Scalability of a Satellite Dish Solar Reflector for Use in the Synthesis of Biodiesel

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Abstract: Recently, solar reflectors developed from and demonstrated using repurposed satellite dishes have been incorporated as the sole thermal heat source for lab-scale synthetic chemical reactions. These solar reflectors use directed solar irradiation to conduct synthetic reactions, rather than the traditional route of collecting solar irradiation and then using an intermediate heat exchanger to transfer the thermal heat needed. The prior work has demonstrated that direct solar heat transfer can successfully be incorporated as the thermal heat source for various chemical reactions on the milliliter to liter scale. The present work answers the obvious question, can direct solar heating be scaled to practical capacities, i.e. 100s to 100s of thousands of liters. To answer this question, a mathematical model was developed to assess the scalability of the direct solar heating method. A case study was performed for the production of methylesters from soybean oil (biodiesel). A design-basis was developed to provide a common point of reference for comparing systems of different production capacities using a fixed reactor-reflector geometry to illustrate the effect of scale. The results suggest that batch processes are easily scaled to $10^5$ L and continuous process to $10^4$ L. Reactor and reflector sizes are predicted along with solar heated surface temperatures.
Introduction

Recently, Agee, et al.\textsuperscript{1-4} and others\textsuperscript{5-6} have suggested using direct solar heating to conduct synthetic organic reactions, demonstrating their concept on small batches on the order of liters in size. Figure 1 is a picture of a typical Agee, et al. set-up. An unused satellite dish was repurposed into a reflective parabolic mirror that serves as the sole heat source to drive synthetic chemical reactions. Various satellite dishes were completely covered with Metalized Mylar\textsuperscript{®} tape to attain the reflective properties needed to collect and focus the solar radiation. Since the feed horn of the dish is located at the focal point, they removed it and placed reaction flasks in this position to maximize the solar flux.

![Figure 1: Repurposed satellite dish heat source, shown here with a reaction vessel, condenser and wind-break positioned at the focal point of the dish, after Agee et al.](image)

To absorb the incident solar energy efficiently, the reaction flask bottoms were painted black using VHT\textsuperscript{®} Flame Proof paint, which can withstand intermittent temperatures of up to
1093°C (Figure 2). Furthermore, it was determined that if the flasks were not painted, the directed sunlight would mostly pass directly though the reaction vessel and contents, resulting in a very low heating efficiency.

![Painted reaction flask for solar heating](image.png)

**Figure 2**: Painted reaction flask for solar heating, shown here inside wind-break.

To demonstrate scalability of the direct solar heating process for synthesis of organic compounds, a case study was performed for the production of methylesters from soybean oil (biodiesel). Prior inventors and researchers have suggested the solar powered or solar assisted production of biodiesel.⁵⁻⁶ In all cases, however, the solar energy was collected in a primary device, such as a water heater, and then transferred to the biodiesel reactor using a secondary heat exchanger.

Agee et al.³, however, was able to synthesize biodiesel through direct solar irradiation. To perform the reactions in their study, they used two different size solar reflectors, a small reflector to heat up to a one liter flask and a large reflector to heat up to a six liter flask. On the milliliter scale they used a solar reflector made from an 81 cm × 55 cm satellite dish (Figure 1). On a liter scale they used a larger dish with a diameter of 89 cm × 99 cm.
This work has demonstrated that direct solar heat sources can be used successfully in the place of, for example electric heating, to synthesize biodiesel via transesterification reactions on the milliliter and liter scale. The obvious question is, can direct solar heating be scaled to practical capacities, e.g. between about 100 and 40,000 gal/d? A capacity of 100 gal/d might accommodate a small individual user, while 40,000 gal/d is nominally 1/100 of the present US biodiesel capacity and so represents an industrial-scale producer. The goal of this study was to develop a mathematical model to assess the scalability of the direct solar heating method.

**Experimental**

A design-basis was developed to provide a common point of reference for comparing systems of different production capacities. The basis assumptions include the following:

1. A constant conversion of triglyceride to methylester.
2. A batch reactor cycle time of 10 hour.
3. The collector is assumed to always point directly toward the sun and the heat transfer calculations account for shading by the reactor.

While there are many geometries that can be used to collect and apply direct solar heating to a vessel, a simple fixed geometry is used here to illustrate the effect of scale, refer to Figure 4. Similar to the geometry used by Agee, et al., the case study geometry assumes that only the hemispherical bottom of the reactor will be irradiated. Furthermore, the solar collector-reactor relative geometries were designed to have the following geometric similarities:

1. Height of the reactor = Diameter of the reactor.
2. Top and bottom of the reactor vessel are hemi-spherical.
3. Top hemi-sphere is not included in the reactor volume.
4. Focus \( p \) is at \( y_{\text{max}} = \frac{D}{\sqrt{8}} \) when \( x_{\text{max}} = \frac{D}{2} \) so that \( p = \frac{D}{\sqrt{8}} \) given that \( y = \frac{x^2}{2p} \).

