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Using Taguchi experimental design to calculate and analyze thermal conductivity for (polyacrylamide – kaolin) composite

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Abstract

The research is interested in studying the thermal property of the composite material because of its importance in the thermal uses of composite materials. The composite material was prepared with different amounts of kaolin (0, 0.2, 0.5, 0.6, and 0.8 g) in (polyacrylamide -kaolin) composite. Its thermal conductivity and specific heat capacity were studied. Taguchi Array L25(5^2), factors 2, Runs 25, columns 25(5^6) Array 12, was used as an experimental design and 25 samples were prepared using this array. The results improved that the thermal conductivity of the composite material decreases with a high kaolin amount toward temperature increase. Moreover, a case with the composite material's specific heat capacity. The current research describes using Taguchi experimental design to select the optimal factor level from the process to get a maximum thermal conductivity of composite material. The basis for choosing the orthogonal matrix is to take each of the different quantities of kaolin (0,0.2, 0.5, 0.6, and 0.8g) at different temperatures. Taguchi program is applied to the combination of factors and their levels. Besides, the output parameter representing thermal conductivity of (polyacrylamide – kaolin) composite with repetition to the given input parameters using smaller the better. The test results show the factor that influences the amount of kaolin (0.2g), and temperature(70°C). By using the factor and its level, thermal conductivity is (0.428 $w \cdot m^{-1} \cdot °C^{-1}$).

Keywords: Composite material; kaolin; polyacrylamide; Lee's disc method; specific heat capacity; Taguchi method; thermal conductivity.

1. Introduction Clay minerals have been used extensively in the areas of heat therapy or for cosmetic purposes due to their physical, and chemical properties and their suitability for thermal behaviors [Carretero *et al.*, 2013, Fernando *et al.*, 2007]. The addition of nano-filler particles to polymer systems can have a significant effect in improving their mechanical and electrical properties as well as chemical and thermal resistance. These improvements are based on the surface chemistry of polymer, nano filter and dispersion quality of nanofillers because of the strong polymer and clay interactions [Raphael *et al.*, 2018, Josergio *et al.*, 2015]. There are scientific studies that dealt with the thermal properties of composite materials, including the temperature influence on the time period for formation of polyacrylamide graft starch/clay at pH = 8. The test results showed a decrease in the formation time with increasing temperature, while the strength of compound, increased with the temperature. During a chemical reaction, new cross-linking sites are generated with an increased mobility and transfer of molecules between nanocomposite and crosslinking molecules at high temperatures [Rituraj & Vikas, 2017]. The series of (polyacrylamide-Na-montmorillonite) nanocomposites were made using in situ free radical polymerization. The results of X-ray examination showed that the nanocomposites are more thermally stable than pure polyacrylamide [Zafer & Müşerref, 2014]. A nanocomposite of (copper oxide/-polyacrylamide) nanocomposite was prepared as an aqueous drilling liquid additive in different concentrations of ion and improved rheology, filtration, and thermal conductivity. The results show a significant viscosity improvement of the drilling fluid. Moreover, a significantly high thermal conductivity also detected. Thermal conductivity for brine was more than the deionized original drilling fluid [Saboori *et al.*, 2019]. Amount effect of crosslinking bonds on the porosity, thermal, swelling, and crystallinity properties of polyacrylamide (PAAM) creole balls. Also, the manufacture of a series of compounds (COMs) using polyaniline (PAN) increased pore size with the increase in N, *N′*-methylene bisacrylamide MBA, and conductivity values [Mehmet & Sema, 2019]. Morphology effect on behavior of composites of polyacrylamide/cellulose nanocrystals (PAM/CNC) and exact structural, thermal and mechanical properties [Marina *et al.*, 2020]. The colloidal and thermal properties of some kaolin deposits, the results showed suitable viscosity, acceptable pH of the skin, and good thermal properties for therapeutic uses [Ana *et al.*, 2019]. Influence of silver nanoparticles as reinforced additives for polyether ketone matrix on thermal properties. The results showed the specific heat capacity for the compounds decreased with an increase of silver particles content under the electro filtration threshold, while above it the specific heat capacity decreased slower and was close to the specific heat capacity of the compressed silver nanoparticles [Lisa *et al.*, 2016]. Thermal conductivity was studied using Taguchi L9 for experiment design and 9 samples were prepared distilled water-based CuO, Fe3O4, and CuO+Fe_3O_4 nanofluids. The effect of each level on thermal conductivity is analyzed by calculating the Signal to Noise ratio (S/N). The results demonstrate the increased thermal conductivity of the nanofluids [Nikhil & Vadiraj, 2021]. In this search has been used Lee's Disc method, which is a simple and effective way to calculate a material's thermal conductivity with low thermal conductivity. Calculating thermal conductivity and the specific heat capacity of (polyacrylamide - kaolin) composite by adopting a change in the amount of kaolin present in the compound material.

