

Article

Humidity Diffusion Process Analysis and Life Prediction of a VSC-HVDC Control Protection Device Based on a Finite Element Simulation Method

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Abstract: Voltage Source Converter-based High-Voltage Direct Current Transmission (VSC-HVDC) is essential for integrating renewable energy sources and facilitating inter-regional power transmission. This study evaluates the reliability of control and protection devices within these systems, which are crucial for the stable operation of power grids. Humidity significantly affects both the operational conditions and lifespan of these devices. Previous studies, reliant on extensive full-condition fatigue testing, have lacked effective test models and detailed analyses of mechanisms. To address this gap, a humidity diffusion model was developed to comprehensively investigate moisture diffusion mechanisms. Using the insights gained, the Hallberg–Peck model was applied to predict the lifespan of these devices, quantitatively assessing how changes in humidity affect their reliability. This approach employs a stringent failure criterion, leading to a conservative predicted lifespan. This method achieved a prediction accuracy of 85.648% compared to the benchmarks in GB/T 2423.50-2012, validating the accuracy of our model and the effectiveness of our simulation technology under stringent conditions. This research provides vital theoretical data and serves as an essential tool for guiding the precise maintenance of equipment in varying environmental humidity levels.

Keywords: VSC-HVDC; humidity diffusion; lifespan; key components; reliability assessments



Citation: Li, C.; Cheng, Y.; Hou, X. Humidity Diffusion Process Analysis and Life Prediction of a VSC-HVDC Control Protection Device Based on a Finite Element Simulation Method. *Electronics* **2024**, *13*, 2888. <https://doi.org/10.3390/electronics13152888>

Academic Editors: Roberto Nardone, Giovanni Paragliola and Carmelo Mineo

Received: 30 June 2024

Revised: 16 July 2024

Accepted: 20 July 2024

Published: 23 July 2024



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1. Introduction

As the global economy grows, environmental challenges have become more pronounced, driving the need for clean, green energy solutions. This shift necessitates a move away from traditional energy sources towards electricity, and particularly renewable sources like wind power, which are essential for sustainable energy development. Offshore wind power, in particular, offers several advantages over onshore alternatives, such as lower land usage, consistently higher wind speeds, and reduced visual and noise pollution. These benefits, combined with its proximity to load centers, have heightened global interest in recent years. Moreover, the lower costs of line installation for DC transmission present significant technical and economic benefits for deploying large-capacity offshore wind power transmission systems [1–3]. Voltage Source Converter-based High-Voltage Direct Current (VSC-HVDC) systems, which operate independently of traditional power supply supports, can effectively reduce the variability and unpredictability of renewable energy generation [4]. This capability minimizes power and voltage fluctuations on the grid, making the VSC-HVDC an optimal choice for transmitting offshore wind power [5].

The control and protection system is crucial for ensuring the safe and stable operation of VSC-HVDC systems, especially in offshore environments. A distributed high-performance computing architecture system includes various electronic components that are highly susceptible to adverse environmental conditions such as high temperatures, humidity, and salinity. High temperatures accelerate chemical degradation processes like corrosion and oxidation. Humidity can undermine insulation, cause material delamination,

and induce structural cracks. Additionally, salinity exacerbates corrosion and conductivity issues, further shortening the lifespan of components [6–8]. Given these challenges, this study focuses on the impact of humidity on the device reliability. Previous methods for assessing the impact of humidity on device reliability primarily relied on fatigue testing experiments. While comprehensive, these tests were costly and time-consuming [9]. Additionally, variability in the initial physical conditions of the tested components often led to inconsistent results. For instance, the regional differences in humidity across China from the dry conditions in the north–west to the highly humid environments along the southern coast exemplify the challenge of using standard fatigue tests to predict device behavior accurately in diverse settings. Such tests require extensive resources and struggle to replicate the specific environmental conditions encountered by electronic components in real-world settings. This variability, particularly evident in areas with fluctuating humidity levels, highlights the need for more precise and adaptable measurement techniques that can accurately reflect the true operational environment.

Finite element analysis provides a potential solution to the challenges previously described. It models the ingress of moisture into electronic devices efficiently within a computational simulation, significantly reducing the costs associated with traditional experimental testing. A key advantage of this method is its foundation in theoretical models, which ensures accurate and consistent results and minimizes the variability due to experimental sample quality. This enhancement in precision not only improves the evaluations but also extends their universal applicability, offering strong support for the stable operation and maintenance of the control protection devices in VSC-HVDC systems.

In recent years, the scope of finite element simulation studies on electronic devices has expanded significantly. These studies predominantly focus on the impacts of adverse environmental conditions, such as high temperature, high humidity, and high salinity on device functionality [10–12], revealing key factors affecting performance, though often lacking in detailed analysis. Additionally, fatigue testing experiments [13,14] provided reliable results from experimental setups, though they are recognized as being time-intensive, costly, and somewhat limited in applicability. Studies using finite element software to analyze the temperature distribution [15–17] rely on robust theoretical models, ensuring consistent outcomes but focusing solely on the temperature effects. Detailed explorations of the effects of humidity on device corrosion and insulation degradation were also conducted [18], but these studies typically did not include quantitative analysis or lifespan predictions. Finally, research on the consistency of temperature and humidity diffusion [19–21] discusses similarities in their diffusion processes, but their practical applications are limited. More detailed content is referenced in Table 1.

In the reliability analysis of VSC-HVDC systems, this article proposes an innovative humidity diffusion process analysis and life prediction of a VSC-HVDC control protection device based on a finite element simulation method, effectively addressing existing gaps in this field. This simulation method not only significantly reduces the time required for the reliability analysis but also ensures the effectiveness and accuracy of the results. Furthermore, this study incorporates a lifespan prediction model to quantify the impacts of humidity, enhancing the visualization and quantitative understanding of humidity effects on devices. The detailed contributions of this research are as follows:

1. This study addresses the scarcity of humidity simulation methods by applying finite element heat simulation techniques to the humidity transfer processes, thereby broadening the application spectrum for electronic device simulation.
2. By employing a life prediction model, we have accurately forecasted the lifespan of pertinent devices, thus confirming the model's high reliability and precision. Our method substantially lowers both time and economic costs when compared to traditional experimental testing.
3. This research provides precise guidelines for equipment operation and maintenance. Furthermore, the simulation methods and models developed here can be utilized for

the lifespan assessments of devices in high-humidity environments, enhancing their applicability across a wide range of fields.

Table 1. Comparisons among existing methods.

