The effect of temperature rise on the thermal conductivity of composite (perovskite/polymer) solar cell

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Abstract

The efficiency of solar cell and the corresponding output power is mainly affected by the rise in the film temperature, and in such cases, the stability in thermal conductivity value is required to ensure adequate rate of heat loss. This study investigates the effect of temperature rise on the overall thermal conductivity of the perovskite cell including the response of polymeric additives that have been used recently to enhance the interaction between different grains in perovskite films. The polymers under study are: polyethylene oxide (PEO), polyacetylene (PA), polythiophene (PT), polystyrene (PS) and polymethyl methacrylate (PMMA). The work assumes mathematical procedure that links the variation of temperature to the degree of polymer's crystallinity and then converting this impact in terms of thermal conductivity. The calculations assumed three different concentrations of the polymer as: 1, 3 and 5%. Each polymer has served with two degrees of crystallinity. In general, the results show that the effect of added polymers on the final value of the thermal conductivity of the film may be positive or negative depending on three main factors: k-value of the perovskite-based material, k-value of the polymer and concentration of the polymer. The effect of the polymer appears more when it is used with the low k-value perovskite material (0.2 W/m·K) rather than with high k-value perovskite material (0.8 W/m·K). The addition of PEO to the perovskite-based materials makes the overall k-value of the film reaches to 3.7 W/m·K and even higher when the temperature rises up. Hence, this polymer is useful in high operation temperature. In the case of using polymers (PA and PT), the overall k-value of the film was less sensitive. The use of amorphous polymers (PS and PMMA) has not witnessed any significant contribution in the overall k-value of the film.

Keywords: temperature rise, thermal conductivity, polymers, perovskite, solar cells

Kulcsszavak: hőmérséklet-emelkedés, hővezető képesség, polimerek, perovszkit, napelemek

1. Introduction

Recently, solar cells including many categories, such as: silicone-based cells, concentrated photovoltaics, organic photovoltaics, cadmium telluride cells, copper indium gallium selenide (CIGS) cells, multi-junction cells, tandem cells, quantum-dot cells and perovskite cells. These types have been receiving attention from both researchers and manufacturers [1]. A perovskite solar cell is a developed type of solar cells which includes perovskite-structured compounds, mostly semiconductors such as: calcium titanium oxides with hybrid organic-inorganic lead-based materials or tin halide-based materials. The materials used in the perovskite type have witnessed many improvements to become more economic as well as energy efficient, where maximum efficiency has reached up to 25% [2-6]. The characteristics of organic-inorganic perovskite regions are the interest for recent studies to develop the performance of these cells by enhancing many preferable parameters such as: absorption coefficient, bandgap, carrier mobility and carrier lifetime [7, 8]. The crystallization of the cells is another imperative feature for high performance perovskite cells, where it is related to the light absorption and carrier transportation. The presence of defects and crosslinking patterns may affect the performance of the cells by accelerating the carriers' recombination. Therefore, more attention has been seeking to reduce the defects and pinholes in order to obtain perfect perovskite cells [9-11].

Polymeric materials have been involved in perovskite cells as additives to enhance the general performance of the solar film and the overall conversion efficiency. In this aspect, common polymers that are used include: polyethylene oxide (PEO), polyvinylpyrrolidone (PVP), polyacrylonitrile (PAN), polyetherimide (PEI), polymethyl methacrylate (PMMA), polyacetylene (PA), polythiophene (PT), polystyrene (PS) and some other polymers [12-15]. From previous studies, polymers can be used as additives to improve the crystallization morphology by enhancing the interaction between different grains in perovskite films [16, 17], and by facilitating the nucleation and regulating the crystal growth [18-20]. Polymers can be immersing easily in polar solvents, which reduces the contact angle [21] and increases the device stability [22, 23]. Furthermore, polymers demonstrated for the improving of electrical, optical and other physical properties of perovskite-structured materials [24-31].

Polymers usually have med-to-high degree of crystallinity, where the structure of the molecules is identical partially. The degree of crystallinity has a big influence on many thermo-physical properties as well as mechanical features. However, synthetic polymers are usually semi-crystalline and their degrees of crystallinity are typically range between 10-80% [32-35]. The degree of crystallinity is an important factor affecting the thermal conductivity of semi-crystalline polymers. Where, maximum thermal conductivity achieved at high degree of crystallinity, where packed structure accelerate the heat [34]. However, in semi-crystalline polymers, thermal conductivity above room temperature gradually decreases by the increasing of temperature. This can be attributed to the loss of crystalline regions due to the heat flow [36-39]. Since, the most of solar radiation incident on the film is not converted into electricity, but it is absorbed as a heat thus it rises up the film temperature which causes a reduction in the efficiency. Access heat can be removed from internal layers mainly by heat conduction, which is related to the thermal conductivity of the material. Therefore, higher heat conductivity means efficient performance, and thus higher output power [40-45]. Hence, when temperature rises, a variation in thermal conductivity of the polymer affects the cell performance.

The object of the current study is to predict theoretically the effective thermal conductivity of the perovskite film due to the thermal behavior of polymeric additives that influence the overall performance of the solar cell. It is worth to mention that there is limited literature regarding the thermal conductivity of composite perovskite/polymer films. The novelty of the study is to present a mathematical model that links the effect of temperature on thermal conductivity of polymeric additives (with their specific concentration ratio and degree of crystallinity) to the overall thermal conductivity of the perovskite solar cell.

2. Materials and methods

In order to find the variation in the thermal conductivity of perovskite film including the thermal behavior of polymeric additives in the cell, some common polymeric materials are considered, such as: polyethylene oxide (PEO), polyacetylene (PA), polythiophene (PT), polystyrene (PS) and polymethyl methacrylate (PMMA). These materials show different features and wide range of thermo-physical properties, as shown in *Table 1*.

Polymer	Degree of crystallinity (%)	Density of crystalline structure (g/cm³)	Density of amorphous structure (g/cm³)	Thermal conductivity of crystalline structure (W/m·K)
PEO	60-80 [46]	1.24 [47]	1.12 [47]	60 [48]
PA	50-70 [49]	0.6 [50]	0.4 [50]	0.95 [51]
PT	40-60 [52]	1.18 [53]	1.12 [53]	0.62 [51]
PS	3-8 [54]	1.05 [55]	1.03 [55]	0.18 [56]
PMMA	~ 0 [57]	1.19 [57]	1.19 [57]	0.16 [58]

Table 1. Thermo-physical properties of polymers (pure solid additives)
1. táblázat A polimerek hőfizikai tulajdonságai (tiszta szilárd adalékok)

Since the intended goal is to determine the change in thermal conductivity of these polymeric materials due to the variation in the temperature of the film, hence the current mathematical procedure suggests finding the variation in the temperature with respect to an intermediate parameter which is the degree of the crystallinity, and then seeking to link this parameter to the thermal conductivity of the polymer and corresponding impact on the thermal conductivity of solar cell as overall.

