A Dual-Transport Model of Moisture Diffusion in PV Encapsulants for Finite-Element Simulations

Stefan Mitterhofer, Chiara Barretta, Luis F. Castillon, Gernot Oreski, Marko Topič, and Marko Jankovec

Abstract—A better understanding of moisture ingress in photovoltaic modules is crucial for better predictions of their long-term behavior in the field. Current calculations and simulations of moisture uptake in photovoltaic modules are based on the Fickian diffusion model in a homogeneous material. In this article, in situ humidity measurements in four different encapsulants exposed to transient humidity conditions are compared with Fickian simulations. It is found that the model cannot accurately describe the measured moisture ingress and egress curves. Thus, a new model for finite-element simulations based on two transport mechanisms is applied. The mesh is split into two regions, where channels with a high diffusion coefficient lead through a bulk with a low diffusion coefficient. The diffusion in both regions as well as the flow between them is simulated as Fickian. The new model is able to predict the measured ingress and egress curves more accurately than the Fickian model in all four encapsulants. The same simulation parameters can accurately describe ingress for various relative humidity values between 20% and 80%, as well as egress from 40% to 20%. This allows further prediction of moisture ingress after the measurement of a single ingress curve and a corresponding parameter optimization. However, a nonlinearity of the diffusion during egress at higher moisture values in the encapsulants is found.

Index Terms—Finite-element simulations, moisture ingress, photovoltaics (PVs), polymers.

I. INTRODUCTION

PHOTOVOLTAIC (PV) modules installed in the field experience a wide variety of climatic stresses. Moisture is one such factor affecting their degradation, in forms of relative humidity (RH) in the air, dew, and precipitation. It can ingress into the polymers used as encapsulants and backsheets, influencing various degradation modes of modules mounted in the field. Examples include yellowing and browning of the encapsulant, delamination, corrosion and potential-induced shunting [1]–[5]. The consequences can be severe power losses and safety issues [3]. Thus, understanding moisture ingress into PV modules and different materials used in their production is crucial to ensure a long lifetime and operation in the field.

Simulations and calculations of moisture ingress in PV modules and encapsulants are based on the Fickian diffusion model [6]–[15]. The material is homogeneous and described by a single diffusion coefficient $D$. It shows a temperature ($T$) dependence according to the Arrhenius law, but is independent of the moisture concentration. However, moisture ingress in polymers is a complex topic. It is influenced by many material parameters, including the polymer network structure [16], polarity [16], microvoids in the material [17], free volume [18], crystallinity [19], and cross-linking degree [20], to name a few. Mechanical stress and strain further affect the ingress [21]. Diffusion along interfaces between materials and between different phases in the material is different from diffusion in the bulk [22]. The material can change its properties while aging, changing the ingress between sorption, desorption, and resorption [23]. Furthermore, polymers are a large group of materials and measured ingress curves can vary a lot from each other. Theories resulting in more accurate simulations or calculations for some polymers may not yield similar improvements for others, or may not be applicable due to a different polymer structure.

Thus, it is no surprise that the simple Fickian model applied to a homogeneous material shows limited accuracy in predicting the measured ingress curves in PV encapsulants, for example, ethylene vinyl acetate (EVA), thermoplastic olefins (TPO), polyolefin elastomers (POE), and ionomers [24].

