Solar Assisted Essential Oil Distiller

Solar Trough Design - preliminary Analysis

1. Background information

1.1 Project description

The objective of the project is to develop a working prototype of an essential oil distiller that operates minimizing the use of non-renewable energy sources by using solar energy. This report describes a preliminary analysis of the distiller subsystem whose function is converting radiant energy to thermal energy in order to boil water to supply steam for the distillation process.

1.2 Concept selection

After detailed feasibility analysis developed in the previous project phase, a hybrid concept consisting in a solar convergent reflector and a gas burner was selected to provide power to the distillation process. The selection of the reflector geometry considered two different ideas: paraboloid reflectors (Sheffler reflectors) and uniform transversal section parabolic reflectors (solar trough). Both concepts need some sort of correction system because of the variation of sunrays incidence angle due to Earth’s rotational and translational movement.

1.3 Reflector Selection

Paraboloid reflectors geometry is defined by an intersection of a cylinder and a paraboloid surface as shown in the fig1a. This geometry has a characteristic of concentrating sunrays in a fixed point regardless of the reflector correction movement. Solar troughs geometry is defined by a quadratic surface with one independent axis whose transversal section is a parabola. Since we have a constant cross section along the independent axis, the idealized focal area is a straight line. A receiver tube is connected at the trough structure containing this focal line.
Due to a more complex geometry of the paraboloid reflector and consequently higher potential design risks and costs, the solar trough was the selected concept for reflector geometry.

Fig. 1: Geometry example (A) Paraboloid reflector, (B) Solar trough.
2. Positioning and positioning correction

Sunrays are reflected by the parabolic surface and converge at the focal line. Deviations of sunrays incidence perpendicularity in both transversal and longitudinal axes can be detrimental for trough efficiency or even completely undermine its functioning. Earth’s rotational and translational movement will change the relative position between Earth and Sun, and consequently the solar incidence angle will be constantly changed. Therefore, there should be a system to correct the trough position. A passive solar tracker will be used for Earth’s rotational movement correction, and we can safely assume that a periodic manual correction is sufficient for Earth’s translational movement correction.

2.1 Effect of the incidence perpendicularity variation

The complete loss of efficiency is easily observed in the situation where there is no correction for the Earth’s rotational movement. Fig 2 shows the effect on the receiver of the loss of perpendicularity. The green lines represent the sunrays before reaching the reflector, the red lines are the reflected sunrays, the blue curve is a cross section of the reflector and the circle is the cross section of the receiver. Note that the reflected sunrays cannot reach the receiver.

![Fig. 2: Effect on the receiver of the loss of perpendicularity of incidence (transversal plane)](image)

The effect of perpendicularity loss due to translation movement is not as detrimental as the effect observed in the situation described above. However, for small length troughs, the overall efficiency could be substantially affected. The flux through a surface changes in function of the variation of the angle between the incidence direction and the surface normal vector. A
perpendicular incidence will give the maximum flux through the surface. The fig 3 shows that for a determined angle, the flux through the area A is equivalent to a perpendicular flux through the area $A' < A$.

Moreover, a non-perpendicular incidence can make part of the trough useless (fig 4). This effect is especially detrimental for small length troughs.
Fig. 4: Effect on the receiver of the loss of perpendicularity of incidence (longitudinal plane)

2.2 Reference position and corrective rotation.

We must define a reference position and the freedom of rotation in both longitudinal and transversal axes of the trough and design a stand that allows such freedom of movement.

The freedom of rotation in the longitudinal axis (rotational correction) should obviously be something around 180 degrees. Constrains in the whole trough structure can potentially limit such freedom of rotation, so a marginal value of $150 \leq \Phi \leq 180$ degrees was defined for rotation freedom in this axis.

The definition of a reference position and the variation of the inclination for translational correction is entirely based on observation.

Consider the plane defined by the Earth’s orbit as shown in the fig 5. The rotational Earth axis is not perpendicular to the normal vector of the orbit plane. There is an angle of 23.5 degrees between the rotational axis and the orbit normal vector (fig 6). The effect of this deviation is a variation of the solar incidence angle in a fixed interval of 47 degrees throughout the year. The fig 7 and 8 are useful to show this effect. The arc described by this angle, containing the equator line at the center, defines the only one region on the Earth surface that can receive solar rays in a perpendicular plane.
We defined the reference position as 19 degrees (from the ground to the trough aperture area, with the trough longitudinal plane aligned to the N-S direction) that is the latitude value of the region where the trough will be used. The fig 9A and 9B show more easily the reference position.
Fig. 7: Effect of the Earth’s rotational axis inclination on the sunrays incidence angle (translational movement representation).

