Jestr

Journal of Engineering Science and Technology Review 15 (SI) (2022) 35 - 40
Special Issue in honor of Prof. T. Tanaka

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Research Article

Mathematical Modelling on Thermal Conductivity of Silicone Rubber Micro Nanocomposites by including Agglomeration Effect

Pabbati Vinod[1,*], Myneni Sukesh Babu[1], M.G. Danikas[2], Stefan Kornhuber[3] and R. Sarathi[1]

[1]*Department of Electrical Engineering, IIT Madras, Chennai, 600 036, India*
[2]*Department of Electrical & Computer Engineering, Democritus University of Thrace, Xanthi, Greece*
[3]*Department for High Voltage Engineering, University of Applied Sciences, Zittau/Görlitz, Zittau, Germany.*

Received 30 December 2021; Accepted 10 March 2022

Abstract

Silicone rubber (SR) micro nanocomposites are prepared by reinforcing the base SR insulating material with two different fillers (micro ATH and nano-alumina), in order to improve the electrical, thermal, and mechanical characteristics of SR material. Micro ATH fillers are cost-effective and enhance the resistance towards electrical discharges, whereas the inclusion of nano-alumina fillers improve the thermal conductivity of the composite material. To evaluate the thermal conductivity of polymer composites theoretically, a number of mathematical models have been developed. The thermal conductivity of polymer composites with hybrid fillers can be determined theoretically using Agrawal's model. The present research focuses on determining the effective thermal conductivity of silicone rubber micro nanocomposites while taking into account important factors such as the hybrid fillers with unequal sizes and also considering the agglomeration concept. The volume fraction of aggregated nano-alumina fillers is noticed to increase significantly with increment in the weight percentage of nano-alumina fillers. In comparison to Agrawal's model, the modified thermal conductivity model mentioned in the current research work has provided lesser error with respect to experimental data.

Keywords: agglomerations, alumina, ATH, silicone rubber, thermal conductivity

1 Introduction

Silicone rubber insulators are gaining more attention in power system, as outdoor high voltage insulators because of their superior properties such as lighter weight, better surface hydrophobicity, higher vandal resistance over traditional glass, ceramic and porcelain insulators [1]. The concept of introducing fillers of various sizes, shapes, and concentrations into polymeric materials has the potential to improve electrical, mechanical and thermal properties of insulator substantially [2]. Nanofillers are more effective than micro fillers because they require significantly lesser weight percentages compared to micro fillers, to attain enhanced properties. It is because of the high surface area to volume ratio of nano fillers when compared to micro fillers [3].

The use of nano-alumina fillers in polymer composites is becoming more popular for enhancing properties such as surface tracking resistance, dielectric properties, contamination resistance and thermal degradation resistance. The incorporation of alumina nanoparticles into silicone rubber composites has improved the thermal conductivity of the composite, according to Zha et al [4]. When nano-alumina fillers were added to silicone rubber insulators, Fairus et al. have observed an increase in surface tracking resistance as well as thermal conductivity [5]. Inclusion of micro ATH fillers into SR material can greatly reduce the eroded moss of insulators when subjected to electrical discharges. Ghunem et al. have noticed that the presence of micro ATH particles in silicone rubber composites enhanced the resistance to dry band arcing and reduced the erosion caused by electrical discharges [6]. According to Mayer et al, addition of ATH fillers to silicone rubber insulators have improved the thermal conductivity as well as surface erosion resistance [7].

The addition of hybrid fillers into a polymer composite can considerably improve the desired properties of the insulating material. Tariq et al have observed that the addition of hybrid fillers such as micro ATH and nano-alumina fillers to silicone rubber composites, has increased the surface resistance towards corona discharges [8]. According to recent research, adding micro ATH and nano-alumina to silicone rubber composites has exhibited improved resistance towards salt fog ageing [9].

Thermal conductivity is one of the important factors in case of polymeric insulators. When the insulators are exposed to electrical discharges, localised temperature rise tends to develop, resulting in the thermal degradation or thermally influenced chemical changes in the polymeric insulator, reducing the lifespan of the insulator [10]. Hence, in the present study, nano-alumina and micro ATH fillers, which has high thermal conductivity were chosen to be included into the base SR material, in order to improve the thermal conductivity of the polymeric composite insulating material.

