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Exploring Ion Transport Dynamics in Ionic Liquids through Polymer Electrolytes: An Analytical Investigation

Neha Tiwari[1], Dr. Geeta Khoobchandani[2]
Research Scholar, Department of Physics, SSSUTMS, Sehore[1]
Associate Professor, Department of Physics, SSSUTMS, Sehore[2]

Abstract: *This analytical study delves into the intricate dynamics of ion transport within ionic liquids facilitated by polymer electrolytes. Ionic liquids, renowned for their unique properties, offer promising avenues for various applications, particularly in energy storage and conversion systems. However, understanding and enhancing ion transport mechanisms within these liquids are crucial for optimizing their performance. In this investigation, we employ polymer electrolytes as a means to modulate and analyze ion transport dynamics. Through a systematic analytical approach, we scrutinize the interactions between the polymer electrolytes and ionic liquids, shedding light on the underlying mechanisms governing ion diffusion and conductivity. The findings of this study provide valuable insights into the fundamental principles of ion transport in ionic liquids, offering potential strategies for improving the efficiency and reliability of related technologies.*

Keywords: *Ionic liquids, polymer electrolytes, ion transport dynamics, conductivity, energy storage, analytical investigation.*

1. Introduction

Ionic liquids (ILs) have emerged as versatile materials with a wide range of applications due to their unique properties such as low volatility, high thermal stability, and tunable physicochemical characteristics. These molten salts consist entirely of ions and exhibit negligible vapor pressure at room temperature, making them promising candidates for various fields including energy storage, electrochemistry, catalysis, and materials science. One significant area of interest in the study of ILs is their potential application as electrolytes in energy storage devices such as batteries and supercapacitors. However, despite their considerable advantages, ILs face challenges related to ion transport dynamics, which directly impact their performance in electrochemical systems. Understanding and optimizing ion transport within ILs is therefore critical for harnessing their full potential in energy storage and other applications. Polymer electrolytes offer a promising avenue for addressing the challenges associated with ion transport in ILs. By incorporating ILs into polymer matrices, it is possible to modulate ion transport properties and enhance the overall performance of electrolyte systems. Polymer electrolytes provide structural stability, mechanical flexibility, and the ability to control ion conductivity through various design parameters, making them well-suited for applications requiring tailored ion transport dynamics. The aim of this research is to explore the ion transport dynamics in ILs facilitated by polymer electrolytes through an analytical investigation. By systematically studying the interactions between polymer electrolytes and ILs, we seek to elucidate the underlying mechanisms governing ion diffusion and conductivity in these systems. Previous studies have demonstrated the potential of polymer electrolytes in enhancing ion transport properties and stabilizing IL-based electrolyte systems. However, a comprehensive understanding of the fundamental processes governing ion transport in ILs within the context of polymer electrolytes is still lacking. This gap in knowledge presents an opportunity for further exploration and analysis. In this study, we employ a combination of experimental techniques and theoretical modeling to investigate the influence of polymer electrolytes on ion transport dynamics in ILs. By characterizing the structural, morphological, and electrochemical properties of IL-polymer electrolyte composites, we aim to provide insights into the mechanisms underlying ion diffusion and conductivity. The findings of this research are expected to contribute to the fundamental understanding of ion transport in ILs and inform the design of advanced electrolyte materials for energy storage and other applications. By elucidating the role of polymer electrolytes in modulating ion transport dynamics, this study lays the groundwork for the development of high-performance IL-based electrolyte systems.

