

Review Article

Research Progress on Polymeric Inorganic Nanocomposites Insulating Materials

Guang Yu , Yujia Cheng , and Zhuohua Duan 

Mechanical and Electrical Engineering Institute, University of Electronic Science and Technology of China, Zhongshan Institute, Zhongshan 528400, China

Correspondence should be addressed to Yujia Cheng; chengyujia1068@163.com

Received 9 February 2022; Revised 10 September 2022; Accepted 19 September 2022; Published 3 December 2022

Academic Editor: Iaroslav Gnilitzki

Copyright © 2022 Guang Yu et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

With the rapid development of power energy, electronic information, rail transit, and aerospace industries, nanocomposite dielectric materials have been widely used as new materials. Polymer/inorganic nanocomposite dielectric materials possess excellent physical and mechanical properties. In addition, numerous unique properties such as electricity, thermal, sound, light, and magnetic properties are exhibited by these materials. First, the macroscopic quantum tunneling effect, small-size effect, surface effect, and quantum-size effect of nanoparticles are introduced. There are a few anomalous changes in the physical and chemical properties of the matrix, which are caused by these effects. Second, the interaction mechanism between the nanoparticles and polymer matrix is introduced. These include infiltration adsorption theory, chemical bonding, diffusion theory, electrostatic theory, mechanical connection theory, deformation layer theory, and physical adsorption theory. The mechanism of action of the interface on the dielectric properties of the composites is summarized. These are the interface trap effect, interface barrier effect, and homogenization field strength effect. In addition, different interfacial structure models were used to analyze the specific properties of nanocomposite dielectric materials. Finally, the research status of the dielectric properties of nanocomposite dielectric materials is introduced.

1. Introduction

With the rapid development of power energy, electronic information, rail transit, and aerospace industries, nanocomposite dielectric materials have been widely used as new materials [1]. Research on the structure, performance, and application of these materials is in frontier science and technology. They also promote social progress. Research on the hierarchical structure and macroproperties of nanocomposite dielectric materials is crucial for scientific research and technology applications [2]. To promote the technological progress of nanocomposite dielectric materials, the scientific conference themed “hierarchical structure and macroproperty of nanocomposite dielectric materials” was convened in Beijing in 2009. At this conference, numerous experts agreed that nanocomposite dielectric research is a trans-specialty subject [3]. This research is progressive and challenging. Theoretically, the traditional dielectric theory would develop into a low-dimensional dielectric system that possesses

excellent physical and chemical properties and scale effects [4]. The aim is to establish a relationship between the material microstructure and macroproperties. The research core is to investigate the dielectric behavior in the mesoscopic scale, which is between macroscopic and microscopic scales. In addition, in technological applications, nanodielectrics possess unique space–time hierarchical structures, which help promote the development of the field of electrical insulation. According to statistics, a 60% power system failure originates from electrical insulation issues. Dielectric insulating materials and technology are the basis of electrical and electronic engineering. Dielectric insulating materials determine the service life of power equipment and electronic devices. In the fields of power transmission, rail transit, navigation technology, and aerospace technology, nanodielectric materials and technology are widely used [5].

When choosing a dielectric material, a key consideration is the electrical breakdown property, which refers to the capacity of a dielectric material to exhibit insulation

properties under an electric field [6]. An additive can improve and balance the comprehensive performance of solidified polymer dielectrics and also enhance the breakdown strength of materials. Considerable nanomaterials and nanotechnology research has been conducted in this regard [7]. Specifically, a new material base has been established for subsequent cutting-edge breakdown research, and intensive research on breakdown mechanisms is being promoted. Currently, the mechanism underlying the breakdown properties of polymer nanocomposites has been substantially studied [8].

2. Fundamental Effects of Nanoparticles

Nanoparticles possess several unique properties. Therefore, the nanoparticle effect is the main reason for the changes in the physical and chemical properties of the matrix. However, it also has several fundamental effects. These effects are the macroscopic quantum tunneling effect, small-size effect, surface effect, and quantum-size effect [9].

2.1. Macroscopic Quantum Tunneling Effect. The quantum tunneling effect indicates that the probability of microparticles with volatility beyond their energy barrier is zero. When applied to macroscopic quantities, such as microparticle magnetization and magnetic flux in quantum coherent devices, it is known as the macroscopic quantum tunneling effect. It is predominantly used to explain the reason for nickel nanoparticles maintaining superparamagnetism at low temperatures. In addition, it also explains that the phenomena related to the domain wall motion speed are not related to the temperature in the Fe–Ni films.

2.2. Small-Size Effect. When the nanoparticle size is similar to the wavelength of light, the periodic boundary condition of crystalline materials is destroyed. The atomic density in the vicinity of the surface layer of the amorphous nanoparticles is decreased. The electricity, thermal, sound, light, and magnetic properties of the materials change significantly. This is known as the small-size effect. For example, when the ferromagnetic changes to paramagnetic, the color of the metal changes to black. When the superconductors change to a conductor, the ordered structure changes into a disordered structure. Both these effects are small-size effects.

2.3. Surface Effect. When the particle size decreases to the nanoscale, the ratio of material surface atoms to total atoms increases. Because the number of nanoparticle surface atoms increases, the atomic coordination is insufficient. There are numerous dangling bonds that promote the surface chemical mobility [10]. The increase in specific surface area and surface energy would cause an instability in the material conditions. These materials can easily react with other atoms.

2.4. Quantum-Size Effect. When the particle size decreases to the nanoscale, according to the energy band theory, the electron quasicontinuum level changes to a discrete energy level around the metal nanoparticle Fermi level. In semiconductor nanoparticles, the highest discontinuous molecule orbital

energy is occupied, but the lowest molecular orbital energy is unoccupied, and the bandgaps are increased.

2.4.1. Nanocomposite Interface Bonding Theory. The polymer/inorganic nanocomposite interface is the interaction region between the inorganic particles and the polymer matrix. From the test results, the comprehensive performance of composites is not simply the cumulation of single-component performances. Each component plays an independent role, and depends on each other within the interface. The interface interaction of polymers/inorganic nanocomposites is mainly through covalent bonds, hydrogen bonds, van der Waals forces, and electrostatic interactions. The mechanism of the action between the two phases can be summarized as infiltration adsorption, chemical bonding, diffusion, electrostatic, mechanical connection, deformable layer, and physical adsorption theories.

