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Study on the Alleviation of Performance Degradation and Voltage Stability of PEMFC by Adding Silica Under Low-Temperature and Low-Humidity Conditions

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Abstract: This study enhances PEMFC performance at low temperature and low humidity by incorporating hydrophilic inorganic silica materials inside the PEMFC. Firstly, the polarization performance of the cell under varying humidity levels was investigated using a controlled variable method. Secondly, the power stability of the PEMFC was examined by observing voltage stability under constant current. Finally, the cell's transient response at startup was studied. Experimental results indicate that the addition of silica partially mitigates the significant performance decline of the cell under a high humidity range (100% RH–50% RH). However, the effect is relatively average in a low humidity range (50% RH–20% RH).

Keywords: PEMFC; temperature; low humidity; silica; performance degradation

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Citation: Bai, Q.; Hsieh, C.; Liu, Z.; Chen, Q.; Weng, F. Study on the Alleviation of Performance Degradation and Voltage Stability of PEMFC by Adding Silica Under Low-Temperature and Low-Humidity Conditions. *Crystals* **2024**, *14*, 1089. https://doi.org/10.3390/cryst14121089

Academic Editor: Vladislav V. Kharton

Received: 2 December 2024
Revised: 15 December 2024
Accepted: 16 December 2024
Published: 18 December 2024

Correction Statement: This article has been republished with a minor change. The change does not affect the scientific content of the article and further details are available within the backmatter of the website version of this article.

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1. Introduction

Energy is a core challenge for human development, and the unresolved issues of energy, pollution, and unsustainability have led to environmental problems and conflicts. Fossil fuels such as coal, oil, and natural gas have driven rapid human progress but have also caused a series of issues. While electrical energy appears to address pollution and non-renewability, it merely shifts the pollution to an earlier stage. Fuel cells, despite having a history similar to fossil fuels, have been overlooked due to their instability and high cost. However, with the intensifying issues surrounding fossil fuels and the rapid development of fuel cell technology, the world has begun to focus on this seemingly perfect energy system. Fuel cells have strict operational requirements; low humidity can cause the electrolyte membrane to lose water, hindering proton conductivity, while excessive humidity can lead to over-hydration of the membrane, reducing proton conduction efficiency. Furthermore, while increasing temperature enhances catalyst activity and improves performance, it can also dehydrate the membrane electrode assembly (MEA), potentially causing safety hazards. Conversely, lowering the temperature presents opposite challenges. Therefore, traditional proton exchange membrane fuel cells (PEMFCs) require complex external systems for temperature and humidity control, increasing costs and limiting their application. Research on PEMFCs that are insensitive to humidity is of great significance, as it can reduce the costs of temperature and humidity control, thereby expanding their potential applications. This is the main focus of this paper.

Vani R et al. [1] prepared PVA-SSA MEAs (6.25 cm^2) containing different concentrations of SiO_2 using a simple solution casting method. The experimental results indicated that 1 wt% SiO_2 was the optimal ratio, achieving excellent performance under low-humidity conditions. Ada Sacca et al. [2] found that under harsh operating conditions (high temperature and low humidity), adding TiO_2 effectively improved the mechanical properties

of the MEA (25 cm^2). The experiments showed that 10 wt% was the optimal amount of TiO_2, significantly enhancing proton conductivity and reducing the coefficient of expansion. Jiaxi Zhang et al. [3] designed an MEA using SiO_2-MSCC as the anodic catalyst support for PEMFC (5 cm^2), prepared through a templating method. The silica content and pore size were controllable, and the MEA demonstrated high durability and minimal current density loss, showing great potential for application. Yılser Devrim [4] fabricated a sulfonated polyphenylsulfone/phosphotungstic acid/silica (sPP/PWA/SiO_2) hybrid membrane and characterized it for use in PEMFCs (5 cm^2) under low-humidity conditions, demonstrating superior performance compared to conventional Nafion membranes. Chi-Young Jung et al. [5] added SiO_2 of varying particle sizes to the catalyst layer (CL) to study humidity variation inside the cell (5 cm^2). As the diameter of SiO_2 particles decreased, overall cell performance, including ESA, ohmic performance, and CV curves, improved. Keun-Hwan Oh et al. [6] synthesized a silica-embedded hydrogel nanofiller and prepared SPAEK membranes containing the nanofiller. The newly fabricated membranes significantly enhanced water retention, improving proton conductivity by an order of magnitude under low-humidity conditions. Y.P. Ying et al. [7] reviewed the application of SiO_2 in PEMFCs, analyzing and evaluating MEA structure, physicochemical properties, and electrochemical performance. The review concluded that adding SiO_2 to MEAs can improve PEMFC durability, water retention, thermal stability, and proton conductivity. These studies suggest that silica is widely used in MEAs under low-humidity conditions because, in high-humidity environments, adding silica may cause water flooding in PEMFCs, leading to gas blockage and performance degradation. Therefore, the addition of silica presents a dual nature, requiring careful assessment based on operating conditions.

Bin He et al. [8] primarily investigated the factors influencing water transport in open-air-cooled PEMFCs, finding that humidity, temperature, and flow field design parameters directly affect efficiency and lifespan, making their optimization crucial. Hyunsik Oh et al. [9] focused on how cerium-based perovskite mixed metal oxides improve fuel cell performance and durability under low humidity by capturing oxidative radicals, which is considered a solution to performance degradation in such conditions. Kangwei Qiao et al. [10] designed a novel cathode structure where acidic and basic materials are arranged in a specific pattern to achieve self-humidification, addressing traditional PEMFC humidification management challenges. This design optimizes water and proton transport, improving the overall efficiency and stability of the fuel cell. Ziyi Meng et al. [11] developed a graphene oxide-intercalated montmorillonite (GO-MMT) material to improve PEMFC performance under high-humidity conditions. By integrating this material with Nafion membranes, the researchers reduced the fuel cell's reliance on high humidity, enhancing stability and conductivity, thereby improving real-world performance. Xueliang Wang et al. [12] analyzed the improvement of GDL surface properties through deposition processes, demonstrating its role in enhancing performance, reducing water flooding, and increasing gas diffusion capacity. Enhanced hydrophobicity significantly improved PEMFC electrochemical performance. Gozde Ustuner et al. [13] focused on how different operating conditions (temperature, pressure, humidity) affect fuel cell performance, using impedance spectroscopy to decompose the contributions of these parameters to ohmic and polarization resistances, optimizing operating conditions to enhance efficiency. Yangbing Shao et al. [14] used experimental and modeling analysis to study the interactions between water management, membrane conductivity, and electrochemical reactions, revealing that membrane dehydration and reaction non-uniformity in high-temperature, low-humidity environments are primary causes of voltage collapse, providing theoretical support for stabilizing fuel cells under harsh conditions. Xi Chen et al. [15] improved the accuracy and response speed of membrane humidity control by designing a fractional-order PID controller, enhancing fuel cell performance and lifespan. Experimental results showed that this strategy outperforms traditional PID controllers in both dynamic performance and steady-state accuracy. Taotao Zhao et al. [16] designed hydrophilic and hydrophobic surface structures on bipolar plates, effectively reducing water accumulation

