



RESEARCH ARTICLE - PHYSICS

Study of the effect of temperature and concentration variations of some additives in some polymers on the Seebeck effect coefficient and its energy gap

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Article Info.	Abstract
<p><i>Article history:</i></p> <p>Received 26 August 2024</p> <p>Accepted 7 October 2024</p> <p>Publishing 30 March 2026</p>	<p>The objective of this research is to study the Seebeck effect on certain polymers as well as the effect of temperature on their energy gap, therefore the research is divided into two parts, the first concerning the Seebeck effect, and its samples were prepared by adding different concentrations (0.0, 0.028, 0.054, 0.079%) of sodium chloride, sodium carbonate and potassium sulfate to solutions of each of PVA, PEG, CMCHV, PVP and PAM in twice-distilled water. The Seebeck effect coefficient remained practically unchanged with the addition of different concentrations of additives in PEG solutions, but increased with increasing concentrations and temperature in PVP solutions. As for CMCHV solutions and PAM solutions, it decreased with increasing concentrations and temperature. The second part measures the change of energy gap of thin polymer films to which different concentrations of citric acid have been added (40, 57, 66, 72%) due to the change in temperature. The energy gap decreased for all samples with increasing temperature and citric acid concentrations. These results will allow to improve the thermoelectric and electrical properties of polymers and use them in many fields such as industry, medicine and science.</p>
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<p>Keywords: Seebeck effect; energy gap; Polymers; temperature; potential difference.</p>	

1. Introduction

Nonequilibrium thermodynamics describes transport processes in systems that are not in global equilibrium.[1]. The Seebeck effect is related to the theory of non-equilibrium thermodynamics [2]. Thermoelectric material converts heat into electricity and vice versa via the Seebeck effect. Thermoelectric material is of particular importance for energy recovery from waste heat and natural heat source [3]. Thermoelectric effects result from the interference of electric current and heat flow in various materials. [4]. The Seebeck potential is directly proportional only to small changes in temperature, but large changes in temperature give rise to a non-linear relationship with the Seebeck potential [5]. Conductive polymer is of particular interest for thermoelectric applications due to their relatively high electrical conductivity and low thermal conductivity [6].

The energy gap of a polymer is defined as the energy difference between two molecular orbitals, the upper occupied one and the lower unoccupied one, which is usually expressed in electron volts [7-9]. Polymers have properties that make them useful in many different applications of modern technology, especially in construction engineering [10]. Polyvinylalcohol has a semi-crystalline appearance due to hydrogen bonding and the role of the OH group. [11].

it is a widely applied polymer with highly interesting properties, an unique combination of extraordinary physical and chemical properties made it suitable as a biomaterial in numerous significant applications [12]. PVP is a nontoxic, temperature-resistant, biocompatible, inert and biodegradable polymer that can encapsulate drugs at a stable pH and deliver hydrophilic and lipophilic drugs [13].

Polyacrylamide is used to describe any polymer one of whose monomers is acrylamide. [14]. It is a powerful antimicrobial agent that has been used in many medical and industrial applications. It has also been used to improve the shelf life of food products, as a preservative, and to reduce microbial growth in fresh produce. Additionally, polyacrylamide can be used to treat water in order to reduce contaminant levels and prevent infections [15].

CMC is low cost, has excellent hydrophilicity and biocompatibility. It is low cost, has excellent hydrophilicity and biocompatibility. However, it is difficult to achieve good conductivity because it has intrinsic disadvantages such as low mechanical strength [16].

Potassium sulfate dissolves completely and rapidly in water. Its main characteristics are purity, it is a high-quality, chlorine-free, , potent potash fertilizer, especially indispensable for economic crops that are sensitive to chlorine [17].

Citric acid is a crystalline tricarboxylic acid, produced from lemons. [18]. It is used in the food, cosmetic, chemical and pharmaceutical industries [19].

Michael et.al, The high Seebeck coefficient indicates that the metal/polymer/metal design can develop a large entropy difference in internal energy of charge carriers between high and low-temperature metal electrodes to develop electrical potential due to charge transport in conducting polymer film through metal/polymer interface [20]. Sourav et.al, One of the major advantages of polymeric semiconductors is that their thermal conductivity is mostly phononic (lattice thermal conductivity) and remains low with increasing charge carrier concentrations, as needed for TE application [21]. Sai C et.al, this review focuses on molecular perspective and engineering in two key areas: thermoelectric properties in conducting polymers and thermal transport in polymers with phonons as the dominant energy carrier. The review begins with a theoretical explanation of charge and thermal transport in polymers from a molecular and mesoscale perspective. It reviews thermoelectric polymer synthesis and modification methods for increasing thermoelectric efficiency [22]. Khayal et.al, The E_g is measured by examining the ϵ_i optical parameter, whereas the types of electronic transition in the films are detected using Tauc's technique [23]. Szindler et.al, by adding potassium iodide to the meh-ppv polymer it is possible to reduce its energy band gap from 2.16 eV to 1.88 eV and slightly influence on the HOMO and LUMO energy levels [24]. Hamizah et.al, the result has shown that thicker film has lower energy band gap compared to the thinner one. However the electrical conductivity showed an opposite behavior [25].

Table 1: Symbols of the most important physical quantities in the manuscript

Nomenclature & Symbols			
S	Seebeck effect	CMCHV	Carboxymethyl cellulose high viscosity
E_g	energy gap	PAM	Polyacrylamide
T	temperature ($^{\circ}$ K)	PVA	Polyvinylalcohol
V	potential difference (v)	PVP	Polyvinylpyrrolidone
zT	figure of merit	PEG	polyethylene glycol
σ	electrical conductivity(Sm^{-1})	ρ	Resistivity (Ω m)

2. Materials and Measurements

2.1 Materials and Samples preparation

2.1.1 Materials

The solutions of Polyacrylamide(PAM), Polyvinylalcohol (PVA), Polyvinylpyrrolidone (PVP) and polyethylene glycol (PEG) supplied by Sigma-Aldrich GMBH, but Carboxymethyl cellulose high viscosity (CMCHV) was obtained from National Oil Corporation Jowfe Oil Technology/ Ganfouda/ Benghazi/ Libya, , was supplied by Sigma-Aldrich GMBH

2.1.2 Samples preparation

2.1.2.1 The first part: Seebeck effect

Samples(PAM, PVP, PEG, CMCHV) were prepared by dissolving 2.25 grams of polymer in 5 ml of twice-distilled water, then sodium chloride, sodium bicarbonate and potassium sulfate were added in different concentrations (0.0, 0.028, 0.054, 0.079%) each in a separate sample, and two samples of each concentration were prepared. Samples were prepared in this way for all polymers used in the first part of the investigation.

