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# Optical characterization and durability of immersion cooling liquids for high concentration III-V photovoltaic systems

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ABSTRACT

The optical transmittance and durability of several immersion cooling liquids that could be used for high concentration III-V photovoltaic systems are investigated. Firstly, the optical transmittance of the liquid candidates divided into three categories: synthetic oil, silicone oil and mineral oil are determined based on a double optical path-length transmittance method. The normalized photocurrent density of GaInP/GaInAs/Ge triple-junction solar cells when illuminated by the solar spectral irradiance filtered by each liquid is reported. Results show that the liquid candidates exhibit superior transmittance for the UV and visible wavelengths of interest, whereas they display some absorption bands in the 1200–1800 nm spectrum and thus the photocurrent of the bottom subcell Ge decreases. This is not an issue since the bottom subcell normally produces excess current. Then, the optical transmittance of the liquid candidates is monitored during exposure to UV light, damp heat and high-temperature accelerated aging tests. The average transmittance for the wavelengths of interest is introduced to quantify changes in the optical transmittance of immersion cooling liquids after being subjected to the accelerated aging tests. Results from the accelerated aging tests indicate that dimethyl silicone oil, white oils A/B/C and C14 n-alkane are suitable for immersion cooling of multi-junction solar cells whose average transmittance losses are less than the total degradation value of 5% allowed for CPV modules under qualification tests in the IEC62108 standard. The optimum liquid for immersion cooling multi-junction solar cells is found to be dimethyl silicone oil due to its high transmittance for the wavelengths of interest and its loss in average transmittance over each exposure period is always less than 0.5%.

## 1. Introduction

High concentrating photovoltaic systems applying III-V multi-junction solar cells have been attracting a tremendous amount of attention from the scientific community and industrial developers due to the record efficiencies of III-V multi-junction solar cells, which have increased significantly over the past several years up to 46.0% (AM1.5D, 508 suns) [1–4]. Even though III-V multi-junction cells have shown superior performance, more than 50% of the absorbed incident sunlight which cannot be converted into electricity is still dissipated as heat within the cells. It is well known that the efficiencies of solar cells decrease as the cell operation temperature increases. Therefore, the cooling system is very important for concentrating photovoltaic (CPV) applications, especially for high CPV systems with densely packed cells [5]. A significant amount of research on CPV cooling has been carried out, as summarized by Royne et al. [5] and Micheli et al. [6]. Further, a review of the literature on cooling systems for CPV systems concluded that effective uniform cooling is highly important [7]. In fact, in our previous study, we proposed direct liquid immersion cooling for high CPV systems with densely packed solar cells and demonstrated that it is one of the promising solutions for effective uniform CPV cooling [8]. In addition, Han et al. discussed the optical and electrical effects of candidate dielectric liquids on silicon concentrator solar cells [9,10]. The high heat dissipation capability of direct liquid immersion cooling for dish high CPV systems and linear CPV systems with silicon solar cells have been confirmed by several authors [11–13].

There is still, however, not adequate experimental research on which to choose an appropriate immersion cooling liquid for multi-junction solar cells. Besides exhibiting high optical transmittance for the spectral response region of multi-junction solar cells, the durability of appropriate immersion cooling liquids needs to be established since it is extremely significant for CPV practical applications. As a matter of fact, for any optical material with potential application in CPV systems used for various functions ranging from concentrating optics to homogenizers, encapsulants and even heat dissipation, aging tests are necessary before real-world applications, to demonstrate the reliability

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**Nomenclature**

| | |
|---|---|
| $c$ | light speed, m/s |
| $d$ | thickness of cuvette wall, cm |
| $h$ | Planck's constant |
| $I_{AM1.5D}$ | direct solar spectral irradiance at AM1.5, W m$^{-2}$ nm$^{-1}$ |
| $J_{np}$ | normalized photocurrent density |
| $q$ | electron charge, C |
| $R_1$ | reflectance at interface between air and cuvette wall |
| $R_2$ | reflectance at interface between liquid and cuvette wall |
| $T$ | measured transmittance |
| $x$ | cuvette path-length, cm |

*Greeks*

| | |
|---|---|
| $\alpha$ | absorption coefficient of liquid, cm$^{-1}$ |
| $\alpha_0$ | absorption coefficient of cuvette wall, cm$^{-1}$ |
| $\lambda$ | wavelength, nm |
| $\tau$ | transmittance of liquid |

*Abbreviations*

| | |
|---|---|
| CPV | concentrating photovoltaic |
| CPV/T | concentrating photovoltaic/thermal |
| EQE | external quantum efficiency |
| HCPV | high concentrating photovoltaic |
| NIR | near infrared |
| PV | photovoltaic |
| UV | ultraviolet |
| VIS | visible |

of the optical properties. Outdoor aging tests are time-consuming and thus accelerated aging tests are usually carried out [14]. For example, the optical durability of Fresnel concentrators were studied by subjecting them to accelerated aging in an ultraviolet (UV) environmental chamber [15]. In order to analyze the reliability of silicone and ethylene vinyl acetate (EVA) encapsulants for PV modules, McIntosh et al. discussed the effect of damp heat and UV exposure on the optical properties of the encapsulants [16]. Victoria et al. examined the transmittance of several fluids that could be used for immersing concentrator optics, both before and after accelerated UV radiation exposure [17]. Looser et al. achieved the most suitable fluid as a spectral absorption filter for CPV/T systems by analyzing the impact of high temperature and UV light accelerated aging tests on the transmittance of the fluids [18].

