Solar Concentrator for Electro-Conversion of CO_2 to Solid Carbon

Nancy Julius Siambun#, Ooi Shen Ching, Melvin Gan Jet Hong, Chua Bih Lii
Mechanical Engineering Programme, Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, MALAYSIA.
#Corresponding author. E-Mail: nancyjs@ums.edu.my; Tel: +6088-320000.

ABSTRACT Capturing CO_2 gas and converting it to useful product offers an alternative in mitigating the CO_2 gas emission in atmosphere. The process is through electrolysis process in molten salt electrolyte to capture CO_2 gas and convert it to solid carbon. To avoid addition released of CO_2 gas through usage of electricity that mostly generated through fossil fuel burning, green energy from solar has been used for melting the electrolyte and running the electrolysis process. Thus, work has been focused in designing and developing a solar contractor for melting electrolyte and coupled with solar PV panel for driving the electrolysis process. One of the highlighted designs of solar concentrator is its ability to control the molten salt electrolyte temperature using Fresnel lens configuration. The heat energy generated from the solar concentrator melted the salt mixture of Li_2CO_3-$CaCO_3$-LiCl (salt melting temperature ~500 ^oC) and maintained at desired temperature of 550^oC. Electrolysis or electro-conversion process in 180g carbonate salt electrolyte with stainless steel electrodes, and using solar photovoltaic, PV, panel with 12V/17AH battery had successfully produced solid carbon.

KEYWORDS: Solar Concentrator, carbon capture, green energy, molten salt.
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INTRODUCTION

Carbon dioxide (CO_2) gas is responsible for half of the observed greenhouse effect that contributed to the increase of earth temperature thus causing global climate change (Giri & Pant, 2020). Released of CO_2 gas in atmosphere is inevitable due to the high demand for energy from fossil fuel burning. A newly developed technology of capturing and electro-conversion of CO_2 gas to solid carbon through electrolysis process in non-toxic carbonate-base molten salt electrolyte, have shown positive results on the quality of the deposited solid carbon, where it has the potential for various applications such as graphite, catalysis for fuel, *etc*. (Ijije *et al*., 2014; Gakim *et al*.; 2015; Wong *et al*., 2018)**.** However due to the high stability of the electrolyte as indicated by HSC software (Version 6.12, developed by Outotec Research Oy, 1974–2007), the energy use to (i) melt the electrolyte, and (ii) to carry out the electrolysis process to convert CO_2 gas to solid carbon require high energy consumption. Electrical energy that mostly generated through fossil fuel burning, leads to emission of CO_2 gas. This is contradicting to the initial intention to reduce CO_2 gas in atmosphere, thus there is a need to change to renewable energy sources such solar energy for driving the electro-conversion of CO_2 gas to solid carbon.

From this perspective, this paper was aimed to discuss the development of solar concentrator with the ability to melt a salt mixture (electrolytes), and to determine the efficiency of the electro-conversion process of carbon using the solar concentrator. The efficiency is also being compared to the process of carbon production using a reactor in the laboratory set-up.

DESIGN

The designing of solar concentrator that is suitable for carbon captured and electro-conversion was focused on three main parts i.e. (i) parabolic dish and reflecting material, (ii) receiver functioning as electrolysis reactor, and (iii) Fresnel lens configurations. The overall design of solar concentrator is shown in Figure 1 (a). The close-up of part (ii) and (iii) are shown in Figure 1 (b).