2.1.2.2 The Second part: energy gap

The CMCHV and PVA solutions were prepared by dissolving the polymer in twice-distilled water, then added to different concentrations of citric acid (0.0, 40, 57, 66, 72 %), while stirring at room temperature (30° C), then the solutions were poured onto a level glass plate and allowed to dry at room temperature, so thin films almost 0.02 cm thick were formed. The thickness was measured using a digital micrometer.

2.1.2.2.1 Preparation of citric acid

Squeeze the lemon into a graduated cylinder and add the same amount of water, then gradually add the baking soda and filter the mixture. Add the calcium chloride solution to form a precipitate of calcium citrate. Boil the mixture for two minutes and filter. Then gradually add sulfuric acid to form a precipitate of calcium sulfide and citric acid. Filter the mixture through filter paper and concentrate the acid over low heat to form crystals that are dried in the oven.

2.2 The theory

2.2.1 The first part: Seebeck effect

A potential difference (ΔV) occurs when there is a temperature difference (ΔT) between two different conductors (A and B). The relationship between the potential difference and the temperature difference results in the Seebeck coefficient (S) in the following equation [26]:

$$s = \frac{\Delta V}{\Delta T} \quad (1)$$

The Seebeck effect occurs when there is an intersection between two materials; it is a property of the volume and not of the surface [26]. The performance of thermoelectric (TE) material is determined by a dimensionless quantity called figure of merit (zT) which is expressed by [3, 27]:

$$zT = \frac{S^2 \sigma T}{k} \quad (2)$$

where (σ) is the electrical conductivity, (T) is the absolute temperature, and (k) is the thermal conductivity. The Wiedemann Franz law is [28, 29]

$$\frac{k}{\sigma} = LT \quad (3)$$

Substitute from equation (3) into equation (2):

$$zT = \frac{S^2}{L} \quad (4)$$

where $L = \text{Lorenz number} = 2.45 \times 10^8 \text{ (w}/\Omega\text{k}^2)$ [28, 29].

2.2.2 The Second part: energy gap

The relationship between energy gap, resistivity and temperature is expressed by the following equation:

$$E_g = 2 K_B \frac{\log_{10} \rho}{\frac{1}{T}} \quad (5)$$

It is known that: (K_B) = Boltzmann's constant = $8.617 \times 10^{-5} \text{ ev K}^{-1}$, (ρ) is the resistivity, which is equal to [30]:

$$\rho = \frac{RA}{L} \quad (6)$$

From Ohm's law, the resistance (R) = $\frac{V}{I}$, A = Sample cross-sectional area, L = Sample length and T is the temperature in Kelvin.

2.3 Experiments and Calculations

2.3.1 The first part: Seebeck effect

As shown in figure (1), the sample is divided into two parts, the first of which contains the cold junction at room temperature (30° C), and the other contains the hot junction, where this part is heated by raising its temperature to (05° C) from room temperature, up to (95° C). Each of the two junctions is connected across a voltmeter to measure the voltage difference resulting from the heating, and its reading is recorded each time the temperature of the hot junction increases by ten degrees.

The potential difference between each value and its value at room temperature was calculated, as well as the temperature difference with room temperature. The relationship between the change in potential difference and the change in temperature is plotted and the slope of the resulting curves is determined, then, using equation (1), the energy gap was calculated, which was plotted with different concentrations of additives in the solutions, also using equation (2) figure of merit was calculated and it was plotted with different concentrations.

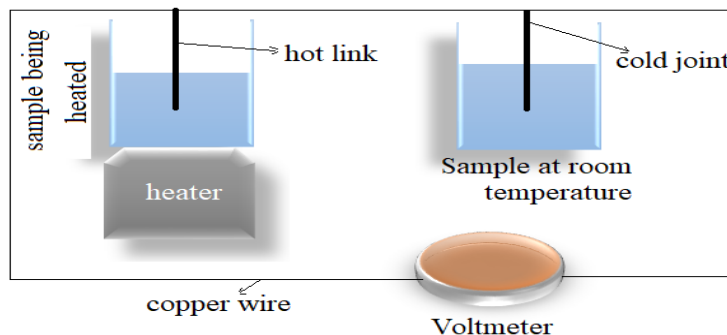


Fig. 1 Schematic diagram of a Seebeck effect circuit

2.3.2 The Second part: energy gap

By applying a potential difference and modifying the temperature, the current intensity in the samples was measured and then from the equation (6), the resistivity was calculated, which was used to calculate the energy gap from the equation (5).

3. Results and discussion

3.1 The first part: Seebeck effect

The results showed that the addition of different concentrations of additives to the solutions did not cause any change in the voltage resulting from a change in the temperature of the solutions PEG, except for a few small values. Therefore, these results have been placed in the table (2), which indicates the appearance of a voltage difference with a change in temperature. However, the addition of sodium chloride, sodium bicarbonate and potassium sulfate in different concentrations did not cause any noticeable change.

Table. 2 Results of the change in the potential difference of solutions (PEG) with changing temperature and concentration of additives.

T(°c)	ΔT(°c)	Δ V(mv)									
		0.0 %	NaCl (%)			NaHCO ₃ (%)			K ₂ SO ₄ (%)		
			0.028	0.054	0.079	0.028	0.054	0.079	0.028	0.054	0.079
30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
35	5.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1
40	10	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.2
45	15	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2
50	20	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2
55	25	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3
60	30	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3
65	35	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.4
70	40	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4
75	45	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4
80	50	0.2	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4
85	55	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.5
90	60	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5
95	65	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.6

Furthermore, there was no change in the potential difference resulting from the change in temperature with the change in sodium chloride concentration in the solutions (NaCl), so the results have been placed in the table (3).

Table. 3 Results of the change in the potential difference of solutions (PEG) with changing temperature and concentration of (NaCl).

