Design and Development of Transparent Luminescent Solar Concentrator using Mixed Rock Salt and Polymethyl Methacrylate

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Abstract. *Silicon-based solar cells are opaque that would limit other benefits of using besides generating electric dc power. As a result, transparent solar cells (TSCs) have been developed to overcome those limitations. However, TSCs usually have complicated manufacturing processes and difficulty in developing the high efficient light absorbing and reflection materials, and therefore having high cost. This research presents design and development of the low cost rock salt based transparent luminescent solar concentrators (TLSCs) which could be used as TSCs. The developed TLSCs utilized the electro-chemical reaction with special salt solute with 36% concentration. This solute was injected into the cell grids made of Poly Methyl Methacrylate sheets with width, length and thickness of 5x5x1.8 cm. The properties of the developed cells were tested in comparison with the conventional crystalline based cells. The open circuit voltage of both cells had the highest values at the room temperature and decreased when the temperature increased but retained constant after tested longer than 60 minutes. The short circuit current for both cells had values changing propositionally to the change of the solar concentration levels. The short circuit current of the silicon-based cells decreased by 15.79% while the proposed cells decreased only by 8.00%. In addition, when combined the two types of the cells in series and parallel connection, it was found that the theoretical power of the cells when connected in parallel provided higher power compared to when connected in series. Enhancing higher efficiency and less cost would be the big challenge for the future work regarding this proposed solar cell.*

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Transparent solar cells, transparent luminescent concentrator cells, rock salt, polymethyl methacrylate

1. Introduction

Solar radiation is clean energy that can be used for millions of years. This leads many countries around the world to heavily utilize more energy from solar radiation. The commonly used devices for harvesting energy from solar radiation are the silicon-based solar cells due to the beneficial of simple, direct electricity generation from the solar radiation. Unfortunately, these types of the cells are opaque that would cause limitations in other aspects of using. These cells require large installation areas for large amount of generated electric power [1]. This is because of the fact that the silicon-based cells can respond to the solar radiation spectrum only in the visible spectrum to some infrared spectrum (500-1,000 nm) [2]; whereas 99% of full radiation spectrum are between 250 nm and 2500 nm: approximately 5% ultraviolet radiation, 43% visible radiation, and 52% infrared, microwave, and radio waves [3]. Currently, silicon-based cells used in installations have energy efficiency of 18-22% [4].

Alternatively, a new type of solar cells has been developed, known as a Transparent Luminescent Solar Concentrator (TLSC) or a transparent solar cell. This cell type was invented by Richard R. L. [5]. This cell employs techniques that reflect and combine ultraviolet and infrared rays together for generating electricity; especially, when these rays are gathered to a greater and strong intensity enough to push valence electrons away from the pn-junction and eventually create electric current [6]. The TLSC were first mentioned on the cover of the journal Advanced Optical Materials in 2014 [7] by researchers at the University of Michigan, USA, who invented the transparent solar cells. The first cell had energy efficiency of less than 5% [8] and in 2019 a research team from University of Aveiro, Portugal, utilized the use of lanthanide ions (Ln3+=Eu3+, Tb3+) - ionosilica (ISs) stained with polymethyl methacrylate (PMMA) sheets that could increase efficiency of the cell up to 4%. However, these ions required high cost and complicated production processes [9]. In order to reduce the material and relevant costs, the local compounds or substances could be considered and utilized.

Rock salt or sodium chloride (NaCl) is the salt obtained from saline soils (not directly from sea salt). By bringing the brine from the dissolved rock salt underground to boil and simmer until the white fine salt is obtained. Rock salt is an enormous resource covering in all provinces in the northeastern region of Thailand [10], which is about 18 trillion tons estimated by the Division of Economic Geosciences [11]. Luckily, rock salt (NaCl) is one of the substances that have the ability to absorb a wide spectrum of solar radiation range of 300–2500nm [12]. Therefore, the study to use rock salt in solar cell production is an interesting idea.