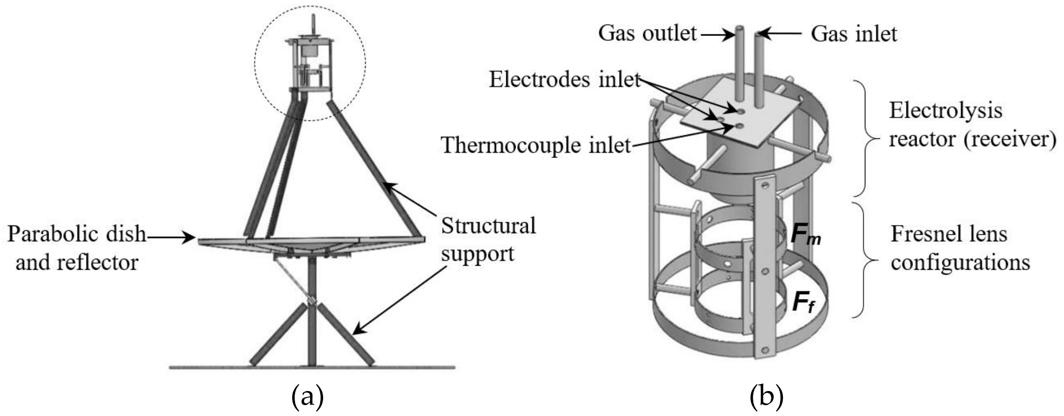

Figure 1. Solar Concentrator for CCEC. (F_m and F_f referring to Fresnel lens 1 and 2 respectively).

Parabolic Dish (Solar Reflector)

The chosen type of solar concentrator is a parabolic dish point-focus. The size and curve of the parabolic dish is specified in terms of a linear dimension such as the aperture diameter *(d)* or the focal length *(f)* and were determined using Equation (1), while the depth of parabola *(h)* was determine using Equation (2) (Mohamed *et al.*, 2012). The calculated sizes are shown in Figure 2 (a).

$$\frac{f}{d} = \frac{1}{\left[4\tan\left(\frac{\varphi rim}{2}\right)\right]} \tag{1}$$

$$h = \frac{d^2}{16f} \tag{2}$$

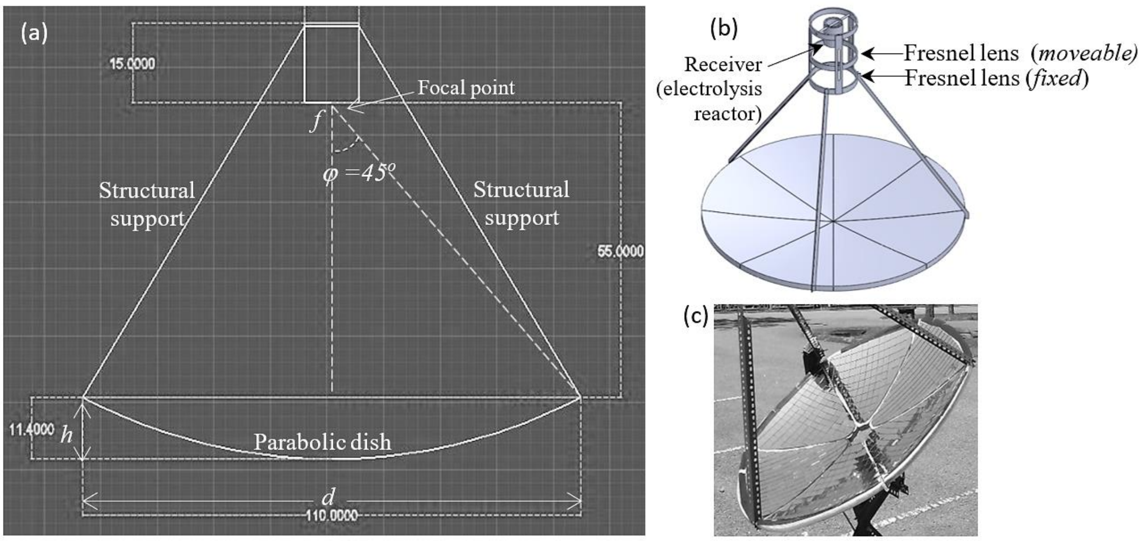

Figure 2. (a) Drawing and (b) schematic diagram of parabolic dish of solar concentrator, and (c) photo of the actual parabolic dish with reflector installed. (All values are in cm).

Silvered glass mirror was selected as the surface collector. Glass mirrors are generally considered to be the baseline reflector material for solar thermal electric applications. Glass mirrors have high specular reflectance (more than 91%), long lifetimes, durability in the field, and (usually) modest degradation of reflectivity over the concentrator lifetime (Jorgensen *et al.*, 1994).