Many non-Fickian models have already been applied for a more accurate description of moisture ingress measurements in other polymers. A common approach is to include two main mechanisms driving the diffusion process. There are many theories about the nature of these two mechanisms, varying for different materials. Some theories are based on the heterogeneity of the polymer, having two different values of $D$, based on polarity [25] or density [26]. In others, two states of water in the polymer are presumed. Water is ingressing either as single molecules or as molecule clusters [27]. Other theories describe two different types of interaction between water and polymer. Water can be bound with single or multiple hydrogen bonds in hydrophilic polymers [28]. Another theory describes the sorption of water either in the free volume or in hydrogen-bonded clusters in the polymer structure [29]. One theory presumes the material relaxation after hygroscopic swelling driving a second, slower diffusion process [30].
Different approaches were taken to implement non-Fickian models in simulations and calculations to predict moisture ingress on a macroscopic scale. One approach added sources and sinks for moisture in the material, defined two states of water and mathematical probabilities to change from one to the other, creating a system of two coupled differential equations [31]. Other approaches include the development of analytical models for simple geometries [26], or decoupling both processes, simulating them independently and sum up the results [32]. Recent work has tried to combine molecular simulations and calculations of flow in nanochannels with macroscopic diffusion through membranes [33]. However, a model and fitting theory for PV encapsulants is still missing in literature.

In this article, we propose and evaluate such a model based on an inhomogeneous morphology of the material. First, the used measurement setup based on miniature T and RH sensors is presented. Then, simulations based on the Fickian diffusion model in a homogeneous material are described. Their results are analyzed and compared with the measurements, showing the shortcomings of the model and the need for a new, more accurate model. The basic ideas behind the proposed new model are described. The model is based on channels running through the bulk of the material and driving the diffusion. The parameters of the simulation, their impact on the results, and the flow of moisture in the model are analyzed. The results are compared with the measurements of four different polymers. In the end, a discussion compares the model with possible physical explanations taken from the literature of other models based on two moisture transport mechanisms.

II. MEASUREMENT SETUP

Printed circuit board strips containing miniature T and RH sensors [34] are encapsulated between two layers of PV encapsulants, as shown in Fig. 1 [35]. One strip contains three sensors inside the polymer and one sensor outside to measure T and RH in the air. The analyzed materials are commercially available EVA, POE, TPO, and ionomer. The strips are connected to custom readout electronics. The setup is controlled by a custom software written in LabVIEW. Measurements are taken every 60 s. A more in-depth description of the setup is published elsewhere [34], [35].

Ingress and egress between 20% and 40% RH, 20% and 60% RH, as well as 20% and 80% RH, at 50 °C are measured inside a climatic chamber.

![Fig. 1. Miniature sensor (left) and sensor strip in the encapsulant (right).](image)

In this section, the simulations based on the Fickian model in a homogeneous material are described. It is the current state of the art for moisture transport simulations in PV encapsulants. The FreeFEM++ software is used in the simulations with the FreeFEM++ development environment [36].

A. Mesh Creation

The mesh used in the simulations is shown in Fig. 2. The thickness of the encapsulants above the sensors is measured optically. The sample is placed under a microscope. The focus is set to the active area of a sensor. Then, it is changed to the surface of the encapsulant. This process is repeated several times in both directions. The thickness is calculated from the so-obtained optical depth and the refractive index of the materials. The latter is rounded to 1.5, which is a reasonable approximation for common PV encapsulants. The results are shown in Table I. Depending on the roughness of the surface and small possible indentations on a micrometer scale, the accuracy of the thickness measurement is estimated to be ±10% of the respective value.

The thicknesses are all larger than the datasheet values of the encapsulants. This is caused by the indentation of the sensor containing the sensor’s active area is. During lamination, it is filled with encapsulant, adding to the total thickness.

![Fig. 2. Mesh used for Fickian simulations. The small picture shows an encapsulated T and RH sensor. The geometry for the boundaries of the mesh is taken from the two-dimensional cross section along the red line. The red area at the bottom of the mesh represents a polymer used by the sensor for its capacitive measurements. The measured encapsulant thicknesses are given in Table I.](image)

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>MEASURED ENCAPSULANT THICKNESS ABOVE THE THREE SENSORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness above:</td>
<td>EVA</td>
</tr>
<tr>
<td>sensor 1 (µm)</td>
<td>570</td>
</tr>
<tr>
<td>sensor 2 (µm)</td>
<td>645</td>
</tr>
<tr>
<td>sensor 3 (µm)</td>
<td>615</td>
</tr>
</tbody>
</table>