The thermal conductivity of a polymeric material is drastically altered when fillers are added. The addition of micro and nanoscale boron nitride to silicone rubber have improved the effective thermal conductivity of the composite material [11]. Sanada et al. have observed that the thermal conductivity of the composite is greatly improved by the multi-walled carbon nanotube (MWCNT), where the MWCNT filler has a higher thermal conductivity value and

*E-mail address: rsarathi@iitm.ac.in

doi:10.25103/jestr.147.06

builds effective continuous pathways, resulting in higher thermal conductivity of the composite [12]. Hence, it is preferable to commence primary research with a theoretical analysis of the thermal conductivity of polymeric composites.

Many theoretical studies on estimating the thermal conductivity of polymeric composites have been developed. Ngo et al. have developed a model for predicting the thermal conductivity of polymer composites that included thermal contact resistance (TCR) [13]. Gao et al observed the variation in the thermal conductivity of polymer composite with respect to various sizes of alumina filler loading [14]. Most of the thermal conductivity models for hybrid filler-added polymer composites tends to deal with the fillers of high thermal conductivity [15-17]. Using finite element analysis, Based on the effective medium approximation (EMA) model, Jiang et al calculated the effective thermal conductivity of polymer composites. The EMA considers the effect of filler structure, aspect ratio, alignment, and interfacial thermal resistance on composite thermal conductivity [11]. Sanada et al. have estimated the thermal conductivity of polymer composites. They have indicated that the addition of micro and nano-alumina fillers have improved the thermal conductivity of the composite [12].

For polymeric composites with hybrid fillers, Agrawal et al. have developed a series heat flow based thermal conductivity model, which provides improved accuracy with less error. However, they have considered the following assumptions: two distinct fillers of approximately equal size, negligible thermal contact resistance, and uniform particle dispersion [18]. Hence, in the present study, an attempt has been made to modify the Agrawal's model, where the following aspects are taken into account for the determination of thermal conductivity of silicone rubber composites theoretically; two distinct filler with unequal sizes (micro ATH and nano-alumina fillers) are chosen and the concept of agglomeration is incorporated.

2 Experimental details

2.1 Sample preparation

Preparing silicone rubber composites is a straightforward two-step process. For effective curing, Part-A is a base silicone rubber (RTV8112, Momentive, USA) and Part-B is a hardener (RTV9858), which are added in a 10:1 ratio. The pure silicone rubber sample is made by combining the required amount of base rubber and hardener in the 10:1 ratio. To ensure proper mixing of the solution, which is allows for 5 minutes of mechanical shear mixing. To eliminate air bubbles from the composition, this mixer is degasified for 15 minutes before being poured into a steel mould. In compression molding, the mould is subjected to a high pressure of 200 kPa for 24 hours at room temperature.

The following steps are used to make silicone rubber micro-nanocomposites: To eliminate moisture from the fillers, micro ATH (10 µm, Astrra chemicals, India) and nano-alumina, Al_2O_3 (100 nm, Hongwu Nanometer, China) fillers are dried in an oven at a constant temperature of 150 ˚C. For uniform particle dispersion, the required weight percentage of micro and nano fillers is added to 100 ml of solvent (ethanol). This solution is subjected to 30 minutes of mechanical shear mixing and 30 minutes of ultrasonication in a pulsed mode of 9 s ON and 9 s OFF. The required amount of Part-A is then added to this solution and mechanical shear mixing is allowed for 30 minutes for better mixing. To eliminate the solvent, this solution is heated in an oven at a constant temperature of 100 ˚C. Upon confirmation of complete solvent evaporation from the solution, Part-B, is added in a 10:1 ratio. The mixer is allowed for mechanical shear mixing for 5 minutes and degasification for 15 minutes. At the last step mixer is poured into steel moulds, which are then compressed under 200 kPa high pressure at room temperature. The samples are used for experimental tests once they have been cured for 24 hours. The silicone rubber composites used in the present study are shown in Tab 1.

Table 1. Silicone rubber test samples composition

Base SR (wt.%)	Micro ATH (wt.%)	Nano Alumina (wt.%)	Identification
100	0	0	S0
60	40	0	S1
59	40	1	S2
57.5	40	2.5	S3
55	40	5	S4

2.2 Thermal conductivity

The thermal conductivity of silicone rubber composites is measured using a hot disc thermal conductivity analyser TPS-500. The test specimen with dimensions of 40 mm × 40 mm × 2.2 mm have been used in the current work and the probing depth for the experiment is maintained at 1.15 mm. The thermal conductivity of the pure silicone rubber sample, micro ATH and nano-alumina fillers are 0.26 W/mK, 21 W/mK and 29 W/mK respectively.