Besides rock salt, polymethyl methacrylate (PMMA), also known as acrylic, has a translucency of up to 92% acid and alkali resistant that could be used as a part of TSCs. This material can also be easily cut and bent and thus possibly replace the glassed components. It is also produced commercially in large quantities and can be used widely with reasonable price [13]. In fact, the PMMA has been used as a raw material for the construction of TLSCs in a number of studies [14]-[15]. For example, Sara Mattiello found out that the use of derivative combination of benzothieno-benzothiophene (BTBT) and polymethyl methacrylate (PMMA) could achieve 3% electrical energy efficiency [16]. Paolo Della Sala combined molecules of cycloparaphenylene (CPP) with polymethyl methacrylate (PMMA) which could increase energy efficiency of the cell up to 11% [14]. As a result, the polymethyl methacrylate (PMMA) is also taken into account in this research.

The objective of this research is to study, design and develop the TLSC using mixed rock salt and polymethyl methacrylate. The proposed device could be used as a substitute for glasses in household buildings [17], agricultural devices and livestock [18], as well as, for future industrial sectors [19] and etc.

2. Material and Method

2.1 Artificial Solar Simulation Room Design

An artificial solar source was designed for experimental laboratory tests. The source consisted of halogen (quartz) lamps, which were stronger than standard glass bulbs because they have to be filled with high pressure. The temperature could rise up quickly. Halogen could be heat up to a gas at lower temperature. Compact size and high lumen output, halogen lamps had higher brightness potential (10-30 lumens/watt). The halogen lamps had a spectrum of light from 650 nm to about 950 nm, could emit light well in the infrared spectrum closed to the actual solar spectrum. Also, the design halogen lamps are more efficient than incandescent lamps; therefore, suitable for using in this research. The lamps used for the artificial solar system storage room was chosen to be the Sylvania lamps, model Reflector Lamp QR51 GU/GX 5.3 + 35W/38DG. The geometric size and angle of light information are shown in Fig. 1 and Fig. 2 while the data of the lamp used for artificial sunlight simulation is shown in Table 1.

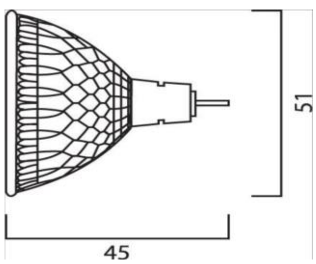


Fig. 1 the geometric size of the lamp

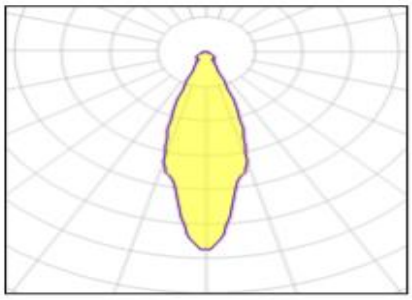


Fig. 2 the angle of light from the lamp

bulb type	Halogen lamps
Lamp power	35 Watts
luminous flux	650 lumens
luminous efficiency	15 lumens / Watts
light color	3000 Kelvin
Color Rendering Index	99
light ratio	92%
angle of light	38 degrees

Table 1 Lamp data used to simulate artificial sunlight

Once all the settings and lamps have been selected, data will be entered into the Dialux program. To simulate the illumination system of the artificial sunlight test chamber as shown in Fig. 3 and 4.

