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Characterizing TiO_2-ZnO Hybrid Nanofluid Viscosity, Correlation Modeling Through Artificial Neural Network, and Rheological Behavior Analysis

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Abstract

This work is an experimental exploration of the viscosity and rheological properties of titanium dioxide-zinc oxide (TiO_2-ZnO) hybrid nanofluid's (HNFs), and the establishment of a novel correlation. The primary goal of this research is to assess how changing the TiO_2-ZnO ratio impacts this attribute and to establish a correlation for predicting viscosity. X-ray diffraction (XRD) was used to initially analyze the TiO_2 and ZnO. The nanofluid was made in two stages, with a base fluid of a 45/55 water/ethylene glycol (EG) mixture. From 0 to 90 °C, the experimental viscosity and rheological parameters of six distinct TiO_2-ZnO nanoparticle compositions were determined. The experimental data shows that the 45/55 composition of TiO_2-ZnO yielded the highest viscosity value over the temperature range tested, whereas the 55/45 composition yielded the lowest. Additionally, as the temperature of nanofluid is raised from 0 to 90 °C, its maximum viscosity decreases by 87.2%. The rheological study of a HNF shows that all TiO_2-ZnO mixtures exhibit Newtonian fluid behavior. An ANN (Artificial Neural Network)-based framework was developed with the help of the experimental research data. For the purpose of training hyperparameters, the Bayesian approach, an autoregressive technique, was chosen. The autoregressive method helped train the model to get excellent correlation values of over 99.1% with MSE (Mean square error) as small as 0.000042.

Keywords

Nanofluid, Viscosity, Artificial neural network, Ethylene, X-ray diffraction, Rheological properties

Introduction

The HNFs are made by dispersing two or more different nanoparticle combinations in a conventional base fluid, either all at once or in separate steps [1]. These nanoparticles have sizes of less than 100 nm and, depending on the substance, a wide variety of morphological forms [2]. As an alternative to traditional coolants such water, oil, and EG, nanofluids are the primary focus of heat transfer research. Recent years have seen a dramatic shift in the focus of nanofluids research away from single-fluid systems and toward hybrid and ternary systems [3]. Using two nanomaterials that have different properties than the basic fluid, a hybrid-type nanofluid can be created. The thermophysical properties of nanofluids are crucial since the applications of these HNFs are focused on the heat transfer mechanism [4]. A heat transfer fluid's viscosity, the inverse of its fluidity nanofluid, is a crucial metric in determining the fluid's thermofluidic properties.

Many studies have been conducted in recent years with a primary emphasis on the thermal conductivity (TC) and the viscosity of HNFs [5]. However, gauging the usefulness of HNFs in convective heat transfer requires more than just their improved TC. The TC of nanofluids can also be predicted using a number of different models. The TC of MWCNT-MgO at constant ratios was recently estimated using a new model, and the author concluded that the approach may be used with other nanofluids as well [6, 7]. Their cost-benefit analysis also showed that MgO-MWCNT/H_2O-EG HNFs are preferable than CuO-MWCNT/H_2O-EG HNFs. A recent analysis of the TC of HNFs noted that, in comparison to mono nanofluids or conventional liquids, HNFs result in a striking improvement in TC, with a significantly higher coefficient of heat transfer. Furthermore, they reported that the TC of HNFs is improved at concentrations of nanoparticles as low as 0.1% by volume [8, 9].

At temperatures between 30 and 40 °C and loadings of 0.01 and 0.10%, the authors [10, 11] conducted experiments to predict the viscosity of ternary TiO_2-SiC, H_2O based HNFs. Their viscosity experiments showed that increasing the volume percentage of HNFs had a major impact on the fluid's internal resistance. Similarly, their forecasting model has a similar margin of error (about 2.6%). While the correlation does take fluid temperature and nanoparticle content into consideration, it does not differentiate between the impacts of Al_2O_3, SiC, and TiO_2. The viscosity of nanofluids can be affected by the materials employed to form the nanostructure. The authors [12] also reported these results, which they arrived at after conducting an exhaustive study of thermophysical properties of nanofluids.

Researchers [13, 14] pointed out that the ANN method is more accurate than the correlation models. Scientists successfully created a stable MWCNT-ZnO hybrid nanofluid by mixing the two materials with distilled water [15, 16]. As the temperature of the nanofluid was increased to 55 °C, they saw that the increase in viscosity caused by the higher volume concentration was attenuated. They also found that the dynamic viscosity of the MWCNT-ZnO HNF was less than that of the mono ZnO/water nanofluid. The error of their fitting between anticipated and experimental data for viscosity is less than 0.01%, and it is valid between 15 and 55 °C [17, 18].