3 Thermal conductivity modelling

The dispersion of micro and nano fillers in to the silicone rubber composite is pictorially represented in Fig 1. Despite of the use of a variety of techniques to disperse the fillers uniformly into the polymer matrix, aggregation of fillers is unavoidable. The insulating material performance tend to weaken considerably by these agglomerations [19]. Agrawal et al. proposed a mathematical model for the calculation of thermal conductivity of hybrid filler-dispersed polymer composites, based on the assumptions that two different types of fillers with almost the same diameter are dispersed uniformly without agglomerations [18]. Two fillers of distinct sizes i.e. micro ATH and nano-alumina fillers, along with agglomeration of nanoparticles are considered in this work for the mathematical modelling of the thermal conductivity of silicone rubber composite material. As the nano fillers tend to agglomerate more easily than micro fillers due to their high surface free energy, only the agglomeration of nano-alumina fillers is considered in the present research [20].

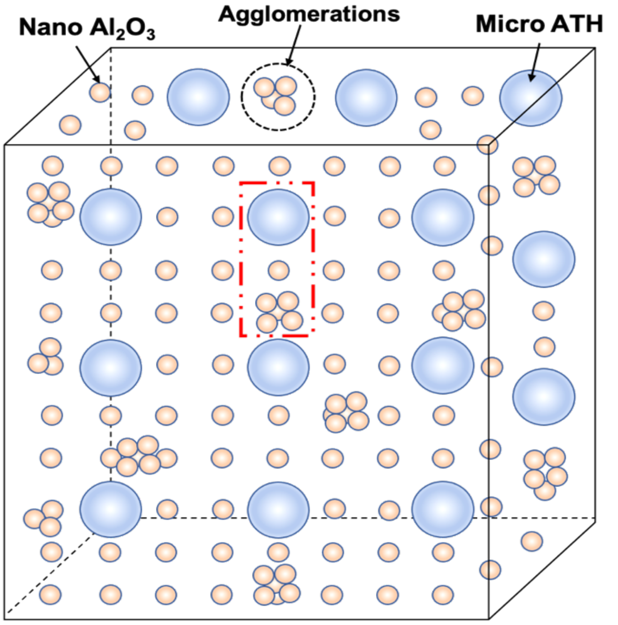

Fig. 1. Silicone rubber composite structure with fillers.

A single micro particle, a single nano particle, and a set of aggregated nanoparticles are considered as a single element for the heat transfer mechanism in the polymer composite structure (as shown in Fig 1), to approximate the mathematical analysis of thermal conductivity with the assumptions that the interface thermal resistance between filler and matrix is negligible, the composite is free of voids, the agglomeration of micro fillers are negligible, and the temperature profile is linear along the direction of heat flow.

Fig. 2 shows the series model of heat transfer in case of single element of the polymer composite structure. When the heat transfer is considered as only one mode of distribution, the equivalent thermal conductivity of a single element of the polymer composite is proportional to the total thermal resistance of the composite according to the law of minimal thermal resistance and equal law of the specific equivalent thermal conductivity [18]. Then the estimated equivalent thermal conductivity of the single element of composite is strongly approximated to the total equivalent thermal conductivity of the polymer composite.

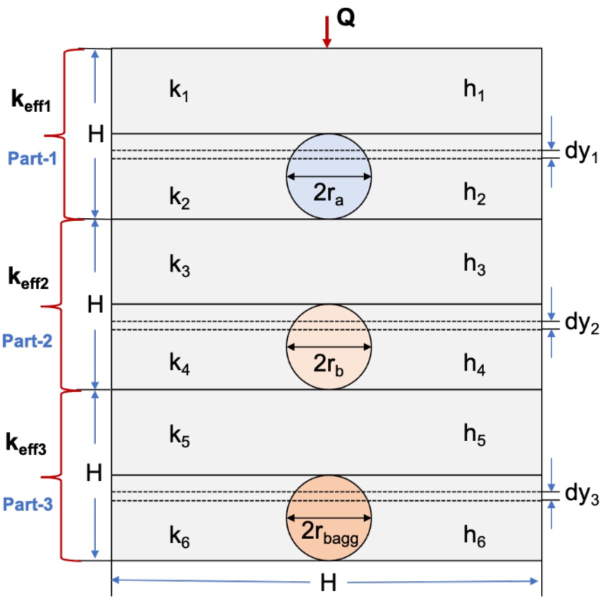

Fig. 2. Single element series model of heat transfer in polymer composite.