**Figure 3:** Design basis reactor geometry for geometrically similar reactor-collector systems used in the modeling study, solid arrows indicate the path of incident solar radiation.

This was done so that when the reactors’ bottom hemisphere equator is located at the focal point, all of the reflected radiation will intersect somewhere on the hemisphere and not above. This made it simple to track the reactor’s heated surface area which is a function of the \( \frac{D_{\text{collector}}}{D_{\text{tank}}} \).

**Description of Model**

A simple chemical schema for production of biodiesel and associated chemical kinetic rate laws Eqs. (1 and 2) was taken from Noureddini et al.\(^9\)

\[
TG + CH_3OH \quad \xrightarrow{k_2, k_1} \quad DG + R_1COOCH_3 \quad \text{(R1)}
\]

\[
DG + CH_3OH \quad \xrightarrow{k_4, k_3} \quad MG + R_2COOCH_3 \quad \text{(R2)}
\]

\[
MG + CH_3OH \quad \xrightarrow{k_6, k_5} \quad GL + R_3COOCH_3 \quad \text{(R2)}
\]
\[ r_1 = \frac{d[TG]}{dt} = -k_1[TG][MeOH] + k_2[DG][MeOH] \]  

\[ r_2 = \frac{d[DG]}{dt} = k_1[TG][MeOH] - k_2[DG][ME] - k_3[DG][MeOH] + k_4[MG][ME] \]  

\[ r_3 = \frac{d[MG]}{dt} = k_3[DG][MeOH] - k_4[MG][ME] - k_5[MG][MeOH] + k_6[GL][ME] \]  

\[ r_4 = \frac{d[E]}{dt} = k_1[TG][MeOH] - k_2[DG][ME] + k_3[DG][MeOH] - k_4[MG][ME] + k_5[MG][MeOH] - k_6[GL][ME] \]  

\[ r_5 = \frac{d(GL)}{dt} = k_5[MG][MeOH] - k_6[GL][ME] \]  

where, TG, DG, MG, ME, GL, MeOH and NaOH are triglyceride, diglyceride, monoglyceride, methylester, glycerol, methanol, and sodium hydroxide respectively. After validating that the Noureddini schema is self-consistent\(^{10}\), their kinetic model was applied to a likewise self-consistent model for simulating either a batch or continuous stirred tank reactor (CSTR) reactor. Seven balances, four associated reaction rate relationships, three kinetic rate laws, stream constraints and a heat balance were written and solved simultaneously to model the reactor. Table 1 summarizes the requisite physical property data used. Entrepreneur

<table>
<thead>
<tr>
<th>Component</th>
<th>Molecular Weight (g/mole)</th>
<th>Density (g/L)</th>
<th>Heat Capacity (J/g Δ°C)</th>
<th>Heat of Formation (J/mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triglyceride</td>
<td>885.45(^{13})</td>
<td>917(^{c})</td>
<td>2.5(^{14})</td>
<td>-2400(^{11})</td>
</tr>
<tr>
<td>Diglyceride</td>
<td>621(^{13})</td>
<td>850</td>
<td>2.5</td>
<td>-1800(^{11})</td>
</tr>
<tr>
<td>Monoglyceride</td>
<td>356.55(^{13})</td>
<td>850</td>
<td>2.5</td>
<td>-1200(^{11})</td>
</tr>
<tr>
<td>Methylester</td>
<td>296.49(^{13})</td>
<td>875</td>
<td>2.5</td>
<td>-622.58(^{12})</td>
</tr>
<tr>
<td>Glycerol</td>
<td>92.09(^{13})</td>
<td>1250(^{16})</td>
<td>2.5</td>
<td>-669(^{16})</td>
</tr>
<tr>
<td>Methanol</td>
<td>32.04(^{15})</td>
<td>791(^{15})</td>
<td>2.5</td>
<td>-238.4(^{15})</td>
</tr>
<tr>
<td>Sodium Hydroxide</td>
<td>39.99(^{15})</td>
<td>-</td>
<td>-</td>
<td>-426.7(^{17})</td>
</tr>
</tbody>
</table>
It is important to note that an internally consistent set of standard heats of formation was difficult to find. Indeed, heats of formation for the TG, DG, MG and ME vary considerably source to source. The TG, DG and MG dataset was taken from Zong, et al.\textsuperscript{11} who provides the heats of formation for TGs, DGs and MGs as a function of carbon chain length. The ME data was taken from Borghi, et al.\textsuperscript{12} and compared to that provided by Glisic, et al\textsuperscript{13}, who also reports values for the TG, DG and MG, however, all of which appear to be either in error (might have an incorrect sign since the values are all positive rather than negative as expected). Values for glycerol and methanol were easily found in material safety data sheets\textsuperscript{15-17} from Internet resources.