References	Research Focus	Key Features	Limitations
[10–12]	Impact analysis of high temperature, high humidity, and high salinity on equipment	Identification of key factors affecting device functionality	Lack of detailed analysis on identified factors
[13,14]	Fatigue testing experiments for electronic devices	Reliable results derived from experimental setups	Time-intensive, costly, and of limited applicability
[15–17]	Temperature diffusion studied using finite element software	Based on a robust theoretical model, yielding consistent outcomes	Focus limited to temperature effects
[18]	Discussion on corrosion and insulation degradation due to humidity	Detailed exploration of humidity's impact on devices	Absence of quantitative analysis or lifespan predictions
[19–21]	Consistent Diffusion Model for Thermo-hygrometric	Highlights similarities in temperature and humidity diffusion	Limited practical application and shallow in application depth
Purposed method	Simulation experiments on the effects of humidity on devices	Utilizes finite element software to model humidity diffusion and quantifies its impact using a lifespan prediction model	Additional variables need to be considered to enhance model accuracy

2. Humidity Diffusion Theory and Life Acceleration Model

2.1. Humidity Diffusion Theory Derived from Temperature Model

Humidity diffusion and temperature diffusion have many similarities. For the process of steady-state diffusion of temperature and humidity in the same material, Fick's diffusion law can be used to describe it:

$$J = -\nabla C \quad (1)$$

$$\frac{\partial C}{\partial t} = \nabla \cdot (D \nabla C) \quad (2)$$

where J ($\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) is the amount of material passing through a unit area in a unit time; D (m^2/s) is the diffusion coefficient, which represents the ability of material diffusion; and C (kg/m^3) is the concentration of the substance in the mixture.

This study involves the unsteady temperature and humidity diffusion process between different materials, and its expression can be derived from the Fick diffusion law [19], which is in the form:

$$\frac{\partial C}{\partial t} = D \left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2} \right) \quad (3)$$

Considering the many common characteristics of temperature and humidity diffusion, and that the existing finite element simulation software does not have a simulation module for humidity, we intend to use its temperature simulation module for the humidity simulation. However, there are still some differences between them. To ensure the accuracy of the simulation results, it is necessary to modify the temperature simulation model according to these differences. In the process of humidity diffusion, the differences with temperature are:

- (1) The speed of reaching thermal equilibrium during the simulation is very fast, while the process of wet equilibrium is very slow, taking several days or even months.
- (2) In the thermal diffusion process, the temperature changes continuously at the junctions of different materials, while in the wet diffusion process, the humidity changes are not continuous, as shown in Figure 1a, which cannot meet the boundary conditions of the finite element simulation.

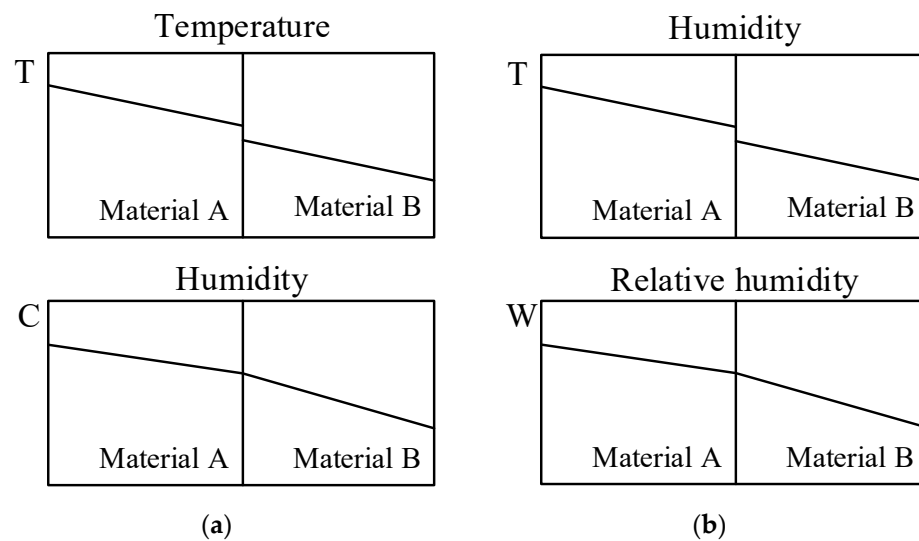


Figure 1. Temperature and Humidity Variations Across Different Materials (a) variation of temperature and humidity between different materials; (b) variation of humidity and relative humidity between different materials.

The corresponding solution is:

- (1) Select the transient thermal simulation module in the temperature analysis to extend the simulation time span and observe the whole process of moisture intrusion into the device.
- (2) Use relative humidity to replace absolute humidity:

$$w = \frac{C}{C_{sat}} \quad (4)$$

where C_{sat} is the saturated moisture content of the material; C is the current moisture content of the material; and w is the relative humidity. Obviously, a relative humidity of $w = 1$ means that the material has completely absorbed the moisture, and $w = 0$ means that the material is in a dry state. Now, the relative humidity w is continuous at the junction of the two materials, as shown in Figure 1b.

After modifying the humidity parameter, the diffusion equation is in the form:

$$\frac{\partial w}{\partial t} = D' \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \quad (5)$$

Next, we can utilize the relationships outlined in Table 2 [21] to perform the humidity simulations within the finite element temperature simulation module. For instance, to simulate an ambient humidity of 50%, we need only input 0.5 °C in the ambient temperature field, thereby accurately representing the humidity condition.

Table 2. Humidity simulation parameter derived from the correspondence thermal model.

Thermal	Humidity
Initial parameters	Substitute parameters
T	w
ρ (g m ⁻³)	1
K (W·m ⁻¹ ·K ⁻¹)	$D \times C_{sat}$ (g·m ⁻¹ ·s ⁻¹)
C (J·kg ⁻¹ ·K ⁻¹)	C_{sat} (kg·m ⁻³)

2.2. Life Prediction Model

In many accelerated experiments, the device is often operated under a high pressure by enhancing the corresponding temperature and humidity conditions, in order to obtain more important information about the device and the failure mechanism in a short time, so as to evaluate the reliability and life expectancy of the device in the daily environment.