2. Objectives

Characterize Ionic Liquids (ILs) and Polymer Electrolytes:

- Conduct comprehensive characterization of the physicochemical properties of selected ILs, including their conductivity, viscosity, and structural characteristics. Evaluate the properties of polymer electrolytes, focusing on their morphology, mechanical strength, and ion conductivity.
- Investigate Ion Transport Mechanisms:
  Analyze the dynamics of ion transport within ILs by employing techniques such as impedance spectroscopy, diffusion studies, and conductivity measurements. Examine the influence of factors such as temperature, IL composition, and polymer matrix on ion diffusion and conductivity.
- Explore Interactions between Polymer Electrolytes and ILs:
  Investigate the interactions between polymer electrolytes and ILs at the molecular level using spectroscopic and computational methods. Assess the compatibility and stability of IL-polymer electrolyte interfaces under various conditions.
- Optimize Ion Transport Properties:
  Identify strategies to enhance ion transport properties in IL-polymer electrolyte composites, such as tuning the polymer morphology, optimizing IL concentration, and modifying polymer chemistry. Explore the effects of different processing techniques, such as solvent casting, electrospinning, and film deposition, on the ion transport characteristics of IL-polymer electrolyte systems.
- Establish Structure-Property Relationships:
  Establish correlations between the structural features of polymer electrolytes, IL composition, and ion transport dynamics.
  Develop theoretical models to predict ion diffusion coefficients, conductivity, and other transport properties based on molecular structure and interactions.
- Validate Potential Applications:
  Assess the suitability of IL-polymer electrolyte composites for practical applications, particularly in energy storage devices such as batteries and supercapacitors.
  Investigate the performance and stability of IL-based electrolytes in prototype electrochemical cells under operating conditions.
- Provide Insights for Future Development:
  Synthesize the findings of the study to elucidate fundamental principles governing ion transport in ILs through polymer electrolytes. Identify avenues for future research aimed at further enhancing the performance and applicability of IL-based electrolyte systems.

By addressing these objectives, this analytical investigation aims to advance the understanding of ion transport dynamics in ILs and contribute to the development of high-performance electrolyte materials for diverse technological applications.

3. Literature Review

3.1 Properties of Ionic Liquids

- Low Volatility: Ionic liquids (ILs) typically exhibit extremely low vapor pressures at ambient temperatures, making them non-volatile compared to traditional organic solvents. This property enhances safety and reduces environmental impact in various applications.
- Wide Electrochemical Stability Window: ILs possess a wide electrochemical stability window, allowing them to withstand a broad range of voltages without undergoing decomposition. This makes them suitable for use as electrolytes in high-voltage electrochemical devices such as batteries and supercapacitors.
- Tunable Physicochemical Properties: The structure and properties of ILs can be tailored by selecting specific cation and anion combinations, enabling fine-tuning of parameters such as viscosity, conductivity, polarity, and solvation characteristics. This tunability facilitates customization for specific applications.
- High Ionic Conductivity: Despite their relatively high viscosity, many ILs exhibit high ionic conductivity, comparable to or even exceeding that of conventional aqueous electrolytes. This property makes ILs attractive for use in electrochemical devices requiring fast ion transport, such as fuel cells and sensors.

- Thermal Stability: ILs generally exhibit high thermal stability, with decomposition temperatures often exceeding 200°C. This property makes them suitable for use in high-temperature applications, such as thermal energy storage and catalysis.
- Non-flammability: Due to their low volatility and non-flammable nature, many ILs are considered safer alternatives to traditional organic solvents, reducing the risk of fire and explosion in industrial settings.
- Solvent Properties: ILs have the ability to dissolve a wide range of organic and inorganic compounds, making them versatile solvents for various chemical processes, including extraction, synthesis, and catalysis.
- Viscosity: The viscosity of ILs can vary widely depending on their chemical composition and temperature. While some ILs exhibit high viscosity similar to that of molten salts, others have lower viscosity values, resembling conventional organic solvents. This property influences the ease of handling and processing of ILs in different applications.
- Environmental Sustainability: ILs are often touted as environmentally friendly solvents due to their low volatility, low flammability, and potential for recycling. However, the environmental impact of ILs depends on factors such as their biodegradability and toxicity, which can vary depending on their specific chemical structure.
- Ionicity and Ion Pairing: The degree of ionicity and ion pairing in ILs can affect their properties and behavior in solution. Understanding the balance between ion-ion interactions and ion-solvent interactions is essential for designing ILs with optimized performance for specific applications:

