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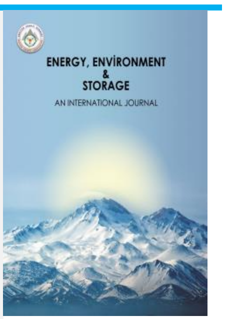

Optimization of the Effects of Binary Hybrid Nanofluid Synthesis Parameters on the Thermal and Hydraulic Characteristics

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ABSTRACT. Due to the growing interest in hybrid nanofluids, researchers have been primarily focused to obtain the thermophysical properties of hybrid nanofluids. Several parameters such as temperature, volume or weight fractions, nanoparticle types and shapes affected the thermophysical properties of nanofluids. Accordingly, the optimization in thermal conductivity and viscosity of nanofluids obtained by mixing binary nanocomposite particles GnP-Fe_3O_4 in an ethylene glycol-water base fluid with a mixing ratio of 20-80 % was investigated in this study. The Taguchi approach is used for single-objective optimization and the significance values of the synthesis parameters were determined using the ANOVA technique. Five different factors, including mechanical strring time, ultrasonic mixing time and power, surfactant mixing ratio, and nanofluid weight ratio, were optimized at three different levels during the synthesis of hybrid nanofluids. The experimental $L_{27}(3^5)$ orthogonal array trial was built in order to carry out the optimization. According to the results, mechanical striring time was found to have the least impact on both thermophysical parameters, whereas ultrasonic mixing power, nanofluid weight ratio, and ultrasonic mixing time were also ranked from low to high impact. The usage of surfactant was shown to be the parameter that had the greatest impact, with rates of 63.57% and 65.31%, on thermal conductivity and viscosity, respectively.

Keywords: Taguchi ANOVA, Nanofluid, Thermal conductivity, Viscosity

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1. INTRODUCTION

Heat control in thermal systems is considered one of the most common problems of today, and numerious studies are being conducted on the removal, recovery and storage of the energy from the thermal system [1-4]. Nanofluids have demonstrated their ability to be used in applications such as energy storage, heat exchangers, and heat sinks, resulting in improved heat transfer performance. The determination of the thermophysical properties of nanofluids that increase heat transfer rate in thermal systems has also become a precondition in order to reveal the activity mechanisms of nanofluids. Studying the thermophysical characteristics of hybrid nanofluids is mostly done to identify methods for enhancing cooling systems. [5]. The temperature of the nanofluid, particle fraction, base fluid type, nanoparticle size, shape, and type all affect the thermophysical properties of the nanofluid, such as specific heat, viscosity, and thermal conductivity [6]. Therefore, the evaluation of thermal conductivity focuses on improving heat transfer, while viscosity is evaluated for its effect on pressure drop under the same flow conditions.

Nowadays, nanotechnology enables the development of new types of nanofluid called composite or hybrid, which are obtained by mixing two or more nanoparticles with the base fluid. Despite ongoing research on nanofluids, it is evident that the studies focusing on the application of hybrid nanofluids in heat transfer are both contemporary and insufficient [7,8].

The thermal conductivity of a ZnO/TiO_2/EG hybrid nanofluid was studied by Toghraiel et al. [9] in the temperature range of 25 to 50°C and in the particle volume fraction range of 0 to 3.5%. The highest temperature and volume fraction were identified as generating hybrid nanofluids with the maximum thermal conductivity. The thermal conductivity of Al_2O_3-Cu/water hybrid nanofluids with volume concentrations ranging from 0.1% to 2% was examined by Suresh et al. [10]. For a volume concentration of 2%, the experimental measurement of thermal conductivity revealed a maximum improvement of 12.11%. Experimental research on the viscosity of TiO_2-Ag/engine oil and Al_2O_3-Ag/engine oil nanofluids was conducted by Liu et al. [11]. They claimed that as particle loading increases, viscosity decreases. Hemmat Esfe et al. [12]

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investigated at the Cu/TiO_2-water/EG hybrid nanofluid's thermal conductivity. At various composition concentrations (0.1, 0.2, 0.4, 0.8, 1, 1.5, and 2%) and temperatures ranging from 30 to 60 °C, the thermal characteristics of this nanofluid were measured. According to the findings, hybrid nanofluids' thermal conductivity improved as particle loading and temperature increased. The effects of temperature and particle concentration on the dynamic viscosity of the MgO-MWCNTs/EG hybrid nanofluid were investigated by Soltani and Akbari [13]. It was found that the dynamic viscosity can rise by up to 168% as the solid volume fraction rises from 0.1 to 1%.