and blockage, thus improving water management efficiency and enhancing overall fuel cell performance and stability. Yangbing Shao et al. [17] mainly studied water management in PEMFCs under high-temperature, low-humidity environments during load cycling. They focused on the impact of water generation, transport, and consumption on fuel cell performance, analyzing the challenges and solutions for water management under different operating conditions. Through experimental and theoretical analysis, the authors proposed optimized water management strategies to improve PEMFC efficiency and reliability in heavy-duty applications.

Through a survey of papers, it was found that current humidity-related studies are primarily divided into two approaches. Prior to 2020, most research focused on adding hydrophilic inorganic materials to enhance the water retention of the MEA in low-humidity environments [1–7]. After 2020, the focus shifted to improving PEMFC water management through novel structural designs, non-MEA modifications, models, or PID control. Recent studies are based on the rapid development of neural networks and advanced processing techniques, which, though promising, have high costs and limited general applicability, reducing their practical value. In contrast, self-humidification research based on the MEA core has strong versatility and better stability. Therefore, this study continues to explore self-humidification within the MEA framework. Previous research [1–5] predominantly used small-area MEAs (5–6.25–25 cm^2), which have limited practical relevance (Table 1). This study will investigate the performance of large-area MEAs (100 cm^2) after self-humidification improvements, significantly enhancing the practical value of research in this area, and representing the key innovation of this paper.

Table 1. Comparison of PEMFC operating conditions and area.

Authors	Temperature	Humidity (RH)	Area (cm^2)	Remark	Content (wt%)
Vani R [1]	70 °C	21, 30, 100%	6.25	SiO_2	0.1, 1, 5, 10
Ada Sacca [2]	60 °C	50%	25	TiO_2	5, 10, 15
Jiaxi Zhang [3]	60 °C	20, 37, 62, 100%	5	SiO_2	1.6
Yılser Devrim [4]	70–120 °C	30–100%	5	SiO_2	10
Chi-Young Jung [5]	70 °C	20, 100%	5	SiO_2	1
Keun-Hwan Oh [6]	70, 80 °C	38, 100%	-	SiO_2	1, 2
Y.P. Ying [7]	—	—	-	SiO_2	5, 10
Ours	65, 80, 85 °C	10–100%	100	SiO_2	0, 2, 3, 4

In addition, currently hydrophilic materials mainly use two types: TiO_2 and SiO_2. In this study, SiO_2 was used for the following reasons: First, SiO_2 possesses high gas impermeability, excellent corrosion resistance, and strong stability, which are crucial for preventing gas penetration, electron leakage, and chemical degradation. While TiO_2 also offers stability and corrosion resistance, it may not match the gas impermeability of SiO_2. Additionally, silica has lower proton conductivity compared to TiO_2. Finally, SiO_2 is more cost-effective and readily available.

2. Materials and Methods

To ensure the coherence of the study, custom-made Membrane Electrode Assemblies (MEAs) were utilized in this experiment. MEAs manufactured by Nanya Corporation (Taiwan, China) were utilized, featuring a reaction area of 100 × 100 mm. The platinum loading on the anode side was 0.2 mg/cm^2, while the cathode side had a platinum loading of 0.4 mg/cm^2. The membrane material used was Nafion 211, produced by DuPont (Beijing, China), and the gas diffusion layer was SGL 10BC. To ensure protection outside the reaction area, a lamination-like hot-pressing method was applied, similar to the use of laminating pouches.

This approach facilitates the observation and analysis of the impact of the manufacturing process on the appearance and performance of the cells, laying a foundation for subsequent research. Based on preliminary experiments and a review of relevant literature [1–7], the study selected temperatures of 65 °C, 80 °C, and 85 °C for the Proton Exchange Membrane Fuel Cell (PEMFC) experiments.

2.1. Single Cell Construction

To ensure that the power output meets the required specifications, the Membrane Electrode Assembly (MEA) fabricated for this study has a reaction area of 100 cm^2. For the sake of research continuity, this paper will provide a concise description of the manufacturing process of the Proton Exchange Membrane Fuel Cell (PEMFC), including the following components: the Gas Diffusion Layer (GDL), the Catalyst Layer, the Membrane Electrode Assembly (MEA), and the cell assembly process.

2.1.1. Gas Diffusion Layer (GDL)

The production of the GDL for PEMFCs involves selecting carbon paper or cloth for their conductivity and stability, followed by surface treatment to improve adhesion. A carbon powder coating is applied to enhance conductivity and strength, then cured at high temperatures. After testing for conductivity and porosity, the GDL is cut to fit the fuel cell, ensuring efficient gas distribution and Catalyst Layer support [18–20].

2.1.2. Catalyst Layer

The Catalyst Layer in a PEMFC consists of a catalyst, proton conductor (ionomer), and additives like pore formers, PTFE, and ceramics. It lowers activation energy for reactions and improves electron conduction. A three-phase interface (solid, liquid, gas) is essential, and additives like pore formers enhance water management and gas entry [21–23].

2.1.3. The Membrane Electrode Assembly (MEA)

The MEA in PEMFCs, consisting of the GDL and Catalyst Coated Membrane (CCM), is vital to performance and longevity. The CCM is made by spraying a catalyst onto the Proton Exchange Membrane (PEM), which conducts hydrogen ions while preventing gas crossover [24–26].

2.1.4. Cell Assembly Process

The fuel cell assembly is critical for performance. For low-temperature operation, it involves cleaning bipolar and graphite plates, stacking end plates, current collectors, and the Membrane Electrode Assembly (MEA), and insulating bolts with Teflon. The components are secured with nuts to complete the assembly.

2.2. Cell Activation and Electrochemical Impedance

Following the leak test, the fuel cell must undergo an activation procedure before performance testing can commence. The activation process is outlined as follows:

(1) After introducing the gases, maintain an open-circuit voltage for ten minutes.
(2) Operate the cell at 0.6 V and 0.2 V for 30 min each, performing this cycle 10 times.
(3) Activation is considered complete when the polarization curve stabilizes and the performance meets the specified standards.