Despite the extensive study of HNFs, accurately predicting their dynamic viscosity remains a significant obstacle. When it comes to estimating the dynamic viscosity of a TiO_2-ZnO/water-EG HNF, the authors were unaware of a single correlation model. This leads us to investigate how the temperature of the HNF and the ratio of TiO_2-ZnO nanoparticles affect its dynamic viscosity and rheological behavior. The temperature of experimentation ranges from 0 to 90 °C. An ANN-based prognostic model was built using data from extensive laboratory experiments. The ANN model was optimized using the Bayesian method for better performance.

Methodology

Materials

This work made use of TiO_2 and ZnO nano-powders with particle sizes of 17 nm and 30 nm. TiO_2 nano-powder has a molecular weight of around 79.9 g/mol, while ZnO nano-powder has a molecular weight of 81.38 g/mol. The TiO_2 nano-powder look white, whereas the ZnO ones have a somewhat yellowish hue. Nanofluid was prepared using a base fluid of EG and distilled water. In addition, the polyvinyl pyrrolidone (PVP) surfactant was incorporated into the experiment to maintain the excellent stability of the nanofluid. The experimental materials and their individual characteristics are listed in table 1.

Table 1: Nanomaterial and fluid-base properties.

Properties	TiO_2	ZnO	H_2O	EG	Surfactant
Size	17 nm	30 nm	-	-	-
Color	White	Light yellow	Clear	Clear	White
Morphology	Spherical	Plate	Liquid	Liquid	Powder
Purity	99.50%	99.8	-	-	-
Density (Kg/m^3)	4260	5600	1002	1120	1268
Formulaweight (g/mol)	79.9	81.38	18.02	63.4	-
Specific heat (J/KgK)	683	98	4230	2428	-

Preparation of nanofluid

The double-step approach is a common method for preparing HNFs. The first step is to produce the nanoparticles independently, and the second is to disperse the nanoparticles in the base fluid. Different TiO_2/ZnO nanoparticle combinations were dispersed in a 55/45 base fluid mixture of distilled water and EG for the current study. The mixture's base fluid is prepared by combining 65 ml of water and 45 ml of EG. The nanoparticles were mixed with the surfactant PVP at a 1:10 ratio. Mechanical stirring with an MSH-30D WiseStir at 800 rpm for 90 min was used to first distribute the weighted TiO_2-ZnO nanoparticles in a water/EG mixture. Nanoparticles in the base fluid were kept at a constant 1 vol.% concentration for all HNF ratios. The necessary mass of nanoparticles was determined by entering the values for the mass and density of the HNFs and the base fluid.

The quantities of each component utilized to make the TiO_2-ZnO nanoparticle- containing HNF compositions are listed in table 2. TiO_2-ZnO nanoparticles shape and structure were analyzed using two distinct methods. XRD is the basis for the first methodological strategy. Cu-Ka radiation with a diffraction angle (2θ) between 15° and 70° was used to illuminate the nanoparticles, with exposure times spaced by 0.02°. Nanoparticles of TiO_2 and ZnO were analyzed for their crystal structure, chemical make-up, and crystalline grain size

Table 2: Quantity of materials.

Nanoparticles mixing		Mass of nanoparticle		Surfactant	Base fluid (ml)	
TiO_2	ZnO	TiO_2	ZnO	PVP	H_2O	EG
15	85	0.812 ± 0.001	5.312 ± 0.001	0.641 ± 0.001	60	40
30	70	1.724 ± 0.001	4.336 ± 0.001	0.526 ± 0.001	60	40
45	55	2.015 ± 0.001	3.241 ± 0.001	0.514 ± 0.001	60	40
60	40	2.746 ± 0.001	3.224 ± 0.001	0.551 ± 0.001	60	40
75	25	3.351 ± 0.001	1.960 ± 0.001	0.510 ± 0.001	60	40

using XRD. Position and intensity of diffraction peaks were compared to standard patterns to determine the nanoparticles' structure.

pH measurement

The measurement of zeta potential is a tried-and-true method used by many researchers [19] to assess the consistency of HNFs' distribution. This technique measures the electromotive force between the huge phase of basic fluid and fluid layer (liquid) adsorbing onto the nanoparticles (solid). Stability of nanoparticle suspension in the base fluid is indicated by a high zeta potential value in millivolts (positive/negative). The zeta potential of each HNFs sample was determined, as well as the average size of the TiO_2-ZnO nanoparticles dispersed in the base fluid, using a Brookhaven Zeta Plus analyzer. Each mixture was measured three times at 25 °C and the average was used for the study.

