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# Performance Evaluation of Absorber Reactors for Solar Fuel Production

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Waste to energy conversion through thermochemical processing offers a potential option for valorisation of waste biomass, however, it requires external heat supply to process the waste. Solar energy is a promising solution to convert the waste and produce alternative fuels that can replace coal, oil and natural gas for heat and electricity generation. To realize this, the radiation from the sun should be converted to thermal energy. Among the solar concentrators, parabolic dish gives the highest concentration ratio per area in converting the solar energy to heat and electricity. The absorber is the main part of the dish which is placed at the focal point and converts the radiation to thermal energy. In this work, experiments were conducted on stainless steel, copper, ceramic and glass reactors as absorber materials of parabolic dish with aperture diameter 1.8 m coated with aluminium pet as reflective material. The objective of this research was to evaluate solar radiation-absorbing performance of the reactors and design efficient reactor for solar fuel production. Two sets of experiments were conducted. First, each of the reactors was placed at the focal point then the heating rate and maximum temperatures inside the reactors were recorded as a function of radiation intensity using K-type thermocouples. Secondly, each reactor was coated using carbon soot and then the experiment was repeated. Results showed that the coated glass reactor has the best performance in all the absorbers. Of the uncoated reactors, the stainless steel gave best results with stable and uniform temperature distribution inside the reactor. The results can be used as benchmarks for future design and application of the solar thermal technology.

## 1. Introduction

Fossil fuels as sources of energy have immense social and environmental impacts. The extraction processes generate water and air pollution, and harm local communities. Transporting fuels from the mine site causes air pollution and lead to severe accidents and leaks. Combustion of fossil fuels contributes to toxic and global warming emissions, such as sulphur dioxide, nitrous oxides (NOx), particles and greenhouse gas emissions. Moreover, fossil fuels have limited reserves and once used these resources will deplete. In fact, with the current production pattern of the crude oil, reserves will come to an end at around 2060s (Metzger and Hüttermann, 2009). With all these formidable challenges, innovative, environmentally acceptable and feasible alternative energy sources will need to be developed before the fossil fuels are consumed faster than demand.

It is known that biomass is one of the primary sources of renewable energy. Biomass is carbon-dioxide neutral as the amount of carbon dioxide emitted during combustion is equivalent to that consumed during photosynthesis (Han and Kim, 2008). In the last few decades there has been significant increase in the quantity of organic wastes, which is the main source of biomass, mainly due to increased human population and urbanization (Gouda et al., 2016). The annual capacity of biomass can reach 108 Gtoe (Kan et al., 2016). Thus provided this source is sustainably introduced to our energy mix it can contribute 10 to 14 % of the world's energy supply which can reduce global environmental impacts and provide commercially attractive opportunities to meet our energy needs and services (Werle, 2015). Waste to energy conversion through thermochemical processing offers a potential option for valorisation of waste biomass, however, it requires external heat supply to process the waste. Solar energy is a promising solution to extract important fuels and chemicals from organic wastes. In just a year, the earth receives about 885 TWh of energy from the sun. This is equivalent to 4,200

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times the energy that mankind would consume in 2035 following the International Energy Agency Current Policies Scenario (Solar, 2011). However, the solar energy is diffused and bounded by time and place so it has to be concentrated and stored in the form of chemicals.
This research deals with design, manufacturing and experimental testing of solar concentrator with the aim of producing solar fuels from organic wastes through thermochemical conversion processes. Different sets of tests were conducted to evaluate best performing type of material reactor among stainless steel, copper, glass, aluminium and alumina ceramics.