3. Results and Discussion

This study employed the Catalyst Coated Membrane (CCM) spraying method, utilizing a spraying solvent prepared from isopropanol and distilled water, to analyze the performance differences of the fuel cell under varying relative humidity conditions. Additionally, the impact of adding 2 wt% silica to the catalyst layer was investigated to assess the performance variations of the fuel cell under low-humidity conditions.

In the preliminary study, this paper explored the effect of different silica contents on fuel cell performance (Figure 1). If the silica content was too low, the water retention effect was insufficient. Increasing the silica content caused a certain degree of water flooding, leading to MEA expansion and catalyst delamination, which resulted in irreversible damage to the PEMFC to some extent. Therefore, 2 wt% silica was selected as the optimal solution in this study.

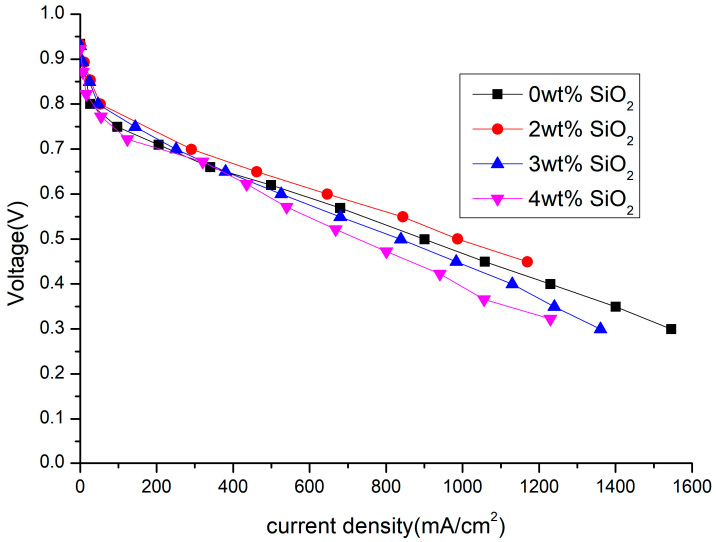


Figure 1. Performance curve with different proportions of silica added.

The experimental conditions of this paper are as follows: air is introduced into the cathode and hydrogen is introduced into the anode, with a frequency of 0–1000 Hz. The gas flow rate in this paper is calculated using the following formula:

$$P = I*\lambda*n*C \quad (1)$$

where P is the gas flow rate (mL/min), I is the PEMFC current (A), λ is the gas stoichiometry (multiple), n is the number of fuel cells, and C is the required gas volume per unit area (the oxygen volume required to generate 1 A current per unit area is 3.5 mL/min, the air volume is 17.5 mL/min, and the hydrogen volume is 7 mL/min). Since λ and n have no units and I is used to adjust the multiple of C, the final output P unit is mL/min.

To enhance the practical applicability of the research, this study does not utilize the small-area MEAs (6.25 cm^2 or 9 cm^2) commonly used in many references. Instead, the reaction area is increased to 100 cm^2, which allows for higher power output from the cell. The focus of this study is on the performance variations of PEMFC with hydrophilic materials added to the MEA under different temperature and humidity conditions. Consequently, a fixed gas stoichiometry approach was employed, with the anode and cathode operating at stoichiometries of 1.2 and 4, respectively. The catalyst loadings for the anode and cathode were 0.2 and 0.4 mg/cm^2, respectively, and the silica content was 2 wt%.

Figures 2 and 3 are AC impedance curves at different humidity at 65 °C. From the two figures, it can be seen that the impedance under different Nafion weights is very different. When the amount of Nafion is too high, the impedance will be greatly increased, resulting in a decrease in performance, which is consistent with the results in preliminary experiment. When Pt/C:N-2:0.75, both ohmic impedance and polarization impedance are optimal values.

In addition, under 100% humidification, the impedance values under the conditions of Pt/C:N-2:0.5 and Pt/C:N-2:0.3 are relatively close. But when the humidity drops to 50%, their ohmic impedance and polarization impedance increase significantly. This shows that low humidity will make the reaction environment inside the fuel cell harsh, thereby affecting its performance.

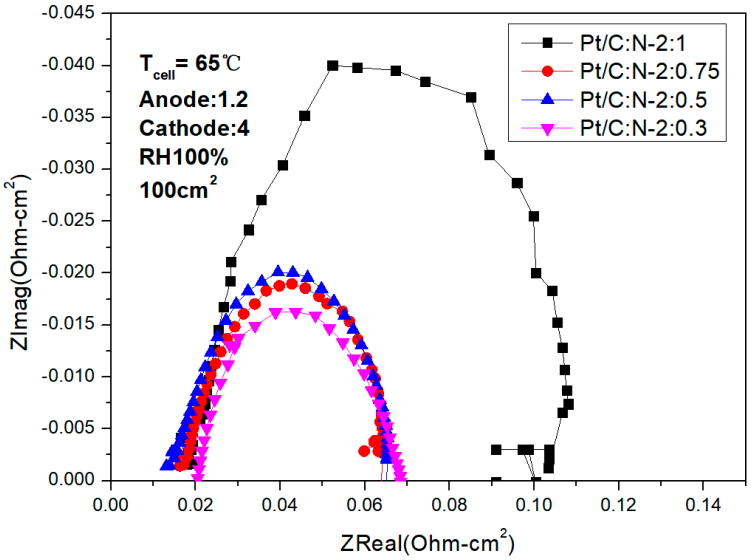


Figure 2. AC impedance curve under 100% humidification (65 °C).

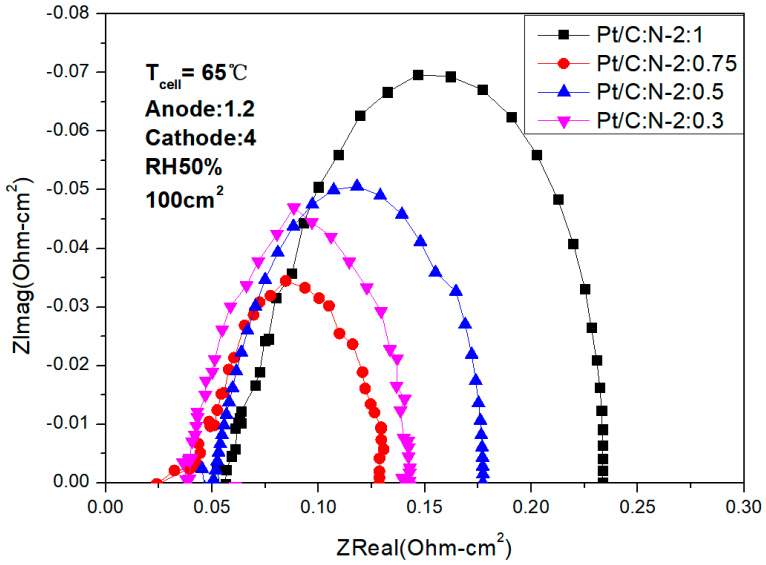


Figure 3. AC impedance curve under 50% humidification (65 °C).