As mentioned earlier, several factors, including the ratio of nanofluid to nanoparticle concentration, the type of nanoparticle, whether it is used in mono or hybrid applications, and the synthesis method, affect the thermal and hydraulic properties of nanofluids. In this case, the effects of these various characteristics have been investigated through optimization studies. By experimenting with several nanoparticles, including graphite, alumina, and zirconia, Abdullah et al. [14] were able to identify the best nano-oil combination. Using the Taguchi L_9 orthogonal array, the impact of parameters that included various quantities of surfactants and sonication time was examined. In comparison to the other samples, it was determined that the zirconia nanoparticle with SDBS surfactant and 10 minutes of sonication were the most ideal parameters for determining the stability of nano-oil. According to Rubasingh and Selvakumar [15], Taguchi design and Grey relational analysis were the most alluring approaches for taking into account the impact of the volume fractions (1 vol.%, 2 vol.%, 4 vol.%, and 8 vol.%) of TiO_2/ZnO nanocomposite on impressive thermophysical properties for the thermal performance of nanofluids. The stability of Al_2O_3/water nanofluids was investigated by Choudhary et al. [16] utilizing zeta potential analysis. The parameter that can interfere with the stability and thermal conductivity of nanofluids is optimized using the Taguchi method. S. Ravi Babu and G. Sambasiva Rao [17] employed the Taguchi technique to examine the stability of aqueous aluminum oxide, and the nanoparticle volume concentration, surfactant volume concentration, and sonication time were the variables used for optimization. They claimed that the stability of the nanofluid is closely correlated with the volume fraction, sonication time, pH level, and the ratio of surfactant volume to nanoparticle volume. The orthogonal layer (L_{25}) of the Taguchi design experiment was organized.

The authors noted that the thermal and hydraulic properties of base fluids are impacted by the unary or binary use of nanoparticles. The authors also discovered that factors like nanofluid fraction and synthesis methods improve the general properties of nanofluids. Thus, in this paper, the Taguchi method is used to assess the effects of mechanical stirring, ultrasonic sonication time and power, surfactant mixing ratios, and volume fractions with multi-levels on the thermal conductivity and viscosity of a binary hybrid GnP-Fe_30_4/water-ethylene glycol nanofluid. ANOVA, in addition to the Taguchi approach, is a contributing methodology for determining statistically significant variance between the means of independent parameters. The ANOVA and Taguchi techniques are utilized combined in the current study due to the significance of the data they provide, and no previous research has presented such an approach to the thermal conductivity and viscosity of the binary hybrid nanofluid of synthesis techniques. In this regard, it is a significant study in terms of applying a comparable approach to the hybrid nanofluids and getting qualified results with a little number of measurements.

2. MATERIALS AND METHODS

2.1 Synthesis of nanofluids

In this study, the synthesis approach of GnP/Fe3O4 water-ethylene glycol nanofluid is optimized to determine the influence of the technique on thermal conductivity and viscosity. The method used varies with 0.5, 0.75, and 1% weight fractions, surfactant/nanoparticle fractions of 1/10, 2/10, and 3/10, mechanical stirring times of 10, 20, and 30 minutes, ultrasonic sonication times of 30, 45, and 60 minutes, and sonification powers of 80, 100, and 120 watts.