2. Materials and preparation method

2.1 Material sources and preparation method

White powder from polyacrylamide is supplied from (Interchimiques SA France), mineral clay (kaolin), and deionized water. Jaw crusher model (BB200), planetary ball mill model (PM200), sensitive balance (Kern) model (ACB 120-4), hot plate stirrer supplied from Daihan Labtech Co.Ltd., sieving device, Lee's disc supplied from (Griffin & George/ England), many of thermometers. The hand molding method was used to prepare the composite material casting. Kaolin stone was crushed into stones of various granular sizes by a Jaw crusher followed by the grinding process using a ball mill to obtain kaolin powder with finer granular size. Magnetic stirrer (600 rpm) at (60 ± 2°C) was used to mix variable amounts of kaolin (0, 0.2, 0.5, 0,.6, and 0.8 g) with polyacrylamide in the presence of deionized distilled water to obtain a dense homogeneous solution. Then put it in a hand mold and let it dry (24 hours). Then the resulting composite was cured at (70°C). The casting cut the composite material into several samples in form of discs with dimensions to f Lee's disc (diameter 40 mm and thickness 2 mm). Using Lee's disc device, the thermal conductivity was calculated, where the heat is transmitted from the heater to the brass disc followed by the bad conductor sample disc S that is placed over, a metallic disc M. Heating is chambered on the metallic disc, and thermometers are placed inside the disks to read the temperatures of discs that complete contact so that the heat transferred between them does not leak. At a steady state is reached (T_1 and T_2), the different temperatures between the two ends of bad conductor are (T_1- T_2). To calculate the thermal conductivity, the following equation could be applied [Paul & Layi, 2014]:

$$K = \frac{mcd\left(\frac{dT}{dt}\right)T2}{A(T1-T2)} \tag{1}$$

Where, K: thermal conductivity (w· m^{-1}· °C-1), T_1, T_2: temperatures of metallic disc M and brass disc B respectively (°C), d: specimen thickness (mm), A: the specimen cross-sectional area (mm^2), m: mass of the disc (g), c: disc heat capacity (J· Kg^{-1}·$°C^{-1}$), $\left(\frac{dT}{dt}\right)$: rate of cooling at T_2 (°C· sec^{-1}).

While the specific heat capacity of the (polyacrylamide - kaolin) composite at various amounts of kaolin was calculated from equation [Lisa *et al.*, 2016]:

$$Cp\,(w) = w\, Cp_{(clay)} + (1- w)\, Cp_{(polymer)} \tag{2}$$

Where, Cp (w): is specific heat capacity for a composite material at various amounts of kaolin (J·Kg^{-1}· $°C^{-1}$), w: the amount of clay (g), $Cp_{(clay)}$: kaolin specific heat capacity, $Cp_{(polymer)}$: polyacrylamide specific heat capacity.

2.2 Taguchi's experimental design (DOE)

Initially, determining the thermal conductivity characteristic of composite material is optimized. Taguchi experimental design is a statistical method used in many purposes such as independent response estimation of response by a minimum number of experiments, and the increasing rise of product quality. This method consists of many steps: determine control factors and the level from these factors by choosing a suitable orthogonal matrix, selecting control factors and putting them in an orthogonal matrix, confirming experiment conduct, and quality rising according to optimal level factor [Mohammad *et al.*, 2015, Piyush *et al.*, 2018, E Ginting & M Tambunan, 2018].