Commonly used acceleration models are the Arrhenius model, Hallberg–Peck model, and the Eyring model [22,23]. They use acceleration factors to correlate the life of electronic devices at different temperatures and humidity, so as to calculate the expected life of the device under various environmental conditions. Among them, the Hallberg–Peck model comprehensively considers the influence of temperature and humidity, so this paper uses this model to simulate and verify the life changes of the device in various temperature and humidity environments, and its expression is as follows:

$$A_f = \left(\frac{RH_t}{RH_u} \right)^2 * e^{\frac{E_a}{K} \left(\frac{1}{T_u} - \frac{1}{T_t} \right)} \quad (6)$$

where A_f is the acceleration factor and E_a (eV) is the activation energy when the device fails. K is the Boltzmann's constant, and its value is 8.617385×10^{-5} eV, which is consistent with the E_a unit. T_u (K) is the temperature in the normal use environment; T_t (K) is the temperature when the temperature is accelerated; RH_u (%) is the relative humidity value in the normal use environment, and RH_t (%) is the relative humidity value when the humidity is accelerated.

Through investigations of the device's operating environment, we have confirmed that the devices are typically exposed to a temperature range of 293 K to 333 K and a humidity range of 20% to 80%. For electronic devices, the typical range of activation energy (E_a) is from 0.5 eV to 0.6 eV.

Within these ranges, we conducted sensitivity analyses, and the results are presented in Figure 2. The sensitivity analysis results indicate that temperature and humidity have a far greater impact on the device performance than activation energy. Therefore, in our subsequent life predictions, we will focus primarily on these two factors.

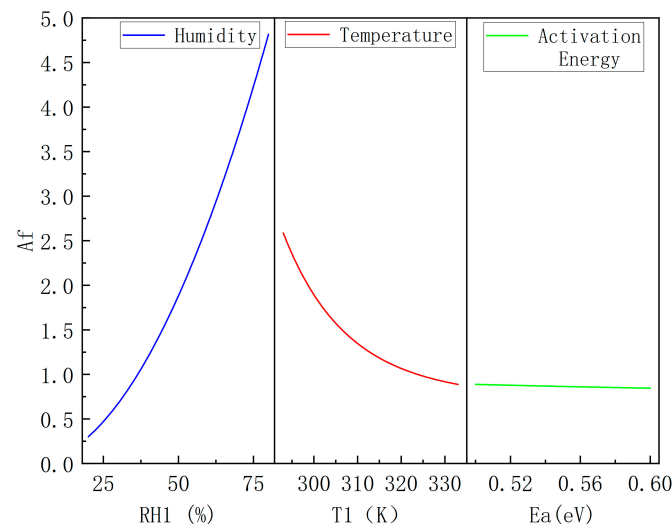


Figure 2. Analyzing the Sensitivity of A_f to Humidity, Temperature and Activation Energy.

3. Finite Element Analysis of Humidity Factors

Figure 3 shows the flow chart of the simulation experiment analysis of humidity using the finite element method.

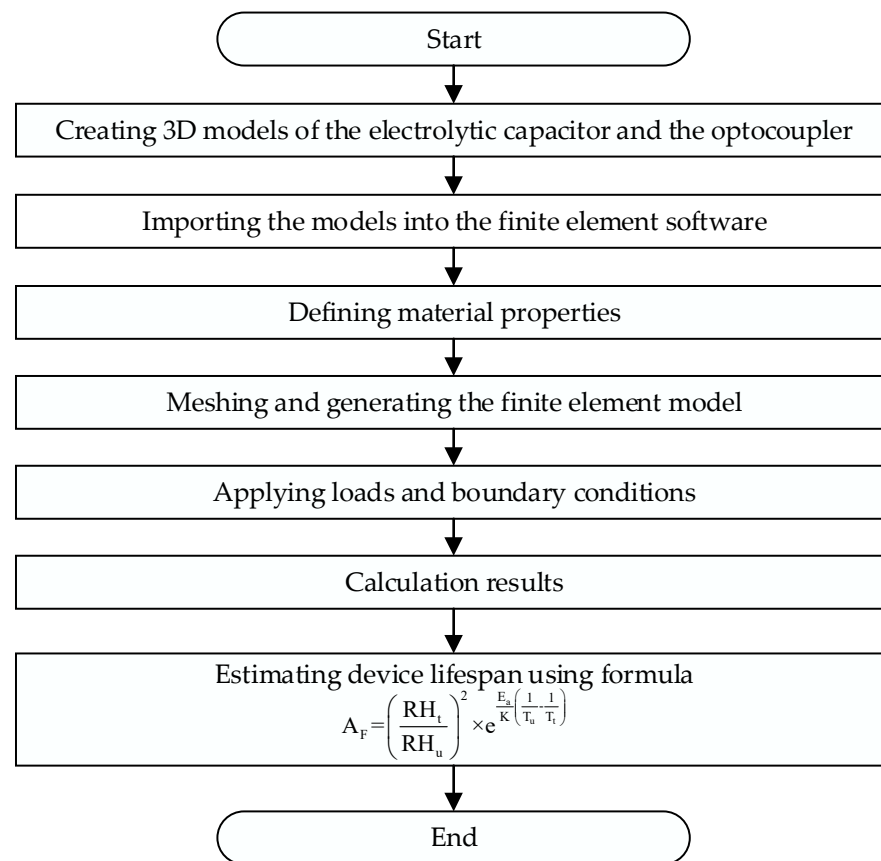


Figure 3. Finite element simulation flowchart.

In our finite element simulation, we initially create accurate 3D models of the electrolytic capacitor and the optocoupler, reflecting their physical characteristics. These models are imported into the finite element software where we define the specific material properties, such as the humidity diffusion coefficient (D) and the saturated moisture content (C_{sat}), which will be elaborated on later in the text.

We then proceed to mesh these models to create a finite element mesh that facilitates precise calculations. After the meshing, we apply specific loads and environmental conditions, such as temperature and humidity, along with electrical loads, as the boundary conditions to replicate the operational conditions of the devices.

The simulation is then utilized to observe the process of humidity diffusion into the devices and to determine the humidity distribution once equilibrium is reached. Additionally, we employ the Hallberg–Peck model to estimate the lifespan of the devices. This model uses the data on humidity distribution to predict the device lifespan and quantifies the impact of humidity on the device functionality.

3.1. Modeling

The VSC-HVDC is composed of chips, inductors, resistors, capacitors and other components. Among them, the capacitors and optocouplers are easily affected by humidity in the environment, and their failure rate is very high in the maintenance report, so they were selected as the key components that affect the reliability and life of the equipment. Then, we use SolidWorks to model the aluminum electrolytic capacitor model CD11-50V-22uF and the optocoupler model ACPL-M61L as shown in Figure 4.