Furthermore, an internally consistent set of heat capacity data was difficult to attain. The heat capacity the TG taken from Santos, et al.\textsuperscript{14} who provides data that at a temperature corresponding to the boiling point of methanol, the specific heat capacity of TG would be 2.5 J/g·K. Also, the authors mention that the specific heat for most of the oils used do not vary substantially and their values could potentially be used for engineering design purposes. Since no further information on the specific heats could be attained for the DG, MG, or ME, the specific heats of these species were scientifically estimated based on the information presented in previous publications.\textsuperscript{11-14} Again, values for glycerol and methanol were easily found in material safety data sheets.\textsuperscript{15-17}

Density data was obtained from a variety of sources. The TG density was obtained through authors’ own measurements. DG, MG, and ME density data could not be located within the literature. However, the density of each of these species were deduced from the literature to be similar to that of the TG. Glycerol and methanol density values were also taken from material safety data sheets.\textsuperscript{15-17}
The TG, DG, MG, and ME molecular weight dataset was taken from Glisic, et al.\textsuperscript{13} who provides molecular weights for each derivative of oleic acid. Molecular weight data for glycerol, methanol, and sodium hydroxide were provided through material safety data sheets.\textsuperscript{15-17}

The following model equations define the reactor mass and energy balance and associated solar heat flux calculations:

Component Balances (seven)

\[
\frac{dx_i}{dt} = F x_i^F - P x_i^P + R_i
\]  

(2)

Phase Constraint (one)

\[
\sum_{i=1}^{N=7} x_i = 1
\]  

(3)

Reaction Rate Relationships (four required to fully define the relationship between the seven components)

\[
R_{ME} - 2 R_{GL} - R_{MG} + R_{TG} = 0
\]  

(4)

\[
3 R_{GL} + R_{DG} - R_{ME} + 2 R_{MG} = 0
\]  

(5)

\[
R_{ME} + R_{MeOH} = 0
\]  

(6)

\[
R_{NaOH} = 0
\]  

(7)

Kinetic Rate Laws (four required to fully define the relationship between the seven components)

\[
R_{TG} = \frac{-r_1}{c_T}
\]  

(8)

\[
R_{DG} = \frac{r_1 - r_2}{c_T}
\]  

(9)
\[ R_{MeOH} = \frac{-r_1 - r_2 - r_3}{C_T} \]  

(10)

Heat Balance (one)

\[ \bar{\rho} V \bar{C}_p \frac{dT}{dt} = Q_h + Q_s + Q_{Rxn} + Q_l \]  

(11)

where the \( x_i^f \) is the mole fraction of species \( i \), \( i = \text{TG, DG, …, NaOH} \), and stream \( j = F \) or \( P \). \( F \) and \( P \) are the feed rate and product rates respectively, \( R_i \) are the reaction rates in inverse s, \( r_j \) are the individual rates laws defined by Equations (1 and 2), \( \bar{\rho} \) is the average density of the fluid in the reactor, \( \bar{C}_p \) is the average heat capacity of the fluid in the reactor, \( V \) is the volume of the fluid in the reactor, \( Q_h \) is the heat transferred to the reacting fluid by solar heating, \( Q_s \) is the sensible heat change, \( Q_{Rxn} \) is the reaction heat change, \( Q_l \) is the heat loss and \( C_T \) is the total concentration of the reacting fluid and where:

\[ Q_h = I_b \eta_c \eta_t \frac{\pi}{4} (D_c^2 - D_t^2) \]  

(12)

\[ Q_s = P \bar{C}_p (T_{in} - T) \]  

(13)

\[ Q_{Rxn} = \sum_{i=1}^{N=7} H_i^{f_o} R_i \]  

(14)

\[ Q_l = h_c A (T - T_s) \]  

(15)

where \( I_b \) is the incident insolation, \( \eta_c \) is collector reflectivity, \( \eta_t \) is heat transfer surface absorptivity, \( D_c \) is the diameter of the solar collector, \( D_t \) is the diameter of the reactor tank, \( T_{in} \) is the sensible heat flow in, \( T \) process temperature, \( \bar{C}_p \) is the average specific heat of the reactor charge, \( P \) is the product flow rate (for continuous case only), \( H_i^{f_o} \) are the heats of formation, \( R_i \) are the reaction rates and \( h_c \) is the external convective heat transfer coefficient given by:
\[ \overline{N}u_D = \frac{h_x D}{k} = 2 + \frac{0.589Ra_D^{1/4}}{1 + \left[\frac{10.469}{Pr^{1/6}}\right]^{4/9}} \]  

(17)

for a sphere in otherwise stagnation air. Here, \( Nu_D \) is the Nusselt number, \( Ra_D \) is the Rayleigh number \( \left( \frac{g \beta}{u \alpha} (T_s - T_\infty) D^3 \right) \), and \( Pr \) is the Prandlt number \( (C_p \mu/k) \).