2.2.1 Signal- to- noise ratio of Taguchi experimental design

Table 1, lists the control factor measurements, through which the variance of the product is reduced by effects that reduce noise parameters, while control factors and design could be controlled but the noise factors could not be controlled. Maximum values of the determining control factor settings that decreased noise factors effects, the equation is stated used in this research as follows:

$$S/N = -1 \log \frac{1}{n} \sum Y^2 \quad (3)$$

Where n is the number of tests and Y is the response factor [Mohammad *et al.*, 2015, Piyush *et al.*, 2018].

Table1. Signal-to-noise ratio [Piyush *et al.*, 2018].

Signal-to-noise ratio	Goal of the experiment	Data characteristics
Larger is better	Maximize the response	Positive
Nominal is best	Target the response and you want to base the signal-to-noise ratios on standard deviations only	Positive, zero, or negative
Nominal is best (default)	Target the response and you want to base the signal-to-noise ratios on means and standard deviations	Non-negative with an absolute zero in which the standard deviation is zero when the mean is zero
Smaller is better	Minimize the response	Non-negative with a target value of zero

3. Results and discussion

3.1 Thermal conductivity test

Results obtained from the disc test for specific heat capacity and thermal conductivity for the composite material will be shown in figures (1,2, and 3):

Figure (1) shows that thermal conductivity for polymeric compound in a specific amount of the reinforced additive (kaolin) increases with increasing temperatures, even though it is reinforced with a thermally insulating material compared to the polymer alone. Due to the difference in chemical composition between them, and the rate of heat flux passing through them. In the case of adding variable amounts of kaolin to the polyacrylamide, we notice a decrease in thermal conductivity value of the compound material with an increase in the amount of clay for the same temperature. The combination that equals to (0.5, 0.6g) is considered the most stable, as the increase in thermal conductivity is directly proportional to the increase in temperature. Therefore, the amount of kaolin is considered a factor affecting the thermal conductivity of the composite materials.

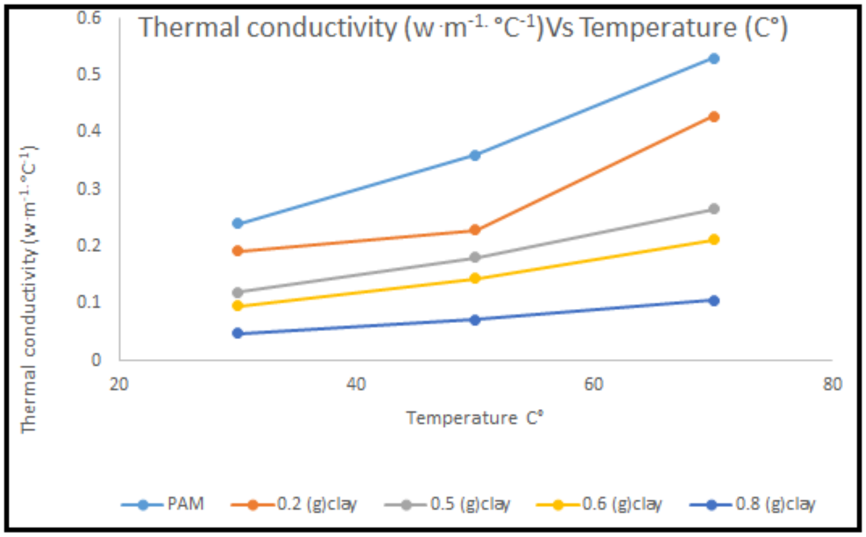

Fig. 1. Thermal conductivity (w·m$^{-1.}$ °C^{-1}) vs temperature (°C) to the composite material at various amounts of kaolin

Figure (2) shows the thermal conductivity of (polyacrylamide -kaolin) composite as a function of temperature, and the amount of kaolin added. An obvious fluctuation between temperature and clay concentration. On the contrary, the thermal conductivity value increases with the increase in temperature and then begins to decrease with increase in proportion of clay with the compound material until it is approximately be stabilized.