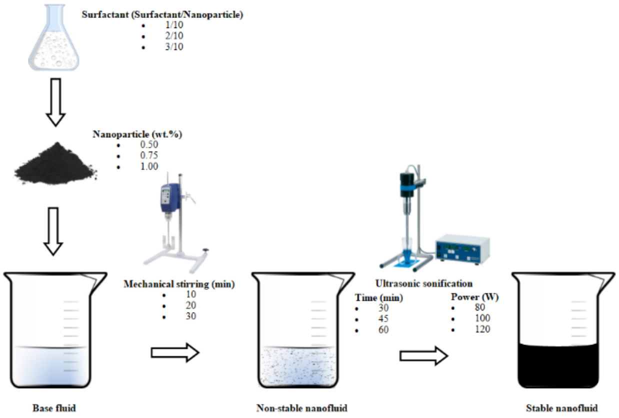

Fig. 1. Schematics of used technique to prepare nanofluid

Fig. 2. Nanofluid preparation and property measurement setup

Table 1 The thermophysical properties of nanoparticles [18].

Properties	GnP	FE_3O_4
Specific heat (J/kgK)	790	104
Density (kg/m3)	2250	5180
Thermal conductivity (W/mK)	3000	17.65
Particle size(nm)	3	12-29
Purity	>99.9%	>99.5%

GnP and Fe_3O_4 nanoparticles, whose thermophysical characteristics are presented in Table 1, are acquired commercially. The hybrid nanofluids composed of GnP-Fe_3O_4/water-ethylene glycol was prepared utilizing the two-step method as given in Fig.1 [19]. Initially, surfactant (SDBS) dissolved in pure water is prepared in three different ratios based on the precision balance nanoparticle weight values (Figure 2. (e)). Using a mechanical stirrer (Fig. 2 (b)), the base fluid is next treated with GnP-Fe_3O_4 nanoparticles and surfactant solutions to generate nanofluids. To create highly stable hybrid nanofluids, a BANDELIN HD3400 ultrasonic sonicator is used, as shown in Fig. 2(f). After all the nanofluid models are prepared, zeta potential analyses, thermal conductivity, and viscosity measurements are conducted.

2.2 Measurement of thermophysical properties of nanofluid

Before evaluating the thermal conductivity and viscosity of the hybrid nanofluid samples, the samples' stability is assessed using the zeta potential analyzer (Zetasier), as shown in Fig. 3(a). One of the most prominent approaches for assessing the stability of nanofluids is zeta potential analysis. When the zeta potential value is in the ±30 mV region, nanofluids are said to precipitate. Nanofluids having a Zeta potential value of ±0-15 mV exhibit low stability, ±15-30 mV moderate stability, ±30-45 mV high stability, and ±45-60 mV very strong stability [20].

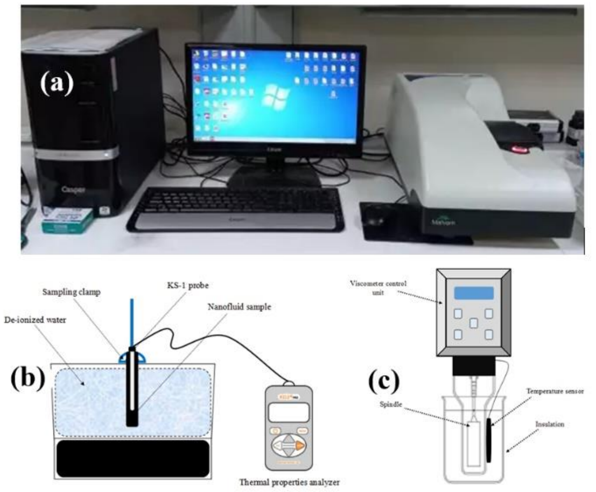

Fig. 3. (a) Zeta potential analyzer, schematics of (b) thermal conductivity and (c) viscosity measurement systems.

Using a thermal conductivity measuring device, the thermal conductivity values of hybrid nanofluid models with various configurations are determined, as shown in Fig. 3(b). The nanofluid sample is heated to the desired temperature using an ultrasonic bath as given in Fig 2(c). The KD2 Pro thermal properties analyser (Fig.2(d)), which measures thermal conductivity, is used in combination with the KS-1 probe. By analysing the mean readings following three repetitions of the measurement, thermal conductivity values are calculated. The dynamic viscosity of hybrid nanofluid samples is measured with a rotational viscometer (Fig. 2(a)). After the calibration of the used spindle that is appropriate for present study viscosity range, a dynamic viscosity measurement set-up is used as given in Fig. 3(c). The nanofluid is spilled into a 100 ml beaker and the measurement is carried out at a rotational speed of 60 rpm under the constant temperature with a measurement accuracy of 1 %. A temperature sensor was used to determine whether the temperature of the nanofluids is at the desired temperature.

