Solar Energy 150 (2017) 128–135

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Reliability-based structural optimization of 300 × 300 mm^2 dye-sensitized solar cell module

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ARTICLE INFO

Article history:
Received 15 March 2017
Accepted 14 April 2017

Keywords:
Dye-sensitized solar cell
Reliability
Structural optimization
Cell width

ABSTRACT

Dye-sensitized solar cell (DSC) is a promising candidate for the application in building-integrated photovoltaics (BIPV). At higher temperature above 85 °C, the reliability of the module has remained a major challenge yet. A large DSC module, sized 300 × 300 mm^2, is developed. In the preliminary module design, the width of cell is 11 mm and the coefficients of temperature expansion (CTE) for sealant and electrolyte are 699 and 807 ppm/°C, respectively. The modules are stored in 85 °C. The power conversion efficiency of the modules drops rapidly in 100 h during the test. To analyze and enhance the module design in view of reliability, finite element model is developed for the module. Stress analysis reveals that high stresses in electrode cause the breakage of electrode and sealant in succession and the loss of electrolyte finally. From a parameter sensitivity analysis with the finite element model, it is identified that the maximum stress in electrode can decrease when the cell width increases. CTEs of sealant and electrolyte can be also optimized as analysis confirms that the maximum stress in electrode drops when the CTEs of sealant and electrolyte decrease. Based on the studies, new module design is formulated, which have the cell width of 18 mm and the CTEs of 277 and 656 ppm/°C for sealant and electrolyte, respectively. The new modules are tested in 85 °C and show much better lifetime than the preliminary one without the leakage of electrolyte.

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1. Introduction

While DSCs have lower power conversion efficiency than silicon-based solar cells, they have many relative advantages such as simple production process, cost-effective efficiency, using environmentally sustainable materials, wide range of color possible, semi-transparency, and working in cloudy weather or low-light conditions. Particularly, the qualities of color selection and semi-transparency make DSCs a promising candidate for BIPV application (Pagliaro et al., 2010).

But the reliability of DSC module is still in question. Especially long-term reliability at higher temperature more than 85 °C has remained a major challenge. Because damp heat 1000 h test under 85 °C and 85% RH condition is a part of minimum qualification test defined by international standards such as IEC 61215 (International Electrotechnical Commission, 2005), DSC community also wishes that DSC modules would be qualified for 1000 h in 85 °C high temperature as the first step to demonstrate their long-term reliability. But many studies have reported that the power conversion efficiency of DSCs showed a rapid degradation after exposed under 85 °C temperature. As a matter of convenience, the time when DSC module power drops to 80% compared to initial status in 85 °C high temperature condition will be referred as '85 °C life' in this paper. As summarized in Table 1, Hinsch et al. tested small size of DSC modules sealed with hot melt foil and hermetic glass frit and reported 700 h of 85 °C life (Hinsch et al., 2001). But less than 100 h of 85 °C life was also reported when DSC modules were sealed only with hot melt foil (Sommeling et al., 2004). Sastrawan et al. tested a large size DSC module sealed with glass frit and reported 600 h of 85 °C life (Sastrawan et al., 2006). When thermoplastic gaskets were used for sealing DSCs, less than 100 h of 85 °C lives were reported for liquid solvent (Bari et al., 2011; Cester et al., 2015; Wang and Wong, 2015). Note that 85 °C life occurred in less than 100 h in most of the studies unless extra and expensive hermetic sealing was adapted. Recently drops to 74% at 1000 h were reported in 85 °C condition with polyolefin-based sealant but didn't provide 85 °C life in the paper (Kwak et al., 2016).

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http://dx.doi.org/10.1016/j.solener.2017.04.038
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Table 1
Summary of 85 °C lives in the previous studies.

Ref.	Module size (mm × mm)	Cell size (mm × mm)	No. of cell in a module	Sealing method	85 °C life
Hinsch et al. (2001)	75 × 100	8 × 50	5	Hotmelt foil (Surlyn) + glass frit	700 h
Sommeling et al. (2004)	75 × 100	8 × 50	5	Hot melt foil	Less than 100 h
Sastrawan et al. (2006)	300 × 300	50 × 300	6	Glass frit	600 h
Bari et al. (2011)	N.A.	5 × 5	3	Thermoplastic gasket	About 2 h
Cester et al. (2015)	N.A.	5 × 5	N.A.	Thermoplastic gasket	Less than 10 h for 80 °C
Wang and Wong (2015)	N.A.	16 mm^2	N.A.	Thermoplastic hot melt (Surlyn)	50 h for organic solvent 750 h for ionic liquid electrolyte
Kwak et al. (2016)	300 × 300	13 × 300	22	Polyolefin-based sealant	Drop to 74% at 1000 h