2.4.2. Infiltration Adsorption Theory. In this theory, the high polymer adhesion can be divided into two phases: first, the high polymer macromolecular chains approach the polar group on the adherend surface according to the macro- and micro-Brownian movement. The nanofluid viscosity is higher with the nanoparticles increasing. This is because the frictional resistance between the particles in nanofluid increases with the nanoparticles increasing. For the same content, the smaller the nanoparticles size is, the higher the nanofluid viscosity is. The nanofluid viscosity is lower with the temperature increasing. The main reason is the rise of temperature, which causes the molecules' distance increasing and attraction between molecules decreasing. Second, when the distance between the adherend and the binder molecule is less than 105 nm, the van der Waals force produces adsorption.

2.4.3. Chemical Bond. When the groups in the two substances react, the two substances join via chemical bonding, and an interfacial structure is formed. The strength of interfacial bonding depends on the quantity and type of chemical bonds between the two substances. Because of the high energy in chemical bonds, these interfaces are stable. A prime example is an interface formed between the fiberglass and the coupling agent in the matrix. The coupling agent is a layer of material with a bifunctional coating on the glass fiber surface. Parts of the functional group in the coupling agent form covalent bonds with the molecules on the glass fiber surface. Other parts of the functional group connect with the matrix resin via chemical bonding. Both combine closely with the coupling agent.

2.4.4. Diffusion Theory. The head end of the macromolecular segment and extending end of branched chains on two high-polymer surfaces will cause diffusion and entanglement on the interaction surface, thereby forming a molecular network. The degree of diffusion and entanglement is related to the molecular structure, component, and free energy of the molecular segments on the matrix surface. After surface treatment, the surface molecules are effectively diffused and entangled in the interface action area. The degree of closeness of the interface depends on the head end of the macromolecular segment quantity, molecular polarity, interactive force, and entanglement molecule quantity. In this theory, a

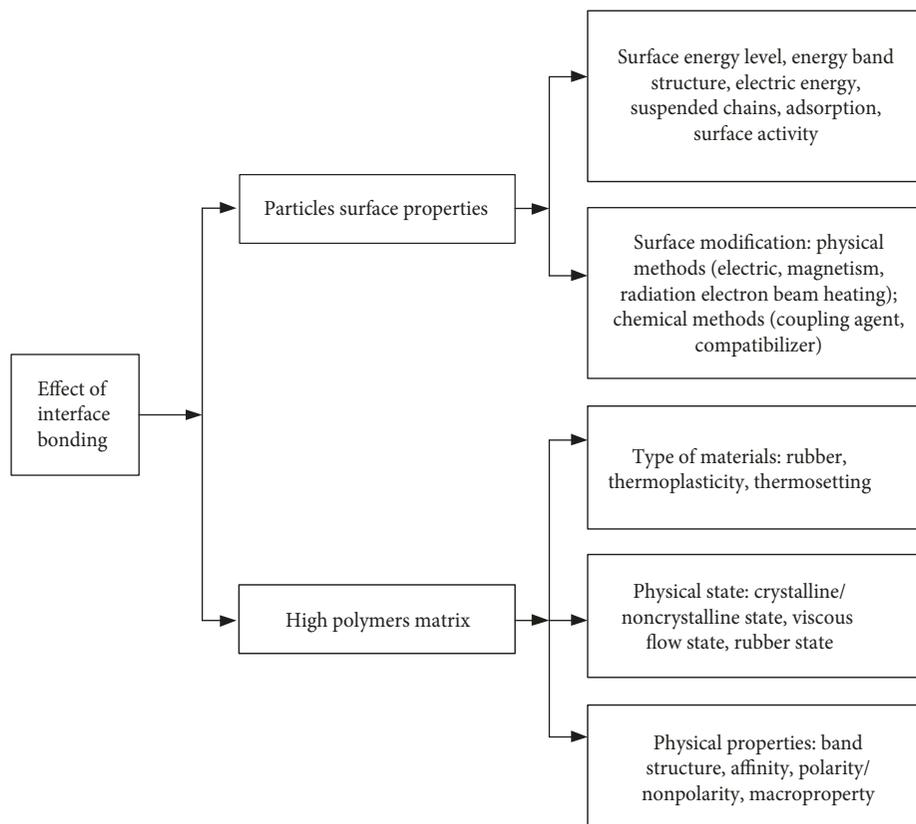


FIGURE 1: The factors which affect the interface binding.

combination of chemical bonds with molecular diffusion forms an interpenetrating polymer network structure at a certain thickness of the interface layer.

2.4.5. Electrostatic Theory. Contact between two substances causes the formation of an electric double layer, from which the electrostatic interactions form. In this theory, it is challenging to form a close interface structure using polymers of similar polarities. However, a strong bond strength exists between homopolar polymers, which forms a close interface structure.

2.4.6. Mechanical Connection Theory. In this theory, the bonding between two phases is realized only via mechanical action. Therefore, mechanical connection theory matches the bonding theory.

2.4.7. Deformable Layer Theory. In this theory, after the material surface modification, the treatment agent forms a plastic layer on the interface surface. This can decrease the interfacial stress. In addition, it can reduce the effect of interfacial forces.

The surface modification is used as a part of the interface. Its mechanical properties play a role in the even transferring of stress and weakening of the interfacial stress. In addition, it plays a buffering role.

2.4.8. Physical Adsorption Theory. When the adsorption of each component is different, the close interface structure can be constituted by physical adsorption.

2.4.9. Maxwell–Wagner–Sillars Phenomena. Owing to the difference of dielectric constant and conductivity between the heterogeneous, the free charge carrier accumulates in interface under electric field effect. It is interfacial polarization. The polarization is produced. In low filler content, the matrix crystalline characteristics in composite make the main effect on Maxwell–Wagner polarization intensity. With a one-dimensional crystal distribution model, the interface density in composites is characterized. Combined with the position of composites loss peak, there is an obvious negative correlation between interface density and Maxwell–Wagner interfacial polarization slack time.

In nanocomposites, as the nanoparticle size decreases, the specific surface area of the nanoparticles increases. In the polymer matrix, the proportion of the interface structure also increases. Therefore, the interface structure is the most important factor affecting the properties of composites. The factors influencing interfacial bonding are shown in Figure 1.