Rheological data measurement

The instrument is made up of a spinning spindle and a cylindrical housing in which the nanofluid sample can be stored [20, 21]. The HNF sample was heated or cooled to precise temperatures between 0 and 90 °C using a thermal bath. The rheometer and all of its associated data on viscosity, shear stress, shear rate, and torque are controlled and stored in a computer application called RheoCal. The dynamic viscosity of the H_2O/EG base fluid was also measured at temperatures ranging from 0 to 90 °C. For each sample, we took six measurements to determine the average viscosity. The temperature ranged from 0 to 90 °C, and the measurement interval was 15 min. The rheological data was utilized to distinguish between Newtonian and non-Newtonian behavior in the fluid. The range of measurable shear rates is from 5.0 to 4800 s^{-1}. Using a HNF ratio and temperatures ranging from 0 to 90 °C in 15° increments, we determined the shear rate and shear stress of each sample.

Bayesian optimization for hyperparameters

Models are built with random distributions of data for use in learning, testing, and validation. Selecting an Activation Function and Network Topology for an ANN Model (neurons, layers, and epochs) [22-24]. The process of teaching a model is equally crucial. Since the ANN was trained with predetermined input controls and output metrics, it falls under the category of supervised learning. The onus for fixing the network's flaws falls primarily on the shoulders of the learning algorithm used. MSE's error measure became synonymous with the cost function. In addition, the incorrect signal had been backpropagated until the minimum signal value was obtained after multiple training sessions. In order to fully comprehend the reliability of technically advanced ANN prediction models, the testing and validation phase was essential once the training phase was finished.

For effective model development, it is necessary to optimize the ANN's many hyperparameters. Hyperparameters are variables that can be adjusted to alter how an ANN performs, such as the learning rate, activation function, number of neurons and epoch [25]. Determining hyperparameters by hand takes a lot of effort and time. It is carried out using a method based on trial and error, which is inefficient. The Bayesian approach is another practical and powerful method for optimizing hyperparameters. The kernel parameters are estimated empirically using the Bayes method in Bayesian approach. Hyperparameters can be optimized without any input from the user due to Bayesian approach.

Results and Discussion

The XRD patterns of ZnO and TiO_2 nanoparticles are shown in figure 1a and 1b, respectively. Figure 1a shows that the three 2θ angles of 26.52°, 31.48°, and 39.26° produce the strongest peak. ZnO nanoparticles have been found to include the maghemite phase, as suggested by refined XRD data. Table 3 shows the results of a Sherrer equation calculation utilizing the three strongest peaks to determine that the average crystalline size of ZnO is around 30.07 nm. Figure 1b displays the results of an XRD study conducted on TiO_2 nanoparticles. Current TiO_2 nanoparticle XRD data was compared to a reference database. Furthermore, the TiO_2 nanoparticles have a monoclinic crystalline structure. The three most prominent peaks occur at 28.46°, 36.53°, and 61.68° of the available 2θ angles. Using the Sherrer equation, can estimate that the average crystallite size of TiO_2 nanoparticles is 8.31 nm. TiO_2 nanoparticles are consistent with their particle size, which shows a size of less than 17 nm when compared to ZnO nanoparticles of a similar shape and size.

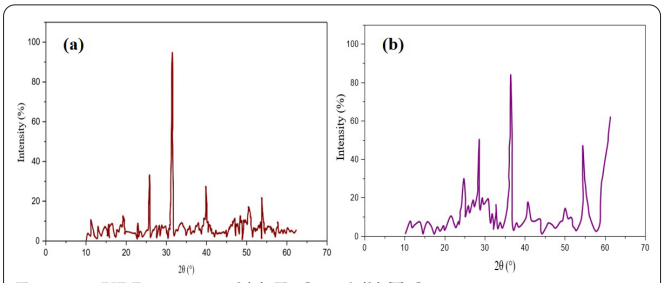


Figure 1: XRD pattern of **(a)** ZnO and **(b)** TiO_2.

Table 3: Nanoparticles crystallization dimensions.

Nanoparticles	θ	FWHM	Size of particle	Average size of particle
2θ	(°)	β (°)	(nm)	(nm)
TiO_2	28.46	1.40	17.46	17.66
	36.53	1.62	17.52	
	61.68	1.04	18.0	
ZnO	26.52	0.4128	30.44	31.0
	31.48	0.3347	31.04	
	39.26	0.2934	31.52	

Stability of nanofluids

The zeta potential and particle size distribution were used to assess the durability of TiO_2-ZnO HNFs. Table 4 shows that the TiO_2-ZnO HNFs with a particle ratio of 45:55 had a peak zeta potential value of 34.6 mV, indicating good stability. In the scientific literature, zeta potential values above 35 mV are regarded as stable. Thus, the 45:55 mixing ratio, with its determined zeta potential of 34.6 mV, can be deemed to attain

Table 4: Stabilization of hybridized nanofluid.