## 2. Design and construction of the solar concentrator

### 2.1 Dish design and environmental factors

The design of paraboloid concentrator requires the quantity of heat and the maximum solar irradiation level of the experiment. Assuming Macquarie University (33.7738° S, 151.1126° E) as the experimental site, the solar irradiance level can be taken as $I_b$ = 1,000 W/m$^2$, though the peak value is 1,260 W/m$^2$. Average ambient temperature and wind speed are 23 $^o$C and 8 to 14 kph m/s(Geoscience, 2010).
The heat of reaction was determined to be 80 – 280 J/g for cellulose and increase with conversion ratios up to 2,500 – 4,000 J/g for the forestry and agricultural residues (Chen et al., 2014). These results were used in the design as fundamental data for solving heat energy requirements to pyrolyse 3 g of biomass in a unit time.
The effective energy intercepted by the paraboloid reflector and transmitted to the reactor can be expressed by Eq(1) (Pavlovic et al., 2015).

$$Q = I_b A_c \rho \gamma \alpha \quad (1)$$

Where $Q$ is input heat to the receiver in kW; $I_b$ is irradiance in kW/m$^2$; $A_c$ is collector (aperture) area in m$^2$, $\rho$ is reflectance; $\gamma$ intercepting factor; $\alpha$ is absorptivity (Abid et al., 2016).

### 2.2 Material Property

Dish surface was coated with aluminium polyethylene terephthalate (Al pet) with reflectivity of 0.88 (manufacturers' data), and the absorptivity $\alpha$ of the reactor is assumed as 0.95.

### 2.3 Parameter design

The intercepting factor $\gamma$ generally depends on the accuracy and precision of the manufacturing processes of the dish and is taken in the range of 0.9 - 0.98.
Substituting 1,000 W/m$^2$ for $I_b$ and values of all the respective constants in Eq(1), the total area of the parabolic dish that can generate the heat of reaction is estimated to be 2.65 m$^2$. A dish with an aperture diameter of 1.8 m and focal length to dimeter ratio (f/d) 0.3788 gives the required area. Focal length located slightly above the centre of gravity reduces the heat losses that may be caused by wind forces (Hijazi et al., 2016). Consequently *f/d* ratio of around 0.3 is selected for the dish used in this study.
The surface of the solar dish is generated by entering x and y coordinates for selected points. Software Parabola Calculator 2.0, shown in Figure 1 was used to determine the necessary locus points that define the parabola. A circular paraboloid, like the one shown in Figure 1, is obtained by rotating the parabola segment around its axis. The rim angle, defined by Eq(2) also defines the shape of the paraboloid.

$$\frac{f}{D} = \frac{1}{4\tan(\psi_{rim}/2)} \quad (2)$$

Since the *f/d* ratio is 0.3788, the rim angle $\psi_{rim}$ becomes 113$^0$.
Usually paraboloids with large rim angles are most appropriate for external volumetric receivers (Pavlovic et al., 2015). Since this design accommodates cylindrical reactor at its focus, the rim angle obtained, in this case, is assumed appropriate.
With the above assumptions the total heat generated from the solar dish is estimated at:

$Q = I_b A_c \rho \gamma \alpha$ = 1,000 W/m$^2$ x 2.65 m$^2$ x 0.95 x 0.95 x 0.95 = 2,272 W = 2.27 kW

The geometric concentration ratio is defined as the ratio of the area of the optical system (aperture area) to the energy absorbing area of the receiver Eq(3), in this case the reactor.