As shown in Figure 1, the effect of interfacial bonding on composite properties is generalized according to the nanoparticle surface properties and polymer matrix. In the research of nanodielectrics, the action mechanism of the interface on the dielectric properties of composites can be summarized as follows:

- (1) Interface trap effect: adding nanoparticles into the matrix introduces numerous interface traps. These traps effectively capture the carriers. Thus, the carrier

mobility and mean free path are reduced, thereby affecting the charge transportation process and conductivity properties of the nanodielectric. The carrier energy in the dielectric decreases. Thus, the destruction caused by the carrier impacts the polymer molecular segment decreases, consequently prolonging the polymer service life [11].

- (2) Interface barrier potential effect: the nanocomposites possess excellent properties such as partial discharge-resistance aging, electrical tree resistance, electrical leakage mark resistance, and thermal conductivity. This is due to the blocking and scattering effects of the interface barrier between the polymer matrix and the inorganic nanoparticles. In addition, inorganic nanoparticles provide a pathway for phonon thermal conduction [12].
- (3) Homogenization field strength effect: the trapped carrier causes homopolar charge accumulation in the local polymer. A reversed electric field appears, which offsets part of the applied electric field. The field strength required for the charges injected from the electrode increases. On the one hand, space charge accumulation decreases. On the other hand, the internal electric field distribution homogenization of the polymer increases the short-time breakdown voltage of the polymers [13].

In addition, the polymer/inorganic nanoparticle interface has distinct effects on the composite crystallinity, chain entanglement density, and molecular movements [14].

3. Interface Model of Nanocomposite Dielectric

The interface structure of a nanodielectric is an important factor that affects the dielectric properties. Therefore, in T. J. Lewis's opinion, the interface structure is essentially the same as that of the nanodielectric. Since 2000, researchers have discussed the relationship between the interface and dielectric properties from different angles. Different interface structure models were used to explain the special properties of nanocomposite dielectrics [15]. The main interface structure models currently are discussed in the following subsections.

3.1. Wikes Model of Interface. The different interfaces depend on the nanoparticles or the polymer matrix properties. The morphology of the mesoscopic region can be observed using X-ray diffraction, and the Wikes model of the interface is shown in Figure 2 [16]. The sol-gel method is one kind of stable transparent sols system. It uses the chemical compound with high chemically active component as the precursor. The raw material is mixed uniformly under liquid phase. The material goes through hydrolysis and condensation. The sol polymerizes slowly during the aged micelle, from which the gel with a three-dimensional net structure generates. After the drying and sintering, the nanostructure material is prepared. When the polymers react with nano-SiO₂ particles via the sol-gel method, a Si-rich layer forms at the

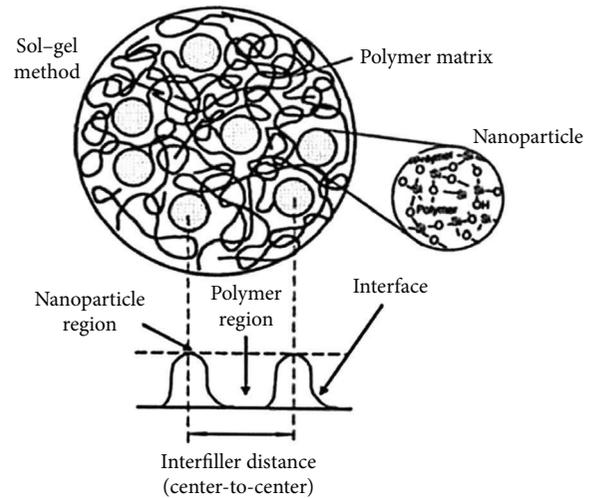


FIGURE 2: Wikes model of interface.

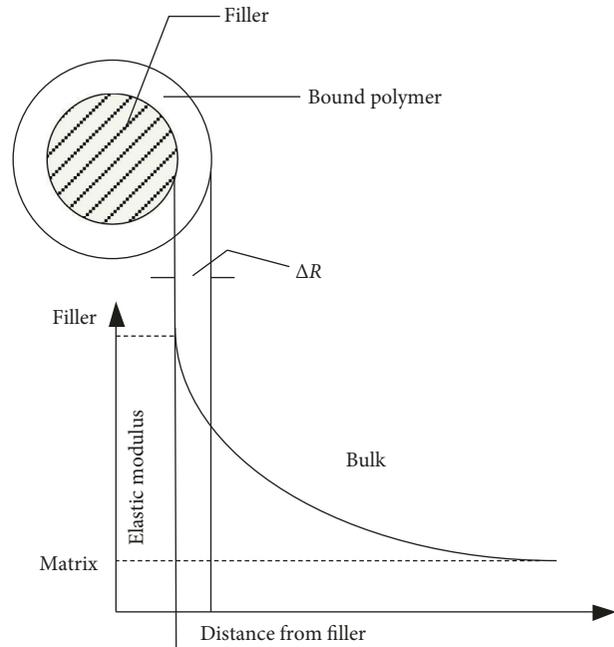


FIGURE 3: Polymer-binding mode.

interface. The nano-SiO₂ particles are compatible with polymers, and two states are present:

- (1) Some of the nano-SiO₂ particles spread in the covalent bond system outside the polymer area.
- (2) The interpenetrating network structure is formed via hydrogen bond interactions.

3.2. Polymer-Binding Model. Based on the theory of mechanical interaction, in the polymer-binding model, the macromolecular chains of the polymer matrix are restricted in the vicinity of the nanofiller interface, and a binding layer is

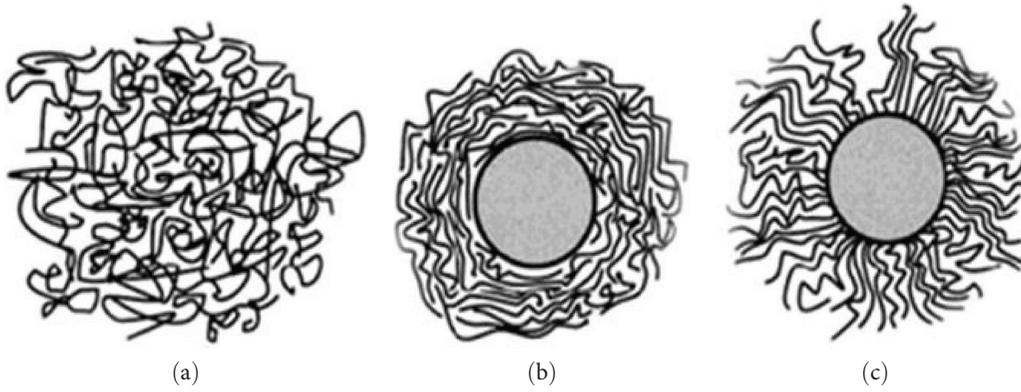


FIGURE 4: Interface-ordering model: (a) high polymer chain free arrangement in polymer matrix; (b) high polymer chain paralleled arrangement around the nanoparticles; (c) radial high polymer chain bonding with nanoparticles.

formed. The thickness of the binding layer depends on the interaction force between the polymer molecular chains and nanofillers. If this interaction force is strong, the thickness of the binding layer increases. The polymer-binding model is shown in Figure 3 [17].