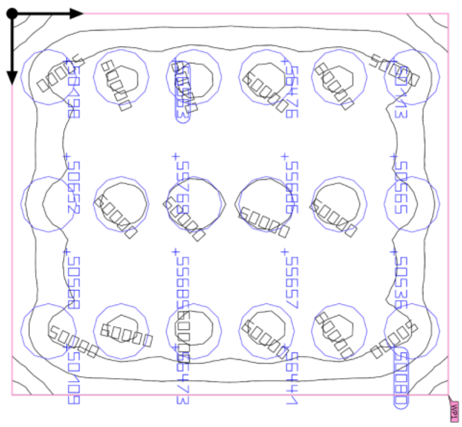


Fig. 3 The result of simulation of lighting system with Dialux program

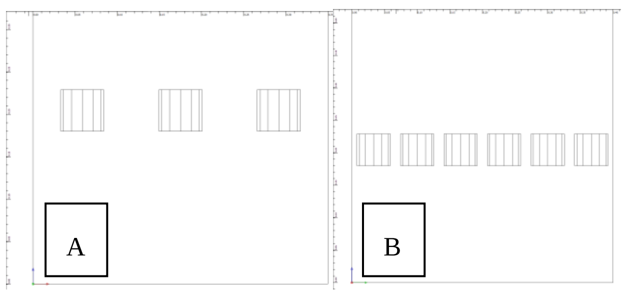


Fig. 4 (A) front view lamp installation and (B) Show side view lamp installation

The designed artificial solar simulation room consisted of 18 sets of 35-watt halogen lamps arranged 3 in x-axis, 6 lamps in y-axis, with a distance of 0.18 m from the lamp to the test area. The light distribution line inside the test chamber was between 50,000 and 60,000 lux, with an average value of 50,122 lux. According to the British Standards Institution's artificial solar system requirements, it must be in the range of 27,798 lux to 51,625 lux of light intensity. Therefore, meet the requirements which will use the power supply Voltage size 12V. Supply current up to 100 amperes to power halogen lamps and temperature inside the test chamber is detected in the center of both sides by having the temperature sensor lift up from the test area 2.5 centimeters**.**

2.2 Design of TLSC

Design of the TLSC requires achieving a systematic grid structure. Then bring each grid to be connected together in a compound circuit as appropriated. The structure design of the transparent solar cells was designed to look like a rectangular block, size width x length x height 5x5x1.8 centimeters. There were polycrystalline solar cells attached to the edges of the transparent solar cells as shown in Fig. 5.

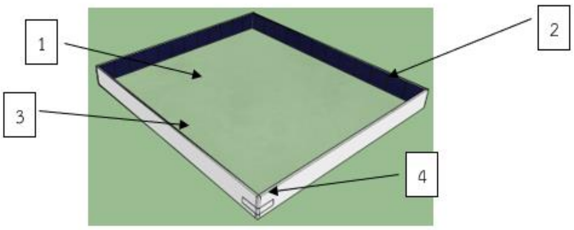


Fig. 5 The structure design of the transparent solar cells consists of (1) rock salt solution (NaCl), (2) polycrystalline solar cells, (3) polymethyl methacrylate and (4) tabbing wire

The cell was added the rock salt or sodium chloride dissolved with distilled water with the concentration of 36% into the structure of the cell. Once the structure of the transparent solar cell was designed, a system to connect each particular electric cell within the grid was consequence designed, which was connected in series by using the tabbing wire to connect between the cells to produce more voltage as shown in Fig. 6.

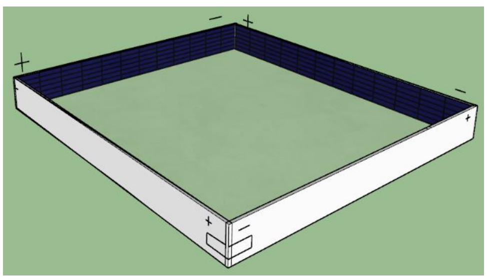


Fig. 6 Design a power grid interconnection for the developed cell

From Fig. 6, the design of transparent solar cells will use polycrystalline solar cells with the information as shown in Table 2.