2.3 Optimization study parameters and levels

The Taguchi method is an approach to experimental design that is based on analysis of variances (ANOVA) and aims to identify the significant variables influencing experiment variation. The Taguchi technique uses orthogonal arrays for experimental design, which can decrease the quantity of experiments and the amount of work required for each experiment, as well as the time required for each experiment and the signal-to-noise ratios (SNR). Orthogonal arrays are classified according to their factors and levels. One of the most essential aspects of Taguchi analysis is the creation of the orthogonal array type. According to the current research, there are five factors with three levels as given in Table 2. The $L_{27}(3^5)$ type is generated using the Minitab 18.0 software program, as shown in Table 3.

Table 2 Experimental factors and levels

Factors	Levels		
	1	2	3
A-Mechanical stirring(min)	10	20	30
B-Ultrasonic sonication time (min)	30	45	60
C-Ultrasonic sonication power(W)	80	100	120
D-Surfactant fraction(surfactant/nanoparticle)	1/10	2/10	3/10
E-Nanofluid weight fraction(%)	0.5	0.75	1

Table 3 The experimental plan that is created using the $L_{27}(3^5)$ orthogonal array.

Trial	Factors				
	A	B	C	D	E
1	1	1	1	1	1
2	1	1	1	1	2
3	1	1	1	1	3
4	1	2	2	2	1
5	1	2	2	2	2
6	1	2	2	2	3
7	1	3	3	3	1
8	1	3	3	3	2
9	1	3	3	3	3
10	2	1	2	3	1
11	2	1	2	3	2
12	2	1	2	3	3
13	2	2	3	1	1
14	2	2	3	1	2
15	2	2	3	1	3
16	2	3	1	2	1
17	2	3	1	2	2
18	2	3	1	2	3
19	3	1	3	2	1
20	3	1	3	2	2
21	3	1	3	2	3
22	3	2	1	3	1
23	3	2	1	3	2
24	3	2	1	3	3
25	3	3	2	1	1
26	3	3	2	1	2
27	3	3	2	1	3

A performance statistic is used to evaluate the determined characteristics of the objectives (SNR). As opposed to noise, which affects test results but cannot be included in the design of the experiment, signal refers to the actual value in the experiment. Generally speaking, there are three ways to evaluate the SNR: "larger the better," "nominal the better," and "smaller the better"[21,22]. Nanofluids are frequently used in studies aimed at enhancing heat transfer. While they contribute positively to improving heat transfer in thermal systems, they also have an undesired effect of increasing pressure drop. The main approach in this study aims to develop a hybrid fluid model that achieves a relatively higher thermal conductivity, which is a measure of heat transfer capability, while keeping the increase in viscosity, which is the fundamental cause of pressure drop, lower. Therefore, the "larger is better" approach is used in evaluating thermal conductivity, while the "smaller is better" approach is employed in assessing viscosity. The following Eqs. 1 and 2 are employed in this evaluation based on the characteristics.

$$Z_H = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i^2}\right) \tag{1}$$

$$Z_L = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right) \tag{2}$$

The performance of the i^{th} experiment is denoted by Y, while Z is the value of performance statistics, and n represents the number of repetitions of verification experiments.

3. RESULT

3.1 Taguchi analyses

The Taguchi experimental design method enables simultaneous consideration of multiple factors and delivers the best outcome with the fewest experiments. The experimental study data are then transformed into a signal to noise ratio using the Taguchi technique.

According to the experimental plan that given in Table 3., Table 4. lists the measured thermophysical characteristics of the ethylene glycol-water-based GnP-Fe_3O_4 nanofluid and the SNR values of the parameters.