3.3. Interface-Ordering Model. The interface thickness between the polymer matrix and nanoparticles is related to the chemical bond or physical bond. The polymer macromolecular chains are attached to the nanoparticle surface via physical and chemical actions. The macromolecular chains are arranged on the nanoparticle surface in radiating or parallel ways. The structure was ordered around the nanoparticles. The interface structure depends on the polymer matrix as well as on the addition of particle types and surface modification conditions. Because the forces acting between the nanoparticles and the polymer matrix are different, the different interfaces have different effects on the nanocomposite properties. When they possess the same polarity, the polymer macromolecular chains connect to the nanoparticles via bonding interactions. An orderly arrangement forms. A sketch map of the interface-ordering model is shown in Figure 4 [18].

3.4. Single-Layer Structure Model. This model was proposed by Professor T. J. Lewis at Wales University. It is based on the research of colloid chemistry double electrical layer theory, as shown in Figure 5. A in Figure 5 shows the addition of the nanoparticles, B shows the polymer matrix, and AB shows the interface between the nanoparticles and polymer matrix. Suppose that the nanoparticles disperse uniformly in the matrix, and the image charges appear in the matrix because of the adsorption from the ionizing in the nanoparticle surface groups or ions in the matrix. Professor T. J. Lewis believes that the electron polarization and permanent dipole steering in the matrix can be expressed by the Born formula, which is shown in Formula (1). In Formula (1), U is the lattice energy of ionic crystal. M is Madelung constant, which is related to ion crystal structure. Z_+ and Z_- are cationic charges and anionic charges, respectively. r_0 is the spacing between the adjacent cation and anion. The unit of U is kJ/mol. The unit of r_0 is pm.

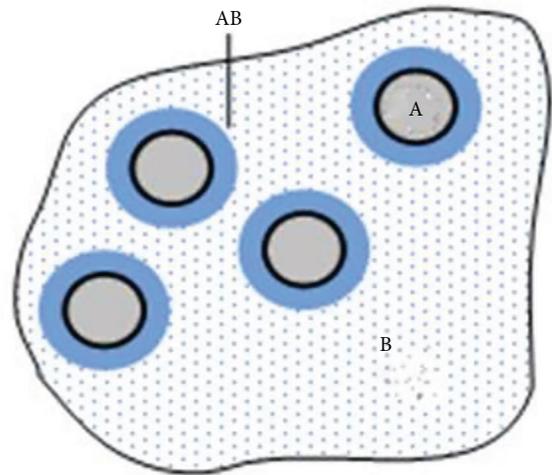


FIGURE 5: Single-layer structure model.

$$U = \frac{138940MZ_+Z_-}{r_0} \left(1 - \frac{1}{n}\right). \quad (1)$$

In the matrix, the electrolyzed and movable charges produce a spreading charge dielectric bilayer. It can be defined using the Poisson and Boltzmann equations [19], which are shown in Formulae (2) and (3). In Formula (2), Δ is Laplacian operator. f and φ are real-value and complex-value equations in manifold. In Formula (3), $h = 2kTm$. k is Boltzmann constant. ρ , v , and T are density, velocity, and temperature under the equilibrium state, respectively.

$$\Delta\varphi = f, \quad (2)$$

$$f_0 = (\rho/m)(h/\pi)^{3/2} \exp(-hv^2). \quad (3)$$

3.5. Multicore Model. The spherical inorganic nanoparticle/polymer composite multicore model was proposed by Professor Tanaka at Waseda University. It is based on the single-layer structure model proposed by Professor T. J. Lewis. This model

is proposed to describe the interface structure and charge-transport properties [20], as shown in Figure 6. Professor T. J. Lewis finds that the nanocomposites show unique heat and electrical properties compared with the traditional micro-composites. The glass transition temperature changes. The dielectric constant decreases (the nanoparticles adding restrains the interfacial polarization between the particles with the matrix effectively). The space charge is restrained. Therefore, the nanocomposites become the research focus in the field of electrical insulating materials and electronic devices.

Professor Tanaka [21] believed that the nanocomposite dielectric interface is a transition region. The interface area consists of a bonding layer, binding layer, and loose layer. This model has been accepted by numerous researchers. The multicore mode was used to qualitatively explain the nanodielectric property changes in the experiment. These include the breakdown property [21], dielectric constant, partial discharge property, space charge inhibition, electrical tree properties [22], dielectric conductivity, and corona-resistance properties.

Professor Tian uses the multicore mode to analyze the partial discharge-resistance property and electrical tree-resistance property of nanodielectrics [23]. He believes that the interface structure between polymers with inorganic particles is the interaction zone, whose size is not larger than 20 nm. Because of the small-size effect of nanoparticles, when the nanoparticles are added to the polymer matrix, the percolation thresholds in the interface change. Furthermore, the dielectric properties of the polymer nanocomposites are affected. In some studies, the nanocomposite-free volume exists in the loose layer of the multicore mode. The addition of nanoparticles to the polymer matrix can effectively reduce the free volume. The composite breakdown field strength value is increased [24].

With the constant study of nanodielectric properties, combining the interface structure with macro performance analysis would provide a theoretical basis for the dielectric properties of nanocomposites. Although there are several interface models to explain the dielectric properties of nanocomposites, a few limitations and defects remain. The current model could not explain every experimental phenomenon. Therefore, the development trend of nanodielectrics should be further studied.

4. Research Status of Nanocomposites Dielectric Properties

Polymer/inorganic nanocomposites have been widely used by researchers because of their excellent dielectric properties. Since 2002, researchers have conducted numerous experiments on nanocomposite polarization performance, breakdown properties, partial discharge resistance properties, and space charge properties. There have been some predominant achievements in this regard.

