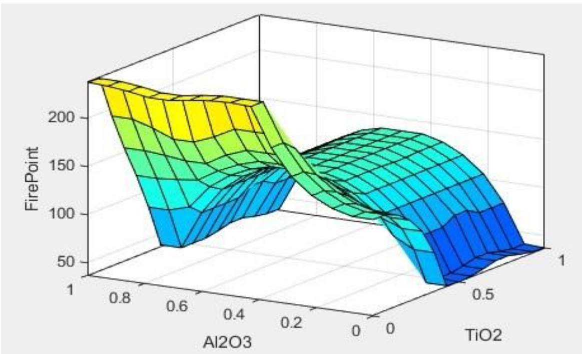
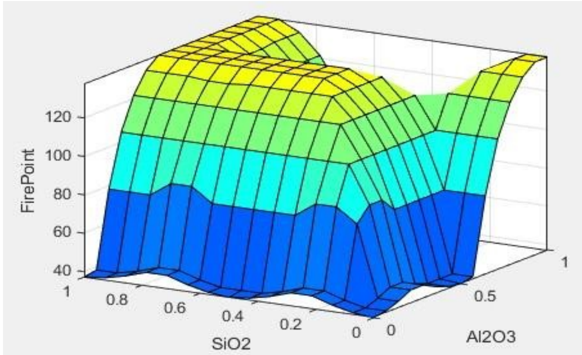


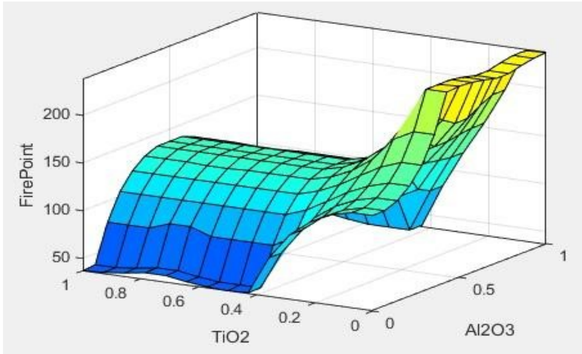

c.




d.




e.




f.

**Fig. 7.** Predicted fire point by fuzzy logic in relation to SiO2, TiO2 and Al2O3. (a) Fire point (°C) in relation to concentration of SiO2 and TiO2. (b) Fire point (°C) in relation to concentration of SiO2 and Al2O3. (c) Fire point (°C) in relation to concentration of TiO2 and SiO2. (d) Fire point (°C) in relation to concentration TiO2 and Al2O3. (e) Fire point (°C) in relation to concentration of Al2O3 and SiO2. (f) Fire point (°C) in relation to concentration of Al2O3 and TiO2.

Fig. 7 shows the relationship between three input parameters, that is, 0 wt.% to 1 wt.% of SiO2, TiO2 and Al2O3 and their fire point temperature in °C as the output parameter in a 3-D input–output space. Fig. 6a, c, d and f, shows the minimum level of the wt.% of TiO2 to obtain the maximum fire point temperature, and Fig. 5b and e, shows an increase in the level of 0.4 wt.% to 0.6 wt.% of Al2O3, and 0.6 wt.% to 1 wt.% of SiO2 to obtain the maximum fire point temperature. The influence of the TiO2 nanoparticle is less than that of the other two nanoparticles.

In this study, the desired values for fuzzy logic are assumed to be HIGH for the selected applications for all the outputs. Using fuzzy logic 8,000 samples are generated taking 27 input samples. Of these 8,000 samples, the maximum flash point from fuzzy logic is found to be 232°C when the lubricant contains 1% of SiO2, 0.05% of TiO2 and 0.05% Al2O3. Similarly, the maximum fire point obtained in fuzzy logic is found to be 261°C when the lubricant contains 0.05% of SiO2, 0.05% of TiO2 and 0.05% Al2O3. The sample containing 0.95% of SiO2, 0.05% of TiO2 and 0.5% Al2O3 shows the best optimum values of both flash and fire points of 229.39°C and 259.16°C, respectively.

Although the unique sample identified from the 8,000 samples simulated using fuzzy logic, exhibits the optimum values for both flash and fire points, it is observed that they are not the best desirable values compared with the other researches carried out with one of any three nano-additives of Al2O3, TiO2 and SiO2 blended with other base oils as indicated in Tab. 6. However, the mix of these three nano-additives is observed to be enhancing the other tribological properties of wear rate, CoF and shear rate of the base oil SN 500 compared with the other researches carried out in this domain. Hence, the research carried out for enhancing most of the tribological properties of a lubricant oil using the mix of these three nano-additives is found to be more promising and adding useful knowledge to this domain [29].

**Tab. 6.** Comparison of various research findings on enhancing flash point of a lubricant

| Researcher | Base oil investigated | Nanoparticle blended | Attained flash point °C | % increase / decrease |
|---|---|---|---|---|
| Awad et al. | Stock-60 | 1.85 wt.% of $Al_2O_3$ | 248 | +9.373 |
| Deepak et al. | SAE20W40 | 0.2 wt.% of $TiO_2$ | 246.2 | +12.73 |
| Desai et al. | SAE20W40 | 0.6% of mass fraction of $SiO_2$ | 200 | −9.7% |
| Gumus et al. | Nano diesel-2 | 50 ppm of $Al_2O_3$ | 68 | +13.33% |
| Koppula et al. | SAE 0W20 | 1.2 wt.% of $Al_2O_3$ | 243 | +21.5% |
| Sajith et al. | SAE20W40 | 0.02 % volume fraction of $Al_2O_3$ | 228 | +2.2% |
| Authors of this manuscript | SN500 | 1 wt.% of each $SiO_2$, $TiO_2$ and $Al_2O_3$ | 232 | +2.66% |

## 5. CONCLUSION

An attempt has been made in this research to determine the optimum mix of three nano-additives of SiO2, Al2O3 and TiO2 blended with the base SN500 lubricant oil, for enhancing the level of the thermophysical properties of density, flash and fire points using fuzzy logic approach. The experimental analysis of 27 samples resulted in three different samples of 1, 3 and 9 for higher (desirable) values of fire point, density and flash points, respectively. However, it is required to determine one sample with a desirable value for all three thermoplastic properties of density, flash and fire point. The fuzzy logic approach used in this research facilitates to determine such unique samples beyond 27 experimental samples. From the fuzzy logic analysis, the sample number 3 possesses the desirable values of 0.9008 gm/ml, 231°C and 252°C for density, flash and fire points, respectively.

This approach can be extended further to determine a sample of lubricant with the optimum mix of any number of nano-additives along with the enhancement of various lubricant properties at their desirable levels. The scope of further work includes enhancing other thermophysical properties such as viscosity, thermal conductivity and shear rate. The other promising optimisation techniques such as RSM, ANN and SVM may also be attempted by researchers in this field for determining the optimum mix of various nano-additives with the base oil to attain the desirable level for all the characteristics of interest simultaneously.

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