Table 4 The experimental measurement and SNR values for thermal conductivity and viscosity

Trial	Measurement		SNR	
	Thermal conductivity (W/mK)	**Viscosity (kg/ms)**	**Thermal conductivity (W/mK)**	**Viscosity (kg/ms)**
1	0,5122	0,00160	-5,81121	55,9176
2	0,5173	0,00161	-5,72515	55,8635
3	0,5229	0,00163	-5,63163	55,7562
4	0,5150	0,00154	-5,76386	56,2496
5	0,5173	0,00155	-5,72515	56,1934
6	0,5179	0,00156	-5,71508	56,1375
7	0,5113	0,00141	-5,82648	57,0156
8	0,5126	0,00146	-5,80443	56,7129
9	0,5139	0,00148	-5,78243	56,5948
10	0,5004	0,00151	-6,01365	56,4205
11	0,5014	0,00152	-5,99631	56,3631
12	0,5025	0,00154	-5,97728	56,2496
13	0,5291	0,00157	-5,52924	56,0820
14	0,5262	0,00158	-5,57698	56,0269
15	0,5310	0,00159	-5,49811	55,9721
16	0,5110	0,00152	-5,83158	56,3631
17	0,5230	0,00153	-5,62997	56,3062
18	0,5243	0,00155	-5,60840	56,1934
19	0,5038	0,00156	-5,95484	56,1375
20	0,5158	0,00157	-5,75037	56,0820
21	0,5159	0,00158	-5,74869	56,0269
22	0,5029	0,00151	-5,97037	56,4205
23	0,5082	0,00152	-5,87931	56,3631
24	0,5095	0,00153	-5,85712	56,3062
25	0,5343	0,00156	-5,44430	56,1375
26	0,5331	0,00158	-5,46383	56,0269
27	0,5318	0,00160	-5,48503	55,9176

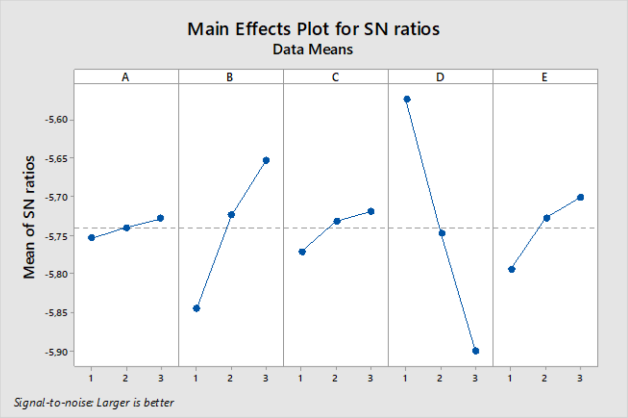

Fig. 4. The mean of SNRs for thermal conductivity.

Fig 4. shows the mean of SNRs for thermal conductivity. The SNR values of mechanical stirring, ultrasonic sonication time and power, and nanofluid weight fraction progress an increment trend with risen level of each parameter. On the contrary, the SNR values tend to decrease with the use of higher fraction of surfactant as in Fig. 4.

Table 5 Average SNR values for thermal conductivity

Factors	**Levels**		
	1	**2**	**3**
A	-5,75	-5,74	**-5,73**
B	-5,85	-5,72	**-5,65**
C	-5,77	-5,73	**-5,72**
D	**-5,57**	-5,75	-5,90
E	-5,79	-5,73	**-5,70**

Mean=-5,74 dB

***Optimum level**

Table 5 summarizes the average SNR values for factors with a variety of levels. The obtained findings indicate that, the highest SNR value of -5.57 dB is confirmed for factor D (surfactant fraction) at the lowest level of 1/10, while the lowest SNR of -5.90 dB is determined for the highest level of 3/10. The highest SNR values for thermal conductivity are obtained with the highest levels of mechanical stirring, ultrasonic sonication time and power, and nanofluid weight fraction. As given in Table 5. the configuration of A3B3C3D1E3 shows the best SNR values or thermal conductivity.