III. FICKIAN SIMULATIONS

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B. Differential Equation

Fick’s second law of diffusion in two dimensions is the governing differential equation

$$\frac{\partial C}{\partial t} = \nabla (D \cdot \nabla C).$$  (1)

Here, $C$ is the moisture concentration in the encapsulant. It is proportional to the measured RH at constant temperature.
The time is discretized into several time steps. They are set to coincide with the times at which measurements are taken. To keep the simulation times as low as possible, longer time steps during the later stages of the ingress are taken. The solution at time-step $m$ is obtained with the Crank–Nicolson method \[37\].

Thus, we conclude that a new model is required for more accurate simulations of moisture diffusion in PV encapsulants.

### IV. Dual-Transport Model Simulations

#### A. Basic Considerations

A new model including two different transport mechanisms is proposed to improve the accuracy of the simulations. The requirements set for this model are as follows.

1. It should build upon the previously used model.
2. It should be kept as simple as possible, with a low number of material parameters.
3. It should increase the accuracy of the simulations for all measured encapsulants using the same material parameter set.

To simulate these two mechanisms, the material is split into two regions, namely channels and bulk. This basic idea stems from previous attempts of combining flow in nanochannels with macroscopic flow in the literature \[33\]. Diffusion in both regions, as well as from one region to the other, is simulated with the Fickian diffusion equation \(1\). The diffusion coefficients are set such that diffusion is faster in the channels and slower in the bulk. The saturation moisture contents in bulk and channels are the same.

The same boundary conditions as described in Section III-C are used. Thus, the only difference between the homogeneous Fickian model and the new model is the implementation of an inhomogeneous mesh with two diffusion coefficients. In the following, the “Fickian model” or “Fickian diffusion” denotes Fickian diffusion in a homogeneous material. For mesh creation...
Fig. 5. Depiction of the channel configuration added to the material. The small picture shows an encapsulated T and RH sensor. The two-dimensional geometry is created along the cross section indicated by the red line. The additional gray area in the bottom is the polymer used in the sensor for the measurements.

### TABLE II

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>SC [%]</td>
<td>Share of channels in the material</td>
</tr>
<tr>
<td></td>
<td>Fgeo</td>
<td>Geometric factor</td>
</tr>
<tr>
<td></td>
<td>Hsens (μm)</td>
<td>Height of the sensor polymer area</td>
</tr>
</tbody>
</table>
| Mesh      | Qmesh (10⁻⁶⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻~-~-~
| Diffusion | D_b (m²/s) | Diffusion coefficient bulk |
|           | D_c (m²/s) | Diffusion coefficient channel |

and solving the differential equation, again the FreeFEM++ software with the FreeFEM++-cs development environment is used [36].

**B. Simulations**

The channels are implemented in four directions. This is a middle ground between a lower amount of directions, increasing the anisotropy caused by the geometry, and a higher amount, adding complexity to the model. An example of a model is shown in Fig. 5. In the simulations, the interface is considered as part of the bulk.

The simulation parameters are shown in Table II. Two parameters, SC and Fgeo, control the geometry of the channels in the material. SC is the ratio between the total area of the channels and the total area of the entire mesh. The geometric factor Fgeo determines the number of building blocks, the basic elements that are repeated, as shown in Fig. 5. Over the width of the entire mesh, the number of repeating blocks is 3·Fgeo. Fig. 5 shows the model with Fgeo = 5. The parameters Fgeo and SC together determine the width of the channels and the distance between them.

Parameter Hsens changes the size of the sensor polymer’s area. If the diffusion coefficient in that area is very high, an increase of its size with a constant solubility of water in the material is equivalent to an increase of said solubility while keeping size constant in the simulations.