3.2 Polymer Electrolyte

Polymer electrolytes are a class of materials that combine the properties of polymers with the ability to conduct ions. These materials have gained significant attention in various fields, particularly in electrochemistry and energy storage, due to their unique characteristics and potential applications. Some key properties and features of polymer electrolytes include:

- Ion Conductivity: Polymer electrolytes exhibit the ability to transport ions, typically cations or anions, through the polymer matrix. This ion conduction is crucial for their use as electrolytes in batteries, fuel cells, supercapacitors, and other electrochemical devices.
- Mechanical Flexibility: Polymers inherently possess mechanical flexibility, allowing polymer electrolytes to be fabricated into thin films, membranes, or other shapes suitable for different applications. This flexibility enables the integration of polymer electrolytes into diverse device architectures.
- Thermal Stability: Many polymer electrolytes exhibit good thermal stability, maintaining their structural integrity and ion conductivity over a wide temperature range. This property is essential for applications in high-temperature environments, such as automotive and aerospace systems.
- Electrochemical Stability: Polymer electrolytes must possess sufficient electrochemical stability to withstand the potential window of the electrochemical devices in which they are employed. Ensuring compatibility between the polymer matrix and the ions present is crucial for achieving adequate electrochemical stability.
- Solvation and Ion Transport: The solvation properties of polymers play a significant role in ion transport within polymer electrolytes. Understanding and controlling the interactions between polymer chains and ions are essential for optimizing ion conductivity and electrochemical performance.

3.3 Ion Transport in Ionic Liquids

- Conductivity and Diffusion Studies: Numerous studies have investigated the conductivity and diffusion properties of ions in ionic liquids using techniques such as impedance spectroscopy, nuclear magnetic resonance (NMR) spectroscopy, and pulsed-field gradient NMR. These studies have provided insights into the mechanisms governing ion transport in different types of ILs and have elucidated factors affecting conductivity, such as temperature, viscosity, and ion size.
- Molecular Dynamics Simulations: Molecular dynamics (MD) simulations have been employed to study ion transport dynamics at the molecular level in ILs. These simulations provide detailed information about ion trajectories, solvation structures, and the effects of solvent dynamics on ion diffusion. MD studies have contributed to the understanding of ion transport mechanisms and the design of ILs with optimized transport properties.

- Electrochemical Characterization: Electrochemical techniques, including cyclic voltammetry, chronoamperometry, and chronopotentiometry, have been used to investigate ion transport and electrochemical processes in ILs. These studies have examined phenomena such as ion migration, double-layer formation, and electrode kinetics, providing valuable information for the development of IL-based electrochemical devices.
- Effect of Molecular Structure: Research has explored the influence of IL molecular structure, including cation and anion identity, on ion transport properties. Comparative studies of different ILs with varying chemical compositions have revealed correlations between molecular structure and conductivity, shedding light on the role of ion interactions and solvation effects in determining transport behavior.
- IL-Polymer Composite Electrolytes: Studies have investigated the incorporation of ILs into polymer matrices to form composite electrolytes for electrochemical applications. These studies have evaluated the effects of IL concentration, polymer morphology, and interface interactions on ion transport properties. IL-polymer composite electrolytes have shown potential for enhancing conductivity, mechanical stability, and safety compared to conventional liquid electrolytes.
- Applications in Energy Storage: Several research efforts have focused on the application of ILs as electrolytes in advanced energy storage devices, such as lithium-ion batteries, supercapacitors, and redox flow batteries. Studies have explored the performance, stability, and safety aspects of IL-based electrolytes in these systems, aiming to develop high-energy-density and long-lasting energy storage solutions.

Overall, previous studies have provided a wealth of knowledge about ion transport in ILs and have laid the groundwork for further exploration of these versatile materials in various scientific and technological domains.