3.1. Performance Degradation of PEMFCs Under Various Humidification Conditions

3.1.1. Degradation of PEMFC Performance at 65 °C

In practical operations, rapid changes in cell humidity are rarely encountered. Therefore, this study gradually reduced the cell humidity from 100% to 20% to observe performance variations. Figure 4 illustrates the performance curves of the PEMFC at a working voltage of 0.6 V under different humidity levels. It was observed that the performance degradation rates from high to low humidity were 17%, 12%, 11%, 5%, and 34%, respectively. At 65 °C, a decrease in humidity does not lead to a uniform or geometric progression in performance degradation. Initially, a reduction in humidity results in an immediate decline in proton conductivity, subsequently causing a performance decline. However, after a certain period, the water retention properties of silica begin to take effect, leading to a reduction in the rate of performance degradation as humidity decreases. Nevertheless, once the humidity drops to 20%, silica cannot alleviate the performance decline associated with low humidity, resulting in a significant increase in the extent of performance degradation.

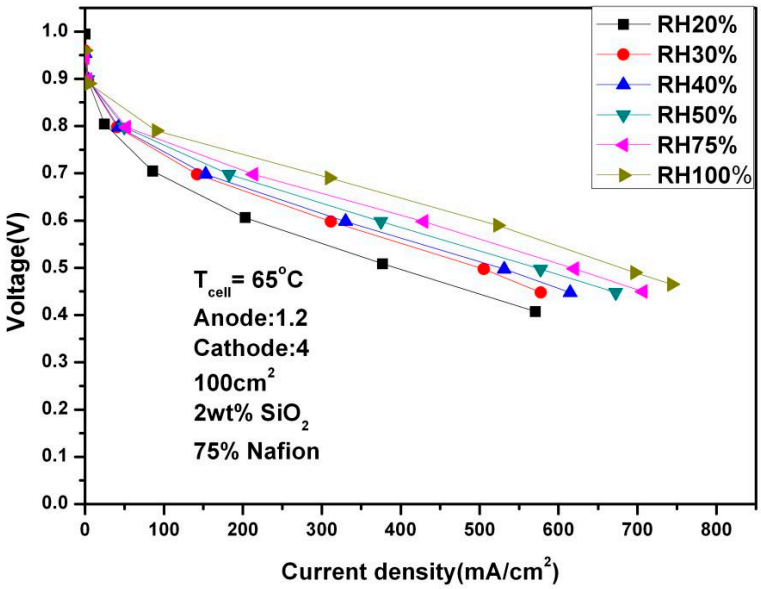


Figure 4. Polarization curves of PEMFC at 65 °C under various humidification levels.

3.1.2. Degradation of PEMFC Performance at 80 °C

Upon increasing the temperature to 80 °C, which further activates the cell, the lower limit of humidity was also reduced to 10%, making the study more representative of practical conditions. As shown in Figure 5, at 0.6 V, the performance degradation of the cell under varying humidity levels is sequentially 12%, 14%, 23%, 24%, 27%, and 40%. With the rise in temperature, each 10% reduction in humidity under low-humidity conditions results in over 20% performance degradation. Experimental results indicate that as the temperature increases, the extent of performance degradation in the fuel cell significantly rises. This enhancement in degradation is attributed to the increased rate of water evaporation at elevated temperatures. High-temperature, low-humidity conditions remain a challenging operational environment for PEMFC.

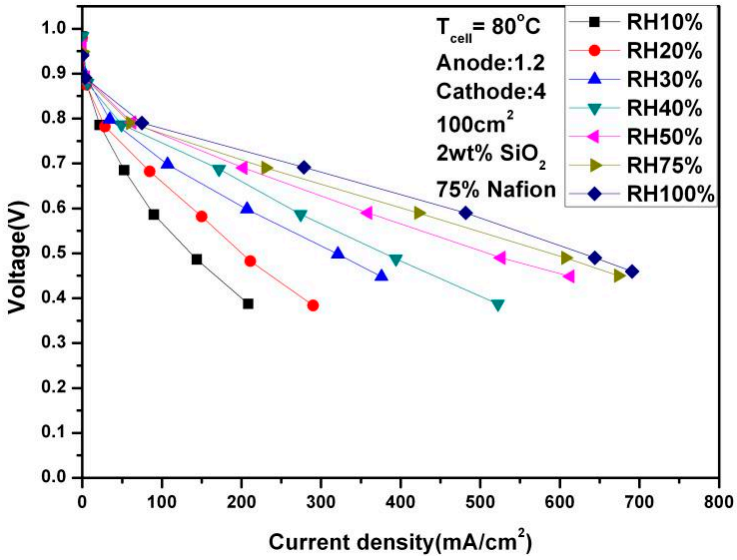


Figure 5. Polarization curves of PEMFC at 80 °C under various humidification.

3.1.3. Degradation of PEMFC Performance at 85 °C

Through research on existing papers, it has been found that 85 °C represents the upper temperature limit for most small-scale low-temperature and low-humidity PEMFC. Consequently, this temperature was also set as the upper limit for the study. As indicated

by the performance curves in Figure 6, the degradation rates with decreasing humidity are sequentially 3%, 12%, 27%, 21%, 52%, and 34%. An increase in temperature also enhances the catalyst's activity, thereby increasing the water production rate. Consequently, during the initial stages of reduced humidity at 85 °C, the performance of the Proton Exchange Membrane Fuel Cell (PEMFC) exhibits minimal degradation. However, as the humidity continues to decrease, the degradation of PEMFC performance becomes most pronounced due to the dry membrane condition induced by high temperatures. The figure shows that when the humidity decreases from 30% RH to 20% RH, the current density significantly drops by 52%. A similar trend is observed at 65 °C, suggesting that 30% RH is a critical threshold for performance changes in PEMFC under low-humidity conditions, providing important reference value.