Fig. 8: Effect of the translational movement in the sunrays incidence angle

By observation, exemplified in the fig 8, 9A and 9B, we can define the variation of the reference position for Earth rotational movement correction. Considering a reference axis parallel to the ground surface and a positive rotation in the clockwise direction, the upper and lower values for the interval of rotation of the trough (in the transversal axis) for translational correction can be defined as follow:

$$\theta_{\text{min}} = \theta_{\text{ref}} - 23.5^\circ = -4.5^\circ$$

$$\theta_{\text{max}} = \theta_{\text{ref}} + 23.5^\circ = 42.5^\circ$$

$$\theta_{\text{ref}} = 19^\circ$$
3. Supplied power

3.1 Available insolation estimation

Considering the insolation graph of Key West shown in the figure 10, we can observe an average insolation of 806.86 W/m^2 in the 9 hours period from 7:16 to 16:16. This assumption may be considered conservative because the measurement uses stationary plates to collect the insolation, keeping the receiver plate perpendicular to the sunrays would increase the average insolation.

For the available insolation, it will be considered an average insolation of 806.86 W/m^2 over a nine hours period for preliminary power estimations.
3.2 Required power estimation

A reasonable ratio (mass of vetiver)/(mass of water) required for the distillation process is 0.0555 (see reference 7 in the reference folder). To process one pound of vetiver, the amount of water required will be:

Fig. 10: Available insolation considered for preliminary power estimations
The total energy required to boil 8.165 kg of water is:
Considering a process period of 18 hours (that would demand two periods of nine hours), the power required will be:

\[ P = \frac{Q}{18h} = 323.86 W \]

4. Defining a specific parabola shape

The shape of the selected parabola can substantially increase the load on the tracking system. The objective of the calculations is finding the parabolic shape that minimizes loads on the
tracker. We can state that if we can find a particular shape where the focal line is collinear to the rotational axis and the centroid line, except for frictional forces (ideal situation) any torque should be able to move the trough. In other words, it means that the only resistance to the movement would be the rotational inertia.

Consider a parabola equation given by

$$ y = ax^2 $$

and having a unitary aperture

The coordinates of the focal point are $f(0, 1/(4a))$, so we can define the focal length $f=f(1)/(4a)$.

The problem is basically find a function $\psi(a) = \bar{y}(a) - f(a)$ where $\bar{y}(a)$ is the $y$ coordinate of the centroid as a function of “$a$”, and then calculate the value of “$a$” that makes $\psi$ be zero.

The $y$ coordinate of the centroid is:
\[
\bar{y} = \int_{L} y \, dL
\]

\[L = \int_{L} dL\]

\[dL^2 = dx^2 + dy^2 \rightarrow dL = \sqrt{dx^2 + dy^2}\]

\[dL = \sqrt{1 + \left(\frac{dy}{dx}\right)^2} \, dx\]

\[\frac{dy}{dx} = 2ax\]

\[(\frac{dy}{dx})^2 = 4a^2 x^2\]

\[\bar{y} = \frac{\int_{L} y \, dL}{\int_{L} dL}\]

\[= \int_{\frac{1}{2}}^{\frac{1}{2}} a x^2 \sqrt{1 + 4a^2 x^2} \, dx\]

\[= \int_{\frac{1}{2}}^{\frac{1}{2}} a x^2 \sqrt{1 + 4a^2 x^2} \, dx\]
The expression result is:

\[
\psi(a) = \frac{\sqrt{a^2+1} (2a^3+3a) - \text{arcsinh}(a)}{32 a^2}
\]

so \(\psi\) will be:

\[
\psi(a) = \frac{\sqrt{a^2+1} (2a^3+3a) - \text{arcsinh}(a)}{32 a^2} - \frac{1}{4a}
\]

the function behavior is shown in the fig 11.
Making $\psi(a)=0$ yields $a=1.5933$

$\bar{y}(a=1.5933) = f(a=1.5933) = 0.1569$
The parabola shape is:

\[ y = 1.5933x^2 \]

Notice: This equation considers a unitary aperture. You may multiply the unitary aperture parabola geometry by any scale factor. The equation will change, but the shape (dimension proportions) will be always the same.

5. Preliminary analysis

5.1 Preliminary design

parabola aperture: 1 m
parabola length: 1.3314 m
assume efficiency 30% \( \Rightarrow \) \( E_0 \) = 3

Aperture area \( = 323.86 \text{ W} \times \frac{1 \text{ m}^2}{806.86 \text{ W}} \times E^{-1} \)

Aperture area \( \approx 1.338 \text{ m}^2 \)

Reflective surface \( = 1.3314 \times 1.338 = 1.7814 \text{ m}^2 \)

Plates are selling with \( 48'' = 1.2192 \text{ m} \)

New parabola aperture \( = 1.2192 \times \frac{1}{1.3314} \approx 0.9157 \text{ m} \)

