Penetration of Moisture in a Solar-Panel Edge Seal

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Abstract: The search for lower cost photovoltaic panels for the conversion of solar to electrical energy has led to the selection of solar cells and interconnects with sensitivity to degradation by moisture. The addition of an edge seal containing a desiccant can reduce the amount of water reaching the photovoltaic panel. This report discusses the modeling of the water transport into the solar module to determine the amount of edge seal and desiccant sufficient for a 20 year lifetime.

Transport is modeled as a Stefan problem. The freezing front of the original Stefan problem becomes a moisture front representing the border where the desiccant is combining with the water. The model is implemented using COMSOL Multiphysics®[1] engineering simulation software (hereafter referred to as COMSOL) incorporating weather data (temperature and humidity) and temperature dependent permeability. The Deformed Geometry physics defines the front. The model and experimental data at constant conditions are compared.

Keywords: solar, photovoltaic, Stefan, phase change

1. Introduction

The basic question is: How long will it be until water passes through the edge-seal? Even though some water will not completely degrade the solar panel, this report will consider the first breakthrough of water to be the end of life for the edge seal. Water diffusing through the edge-seal will combine with the desiccant. There are two types of desiccants: one reacts irreversibly with the water (for example Calcium Oxide), and the other adsorbs water reversibly (for example Zeolites)[1]. This report strictly deals with reactive desiccants, but adsorbing desiccants should behave similarly.

The reaction rate between water and the desiccant is assumed to be rapid enough that no water can pass until the desiccant has been completely saturated. The point of saturation is a moisture front that progresses through the seal, with an effective concentration of zero moisture at the front. The rate of movement of the front is dependent on the capacity of the desiccant, the desiccant concentration in the edge seal, and the flux of water at the front.

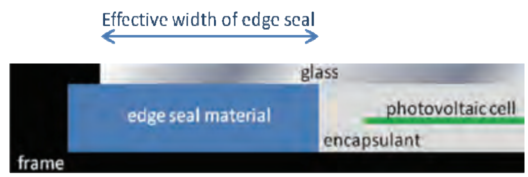

Figure 1. Schematic view of edge seal (not to scale)

The key step in the model development presented in this report is realizing that consumption of water by the desiccant is essentially a reaction and can be modeled as a phase change similar to the phase change involved in freezing. Water diffuses through the edge-seal similarly to the transport of heat through a solid. The water capacity of the desiccant is analogous to the latent heat of freezing. Just as no heat passes though a region until the freezing has been accomplished, no water will diffuse through a region until the desiccant has been consumed.

Josef Stefan[2] was the first to apply the mathematics of freezing at the surface of a solid to physical data. His formulation and solution are directly applicable to the present problem.

2. Water Diffusion Model

The diffusion of water through the edge seal is described by one-dimensional Fickian diffusion in a semi-infinite slab assuming that corner effects can be ignored. The surface concentration boundary condition is set by the solubility of water in the edge seal and the temperature and relative humidity of the atmosphere. The water concentration condition at the moving front is set to zero.

[1] A registered trademark of COMSOL AB

In a freezing problem there is only one species, and it is at the freezing point at the boundary. In mass diffusion, there will be a partition between the bound species and the mobile species. Strictly speaking, the Stefan solution requires that the transition be steep. This implies that the reaction rate with water is fast compared to the diffusion time. Irreversible desiccants, such as CaO, will have negligible reverse reaction and the equilibrium can be ignored. Reversible desiccants, such as zeolites, must have a large equilibrium constant for the Stefan model to apply. The position of the front, xf, is described by another differential equation, derived by considering that the flux of water at the moisture front is equal to the concentration of desiccant times the rate of advancement of the front. This is the Stefan condition.

$$C_d \frac{\partial x_f}{\partial t} = -D \frac{\partial C}{\partial x} \qquad (1)$$

where C_d is the concentration of desiccant (expressed in units of water equivalents in the same units as the water concentration)

3. Stefan's Classical Solution

Josef Stefan gave a closed form solution applicable for constant conditions at the surface and constant diffusivity and solubility. Define a Stefan number as the ratio of the surface concentration to the desiccant concentration in equivalent units.

$$St = \frac{C[x=0]}{C_d} \qquad (2)$$

Stefan[2] gives a solution to the problem. The formulation of the problem was discussed in Lamé & Clapeyron[3] and the mathematics was described by Neumann[4], but these problems are called "Stefan problems" because he made the first practical use of the mathematics. The phase change problem also merits a chapter in Carslaw & Jaeger[5]. Previous COMSOL conference papers have also discussed the Stefan problem[6,7]. The water concentration profiles are described by this equation.

$$C[x,t] = C[x=0,t]\left(1 - Erf\left[\frac{x}{2\sqrt{D\,t}}\right] / Erf[\lambda]\right) \qquad (3)$$

The moisture front position is described by this equation.

$$x_f[t] = 2\,\lambda\,\sqrt{D\,t} \qquad (4)$$

Note that both Crank[8] and Danckwerts[9] describe this solution, but they give a graphical construction method to calculate the value of λ. The earlier works give an implicit formula for λ that is much more suited to the current computational tools.

$$St = \lambda\,\sqrt{\pi}\;Exp\left[\lambda^2\right] Erf[\lambda] \qquad (5)$$

If St is known λ can be calculated.