T(°c)	$\Delta T(^{\circ}c)$	PVP			
		$\Delta V(mv)$			
		NaCl (%)			
		0.0	0.028	0.054	0.079
30	0	0.0	0.0	0.0	0.0
35	5	0	0	0	0
40	10	0	0	0	0
45	15	0	0	0	0.1
50	20	0.1	0.1	0.1	0.1
55	25	0.1	0.1	0.1	0.1
60	30	0.1	0.1	0.2	0.1
65	35	0.1	0.1	0.2	0.2
70	40	0.2	0.2	0.2	0.2
75	45	0.2	0.2	0.2	0.2
80	50	0.2	0.2	0.2	0.2
85	55	0.2	0.2	0.3	0.3
90	60	0.3	0.3	0.3	0.3
95	65	0.3	0.3	0.3	0.3

Figure (2) shows the relationship between the change in potential difference and the change in temperature for solutions (PVP) containing different concentrations of (NaHCO_3). It is clear that the amount of change in potential difference increases with increase in the amount of change in temperature and also with increase in the concentrations of (NaHCO_3) in the solutions.

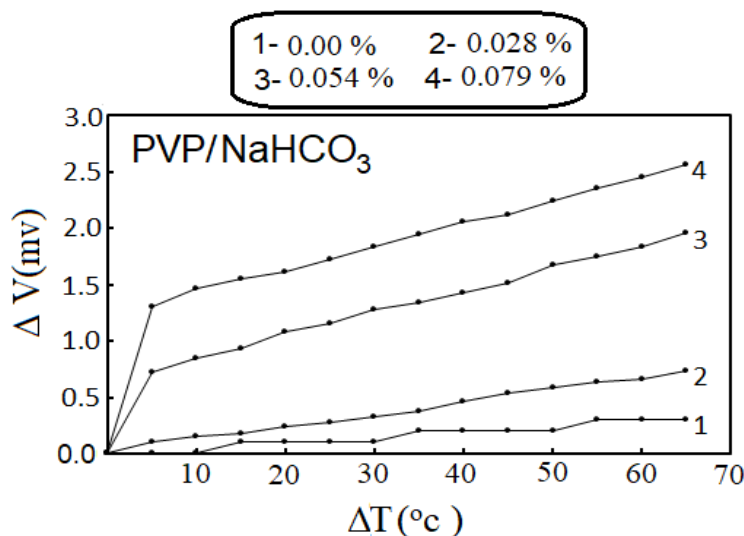


Fig. 2 Relationship between the change in potential difference and the change in temperature for solutions (PVP) containing different concentrations of (NaHCO_3)

Also, figure (3) shows the relationship between the change in potential difference and the change in temperature for solutions (PVP) containing different concentrations of (K_2SO_4). As we observe, the results indicate what figure (2) indicates, namely that the amount of change in potential difference increases with increasing amount of change in temperature due to the Seebeck effect and also with increasing concentrations of (K_2SO_4) in the solutions.

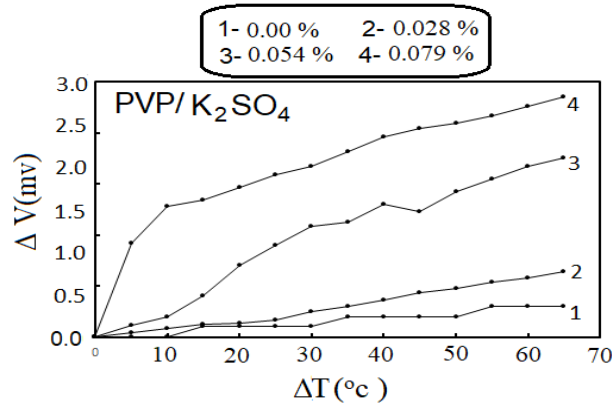


Fig. 3 Relationship between the change in potential difference and the change in temperature for solutions (PVP) containing different concentrations of (K_2SO_4).

From figure (4), it can be seen that the Seebeck effect coefficient (S) increases with increasing concentrations (C) of ($NaHCO_3$) and (K_2SO_4) in (PVP) solutions. Moreover, the Seebeck effect coefficient for solutions containing ($NaHCO_3$) is higher than that for solutions containing (K_2SO_4).

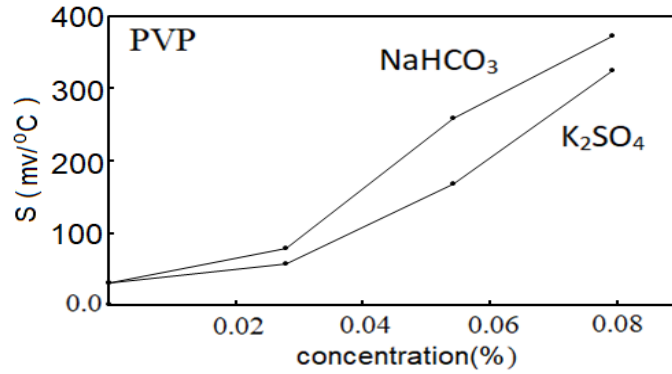


Fig. 4 Concentration of $NaHCO_3$ and K_2SO_4 vs Seebeck effect coefficient of PVP solutions.

Since (zT) is related to (S), the form of figure (5) is similar to figure (4) except that the values of (zT) are smaller than the values of (S). Similarly, it can be seen that the figure of merit increases with increasing concentrations of ($NaHCO_3$) and (K_2SO_4) in (PVP) solutions. Moreover, the figure of merit for solutions containing ($NaHCO_3$) is higher than that for solutions containing (K_2SO_4).

