Thermal Diffusivity and Thermal Effusivity Enhancement of Graphene based Polyvinyl Chloride Nanocomposites

T. A. El-Brolossy 1*, A. Almutawa 2

1 Physics Department, Faculty of Science, Ain shams University, Cairo, Egypt.
2 Physics Department, Faculty of Science, King Faisal University, Al-Ahsa, Saudi Arabia.

*E-mail: elbrolosyta@gmail.com

Abstract. The development of thermal diffusivity, thermal effusivity and heat capacity per unit volume of polymer nanocomposites, based on PVC filled with different concentration of graphene flakes up to 1.3 vol.% have been investigated using photoacoustic technique. The composites were prepared in the form of thin films with relatively small thickness (23–30 μm). Morphological and structural characterizations of the prepared composite films have been performed using laser confocal microscope, SEM and Raman spectroscopy. The composites exhibit an improvement in both thermal diffusivity (175%) and thermal effusivity (136%) of their values for neat polymer at the highest graphene content used. However, with increasing graphene content no significant variations in the measured values of heat capacity were obtained. The experimental results were analyzed using the mixed model for the thermal conductivity of a two-phase system. We obtained good agreement between our results and the predictions of this model at thermal diffusivity (= (1.5 ± 0.07) × 10⁻⁴ m²s⁻¹) and thermal effusivity (= (1.83 ± 0.06) × 10⁴ Ws¹²m⁻²K⁻¹) of fillers. The predicted thermal diffusivity value of graphene flakes is comparable to the published thermal diffusivity of graphene plates. On the other hand, according to the author’s knowledge, the thermal effusivity of graphene was not previously studied. However, the thermal effusivity predicted in this work is in fair agreement with that estimated using the reported thermal properties data of graphene.

Keywords: Graphene flakes, polymer nanocomposites, photoacoustic, Thermal diffusivity, Thermal effusivity.

1. Introduction

Effective thermal managing in modern electronics devices has become of fundamental necessity. As the electronic components of these devices have become more integrated and miniaturized, the heat they generate could reduce the lifetime and efficiency of the device if not dissipated rapidly. Therefore, materials with considerable thermal conduction are necessary to remove the heat away and maintain the system [1]. Polymer nanocomposite with enhanced thermophysical properties can effectively dissipate such heat. Generally, polymers have various applications [2, 3] however most polymers have many defects due to their amorphous state that cause several phonon scatterings leading to a low thermal conductivity (0.1 - 0.5 Wm⁻¹K⁻¹) [4]. The progress of polymeric nanocomposites based on standard polymers and conductive carbon rich materials, especially carbon nanotubes (CNTs), [5–9] is very promising way to obtain new materials with novel structural and functional properties surpass those of the neat components and other nanocomposite systems with other fillers [10–13].

Compared to CNTs, graphene sheets (GS) have higher surface-to-volume ratios due to the unreachable of the inner surface of the nanotubes to the polymer molecules. Also, the reported value of thermal conductivity of single layer graphene attains 4000 – 7000 W/m·K at room temperature which is higher than that of CNTs [14–16]. Furthermore, graphene is obtained from naturally occurring graphite suggesting that lighter and functional improved graphene-reinforced nanocomposites can be produced at lower cost. This renders graphene sheets possibly more promising for varying all matrix properties including thermal properties and thermal stability. In recent years, efforts are devoted towards graphene-based nanocomposites [17-19]. More
recently, the thermal conductivity of graphene-based composites has made rapid progress [20–24]. However, the size and thickness of GSs show a discrepancy depending on how they are produced; accordingly, their reported thermal conductivity values vary considerably [25]. Also, due to the extremely large specific surface area of graphene, the number of interfaces as well as the interfacial bonding between graphene and the host polymer controls the interfacial thermal resistance and consequently the heat transfer process through the produced nanocomposite. Therefore, more research on graphene-based polymer nanocomposites of enhanced thermal properties is needed.

Not only thermal conductivity is the relevant thermal parameter concerning heat conduction in solids, but also both of thermal diffusivity (α) and thermal effusivity (e) are two highly significant thermal parameters that govern heat transfer and heat exchange processes for solid or liquid substances respectively. These quantities are given by $\alpha = k/\rho c$, and $e = \sqrt{k/\rho c}$, where $c$ is the specific heat capacity, $\rho$ is the mass density while $k$ is the thermal conductivity. Thermal diffusivity is a characteristic property measures the rate of heat diffusion within the material; it controls how fast heat will flow within the material. On the other hand, thermal effusivity is the ability of the material to exchange heat or it controls the heat transfer process at the material’s interfaces. Therefore, it is related to thermal impedance at material’s surface. Such thermophysical properties of graphene-based polymer nanocomposites are rarely studied or even not exist in literatures [26].