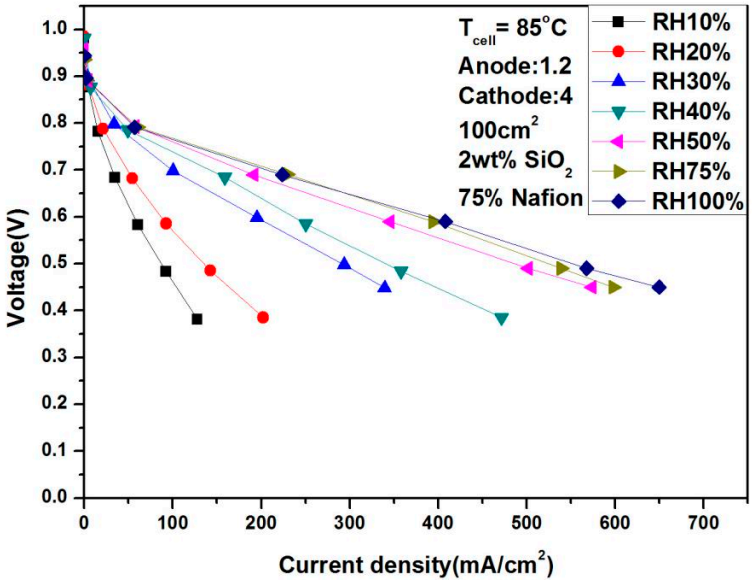


Figure 6. Polarization curves of PEMFC at 85 °C under various humidification.

The research at this stage revealed that the degradation rate of performance between 100% and 50% RH is significantly lower than that between 50% and 20% RH. The significant performance decline below 50% RH occurs specifically at temperatures of 80 °C and 85 °C. This is due to the increased evaporation rate at elevated temperatures under excessively low humidification conditions, leading to rapid moisture loss. Consequently, the mechanical strength of the MEA decreases, resulting in a notable performance degradation. Despite the addition of silica, there was still no significant improvement in mitigating the performance decline under such low-humidification operating conditions.

3.2. Voltage Stability of PEMFC Under Low Humidity

Polarization curves only reflect performance variations of PEMFC from one perspective. This study will further investigate voltage stability. A constant current method was employed, with the current fixed at 40 A under different temperatures, to study voltage variations in PEMFC. Preliminary research indicated that when humidity is above 50%, voltage changes are minimal. Therefore, to reduce the workload, this part of the study will focus on PEMFC operated at humidities below 50%.

3.2.1. Voltage Variations of PEMFC Under Constant Current at 65 °C

Figure 7 illustrates the voltage fluctuations of PEMFC at 65 °C as relative humidity decreases from 50% RH to 20% RH. The curve indicates that under a constant current of 40 A, the voltage fluctuation remains within the range of 0.01 to 0.03 V, with no significant deviations observed. On the other hand, as relative humidity decreases, the voltage value also gradually declines. This suggests that, despite the addition of hydrophilic

materials, the cell performance still deteriorates with decreasing humidity at extremely low humidity levels.

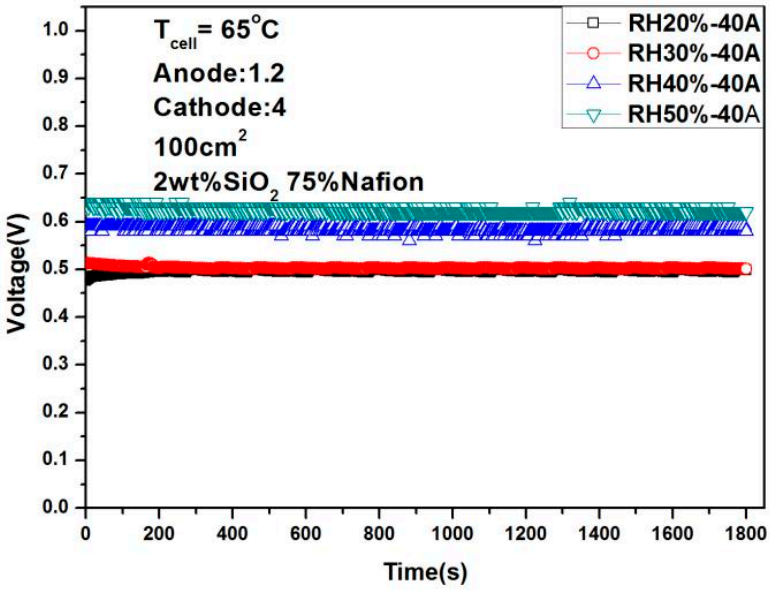


Figure 7. Performance Curve of PEMFC under Constant Current in Low Humidity at 65 °C.

3.2.2. Voltage Variations of PEMFC Under Constant Current at 80 °C

As the temperature increases, it was observed in preliminary experiments that at 20% RH, the excessive evaporation leads to severe dry membrane phenomena and substantial performance degradation. Therefore, at 80 °C and 85 °C, the lower humidity limit was set to 30% RH. Figure 8 shows that with increasing temperature, the voltage fluctuations under constant current conditions become significantly more pronounced, which is attributed to the increased evaporation rate. Under the 30% RH condition, the voltage difference between the maximum and minimum values reached 0.05 V, and periodic voltage fluctuations were observed. These fluctuations are attributed to the cyclical nature of water production and loss during the cell's operation.

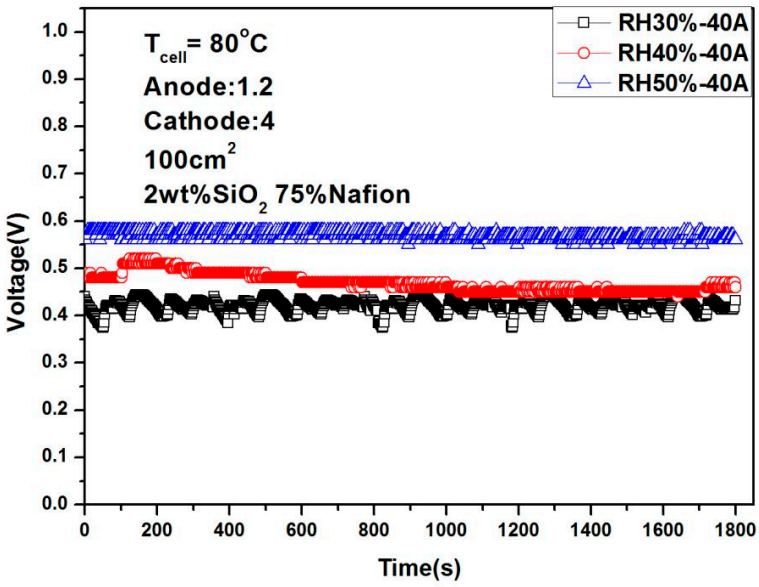


Figure 8. Performance Curve of PEMFC under Constant Current in Low Humidity at 80 °C.