The PI–Al system and PI–Si system refer to the carbon atom in molecules interconnected by the bonding methods of sp^2 and sp . The delocalization of molecular orbital organic molecules are produced. Murugaraj et al. [25] explored the

polarization performance of polyimide composites with nano- Al_2O_3 and nano- SiO_2 particles. Based on the interface phase K_0 regulation, the effect of the nanoparticle volume fraction on the composite dielectric constant was explored. From the test results, in the PI–Al system, K_0 was 3.24, and a dielectric constant of 280 was achieved. In the PI–Si system, K_0 was 5.01, and a dielectric constant of 19.24 was achieved. Researchers believe that the high dielectric constant is due to the interfacial phase polarization. The effects of chemical bonds and long-range forces exist between the nanoparticles and polymers. Saha [26] also proposed that interface polarization plays a significant role in the high dielectric constant form.

Professor Murugaraj studied the effect of nanomontmorillonite (MMT) particles with different contents on the breakdown properties of low-density polyethylene (LDPE). To explore the effect of different nano-MMT contents on the breakdown field strengths of composites, different contents of nano-MMT, namely, 0.5%, 1%, 3%, and 5%, were considered. The Weibull distribution was used to analyze the breakdown data. The test results are shown in Figure 7. As shown in Figure 7, as the MMT content increases, the breakdown field strength of nano-MMT/LDPE first decreases. Subsequently, it increases and later decreases [25].

Zheng et al. [27] studied the effect of nano-ZnO and nano-SiC particles on the nonlinear conductance of a polyethylene matrix. From the experimental results, these two nanoparticles improved the polyethylene nonlinear coefficient to varying degrees. In addition, the composite electrical tree breakdown time was promoted [27].

Professor Yu studied the effect of nano-ZnO particles on the breakdown properties of LDPE. As observed from the experimental results, when the mass fraction of nano-ZnO particles was 3 wt%, the sample breakdown field-strength value was the highest. In addition, the addition of nano-ZnO particles plays the role of an ultraviolet ray inhibitor [28].

Venkatesulu and Thomas [29] conducted the corona-resistance test on silicone rubber composites with different mass fractions of nanoparticle. In this test, the withstand voltage durability of insulation material under the surface partial discharge or corona can be measured. A certain voltage is applied in the samples. In condition of surface discharge, the samples are breakdown. From the test results, when the mass fraction of nanoparticles was 1%–3%, the corona-resistant performance of the nanocomposites was better than that of pure silicon rubber. The widths of the electric cracks in the different samples are shown in Figure 8.

Yan et al. [30] studied the electrical tree growth properties of nano-MMT/LDPE composites. As shown by the test results, the addition of nano-MMT particles effectively restrained the growth rate of the electrical tree. The fractal dimension of the electrical tree increased, and the diffusion rate decreased. The stagnated period appears earlier, and the duration is long. The effect of nano-MMT particles on the electrical tree growth channel is shown in Figure 9.

Ma et al. [31] studied the effect of adding nano- TiO_2 particles on the polyethylene space charge performance. As

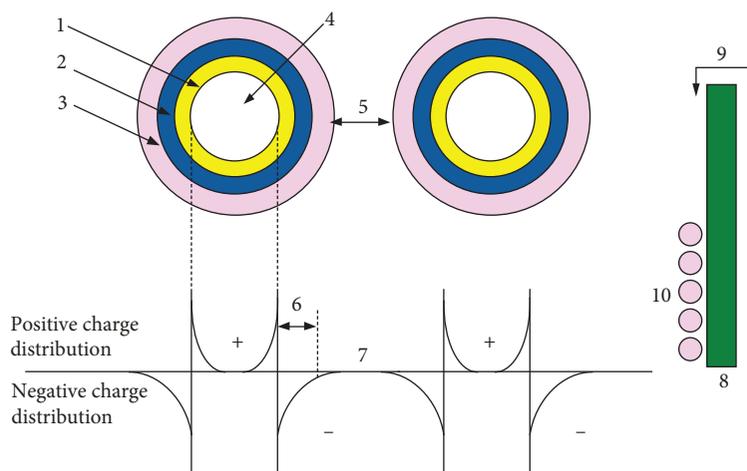


FIGURE 6: Single-layer structure model. 1—binding layer; 2—trapping layer; 3—loosening layer; 4—nanoparticle; 5—interparticle distance; 6—Debye shielding distance; 7—possible overlapping of the third layers and charge tails of nanoparticles; 8—electrode facing accumulated charge tails of nanofillers; 9—charge carrier injection via Schottky emission at high electric field; 10—collective charge tail effect will modify.