As shown in Fig 2, the heat flow is considered to be in the direction of top to bottom. The single element of the composite structure has the dimensions of 3H × H ×H with three single particles. It is assumed that the aggregated alumina nanoparticles are in spherical shape. Then, the micro ATH, nano-alumina and agglomeration of nano-alumina particles are assumed to have the diameter of $2r_a$, $2r_b$ and $2r_{bagg}$ respectively. In the present study, the diameter of each filler type is not equal i.e., $2r_a \neq 2r_b \neq 2r_{bagg}$.

The single element of polymer composite is divided into three parts, of which each individual part is divided into two sub-parts, which has the pure polymer part and a part with the combination of polymer and filler. Thickness of the each of the three parts is H with the effective thermal conductivity of k_{eff1}, k_{eff2}, and k_{eff3} respectively. For the parts 1, 2 and 3, the mean thermal conductivity coefficients of the polymer matrix sub-part are k_1, k_2 and k_3 and sub-part with the combination of polymer with the micro, nano and aggregated nano filler is k_2, k_4 and k_6 respectively. The thickness of sub-parts with the combination of polymer with micro, nano and aggregated nano filler are h_1=H-$2r_a$, h_3=H-$2r_b$ and h_5=H-$2r_{bagg}$ respectively, where the thickness of sub-parts with only polymer matrix are h_2=$2r_a$, h_4=$2r_b$ and h_6=$2r_{bagg}$ respectively.

3.1 Volume fraction of fillers in polymer composites

$$\phi_a = \frac{V_a}{V_c}, \quad \phi_b = \frac{V_b}{V_c} \ and \ \phi_{bagg} = \frac{V_{bagg}}{V_c} \tag{1}$$

Where, ϕ_a, ϕ_b and ϕ_{bagg} are volume fractions of micro ATH filler, nano-alumina filler and aggregated nano-alumina fillers respectively. V_a, V_b, V_{bagg} and V_c are volume of micro filler, nano filler, aggregated nano fillers and composite respectively. We know that the spherical filler volume is $\frac{4\pi r^3}{3}$, where r is radius of the filler and volume of single element of composite structure in the present study is $3H^3$, where H is side length of each part.

3.2 Mean thermal conductivity

From the Fig. 2, the mean thermal conductivity of the only polymer sub-part is same as the thermal conductivity of the polymer in each part.

$$k_1 = k_3 = k_5 = \int_{h_1} k_p \frac{dy}{h_1} = k_p \tag{2}$$

Where, k_p is thermal conductivity of polymer.

A thin layer of thickness (dy) is taken into account when estimating the approximate thermal conductivity, and the Fourier's law of heat conduction is applied. Then, the mean thermal conductivities k_2, k_4 and k_6 can be evaluated as,

$$k_2 = \frac{Q_p + Q_a}{\left(\frac{dT}{dy}\right)S} = \frac{k_p S_p}{S} + \frac{k_a S_a}{S} \tag{3}$$

Similarly, $k_4 = \frac{k_p S_p}{S} + \frac{k_b S_b}{S}$ and

$$k_6 = \frac{k_p S_p}{S} + \frac{k_{bagg} S_{bagg}}{S} \tag{4}$$

Where, k_a , k_b and k_{bagg} are thermal conductivity of micro filler, nano filler and aggregated nano fillers respectively. Q_p and Q_a are heat quantity flow through the cross sectional area of the only polymer and micro filler respectively. S, S_p, S_a, S_b and S_{bagg} are cross-sectional area of single element composite, only polymer, micro filler, nano filler and aggregated nano filler respectively in the direction of heat flow.