Fig. 5. demonstrates the average SNR distribution versus variety parameters and levels. The acquired data show that the surfactant ratio has the greatest impact on the range of SNR distribution for viscosity; besides, the SNR values tend to rise with ascending of ultrasonic sonication and time, and the surfactant fraction.

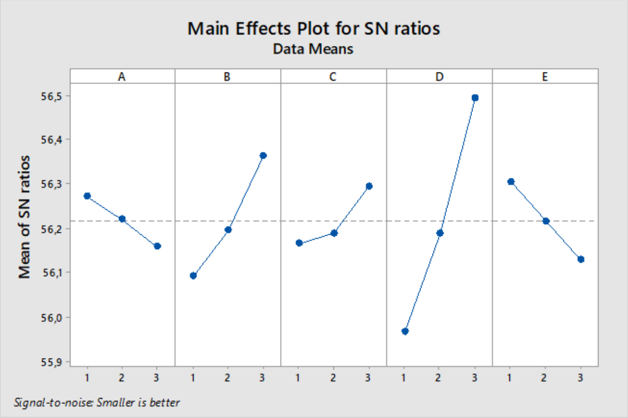

Fig. 5. The mean of SNRs for viscosity.

Table 6 Average SNR values for viscosity

Factors	Levels		
	1	2	3
A	**56,27**	56,22	56,16
B	56,09	56,19	**56,36**
C	56,17	56,19	**56,29**
D	55,97	56,19	**56,49**
E	**56,30**	56,22	56,13

Mean=56,22 dB

***Optimum level**

As can be understood from Table 6, the surfactant fraction is the most effective parameter on viscosity as well as thermal conductivity. While the highest SNR value is obtained at the highest level of this factor, the lowest SNR value is also obtained at the lowest level of the surfactant fraction factor. The highest level of ultrasonic sonication time and power, and surfactant fraction also achieve the highest SNR for viscosity. The optimum configuration for viscosity is determined as A1B3C3D3E1, with an average SNR of 56.22 dB obtained from all factors and levels.

3.2 ANOVA approach

The Taguchi technique is based on the analysis of variance (ANOVA), which is used when comparing two or more independent groups. In the current study, the influence of five independent factors on the thermal conductivity and viscosity of hybrid nanofluid is examined; as a result, an ANOVA is used to calculate the effect rates of the independent parameters.

The results of the ANOVA for the effects of thermal conductivity by the applied variables and levels are shown in Table 7. Accordingly, the contributions are as follows in order of importance: surfactant fraction, ultrasonic sonication time, nanofluid weight fraction, and ultrasonic sonication power and mechanical stirring. Table 7 shows that the surfactant fraction, which has a 63.57% contribution rate, is the most effective parameter.

As shown in Figure 6, ultrasonic sonication time provides the second highest and the nanofluid weight fraction provides the third highest contribution to thermal conductivity with 23.53% and 5.49%, respectively, while mechanical stirring provides the lowest contribution with 0.39%.

Table 7 ANOVA results for thermal conductivity

Factors	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Test
A	2	0,002984	0,39%	0,002984	0,001492	0,51
B	2	0,170625	25,53%	0,170625	0,085312	28,98
C	2	0,01357	1,79%	0,01357	0,006785	2,3
D	2	0,48144	63,57%	0,48144	0,24072	81,76
E	2	0,041585	5,49%	0,041585	0,020793	7,06
Error	16	0,047106	0,02%	0,047106	0,002944	
Total	26	0,757311	100,00%			

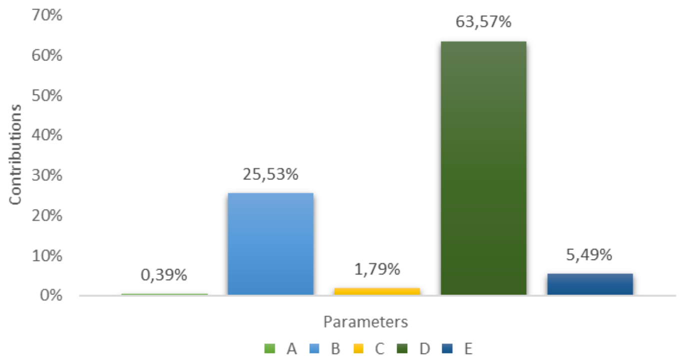

Fig. 6. The contribution rate for thermal conductivity.