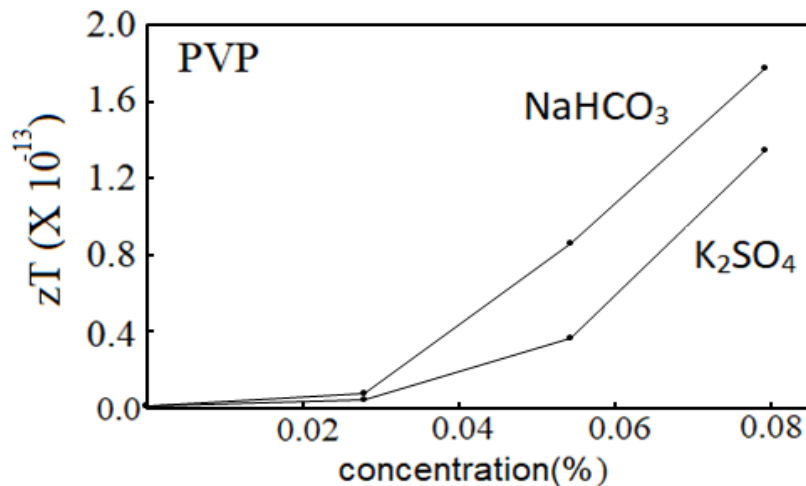


Fig. 5 Concentration of $NaHCO_3$ and K_2SO_4 vs figure of merit of PVP solutions.

When sodium chloride is added to CMCHV solutions, the amount of change in potential difference resulting from the Seebeck effect increases with increasing temperature change, but decreases with increasing sodium chloride concentration, as noted in figure (6).

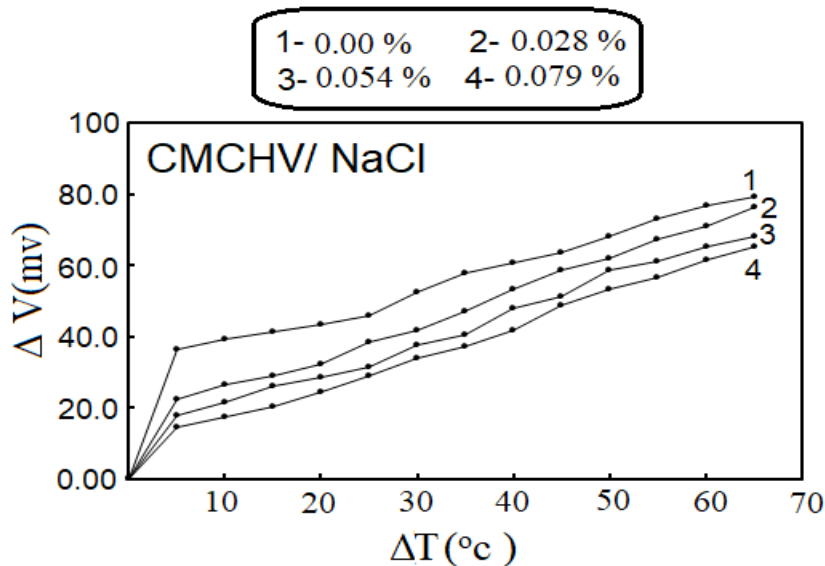


Fig. 6 Relationship between the variation of the potential difference and the variation of the temperature for CMCH) solutions containing different concentrations of (NaCl).

Figure (7) shows the relationship between (ΔV) and (ΔT) for CMCH) solutions to which NaHCO_3 was added at different concentrations. The amount of change in (ΔV) increased when the amount of change in (ΔT) increased, but increasing the concentrations of NaHCO_3 decreased (ΔV).

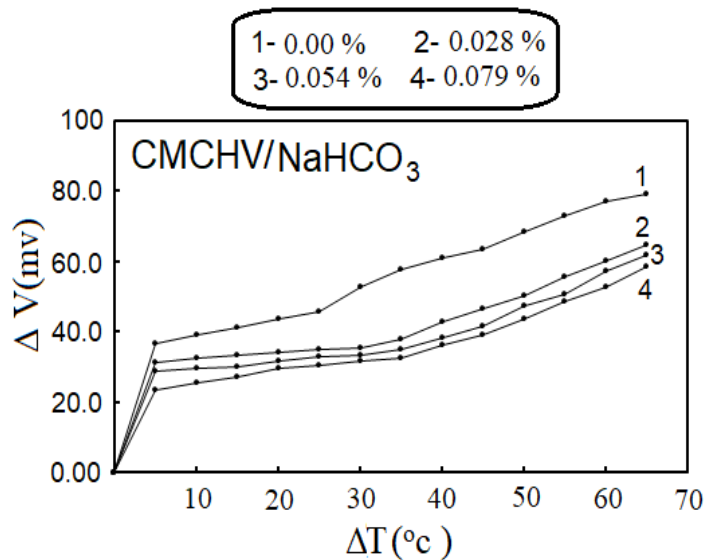


Fig. 7 Relationship between the variation of the potential difference and the variation of the temperature for CMCH solutions containing different concentrations of (NaHCO_3).

The same results from figures (6) and (7) are shown in figure (8) by adding different concentrations of K_2SO_4 to CMCHV solutions, where (ΔV) increases with an increase in (ΔT) and decreases with an increase in the concentrations of K_2SO_4 .

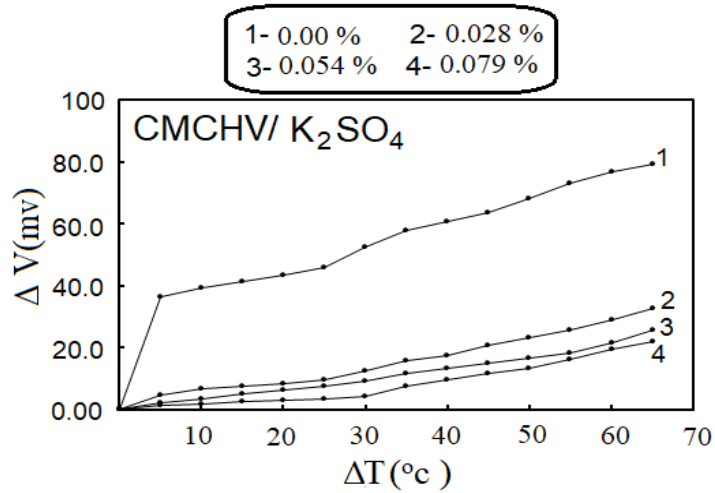


Fig 8 Relationship between the variation of the potential difference and the variation of the temperature for CMCH solutions containing different concentrations of (K_2SO_4).

The relationship between the Seebeck effect coefficient and the concentrations of additives in CMCH solutions in figure (9) shows that the coefficient values decrease with increasing concentrations.