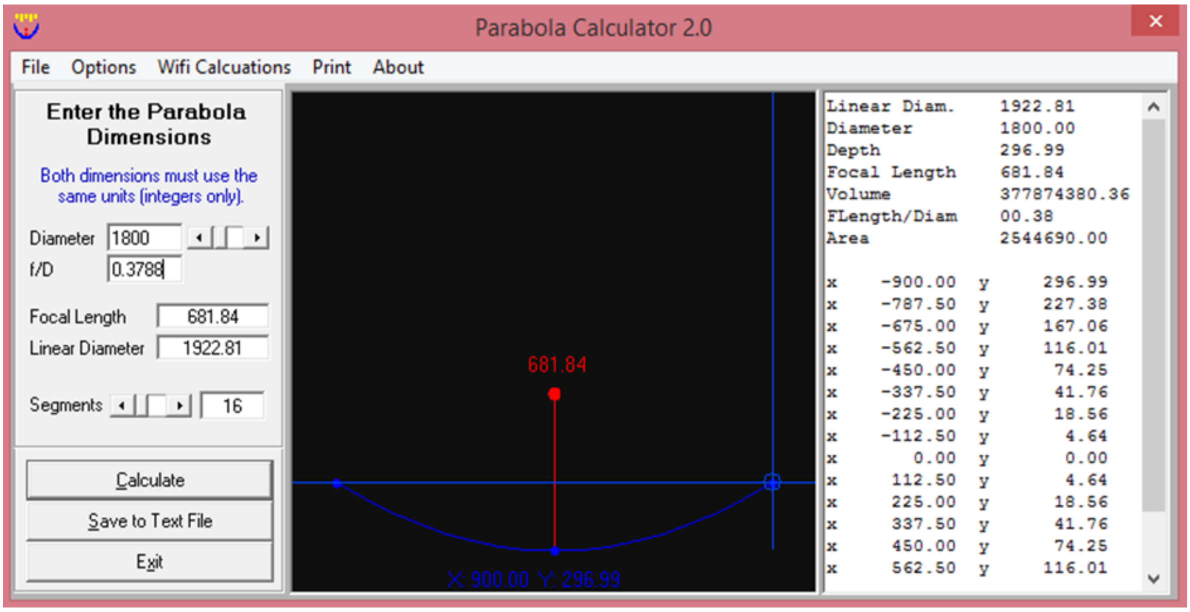


*Figure 1: Parametric design and locus of points of the solar dish*

Thus, the concentration ratio *C* of this design is:

$$C = \frac{A_C}{A_r} = 346.15 \qquad (3)$$

In this work a solar dish with 1.8 m aperture diameter covered with aluminium pet was designed taking into consideration the design parameters from Table 1. The aluminium pet was found to be appropriate option as a reflective coating due to its cost, weight, efficiency, it is easy to clean and is resistant to severe weather conditions. Manual tracking system was used for rotation of the disc to ensure the dish always faces the sun for maximum radiation.

Reactor-absorber was placed at the focal region where reflected radiation is concentrated. The key point to achieve better performance with the reactor-absorber is to determine the flux distribution at the focal region. To reduce heat losses and cost of the whole system, the absorbing material was made as small as possible (Pavlovic et al., 2015); but it should also be large enough to capture as much of the reflected rays as possible (Asmelash et al., 2014).

*Table 1: Design parameters of solar parabolic dish*

| Parameters | Numerical value | Unit |
|---|---|---|
| Aperture diameter | 1.8 | [m] |
| diameter of smaller (bottom) hole | 20 | [cm] |
| Gross collector area | 2.65 | [$m^2$] |
| Gross collector volume | ~0.65 | [$m^3$] |
| Cross sectional area of the opening parabola | 2.5446 | [$m^2$] |
| Reactor shape | Directly irradiated | - |
| Reactor diameters | 7-14 | [mm] |
| Reactor height | 20 | [cm] |
| Reactor volume | 26.546 | [$cm^3$] |
| Base ring area | $3.623*10^2$ | [$cm^2$] |
| Effective area of the concentrator | 2.61 | [$m^2$] |
| Reflective material | Al pet | |
| Concentration ratio | 346.15 | - |
| Depth of concentrator | 296.99 | [mm] |
| Focal length | 682 | [mm] |
| f/d ratio | 0.3788 | - |
| Rim angle $\psi$ of paraboloid | 113 | [$^0$] |

In this work SolTrace was used to determine the heat flux distribution around the focal region of the dish through which the optimum size and exact location of the reactor around the focal region were determined.
A theoretical calculation of stagnation temperature based on maximum heat flux value is given by Eq(4) (Ekman et al., 2015). Stagnation temperature is the highest temperature a receiver would achieve when the energy being absorbed is as fast as it is re-radiated.

$$Q = \sigma T^4 \qquad (4)$$

Where $Q$ is the radiated flux per square meter equal to 69,087 W/m$^2$ (found from SolTrace simulations) and $\boldsymbol{\sigma}$ is the Stefan-Boltzmann constant. The thermal flux in this case would result in a corresponding stagnation temperature of 1,079 $^o$C.

## 3. Experiment with the reactor- absrober materials

The experiment was conducted using glass, copper, stainless steel, aluminium and ceramic reactors. The diameter of the reactors ranges from 7 mm to 14 mm but their heights were 35 cm. Table 2 shows the dimensions and thermal conductivity of each reactor.