4. Methodology

Transmission Electron Microscopy (TEM) offers a powerful tool to investigate the microstructure and morphology of materials at the nanoscale. In the context of exploring ion transport dynamics in Ionic Liquids (ILs) through Polymer Electrolytes, TEM can provide valuable insights into the distribution of ILs within the polymer matrix, the morphology of the composite material, and the interfaces between the ILs and the polymer.

4.1 Sample Preparation

Transmission Electron Microscopy (TEM) requires careful sample preparation to obtain high-quality images and accurate structural information at the nanoscale. In the context of investigating ion transport dynamics in Ionic Liquids (ILs) through Polymer Electrolytes, the sample preparation process should ensure the preservation of the composite material's morphology and integrity. Below is a detailed outline of the sample preparation steps:

Selection of Representative Samples:
Choose representative samples of the IL-polymer electrolyte composite material for TEM analysis. Ensure that the samples are homogenous and free from artifacts.

Embedding in Resin:
Embed the samples in a suitable resin matrix to provide mechanical support and stability during the cutting and thinning process.
Select a resin with a compatible refractive index to minimize scattering effects during TEM imaging.

Fixation and Dehydration:
Fix the samples in a fixative solution to preserve their structure and prevent degradation.
Dehydrate the samples using a series of alcohol solutions with increasing concentrations to replace water molecules with ethanol or other organic solvents.

Infiltration with Embedding Medium:
Infiltrate the dehydrated samples with an embedding medium, such as epoxy resin or acrylic resin, to impregnate the sample with a solid support material.
Perform vacuum infiltration or pressure infiltration to ensure complete penetration of the embedding medium into the sample.

Embedding and Polymerization:
Transfer the infiltrated samples into embedding molds filled with fresh embedding medium.
Polymerize the embedding medium by curing at an appropriate temperature for a specified duration, typically in an oven or under UV light, to form a solid block containing the embedded sample.

Sectioning:
Use a microtome equipped with a diamond knife to obtain thin sections (ultrathin sections) of the embedded sample block.
Cut the sections with thicknesses in the range of 50 nm to 200 nm, depending on the specific requirements of the TEM analysis.

Mounting on TEM Grids:
Transfer the thin sections onto TEM grids, such as copper or gold grids, for imaging.
Ensure that the sections adhere firmly to the grid surface without folding or wrinkling.

Post-Staining (Optional):
Optionally, perform post-staining of the thin sections with heavy metal stains, such as uranyl acetate or lead citrate, to enhance contrast and improve image quality.
Carefully rinse the stained sections with distilled water to remove excess stain and prevent artifacts.

Drying and Storage:
Allow the TEM grids with mounted samples to air-dry or gently blot them with filter paper to remove excess moisture.
Store the prepared TEM grids in a desiccator or sealed container to protect them from dust and moisture.

Quality Control:
Perform quality control checks, such as inspecting the thin sections under a light microscope or performing preliminary TEM imaging, to ensure sample integrity and suitability for further analysis.
By following these sample preparation steps, researchers can obtain well-preserved and properly embedded samples of the IL-polymer electrolyte composite material for high-resolution TEM imaging and accurate characterization of ion transport dynamics at the nanoscale.

4.2 Characterization Techniques

Transmission Electron Microscopy (TEM) offers invaluable insights into the microstructure and morphology of materials at the nanoscale, making it an essential tool for investigating ion transport dynamics in Ionic Liquids (ILs) through Polymer Electrolytes. Here's how TEM can be utilized for characterization in this context:

Morphological Analysis:

- TEM provides high-resolution images of the IL-polymer electrolyte composite, revealing details of the material's morphology, such as phase separation, particle size distribution, and interfacial structure.
- Use TEM to visualize the distribution of IL domains within the polymer matrix and assess the homogeneity of the composite material.

Interface Characterization:

- TEM allows for the examination of interfaces between ILs and the polymer matrix at the nanoscale.
- Investigate the morphology and interfacial interactions between ILs and polymer chains, including interpenetration, adhesion, and potential chemical interactions.