According to the datasheet, the RH response time of the sensor in the air is in range of seconds, thus moisture diffuses quickly in the sensing polymer. Therefore, we set its diffusion coefficient arbitrarily to 1 m²/s. This value is many orders of magnitude larger than diffusion coefficients in the encapsulant, assuring diffusion through the sensor polymer itself does not influence the simulated ingress.

The parameter Qmesh changes the quality of the mesh. Each boundary defined in the geometry is split into Qmesh number of intervals every 0.1 mm to serve as base for the triangulation, i.e., the mesh creation. A higher value of Qmesh results in a higher accuracy of the simulation, but increases the required time. The elements of the mesh are continuous piecewise quadratic.

**C. Parameter Analysis and Optimization**

First, the impact of the parameters on the simulation results is analyzed. Then, the parameters are manually optimized for the measured encapsulants. For this purpose, a rough approximation of these parameters is extracted from the previously obtained curves during the parameter analysis at first. Then, the trends of parameter variations and interaction between the parameters are analyzed in more depth close to this point. These trends are used to find a good fit between measurement and simulation, visually and with a minimized root-mean-squared error. Fig. 6 shows a flowchart of the optimization process.

**V. RESULTS**

**A. Parameter Variation**

The impact of the parameters on the simulation results is analyzed. The measurements of the sensor in the air during ingress from 20% to 80% RH are used as a time dependent boundary condition.

1) Variation of the Diffusion Coefficients: In this article, SC is set to 10%, DC to 5·10⁻¹⁰ m²/s, Qmesh to 20, and Hsens to 50 μm. Parameter DB is varied and kept lower than DC, since our initial proposition was that bulk has lower diffusion rate
than channels. We introduce parameter $\alpha$ as the ratio between $D_B$ and $D_C$:

$$D_B = \alpha \cdot D_C, \quad 0 \leq \alpha \leq 1.$$  \hspace{1cm} (3)

When the value of $D_B$ is in the same order of magnitude as $D_C (\alpha > 0.1)$, moisture is quickly absorbed from the channels into the bulk. The results are Fickian ingress curves, resembling the diffusion in a homogeneous material with a diffusion coefficient between $D_C$ and $D_B$. Reducing $\alpha$ further, the results still resemble Fickian curves with only slight decrease of the slope, as shown in Fig. 7.

If $\alpha$ is reduced to a range between $10^{-3}$ and $10^{-4}$, the interaction with the bulk becomes so slow that small amounts of moisture can reach the sensor through the channels without being absorbed in the bulk. This reverses the trend and causes a faster ingress shortly after the step change of the air humidity. Later, the moisture ingress becomes slower due to delayed bulk interaction, as shown in Fig. 8.

Reducing $\alpha$ further, the bulk becomes almost impermeable in the time scale the moisture takes to reach the sensor through the channels. The simulated ingress curves asymptotically approach a Fickian ingress curve at $\alpha = D_B = 0$.

In this way, a set of curves with different slopes can be obtained by only changing $\alpha$ and keeping all other parameters constant, with Fickian diffusion as limit at both limit cases: $\alpha = 0$ and $\alpha = 1$. Changing $D_C$ causes this set of curves to move along the time axis, similar to a variation of $D$ in the Fickian model.

2) Variation of the Share of the Channels: Increasing $S_C$ raises the share of the channels in the entire mesh. Thus, diffusion through the channels becomes prevalent while the impact of the bulk becomes smaller. The simulated set of curves (obtained varying the ratio $\alpha$) shifts to an earlier time by increasing $S_C$, while the range becomes narrower, finally breaking down to a single Fickian ingress curve at $S_C$ approaching 100%, as shown in Fig. 9.

3) Variation of the Mesh Quality: Increasing the quality of the mesh by increasing the number of elements in the triangulation results in more accurate simulations at the cost of a longer required time, as shown in Fig. 10. In a homogenous geometry simulation problem, a coarse mesh is sufficient. However, the higher mesh quality is required in this case due to many material interfaces.