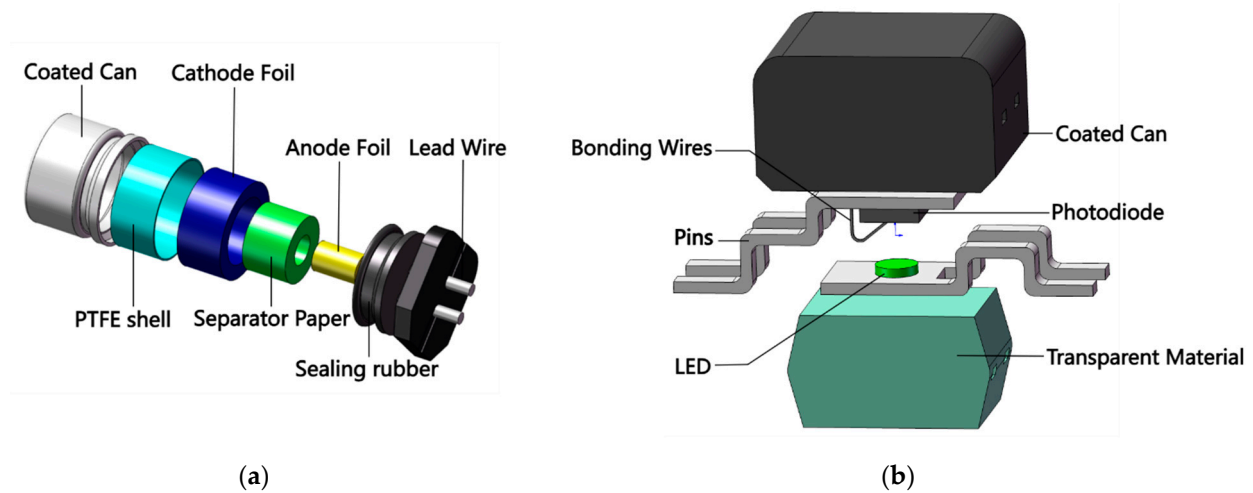


Figure 4. Key component structure diagram (a) exploded view of electrolytic capacitor with each component structure; (b) exploded view of optocoupler with each component structure.

3.2. Simulation Data Preprocessing

The wet diffusion coefficient D and saturated moisture content C_{sat} vary with temperature [24–26], and the variations of these parameters with various materials at different temperatures are shown in Table 3:

Table 3. Humidity parameter data of related materials.

Material	30 °C		60 °C	
	C_{sat} [kg·m ⁻³]	D [m ² /s]	C_{sat} [kg·m ⁻³]	D [m ² /s]
Polyethylene	7.81	3.13×10^{-13}	13.4	1.14×10^{-12}
Epoxy	6.59	3.95×10^{-13}	13.20	9.93×10^{-13}
Air	0.0303	2.66×10^{-5}	0.1313	3.19×10^{-5}
Polycarbonate	23.69	4.80×10^{-13}	26.19	2.55×10^{-12}
Rubber	8.29	6.69×10^{-16}	14.72	1.75×10^{-15}

The change of D and C_{sat} can be described by the following formula [27]:

$$D = D_0 \exp\left(\frac{Q_D}{KT}\right) \quad (7)$$

$$C_{\text{sat}} = C_0 \exp\left(\frac{Q_C}{KT}\right) \quad (8)$$

where Q_D and Q_C are the activation energy constants of the substance to reach the activated state; K is the Boltzmann's constant; and T is the thermodynamic temperature. According to the above data and formula, the changes to D and C_{sat} in various materials at different temperatures can be solved. Finally, the above data will be imported into the finite element tool for reserve.

3.3. Determine the Initial and Boundary Conditions

When the surface of electronic devices is in contact with the environment, the surface humidity is not equal to the ambient humidity, and due to the differences in structure, the humidity is also different everywhere on the surface. In order to determine the initial condition of the surface humidity, this part uses a fluid simulation for analysis, and the specific process is as follows:

1. Modeling of wet air

A fluid simulation analysis requires establishing a model of the air domain surrounding the device. To more accurately simulate the diffusion behavior of water vapor around the device in the respective humidity environment, it is necessary to establish a simulated water vapor shell around the device, as shown in Figure 5. We specifically chose the air domain direction to closely simulate the airflow conditions encountered in actual application environments. This choice is based on the typical placement and installation manner of the devices in use. For instance, in this study, the direction of the air domain is determined according to the positions of the cooling fans and ventilation ports within the chassis, tailored to the specific circumstances described in our paper. Should this model be applied in different working environments, we can adjust the direction of air accordingly to more accurately simulate the air movement and humidity conditions on the device surfaces in those specific settings.

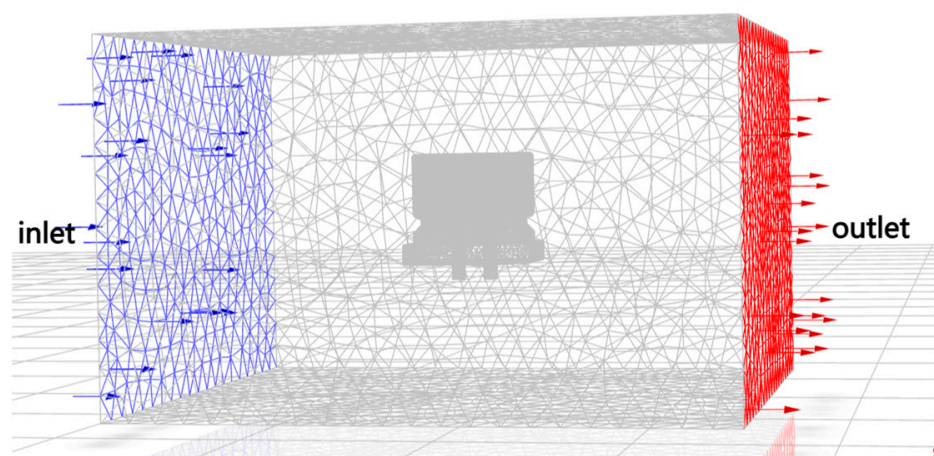


Figure 5. Moist air domain establishment and meshing.

2. Setting up simulation model

The standard k - ϵ model was proposed by Launder and Spalding [28]. By solving the equation of turbulence kinetic energy (k) and turbulent dissipation rate (ϵ), we can obtain the solution of k and ϵ , and then calculate the turbulent viscosity with k and ϵ values [29]. This model can better simulate the flow state of water vapor around the device, and it is widely used with high stability. So it is set as the simulation model of water vapor diffusion.