This solution is valid only for constant surface conditions and constant material properties. However, it is useful in validating numerical solutions, and in analyzing some experimental results.

Kempe *et al* [*10*] measure moisture penetration using constant conditions of 85°C and 85% relative humidity. They show that the best material has a penetration of 8.0 mm in 2000 hours. Kempe *et al* show an expression for moisture front advancement at 85°C and 85% relative humidity.

$$x_f[t] = 0.018\left(cm/\sqrt{hour}\right)\sqrt{t} \qquad (6)$$

4. Numerical Solution

If C_d is the concentration of the desiccant, we can write an expression for the advancement of the front (the Stefan condition).

$$\frac{\partial x_f}{\partial t} = \frac{q\,[mole/(m\text{^}2*\sec)]}{C_d\;[mole/m\text{^}3]} = -\frac{D}{C_d}\frac{\partial C}{\partial x} \qquad (7)$$

COMSOL will solve for the moisture diffusion (using the Transport of Diluted Species physics), and the front motion can be solved by allowing one boundary to move (using the Deformed Geometry physics). The boundary motion is set by using the Stefan condition in equation 7. This numerical approach frees the model to allow varying surface conditions and varying parameter values.

The model was solved for constant conditions of 85°C and 85% relative humidity to compare the numerical solution to Stefan's analytical solution. Figure 3 shows that the two models track very close together, assuring us that the COMSOL model is accurately solving the problem. Kempe *et al* [*10*] conclude that 1 centimeter of this edge-seal material is sufficient to protect the photovoltaic cell.

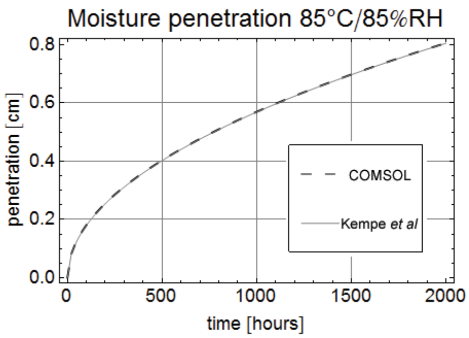

Figure 3. Comparison of numerical solution (COMSOL) and analytical model fit to data (Kempe *et al*)

5. Penetration in Varying Conditions

Temperature and humidity experienced by the photovoltaic panels vary at least on an hourly basis. The COMSOL Multiphysics model allows easy implementation of a weather model. The temperature dependence for the moisture permeability of the edge seal can be entered as an Analytical Function. A simple time varying humidity is illustrated in Figure 4 below.

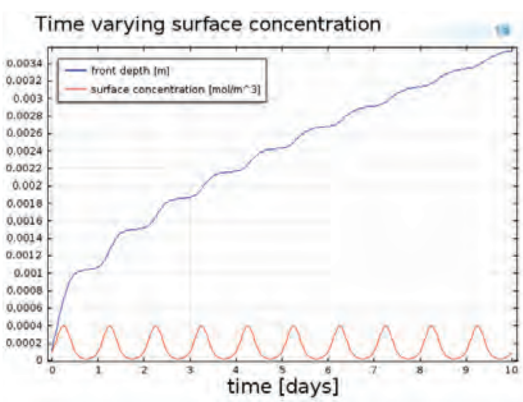

Figure 4. Moisture front advancement with varying temperature

The figure shows a daily variation in humidity, and its effect on the advancement of the moisture front. As one would expect, high humidity at the surface will drive the moisture into the interior more quickly, but as the moisture front goes deeper into the seal, the effect of the surface variations is reduced. It is useful to also consider the actual moisture profiles as illustrated in Figure 5.