4) Variation of the Sensor Polymer: Increasing the size of the sensor polymer's area slows down the measured ingress curves primarily in the early stages of the diffusion, as shown in Fig. 11. The properties of the sensor polymer, including the solubility of water inside it and correspondingly the parameter $H_{\text{sens}}$ to simulate it, are unknown parameters for the simulations. The solubility does not change over time, shown by its repeatable measurements [38]. It can be set constant in all simulations.

5) Scale of the Geometry: Now that the influence of the parameters has been analyzed, a more detailed look on the scale of the geometry and the relation to the parameters is taken. For this purpose, a $100 \times 100 \mu m$ area is analyzed. The number of
blocks in one direction is increased from 1 to 10 in steps of 1 and their size reduced accordingly while $S_C$ is constant at 10%, as shown in Fig. 12.

To calculate the moisture going through the entire stack, a 0.1-$\mu$m wide area with very high diffusion coefficient is added at the bottom. The output is the humidity in this area. The small width is chosen to minimize its solubility impact.

$D_C$ is set constant at $10^{-1}$ m$^2$/s. $Q_{\text{mesh}}$ is 20 times the number of blocks, changed to minimize the effects of a changing mesh quality in relation to the size of the triangles. For each case, $\alpha$ is optimized to minimize the average pointwise difference to the simulation with the highest resolution. The maximal absolute error while changing the number of blocks by one order of magnitude, as is the case in Fig. 12, is less than 1% RH.

If we keep the mesh quality $Q_{\text{mesh}}$ constant, the simulated ingress curves deviate with an increasingly fine geometry. This limits the number of blocks, and accordingly $F_{\text{geo}}$ in the simulations of the setup, in both directions. On one side, a very low value $F_{\text{geo}}$ results in a larger error in the simulations. On the other side, a very high value $F_{\text{geo}}$ requires an accordingly fine mesh not to result in a larger error, which significantly increases simulation time.

**B. Visualization of Moisture Ingress in the Encapsulant**

To visualize the pathway of moisture in the simulations, the moisture in the encapsulant is plotted at various times during an ingress simulation, as shown in Fig. 13. The parameters are taken from the optimization for the EVA measurements, as given in Table III.

**C. Parameter Optimization**

The optimized simulation parameters are obtained by fitting the measured ingress curves at air humidity step change from 20% to 60% RH. Parameters $F_{\text{geo}} = 5$, $Q_{\text{mesh}} = 30$, and $H_{\text{sens}} = 50$ $\mu$m are kept constant. The obtained fitting parameters are given in Table III.

After that, the same parameters are used to simulate moisture ingress at air humidity step changes from 20% to 40% and from 20% to 80%. In Fig. 14, only the comparison at the 20% to 40% RH air humidity step change are shown for clarity, although the fits are similarly good in all cases. This proves the
Fig. 14. Comparison between measurements and simulations with the new dual-transport model and the Fickian model. The top graph shows the results for EVA and TPO, the bottom for POE and ionomer.

Fig. 15. Measured and simulated egress in POE.

The linearity of the moisture ingress process. Optimized Fickian simulations in a homogeneous material (dashed lines) are added for comparison.

The measured ingress curves can vary between the three sensors in the same material. These differences are most pronounced in ionomer. The simulations with the corresponding thickness show that these differences are caused by the varying thickness of the encapsulant above the sensor.

The obtained parameters are used to simulate the egress from 80%, 60%, and 40% to 20% RH, respectively. The simulations yield good results for the latter, with a maximal absolute error of less than 1% RH in all encapsulants. However, the fit is worse for step changes with higher initial water concentrations. The dual-transport model overestimates the egress speed, resulting in an absolute error of up to 6.5% RH at 80% initial RH, as shown at the example of POE in Fig. 15. The maximal absolute error is around 2.5% with 60% initial RH. However, the model is still more accurate than the Fickian model, as shown in Fig. 15.