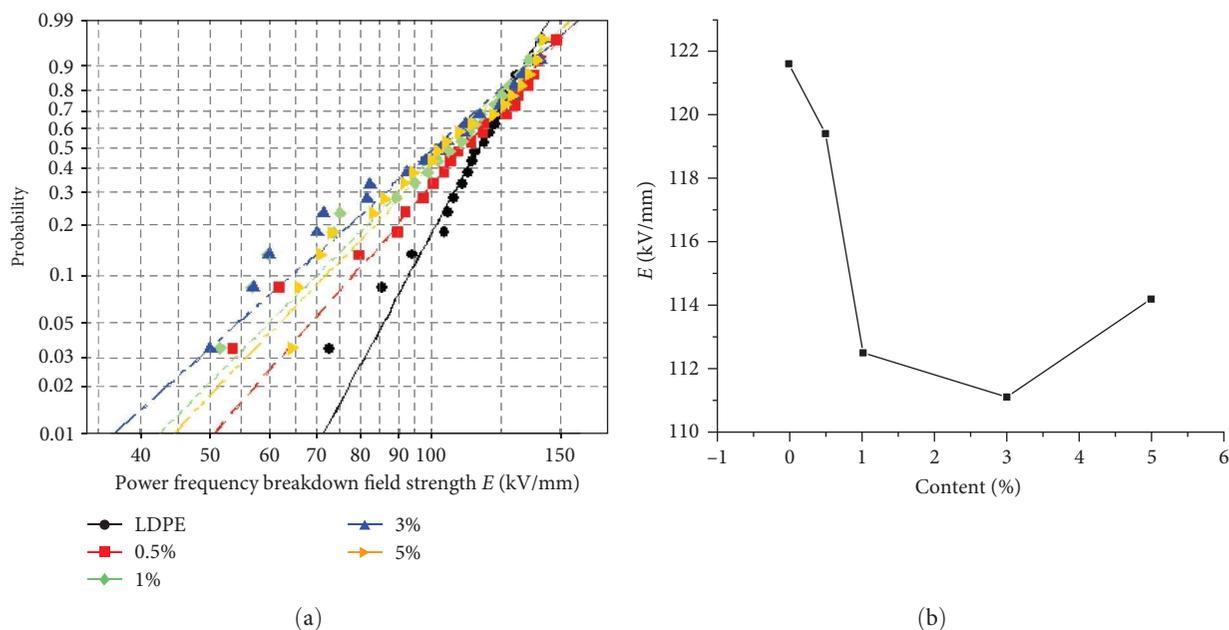


FIGURE 7: (a) Weibull distribution and power frequency breakdown; (b) Weibull parameters: composites with different MMT contents.

shown by the test results, after the aminoethyl-aminopropyl-dimethylsiloxane surface modification on nano-TiO₂ particles, the nanocomposite space charge inhibition was significantly enhanced. In addition, the dielectric strength did not decrease.

Lioa et al. [32] studied the space charge characteristics of polyethylene composites with a 1% nanoparticle mass fraction. As shown by the test results, the addition of nanoparticles introduces shallow electron traps and electron hole deep traps in the polymer matrix, which change the polyethylene band structure. The ohmic contact between the dielectric and electrode changes to a blocking contact. Charge injection has an inhibitory effect. Thus, the space charge accumulation in the dielectric decreases.

Zha et al. [33] studied the effect of electrical aging on the space charge properties of polyimide/nanoTiO₂ composites. As shown by the test results, adding nanoparticles introduces the local trap level, which changes the space charge distribution in the polymers. Therefore, the service life of the samples was prolonged.

Yin et al. [34] studied the effect of adding nano-MgO particles on the space charge distribution in a polyethylene matrix. From the test results, when the mass fraction of nano-MgO particles was less than 2%, the space charge injection volume of the nanocomposite was lower than that of pure LDPE. When the applied electric field was higher than 60 kV/mm, homopolar space charges appeared in the nanocomposite. As shown by the test results of the conductance

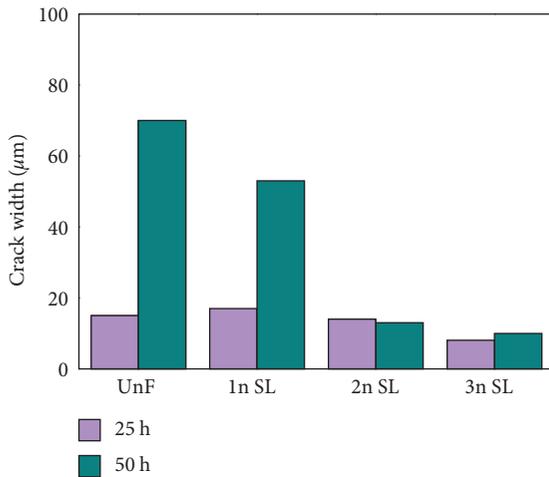


FIGURE 8: The widths of the electric cracks in the different samples.

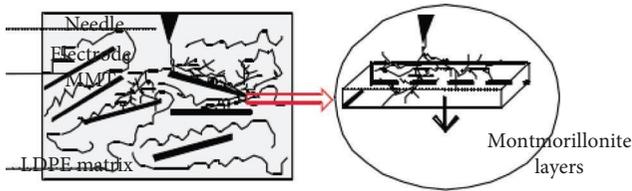


FIGURE 9: Effect of nano-MMT particles on the electrical tree growth channel.

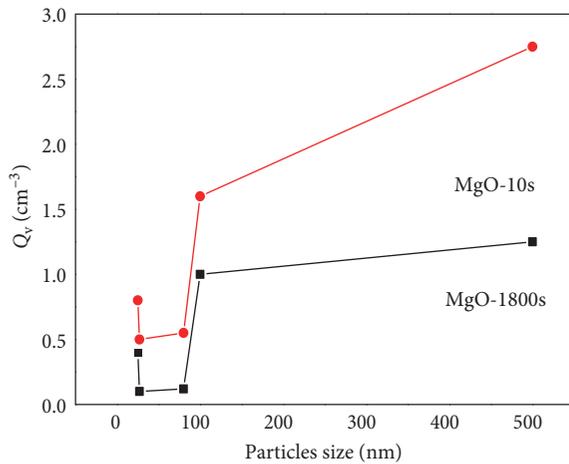


FIGURE 10: Relation between medium charge density and particle size of nano-MgO.

current characteristics, adding nano-MgO particles could raise the threshold electric field according to the space charge accumulation in the LDPE matrix. When the nano-MgO particle sizes are 30 and 80 nm, the space charge accumulation in the nano-MgO composites is less. When the nano-MgO particle size is larger than 80 nm or smaller than 30 nm, the space charge distribution condition in nanocomposites is complex, as shown in Figure 10. In addition, the electrode

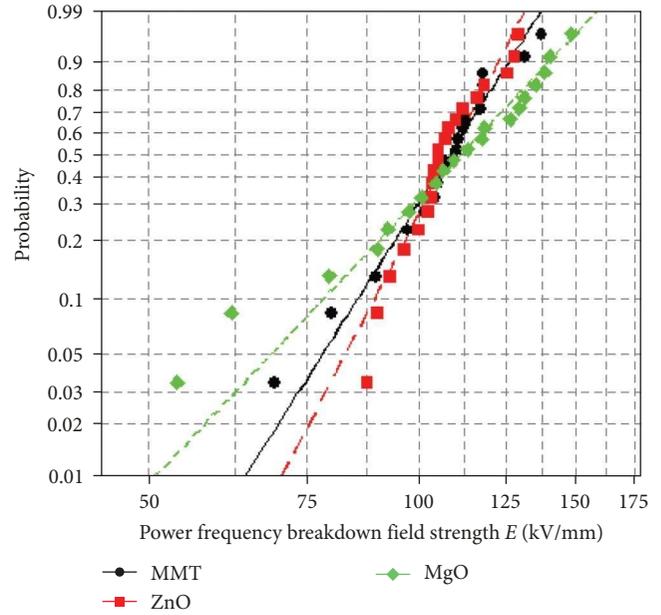


FIGURE 11: Weibull distribution of power frequency breakdown in different nanocomposites.

materials have a significant effect on the injection of the sample space charges [34].