Nanofluid ratio (TiO_2:ZnO)	Stabilitydetector	pH value	Distribution of particle size	Zeta potential
15:85	Some stability	8.7	268.4	-00.1
30:70	Moderate stability	8.2	223.9	31.5
45:55	Good stability	8.4	206.4	38.4
60:40	Some stability	8.4	234.38	32.6
75:25	Moderate stability	8.9	219.42	34.7

satisfactory stability. TiO_2-ZnO is well dispersed in the base fluid, as seen by the narrower particle size distribution (about 206.4 nm). Zeta potentials for all the other possible HNFs ratios are above 25 mV, demonstrating that the TiO_2-ZnO combination is moderately stable. All nanofluid ratios show a pH value between 8.0 and 8.6. Meanwhile, the base fluid has a pH of around 7.6. This demonstrates that the TiO_2-ZnO HNF has a pH value is greater than that of the base fluid. Brownian motion causes particles to attract and collide unless there is enough electrostatic repulsion force provided by an increase in zeta potential, which is created by an increase in pH value. As a result, the nanofluid became significantly more stable, with almost no sedimentation.

Effect of TiO_2-ZnO ratio and temperature on dynamic viscosity

Figure 2 depicts the verification of base fluid (H_2O/EG 55:45) dynamic viscosity measurement using the reference data sourced at temperatures between 30 and 70 °C. At 55/45 ratios, the greatest discrepancy among original and experimental value for H_2O /EG is around 12%. This equates to a precise measurement of viscosity. Furthermore, the measured viscosity trend line is consistent with the trend of the plotted real data as the temperature of the base fluid increases.

Figure 3 shows the temperature dependency of the dynamic viscosity of the generated HNFs differs depending on the composition of TiO_2 and ZnO. As the temperature is raised from 0 to 90 °C, the dynamic viscosity of TiO_2-ZnO suspended in water/EG drops noticeably for all ratios. All ratio hybrids have a much higher dynamic viscosity at 0 °C compared to 100 °C. The TiO_2-ZnO (45/55) combination showed the greatest reduction in dynamic viscosity, at a rate of 89%. At low temperatures, energy was lost by the base fluid's molecules, whereas at high temperatures, it was acquired. The temperature impact also reduces the intramolecular force between molecules. The viscosity of the HNFs was lowered the viscosity of base fluid was greatly reduced. The base fluid viscosity reduced by 0.64%, from 2.4218 to 0.912 mPa, while the temperature was raised from 0 to 90 °C. However, it has been found that a TiO_2-ZnO suspension in the base fluid can lower viscosity by as much as 89% for a 45/55 ratio. It is evident that the decrease in water/viscosity EG at high temperatures is improved by addition of TiO_2-ZnO nanoparticles.

Changing the ratio of water to EG in a suspension of ZnO-TiO_2 nanoparticles causes a corresponding change in the dynamic viscosity, as seen in figure 4. The analysis considers a wide range of combination ratios and temperatures (from 0 to 90 °C). As can be seen in figure 4, all of the relative viscosities are greater than 1.5, indicating that the HNFs combination samples have a higher viscosity than the base fluid. This

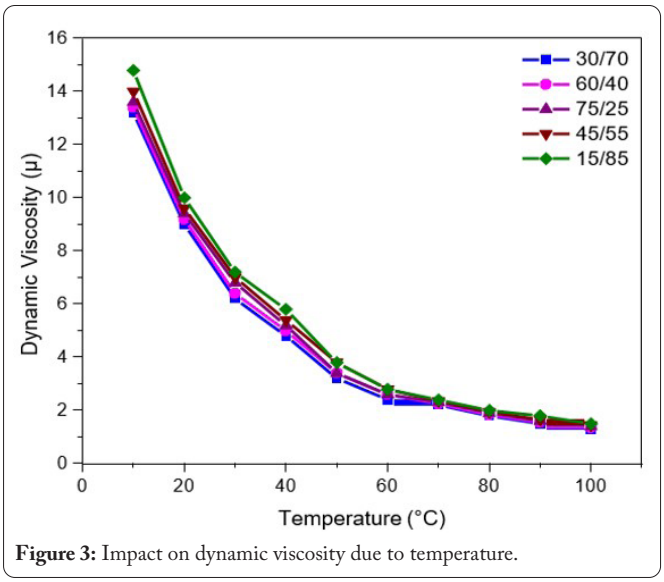


Figure 3: Impact on dynamic viscosity due to temperature.