In last couple of decades, optical measurement methods have been recognized as non-invasive and accurate techniques for thermal measurements [27-29]. In this work we employ the photoacoustic (PA) technique as an optical technique to follow the development of both thermal diffusivity and thermal effusivity of Polyvinyl chloride/graphene nanocomposite with increasing graphene content.

2. Theoretical Aspects

The nonradiative relaxation of photoexcited states usually results in heating of the sample. The released heat energy carries information regarding both the absorbed energy and the thermal properties of the sample. A group of such spectroscopic methods based on the detection of photo-induced heating of the sample are called the photothermal methods. The PA technique is a photothermal detection method that has been attested [30, 31] to be a potent tool for studying optical and thermal properties of materials. The master process of PA technique is based on illuminating the sample placed in a closed chamber filled with a gas such as air with monochromatic radiation of any desired wavelength and modulated intensity with suitable acoustic frequency (f). The nonradiative decay of the absorbed radiation produces a periodic heat diffused from the sample to the air adjacent to the sample surface. This temperature variation creates a pressure fluctuation in the air within the cell which is detected as an acoustic signal by a sensitive microphone attached to the chamber. At fixed incident wavelength the PA signal becomes function of modulation frequency only. One of the important parameters that control the amplitude of the PA signal is the thermal diffusion length $l_\text{d} = (\alpha/\pi f)^{1/2}$. For an appropriate sample thickness $l_s$, one can obtain a cross over from a thermally thin regime ($\mu > l_s$), to a thermally thick regime ($\mu \leq l_s$) by increasing the modulation frequency $f$. According to Charpentier et al. [30] as well as Bennett and Patty [33] the PA signal amplitude $Q$ for the case of an optically opaque sample can be expressed as

$$Q = A \left(\frac{1 + R^2 e^{-4\pi k^2 a^2}}{\pi f} \right) \left[(1 - R^2 e^{-4\pi k^2 a^2})^2 + 4R^2 e^{-4\pi k^2 a^2} \sin^2 2\pi t \right]^{-1/2}$$

With $x = \frac{l_s}{\mu_\text{d}}$, $\mu_\text{d} = \left[\frac{l_s (\pi f)^{1/2}}{a} \right]$, $A$ is constant non-related to the sample and $R = (1 - b)/(1 + b)$ is the thermal wave reflection coefficient with $b$ given by $b = e_s/e_x = (\kappa_p/c_p/\kappa_x/c_x)^{1/2}$. Here $e_s$ and $e_x$ are thermal effusivities of the backing material and the sample, respectively. Equation (1) can be used to estimate thermal diffusivity and thermal effusivity of solid samples under certain experimental conditions.

3. Experimental Setup

3.1 Materials

Polyvinyl Chloride (PVC) average molecular weight 1020 was purchased from Sabic, KSA and solvent Tetrahydrofuran (THF) stabilized with 0.1% quinine from LOBACHEMIE. Graphene was obtained from
SKYSPRING Nanomaterials Graphene Nano powder product 0540DX. Graphene nanopowder, product 0540DX are very thin (1 – 5 nm), flat particles with large diameters (< 2 μm). Owing to the flat shape of these particles, they are particularly sensitive to van der Waals attractive forces and have an affinity to re-aggregate in the dry state. For this reason, we got our nanopowder in a granular form. These granules are friable collections of individual particles that prevent agglomerations and are easily broken with mechanical agitation.