3. Define materials and fluids

Set the materials of each component of the device, and define the fluid according to the relationship between the pressure of water vapor in the air and the relative humidity, and then start the simulation.

4. Simulation results

Taking 25 °C and 50%RH as an example, after setting the initial conditions, the model was initialized and the data iteratively calculated. It can be seen from the transient residual diagram in Figure 6a that after 30 iterations, the residual data showed a downward trend, indicating that the water vapor pressure data on the device surface tended to be stable. The water vapor pressure distribution on the electrolytic capacitor surface is shown in Figure 6b.

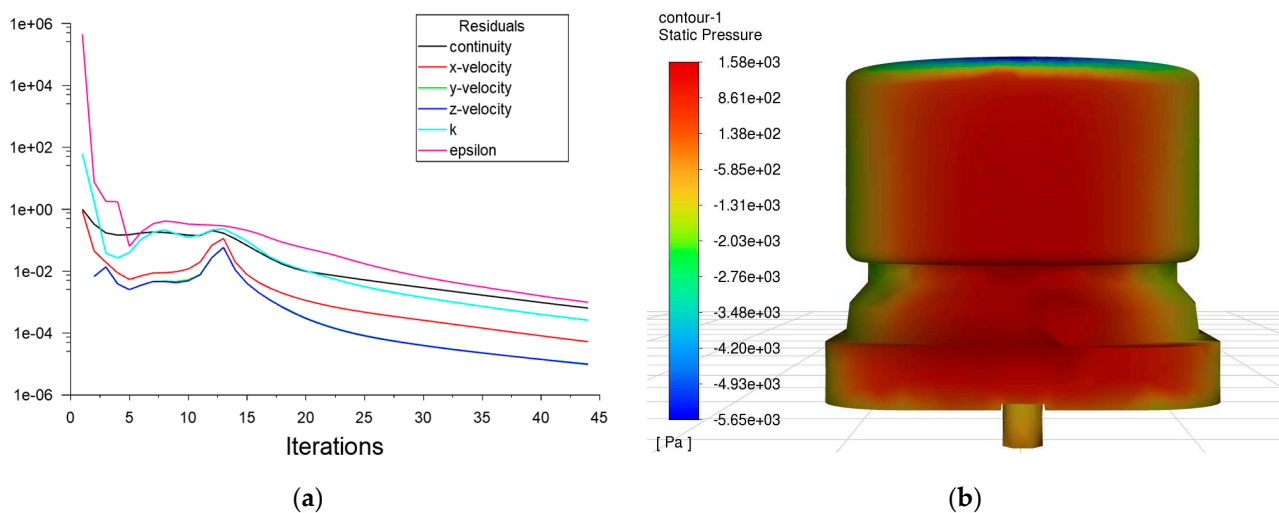


Figure 6. Simulation results of moisture diffusion (a) transient residual diagram; (b) distribution of water vapor pressure on electrolytic capacitor surface.

It can be seen that there is a certain difference between the ambient humidity and the humidity on the surface of the device. Therefore, to ensure the accuracy of the simulation experiment, we should use the surface humidity data as the initial condition. We selected the highest value of surface humidity as the initial condition for subsequent simulations of moisture diffusion into the device. This approach allows us to conservatively estimate the lifespan of the components, which is crucial because damage to these components can significantly impact the normal operation of the equipment. Additionally, this method also helps us to identify areas where moisture penetrates more deeply, facilitating the future maintenance of the device.

3.4. Finite Element Simulation of Moisture Diffusion

3.4.1. Meshing, Input Initial Conditions

The surface humidity data from the fluid simulation are imported as initial conditions, then the device is meshed and checked that the contact sites are correct.

3.4.2. Setting Simulation Parameters

The material parameters of each part of the two devices are defined according to the data in Section 3.2. Since the steady-state thermal module is used for the humidity simulation, setting the initial temperature to 1 means that the relative humidity reaches 100%, that is, the external surface of the electronic device has reached a completely wet state. In the setting of the analysis time, the simulation time is set to more than 200 h to ensure that the electronic devices are fully close to the humidity equilibrium state because the wet diffusion speed is relatively slow.

3.4.3. Simulation Results and Analysis

(1) We analyzed the humidity distribution of the aluminum electrolytic capacitor model. When the ambient relative humidity is set to 50%, the humidity distribution inside the device is shown in Figure 7a, and the relative humidity variation of each material is shown in Figure 7b. Humidity diffusion is a relatively slow process, so the time required to achieve humidity equilibrium is often lengthy, typically ranging from several days to months. Therefore, the duration of the simulation reflects the time required for the device to reach a humidity balance.

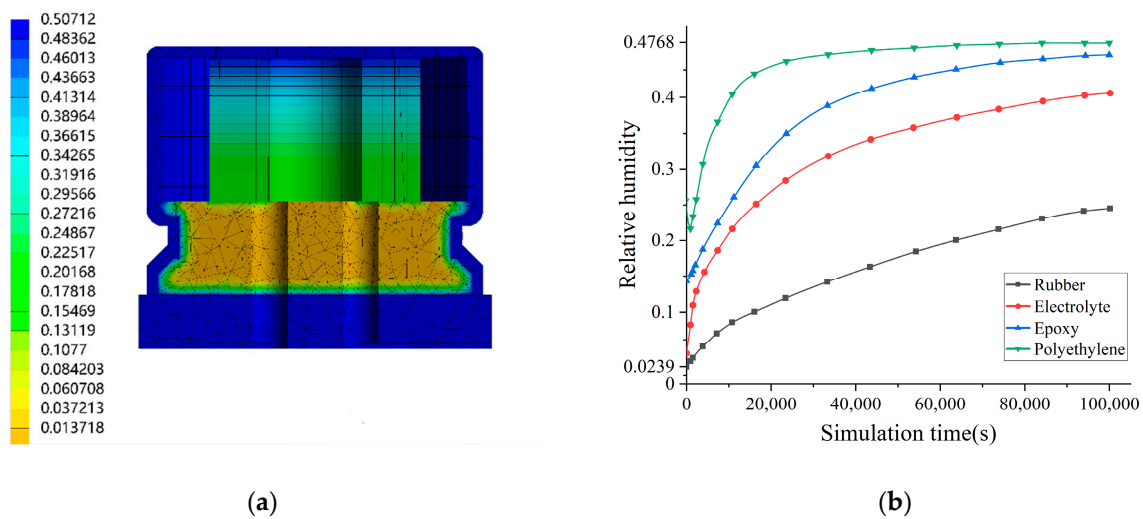


Figure 7. Humidity diffusion analysis diagram (a) humidity distribution of aluminum electrolytic capacitors; (b) relative humidity changes of different materials of electrolytic capacitor.