Green et al. [35] added nano-MMT particles to LDPE. To compare the power frequency breakdown properties of three nanocomposites, 3% nano-MMT/LDPE, 1% nano-ZnO/LDPE, and 0.5% nano-MgO/LDPE are selected for the controlled experiment. The Weibull distribution of the power frequency breakdown is shown in Figure 11. As shown in Figure 11, the power frequency breakdown field strength of the nano-MgO/LDPE is the highest. Notably, the dielectric strengths of most polymer dielectrics are lower than that of a polymer matrix. The other reason is that, except for the dispersion of the nanoparticles, the dielectric constant and conductivity of the nanoparticles are higher than that of the polymer matrix. Although the nanoparticle sizes are small, the local distortion of the electric field increases. Especially when the particles are nonspherical, the electric field distortion is more significant. Some researchers have investigated the effect of crystalline morphology on breakdown strength via electrical treeing path observation. According to the experimental result, the breakdown easily occurs in a spherulite interface but not in the crystal and amorphous regions. There are two kinds of amorphous structures: weak and strong amorphous. The spherulite interface is formed in a weak amorphous structure. Because of its low density, the amorphous regions of a crystal-thin film possess high breakdown strength.

5. Conclusions

Nanoparticles possess a large specific surface area. As the particle size decreased, the number of surface atoms, surface energy, and surface tension increased sharply. Thus, the interface interaction between the nanoparticles and matrix

is strong. The physical and mechanical properties of nanocomposites are significantly superior to those of conventional composites with the same components. The nanoparticles also provide thermal, magnetic, and optical characteristics and dimensional stability to the composites. Therefore, nanocomposite preparation is an important method for obtaining high-performance materials. There are three common structural features in all nanomaterials: (1) the structural units are in the nanoscale or characteristic dimension size are in the nanoscale (1–100 nm), (2) there are numerous interfaces and free surfaces, and (3) there are either strong or weak interactions between each unit. Because of their special structures, nanomaterials possess some unique characteristics. In addition, when the physical scale reaches the nanoscale (smaller than 100 nm), the material possesses strong electrical neutrality retention. In low temperature, the free electronic energy level discretization happens. Some properties in system such as magnetic susceptibility, specific heat capacity, and nuclear magnetic resonance are affected (Kubo effect) [36]. The change in the surface (Fermi surface) electron levels promotes the nanomaterials exhibiting a unique performance. Thus, material modification is relatively easy in nanocomposites, and these materials are widely used.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Conceptualization: Yujia Cheng and Guang Yu; methodology: Guang Yu; software: Zhuohua Duan; validation: Guang Yu; formal analysis: Guang Yu; investigation: Yujia Cheng; resources: Zhuohua Duan; data curation: Guang Yu; writing—original draft preparation: Guang Yu; writing—review and editing: Guang Yu; visualization: Yujia Cheng; supervision: Yujia Cheng; project administration: Yujia Cheng; funding acquisition: Zhuohua Duan. All authors have read and agreed to the published version of the manuscript.

Funding

This research was aided by the Colleges Young Creative Talents Project of Guangdong province, No. 2020KQNCX118; Zhongshan Social Welfare and Basic Research Initiative, No. 2020B2025; and the Science and Technology Foundation of Guangdong Province under grant 2021A0101180005.

Acknowledgments

We thank Zhuohua Duan and Xianfeng Zhang for their help.

References

- [1] S. P. Asrafali, T. Periyasamy, R. Haldhar, S. Madhappan, and S.-C. Kim, "Fabrication of SiO₂-reinforced polybenzoxazine composites and their thermal and dielectric properties," *Journal of Polymer Research*, vol. 29, Article ID 176, 2022.
- [2] D. Yim, J. Park, S. Jang, J. Choi, and N.-H. Park, "Fabrication and properties of glass fiber-reinforced composites using polyimide prepregs with inorganic nanofillers," *Fibers and Polymers*, vol. 22, pp. 804–810, 2021.
- [3] M. Wu, L. Lu, L. Yu et al., "Preparation and characterization of epoxy/alumina nanocomposites," *Journal of Nanoscience and Nanotechnology*, vol. 20, no. 5, pp. 2964–2970, 2020.
- [4] J. Al Boukhari, A. Khalaf, and R. Awad, "Structural analysis and dielectric investigations of pure and rare earth elements (Y and Gd) doped NiO nanoparticles," *Journal of Alloys and Compounds*, vol. 820, Article ID 153381, 2020.
- [5] Y. Cheng, L. Bai, G. Yu, and X. Zhang, "Effect of particles size on dielectric properties of nano-ZnO/LDPE composites," *Materials*, vol. 12, no. 1, Article ID 5, 2019.
- [6] H. Yan, S. Song, H. Zhao, and Z. Yao, "Dielectric properties of polystyrene graft copolymer/low density polyethylene," *High Voltage Engineering*, vol. 44, no. 12, pp. 3840–3847, 2018.
- [7] M. Hajibeygi, M. Mousavi, M. Shabaniyan, and H. Vahabi, "The effect of phosphorus based melamine-terephthaldehyde resin and Mg-Al layered double hydroxide on the thermal stability, flame retardancy and mechanical properties of polypropylene MgO composites," *Materials Today Communications*, vol. 23, Article ID 100880, 2020.
- [8] J. Zhang, J. Zuo, W. Ai et al., "Preparation of a new high-efficiency resin deodorant from coal gasification fine slag and its application in the removal of volatile organic compounds in polypropylene composites," *Journal of Hazardous Materials*, vol. 384, Article ID 121347, 2020.
- [9] P. Chen, S. Wang, Z. Chen, and J. Li, "Effect of nano-TiO₂ on dielectric properties of XLPE for HVDC cable," *High Voltage Engineering*, vol. 44, pp. 3848–3856, 2018.
- [10] T. Takeda, H. Suzuki, and T. Okamoto, "Correlation between space charge distribution under DC voltage and dielectric breakdown properties in XLPE under impulse voltage superposed onto DC voltage," in *Proceedings of 2001 International Symposium on Electrical Insulating Materials (ISEIM 2001). 2001 Asian Conference on Electrical Insulating Diagnosis (ACEID 2001). 33rd Symposium on Electrical and Ele*, pp. 493–496, IEEE, Himeji, Japan, November 2001.
- [11] S. Nilboworn, P. Wounchoum, W. Wichakool, and W. Thongruang, "Electrical properties characterization and numerical models of rubber composite at high frequency," *Advanced Materials Research*, vol. 844, pp. 429–432, 2013.
- [12] R. C. Smith, C. Liang, M. Landry, J. K. Nelson, and L. S. Schadler, "The mechanisms leading to the useful electrical properties of polymer nanodielectrics," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 15, no. 1, pp. 187–196, 2008.
- [13] S. Li, G. Yin, S. Bai, and J. Li, "A new potential barrier model in epoxy resin nanodielectrics," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 18, no. 5, pp. 1535–1543, 2011.
- [14] J. Njuguna, K. Pielichowski, and S. Desai, "Nanofiller-reinforced polymer nanocomposites," *Polymers for Advanced Technologies*, vol. 19, no. 8, pp. 947–959, 2008.
- [15] T. J. Lewis, "Interfaces are the dominant feature of dielectrics at the nanometric level," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 11, no. 5, pp. 739–753, 2004.
- [16] M. F. Fréchette, "What are nanodielectrics?" *IEEE Electrical Insulation Magazine*, vol. 29, no. 6, pp. 8–11, 2013.
- [17] Y. Yamano, "Control of electrical tree at initiation stage in LDPE by mixed addition of Al₂O₃ nano-particle and azobenzene compound," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 21, no. 1, pp. 209–216, 2014.
- [18] J. K. Nelson, *Dielectric Polymer Nanocomposites*, Springer, 2010.