Integrating the Eq. (3) with respect to thickness,

$$k_2 = \int_{h_2} \frac{1}{h_2}\left(\frac{k_p S_p}{S} + \frac{k_a S_a}{S}\right) dy_1 = \frac{1}{h_2 S}\left(k_p V_p + k_a V_a\right) \quad (5)$$

Where, V_p is volume of polymer. Similarly, k_4 and k_6 are also integrated with respective thickness terms,

$$k_4 = \frac{1}{h_4 S}\left(k_p V_p + k_b V_b\right) \text{ and }$$
$$k_6 = \frac{1}{h_6 S}\left(k_p V_p + k_{bagg} V_{bagg}\right) \quad (6)$$

The thermal resistance of each part is,

$$R_1 = \frac{h_1}{k_p S}, R_3 = \frac{h_3}{k_p S} \text{ and } R_5 = \frac{h_5}{k_p S} \quad (7)$$

$$R_2 = \frac{h_2}{k_2 S} = \frac{h_2^2}{k_p V_p + k_a V_a},$$
$$R_4 = \frac{h_4^2}{k_p V_p + k_b V_b} \text{ and }$$
$$R_6 = \frac{h_6^2}{k_p V_p + k_{bagg} V_{bagg}} \quad (8)$$

The effective thermal conductivity of each part is evaluated based on the thermal resistance of the sub-part, it means that the thermal resistance of only polymer sub-part and thermal resistance of the sub-part with combination of polymer and filler. The thermal resistance of each part is shown in Eq. (7) and (8).

$$k_{eff1} = \frac{H}{RS} = \frac{H}{(R_1 + R_2)S} \quad (9)$$

By substituting R_1, R_2 terms, h_1, h_2 and H in Eq. (9), k_{eff1} can be written as,

$$k_{eff1} = \frac{1}{\left[\frac{1}{k_p} - \frac{1}{k_p}\left(\frac{18\phi_a}{\pi}\right)^{\frac{1}{3}} + X\right]} \quad (10)$$

Where X can be represented as follows,

$$X = \frac{4 r_a \cdot H^2}{\left(\frac{4\pi}{9\phi_a}\right)^{\frac{1}{3}}\left(k_p V_p + k_a V_a\right)} \quad (11)$$

If the composite is free from voids, the total volume of the composite,

$$V_c = V_p + V_a + V_b + V_{bagg} \quad (12)$$

$$V_p = V_{sa} - V_a \quad (13)$$

Where V_{sa} is,

$$V_{sa} = \frac{4\pi}{3}\left(\frac{r_a^3}{\phi_a} - r_b^3 - r_{bagg}^3\right)$$

By substituting H and Eq. (13) in Eq. (11),

$$X = \frac{4 r_a^3 \cdot \left(\frac{4\pi}{9\phi_a}\right)^{\frac{1}{3}}}{\left(k_p\left(\frac{4\pi}{3}\left(\frac{r_a^3}{\phi_a} - r_b^3 - r_{bagg}^3\right)\right) + \frac{4\pi r_a^3}{3}(k_a - k_p)\right)} \quad (14)$$

The complete expression for k_{eff1} is,

$$k_{eff1} = \frac{1}{\left[\frac{1}{k_p} - \frac{1}{k_p}\left(\frac{18\phi_a}{\pi}\right)^{\frac{1}{3}} + X\right]} \quad (15)$$

Where,

$$X = \left[\frac{\pi}{3}\left(\frac{9\phi_a}{4\pi}\right)^{\frac{1}{3}}\left\{k_p\left(\frac{1}{\phi_a} - \left(\frac{r_b}{r_a}\right)^3 - \left(\frac{r_{bagg}}{r_a}\right)^3\right) + (k_a - k_p)\right\}\right]^{-1} \quad (16)$$

The effective thermal conductivity of the silicone rubber material is evaluated based on the series heat flow model in the composite, where three parts are taken into account, which are k_{eff1} represents the effective thermal conductivity of Part-1 (only polymer and combination of polymer and micro ATH filler), k_{eff2} represents the effective thermal conductivity of Part-2 (only polymer and combination of polymer and nano-alumina filler) and k_{eff3} represents the effective thermal conductivity of Part-3 (only polymer and combination of polymer and aggregated nano-alumina filler).

$$k_{eff} = 3 \times \left[\frac{1}{k_{eff1}} + \frac{1}{k_{eff2}} + \frac{1}{k_{eff3}}\right]^{-1} \quad (17)$$