The thermal conductivity of common polymeric materials is usually ranged between 0.2-1.0 W/m·K, with unique values for some others [35]. Polymers with high thermal conductivity values are required when the purpose is to release the heat. Many factors affect the thermal conductivity of a material such as: temperature, density, porosity, moisture, degree of crystallinity, chain structure, orientation of grains, size of molecules and impurities [59, 60]. The coefficient of thermal conductivity of polymers has different behaviors whether the polymer is thermoplastic or thermosetting, crystalline or amorphous and below or above glass-transition temperature [61, 62]. The increasing of the crystallinity leads to increase the thermal conductivity, thus thermal conductivity of crystalline region is higher than thermal conductivity of amorphous region [63-65]. However, the thermal conductivity of a semi-crystalline polymer is given by [34]:

$$k_{po} = X_c\, k_c + (1-X_c)\, k_a \qquad (1)$$

Where;
k_{po}: thermal conductivity of the semi-crystalline polymer.
k_c: thermal conductivity of crystalline part.
k_a: thermal conductivity of amorphous part.
X_c: degree of crystallinity of the polymer.

The last equation can be re-written as;

$$k_{po} = [(1 - Z)\, X_c + Z]\, k_c \qquad (2)$$

Where (Z) is the ration between (k_a) and (k_c).

Since, the thermal conductivity is influenced by the density, where the higher density material has the higher thermal conductivity and the increasing in the crystallinity of the polymer leads to increase both: density and thermal conductivity in the same manner [66]. Thus, the ratio (Z) can be presented in terms of density, as following;

$$Z = \rho_a\,/\,\rho_c \qquad (3)$$

During temperature rise, the thermal conductivity of the semi-crystalline polymers (PEO, PA and PT) decreases with respect to the increasing in the temperature. This can be attributed to the phenomenon of Umklapp scattering process, which occurs in the boundary of lattice where it increases the momentum of phonon. By rising the temperature, this process becomes more frequent and the phonon free path decreases, thus less ability to conduct the heat [61, 62]. For PS and PMMA, since the structure of these polymers is amorphous, so they show different behavior with temperature. Where, the thermal conductivity increases with the increasing of the temperatures in association with the increasing of the specific heat, and this attributed to the increase of the thermal activation of

the phonons due to the molecular vibration within the lattice [58, 61].

Hence, the general form of thermal conductivity-temperature relationship has the following linear formula:

$$k_p = k_{po} + \mu\, T \qquad (4)$$

Where:

k_p: thermal conductivity of the polymer as a function of temperature.

k_{po}: thermal conductivity of the polymer at room temperature.

μ: index of variation.

T: temperature.

The index of the variation with the temperature within the range 20-100 °C can be extracted from specific studies that investigated the temperature effect on the thermal conductivity of the selected polymers, as shown in *Table 2*.

Polymer	Index of variation
PEO	- 0.3 [48]
PA	- 0.004 [51]
PT	- 0.002 [51]
PS	+ 0.0006 [56]
PMMA	+ 0.0008 [56, 58]

Table 2   The index of variation of thermal conductivity of polymers with the temperature

2. táblázat   A polimerek hővezető képességének változási indexe a hőmérséklet függvényében

Perovskite-based materials usually have thermal conductivity values between 0.2-0.8 W/m·K at room temperature, and it may be even more for some compositions [67, 68]. During the operating and exposing to sunlight, high film temperature can lead to the degradation of perovskite solar cells due to burn-in, defects formation, films cracking, and delamination at the layers' interfaces. Keeping high thermal conductivity is essential to reduce the film temperature and facilitating the dissipation of accumulated heat. However, the interested thing about these materials is that as temperature increases, many parameters increases as well, such as: number of free electrons, lattice vibrations, thermal activation of the phonons and specific heat [69]. Thus, the thermal conductivity of the perovskite-based material is expected to increase. It is noticed that the variation of thermal conductivity with the temperature (within 20-100 °C) for low k-value of perovskite material is generally has the form [70, 71]:

$$k_v = k_{vo} + 0.001\, T \qquad (5)$$

Where, k_{vo} is the k-value of the perovskite-based material at room temperature. While, the variation of k-value with the temperature for high thermal conductivity perovskite material is generally appeared as [72, 73]:

$$k_v = k_{vo} + 0.02\, T \qquad (6)$$

Finally, the overall k-value of the whole perovskite film is the summation of both k-value of perovskite-based materials (k_v) and k-value of polymeric additives (k_p) according to the mixing rule of composite materials and depending on the content of perovskite-based materials (φ_v) and the content of polymeric materials (φ_p). Thus:

$$k = k_v\, \varphi_v + k_p\, \varphi_p \qquad (7)$$

Take into account that the concentration of polymeric materials involved within the whole structure of the film in the perovskite cell is between 1-5 wt% [12-31].

3. Results and discussion

This study includes theoretical analysis to predict the overall thermal conductivity of the perovskite film including the variation happens in the thermal conductivity of polymers that usually involved within the film to enhance the performance of the solar cell. As mentioned previously, five types of polymeric materials have been included in the calculations with their properties. The polymers are: polyethylene oxide (PEO), polyacetylene (PA), polythiophene (PT), polystyrene (PS) and polymethyl methacrylate (PMMA). The calculations assumed three different concentrations of the polymeric additives as: 1, 3 and 5%. Each polymer has served with two degrees of crystallinity; i.e. the maximum value and the minimum value. The thermal conductivity of the perovskite-based material has two values as; 0.2 and 0.8 W/m·K (designed values). The range of temperatures considered was between 20-100 °C.

In general, the low thermal conductivity of perovskite composites is attributed to the shorter lifetimes of the optical phonons and the smaller group velocity of acoustic phonons [73]. Take into account the effects of the values and distribution of band gaps [74].

The results show that the effect of added polymers on the final value of the thermal conductivity of the film may be positive or negative depending on three main factors: k-value of the perovskite-based material, k-value of the polymer and concentration of the polymer. As for the degree of crystallinity, it had no significant effect because the variance in the k-value was very small. Also, the effect of the polymer appears more when it is used with the low k-value perovskite material (0.2 W/m·K) because of the closeness of this k-value with the k-value of the polymer. But when it is used with the high k-value perovskite material (0.8 W/m·K), the perovskite will dominate for two reasons; firstly, its high k-value compared to the polymer, and secondly because of the accelerated increase of this value when the temperature rises comparing to the slow change that occurring on the k-value of the polymer.