3.2 Preparation of PVC/GNF nanocomposites Samples

The method which was extensively used in dispersing of nano materials within thermoplastic resins is done by dispersing the particles in an aromatic solvent, dissolving the polymer in the same solvent, mixing the two solutions with required ratios and then evaporating the solvent to obtain the thermoplastic with an excellent dispersion of nanopowder. We have used this technique to prepare nanocomposite sheets of PVC with graphene flakes (PVC/GNF) of various GNF wt. % using THF as a solvent. In a typical process, PVC was first dissolved in 40 mL of THF with continuous stirring (for about 3 h) up to complete dissolution. The appropriate amount of graphene was dispersed in THF by ultrasonic vibrations for 10 minutes. The two solutions were mixed with continuous stirring for 24 h to form stable graphene/polymer solution. This confirms the proper dispersion with no detectable precipitation. The resulting solution will be poured to Petri dishes with fixed area and dried at room temperature. After solvent evaporation, the film was peeled off where its thickness was determined using digital micrometer. The prepared films were labeled PVC-Pure, PVC/GNF-0.1%, PVC/GNF-0.3%, PVC/GNF-0.5%, PVC/GNF-0.8%, PVC/GNF-1.0% and PVC/GNF-2.0%. Fig. (1) shows the photographic pictures of some prepared films. The films seem almost homogenous, with a clear increase in the darkness as GNF loading increases.

![Figure 1](image1.png)

| Pure PVC | 0.5 % GNF | 2.0 % GNF |
|----------|-----------|-----------|

3.3. Photoacoustic Experiment

Photoacoustic technique in front surface illumination for optically opaque samples has been used to estimate thermal properties of composite samples. Samples are films prepared as described previously with thickness (~23 – 33 μm) measured using digital micrometer. Good adhesion (using silicon grease) to the quartz glass plates as a backing material ensuring good thermal contact and avoiding the appearance of extra thermal resistance. The used quartz plates are of circular shape (5 mm diameter and 1.5 mm thickness) with well-known thermal properties ($\varepsilon_q = 1503$ Ws$^{1/2}$ m$^{-2}$ K$^{-1}$, $\alpha_q = 0.87 \times 10^{-6}$ m$^2$/s). To get rid of the effect of varying absorption energy of the samples and verify the required condition of strong PA signal, we quoted the sample surface with very thin layer of black ink. This ultra-thin thermal layer ensures the same absorption energy for all samples without any significant effect on the measured thermal properties of the sample. As a result, variations in the measured PA signal from one sample to the other depend only upon the variation in their thermal properties. The sample was then placed within the PA cell and illuminated with 514.5 nm line of Ar$^+$ laser as an exciting beam with about 20 mW powers. We used a mechanical chopper to chop the incident beam at the desired frequencies covering the range from thermally thin to thermally thick region for all samples. The PA signal amplitude was recorded using a dual channel digital lock-in amplifier (SR830). For further confirmation of the results the measurements were performed for more than one sample of the same type.

4. Characterization

4.1 LCM and SEM

The surface morphology of the prepared composites was investigated using laser confocal microscope (LCM) of the micro Raman model: Labram HR Evolution-Horiba as well as SEM. A confocal microscope
creates sharp images of a specimen that would else appear hazy when viewed with a conventional microscope. The image is clear and of better contrast than that of a conventional microscope. This is illustrated in Fig. 2 (a-c) that shows the two-dimensional LCM images of 0.1% wt., 0.5% wt. and 2%-wt. PVC/GNF composite samples respectively. The images provide clear difference in the surface morphology and particle distribution with increasing GNF loading. A reduction in the space between particles with increasing GNF content is evidently observed. Also, as the concentration increases the graphene plates tend to aggregate as clearly observed for the sample of the highest concentration.

The SEM image of the graphene powder using [Fe-SEM JSM -7600 Jeol. Japan] presented in Fig. 3 (a). The layered structure of the friable granular graphene is clearly observed. The image shows several thin layers stacked over each other. Also, the surface morphology of the prepared samples has been studied using SEM. Fig. 3 (b & c) shows SEM images of neat PVC and PVC/GNF 2% wt. respectively. The smooth and flat surface of the pure PVC is clearly observed. In contrast, the random distribution of hills in the composite image reveals that most of the graphene nano flakes are well dispersed in the PVC matrix, with a few restacks. It should be noted from the low contrast of the image that graphene flakes seem to be masked inside the polymer matrix and are well dispersed in the PVC.

4.2 Raman measurements

The Raman spectra of GNF sample and PVC/GNF nanocomposites have been obtained using the micro Raman spectrometer (model: LabRam HR Evolution-Horiba). The excitation source is He-Ne Laser of spot-size: 1-2 microns at 10% numerical density filter for 633 nm. Fig. 4 (a) shows Raman bands of Graphene powder in the range (800 – 2900 cm\(^{-1}\)). The spectrum shows the two characteristic bands, G band at (≈1575 cm\(^{-1}\)) and 2D band at (≈ 2645 cm\(^{-1}\)). The intensities and shapes of these bands reveal the multilayer structure of the graphene sample. Also, the appearance of a band at (≈ 1325 cm\(^{-1}\)) which is assigned as D band indicates the presence of defects and disorders in the graphene structure.