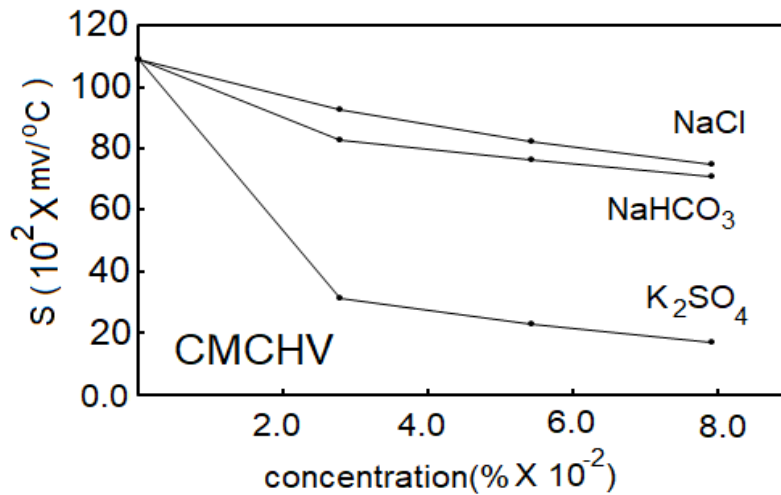


Fig. 9 Concentration of NaCl, NaHCO₃ and K₂SO₄ vs Seebeck effect coefficient of CMCHV solutions.

There is an inverse relationship illustrated in figure (10) between figure of merit and the concentrations of additives in CMCHV solutions.

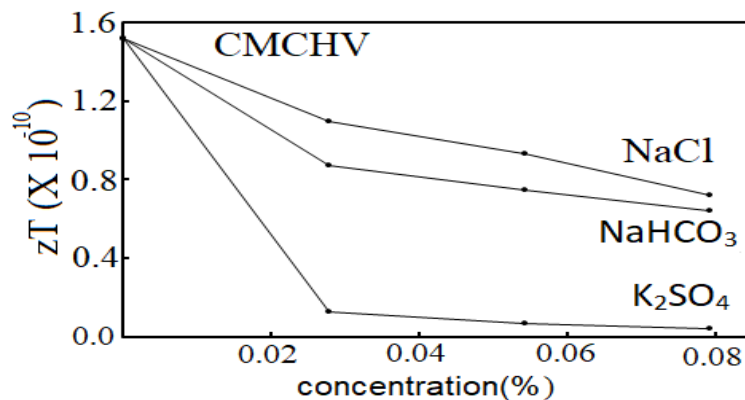


Fig. 10 Concentration of NaCl, NaHCO₃ and K₂SO₄ vs figure of merit of CMCHV solutions.

When adding different concentrations of sodium chloride, sodium bicarbonate, and potassium sulfate, the change in potential difference resulting from the Seebeck effect increases with increasing temperature, but decreases with increasing concentration of these materials, as shown in Figures (11), (12), and (13).

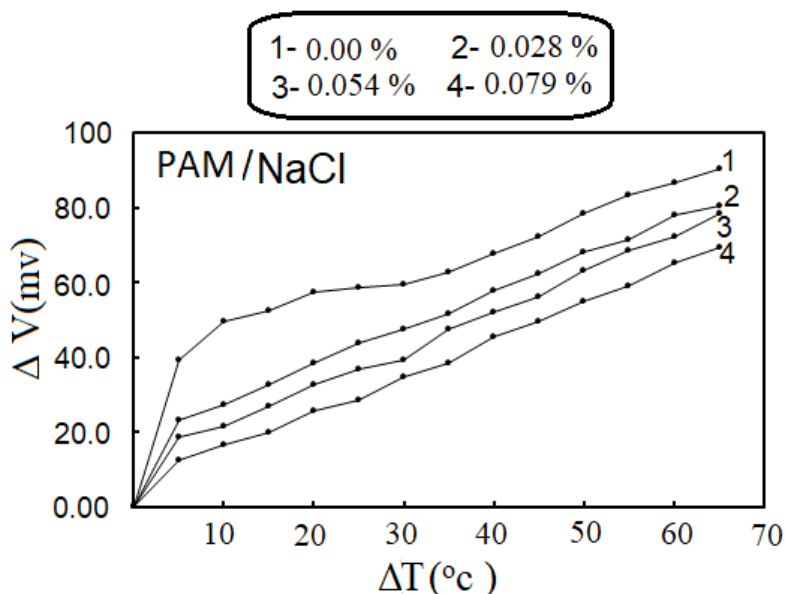


Fig. 11 Relationship between the variation of the potential difference and the variation of the temperature for PAM solutions containing different concentrations of NaCl.

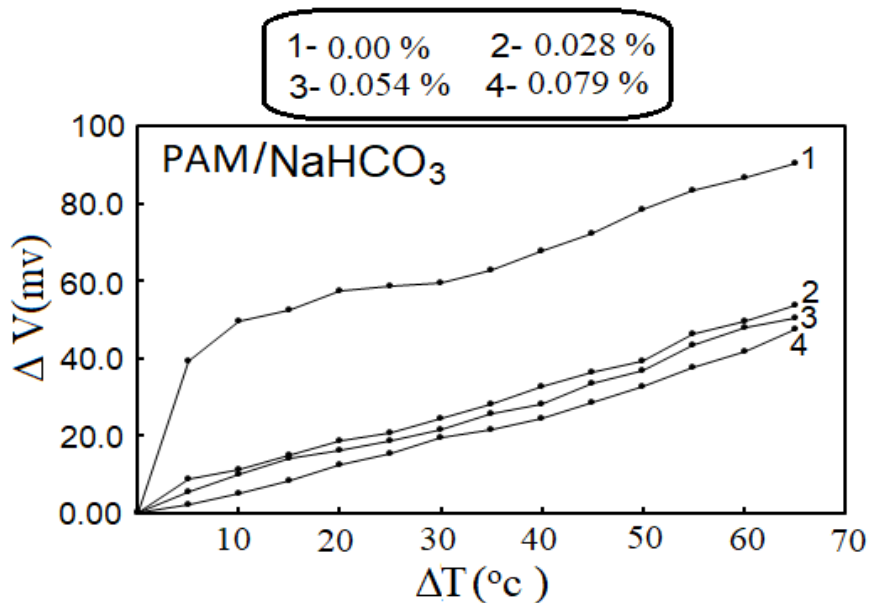


Fig. 12 Relationship between the variation of the potential difference and the variation of the temperature for PAM solutions containing different concentrations of NaHCO₃