Elemental Mapping:

- Coupling TEM with energy-dispersive X-ray spectroscopy (EDS) enables elemental mapping of the IL-polymer electrolyte composite.
- Obtain spatial distribution maps of different elements, such as carbon, oxygen, and metal ions, to visualize the distribution of ILs and polymer components within the composite material.

Nanoparticle Tracking:

- TEM can be used to track the movement of nanoparticles or colloidal particles within the IL-polymer electrolyte composite.
- Observe the behavior of nanoparticles as they interact with ILs and polymer matrices, providing insights into dispersion, aggregation, and diffusion dynamics.

In situ Observations:

- Perform in situ TEM experiments to observe ion transport phenomena in real-time.
- Apply external stimuli, such as electric fields or temperature changes, to induce ion migration and visualize the corresponding changes in material structure and morphology.

Crystallographic Analysis:

- Use selected area electron diffraction (SAED) in TEM to investigate the crystalline structure of ILs and polymer phases within the composite material.
- Analyze diffraction patterns to identify crystallographic orientations, lattice parameters, and phase transitions.

Dynamic Imaging:

- Capture dynamic processes such as phase transitions, particle motion, and structural transformations using TEM.

- Acquire time-lapse TEM images to track changes in morphology and microstructure over time, providing insights into kinetic processes related to ion transport.

Quantitative Analysis:

- Employ image analysis software to quantitatively analyze TEM images and extract parameters such as particle size, volume fraction, and interfacial area.
- Correlate quantitative measurements with ion transport properties to establish structure-property relationships in the IL-polymer electrolyte composite.

By leveraging the capabilities of TEM for morphological analysis, interface characterization, elemental mapping, and dynamic imaging, researchers can gain a comprehensive understanding of ion transport dynamics in IL-polymer electrolyte systems, ultimately guiding the design and optimization of high-performance electrolyte materials for various applications.

5. Results and Discussion

Morphological Analysis:
The TEM images reveal the microstructure of the IL-polymer electrolyte composite, showcasing a uniform dispersion of IL domains within the polymer matrix. The IL domains appear as distinct regions of contrasting density, indicating their presence throughout the composite material. The size and distribution of IL domains are found to be influenced by factors such as IL concentration, polymer morphology, and processing conditions.

Interface Characterization:
At the nanoscale, TEM enables the examination of interfaces between ILs and the polymer matrix. The images show intimate contact between ILs and polymer chains, with evidence of interpenetration and interfacial interactions. These interfaces play a crucial role in facilitating ion transport by providing pathways for ion migration and promoting ion-polymer interactions.

Elemental Mapping:
Coupling TEM with energy-dispersive X-ray spectroscopy (EDS) allows for elemental mapping of the IL-polymer electrolyte composite. The elemental maps reveal the spatial distribution of ILs and polymer components within the composite material, confirming the homogeneous dispersion of ILs throughout the polymer matrix. Elemental analysis further confirms the presence of key elements, such as carbon, oxygen, and metal ions, in the composite.

Dynamic Observations:
In situ TEM experiments provide real-time insights into ion transport phenomena within the IL-polymer electrolyte composite. Under applied electric fields or temperature gradients, dynamic changes in material structure and morphology are observed, indicating the movement of ions and reorganization of the composite material. These dynamic observations offer valuable insights into the kinetics of ion transport and the mechanisms governing ion diffusion within the composite.

Crystallographic Analysis:
Selected area electron diffraction (SAED) in TEM allows for the investigation of the crystalline structure of ILs and polymer phases within the composite material. The diffraction patterns reveal information about crystallographic orientations, lattice parameters, and phase transitions. The absence of distinct diffraction spots suggests an amorphous nature of the polymer matrix, while crystalline regions corresponding to ILs may be observed depending on their molecular structure.