### 3.1 Uncoated reactor-absorber temperature performance

Temperatures in the unloaded (empty) reactors and global net radiations were recorded using K-type thermocouple and pyrometer with Campbell Scientific data logger respectively. The experiments were also repeated using the same reactors coated using carbon soot to create blackbody receiver. All procedures were run in more than three times to obtain the reported results and at all times the tests were run until the stagnation temperatures were reached.
Table 3 shows temperature performance of the uncoated reactors and radiation intensity. While running the experiment, the radiation was increasing continuously from 280 to 860 W/m$^2$. In all the experiments the temperature of the reactors increased with the radiation until the stagnation temperatures were achieved. At all net radiation levels greater than 300 W/m$^2$, temperatures of the reactors increased to their maximum values and then remained constant at these values indicating the thermal energy being absorbed by the reactors is as fast as the energy being dissipated.
Maximum temperature of 900 $^o$C was recorded with the stainless steel reactor at 744 W/m$^2$ with an average heating rate of 500 $^o$C/min. The effect of radiation on the reactor temperature can be linearly expressed as in Eq(5).

$$T = 25.274I – 17,743; [R^2 = 0.9308] \qquad (5)$$

where T stands for the temperature in $^o$C and $I$ is radiation in W/m$^2$.
The second best performing reactor in terms of attaining maximum stagnation temperature was glass reactor. Maximum stagnation temperature of 845 $^o$C was recorded for a corresponding radiation of 860 W/m$^2$. The response in temperature as a result of the changes in radiation was almost similar with the other reactors. Heating rate of the glass at 169 $^o$C/min, was lower than stainless steel and copper at the beginning but surpassed the copper reactor after few seconds.
The maximum stagnation temperature in the copper reactor was 749 $^o$C, achieved after 6 minutes of the start of the experiment. Corresponding radiation level was 530 W/m$^2$ and the heating rate was 125 $^o$C/min. As with the other reactors the temperature was affected by the radiation which can be expressed using Eq(6).

$$T = -0.0086I^2 + 9.3821I – 1,820.5; [R^2 = 0.906] \qquad (6)$$

Copper had lower heating rate, response time and took longer time to reach its maximum stable temperature than the stainless steel.
The stagnation temperature for the alumina ceramic reactor was 520 $^o$C which started after 6 min of the set-up, when the radiation reached 775 W/m$^2$. Unlike all other reactors the rise in temperature was not sharp at the beginning. Heating rate of 87 $^o$C/min was recorded with the ceramic reactor.

*Table 2: Dimensions and thermal property of the reactors*

| Reactor material | Diameter [mm] | Thermal conductivity [W/m.K] at 298K | Wall thickens [mm] |
|---|---|---|---|
| glass | 12 | ~1 | 0.8 |
| copper | 13 | 401 | 0.8 |
| stainless steel | 10 | 16 | 0.6 |
| aluminium | 10 | 205 | 1 |
| alumina ceramic | 7 | 16 | 1 |

*Table 3: Temperature performance of the uncoated reactors*

| Reactor material | Stagnation temperature [ºC] | Radiation [W/m²] at maximum temperature | Heating rate [ºC/min] |
|---|---|---|---|
| glass | 845±25 | 860±6 | 169±5.6 |
| copper | 749±15 | 530±4 | 125±-5 |
| stainless steel | 900±8 | 744±3 | 500±3 |
| aluminium | 340±10 | 722±4 | 57±6.3 |
| alumina ceramic | 520±10 | 775±5 | 87±3 |

The temperature is linearly related to the radiation, as in Eq(7). The low performance with the ceramic reactor was due to the white colour of the alumina ceramics and its low thermal conductivity relative to the other materials.