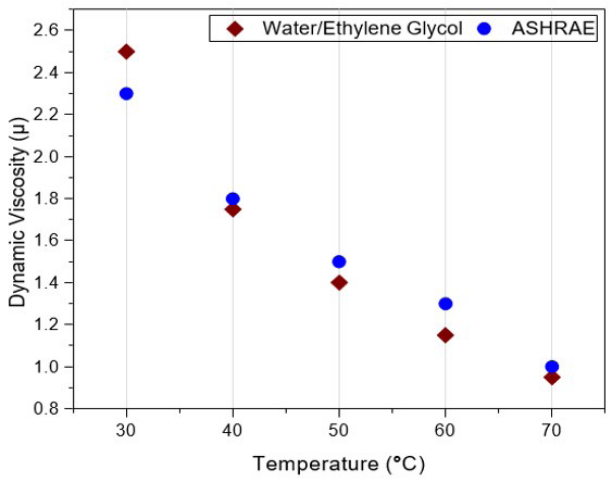


Figure 2: Validation of dynamic viscosity.

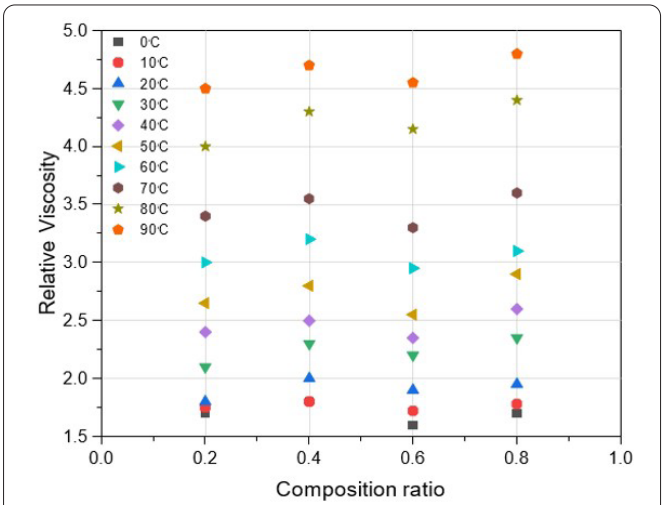


Figure 4: Effect of TiO_2-ZnO ratio on dynamic viscosity.

result agrees with what has been written about the viscosity of both pure and mixed nanofluids. The intriguing finding of the current investigation is that the modification in the composition of ZnO and TiO_2 nanoparticles causes both growing and decreasing trends in the enhancement of viscosity. The hybrid composition of TiO_2-ZnO with a 45/55 ratio (0.4) has the highest viscosity value at each 15 °C temperature interval between 0 and 90 °C. At 100 °C, the greatest relative viscosity of 5.12 implies that the viscosity is increased by roughly 5.12 times compared to the base fluid. Increased ZnO nanoparticle concentration is responsible for the observed increase in viscosity.

Changes in ZnO-TiO_2 ratio cause the nanoparticle composition to waver, causing the viscosity to either increase or decrease. The data show that as the concentration of TiO_2 nanoparticles in water/EG climbs above 45%, the viscosity of the combination decreases, only to rise again as the concentration of TiO_2 nears 75%. At the highest TiO_2 concentration (75%), the relative viscosity both increases and decreases to around 1.92 and 4.75 times that of the fluid, respectively. Particle composition has a smaller impact on viscosity changes than does temperature increase.

HNFs' rheological characteristics are used to illustrate how the TiO_2-ZnO composition affects the base fluid's (water/EG) tendency toward Newtonian or non-Newtonian fluid conduct. Figure 5 shows, for shear rates between 5 and 4600 s^{-1}, how the temperature of the fluid affects the rheological behavior of a base fluid suspended with a 75/25 TiO_2-ZnO composition. The theoretically employed fluid is a Newtonian fluid at the base. Shear stress and shear rate were shown to have a linear relationship, indicative of the Newtonian fluid nature of an HNF. By adding base fluid, 75% TiO_2 nanoparticles and 25% ZnO nanoparticles maintain the base fluid's Newtonian fluid behavior. The HNFs exhibited Newtonian behavior between 0 to 90 °C. Even at the maximum mass concentration of 1%, there is clear evidence that different TiO_2-ZnO ratios have no impact on the characteristic of base fluid. These findings confirm those of a prior work that used a variety of nanoparticle compositions of TiO_2 and ZnO with water as the base fluid.