The surface temperature of the reactor, \( T_h \), can thus be calculable from:

\[ h A_t (T_h - T) = Q_h \]  

(18)

where \( h \) is the combined heat transfer coefficient for the reactor, \( A_t \) is the heat transfer surface area (the irradiated area) and \( T_h \) is the temperature of the surface heated by solar radiation and where \( h \) is given by:

\[ xxx \]  

(19)

The model equations were solved numerically. For the batch case, \( F = P = 0 \). Other model inputs including the solar insolation \( I_b \), collector reflectivity \( \eta_c \) and heat transfer surface absorptivity \( \eta_t \), and convective heat transfer coefficient were taken to be 1 kW/m\(^2\), 0.65, 0.95 and 750 W/m\(^2\)-s respectively, all of which are nominal values for these parameters.\(^{18-19}\) For the continuous reactor a constant \( V/F \) (residence time) of 19.7 minutes (a value that produced good TG to ME conversion) was assumed, so that as the reactor volume was scaled, the feed flowrate \( F \) was scaled proportionally. Finally, the feed composition and the reactor initial batch composition was fixed at a 6:1, MeOH:TG ratio consistent with that used by Noureddini, et al.\(^9\)

The reactor model was benchmarked using the dataset in Noureddini, et al.\(^9\) wherein they show a batch achieving an overall TG to ME conversion of 85% in roughly 100 minutes. Similar results were achieved using the baseline model and inputs as defined above.
Results and Discussion

Model results are summarized in Figures 5 and 6 and Tables 2 and 3 for the batch and continuous processes respectively. As expected, as reactor volume increases, a relatively higher temp at the solar heated surface is needed to get heat energy into the process. This happens because the surface to volume ratio goes down as the reactor volume increases; while the heat load increases linearly with reactor volume the available surface for heat transfer increases slower with respect to the reactor volume.
As seen in Table 2, the size of the solar reflector seems feasible relative to the diameter of the reactor (D\textsubscript{T}). For a reactor with a volume capacity of 1000 L, the dish diameter only needs to
be 5.085 m. This seems easily obtainable. Likewise for, a reactor with a volume of 10,000 L, a 15.91 m collector is needed which also is easily feasible.

At a reactor volume of 100,000 L, we see that the diameter of the collector (D_c) grows to be 50.1 m. Although this is not impossible, the idea of scaling up to this size brings to the forefront the question of economic viability. While economics are outside the scope of this paper, the final decision to construct at this scale would be driven by economics since it appears that scaling a batch reactor to the 100,000 L scale is technologically plausible.

Likewise, for a continuous reactor, scaling appears viable up to at least the 10,000 L capacity range. Beyond 10,000 L the temperature difference between the process and the solar heated surface becomes large and a detailed heat transfer calculation would need to be done to ensure that boiling would not occur due to convective heat transfer limitations on the process side.

When comparing the batch process (Table 2) to the continuous process (Table 3) we seen that the scale for both processes using the solar reflector heat source are similar to one another. The only difference appears to be that the continuous flow reactor would require a dish slightly less in diameter upon scale up.

### Table 3. Scaling results for batch reactor.

<table>
<thead>
<tr>
<th>D_T (m)</th>
<th>V (L)</th>
<th>D_c (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>0.2</td>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>0.5</td>
<td>100</td>
<td>1.4</td>
</tr>
<tr>
<td>1.0</td>
<td>1000</td>
<td>4.4</td>
</tr>
<tr>
<td>2.1</td>
<td>10000</td>
<td>13.9</td>
</tr>
<tr>
<td>4.6</td>
<td>100000</td>
<td>43.6</td>
</tr>
</tbody>
</table>
Conclusion

It appears direct solar heating is a viable option at scales up to at least 10,000 L for continuous processes and up to 100,000 L for batch processed. By using the direct solar heat source, no greenhouse gases are produced as are for electric, hot water or steam heating and the energy transfer is more efficient than when indirect solar heating is used. Having already been
demonstrated on a small scale for the production of biodiesel and for a variety of organic compounds\textsuperscript{1-4}, the direct exposure technique needs to be physically tested to fully analyze this scientific endeavor.

References


[4] Amin, Shikha; Barnes, Ashley; Buckner, Courtney; Jones, Jordan; Monroe, Mattie; Nurmomade, Leon; Pinto, Taylor; Starkey, Samuel; Agee, Brian; Crouse, David; Swartling, Daniel. Diels-Alder Reaction Using a Solar Irradiation Heat Source Designed for Undergraduate Organic Chemistry Laboratories. J. Chem. Educ., 2015, DOI: 10.1021/ed500850c.