Then by modifying the ambient humidity data, we can obtain the humidity distribution in different humidity environments.

It can be seen from Figure 7 that the humidity diffusion speed shows a trend of rapid change followed by a slow down. After about 200 h, the relative humidity reaches a basically stable state, and then the device still absorbs moisture, but the absorption speed becomes significantly slower. At the same time, the humidity percentage gradually decreases from the outside to the inside of the device. In the whole process, the external polyethylene and epoxy materials have the fastest moisture absorption rates and higher relative humidity percentages, which can be used as indicators to evaluate the impact of humidity on the device life.

(2) Then we perform a similar humidity distribution analysis for the optocoupler model, and the results are shown in Figure 8. It can be seen that the diffusion law of humidity in the optocoupler is similar to that of the electrolytic capacitor. Similarly, the polyethylene and polycarbonate materials can be selected as indicators to evaluate the impact of humidity on the device life.

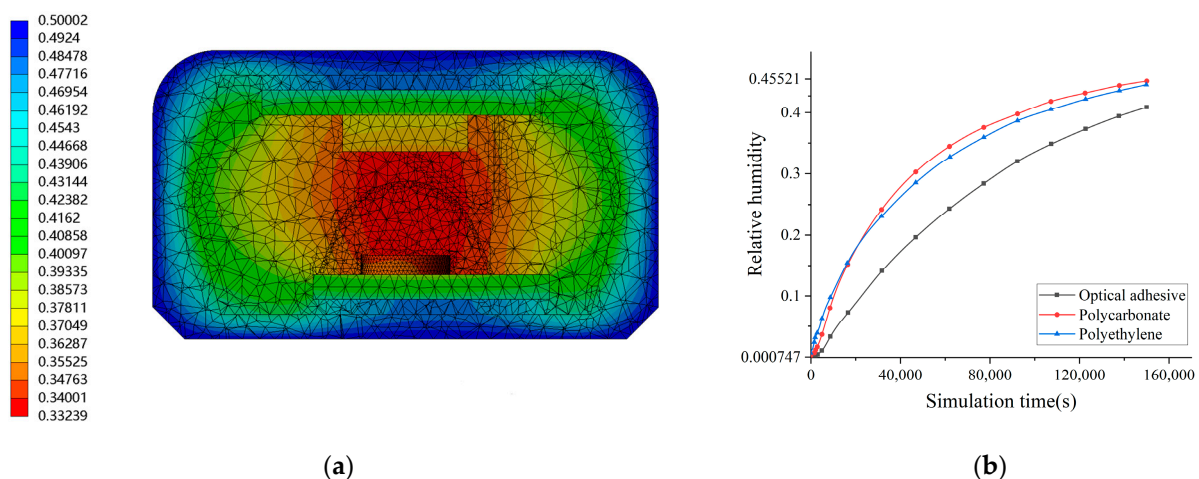


Figure 8. Humidity diffusion analysis diagram (a) humidity distribution of the photocoupler; (b) relative humidity changes of different materials of photocoupler.

4. Verification of Simulation Results

As previously mentioned, conducting fatigue tests requires substantial financial and material resources, as well as considerable time. These costs make it difficult for us to directly undertake such experiments to verify the accuracy of our simulations. Faced with this challenge, we instead rely on the national standard of the People's Republic of China GB/T 2423.50-2012 [30], which specifies a comprehensive fatigue testing procedure specifically designed to assess the performance of electronic devices under extreme temperature and humidity conditions, as shown in Table 4. The test results from this national standard are highly reliable, far surpassing conventional laboratory fatigue tests.

Table 4. Test criteria for the Double 85 experiment.

Temperature [°C]	Humidity [%]	The Rigorous Level of the Double 85 Test			
		I	II	III	IV
85	85	168 h	504 h	1000 h	2000 h

In this context, we have chosen to use the standard test data from GB/T 2423.50-2012 as a benchmark for our simulation results. By comparing our simulation outcomes with the standard test data, we can evaluate the accuracy and effectiveness of our simulation model in replicating the device performance under extreme environmental conditions. This approach not only saves cost and time but also provides a scientifically rigorous method to validate our simulation techniques, ensuring their reliability in practical applications.

We conducted simulations on the devices under “double 85” test conditions and predicted their lifespan using the Hallberg–Peck model. To further verify the accuracy of our simulation results, we chose reliability acceleration experiments similar to the “double 85” experiment, namely HAST and PCT. Under the environmental conditions of these experiments, we replicated the process. Table 5 presents the predicted outcomes.

Table 5. Device lifespan under various reliability tests.

Reliability Acceleration Experiment	“Double 85”	HAST	PCT
Capacitor’s life span	871.57 h	220.65 h	86.71 h
Optocoupler’s life span	1158.35 h	325.46 h	119.23 h
Standard life span	1000 h	264 h	96 h
Accuracy	85.648%	82.58%	82.74%

From the above data, it can be inferred that the accuracy of the simulation model is high, and a single humidity simulation only takes about three hours, which greatly reduces the time cost compared with the conventional acceleration experiment that generally requires hundreds of hours.

5. Lifetime Prediction in Various Humidity Environments

Since the accuracy of the scheme has been verified, we considered expanding the humidity range to understand the impact of humidity changes on the lifetime of the device. By setting the temperature [20, 60 °C], humidity [30, 80%RH], and other parameters in the simulation process, we carried out multiple groups of tests and collected the relative humidity data under different environmental conditions. The details are as follows.

5.1. Lifetime Analysis of CD11-50V-22uF Electrolytic Capacitor

In Section 3.4.3, we chose polyethylene and epoxy as indicators to evaluate the impact of humidity on the device life. Figure 9 shows how their relative humidity varies with the ambient humidity.