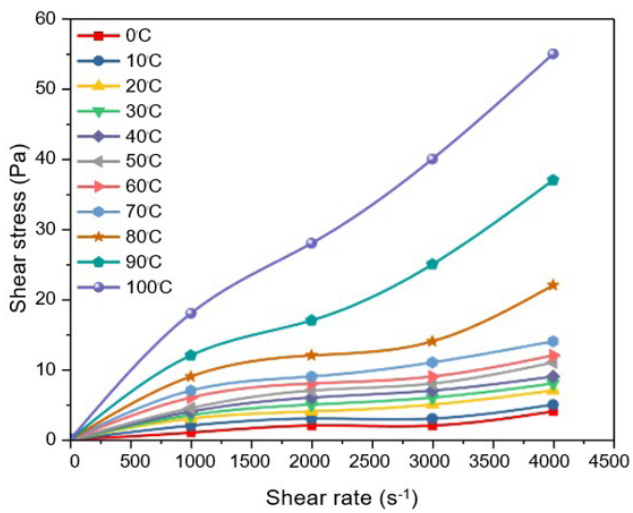


Figure 5: Rheological behavior of 75/25 TiO_2-ZnO composition.

When can be seen in figure 5, figure 6, figure 7, figure 8, and

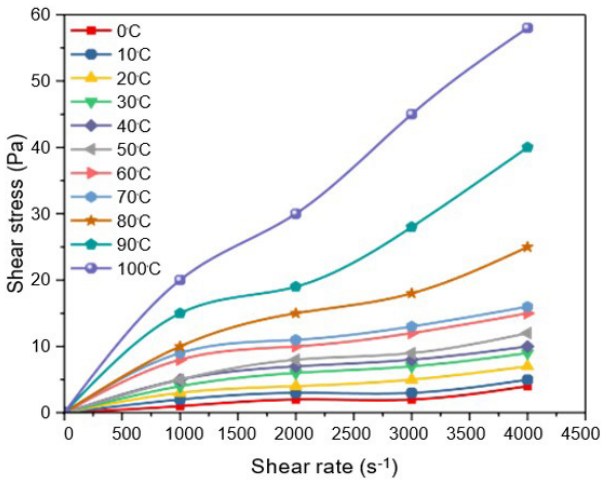


Figure 6: Rheological behavior of 60/40 TiO_2-ZnO composition.

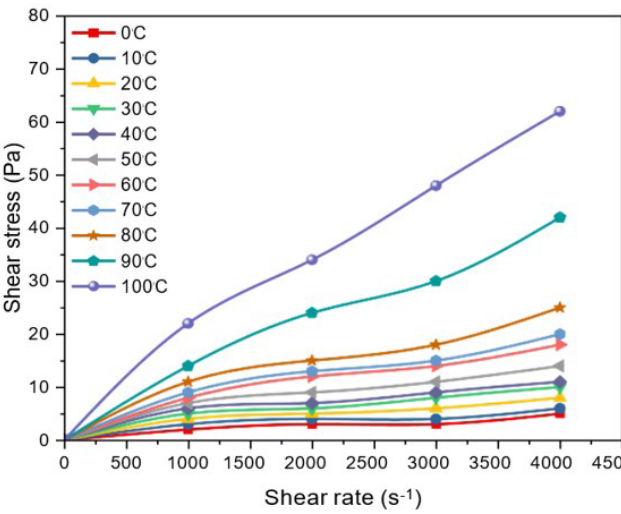


Figure 7: Rheological behavior of hybridized with 45/55 TiO_2-ZnO composition.

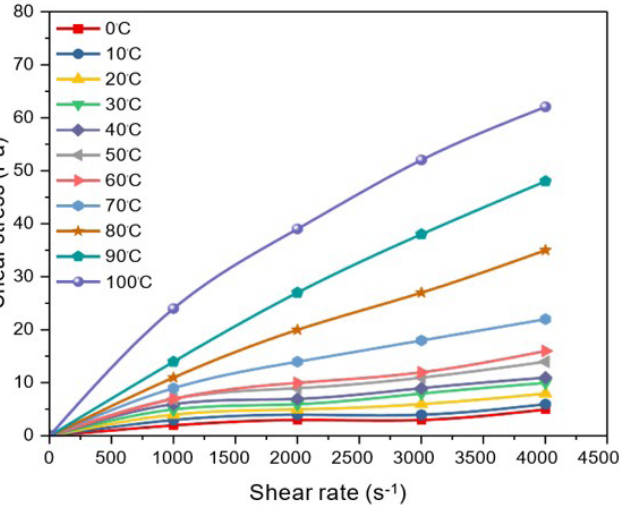


Figure 8: Rheological behavior of hybridized with 30/70 TiO_2-ZnO composition.