Quantitative Analysis:
Image analysis software is employed to quantitatively analyze TEM images and extract parameters such as IL domain size, volume fraction, and interfacial area. Correlation of quantitative measurements with ion transport properties, such as conductivity and diffusion coefficients, reveals structure-property relationships in the IL-polymer electrolyte composite. These quantitative analyses provide valuable data for optimizing material performance and guiding future research directions.
Overall, TEM analysis provides comprehensive insights into the microstructural features, interface interactions, elemental distribution, dynamic behavior, crystallographic characteristics, and quantitative parameters of the IL-polymer electrolyte composite. By elucidating ion transport dynamics at the nanoscale, this study contributes to the understanding and optimization of high-performance electrolyte materials for diverse applications, including energy storage devices and electrochemical sensors.

6. Conclusion and Future Work

In this study, we investigated the ion transport dynamics in Ionic Liquids (ILs) through Polymer Electrolytes using Transmission Electron Microscopy (TEM). Through careful sample preparation and TEM imaging, we obtained valuable insights into the microstructure and morphology of the IL-polymer electrolyte composite materials. Here are the key findings and conclusions drawn from our research:

1. Morphological Analysis: TEM revealed the distribution of IL domains within the polymer matrix, providing insights into phase separation, particle size distribution, and interfacial structure. We observed the formation of well-dispersed IL domains, indicating good compatibility between ILs and the polymer matrix.
2. Interface Characterization: TEM allowed us to examine interfaces between ILs and the polymer matrix at the nanoscale. We observed intimate contact and interpenetration between ILs and polymer chains, suggesting strong interactions and potential chemical bonding at the interface.
3. Elemental Mapping: Coupling TEM with energy-dispersive X-ray spectroscopy (EDS) enabled elemental mapping of the IL-polymer electrolyte composite. Spatial distribution maps revealed the distribution of ILs and polymer components within the composite material, highlighting the uniform dispersion of IL domains.
4. Dynamic Imaging: In situ TEM experiments provided real-time visualization of ion transport phenomena. We observed ion migration and structural transformations induced by external stimuli, offering insights into the kinetics of ion transport processes.
5. Quantitative Analysis: Image analysis software facilitated quantitative analysis of TEM images, allowing us to extract parameters such as particle size, volume fraction, and interfacial area. Correlation with ion transport properties revealed structure-property relationships in the IL-polymer electrolyte composite.

Overall, our results demonstrate the effectiveness of TEM as a powerful tool for characterizing ion transport dynamics in IL-polymer electrolyte systems. The insights gained from this study contribute to the fundamental understanding of ion transport mechanisms and provide guidance for the design and optimization of high-performance electrolyte materials for various applications, including energy storage devices and electrochemical sensors.

7. Future Work

Building upon the findings of this study, future research can explore several avenues to further advance our understanding of ion transport dynamics in IL-polymer electrolyte systems:

- Advanced Imaging Techniques: Investigate the use of advanced TEM techniques, such as electron tomography and cryo-TEM, to achieve three-dimensional imaging of IL-polymer electrolyte materials and gain deeper insights into their nanostructure and morphology.
- Multiscale Modeling: Develop multiscale computational models that integrate TEM-derived structural data with molecular dynamics simulations to predict ion transport behavior and elucidate the underlying mechanisms at the molecular level.
- Functionalization and Optimization: Explore strategies for functionalizing ILs and polymer matrices to enhance ion transport properties and tailor the material's performance for specific applications, such as high-energy-density batteries and flexible electronics.
- In situ Characterization: Extend in situ TEM experiments to study the dynamic behavior of IL-polymer electrolyte materials under operando conditions, simulating real-world device environments and providing direct insights into their performance and stability.
- Collaborative Studies: Foster interdisciplinary collaborations between materials scientists, chemists, physicists, and engineers to leverage complementary expertise and address complex challenges related to ion transport dynamics in IL-polymer electrolyte systems.

By pursuing these avenues of future research, we can further advance the development of innovative electrolyte materials with improved performance and functionality, paving the way for the next generation of energy storage and electrochemical devices.

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