Receiver and Electrolysis Reactor

The receiver is the bottom part of electrolysis reactor. The term is given base on its function to received radiation projected by the Fresnel lens. The building material used for receiver and reactor was stainless steel (thickness 1.5 mm). Stainless steel has high melting point that could sustained carbonate molten salt melting point at ~400^{o}C, and non-reactive to the salt. The shape for the reactor is cylindrical shape, with its bottom (receiver) is coated with a thin layer of black paint as antireflection coating and it was located in the focal zone of the solar dish. The outer surface is insulated with alumina wool to prevent heat loss to surrounding. The lid of the reactor has electrodes, thermocouple and gas inlets and gas outlet as shown in Figure 1 (b).

Fresnel Lenses

Fresnel lens has a flat surface on one side while facets on the other side. This lens is thinner than convex lens. The Fresnel lenses were arranged as in Figure 3. Light beams reflected from parabolic dish went through a fixed and then to a moveable Fresnel lens before focus to the receiver's surfaces. The intensity of heat on receiver was adjusted by moving the moveable Fresnel lens position, therefore controlling the heating temperature of molten salt.

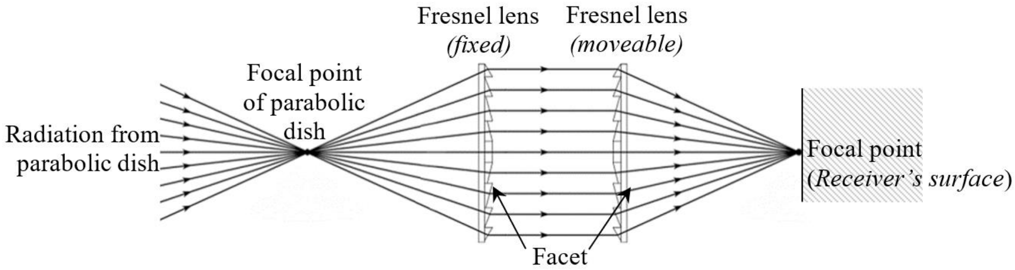

Figure 3. Fresnel lenses arrangement.

Electrolysis Process

The heat radiated from parabolic dish and went through the Fresnel lenses and receiver, heated the solid salt inside the electrolysis reactor that turn it to molten state. The thermocouple and electrodes were inserted into the inlets on the reactor lid once the salt was melted. The anode and cathode electrodes were connected to the positive and negative terminals of a battery that was pre-charged using PV solar panel. Electrolysis was initiated by draining charges (Q) from the 17AH battery. The battery has 12V output voltage.

RESULT AND DISCUSSION

Design of Solar Concentrator

The carbon capture and electro-conversion process carried out in laboratory was using electricity for melting the salt and driving the electrolysis process (Gakim *et al.*, 2015; Tang *et al.*, 2013; Wong *et al.*, 2018). The designed solar concentrator successfully projected heat to the receiver, heating the salt to above 520^{o}C without the need of electricity source. The calculated thermal energy above this temperature is Qu>173kJ. Electrolyte salt mixture of $CaCO_3$-Li_2CO_3-LiCl (mole ratio 0.09:0.28:0.63) has liquidus temperature ~510–520^{o}C (tested in laboratory), was melted and maintained at 550–560^{o}C throughout the electrolysis process by adjusting the distance between Fresnel lenses. Higher intensity of heat reached the receiver when the beams were at their focal point. Moving the non-fixed Fresnel lens reduced the heat intensity thus reducing the molten salt temperature. This is monitored manually.

The average thermal efficiency η_{th} for the designed solar concentrator was approximately 36%. The η_{th}, was calculated using Equations (3a) - (3c) (Vishal & Sardeshpande, 2011).

$$\eta_{th} = \frac{thermal\,energy\,(Q_u)}{Thermal\,energy\,from\,solar\,radiation\,(Q_S)} \tag{3a}$$

$$Q_u = mC\Delta T \tag{3b}$$

$$Q_s = I_{bn}\, A_{ap}\, t \qquad (3c)$$

where, mass m (kg) of sample in the receiver, specific heat C ($kJ/kg.K$) of sample, temperature difference ΔT (K), normal beam radiation I_{bn}, (kW/m^2), aperture area of concentrator A_{ap} (m^2), and duration t (s) of test.