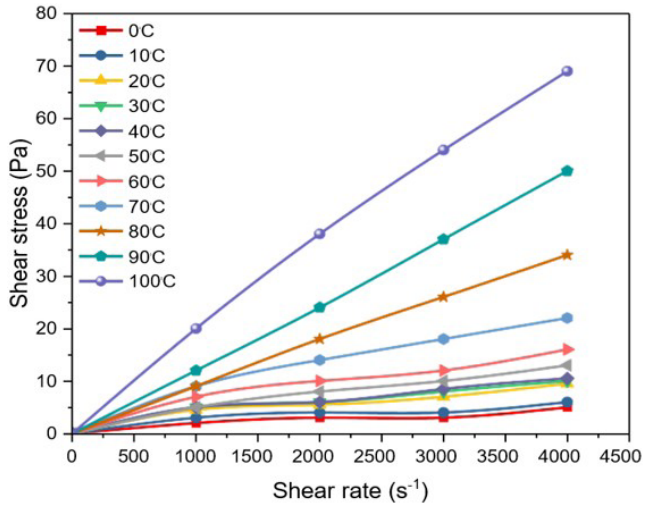


Figure 9: Rheological behavior of hybridized with 85/15 TiO_2-ZnO composition.

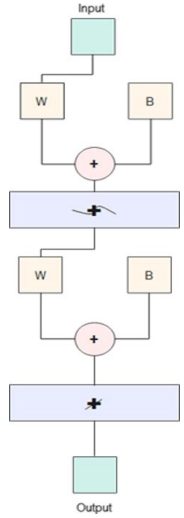


Figure 10: Architecture of ANN model.

figure 9, as the temperature rises, the gradient of the rheological property graph significantly decreases. With a decrease in gradient, viscosity decreases as temperature increases.

Between 45 and 90 °C, the rheological behavior of TiO_2-ZnO HNF is nearly constant regardless of the combination ratio studied. Rheological property of H_2O/EG is relatively insensitive to changes in ZnO-TiO_2 composition, this conclusion holds. The viscosity of TiO_2-ZnO at all examined ratios is nearly independent of the applied shear rate between 10 and 4600 s^{-1}. This demonstrates that the TiO_2- ZnO fluid has a Newtonian behavior. However, the hybrid fluid exhibits a little amount of shear-thinning for shear rates lower than 10 s^{-1}. Although this shear thinning behavior is observed, it only accounts for around 0.12% of the total shear rate studied and has no effect on the otherwise Newtonian behavior of the TiO_2-ZnO hybrid fluid. The maximum amount of possible shear collation has been attained, and the shear rate is adequate. This resulted in a decrease in the viscosity of the HNF as the larger aggregation molecules were broken up into smaller ones.

Model development based on machine learning

Bayesian optimization

The collected dataset was randomly split into three parts, with 75% used for training the ANN model, 15% for testing it, and 15% for validation. During the training of the model, hyperparameter optimization was performed using a Bayesian technique. Overtraining was avoided by using the 5-fold cross-validation method. Figure 10 depicts the overall design of the ANN model used in this study. There are 10 input neurons and a single output neuron in this structure. A series of iterations is used in hyperparameter optimization to fine-tune the learning process. Figure 11 shows the training procedure. Results from the training can be shown in figure 12.

Levenberg-Marquardt training method was used in the training process, and the least MSE was used as the success metric. After the model was built, it was validated by being subjected to tests on new, unpredictable data. During these

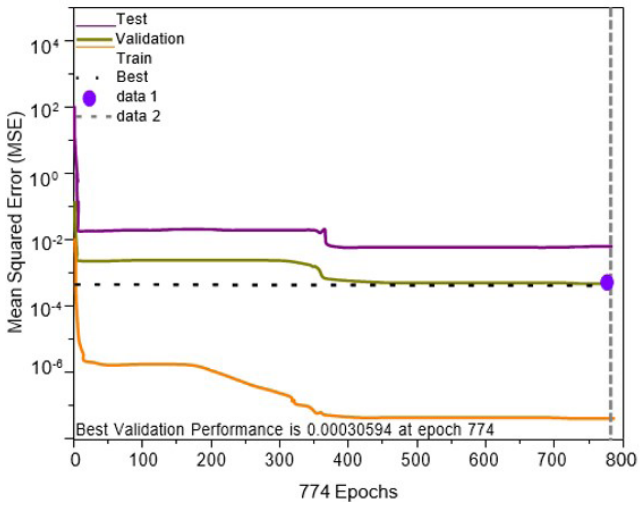


Figure 11: Training model.