Raman scattering measurements of PVC/GNF composites were performed to investigate the structure as well as the distribution of GNF within the PVC matrix. Fig. 4 (b) shows the development of the G band of the GNF within the composite of different graphene wt. %. It is readily observed that the intensity of G band increases with increasing CNF contents. This may be considered as an argument of fair distribution of GNF within the polymer matrix. Also, the obtained G band of GNF within the polymer is (≈1587± 3cm\(^{-1}\)) for 2 % wt,
($\approx 1588 \pm 3 \text{cm}^{-1}$) 0.8 \% \text{wt.} \text{ and } \approx 1592 \pm 3 \text{cm}^{-1}$ for 0.5 \% \text{wt} which are blue shifted relative to that of the granular graphene. This blue shift indicates a decrease in the number of stacked graphene layers within the polymer matrix with a tendency to some agglomeration with increasing loading percentage.

Fig. 4(c) shows 2D band at ($\approx 2664$ cm$^{-1}$) of GNF in 2\% \text{wt.} sample. We couldn’t detect this band in the samples of lower graphene content. Also, this band is blue shifted as well as narrower (smaller FWHM) from that of the graphene powder. These observations confirm the reduction of the number of stacked layers of GNF within the polymer matrix relative to that of graphene powder. This agrees with the nature of our graphene sample which is supplied in a friable granular form (collection of multiple particles). With ultrasonic vibrations during composites’ preparation, these particles were separated and distributed within the polymer matrix.

As it was mentioned before, the D band is associated to the defects and disorders in the graphene structure. Fig. 4(d) shows Raman spectrum of 2\% \text{wt.} sample in the range 1200 cm$^{-1}$ – 1800 cm$^{-1}$. The two graphene bands G and D together with the C – H ant symmetric stretching of PVC was detected. When we compare this spectrum with that of graphene powder (Fig. 3(a) it is directly noticed that the intensity ratio $I_D/I_G$ of PVC/GNF composite of 2\% \text{wt.} is larger than that of graphene powder. Obviously, this means an increase in the defects and/or disorder in the GNF within the PVC matrix relative to the graphene powder. This result suggests interfacial interaction between GNF and PVC.

**Figure 4.** Raman spectra of GNF powder (a), G band of GNF of different concentrations within the PVC matrix as indicated (b), 2D band of 2\% \text{wt} PVC/GNF sample (c) and D and G bands of 2\% \text{wt} PVC/GNF sample (d)
5. Results and Discussion

5.1 Thermal diffusivity and thermal effusivity measurement

A distinctive variation of the PA amplitude with chopping frequency in the range (4 – 700 Hz) in the double logarithmic presentation of the PVC film of thickness 29 \( \mu \)m is presented in Fig. 5(a). Solid line represents the best fit of the experimental data (scattered points) according to the Eq. (1). One can clearly see in Fig. 5 (a) the varying slope at higher frequencies indicating a transfer from thermally thin to thermally thick sample. This contrasted to the straight-line behavior (constant slope) for the thermally thick sample (of thickness 350 \( \mu \)m) shown in the inset of Fig. 5 (a). By the aid of the known thermal effusivity of the backing material and the measured thickness of the sample we obtained fitting curves by fitting the three parameters \( \alpha \), \( e \), and \( A \) to Eq. (1). The estimated values are \( \alpha = 1.28 \times 10^{-7} \, \text{m}^2/\text{s} \) and \( e = 450 \, \text{W} \cdot \text{s}^{1/2} \cdot \text{m}^{-2/2} \cdot \text{K}^{-1} \) accordingly, the thermal conductivity \( k(\sqrt{\alpha}) \) is 0.161 Wm\(^{-1}\) K\(^{-1}\). These values agree well with the reported values of PVC thermal properties [34] which indicates the suitability of the method for such measurements.