$$T = 12.639I - 9268; [R^2 = 0.8278] \quad (7)$$

The stagnation temperature and heating rate with the aluminium reactor were 340 ºC and 57 ºC/min respectively with the corresponding heat flux of 722 W/m². The aluminium reactor was the least performing reactor, mainly because it is a reflective material.  The temperature is directly related to the radiation as in Eq(8)

$$T = 1.8236I - 977.03; [R^2 = 0.8146] \quad (8)$$

It is known that production of solar fuels from pyrolysis of biomass, termed biofuels, requires a temperature as high as 400 to 800 ºC (Jahirul et al., 2012). Thus, the stainless steel reactor at the focal region of the solar dish can generate enough temperature for the thermal treatment of the biomass in the conversion process.
Copper reactor can also generate temperatures that can reach as high as 500 to 700 ºC which can be used for pyrolysis of biomass. The ceramic reactor can also be used for pyrolysis at lower temperatures, up to 500 ºC, torrefaction and pre-treatment of the biomass which requires relatively low temperature in the range of 200 to 300 ºC (Kuzmina et al, 2016). Similarly aluminium reactor can be used for torrefaction and pre-treatment of biomass at temperatures lower than 340 ºC.

**3.2 Coated reactor-absorber performances**

Table 4 shows the temperature performance, heating rate and radiations at which the maximum temperature has occurred for the reactors coated with carbon soot and using the designed solar parabolic dish. As in the previous tests, the temperatures generally increased with the radiation until the stagnation values were reached. The heating rates of all reactors changed considerably comparing to the uncoated reactors. The achieved heating rate using stainless steel tube reduced from 500 to 187 ºC/min; glass from 169 to 80 ºC/min; copper from 125 to 83 ºC/min; but the ceramic and aluminium tube increased the heating rate from 87 to 315 ºC/min and 57 to 132 ºC/min. The concentrated heat oxidized the carbon soot before it reached the walls of the reactors, thus taking longer time than the uncoated reactors. With the aluminium and ceramic reactors the temperature and heating rate showed significant increase with the carbon soot because the reflective property of both reactors was minimized.
Except for the glass reactor, the stagnation temperature did not show significant change with the copper and stainless steel reactors. This was because the carbon combusted few seconds after the reactors were placed at the focal point; hence the coating effect on the stainless and copper was minimal. However, with the glass reactor, the carbon soot combustion increased the temperature reaching and maintaining maximum stagnant temperature of 1,040 ºC. This experiment has also proved that the carbon coated stainless steel, glass, copper, aluminium and ceramic reactors, if integrated with the solar dish can increase the maximum temperatures to drive the pyrolysis, torrefaction and pre-treatment of the biomass in the course of extracting the bio-fuels, such as bio-oil, char and gases.

*Table 4: Temperature performance of carbon soot coated reactor-absorbers*

| Type of reactor | Stagnation temperature [ºC] | Radiation [W/m²] at maximum temperature | Heating rate [ºC/min] |
|---|---|---|---|
| glass | 1,040±28 | 964±5 | 80±6 |
| copper | 748±15 | 885±4 | 83±4.5 |
| stainless steel | 936±12 | 1,003±4 | 187±5 |
| aluminium | >660±8 | 936±5 | 132±5 |
| alumina ceramic | 630±8 | 950±4 | 315±5 |

## 4. Conclusion

In this work solar parabolic dish with 1.8 m aperture diameter was designed and manufactured with the aim of producing solar fuels from organic wastes through thermochemical conversion processes. The dish was covered with 88% reflective aluminium pet and integrated manual tracking system to ensure maximum concentrations. Two sets of experiments, 1) carbon soot coated and 2) uncoated, glass, copper, stainless-steel, aluminium and ceramic reactors were conducted to evaluate best performing reactor-absorber material to design solar assisted biomass pyrolyser to extract biofuel chemicals. Maximum temperature of 1,040 $^oC$ was recorded with the coated glass reactor at a radiation of 964 $W/m^2$. Whereas of all the uncoated reactors, 900 $^oC$ was the maximum temperature recorded with the stainless steel at a radiation of 744 $W/m^2$. In most of the experiments the temperature was directly related with the radiations. Considering biofuel extraction from biomass through pyrolysis processing requires temperatures in the range of 400 to 800 $^oC$, all the coated reactors can generate sufficient temperatures to carry out the pyrolysis with the solar dish, while of all the uncoated reactors glass, copper, steel and aluminium can achieve the pyrolysis temperatures. The aluminium reactor can only be used for torrefaction and pre-treatment processes.

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