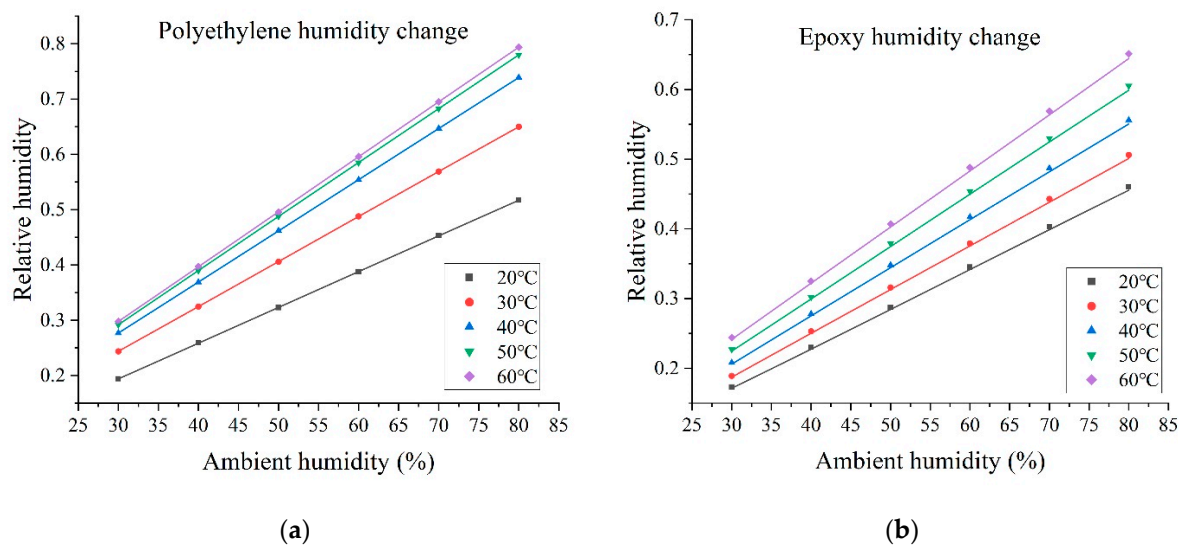


Figure 9. Relationship between the ambient humidity and internal component's humidity of the device (a) the impact of ambient temperature and humidity on the relative humidity of polyethylene; (b) the impact of ambient temperature and humidity on the relative humidity of epoxy.

Substituting the above data into the Hallberg–Peck model, we can obtain the electrolytic capacitor lifetime data by using these two materials as indicators, as shown in Figure 10.

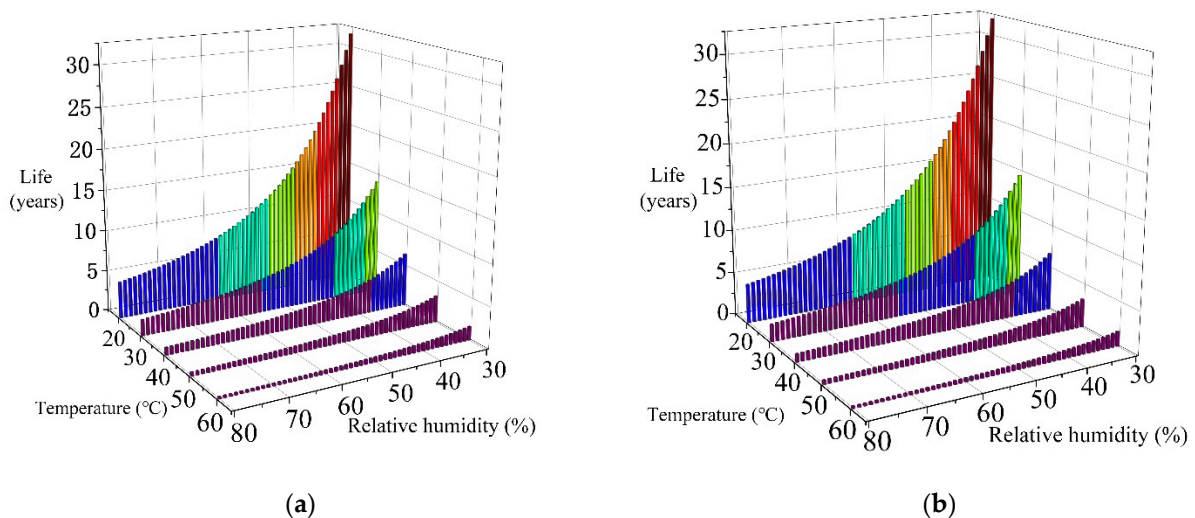


Figure 10. Variation of electrolytic capacitor life with temperature and humidity (a) taking the humidity of polyethylene as the judgment basis; (b) taking the humidity of epoxy as the judgment basis.

The results in Figure 10a,b show an extremely high correlation, with a correlation coefficient of 0.99999. This indicates that there is little difference in the prediction results of the model when these two materials are used to predict the lifetime change. However, in the manufacturing process of electrolytic capacitors, polyethylene is the main material used. Therefore, Figure 10a is selected as the final presented result in this paper.

We perform surface fitting on the above data and obtain the surface model of the influence of temperature and humidity factors on the lifetime of the device, as shown in Figure 11. Due to the finiteness of the surface fitting model, there is a large error in the life data at the boundary. After removing the edge data, the square sum of the residual error in the temperature range [30, 50 °C] and the humidity range [30%, 70%] is 0.92448. Therefore,

the surface model has a high accuracy in describing the life change in this range. The fitting equation is as follows:

$$K = z_0 + A_1x + A_2x^2 + A_3x^3 + A_4x^4 + A_5x^5 + B_1y + B_2y^2 + B_3y^3 + B_4y^4 + B_5y^5 \quad (9)$$

where $(x \in [30, 70], y \in [30, 50])$, and the coefficients are shown in Table 6.

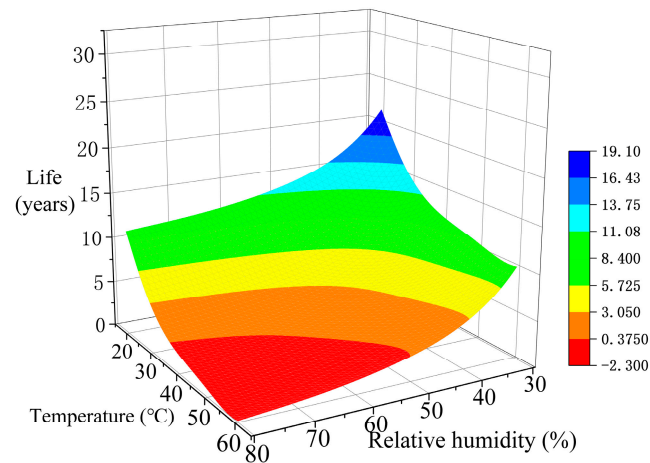


Figure 11. Fitting surface of electrolytic capacitor life with environmental temperature and humidity.

Table 6. Parameters of the fitting surface (electrolytic capacitor).