Figure 5. log – log plot of \( Q \) vs. \( f \) for pure PVC (thin sample 0.029 mm). The inset is the same relation for a thick sample

PA signal amplitude of composite samples of known thicknesses and different GNF weight content (0.1, 0.3, 0.5, 0.8, 1, and 2 wt. %) were measured. Typical variations of the PA signal amplitude with chopping frequency in the double logarithmic presentation for composite samples of (0.1 and 1 wt. %) are shown in Fig. 6 (a & b) respectively. Solid line represents linear fitting of the experimental data (scattered points) according to Eq. (1) as performed before. It is obvious that the behavior of amplitude variations with the chopping frequency is in good agreement with the theory for the two samples. The PA signal of other composites (not shown) revealed similar behavior.

Figure 6. log – log plot of \( Q \) vs. \( f \) for PVC/GNF 0.1 wt. % (a) and 1 wt. % (b)
The estimated values of $\alpha$ of the PVC/GNF composites with different GNF weight percentage, show significant enhancement with increasing GNF content reaches to about 175% of its original value $\alpha_o$ of pure PVC at the highest GNF content used (2 wt. %). This signifies that addition of GNF to PVC provides a new way for heat diffusion and the composite becomes better thermal diffuser than the neat polymer. Also, the obtained values of the thermal effusivity reveal an enhancement with increasing the GNF content. However, in comparison with the results obtained for $\alpha$, improvement of $e$ is lower reaches to about 131.7% of its original value $e_o$ at the highest GNF content as shown in Fig. 7.

Now, we are going to investigate the development of these thermal properties versus the volume percentage of each individual phase of the composite in order to estimate the thermal properties of the filler itself. The GNF volume fraction $\nu$ in the composites was calculated and found to be within the range 0 – 1.3 vol. %. For such type of mixed material, the thermal properties are discontinuous functions of the position, therefore neither Fourier’s law, nor the heat conduction equation are applicable. Consequently, the concept of ‘effective’ properties, that means the properties of the equivalent homogeneous material which produces the same physical effects, appears to be suitable. The effective heat capacity at most times follows the mixture rule. Thus, for a two phase composite the effective heat capacity per unit volume is given by [35]

$$
(\rho c)_\text{eff} = \nu_1(\rho c)_1 + \nu_2(\rho c)_2
$$

(2)

Where $\nu_i$ is the vol. % of component $i$. As can be seen, it only depends on the volume fraction of the components. Using the measured values of both ($\alpha$) and ($e$), ($\rho c)_\text{eff}$ can be determined using the relation

$$
(\rho c)_\text{eff} = \frac{e}{\sqrt{\alpha}}
$$

(3)

Fig. 8 shows the measured values of the effective heat capacity per unit volume of PVC/GNF composites (scattered points) together with the calculated values (solid line) using Eq. (2) versus vol. % of GNF. Clearly, the calculated values of ($\rho c)_\text{eff}$ are nearly constant with increasing $\nu$ in our range which is predicted as both $\rho$ and $c$ varies with $\nu$ in an opposite manner. Wherein $\rho$ of GNF (2.1 g/cm$^3$) is larger than that of PVC (1.39 g/cm$^3$) [34] while $c$ of GNF ($\approx 0.7$ Jg$^{-1}$K$^{-1}$) [36] is lower than that of PVC. The experimental results reasonably agree with these calculated values, where no significant variations in the measured values of ($\rho c)_\text{eff}$ (within the experimental uncertainties) were obtained as can be noticed. This may be a sign of the adequate dispersion of GNF in our PVC matrices. Some authors [37] obtained an unpredicted behavior with
addition of MWCNTs which caused a specific heat capacity enhancement of the polymer composites. They ascribed it to the ineffective dispersion of nanotubes within the polymer matrix.

Figure 8. Volume heat capacity ($\rho c$) as a function of GNF vol. %

Also, the invariance of $\rho c$ with GNF addition suggests that the increase of both thermal diffusivity and thermal effusivity of PVC/GNF composites with increasing GNF loading is essentially due to the enhancement of thermal conductivity. This might allow some of the theoretical and/or empirical models that forecast thermal conductivities of two-phase systems to be valid for both thermal quantities (diffusivity and effusivity).

5.2 Thermal Properties of GNF

We make full use of the mixed empirical model of polymer composites that was based on the parallel and series models of thermal conductivity of two phase systems [38] to foretell both thermal diffusivity and thermal effusivity of the composite samples. This model is given as [9]:

$$\lambda^E = \gamma \lambda_F^E + (1 - \gamma) \lambda_P^E$$  \hspace{1cm} (4)

Where $\lambda$ represents the thermal quantity (either $\alpha$ or $e$); the sub-indices $E$, $F$ and $P$ indicate to composite, filler (GNF) and neat polymer respectively and $\gamma$ is a constant with values between $-1$ and $+1$ based on the experiment.