In this paper, several different cheap, clear, and easily available liquid candidates for immersion cooling multi-junction solar cells have been examined in terms of their optical transmittance based on a double optical path-length transmittance method. In addition, an analysis of the normalized photocurrent density ($J_{np}$) of triple-junction solar cells in the presence of each immersion cooling liquid has been conducted. To maintain a relatively constant power output of the HCPV systems with densely packed multi-junction solar cells, the immersion cooling liquids should withstand for long term operation and environmental exposure without much degradation. Thus, the influence of accelerated aging tests on the optical transmittance of immersion cooling liquids for multi-junction solar cells is investigated. The average transmittance is adopted to quantify the changes in the optical transmittance of immersion liquids after being submitted to the accelerated aging tests.

## 2. Investigated immersion cooling liquids for III-V cells

Since immersion liquids for cooling III-V solar cells under high concentration perform the dual purpose of heat transfer and optical adaptation, the requirements for the liquid properties not only include good heat transfer properties, but also include additional optical and electrical properties. According to the required properties [19] and the available physical properties of the liquids shown in Table 1 [20–23], seven liquids were identified as potential immersion cooling liquids for high concentration III-V photovoltaic systems: Therminol VP-1, dimethyl silicone oil, three types of white oils, C14 n-alkane and C16 iso-alkane. In fact, white oil is also called paraffin oil. Therminol VP-1 is one member of the synthetic oil particularly developed as heat transfer oil by the company called Solutia [20]. Three types of white oil, C14 n-alkane and C16 iso-alkane fall into the category of mineral oil. Depending on the refining process, three types of white oils are selected: food grade white oil, cosmetic grade white oil and industrial grade white oil (referred to as white oils A/B/C throughout the paper). According to the data described in Table 1, almost all of them exhibit good heat transfer properties. Among them, Therminol VP-1 has the highest density of 1060 kg/m$^3$, whereas mineral oils have lower densities ranging between 764 and 880 kg/m$^3$. White oils have higher specific heat in comparison with other liquids. All the selected liquids except for C16 iso-alkane have similar thermal conductivities. The viscosities of C14 n-alkane and C16 iso-alkane are lower, when compared with Therminol VP-1, dimethyl silicone oil and white oils. With respect to the electrical properties of the liquids, Therminol VP-1, dimethyl silicone oil and some mineral oil manufacturers provide dielectric constant data. However, in terms of the optical properties of the liquids, the available information is the refractive indices and transparency in the visible spectrum. For use as an immersion coolant, the optical transmittance is much more significant than as a conventional heat transfer fluids. Therefore, the optical transmittance of these liquids must first be measured for comparison with the spectral response region of multi-junction solar cells. In addition, the durability of the liquid candidates is also one of the key factors when choosing a liquid for high concentration III-V photovoltaic applications. Finally, cost is a further consideration for more economical system. In fact, the seven liquid candidates are commonly-used commercial inexpensive heat transfer fluids. Generally, synthetic oil is the most expensive heat transfer fluid,

**Table 1**
Physical properties of the candidates for immersion cooling liquids [20–23].

| Properties | Therminol VP-1 | Dimethyl silicone oil | White oil A/B/C | C14 n-alkane | C16 iso-alkane |
|---|---|---|---|---|---|
| Color | Clear | Clear | Clear | Clear | Clear |
| Density (kg m$^{-3}$) | 1060 | 915 | 880/822/816 | 764 | 767 |
| Specific Heat (J kg$^{-1}$ K$^{-1}$) | 1570 | 1758 | 2130 | 1578 | N/A |
| Thermal Conductivity(W m$^{-1}$ K$^{-1}$) | 0.14 | 0.12 | 0.15 | 0.14–0.15 | N/A |
| Viscosity(10$^3$ Pa s) | 2.63 | 4.58 | 6.78/2.30/2.45 | 1.60 | 1.94 |
| Boiling point(°C) | 257 | 170 | 255–276 | 254 | 211 |
| Refractive index | 1.65 | 1.40 | 1.48 | 1.43 | 1.42 |
| Dielectric constant | 3.35 | 2.60 | 2.20 | 2.03 | N/A |