Width x Length (cm)	Voltage (Vmp)	Current (Imp)	Power (P)
1.8 x 5	0.5 volts	0.32 amperes	0.16 watts

Table 2 Characteristics of the developed cell

One grid of transparent solar cells uses cells at all four edges, connected in series or in parallel as appropriated, which will get voltage, current and power as shown in (1)-(5).

$$\text{Total voltage (series)} = V1 + V2 + V3 + V4 = 0.5 + 0.5 + 0.5 + 0.5 = 2 \text{ volts} \quad (1)$$

$$\text{Total voltage (parallel)} = V1 = V2 = V3 = V4 = 0.5 \text{ volts} \quad (2)$$

$$\text{Total current (series)} = I1 = I2 = I3 = I4 = 0.32 \text{ Amps} \quad (3)$$

$$\text{Total current (parallel)} = I1 + I2 + I3 + I4 = 0.32 + 0.32 + 0.32 + 0.32 = 1.28 \text{ Amps} \quad (4)$$

$$\text{Total power} = P1 + P2 + P3 + P4 = 0.16 + 0.16 + 0.16 + 0.16 = 0.64 \text{ watts} \quad (5)$$

After that, the connection between the grids is designed. They are connected in a compound circuit to provide voltage similar to that of solid crystal solar cells for comparison and use. It also makes it easy to check when grid errors occur as Fig.7.

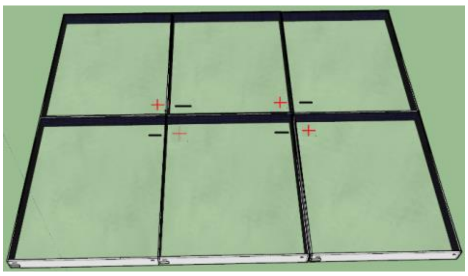


Fig. 7 connection between grids

The calculation is compared with a solid crystal solar cell, size: width and length of 22 and 30 cm, voltage (V) 18 volts, current (I) 0.56 amperes, power (P) 10 watts. Translucent can be calculated as shown in (6)-(9).

wide row grid = 20 / 5 (6)
= 4 grids

long row grid = 30 / 5 (7)
= 6 grids

total number of grids = (20 x 30)/(5 x 5) (8)
= (4 x 6)
= 24 grids

total number of cells = 24 x 4 (9)
= 96 grids

In the design, the grids were serialized in a long row of 6 grids totaling 5 rows while each row was connected in a parallel. The theoretical electric voltage and current are shown in (10)-(11).

Output voltage = voltage of each grid (10)
x Number of grids in a long row
= 2 x 6 = 12 volts

Output current = current in a long line (11)
x Number of grids in a wide row
= 0.32 x 4 = 1.28 Amps

2.3 Test Parameters and Conditions

The designed TLSC was tested in comparison to the solid crystal solar cells using the artificial solar source. The test parameters were the open circuit voltage (V_{oc}), the short circuit current: (I_{sc}) and the apparent (maximum or theoretical) power. These parameters were measured every 30 minutes for 10 times or equivalent to total 300 minutes.

The experimental test results obtained from the experimental test-rig were collected, analyze and compared between the developed TLSC and the conventional crystalline based cells under the controlled solar radiation source mentioned above.

3. Result and Discussion

3.1 Components and Methods of the Proposed TLSC

Development of the proposed TLSC began with the assembly of polymethyl methacrylate as the cell base. The polymethyl methacrylate was constructed with a cubic shape with the width, length and height of 5 cm, 5 cm and 1.8 cm, respectively, as shown in Fig. 8. After polymethyl methacrylate was assembled into grid transparent solar cells, 36% concentration saline solution was injected into the cell's body through the drilled holes and then using a needle to convey the solute. When full, the holes were closed as shown in Fig. 9.

Fig. 8 Grid of transparent solar cells after polymethyl methacrylate assembly

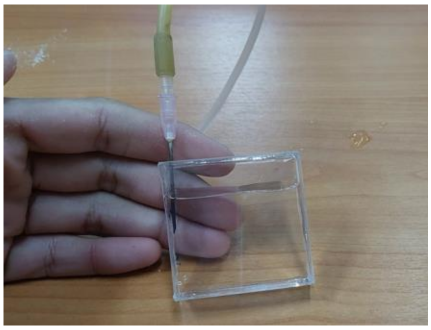


Fig. 9 Injecting 36% concentration saline into the cell's body

The cells were then installed with the four edges of the grids; where each cell was connected by tapping wires which were soldered with lead in serial format as shown in Fig.10. Finally, the grid of TLSC was obtained and tested as shown in Fig. 11.