The predictions of this model fit the measured thermal diffusivity of the composites as shown in Fig. 9(a) at acceptable value of $\gamma = 0.44$ and thermal diffusivity of GNF ($\alpha_{GN} = (1.5 \pm 0.07) \times 10^{-4} \text{m}^2\text{s}^{-1}$). The obtained thermal diffusivity value of GNF is comparable to the values measured by Cabrera, H., et al. [39] for thermal diffusivity of graphene plates. Conversely, the model fits thermal effusivity of the composites as shown in Fig. 9(b) at $\gamma = 0.82$ and thermal effusivity of GNF ($e = (1.83 \pm 0.06) \times 10^4 \text{Ws}^{1/2}\text{m}^{2}\text{K}^{-1}$). The comparison with the reported values of GNF thermal effusivity could not be made as such values are not exist in the literature. However, the calculated thermal effusivity using the estimated value of $\alpha_{GN}$ as well as the reported values of both $\rho$ and $c$ for GNF through the relation $e = \rho c \sqrt{\alpha}$ yields a value ($1.8 \times 10^4 \text{Ws}^{1/2}\text{m}^{2}\text{K}^{-1}$) which is close to the predicted one.

The above results reflect the success of this indirect method to estimate thermal diffusivity and thermal effusivity of GNF. However, the predicted values of these thermal properties especially $\alpha$ lie in the lower limit of the reported values, this might be due to number of graphene layers in our GNF as well as the thermal barrier layer usually exists at graphene/polymer interface, which effectively reduces the heat diffusion in composites.
Figure (9): Thermal diffusivity (a) and effusivity (b) of PVC/GNF as a function of GNF vol. %. Solid lines represent calculated results using equation (4)

6. Conclusion

Photoacoustic experiment in the front surface illumination has been employed to measure thermophysical properties, including thermal diffusivity, thermal effusivity and volumetric heat capacity of PVC/GNF nanocomposites of varying GNF content (0 – 1.3 vol. %). Continuous enhancement of both ($\alpha$) and ($e$) of PVC was obtained via the inclusion of GNF, which attained 1.75 times the thermal diffusivity and about 1.36 times the thermal effusivity at 1.3 vol.%. The normal heat capacity behavior of PVC/GNF composites together with the gradual increase of the G band intensity with increasing GNF content suggest enough dispersion of GNF in our PVC matrices. Using the mixed model for thermal conductivity of a two-phase system,
we were able to estimate acceptable values of thermal diffusivity and thermal effusivity of GNF. These results confirm the appropriateness of this optical method to measure thermal properties of polymer nanocomposites.