3.2.3. Voltage Variations of PEMFC Under Constant Current at 85 °C

Figure 9 illustrates that the voltage curves of the PEMFC at 85 °C exhibit similar characteristics to those at 80 °C, with significant voltage fluctuations observed under low humidity conditions. These fluctuations can be detailed as follows: Firstly, at 50% RH, the voltage remains stable, indicating that this humidity level meets the operational requirements of the cell. Secondly, at 40% RH, the cell initially operates stably for the first 10 min, but performance exhibits noticeable fluctuations over time, attributed to the disruption of the internal water balance. Lastly, as the humidity further decreases to 30% RH, the voltage curve displays periodic fluctuations similar to those observed at 80 °C, which are caused by the cyclical variation of internal humidity within the cell.

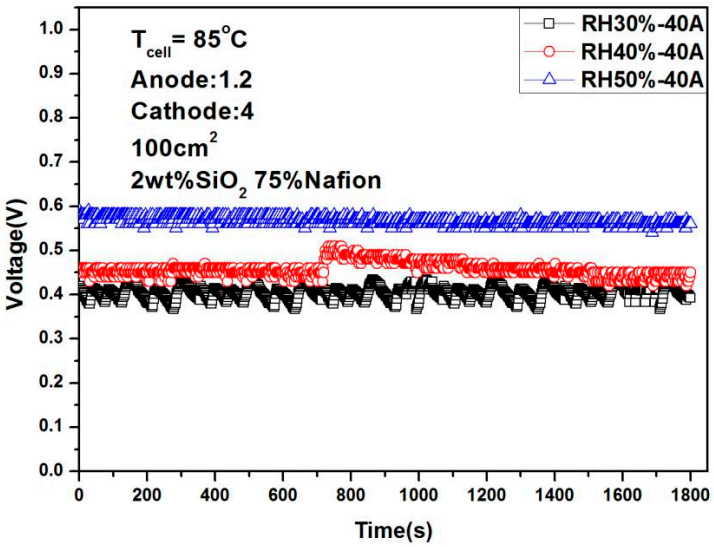


Figure 9. Performance Curve of PEMFC under Constant Current in Low Humidity at 85 °C.

Low humidity conditions can lead to a decrease in the proton conductivity of the membrane electrode, resulting in unstable output voltage. Silica, as an efficient modification material, can effectively enhance the performance of proton exchange membranes in high-temperature, low-humidity environments due to its excellent moisture retention capabilities and stability. Specifically, the addition of silica significantly improves the moisture retention of the membrane electrode, ensuring that the membrane and catalyst remain in an optimal hydrated state, thus maintaining high proton conductivity. Furthermore, silica can enhance the mechanical and chemical stability of the membrane electrode, further extending the lifespan of the fuel cell. These combined effects enable proton exchange membrane fuel cells to maintain stable output voltage in low-humidity environments, facilitating efficient and reliable energy conversion. Therefore, the incorporation of silica in low-humidity environments is an effective approach to improving the voltage stability and overall performance of proton exchange membrane fuel cells, which is crucial for promoting their widespread use and commercialization in practical applications.

3.3. Transient Startup Phenomenon Under Different Humidification

Analogous to the high fuel consumption and rapid load increase observed during the initial startup of internal combustion engines, fuel cells exhibit a similar phenomenon known as transient startup. This phenomenon is characterized by fluctuations in voltage and power, and if not properly managed, can lead to a "starvation" effect, resulting in a rapid decline in voltage. To evaluate the transient startup performance of the fuel cell, this study sets the operating current at 30 A and observes the time required for the cell to reach a stable operational state under various temperature conditions. Additionally, under fully humidified conditions, different current values are applied to assess the transient startup behavior under different load conditions.

3.3.1. Transient Startup Phenomenon at 65 °C Under Different Humidity

Figure 10 illustrates the inrush curves for currents ranging from 0 A to 30 A at 65 °C under different humidity conditions. It is observed that under low humidity conditions, the rapid decline in inrush voltage results in a prolonged stabilization period for the cell's performance. In contrast, the time required for performance stabilization under fully humidified conditions is significantly shorter. Figure 11 compares the performance of the cell under different inrush currents at full humidification. The results indicate that, at the same current levels, the performance under full humidification is notably superior to that under low humidity conditions. However, as the current increases, the voltage drop becomes more severe, with the voltage failing to stabilize at 70 A.

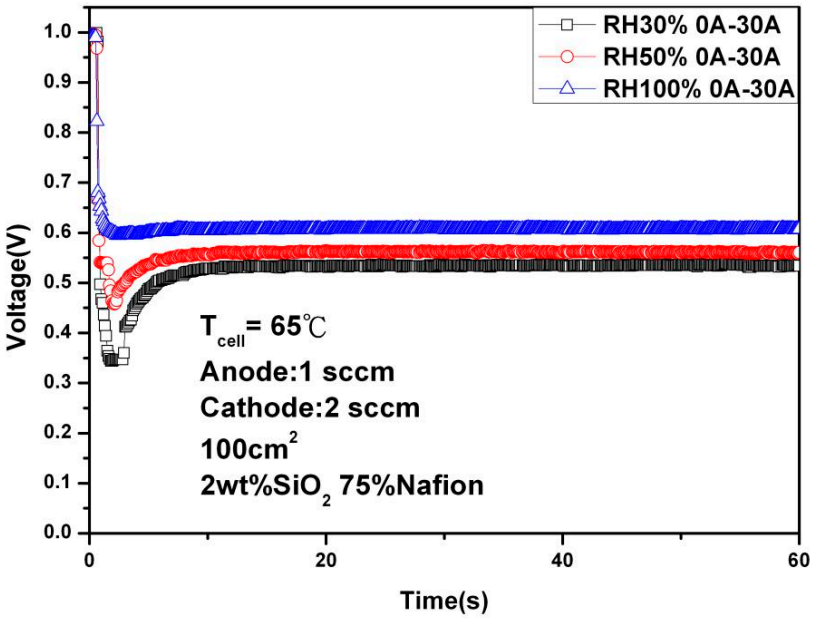


Figure 10. Transient Startup Curves under Constant Current (0 A–30 A) at 65 °C and Various Humidity.