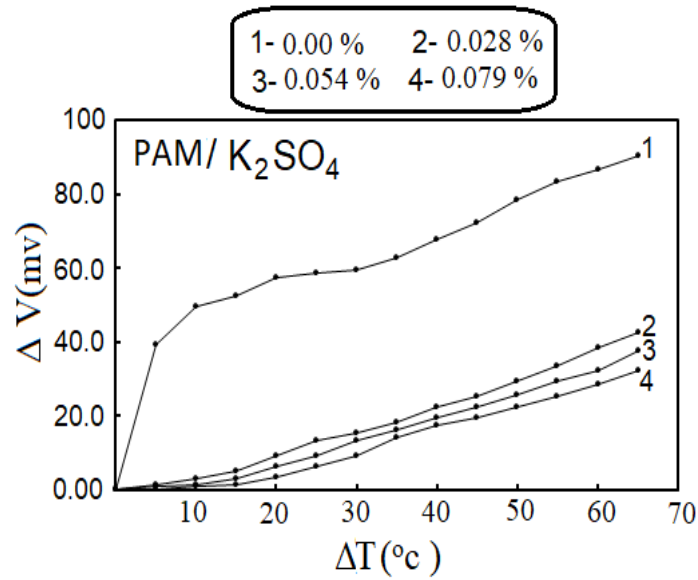


Fig. 13 Relationship between the variation of the potential difference and the variation of the temperature for PAM solutions containing different concentrations of (K_2SO_4).

The relationship between the Seebeck effect coefficient and the concentrations of additives in PAM solutions in figure (14) shows that the coefficient values decrease with increasing concentrations.

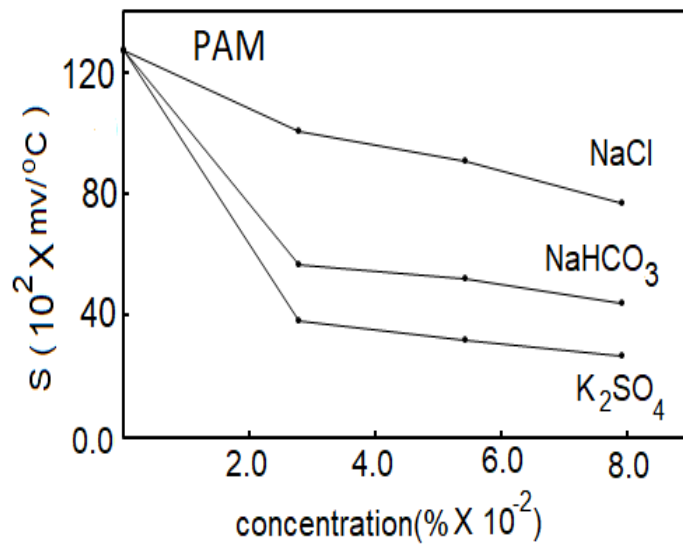


Fig. 14 Concentration of NaCl, NaHCO₃ and K₂SO₄ vs Seebeck effect coefficient of PAM solutions

There is an inverse relationship illustrated in figure (15) between figure of merit and the concentrations of additives in PAM solutions.

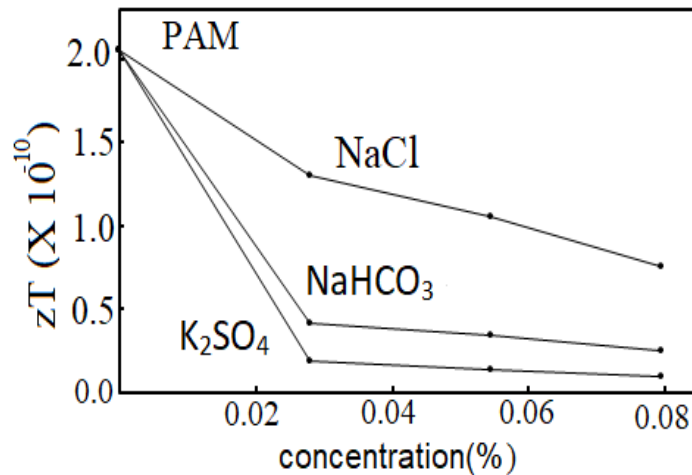


Fig. 15 Concentration of NaCl, NaHCO₃ and K₂SO₄ vs figure of merit of PAM solutions.

3.2 The Second part: energy gap

The relationship between the energy gap of thin films of PVA to which different concentrations of citric acid are added and the temperature is an inverse relationship. Similarly, the relationship between the energy gap and the acid concentration is inverse, as shown in figure (16). The energy gap values decrease until the temperature reaches (420°K), and then their values remain almost constant.

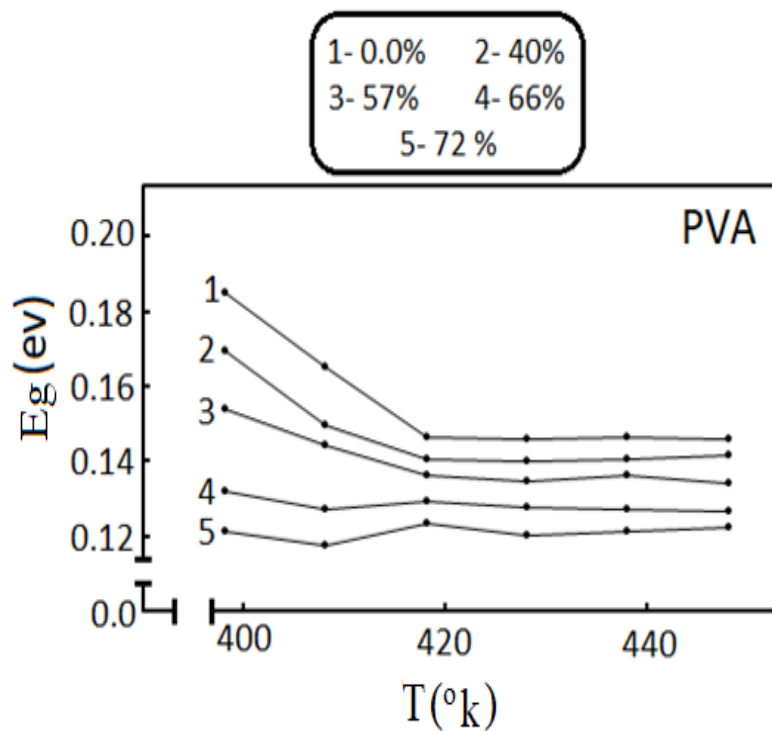


Fig. 16 Energy gap of PVA/C₆H₈O₇ thin films vs different concentrations of citric acid

The relationship between the energy gap of thin films of CMCHV to which different concentrations of citric acid are added and the temperature is an inverse relationship. Similarly, the relationship between the energy gap and the acid concentration is inverse, as shown in figure (17).