References

[1] Chen, H., Ginzburg, V.V., Yang, J., Yang, Y., Liu, W., Huang, Y., Du, L., Chen, B. (2016) Prog. Polym. Sci., 59, 41–85.
[2] Chattopadhyay, S., Madras, G. (2002) Polymer degradation and Stability, 78, 519–524.
[3] Adel, R., Abdallah, T., Moustafa, Y.M., Al-Shagh, A.M., Talaat, H. (2015) Superlattices and Microstructure, 86, 62–67
[4] Huang, X., Jiang, P., Tanaka, T. (2011) IEEE Electr. Insul. Mag., 27, 8–16.
[5] Song, Y.S., Yoon, J.R. (2006) Carbon, 44, 510–517.
[6] Miosala, A., Li, Q., Kinloch, I.A., Windle, A.H. (2006) Compos. Sci. Technol., 66, 1285–1288.
[7] Adel, R., Abdallah, T., Moustafa, Y.M., Al-Sbagh, A.M., Talaat, H. (2015) Composites Part A, 42(4), 394–399.
[8] El-Brolossy, T.A., Ibrahim, S.S., Alkhudhayr, E.A. (2015) Polymer composites, 36(7), 1242–1248.
[9] El-Brolossy T.A., Ibrahim, S. S. (2014) Phys. Scr, 89, 105701 (9pp).
[10] Choi, S., Kim, J. (2013) Compos. B Eng., 51, 140–147.
[11] Li, B., Li, R., Xie, Y. (2017) J. Mater. Sci., 52, 2524–2533.
[12] Im, H., Kim, J. (2011) J. Mater. Sci., 46, 6571–6580.
[13] El-Brolossy, T.A., Ibrahim S.S. (2010) Thermochimica Acta 509, 46–49.
[14] Balandin, A.A. (2011) Nat Mater. 10, 569–81.
[15] Balandin, A.A., Ghosh, S., Bao, W., Calizo, I., Teweldebrhan, D., Miao, F., Lau, C.N. (2008) Nano Letters 8 (3), 902-907.
[16] Ghosh, S., Calizo, I., Teweldebrhan, D., Pokatilov, E.P., Nika, D.L., Balandin, A.A., Bao, W., Miao, F., Lau, C.N. (2008) Appl Phys Lett. 92, 151911.
[17] Mukhopadhyay, P., Gupta, R.K. (2012) Graphite, Graphene, and their polymer nanocomposites. CRC Press.
[18] Kuila, T., Bose, S., Mishra, A.K., Khanra, P., Kim, N.H., Lee, J.H. (2012) Progress in Materials Science., 57(7), 1061-1105.
[19] Regueira, R., Suckeveriene, R.Y., Brook1, I., Mechrez, G., Tchoudakov, R., Narkis, M. Graphene. (2015) 4(01), 7-19.
[20] Burger, N., Laachachi, A., Ferriol, M., Lutz, M., Toniazzo, V., Ruch, D. (2016) Progress in Polymer Science. 61, 1–28.
[21] Shtein, M., Nadiv, R., Buzaglo, M., Kahl, K., Regev, O. (2015) Chem. Mater., 27, 2100–2106.
[22] Li, A., Zhang, C., Zhang, Y-F. (2017) Polymers, 9, 437.
[23] Song, W-L., Wang, W., Veca, I.M., Kong, C.Y., Cao, M-S., Wang, Pe., Meziani, M.J., Qian, H., LeCroy, G.E., Caona, L. Sun, Y-P. (2012) J. Mater. Chem., 22, 17133.
[24] Zhang, C., Hao, X. L., Wang, C. X., Wei, N., & Rabczuk, T. (2017). Scientific reports, 7, 41398.
[25] Noh, Y., Joh, H., Yu, J., Hwang, S.L., Lee, S., Lee, C.H., Kim, S.Y., Youn, J.R. (2015) Sci. Rep. 5, 9141.
[26] Gresil, M., Wang, Z., Poutrel, Q., Soutis, C. (2017) Sci Rep 7, 5536.
[27] Ali, F.M., Yunus, W.M.M., Moksin, M.M., Talib, Z.A. (2010) Rev. Sci. Instrum. 81, 074901.
[28] El-Brolossy, T.A., Saber, O. (2013) Experimental Thermal and Fluid Science 44, 498–503.
[29] El-Brolossy, T.A., Ibrahim, S.S. (2013) Chin. Phys. B. 22(7), 074401.
[30] El-Brolossy, T.A., Abdallah, S., Abdallah, T., Mohamed M.B., Negm, S., Talaat, H. (2008) Eur. Phys. J. Special Topics. 153, 365–368.
[31] El-Brolossy, T.A., Abdallah, S., Hassanein, O.E., Negm, S., Talaat, H. (2005) Journal De Physique IV 125.
[32] Helander, P. (1982) J. Photoacoustics. 1, 103-120.
[33] Chirtoc, M., Tosa, V., Bicanic, D., Torfs, P. Berichte der Bunsengesellschaft für physikalische Chemie, (1991), 95(7), 766-769.
[34] Mamunya, Y., Boudenne, A., Lebovka, N., Ibos, L., Candau, Y., Lisunova, M. (2008) Composites Science and Technology., 68(9), 1981-1988.
[35] Salazar, A. (2003) European journal of physics. 24(4), 351.
[36] Pop, E., Varshney, V., Roy, A.K. (2012) MRS bulletin. 37(12), 1273-1281.
[37] Lizundia, E., Oleaga, A., Salazar, A., Sarasua, J-R. (2012) Polymer. 53(12), 2412-2421.
[38] Shen, M., Cui, Y., He, J., Zhang, Y-M. (2011) International Journal of Minerals, Metallurgy, and Materials. 18(5), 623-631.
[39] Cabrera, H., Mendoza, D., Benítez, J.L., Flores, C.B., Alvarado, S., Marín, E. (2015) Journal of Physics D: Applied Physics. 48(46), 465501.