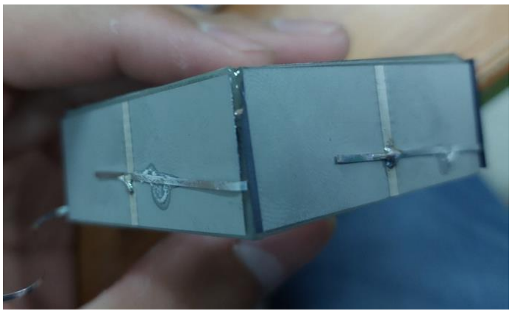


Fig. 10 Connecting electric cells in the grid with tapping wire and lead

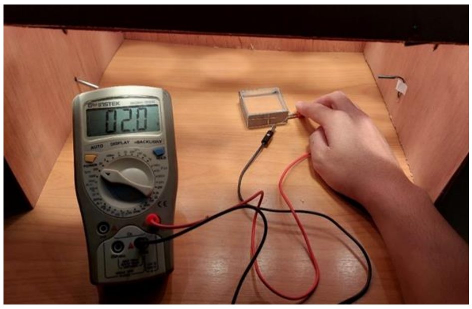


Fig. 11 Preliminary voltage test of the proposed TLSC

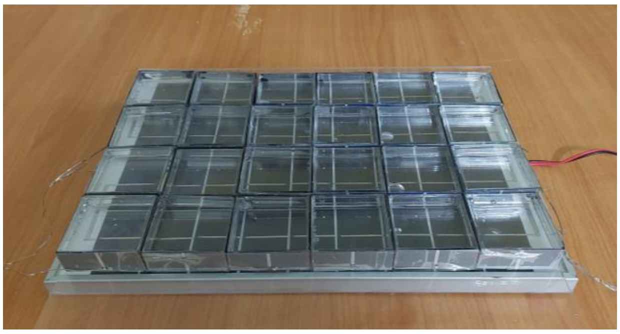
The completed set of 24 cell grids of TLSC were then built while the six grid cells were connected in series circuit of four strings; where each row was connected in parallel. The final size of the proposed TLSC was 30 cm x 20 cm, as shown in Fig 12.

Fig. 12 the proposed transparent solar cells

3.2 Combination of Solid Crystalline Solar Cells and the Proposed TLSC

The integration of the two types of the solar cells was done by placing the proposed TLSC above the solid crystalline solar cells as shown in Fig. 13.

(a)



(b)

Fig. 13 the interaction of the proposed TLSC and the solid crystalline solar cells: (a) Surface view and (b) Top-right side view

3.3 Open Circuit Voltage (V_{oc}) Test Results

Open circuit voltage tests were conducted for both types of the cells. The measured data were collected every 30 minutes using an oscilloscope while the temperature was measured. The results are shown in Fig. 14.

It could be seen from Fig.14 that the open-circuit voltage when connecting grid cell in series provided highest voltage level; followed by the conventional solid crystalline solar cell with parallel connection and the proposed TLSC solely, respectively. The open circuit voltage had the maximum value at the room temperature or about 25 – 26 ^{o}C and decreased when the temperature rise.