The deep analysis of the results has shown that the thermal conductivity of semi-crystalline polymers (PEO, PA and PT) has decreased by the increasing in the temperature, due to less mean free path of phonons, thus it may have a negative impact on the overall thermal conductivity of the perovskite film. On the other hand, the thermal conductivity of amorphous polymers (PS and PMMA) has increased by the increasing in the temperature, due to thermal activation of the phonons, thus it may have a positive impact on the thermal conductivity of overall perovskite cell. However, each polymer has shown some interesting behaviors and intervention effects of polymeric concentration and thermal conductivity of perovskite-based materials.

The addition of PEO to the film has introduced a unique contribution as a semi-crystalline polymer to the perovskite cell due to its high thermal conductivity value (60 W/m·K). This makes the overall *k*-value of the film reaches until (3.7 W/m·K) at room temperature which is higher than the *k*-value of the perovskite-based material and it remains high at any range of temperatures or polymeric concentrations, as shown in *Fig. 1*. The overall *k*-value was between 0.7-3.0 W/m·K for the film of perovskite-based thermal conductivity of (0.2 W/m·K), and between 1.3-4.0 W/m·K for the film of perovskite-based thermal conductivity of (0.8 W/m·K). Hence, this polymer can be useful in application requires efficient heat conduction and thus to obtain higher power efficiency. However, for low perovskite thermal conductivity (0.2 W/m·K), the rise in the temperature up to 100 °C has shown a decreasing in the *k*-value by 25-45% in comparing to the reference value at room temperature (20 °C). While, for high perovskite thermal conductivity (0.8 W/m·K), the rise in the temperature up to 100 °C has shown an increasing in the *k*-value by 10-90% in comparing to the reference value at room temperature. The decreasing in the first case is mainly due to the polymer thermal behavior which was the dominant, where at low value of perovskite *k*-value (0.2 W/m·K) and its corresponding thermal response which was low comparing to the highly response of the polymer that made the overall film follows the polymer behavior. While, in the second case (k_v=0.8 W/m·K), the thermal response of the perovskite was higher, thus the overall film follows the perovskite behavior not the polymer. Furthermore, the increasing in the degree of crystallinity of the polymer from 60 to 80% enhanced the thermal conductivity of the film by 2-3% only, which is disappointed. Note that the increasing in the PEO concentration results in even higher *k*-values in overall.

In the case of using polymers (PA and PT) that have relatively closest thermal conductivity values to the perovskite-based materials, the overall *k*-value of the film was less sensitive to the thermal behavior of the polymeric materials, especially at the high design *k*-value (0.8 W/m·K). The results of adding PA to the film, shown in *Fig. 2*, have revealed an effective thermal conductivity usually more than the designed value at any range of temperatures or polymeric concentrations. However, at low design *k*-value (0.2 W/m·K), the behavior of increasing in overall *k*-value is attributed to the fact that the *k*-value of the polymer was higher in comparing to the perovskite-based material, even though the decreasing ratio in the polymer *k*-value was higher than the increasing ratio in the perovskite *k*-value. At high design *k*-value (0.8 W/m·K), the sensitivity of polymer effect was relatively less due to higher *k*-value of the perovskite-based material compared to the polymer, and secondly because of the faster increase in the *k*-value of the perovskite-based material with the temperature comparing to the slow decreasing in the *k*-value of the polymer. A similar behavior can be seen by the adding of PT to the film, as shown in *Fig. 3*, with even less influence due to the lower *k*-value of PT than that of PA, and corresponding thermal response of PT which was lower than that of PA. However, the rise in the temperature up to 100 °C increased the referenced *k*-value of the film for both PA and PT up to 50% for (k_v=0.2 W/m·K) and up to 150% for (k_v=0.8 W/m·K), where this is actually the same increasing in the *k*-value of the perovskite-based materials. Also,

the enhancement in *k*-value due to increasing in the degree of crystallinity of the polymer was negligible.

In case of adding amorphous polymers (PS and PMMA), that already have low values of thermal conductivity and slow thermal response, the overall *k*-value of the film is rather a function of perovskite-based materials only, even at high temperatures, as shown in *Fig. 4* and *5*, respectively. However, the involving of more than 1% of these polymers within the film was not sufficient to rise the effective thermal conductivity higher, thus it may be a useless choice in the design.
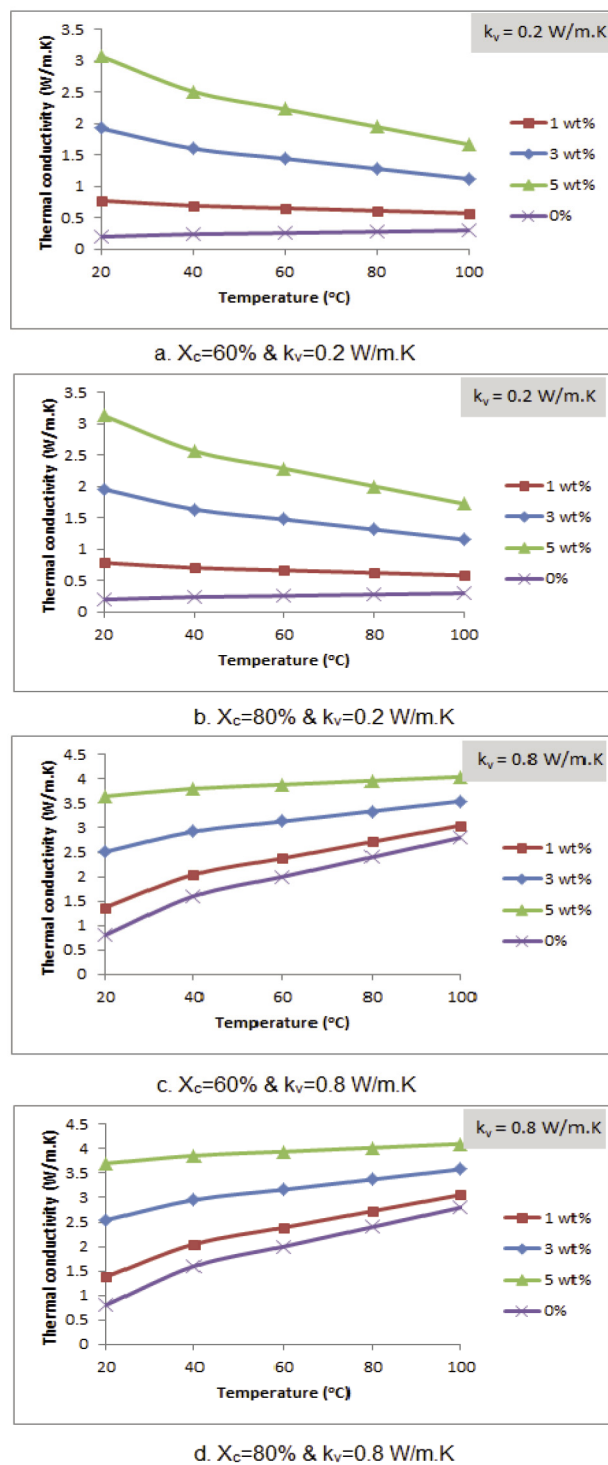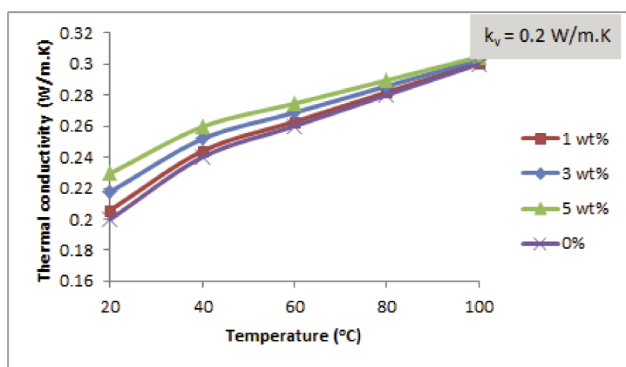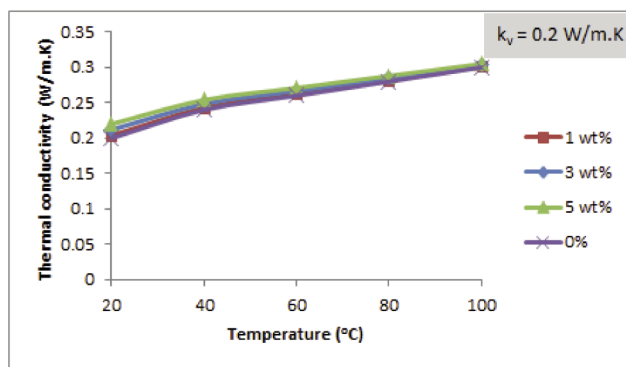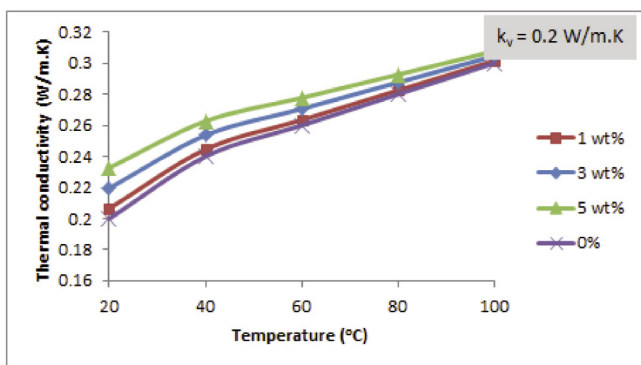