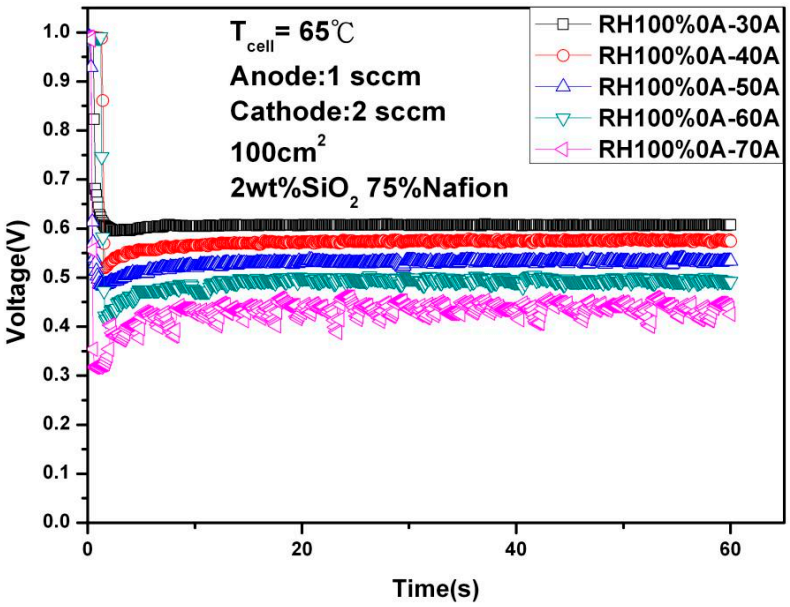


Figure 11. Performance Curves of Transient Startup under Various Current at 65 °C with Full Humidification.

3.3.2. Transient Startup Phenomenon at 80 °C Under Different Humidity

From Section 3.2, it is evident that under low humidity conditions, battery performance declines with increasing temperature. Similar phenomena have been observed in transient opening studies, albeit with slight differences. As illustrated in Figure 12, the rate of voltage decline significantly diminishes as the temperature rises to 80 °C, highlighting the advantage of elevated temperature; however, this also results in a lower stable voltage value compared to that at 65 °C. Figure 13 depicts the current transient opening curves under full humidity conditions. After the addition of silica, the battery rapidly reaches a stable output state at various current levels, although the voltage still fails to stabilize at the critical current value of 70 A.

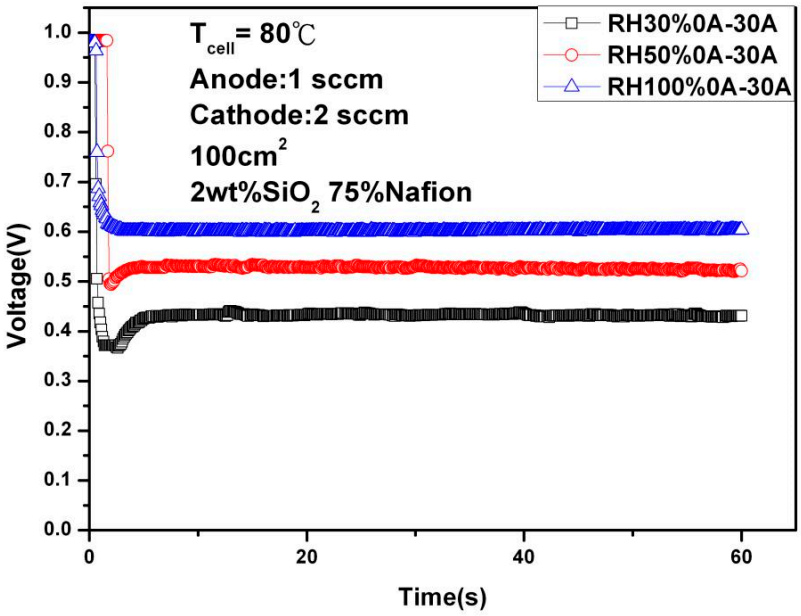


Figure 12. Transient Startup Curves under Constant Current (0 A–30 A) at 80 °C and Various Humidity.

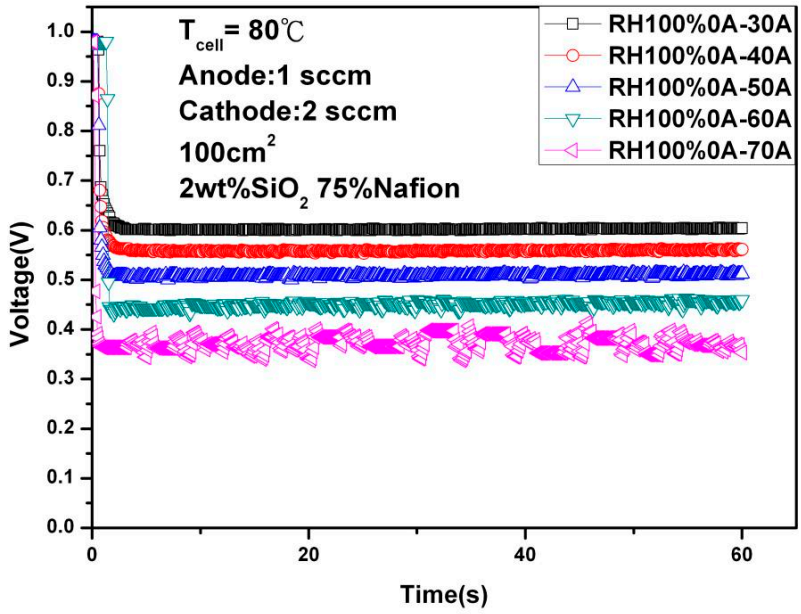


Figure 13. Performance Curves of Transient Startup under Various Current at 80 °C with Full Humidification.

3.3.3. Transient Startup Phenomenon at 85 °C Under Different Humidity

Upon further increasing the temperature to 85 °C, it was observed that the transient opening curves of the PEMFC exhibit a trend similar to that at 80 °C, albeit with greater amplitude fluctuations. As shown in Figure 14, at a constant current of 30 A, the voltage of the PEMFC under 30% RH experiences a more pronounced decline and fails to achieve stable output. In contrast, when the humidity is increased to 50% RH, the voltage remains stable but exhibits a gradual decline over time. Figure 15 illustrates the transient performance curves at different currents under full humidity conditions. From a stability perspective, the currents of 50 A and 60 A demonstrate relatively unstable performance, attributed to the pronounced periodic variation in internal moisture within the cell.