Similarly, the remaining terms k_{eff2} and k_{eff3} are derived by introducing the respective thermal resistance terms. Then by substituting the terms k_{eff1}, k_{eff2} and k_{eff3} in Eq. (17), the effective thermal conductivity of polymer composite is,

$$k_{eff} = 3 \times \left[\left\{\frac{1}{k_p} - \frac{1}{k_p}\left(\frac{18\phi_a}{\pi}\right)^{\frac{1}{3}} + X\right\} + \left\{\frac{1}{k_p} - \frac{1}{k_p}\left(\frac{18\phi_b}{\pi}\right)^{\frac{1}{3}} + Y\right\} + \left\{\frac{1}{k_p} - \frac{1}{k_p}\left(\frac{18\phi_{bagg}}{\pi}\right)^{\frac{1}{3}} + Z\right\}\right]^{-1} \quad (18)$$

Where, X is represented in Eq. (16). If the term ϕ_a in the Eq. (16) is replaced by ϕ_b the Eq. corresponding to X changes to Y. Similarly, ϕ_{bagg} is replaced in place of ϕ_a in the Eq. (16), the Eq. corresponding to X changes to Z. The volume fraction of aggregated nanoparticles (ϕ_{bagg}) can be calculated by the Eq. (19) [21].

$$\phi_{bagg} = \left(\frac{D_p}{D_{agg}}\right)^{\frac{1}{3}} \phi_b \tag{19}$$

Where, D_p is diameter of single filler, D_{agg} is diameter of aggregated fillers and ϕ_b is volume fraction of fillers.

4 Results and Discussion

In recent literature, various mathematical models for estimating the thermal conductivity of polymer composites have been developed. The theoretical calculation of thermal conductivity of polymer composites when reinforced with hybrid fillers is a complex analysis, where researchers have developed mathematical models with acceptable error between experimental and theoretical models [15-17]. Ngo et al. have presented a model for predicting the effective thermal conductivity of polymer composites with heterogeneous fillers [22]. When the thermal conductivity of two fillers differs, the effective thermal conductivity of a polymer composite is highly dependent on the volume fraction ratio of the fillers. However, when the thermal conductivity of two different fillers is equal ($k_1 = k_2$) the effective thermal conductivity of the composite is insensitive to the volume fraction ratio, and it functions as a single filler. When the volume fraction of fillers is not equal ($\phi_1 \neq \phi_2$), the effective thermal conductivity curves tend to be asymmetric. When the volume fraction of fillers is equal ($\phi_1 = \phi_2$), the effective thermal conductivity curves are symmetric with regard to changes in filler thermal conductivity ratio.

Agrawal et al. proposed a model to predict the thermal conductivity of polymer composites incorporating hybrid fillers, with has highest accuracy [18]. However, the limitations of this model are the diameter of two filler is approximately equal and agglomeration of the fillers is neglected. In the process of adding nanofillers to the polymer matrix, agglomeration of fillers cannot be avoided. This formation of agglomerations drastically alters the characteristics of the polymer insulator [19].

In this study, the agglomeration of nano fillers is taken into account while calculating thermal conductivity. From the Eq. (19), the volume fraction of aggregated fillers is calculated. Fig. 3 shows the volume fraction of nano fillers in silicone rubber composite. In the present study, micro ATH and nano-alumina fillers are added to the silicone rubber polymer composite. In comparison to the micro fillers, nano fillers are more likely to form agglomerations than micro fillers, because the higher surface free energy of nano fillers [20]. When the concentration of nano fillers is increased, the volume fraction increases. When the weight percentage of nano filler-loading in the silicone rubber composite is increased, the volume fraction of aggregated nano fillers is noticed to increase (Fig. 3). Hence, it is essential to consider the effect of agglomeration in case of polymer composites.

Based on series heat flow in composite, Agrawal's thermal conductivity model is calculated. This model is ideally suited for hybrid fillers loaded in polymer composites, where the model makes some assumptions, such as that thermal contact resistance is minimized, the composite contains evenly dispersed fillers, and the composite is void-free. The experimental values, theoretical values calculated from Agrawal’s model and the theoretical values obtained from the present model, are depicted in Fig. 4. The Agrawal model was developed using hybrid fillers in polymer composites with filler diameters that were almost identical and by ignoring agglomerations. As a result, when compared to experimental data, there is a larger error compared to the theoretical values obtained from the present model.