Fig. 1 Overall thermal conductivity of perovskite cell at different PEO concentrations
1. ábra Perovszkit cella teljes hővezető képessége különböző PEO koncentrációk mellett
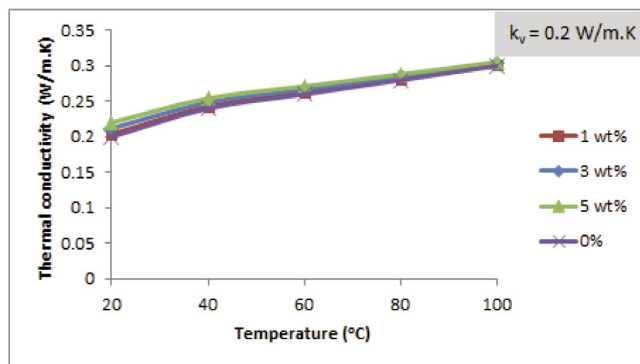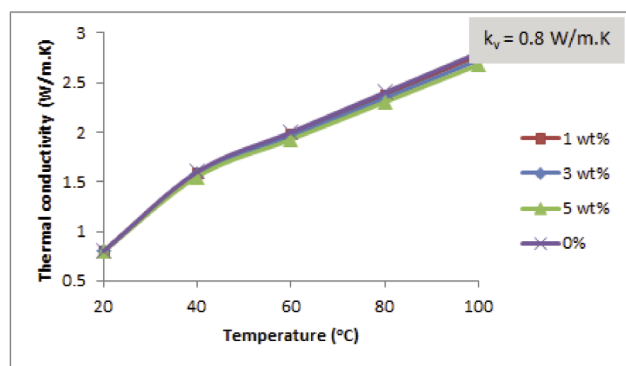
a. X_c=50% & k_v=0.2 W/m.K
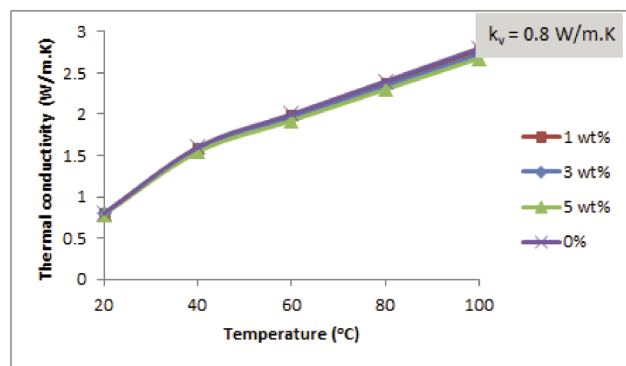