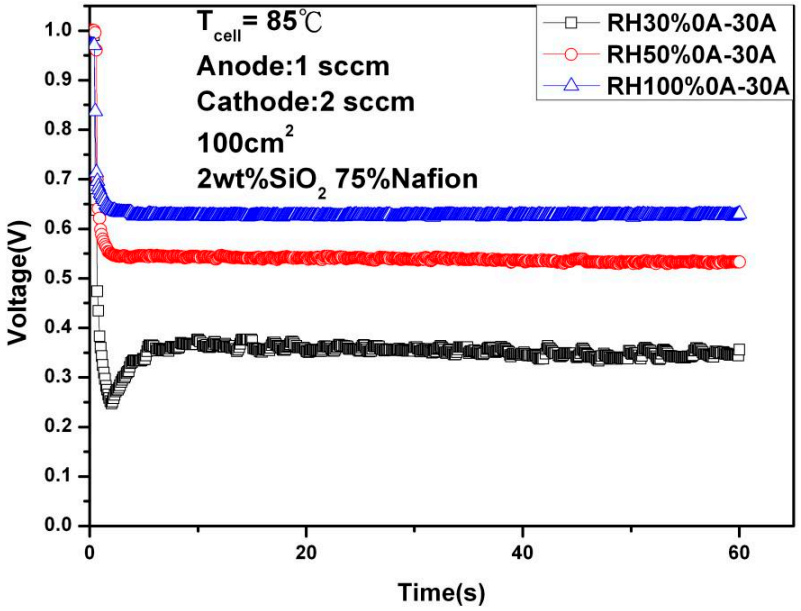


Figure 14. Transient Startup Curves under Constant Current (0 A–30 A) at 85 °C and Various Humidity.

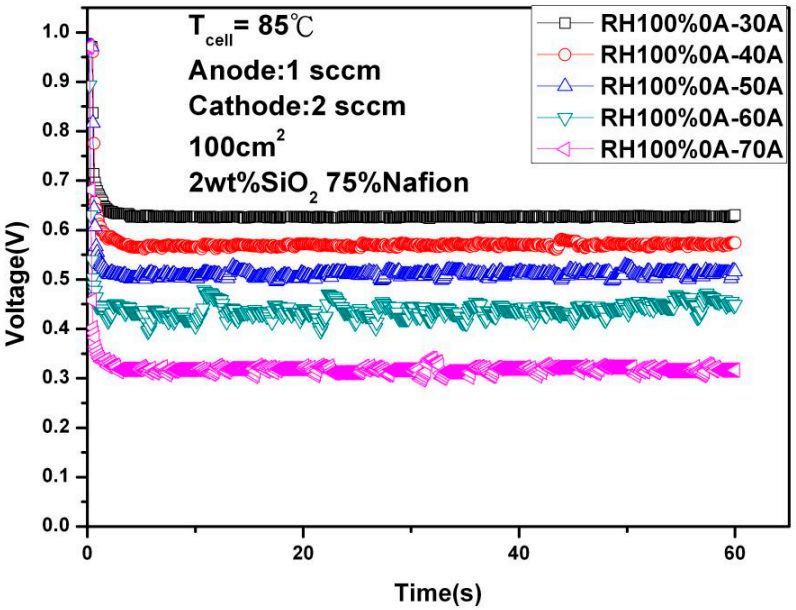


Figure 15. Performance Curves of Transient Startup under Various Current at 85 °C with Full Humidification.

During the transient start-up process, the fuel cell needs to quickly achieve a stable output voltage and power output. The addition of silica can shorten the time required for the fuel cell to reach a stable state, reduce voltage fluctuations during the start-up process, and enhance start-up efficiency. Furthermore, silica can improve the mechanical and chemical stability of the membrane electrode, thereby extending the lifespan of the fuel cell and ensuring its reliability and stability during prolonged operation. Consequently, the incorporation of silica in low-humidity environments is of significant importance for the transient start-up of proton exchange membrane fuel cells, as it not only enhances the start-up efficiency and stability of the cell but also prolongs its operational lifespan. This, in turn, provides strong support for the widespread use and commercialization of proton exchange membrane fuel cells in practical applications.

4. Conclusions

This study demonstrates that within the high humidity range of 100% RH to 50% RH, the addition of silica effectively mitigates performance degradation at high temperatures. Specifically, the decline in performance at 65 °C, 80 °C, and 85 °C is 28.3%, 25.4%, and 15.3%, respectively. This is attributed to the combined effects of the high reactivity induced by high temperatures and the water retention capabilities of silica, which collectively enhance fuel cell performance. However, as humidity further decreases below 50% RH, high evaporation rates at high temperatures impair the ability of silica to fully exert its water retention properties, resulting in substantial performance degradation. Within the range of 50% RH to 20% RH, the performance decline at 65 °C, 80 °C, and 85 °C is observed to be 45.8%, 58.2%, and 73.2%, respectively. Similar trends are also noted during extended load tests and transient startup conditions. The research presented herein indicates that the incorporation of silica significantly slows down the performance decline due to humidity reduction within the high humidity range (100% RH–50% RH), whereas its effectiveness is relatively modest within the low humidity range (50% RH–20% RH). This phenomenon is attributed to a combination of factors including temperature, evaporation rate, water retention capacity, and membrane stability.

Author Contributions: Conceptualization, Q.B. and C.H.; methodology, Q.B.; software, Z.L.; validation, Q.B., Q.C. and F.W.; formal analysis, Q.C.; investigation, Z.L.; resources, Q.B.; data curation, Q.B.; writing—original draft preparation, C.H.; writing—review and editing, Q.B.; visualization, Z.L.; supervision, Q.C.; project administration, F.W.; funding acquisition, Q.B. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the Youth Science and Technology Talent Growth Project of Guizhou Provincial Department of Education (Guizhou Education Technology [2024]No.191), the Guiyang University Doctoral Research Launch Project (No: GYU-KY-[2024]), Guizhou Province high-level innovative talent project (GCC[2023]010), the science and technology top talent project of Guizhou Provincial Department of Education (Grant No.: [2022]086), Guiyang City Science and Technology plan program (Grant No. [2023]48-18), Guizhou Provincial Department of Science and Technology's academic new seedling cultivation and free exploration and innovation special project, the Guizhou Provincial Basic Research Program (Natural Science) (Grant No. Qiankehejichu-ZK[2023]General 014), Growth Project for Young Scientific and Technological Talents in General Colleges and Universities of Guizhou Province (Grant No. Qianjiaoji[2022]303).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: Thanks to Cheng-Kuan Li from Yuan Ze University for his assistance and valuable insights during the paper revision process and in the context of future industrial applications.

Conflicts of Interest: The authors declare no conflicts of interest.

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