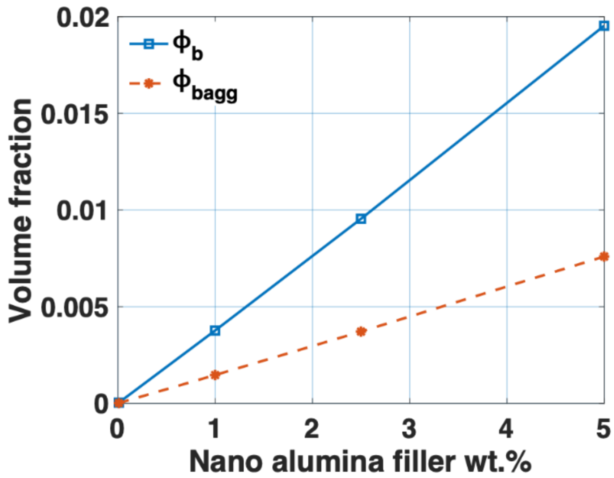

Fig. 3. Variation in volume fraction of nano-alumina fillers in silicone rubber composite.

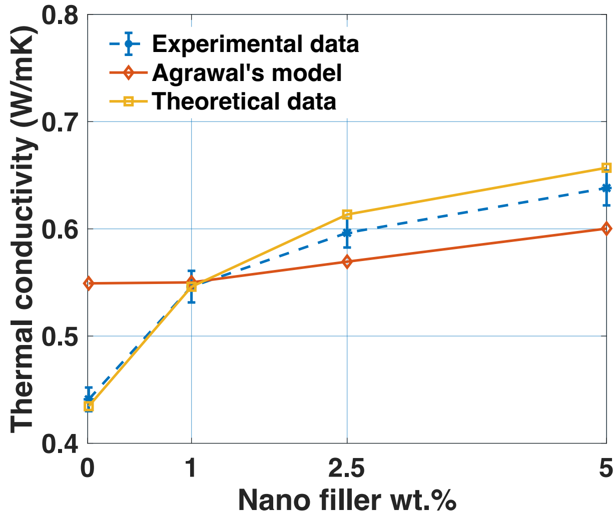

Fig. 4. Effective thermal conductivity of silicone rubber composites.

The proposed model can operate for two different types of fillers with different diameters and also considers agglomeration effect of fillers. When the present theoretical model is compared to experimental data, the least error is shown when the alumina filler weight percentage is low, and the marginally increased error is shown when the nano filler weight percentage is high. Tab 2 shows the error in thermal conductivity values of silicone rubber micro nanocomposites between experimental values and theoretical values obtained from present model.

When the weight percentage of nano fillers is zero, the volume fraction (ϕ_b) and aggregated nano fillers volume fraction (ϕ_{bagg}) are also zero, and when these values are substituted in Eq. (18), the variables Y and Z become indeterminate since some of the terms tends to be infinite. When this happens, the effective thermal conductivity of silicone rubber composites is unknown. To prevent this issue, a very low weight percentage (0.001 %) of nano-alumina is assumed instead of zero weight percentage.

Table 2. Effective theoretical and experimental thermal conductivity values of silicone rubber samples.

Nano filler (wt.%)	Thermal conductivity (W/mK)		Error (%)
	Experimental data	Theoretical data	
0	0.4410	0.4346	-1.45
1	0.5461	0.5460	-0.01
2.5	0.5963	0.6134	2.86
5	0.6381	0.6569	2.94

However, with respect to increase in the nano-alumina filler weight percentage, a marginal increment in error is observed. At higher weight percentage of nano fillers, the positive error is observed, it means the predicted data is higher than the experimental data. This could be due to the assumption of thermal contact resistance to be minimum in the present analysis. The thermal contact resistance varies with the concentration of filler addition to the polymer composites. According to Ngo et al the thermal contact resistance increases as the volume fraction of fillers increases, resulting in a reduction in effective thermal conductivity of polymer composites [13, 23]. Due to this reason, the thermal conductivity data calculated through the current model is marginally higher when compared to experimental data of silicone rubber micro nanocomposites, especially at higher filler weight percentages.

Therefore, the present model has resulted higher accuracy than Agrawal's model with respect to experimental thermal conductivity data of silicone rubber composites, with the inclusion of agglomeration effect and by considering the diameter of two fillers dispersed in polymer composites as unequal.