The lower thermal efficiency of the solar concentrator may due to the total heat loss rate of the receiver (Q_l) that contributed by (i) conductive heat loss from receiver (ii) convective heat loss through the receiver aperture, and (iii) radiative heat loss through the receiver aperture (Vishal & Sardeshpande, 2011). The conductive loss however is usually insignificant compared to convention and radiation losses (Seo *et at.*, 2003), thus in this work the outer walls of the receiver was assumed to be adiabatic and the conductive heat loss from receiver is zero.

Electrolysis Process

The electro-conversion of CO_2 gas to solid carbon was made possible through electrochemical process which was explained in detail by authors elsewhere (Gakim *et al.*, 2015; Wong *et al.*, 2018). However, the important reactions that directly involved in carbon captured or absorption of CO_2 gas (Equation (4)), and electro-conversion (Equation (5) and then (6) - (7)) to solid carbon are stated here.

$$O^{2-} + CO_2\,(g) \rightleftharpoons CO_3^{2-} \qquad (4)$$

Absorption of CO_2 gas (carbon captured)

$$CO_3^{2-} + 4e^- \rightarrow C\,(s) + 3O^{2-} \qquad (5)$$

Carbon conversion in single step

$$CO_3^{2-} + 2e^- \rightarrow CO_2^{2-} + O^{2-} \quad \text{then} \quad CO_2^{2-} + 2e^- \rightarrow C\,(s) + 2O^{2-} \qquad (6)\ \&\ (7)$$

Two steps carbon conversion

In the research reported by authors (Gakim *et al.*, 2015; Wong *et al.*, 2018) using similar salt mixture at 550–560°C temperature with 4V for 1 hours, 0.07g of carbon (89% carbon purity under EDX analysis) was obtained. It was reported that the charge passed through during electrolysis process was proportional to the amount of carbon deposited. Higher charge value produced higher carbon amount.

The total charge in the 17AH battery is 61200C was drained out in 15 – 17 minutes with a maximum of 12V battery output, producing 0.44g of carbon. The solid carbon was deposited on the electrode as shown in Figure 4. The current efficiency (Equation (8)) measured the efficiency of the electro-conversion process, where the ratio between theoretical charge to produce 0.44g carbon and total charge available (6100C) was calculated. Data in Table 1 shows the current efficiency for electro-conversion for the solar concentrator is >100%. The reason for efficiency exceeding 100% is suspected due to the occurrence of catalytic reaction (Wong *et al.*, 2018). The energy consumption to produce 1kg of carbon is 36% less than the process carried out in the laboratory under constant voltage of 4V. The energy consumption was calculated using Equation (9).

Figure 4. Solid carbon deposited on cathode (9 mm cathode diameter).

$$Current\ efficiency\ (\%) = \frac{Theoritical\ required\ charge\ of\ the\ measured\ carbon\ yield}{Charge\ calculated} \quad (8)$$

$$Energy\ consumption\ (kWh/kg) = \frac{Voltage\ (V) X\ Charge\ passed X (1/3600)}{Carbon\ yield\ (kg) X Current\ efficiency\ (\%)} \quad (9)$$

Table 1. Electrolysis data for electrolysis using $CaCO_3$-LiCl-Li_2CO_3 in laboratory and using solar concentrator carbon capture and electro-conversion.

Molten Salt Mixture	Laboratory set-up	Solar concentrator carbon captured and electro-conversion
Voltage applied	Constant 4*V*	Maximum 12*V*
Period (min)	60	15 – 17
Total charge (*C*)	2796	6100
Measured Carbon weight (g)	0.07	0.44
Current efficiency (%)	80.5	>100
Energy Consumption (*kWh/kg*)	55.2	20.1

CONCLUSION

In this work, the process of melting electrolyte salt and driving electrolysis process for the electro-conversion of CO_2 gas to solid carbon were successfully achieved using only solar energy. Parabolic dish solar concentrator with Fresnel lenses configurations having the average thermal efficiency of 39%, was able to melt and maintain the electrolyte salt at 550–560°C throughout the electrolysis process. Try run of electrolysis process using 12*V*/17*AH* battery successfully convert the absorb CO_2 gas to 0.44g of solid carbon in 15 - 17 minutes. It is evident that not only the process of carbon capture and electro-conversion using the solar concentrator eliminate the use of electricity, the conversion process is also rapid and used lower energy.

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