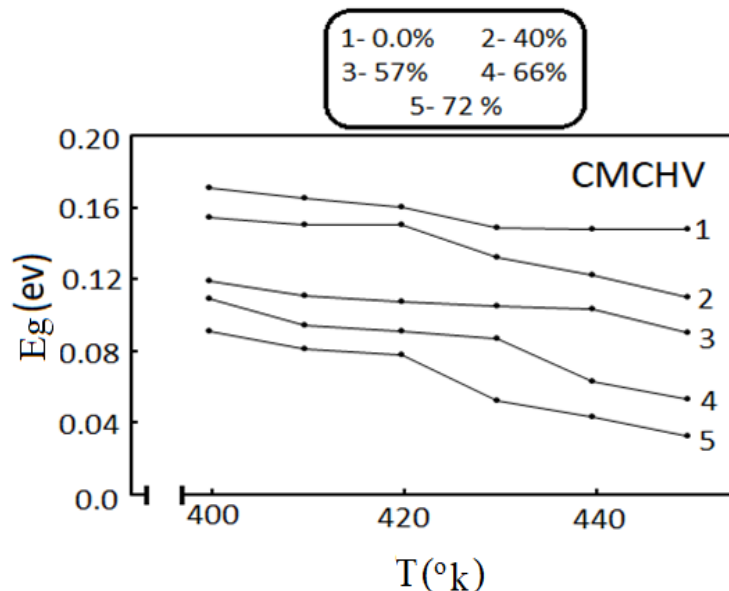


Fig.17 Energy gap of CMCHV/ $C_6H_8O_7$ thin films vs different concentrations of citric acid

Conclusion

In the first part of the study, the Seebeck effect coefficient and the amount of change in potential difference increased with increasing temperature and also with increasing concentrations of sodium bicarbonate and potassium sulfate in PVP solutions, but decreased with increasing temperature and also with increasing concentrations of sodium chloride, sodium bicarbonate and potassium sulfate in CMCHV solutions and PMA solutions. However, the amount of change in potential difference occurs in a small variation compared to the increase in amount of change in temperature and no change occurs with increasing concentrations of additives in PEG solutions. The use of materials with a high Seebeck coefficient is one of the many important factors for achieving efficient behavior in thermoelectric generators, zT value has been successfully presented as a parameter that can be useful for optimization, thus revealing the strengths and weaknesses of all samples, which could be useful for use in many fields. A large S is needed for a good thermoelectric material to have a high ZT .

The decrease in the energy gap of the thin films in the second part of the research is observed. It is known that the lower the energy, the closer the valence band is to the conduction band and the electrons are able to contribute to the intensity of the current passing through the samples. These results will allow to improve the thermoelectric and electrical properties of polymers and use them in many fields such as industry, medicine and science.

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References

- [1] S. Kjelstrup, D. Bedeaux, "Non-equilibrium thermodynamics of heterogeneous systems", World Scientific Publishing Co, Series on Advances in Statistical Mechanics – Vol. 16, 2008. <https://mapmf.pmfst.unist.hr/~pasko/Javni/Nastava/Termodinamika%20nepovratnih%20procesa/Non-Equilibrium%20Thermodynamics%20Of%20Heterogeneous%20Systems.pdf>
- [2] S. Kjelstrup, P.J.S. Viec, L. Akyalcind, P. Zefaniyaa, J.G. Pharoahe, O.S. Burheim, "The Seebeck coefficient and the Peltier effect in a polymer electrolyte membrane cell with two hydrogen electrodes", *Electrochimica Acta* 99, p. 166– 175, 2013. <http://dx.doi.org/10.1016/j.electacta.2013.03.045>
- [3] B. Kim, H. Lim, E. Kim, "Photo-Seebeck effect of conjugated polymers", *Proc. of Spie* Vol. 9171. doi: 10.1117/12.2068245 <https://scholar.google.com.ly/scholar?q=Photo->

Seebeck+effect+of+conjugated+polymers+B.+Kim,+H.+Lim,+E.+Kim&hl=en&as_sdt=0&as_vis=1&oi=scholar