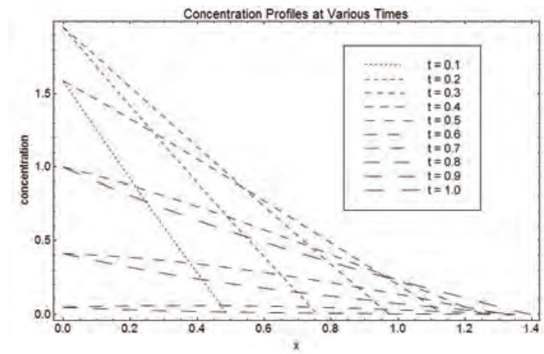

Figure 5. Water concentration during the course of one cycle

Note that the surface concentration may go down, but the moisture gradient never changes sign. This suggests that the use of a reversible desiccant (for example a zeolite) will behave similarly to an irreversible desiccant (for example CaO), because if the moisture gradient never changes sign, the reversible desiccant will never have the opportunity to lose its moisture at the front.

Also note that the concentration profile can curve. The original Stefan model assumes a linear concentration profile. For constant surface conditions and constant parameters this assumption is fairly accurate.

Predictions for various weather conditions require data from field measurements or a thermal model in combination with metrological data. Metrological data from both Miami, Florida and Phoenix, Arizona were used to make "standard" years, with hourly data points, for atmospheric temperature, humidity, and shingle temperature. "Typical Metrological Year" data (TMY) are available from NREL[11], and were combined with a thermal model of the solar collector to generate module temperature and humidity data. Miami international airport file 722020 was used for Miami and Phoenix Sky Harbor International Airport file 722780 was used for Phoenix [11]. Equations 11 and 12 from King et al [12] were directly employed with coefficients from Table 1 for a glass-cell-polymer sheet with an insulated back to obtain module temperatures based on metrological data for Ground Horizontal Irradiance (GHI), wind speed and ambient temperature [11].

A COMSOL Interpolation function is used to take the temperature and humidity data and use it for surface concentration and for the moisture permeability value of the edge seal material.

5.1 Miami Conditions

The model was solved using the estimate of the desiccant loading derived from the Kempe *et al* results. Two "standard" years of conditions in Miami, Florida were simulated and an equivalent constant-condition curve was estimated.

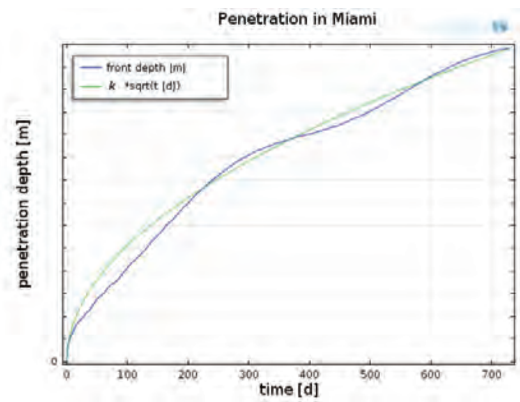

Figure 6. Moisture penetration predicted for Miami

The constant-condition curve is adjusted to intersect the numerical solution at 0 and 730 days. The fact that there is another intersection at exactly 365 days indicates that the solution has a one year repeat pattern, and the constant-condition curve can be used to extrapolate out to 20 years.

5.2 Phoenix Conditions

Two "standard" years of conditions in Phoenix, Arizona were simulated and an equivalent constant-condition curve was estimated. Figure 7 shows the results of the simulation and a curve fit for constant conditions.

The constant-condition curve is adjusted to intersect the numerical solution at 0 and 730 days. The behavior of the curve is the similar to the Miami fit.

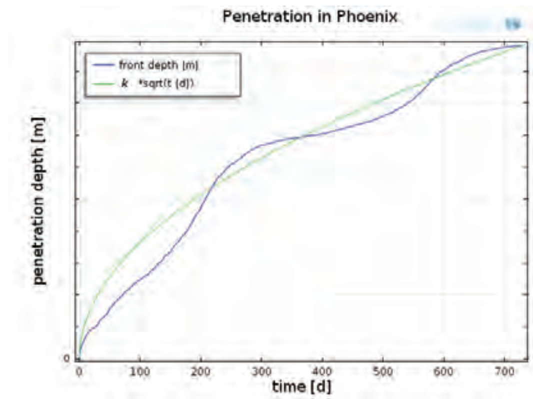

Figure 7. Moisture penetration predicted for Phoenix

6. Conclusions

The COMSOL numerical model of the edge seal moisture breakthrough matches the known analytical solution. The numerical model can be used to make predictions with the varying temperature and humidity of specific locations and can accommodate variable permeability and solubility. The model allows edge-seal performance to be estimated for different weather conditions. This work confirms the work of Kempe *et al*: in real weather conditions a 1 centimeter length of the edge seal studied will provide protection for 20 years in the locations considered. The model can also be used to optimize the edge-seal design.

7. References

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