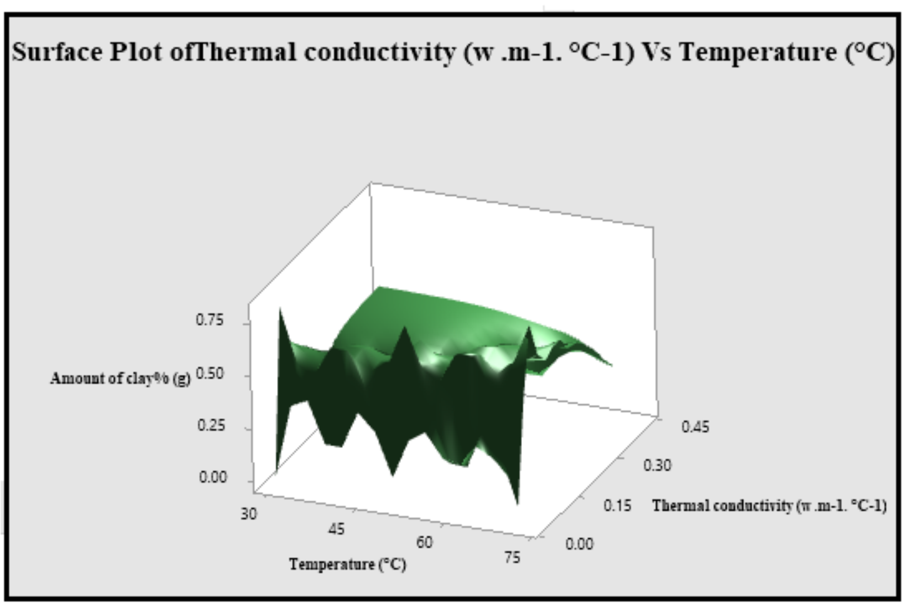

Fig. 2. Surface plot of thermal conductivity (w·m$^{-1.}$ °C^{-1}) vs amount to the clay (g), temperature (°C) of composite material

Figure (3) shows the thermal conductivity affected by a specific heat capacity, both polymer, and composite. The specific heat capacity increases with an increase in the amount of kaolin due to the vibration of the clay particles, which increases with the increase in temperature.

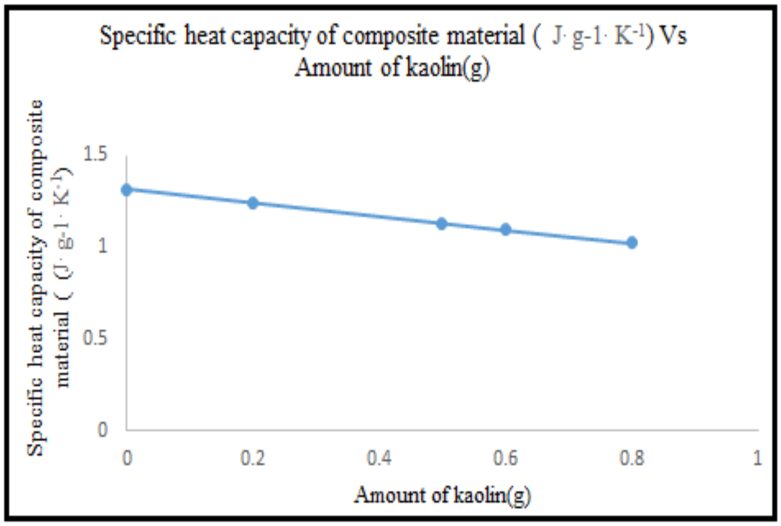

Fig. 3. Specific heat capacity of composite material (J· g-1· K^{-1}) vs amount of the kaolin(g)

3.2 Taguchi's experimental design (DOE)

Figure (4), shows the main effects plot for the SN ratio. The value of thermal conductivity was less than the mean value at 0% clay. Then, it increased above the mean value at 0.2% clay, thermal conductivity reaches the maximum value. Later, it decreased at (0.5, and 0.6) % clay above the mean line, while at 0.8% clay thermal conductivity decreases under the mean line. Another plot shows the temperature factor effect on the thermal conductivity parameters. The X-axis appears as the estimation of temperature and y-axis gives the response value to decide the optimum design conditions.