Table 8 ANOVA results for viscosity

Factors	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Test
A	2	0,05831	3,02%	0,05831	0,029154	10,03
B	2	0,34005	17,59%	0,34005	0,170025	58,47
C	2	0,08526	4,41%	0,08526	0,04263	14,66
D	2	1,26229	65,31%	1,26229	0,631146	217,06
E	2	0,14041	7,26%	0,14041	0,070204	24,14
Error	16	0,04652	2,41%	0,04652	0,002908	
Total	26	1,93284	100,00%			

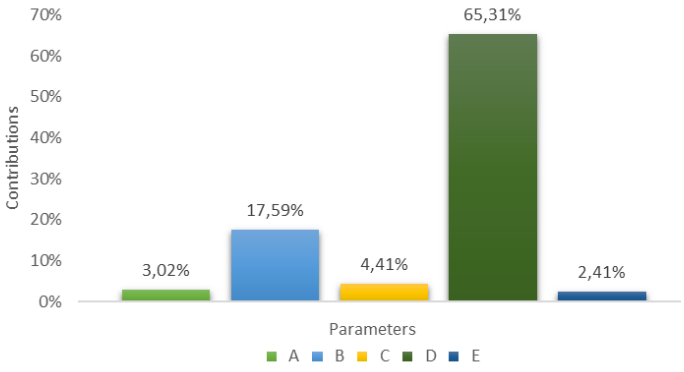

Fig. 7. The contribution rate for viscosity.

As listed in Table 8, the surfactant fraction shows the greatest contribution with 65.31% on viscosity, followed by ultrasonic sonication time at 17.59%, which is similar to the findings for thermal conductivity. The nanofluid weight fraction provides the lowest, followed by mechanical stirring with the second-lowest contribution, and ultrasonic sonication power with the third-lowest contribution order, according to an evaluation of the contribution rates shown in Figure 7.

As evidenced by the findings of the study, the utilization of nanoparticles exhibits a pronounced influence on thermal conductivity while demonstrating a comparatively lesser impact on viscosity. These outcomes are consistent with the research conducted by Wohld et al.[23]. Furthermore, Mane and Hemadri [24] emphasized in their ANOVA results that the CuO+Fe_3O_4 nanofluid contributed the highest enhancement to thermal conductivity, consistent with the findings of this study, highlighting the role of surfactant utilization. Lastly, Karmare et al.[] stated that particle loading is a significant factor influencing both viscosity and thermal conductivity, aligning with the results of our study.

4. CONCLUSION

The effects of varying the mechanical stirring, ultrasonic sonification time and power, surfactant fraction, and nanofluid weight fraction on the thermal conductivity and viscosity of a binary hybrid GnP-Fe_3O_4/ethylene glycol-water nanofluid are taken into account in the current research. The viscosity and thermal conductivity are optimized with a single objective in consideration. The effects of each parameter are also evaluated using ANOVA. The findings are as follows:

- In single-objective optimization, the highest level of factors A, B, C and E produces the highest SNR values for thermal conductivity, while the lowest level of D factor provides the highest SNR value. For viscosity, maximum SNR values are determined at the lowest levels of factors A and E, and at the highest levels of factors B, C and D.
- It is concluded that the optimum experimental variation for thermal conductivity is A3B3C3D1E3, while for viscosity the optimum variation is A1B3C3D3E1.
- For thermal conductivity, the most significant factors are surfactant fraction, ultrasonic sonication time, nanofluid weight fraction, ultrasonic sonication power, and mechanical mixing; for viscosity, the factors are surfactant fraction, ultrasonic sonication time, ultrasonic sonication power, mechanical mixing, and nanofluid weight ratio.
- ANOVA approach determines that the highest contribution for both thermophysical properties is provided by the surfactant fraction, such a result contributes to the fact that it is more possible to determine the thermophysical properties of stable nanofluids.

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