b. X_c=70% & k_v=0.2 W/m.K

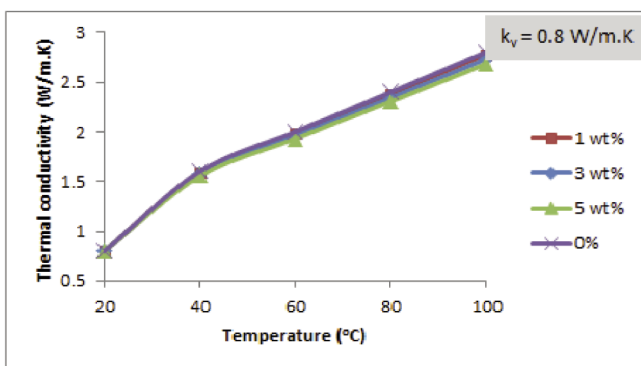c. X_c=50% & k_v=0.8 W/m.K

d. X_c=70% & k_v=0.8 W/m.K

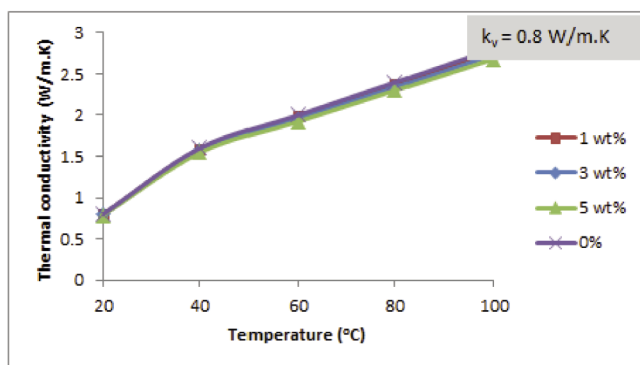a. X_c=40% & k_v=0.2 W/m.K

b. X_c=60% & k_v=0.2 W/m.K

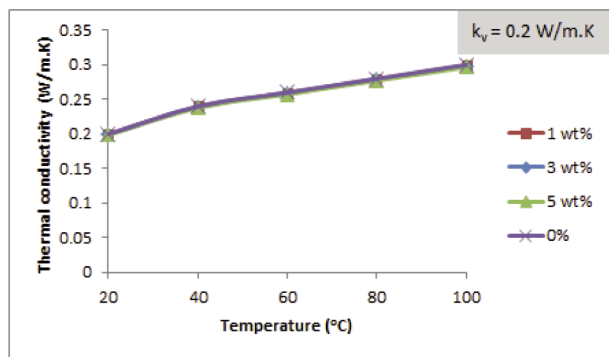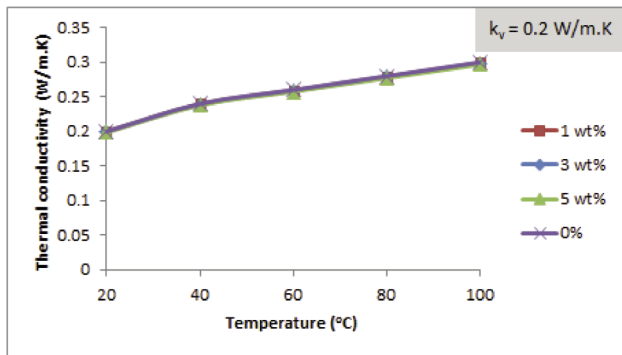c. X_c=40% & k_v=0.8 W/m.K

d. X_c=60% & k_v=0.8 W/m.K

Fig. 2   Overall thermal conductivity of perovskite cell at different PA concentrations
2. ábra   Perovszkit cella teljes hővezető képessége különböző PA koncentrációk mellett
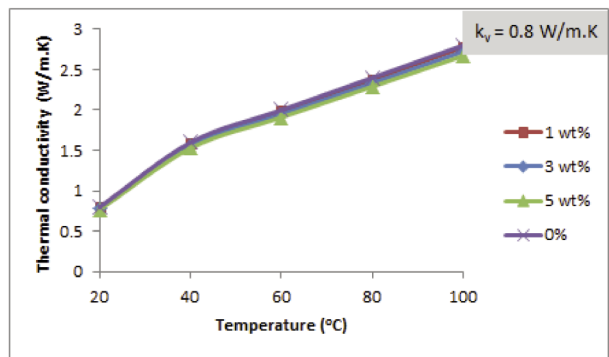
Fig. 3   Overall thermal conductivity of perovskite cell contains at PT concentrations
3. ábra   A perovszkit cella teljes hővezető képessége PT koncentrációban
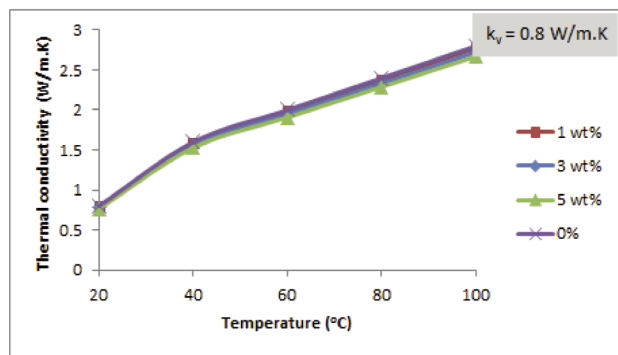
a. X_c=3% & k_v=0.2 W/m.K

b. X_c=8% & k_v=0.2 W/m.K
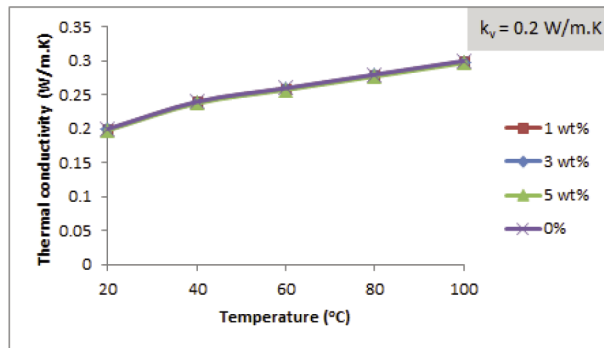

c. X_c=3% & k_v=0.8 W/m.K

d. X_c=8% & k_v=0.8 W/m.K

Fig. 4   Overall thermal conductivity of perovskite cell at different PS concentrations
4. ábra   Perovszkit cella teljes hővezető képessége különböző PS koncentrációk mellett

Study	Added polymers and loadings	Results
Current	PEO, PA, PT, PS and PMMA 1-5% wt.	The addition of PEO to the perovskite makes the overall k-value higher by 2-3 times, and it is reliable for any temperature rise. In the case of using polymers PA and PT, the overall k-value has fair effects. The use of PS and PMMA has no significant effects.
[16]	PFN, PMMA and PS 1-3% wt.	The addition of polymers enhances the crystalline growth. This leads to improve the thermal conduction. Results shown that increasing the amount of PMMA and PS is not required due to very large size aggregates and non-uniform structure, which leads to less ordered crystalline chains.
[17]	PEO 1% wt.	The addition of PEO enhances the power efficiency by 25%. This is satisfies better thermal conduction.
[18]	PEI 1% wt.	The addition of PEI improves the crystallinity of the film, as well as enhances the power efficiency by 26%. This leads to improve the thermal conduction.
[23]	PVP 3% wt.	The addition of PVP improves the crystallinity of the film, as well as enhances the power efficiency by 30%. This leads to improve the thermal stability and thermal conduction.
[70]	N/A	The k-value kept between 0.3-0.4 W/m·K up to 150 ℃.
[71]	N/A	The k-was kept between 0.25-1.0 W/m·K up to 100 ℃ with a drop in the inclination.
[75]	Theoretical approach	At elevated temperatures up to 54 ℃, the k-value was 0.14 W/m·K for the iodine-based perovskite film, and 0.08 W/m·K for the chlorine-based perovskite film.