Trough length \( = 1.4612 \text{ m} = 57.53 \text{ in} \)
5.2 Preliminary costs

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<th>component</th>
<th>supplier</th>
<th>cost</th>
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<tbody>
<tr>
<td>48”x 57.6”x 0.0178” mirrored finish stainless steel plate</td>
<td><a href="https://www.stainlesssupply.com/order-metal-online/docs/g1c1045s2ss0p0/304-stainless-steel-sheet-8-mirror.htm#">https://www.stainlesssupply.com/order-metal-online/docs/g1c1045s2ss0p0/304-stainless-steel-sheet-8-mirror.htm#</a></td>
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<td>¾”x 5ft copper tube</td>
<td><a href="http://www.homedepot.com/p/Homewerks-Worldwide-3-4-in-x-5-ft-Copper-Type-M-Rigid-Pipe-RM06005/202369969?N=5yc1vZbuu2">http://www.homedepot.com/p/Homewerks-Worldwide-3-4-in-x-5-ft-Copper-Type-M-Rigid-Pipe-RM06005/202369969?N=5yc1vZbuu2</a></td>
<td>$13.88</td>
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<td>30mm x 1.4mm x 1500mm glass tube</td>
<td><a href="http://www.glasscraftinc.com/home/gla_1414050076235/page_5424">http://www.glasscraftinc.com/home/gla_1414050076235/page_5424</a></td>
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<td>Coating flat black paint can 11oz</td>
<td><a href="http://www.amazon.com/VHT-SP102-FlameProof-Coating-Black/dp/B000CPJLGM/ref=pd_sim_auto_6?ie=UTF8&amp;refRID=1YQY86BZZXRRBBQYPA59">http://www.amazon.com/VHT-SP102-FlameProof-Coating-Black/dp/B000CPJLGM/ref=pd_sim_auto_6?ie=UTF8&amp;refRID=1YQY86BZZXRRBBQYPA59</a></td>
<td>$10.28</td>
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Preliminary estimated cost for the reflective material and receiver is $136.33, just including materials for the receiver and the reflective panel.

Cost can be dramatically decreased by looking at free available alternatives. We contacted a company that uses lithographic aluminum plates for printing processes, and we got some aluminum plates with zero costs. Probably it will demand some additional treatment to get a reflectance comparable to the commercial polished plates. The same may be done for the other components, specially the wood structure, once we have available discarded material even in our classroom!

6. Further issues and project detailing

This section contains further issues that will be more detailed over the next weeks with the refinement of the design.

6.1 Stand and structure

The stand design and cost were not covered by this preliminary analysis. As mentioned, the stand design should allow positioning corrections, and it also should have enough stiffness to keep the geometry of the reflector.

6.2 Connections and Interfaces

System interfaces will be more clearly defined in the next weeks as well as linking components such as screws, bearings, connections, tubes etc. Bearings will be needed to minimize resistant
torque on the tracker, flexible tubes will be used to connect the receiver to the steamer due to the movement of the trough for positioning correction.

6.2.1 Critical interface issue 1: tracker accuracy

The main issue related to the interface with the tracker is the tracker accuracy and the width of the receiver. A large receiver width increases heat loses, but a small width can decrease optical efficiency due to deviation of the sunrays incidence from the perpendicular direction. The accuracy of the tracker is crucial for the trough. The following videos can exemplify this effect.

http://www.youtube.com/watch?v=VGcJ-Ti3bxA
http://www.youtube.com/watch?v=4AUhH5b2CAc

6.2.2 Critical interface issue 2: pivoting

The main issue related to the other interface is the connection with the steamer. To allow positioning seasonal correction, the stand should be pivoted at some point of its longitudinal axis. Depending on the overall length of the trough and the point of pivoting, a height variation of the trough ends can be substantially high. It may demand the steamer to be placed in a very high level and/or the using of a long flexible tube that can increase heat loses. This effect can be detrimental to the system convenience and efficiency or even make seasonal positioning correction impracticable.

A potential solution could be using the solar flower stand idea where a partial seasonal correction is used, two intermediate positions between equinox and mid-summer/mid-winter incidence angle as shown in the figure 13 for a latitude of 20 degrees.

![Fig. 12 Solar flower stand](image-url)
Fig. 13: Solar flower partial seasonal correction for a 20 degrees latitude

7. Risk assessment

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<th>ID</th>
<th>Risk Item</th>
<th>Effect</th>
<th>Cause</th>
<th>Likelihood</th>
<th>Severity</th>
<th>Importance</th>
<th>Action to Minimize Risk</th>
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<td>Obtain alternative materials/research and contact suppliers</td>
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<td>3</td>
<td>design evaluation</td>
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<tr>
<td>3</td>
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<td>low oil production</td>
<td>supplied power lower than necessary</td>
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8. References

A reference folder with all references used for the thorough preliminary analysis was created at the folder Detailed Design Documents for checking of the preliminary analysis and for future consultations.