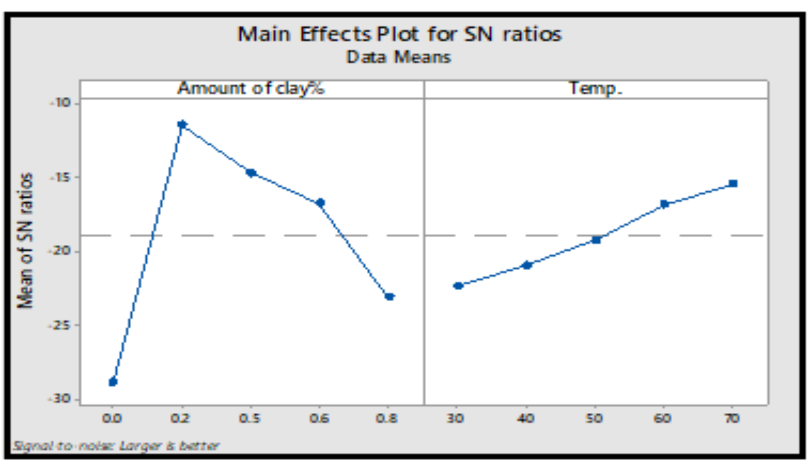

Fig. 4. Main effects plot for S/N ratio

Table 2 is found by MINITAB software. S/N represents the output parameter representing thermal conductivity with repetition to the given input parameters using smaller the better [Piyush Pant *et al.*, 2018].

Table 2. Signal-to-noise ratio (S/N)

No. of experimental	Amount of clay%	Temp. °C	Thermal conductivity (w. m^{-1}. $°C^{-1}$)	SNRA1
1	0.0	30	0.024	-32.3958
2	0.2	30	0.192	-14.3340
3	0.5	30	0.120	-18.4164
4	0.6	30	0.096	-20.3546
5	0.8	30	0.048	-26.3752
6	0.0	40	0.027	-31.3727
7	0.2	40	0.211	-13.5144
8	0.5	40	0.159	-15.9721
9	0.6	40	0.123	-18.2019
10	0.8	40	0.051	-25.8486
11	0.0	50	0.036	-28.8739
12	0.2	50	0.228	-12.8413
13	0.5	50	0.180	-14.8945
14	0.6	50	0.144	-16.8328
15	0.8	50	0.072	-22.8534
16	0.0	60	0.048	-26.3752
17	0.2	60	0.341	-9.3449
18	0.5	60	0.233	-12.6529
19	0.6	60	0.178	-14.9916
20	0.8	60	0.089	-21.0122
21	0.0	70	0.053	-25.5145
22	0.2	70	0.428	-7.3711
23	0.5	70	0.265	-11.5351
24	0.6	70	0.212	-13.4733
25	0.8	70	0.106	-19.4939

4. Conclusion

The research is concerned with studying the thermal conductivity, and specific heat capacity at different temperature degrees for (polyacrylamide -kaolin) composite. Composite material has been prepared at different amounts of kaolin (0, 0.2, 0.5, 0.6, and 0.8 g). The results showed a noticeable improvement in the thermal conductivity of the composites than in the polymer. It decreases with the increase of kaolin, with the highest value of thermal conductivity at (0.2g) kaolin. A direct relationship between the specific heat capacity and the amount of clay. The optimum results were determined based on Signal to Noise Ratio, S/N can be registered by the Taguchi experimental design at (0.2g, and 70 °C) depending on the response to noise factors and signal factors. The above results are similar to the results obtained in previous studies [Lisa *et al.*, 2016, Nikhil & Vadiraj, 2021].

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