Table 3   Comparison with certain studies
3. táblázat   Összehasonlítás egyes tanulmányokkal

a. X_c=0% & k_v=0.2 W/m.K

b. X_c=0% & k_v=0.8 W/m.K

Fig. 5   Overall thermal conductivity of perovskite cell at different PMMA concentrations
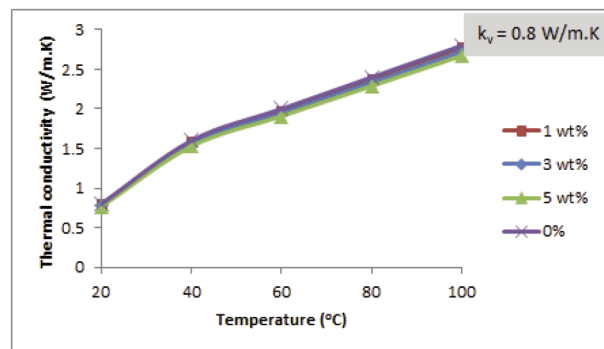*5. ábra   Perovszkit cella teljes hővezető képessége különböző PMMA koncentrációk mellett*

For validation purpose, the current results can be compared with that obtained from certain studies that may help to understand the differences, as shown in *Table 3*.

4. Conclusions

The study linked the impact of changing the thermal conductivity of some common polymeric additives due to temperature rise on the effective thermal conductivity of the overall perovskite film. The obtained results by the calculations yield the following conclusions:

- In general, polymeric additives may have positive or negative contributions on the final value of the thermal conductivity of the film based on the factors: k-value of the perovskite-based material, k-value of the polymer and concentration of the polymer.
- Polymers affect thermally when the perovskite-based material is low (0.2 W/m·K) rather than with high k-value perovskite material (0.8 W/m·K).
- The existence of PEO within the perovskite-based materials makes the overall k-value of the film high at any range of temperatures or polymeric concentrations.
- The overall k-value of the film involved PA and PT was less sensitive to the thermal behavior of the polymeric materials, especially at the high design k-value (0.8 W/m·K).
- The overall k-value of the film has not affected essentially by the adding of amorphous polymers (PS and PMMA).
- There is no significant influence of the degree of crystallinity of the polymer on the overall thermal conductivity of film.

Acknowledgments

References

[1] Kalkman J., Bose S., Merhaba A., Bradley H., Emerging technologies in solar PV: identifying and cultivating potential winners, Arthur D. Little, 2015

[2] Manser S., Christians A., Kamat V., Intriguing optoelectronic properties of metal halide perovskites, Chemical Reviews, 116, 21, 12956–13008, 2016. doi:10.1021/acs.chemrev.6b00136

[3] Kojima A., Teshima K., Shirai Y., Miyasaka T., Organometal halide perovskites as visible-light sensitizers for photovoltaic cells, Journal of the American Chemical Society, 131, 17, 6050–6051, 2009. https://doi.org/10.1021/ja809598r

[4] NREL, Best Research-Cell Efficiencies, National Renewable Energy Laboratory, Retrieved 19-08-2022.

[5] Min H., Lee Y., Kim J., Kim G., Lee S., Kim J., Paik J., Min J., Kim K., Kim S., Kim G., Shin J., Il S., Perovskite solar cells with atomically coherent interlayers on SnO2 electrodes, Nature, 598, 7881, 444–450, 2021. https://doi.org/10.1038/s41586-021-03964-8

[6] Roy P., Sinha N., Tiwari S., Khare A., A review on perovskite solar cells: Evolution of architecture, fabrication techniques, commercialization issues and status, Solar Energy, 198, 665–688, 2020.

[7] Eperon G., Burlakov V., Docampo P., Goriely A., Snaith H., Morphological control for high performance, solution-processed planar heterojunction perovskite solar cells, Adv. Funct. Mater., 24, 151–157, 2014.

[8] Shen Q., Ogomi Y., Chang J., Toyoda T., Fujiwara K., Yoshino K., Sato K., Yamazaki K., Akimoto M., Kuga Y., Katayamad K., Hayase S., Optical absorption, charge separation and recombination dynamics in Sn/Pb cocktail perovskite solar cells and their relationships to photovoltaic performances, J. Mater. Chem. A, 3, 9308–9316, 2015.

[9] Salim T., Sun S., Abe Y., Krishna A., Grimsdale A., Lam Y., Perovskite-based solar cells: Impact of morphology and device architecture on device performance, J. Mater. Chem. A, 3, 8943–8969, 2015.

[10] Nie W., Tsai H., Asadpour R., Blancon J., Neukirch A., Gupta G., Crochet J., Chhowalla M., Tretiak S., Alam M., Wang H., Mohite A., High-effciency solution-processed perovskite solar cells with millimeter-scale grains, Science, 347, 522–525, 2015.

[11] Xiao M., Huang F., Huang W., Dkhissi Y., Zhu Y., Etheridge J., Gray-Weale A., Bach U., Cheng Y., Spiccia L., A fast deposition-crystallization procedure for highly efficient lead iodide perovskite thin-film solar cells. Angew. Chem. Int. Ed. Engl, 53, 37, 9898–9903, 2014.

[12] Wenjing H., Yaoming X., Gaoyi H., Jeng-Yu L., The Applications of Polymers in Solar Cells: A Review, Polymers, 11, 143, 2019. https://doi.org/10.3390/polym11010143

[13] Tripathi N., Shirai Y., Yanagida M., Karen A., Miyano K., Novel surface passivation technique for low-temperature solution-processed perovskite PV cells, ACS Appl. Mater. Interfaces, 8, 4644–4650, 2016.

[14] Li T., Pan Y., Wang Z., Xia Y., Chen Y., Huang W., Additive engineering for highly efficient organic-inorganic halide perovskite solar cells: Recent advances and perspectives, J. Mater. Chem. A, 5, 12602–12652, 2017.

[15] Gnida P., Amin M., Pajak A., Jarzabek B., Polymers in high-efficiency solar cells: The latest reports, Polymers, 14, 1946, 2022.

[16] Masi S., Rizzo A., Aiello F., Balzano F., Uccello-Barretta G., Listorti A., Giglia G., Colella S., Multiscale morphology design of hybrid halide perovskites through a polymeric template, Nanoscale, 7, 18956–18963, 2015.

[17] Chang C., Chu C., Huang Y., Huang C., Chang S., Chen C., Chao C., Su W., Tuning perovskite morphology by polymer additive for high efficiency solar cell, ACS Appl. Mater. Interfaces, 7, 4955–4961, 2015.

[18] Dong Q., Wang Z., Zhang K., Yu H., Huang P., Liu X., Zhou Y., Chen N., Song B., Easily accessible polymer additives for tuning the crystal-growth of perovskite thin-films for highly efficient solar cells, Nanoscale, 8, 5552–5558, 2016.

[19] Bi D., Yi C., Luo J., Décoppet J., Zhang F., Zakeeruddin S., Li X., Hagfeldt A., Grätzel M., Polymer-templated nucleation and crystal growth of perovskite films for solar cells with efficiency greater than 21%, Nat. Energy, 1, 16142, 2016.