By changing the material parameters for egress, this issue can be resolved. A variation of $D_C$ while keeping the other parameters constant is enough, as shown at the same example of POE in Fig. 16. The parameter $D_C$ is 10 for the simulation of egress from 40% RH, 9 for the simulation of egress from 60% RH, and 7.5 in the simulation of egress from 80%.

VI. DISCUSSION

The presented moisture transport model should be taken as a purely mathematical model for finite-element simulations. Nevertheless, its basic ideas and implementations have some foundation in the physical models of the diffusion processes in polymers, as described in the literature. However, the proposed mechanisms are applied to different polymeric materials. Until now, no models based on two transport mechanisms are applied specifically to PV encapsulants, making their direct application questionable and subject to further research. Nevertheless, we find two of them in line with the assumptions and their implementation into the model.

First is the free volume theory [29]. The channels are equivalent to the free volume, whereas the bulk is equivalent with the polymer matrix of the material. Positron lifetime spectroscopy measurements for EVA show that the fractional free volume is about 10% of the material, varying a few percent depending on the vinyl acetate (VA) and polyethylene (PE) contents [39]. POEs are usually ethylene-acrylate copolymers, which are suspected to behave similar to EVA. TPOs are commonly based on PE, suspected to be linear low density or low-density PE. Linear low-density PE measurements have shown a free volume in the range of 2%–4% [40]. However, to the best of our knowledge, no similar measurements of these encapsulants themselves and of ionomer are available in the literature.

The heterogeneity of the polymers is another possible explanation [25]. In PV EVA, usually around 30% of the material consists of the polar VA, whereas the majority is the nonpolar PE. EVA with a larger share of VA has shown to increase the overall diffusion coefficient of the material within certain limits [41], [42], indicating that on one hand the polarity leads to a faster diffusion. However, on the other hand, also the semi-crystallinity of the material has to be considered. Crystalline zones are impermeable. The VA content in EVA reduces the degree of crystallinity, increasing the speed of diffusion through the material [43].
VII. Conclusion

The model presented in this article implements two transport mechanisms by proposing channels with higher diffusion coefficient through the bulk material and links it to measured macroscopic diffusion through the material. Even though the moisture flow in channels, bulk and across the interface is modeled as a Fickian diffusion process, we can accurately describe the observed non-Fickian diffusion cases. In these cases, diffusion through the material to an encapsulated sensor is primarily driven by the channels, whereas the bulk represents a hindering factor. Nevertheless, the model can describe simple Fickian diffusion cases as well.

The root mean square deviation (RMSD) between simulations and measurements is reduced by a factor between 3 and 10 using the new model instead of the homogeneous Fickian diffusion model, depending on the material and the boundary conditions. For example, the RMSD in TPO improves from 2.19% RH to 0.57% RH for the ingress simulations from 20% to 40%, shown in Fig. 14.

The model enables the prediction of moisture ingress after parameter optimization to a single measured ingress curve. Three parameters have to be determined. The share of channels $S_C$ influences the interaction between the two regions and the amount of flow in both. The diffusion coefficient in the channels describes the speed of the diffusion process. The dimensionless parameter $\alpha$, the ratio between the diffusion coefficients in channel and bulk, describes variations from the homogeneous Fickian model. It is purely a mathematical parameter, and not directly linked to any physical property of the material itself. As such, the bulk could be interpreted not only as a representation of a second process, but as a simple simulation equivalent of multiple processes affecting the diffusion in the material.

The same parameters result in a more accurate prediction than the Fickian model for ingress and egress at all measured RH ranges. However, the measurements show some nonlinear behavior in all four analyzed encapsulant materials at egress with high moisture concentration. The diffusion seems to exhibit some dependence on the moisture concentration, resulting in a hysteresis effect for ingress and egress at high RH.

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References