- [4] C. Goupil, H. Ouerdane, K. Zabrocki, W. Seifert, N. F. Hinsche, and E. Müller, "Thermodynamics and thermoelectricity", Wiley-VCH Verlag GmbH & Co. KGaA, 2016 https://application.wiley-vch.de/books/sample/3527413375_c01.pdf
- [5] A. Molki, "Simple demonstration of the Seebeck effect", *Science education review*, 9(3), 2010. <https://files.eric.ed.gov/fulltext/EJ925482.pdf>
- [6] M. Stanford, H. Wang, I. Ivanov, B. Hu, "High Seebeck effects from conducting polymer: Poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) based thin-film device with hybrid metal/polymer/metal architecture", *Research article, Appl. Phys. Lett.* 101, 173304, 2012. <https://doi.org/10.1063/1.4761954>
- [7] E. Bundgaard, "Low band gap polymers for organic photovoltaics," PhD dissertation, Risø National Laboratory and Roskilde University Centre, 2007. <https://backend.orbit.dtu.dk/ws/portalfiles/portal/151471050/17C79B9Fd01.pdf>
- [8] M. C. Scharber and N. S. Sariciftci, "Low band gap conjugated semiconducting polymers", Wiley-VCH GmbH. 2000857 (1 of 9) 2021. DOI: 10.1002/admt.202000857
- [9] E. Bundgaard, F. C. Krebs, "Low band gap polymers for organic photovoltaics", *Science Direct*, 91, 954–985, 2007. doi:10.1016/j.solmat.2007.01.015
- [10] M. M Szindler and M. Szindler, "Comparison of the optical and electrical energy band gap of a thin layer of polyelectrolyte based on MEH-PPV and KI", *IOP Conf. Series: Materials Science and, IOP Publishing* 1178, 012055, 2021. doi:10.1088/1757-899X/1178/1/012055
- [11] A. G. Hadi, Z. Al-Ramadhan and A. Hashim, "Enhanced optical characteristics and low energy gap of SrTiO₃ doped polymeric blend for optoelectronics devices", *Journal of Physics: Conference Series, IOP Publishing* 1963, 012004, 2021. doi:10.1088/1742-6596/1963/1/012004
- [12] M. Teodorescu and M. Bercea, "Poly(vinylpyrrolidone) – a versatile polymer for biomedical and beyond medical applications", *Polymer-Plastics Technology and Engineering*, 54: 923–943, 2015. DOI: 10.1080/03602559.2014.979506
- [13] M. Kurakula, G.S.N. K. Rao, "Pharmaceutical assessment of polyvinylpyrrolidone (PVP): as excipient from conventional to controlled delivery systems with a spotlight on COVID-19 inhibition", *Journal of Drug Delivery Science and Technology*, 1773-2247, 2020. <https://doi.org/10.1016/j.jddst.2020.102046>
- [14] B. Xiong, R. D. Loss, D. Shields, T. Pawlik, R. Hochreiter, A. L Zydney and M. Kumar, "Polyacrylamide degradation and its implications in environmental systems", *npj Clean Water* 1:17, 2018. doi:10.1038/s41545-018-0016-8
- [15] K. Zainulabdeen, R.W. Younis, R. S. Jwad, R. M. Yusop, E. Yousif, A. E. A. Moneim, "An overview of the biological activity of polyacrylamide hydrogels", *Journal of Biotechnology Research Center* 17(2) 2023. <https://doi.org/10.24126/jobrc.2023.17.2.686>
- [16] N. Saadiah M. Ali, A. S. S., D. Zhang, Y. Nagao, "Molecularly conductive behavior of blended polymer electrolyte-based CMC/PVA", *Makara J. Technol*, 27-31, 2019. doi: 10.7454/mst.v23i1.3639
- [17] S. Li, K. Sun, Y. Zhao, G. Nie and S. Song, "Purification and rapid dissolution of potassium sulfate in aqueous solutions", *Royal Society of Chemistry* 9, 2156–2161, 2019. DOI: 10.1039/c8ra08284g
- [18] I. Dudeja, R. K. Mankoo, A. Singh, J. Kaur, "Citric acid: An ecofriendly cross-linker for the production of functional biopolymeric materials", *Sustainable Chemistry and Pharmacy*, Vol, 36, 101307, 2023. <https://doi.org/10.1016/j.scp.2023.101307>
- [19] E. Ksiażek, "Citric acid: properties, microbial production, and applications in industries", *Molecules*, 29, 22, 2024. <https://doi.org/10.3390/molecules29010022>
- [20] M. Stanford, H. Wang, I. Ivanov, and B. Hu, "High Seebeck effects from conducting polymer: Poly(3,4- ethylenedioxythiophene): poly(styrenesulfonate) based thin-film device with hybrid metal/polymer/metal architecture", *Applied physics letters*, 101, 173304, 2012. <http://dx.doi.org/10.1063/1.4761954>

- [21] S, Mondal, D, Dhak, B, Saha,” Polymer and composite based thermoelectrics: Basics, scopes and issues”, Cite this paper: Vietnam J. Chem., 60(6), 689-699, 2022. DOI: 10.1002/vjch.202200118
- [22] S. C. Yelishala, C. Murphy and L. Cui,” Molecular perspective and engineering of thermal transport and thermoelectricity in polymers”, Journal of Materials Chemistry A, 18. 2024. <https://pubs.rsc.org/en/content/articlelanding/2024/ta/d3ta08071d/unauth>
- [23] [23] K. K. Ahmed, S. A. Hussien, S. B. Aziz,” Transferring the wide band gap chitosan: POZ based polymer blends to small optical energy band gap polymer composites through the inclusion of green synthesized Zn²⁺-PPL metal complex”, Arabian Journal of Chemistry, 15, 103913, 2022. <https://doi.org/10.1016/j.arabjc.2022.103913>
- [24] M. M Szindler and M. Szindler, “Comparison of the optical and electrical energy band gap of a thin layer of polyelectrolyte based on MEH-PPV and KI,” IOP Conf. Series: Materials Science and Engineering 1178 (2021) 012055 doi:10.1088/1757-899X/1178/1/012055
- [25] H. N. A. Yusof, H. Salleh, and M. I. N. M. Isa,” Thickness dependent on energy band gap and electrical conductivity of undoped conjugated polymer thin films”, Materials Science Forum, Vol. 846, p. 620-625, 2016. doi:10.4028/www.scientific.net/MSF.846.620
- [26] H. J. Goldsmid,” The physics of thermoelectric energy conversion”, Morgan & Claypool Publishers, 2017. <https://doi.org/10.1088/978-1-6817-4641-8>
- [27] J. Li, A. B. Huckleby, M. Zhang,” Polymer-based thermoelectric materials: a review of power factor improving strategies,” Journal of Materiomics, 8 204-220, 2022. <https://doi.org/10.1016/j.jmat.2021.03.013>
- [28] A. Surve,” The relation between thermal conductivity and electrical conductivity of assorted materials”, International Journal for Technological Research In Engineering Vol, 6, 2019. <https://ijtre.com/wp-content/uploads/2021/10/2019060615.pdf>
- [29] Dissemination of IT for the Promotion of Materials Science (DoITPoMS),” Introduction to thermal and electrical conductivity (all content)”, University of Cambridge, 2024. https://www.doitpoms.ac.uk/tlplib/thermal_electrical/printall.php
- [30] S. Brothers,” Energy band gap by four probe method”, Operating instructions. [https://khalsacollegepatiala.org/dept/deptuploads/25/files/Four%20probe%20method\(1\).pdf](https://khalsacollegepatiala.org/dept/deptuploads/25/files/Four%20probe%20method(1).pdf)