[20] Kim H., Yusoff A., Jang J., Polystyrene enhanced crystallization of perovskites towards high performance solar cells, Nanoscale Adv., 1, 76–85, 2019.

[21] Xue Q., Hu Z., Sun C., Chen Z., Huang F., Yip H., Cao Y., Metallohalide perovskite-polymer composite film for hybrid planar heterojunction solar cells, RSC Adv., 5, 775–783, 2015.

[22] Zuo L., Guo H., DeQuilettes D., Jariwala S., Marco N., Dong S., DeBlock R., Ginger D., Dunn B., Wang M., Yang Y., Polymer-modified halide perovskite films for efficient and stable planar heterojunction solar cells, Sci. Adv., 3, e1700106, 2017.

[23] Guo Y., Shoyama K., Sato W., Nakamura E., Polymer stabilization of lead(II) perovskite cubic nanocrystals for semitransparent solar cells, Adv. Energy Mater., 6, 1502317, 2016.

[24] Chaudhary B., Kulkarni A., Jena A., Ikegami M., Udagawa Y., Kunugita H., Ema K., Miyasaka T., Poly(4-Vinylpyridine)-based interfacial passivation to enhance voltage and moisture stability of lead halide perovskite solar cells, ChemSusChem, 10, 2473–2479, 2017.

[25] Wang Y., Luo J., Nie R., Deng X., Planar perovskite solar cells using CH3NH3PbI3 films: A simple process suitable for large-scale production, Energy Technol., 4, 473–478, 2016.

[26] Zhao Y., Wei J., Li H., Yan Y., Zhou W., Yu D., Zhao Q., A polymer scaffold for self-healing perovskite solar cells, Nat. Commun., 7, 10228, 2016.

[27] Wang F., Shimazaki A., Yang F., Kanahashi K., Matsuki K., Miyauchi Y., Takenobu T., Wakamiya A., Murata Y., Matsuda K., Highly efficient and stable perovskite solar cells by interfacial engineering using solution-processed polymer layer, J. Phys. Chem. C, 121, 1562–1568, 2017.

[28] Ji X., Peng X., Wang Q., Ren J., Xiong Z., Yang X., On the performance of polymer:organometal halide perovskite composite light emitting devices: The effects of polymer additives, Org. Electron., 52, 350–355, 2018.

[29] Jiang J., Lang X., Zeng Q., Faheem M., Rong S., Zhao H., Li Y., Polyacetylene derivatives in perovskite solar cells: from defect passivation to moisture endurance, Journal of Materials Chemistry A, Issue 22, 2021.

[30] Yan W., Li Yu., Sun W., Peng H., Ye S., Liu Z., Bian Z., Huanga C., High-performance hybrid perovskite solar cells with polythiophene as hole-transporting layer via electrochemical polymerization, RSC Advances, Issue 62, 2014.

[31] Yan W., Li Y., Li Yu., Ye S., Liu Z., Wang S., Bian Z., Huang C., High-performance hybrid perovskite solar cells with open circuit voltage dependence on hole-transporting materials, Nano Energy, Volume 16, Pages 428-437, 2015.

[32] Fried J., Polymer science and technology, 3rd ed., Prentice Hall, 2014.

[33] Ebewele R., Polymer science and technology, 1st ed., CRC Press, 2000.

[34] Krevelen D., Nijenhuis K., Properties of polymers, 4th ed., Elsevier, 2009.

[35] Ehrenstein G., Polymeric Materials: Structure, Properties, Applications, 1st ed., Hanser Verlag, 2001.

[36] Jia Y., Mao Z., Huang W., Zhang J., Effect of temperature and crystallinity on the thermal conductivity of semi-crystalline polymers: A case study of polyethylene, Materials Chemistry and Physics, Volume 287, 126325, 2022. https://doi.org/10.1016/j.matchemphys.2022.126325

[37] Guo B., Lin Q., Zhao X., Zhou X., Crystallization of polyphenylene sulfide reinforced with aluminum nitride composite: effects on thermal and mechanical properties of the composite, Iran, Polym. J., 24, 965–975, 2015. https://doi.org/10.1007/s13726-015-0385-5

[38] Robbins A., Minnich A., Crystalline polymers with exceptionally low thermal conductivity studied using molecular dynamics, Appl. Phys. Lett., 107, 201908, 2015.

[39] Yu J., Sundqvist B., Tonpheng B., Andersson O., Thermal conductivity of highly crystallized polyethylene, Polymer, 55, 195–200, 2014.

[40] Ruiz-Reina E., Sidrach-de-Cardona M., Piliougine M., Heat Transfer and Working Temperature Field of a Photovoltaic Panel Under Realistic Environmental Conditions, 2019. Available on: https://www.comsol.com/paper/download/199363/ruizreina_abstract.pdf

[41] Hameed R., Mathematical model to investigate the temperature distribution for photovoltaic panels, Journal of University of Babylon for Engineering Sciences, Vol. 26, No. 8, 2018.

[42] Gaitho F., Ndiritu F., Muriithi P., Ngumbu R., Ngareh J., Effect of thermal conductivity on the efficiency of single crystal silicon solar cell coated with an anti-reflective thin film, Solar Energy, Volume 83, Issue 8, 1290-1293, 2009. https://doi.org/10.1016/j.solener.2009.03.003

[43] Pavlovic A., Fragassa C., Bertoldi M., Mikhnych V., Thermal Behavior of Monocrystalline Silicon Solar Cells: A Numerical and Experimental Investigation on the Module Encapsulation Materials, J. Appl. Comput. Mech., 7, 3, 1847-1855, 2021. https://doi.org/10.22055/JACM.2021.37852.3101

[44] Jeong W., Min J., Kim H., Kim J., Kim J., Lee D., Influence of effective thermal conductivity on the performance of the highly efficient CZTSSe thin film solar cells, IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC), pp. 1893-1896, 2018. https://doi.org/10.1109/PVSC.2018.8547943.

[45] Ilahi S., Almosni S., Chouchane F., Perrin M., Zelazna K., Yacoubi N., Kudrawiec R., Râle P., Lombez L., Guillemoles J., Durand O., Cornet C., Optical absorption and thermal conductivity of GaAsPN absorbers grown on GaP in view of their use in multijunction solar cells, Solar Energy Materials and Solar Cells, 141, 291-298, 2015. https://doi.org/10.1016/j.solmat.2015.06.003

[46] Polaskova M., Peer P., Cermak R., Ponizil P., Effect of thermal treatment on crystallinity of poly(ethylene oxide) electrospun fibers, Polymers, 11, 1384, 2019.