- [19] S. Raetzke and J. Kindersberger, "The effect of interphase structures in nanodielectrics," *IEEE Transactions on Fundamentals and Materials*, vol. 126, no. 11, pp. 1044–1049, 2006.
- [20] T. J. Lewis, "A model for nano-composite polymer dielectrics under electrical stress," in *2007 IEEE International Conference on Solid Dielectrics*, pp. 11–14, IEEE, Winchester, UK, 2007.
- [21] T. Tanaka, "Interpretation of several key phenomena peculiar to nano dielectrics in terms of a multi-core model," in *2006 IEEE Conference on Electrical Insulation and Dielectric Phenomena*, pp. 298–301, IEEE, Kansas City, MO, USA, 2006.
- [22] R. J. Klein, P. Barber, W. M. Chance, and H.-C. Zur Loye, "Covalently modified organic nanoplatelets and their use in polymer film capacitors with high dielectric breakdown and wide temperature operation," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 19, no. 4, pp. 1234–1238, 2012.
- [23] F. Tian, Q. Lei, X. Wang, and Y. Wang, "Effect of deep trapping states on space charge suppression in polyethylene/ZnO nanocomposite," *Applied Physics Letters*, vol. 99, no. 14, Article ID 142903, 2011.
- [24] G. Sethi, E. Furman, B. Koch, and M. T. Lanagan, "Influence of impedance contrast on field distribution and tree growth in laminate dielectrics," *Modelling and Simulation in Materials Science and Engineering*, vol. 22, no. 2, Article ID 025024, 2014.
- [25] P. Murugaraj, D. Mainwaring, and N. Mora-Huertas, "Dielectric enhancement in polymer-nanoparticle composites through interphase polarizability," *Journal of Applied Physics*, vol. 98, no. 5, Article ID 054304, 2005.
- [26] S. K. Saha, "Nanodielectrics with giant permittivity," *Bulletin of Materials Science*, vol. 31, pp. 473–477, 2008.
- [27] J. Zheng, X. Zhou, and X. Xie, "Non-isothermal crystallization kinetics of polypropylene containing silica hybrid particles as fillers," *Acta Materiae Compositae Sinica*, vol. 30, pp. 18–23, 2013.
- [28] G. Yu, Y. Cheng, and X. Zhang, "The dielectric properties improvement of cable insulation layer by different morphology nanoparticles doping into LDPE," *Coatings*, vol. 9, no. 3, Article ID 204, 2019.
- [29] B. Venkatesulu and M. J. Thomas, "Corona aging studies on silicone rubber nanocomposites," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 17, no. 2, pp. 625–634, 2010.
- [30] H.-D. Yan, C. Zhang, W.-K. Li, and J.-W. Zha, "Effect of trap level density on breakdown strength and space charge distribution of polypropylene/low-density polyethylene composites," *Polymer Composites*, vol. 41, no. 2, pp. 780–787, 2020.
- [31] D. Ma, T. A. Hugener, R. W. Siegel et al., "Influence of nanoparticle surface modification on the electrical behaviour of polyethylene nanocomposites," *Nanotechnology*, vol. 16, no. 6, Article ID 724, 2005.
- [32] R. Liao, X. Li, G. Bai, L. Yang, and J. Gu, "Influence of montmorillonite on electrical treeing and breakdown characteristics of low-density polyethylene," *Journal of Reinforced Plastics and Composites*, vol. 33, no. 23, pp. 2117–2128, 2014.
- [33] J.-W. Zha, Z.-M. Dang, H.-T. Song, Y. Yin, and G. Chen, "Dielectric properties and effect of electrical aging on space charge accumulation in polyimide/TiO₂ nanocomposite films," *Journal of Applied Physics*, vol. 108, no. 9, Article ID 094113, 2010.
- [34] Y. Yin, X. Dong, Y. Wang, Q. Wang, and X. Li, "Charge carrier transportation in the composite of nano-MgO and cross-linking polyethylene," in *2009 IEEE 9th International Conference on the Properties and Applications of Dielectric Materials*, pp. 761–764, IEEE, Harbin, 2009.
- [35] C. D. Green, A. S. Vaughan, G. R. Mitchell, and T. Liu, "Structure property relationships in polyethylene/montmorillonite nanodielectrics," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 15, no. 1, pp. 134–143, 2008.
- [36] R. Hemmatian and A. H. M. Isfahani, "Determination of rarefaction effects on transport properties of nanoscale gas flows using Green–Kubo molecular dynamic simulation," *Molecular Simulation*, vol. 45, no. 2, pp. 137–146, 2019.