5 Conclusions

The following outcomes are accrued from the present research:

- The Agrawal's series heat flow thermal conductivity model is modified by considering the effect of radius of hybrid fillers (radius of micro ATH, nano-alumina, and aggregated nano-alumina fillers are r_a, r_b, and r_{bagg} respectively, which are not equal) and the effect of agglomerations, in order to obtain the effective thermal conductivity of silicone rubber micro nanocomposites.
- The volume fraction of aggregated nano-alumina fillers is noticed to increase with increase in the alumina nanofiller concentration, which highlights the importance of agglomerations while evaluating the thermal conductivity of silicone rubber micro nanocomposites.
- The thermal conductivity values of silicone rubber micro nanocomposites are determined theoretically with higher accuracy by using the present model. In comparison to Agrawal's model, the error between theoretical and experimental data is lesser in present model.

Acknowledgement
The author (R.S) dedicate this manuscript to Prof. Toshikatsu Tanaka's 82nd Birthday occasion.

References

1. T. Tanaka and T. Imai, CRC press, (2017)
2. K. K. Khanum, A. M. Sharma, F. Aldawsari, C. Angammana and S. H. Jayaram, IEEE Trans. Indus. Appli. **1**, 686 (2020).
3. L. H. Meyer, E. A. Cherney and S. H. Jayaram, IEEE Electr. Insul. Mag. **4**, 13 (2004).
4. J-W. Zha, Z. Dang, W-K. Min, Li, W-K. Zhu, Y. Hui and G. Chen, IEEE Trans. Dielectr. Electr. Insul. **4**, 1989 (2014)
5. M. Fairus, M. Hafiz, N. S. Mansor, M. Kamarol and M. Jaafar, IEEE Trans. Dielectr. Electr. Insul. **5**, 2901 (2017).
6. R. A. Ghunem, D. Koné, L. Cissé, Y. Hadjadj, H. Parks and D. Ambroise, IEEE Trans. Dielectr. Electr. Insul. **1**, 249 (2020).
7. L. Meyer, S. Jayaram and E. A. Cherney, IEEE Trans. Dielectr. Electr. Insul. **4**, 620 (2004).
8. M. T. Nazir, B. T. Phung, S. Yu and S. Li, IEEE Trans. Dielectr. Electr. Insul. **2**, 657 (2018).
9. P. Vinod, M. S. Babu, R. Sarathi and S. Kornhuber, Jour. Electron. Mater. 5881 (2021).
10. R. A. Ghunem, S. H. Jayaram and E. A. Cherney, IEEE Electr. Insul. Mag. **1**, 12 (2015).
11. G. Jiang, T. Liu, K. Liao and W. Zhu, Silicon. 1 (2021).
12. K. Sanada, Y. Tada and Y. Shindo, Compos. Part A: Appli. Scien. Manuf. **6-7**, 724 (2009).
13. I.L. Ngo, and C. Byon, Inter. Jour. Heat Mass Trans. 539 (2017).
14. B.Z. Gao, J.Z. Xu, J.J. Peng, F.Y. Kang, H.D. Du, J. Li, S.W. Chiang, C.J. Xu, N. Hu and X.S. Ning, Thermochimica Acta. 1 (2015).
15. I.L. Ngo, S.P. Vattikuti and C. Byon, Inter. Jour. heat mass trans. 727 (2017).
16. J. Wang, J.K. Carson, M.F. North and D.J. Cleland, Inter. Jour. heat mass trans. 17-18, 3075 (2006).
17. I.L. Ngo and V.A. Truong, Inter. Jour. Heat Mass Trans. 118605 (2019).
18. A. Agrawal and A. Satapathy, Inter. Jour. Therm. Scien. 203 (2015).
19. M. A. Ashraf, W. Peng, Y. Zare and K.Y. Rhee, Nanoscal. Resear. Letters. **1**, 1 (2018).
20. S. Fu, Z. Sun, P. Huang, Y. Li and N. Hu, Nano Mater. Scien. **1**, 2 (2019).
21. Y. Zare, K. Y. Rhee and D. Hui, Compos. Part B: Engin. 41 (2017).
22. I.L. Ngo and C. Byon, Inter. Jour. Heat Mass Trans. 894 (2015).
23. I.L. Ngo, C. Byon and B.J. Lee, Jour. Heat Mass Trans. 474 (2018).