[47] Wen X., Su Y., Li S., Ju W., Wang D., Isothermal crystallization kinetics of poly(ethylene oxide)/poly(ethylene glycol)-g-silica nanocomposites, Polymers, 13, 648, 2021.

[48] Meng H., Yu X., Feng H., Xue Z., Yang N., Superior thermal conductivity of poly (ethylene oxide) for solid-state electrolytes: A molecular dynamics study, International Journal of Heat and Mass Transfer, Volume 137, Pages 1241-1246, 2019.

[49] Akaishi T., Miyasaka K., Ishikawa K., Shirakawa H., Ikeda S., Crystallinity of bulk polyacetylene, Journal of Polymer Science: Polymer Physics Edition, Volume 18, Issue 4, Pages 745-750, 1980.

[50] Belov D., Efimov O., Belov G., Synthesis, Properties, and Applications of Polyacetylene and Polyacetylene-Based Composites, in the book: Electrical and Optical Polymer Systems, 1st ed., CRC Press, 1998.

[51] Zhang T., Wu X., Luo T., Polymer nanofibers with outstanding thermal conductivity and thermal stability: fundamental linkage between molecular characteristics and macroscopic thermal properties, J Phys Chem C, 118, 21148–21159, 2014.

[52] Shen S., Hu W., Russell T., Measuring the degree of crystallinity in semicrystalline regioregular poly(3-hexylthiophene), Macromolecules, 49, 12, 4501–4509, 2016.

[53] Youm S., Hwang E., Chavez C., Li X., Chatterjee S., Lusker K., Lu L., Strzalka J., Ankner J., Losovyj Y., Garno J., Nesterov E., Polythiophene thin films by surface-initiated polymerization: mechanistic and structural studies, Chem. Mater., 28, 13, 4787–4804, 2016.

[54] Brun N., Bourson P., Margueron S., Duc M., Study of the thermal behavior of syndiotactic and atactic polystyrene by Raman spectroscopy, JEEP, 00004, 2011.

[55] Simpson A., Rattigan I., Kalavsky E., Parr G., Thermal conductivity and conditioning of grey expanded polystyrene foams, Cellular Polymers, Vol. 39, 6, 238–262, 2020.

[56] Mathur V., Sharma K., Thermal response of polystyrene/poly methyl methacrylate (PS/PMMA) polymeric blends, Heat Mass Transfer, 52, 2901–2911, 2016.

[57] Lin T., Li Y., Wang J., You J., Effect of PMMA molecular weight on its localization during crystallization of PVDF in their blends, Polymers, 13, 23, 4138, 2021.

[58] Elimat Z., Zihlif A., Avella M., Thermal and optical properties of poly(methyl methacrylate)/calcium carbonate nanocomposite, Journal of Experimental Nanoscience, 3:4, 259-269, 2008.

[59] Tawfeeq W. Mohammed, Insulation Materials: Principles and Applications, 1st ed., Mustansiriyah University, 2021.

[60] Hung Anh L., Pásztory Z., An overview of factors influencing thermal conductivity of building insulation materials, Journal of Building Engineering, 44, 2021. https://doi.org/10.1016/j.jobe.2021.102604.

[61] Dos Santos W., De Sousa J., Gregorio R., Thermal conductivity behaviour of polymers around glass transition and crystalline melting temperatures, Polymer Testing, 32, 987–994, 2013.

[62] Hongyu C., Valeriy G., Jian Y., Yunfeng Y., Wei L., Yan H., Libo D., Bin C., Thermal conductivity of polymer-based composites: Fundamentals and applications, Progress in Polymer Science, 59, 41-85, 2016.

[63] Zarandi M., Bioki H., Mirbagheri Z., Tabbakh F., Mirjalili G., Effect of crystallinity and irradiation on thermal properties and specific heat capacity of LDPE & LDPE/EVA. Applied Radiation and Isotopes, 70, 1–5, 2012.

[64] Zinet M., Refaa Z., Boutaous M., Xin S., Bourgin P., Thermophysical characterization and crystallization kinetics of semi-crystalline polymers, Journal of Modern Physics, 4, 2013.

[65] Bai L., Zhao X., Bao R., Liu Z., Yang M., Yang W., Effect of temperature, crystallinity and molecular chain orientation on the thermal conductivity of polymers: a case study of PLLA, J. Mater Sci, 53, 10543–10553, 2018.

[66] Zaki N., Experimental and Theoretical Investigation to Study the Effect of Crystallinity on the Thermal Properties of Polymers, MSc Thesis, University of Mustansiriyah, Iraq, 2021.

[67] Haeger T., Heiderhoff R., Riedl T., Thermal properties of metal-halide perovskites, J. Mater. Chem. C, 8, 14289-14311, 2020.

[68] Hu Z., Aigouy L., Chen Z., Fournier D., Thermal conductivity and diffusivity of triple-cation perovskite halide materials for solar cells, Journal of Applied Physics, 127, 125113, 2020.

[69] Osei-Agyemang E., Adu C., Balasubramanian G., Ultralow lattice thermal conductivity of chalcogenide perovskite CaZrSe3 contributes to high thermoelectric figure of merit, npj Comput Mater, 5, 116, 2019. https://doi.org/10.1038/s41524-019-0253-5

[70] Ye T., Wang X., Li X., Yan A., Ramakrishna S., Xu J., Ultra-high Seebeck coefficient and low thermal conductivity of a centimeter-sized perovskite single crystal acquired by a modified fast growth method, J. Mater. Chem. C, 5, 1255-1260, 2017.

[71] Lee W., Li H., Wong A., Zhang D., Lai M., Yu Y., Kong Q., Lin E., Urban J., Grossman J., Yang P., Ultralow thermal conductivity in all-inorganic halide perovskites, PNAS, vol. 114, no. 33, 8693–8697, 2017.

[72] Chen Q., Zhang C., Zhu M., Liu S., Siemens M., Gu S., Zhu J., Shen J., Wu X., Liao C., Zhang J., Wang X., Xiao M., Efficient thermal conductance in organometallic perovskite CH3NH3PbI3 films, Appl. Phys. Lett., 108, 081902, 2016. https://doi.org/10.1063/1.4942779

[73] Haeger T., Heiderhof R., Riedl T., Thermal properties of metal-halide perovskites, J. Mater. Chem. C, 8, 14289, 2020.

[74] Oltulu O., Ozer Z., Mamedov A., Ozbay E., Band structures of metacompsosite based phononic crystals in quasi-Sierpinski fractals, Építőanyag–Journal of Silicate Based and Composite Materials, Vol. 74, No. 2 (2022), 57–60. p. https://doi.org/10.14382/epitoanyag-jsbcm.2022.9

[75] Aleksandrova M., Pandiev I., Singh A., Implementation of 3ω method for studying the thermal conductivity of perovskite thin films, Crystals, 12, 1326, 2022.