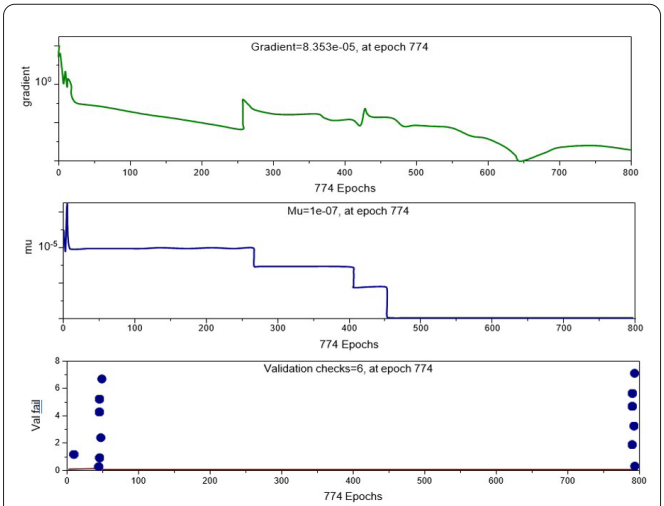


Figure 12: Performance on training.

three stages, the performance of the model is shown in figure 13. All three phases of the model's prediction performance had an R-value greater than 0.9999.

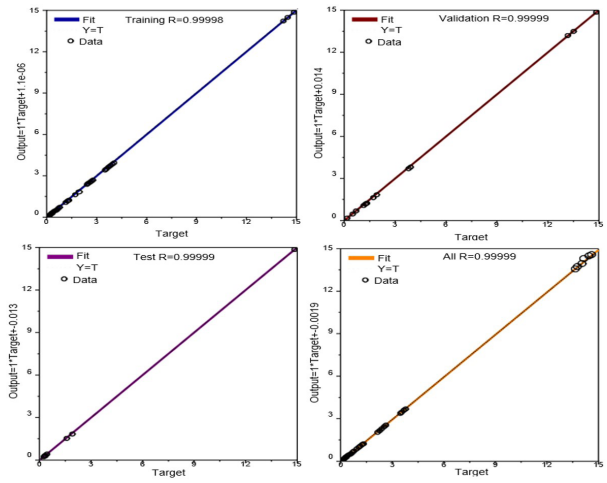


Figure 13: The results of the model's training, testing, and validation phases.

Uncertainty and error analysis

The experimental data's relative uncertainty is a measure of how trustworthy the findings are, therefore understanding it is vital. Viscosity data of base fluid was compared to validate the accuracy of the measuring device. The most that can be off between the norm and the measurements is around 12%. This is evidence of precise measuring. pH measurement tolerances include a standard deviation of 0.16 and a mean standard error of 0.05. Meanwhile, the predicted relative uncertainty for the dynamic viscosity measurement was close to 0.12%. This demonstrates the reliability of the experimental process and the great precision of the measured data.

Conclusion

TAt constant volume concentrations, the dynamic viscosities of a water/EG-based HNF was examined as a function of TiO_2-ZnO nanoparticle composition. Good stability was seen in the formulated HNFs, with only a little amount of sedimentation. It was determined that a 45/55 ratio of TiO_2-ZnO was the most stable nanoparticle composition due to its high zeta potential value and narrow particle size distribution. All nanofluid ratios have a higher pH than the base fluid, indicating the nanofluid is stable. XRD analysis placed the average particle size of TiO_2 and ZnO nanoparticles, respectively, at 8.31 nm and 31.2 nm. At 90 °C, the TiO_2-ZnO hybrid composition of 45/55 demonstrated the greatest viscosity improvement, reaching up to 4.69 times that of water/EG, according to the dynamic viscosity experiments. The impact of nanoparticles composition ratios on dynamic viscosities is shown to be significantly less than that of temperature. The maximum temperature-induced increase in dynamic viscosity is around 57.16%, while the influence of the TiO_2-ZnO ratio is around 4.94%. Because of the presence of nanoparticle compositions in the base fluid, increasing the temperature of a nanofluid can reduce its viscosity by as much as 87.1%. It has been found that the base fluid's Newtonian fluid behavior is unaffected by variations in nanoparticle composition. All possible permutations of HNFs displayed Newtonian fluid behavior between 0 and 90 °C with shear speeds of 10 and 4600 s^{-1}. As a result, it is safe to say that the 45/55 TiO_2-ZnO HNF has great potential for use in convective heat transfer. Data from the experiment was used to inform a ANN-based framework. Training hyperparameters were tuned using a Bayesian autoregressive method. The autoregressive method gave us excellent correlation values of over 98.4% and a minimum MSE as low as 0.000031 while training the model.

Acknowledgements

None.

Conflict of Interest

None.

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