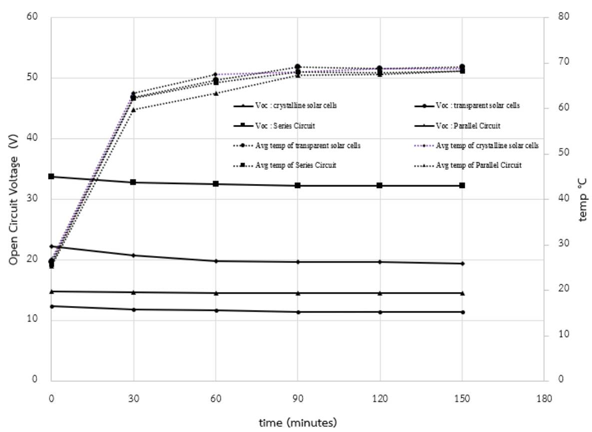


Fig. 14 the open circuit voltage test results

3.4 Short Circuit Current (I_{sc}) Test Results

Fig. 15 shows the test results obtained from short circuit output terminals of the cells. It can be seen that the current for the case of combined proposed TLSC and crystalline cells in parallel circuit connection provided the highest value at about 0.43-0.46 A; following by the case of crystalline cell alone, TLSC alone and combined proposed TLSC and crystalline cells in series circuit connection, respectively.

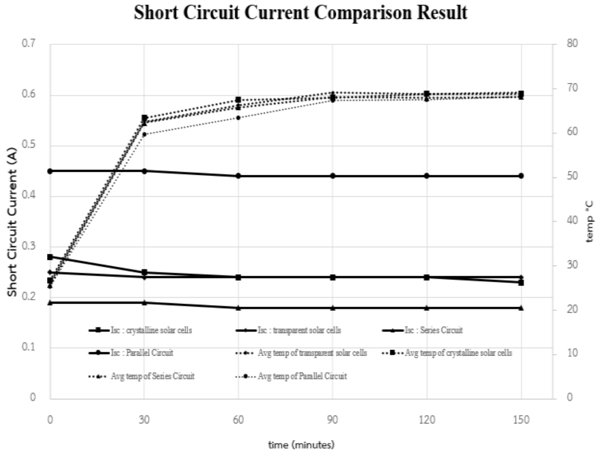


Fig. 15 the short circuit current test results

3.5 Apparent Power (*PT*) Test Results

Fig. 16 shows the comparison of the apparent power of the proposed TLSC and crystalline cell. It is found that the case of combined TLSC and crystalline cell in parallel circuit connection gave the highest value about 6.2 – 6.4 watts; following by the case of combined proposed TLSC and crystalline cells in series circuit connection, crystalline cell alone and TLSC alone, respectively.

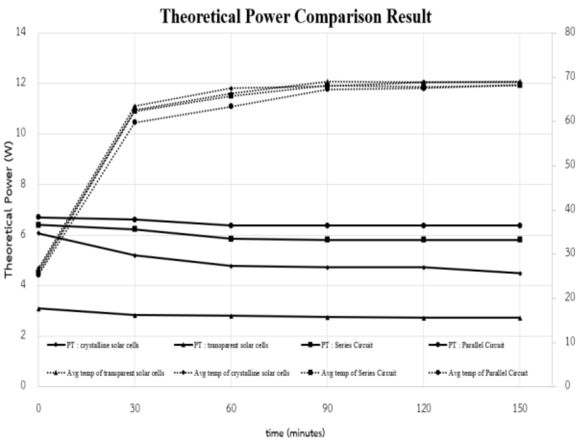


Fig. 16 Theoretical power of the test

4. Conclusions

This paper proposes a new type of Transparent Luminescent Solar Concentrator (TLSC) by using the mixture of rock salt with polymethyl methacrylate. The experimental test-rig has been conducted to test the fundamental, electrical characteristics of the proposed TLSC in compared to the conventional crystalline solar cells. An artificial solar source has been designed via the simulation program and constructed for the laboratory tests. The experimental test results showed that As a result, the heat incident on the surface of the proposed TLSC is always lower than that of the solid crystalline cells. The increase in solar intensity resulted in decreasing of open circuit voltage of both types. The short circuit current of the proposed TLSC was only about 8% while the solid crystalline cell was 15.79%. The combination of both cell types by placing the proposed TLSC cell on the top of the conventional solid crystalline cells in parallel provided the highest apparent power; following by the combined these cells in series connection, solid crystalline solar cells alone and the proposed TLSC alone, respectively.

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