Model	Polynomial2D
z_0	86.64449
A_1	-6.06453 ± 15.79915
A_2	0.17701 ± 0.61532
A_3	-0.0027 ± 0.01169
A_4	$2.09754 \times 10^{-5} \pm 1.08497 \times 10^{-4}$
A_5	$-6.58023 \times 10^{-8} \pm 3.94111 \times 10^{-7}$
B_1	4.21774
B_2	-0.33316
B_3	0.0102
B_4	-1.4068×10^{-4}
B_5	7.30196×10^{-7}
R^2 (COD)	0.79296
Adjusted- R^2	0.92448

5.2. Lifetime Analysis of ACPL-M64L Optocoupler

When studying the life of the optocoupler, we choose polyethylene and polycarbonate as indicators to evaluate the impact of humidity on the device life. Similar to the method used to study electrolytic capacitors in Section 5.1, we finally decided to use the polycarbonate data as the final result of how its lifetime changes. Then we perform surface fitting on these data to obtain the surface model showing the influence of temperature and humidity factors on the life of the equipment, as shown in Figure 12. Due to the finiteness of the surface fitting model, there is a large error in the life data at the boundary. After removing the edge data, the square sum of the residual error in the temperature range $[30, 50^\circ\text{C}]$ and the humidity range $[30\%, 70\%]$ is 0.9092. Therefore, the surface model has a high accuracy in describing the life change in this range. The fitting equation is also (9), and the coefficients are shown in Table 7.

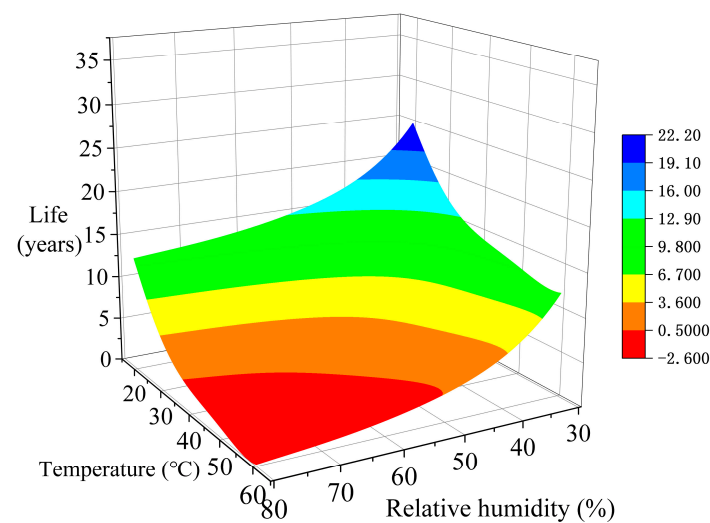


Figure 12. Fitting surface of optocoupler life with environmental temperature and humidity.

Table 7. Parameters of the fitting surface (optocoupler).

Model	Polynomial2D
z_0	174.34837
A_1	-13.47904 ± 33.31123
A_2	0.44457 ± 1.29736
A_3	-0.00748 ± 0.02465
A_4	$6.32041 \times 10^{-5} \pm 2.28757 \times 10^{-4}$
A_5	$-2.12509 \times 10^{-7} \pm 8.3095 \times 10^{-7}$
B_1	4.67462
B_2	-0.37435
B_3	0.01155
B_4	-1.60447×10^{-4}
B_5	8.37784×10^{-7}
R^2 (COD)	0.59798
Adjusted- R^2	0.9092

According to the 2023 data from the National Bureau of Statistics of China [31], the annual average humidity across various provinces in China typically ranges between 30% and 70%. To better categorize the humidity conditions, humidity levels are divided into four categories: dry, moderately dry, moderately moist, and moist, with each category spanning a 10% interval. Utilizing the integral mean as the average lifespan for each interval, the lifespan of devices under different humidity environments can be estimated. At an ambient temperature of 20 °C, the estimated lifespans of two types of devices are presented in Table 8.

Table 8. The lifetime of the device over each humidity range.

Humidity Level	Relative Humidity Range	Lifespan of Capacitor (Years)	Lifespan of Optocoupler (Years)
dry	30–39%	34.94	39.11
moderately dry	40–49%	21.14	24.26
moderately moist	50–59%	14.14	16.23
moist	60–70%	10.12	11.63

As can be seen from Table 8, the lifespan and reliability of the VSC-HVDC are significantly susceptible to high humidity conditions; the higher the humidity, the shorter the predicted life of the devices. So, it is necessary to use dehumidifying equipment to ensure

that it operates in a dry environment. Also, the operation and maintenance department can strengthen the monitoring and maintenance management of equipment before the predicted lifespan.

6. Conclusions

This study explores the mechanism of moisture diffusion and proposes a novel finite element simulation method for humidity. This method employs the wet diffusion coefficient and saturated moisture content as analogs for the conductivity and specific heat capacity used in the heat conduction processes, facilitating the finite element analysis of humidity. The main works are summarized as follows:

- (1) This simulation method is applied to predict the humidity inside the equipment under different humidity environments. The results are substituted into the Hallberg–Peck model for lifespan predictions. Finally, the fitting surface of the device lifespan as a function of the temperature and humidity is obtained. Within a designated humidity range, the fit between the fitting surface and the simulation data is notably high, effectively describing the trend of the device lifespan as a function of humidity variations.
- (2) The average lifespan of the VSC-HVDC is predicted under four humidity levels, and the results can be used to guide the accurate operation and maintenance of the devices in advance, ensuring the stability of the operation of the VSC-HVDC.
- (3) Through simulation experiments and lifespan prediction analyses under the “double 85” test conditions, the lifespan of electrolytic capacitors and optocouplers are found to be 871.57 h and 1158.35 h, respectively. Compared with the national standard GB/T 2423.50-2012, the accuracy of the simulation method is 85.648%, demonstrating its high accuracy. A single humidity simulation only takes about three hours, significantly reducing the time cost compared with experimental verification, further proving the effectiveness of the simulation method.

Author Contributions: Conceptualization, C.L. and X.H.; methodology, C.L. and Y.C.; software, X.H. and Y.C.; validation, C.L. and Y.C.; resources, C.L. and X.H.; writing—original draft preparation, Y.C. and X.H.; writing—review and editing, X.H. and Y.C.; supervision, C.L.; project administration, X.H.; and funding acquisition, C.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported in part by the National Natural Science Foundation of China under Grant 52307232, the Hunan Provincial Natural Science Foundation of China under Grant 2024JJ4055, and the State Key Laboratory of Power System Operation and Control under Grant SKLD23KM12.

Data Availability Statement: Data are contained within the article.

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

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