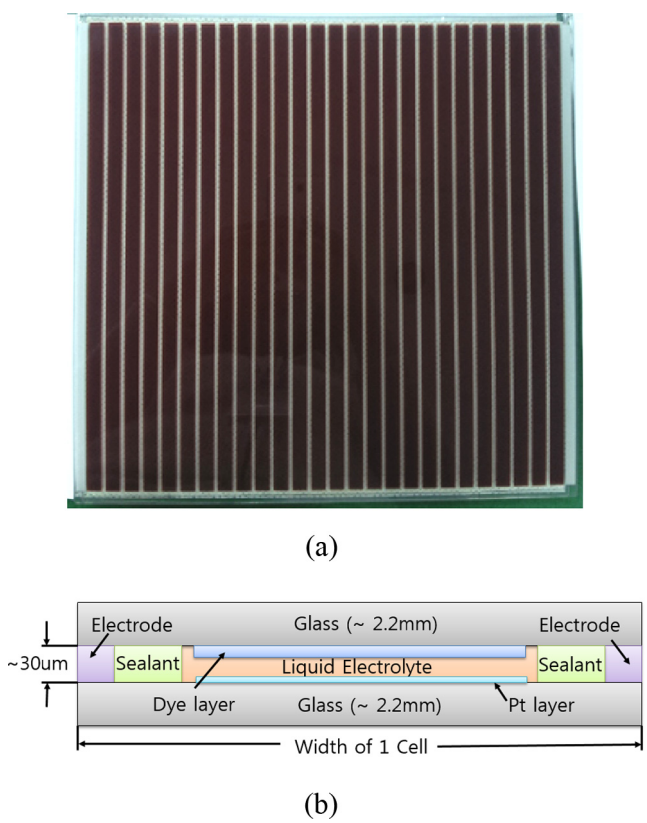

Fig. 1. Structure of DSC module; (a) model A (26 cells) and (b) illustration of cell cross section (not scaled).

The reasons of the rapid power degradation of DSC modules under high temperature are not clearly understood yet. Some of the studies pointed the loss or leakage of liquid electrolyte of the DSC cell as a cause of the efficiency drop under high temperature (Bari et al., 2011; Cester et al., 2015; Jhong et al., 2009; Fu et al., 2012). But the reason why there are leakage or loss of electrolyte, or the degradation mechanism of the technology are not extensively elaborated yet as far as the authors know. As remarked in Reference Hinsch et al. (2001), the authors also believe that long-term reliability of DSCs is not an intrinsic problem of the technology, but can be improved further by better understanding of the degradation mechanisms and structural integrity between the components.

In this study, degradation mechanism is investigated from the view of structural, not chemical, integrity and an optimized structural design is suggested to enhance the reliability of DSC. In Section 2, a large DSC module is introduced. The reliability of the module is tested in 85 °C temperature. It turns out that 85 °C life of the first batch of module is less than 100 h. In Section 3, to improve the reliability, structural analysis using finite element model is conducted for the DSC cell structure. The analysis indicates that there are high stresses in silver electrode and the stresses can be reduced by expanding the cell width. In Section 4, second batch of module with wider cell width is tested and shows better 85 °C life. But there are still electrolyte leakages. In Section 5, to improve the design, the CTE of sealant is adjusted by controlling the curing time and low CTE of electrolyte is chosen. Final design of the module demonstrates better 85 °C life and structural integrity.

Table 2
Summary of developed three DSC module models and their key design parameters.

Model	Model A	Model B	Model C
Size (mm^2)	300 × 300	300 × 300	300 × 300
No. of cells	26	16	16
Cell width (mm)	11	18	18
CTE of sealant (10^{-6}/°C)	699	699	277
CTE of electrolyte (10^{-6}/°C)	807	807	656

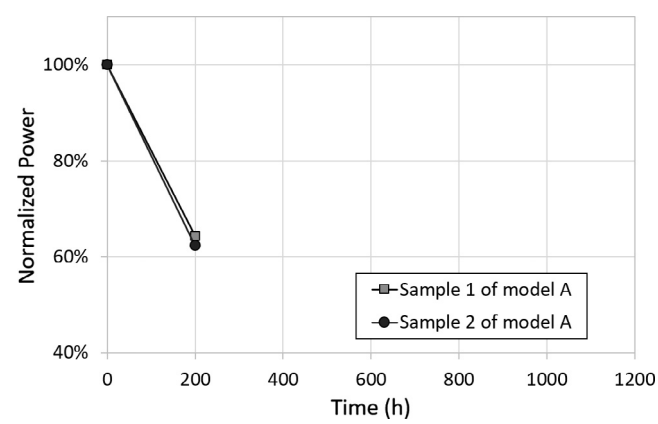

Fig. 2. Power drop of module model A in 85 °C test.

Table 3
Electric parameter changes of model A before and after 85 °C test.

Sample	Power (mW)		Voc (V)		Isc (mA)		FF (%)	
	#1	#2	#1	#2	#1	#2	#1	#2
Before test	2757	2751	16.6	16.6	238	235	70	71
After 200 h	1774	1715	15.3	15.3	165	160	70	70
Decreased amount	36%	38%	8%	8%	31%	32%	0%	1%

2. Design and test of DSC module: model A

A large DSC module, sized 300 × 300 mm^2, is developed for BIPV application as shown in Fig. 1. Two glass plates coated with transparent conductive oxide (TCO) layers are used for the top and bottom parts. Dye on nano particle and platinum electrode layers are printed on each glass plate. To produce electrical power

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