Transient-Heat-Transfer and Stress Analysis of a Thermal-Storage Solar Cooker Module.

by

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Submitted to the
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ABSTRACT

This paper details the analysis carried out in Solidworks to determine the best material and configuration of a thermal-storage solar cooker module. The thermal-storage solar cooker utilizes the high-latent-heat lithium nitrate releases when transitioning from liquid to solid state. However, before this process can transpire the salt has to be completely melted and the energy needed for the melting process is provided by the sun. The purpose of the module is to conduct the solar power from the heat source to the salt. In addition after the melting process, it conducts the latent energy released by the salt to the hot plate used for cooking.

Thesis Supervisor: Professor David Gordon Wilson
Title: Professor Emeritus
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1 Introduction

1.1 Background

Professor Dave Wilson initially came up with a design for the thermal-storage solar cooker module that comprises of a hot plate attached to fins. This module is used to conduct heat into the lithium nitrate salt. However, there are a couple of constraints that include the melting point and decomposition temperature of lithium nitrate. As it is very time consuming and almost impossible to test out every possible design and material type, the need for an analytical reduction method arose. Fig 1 shows the initial design prototyped by Dave Wilson.

Firstly, the thermal modeling would aid the designers in choosing the best material for making the module. There were three different materials for consideration: copper, aluminium and cast iron each having its own advantages and disadvantages. However, the thermal performance of the metals is very critical and can outweigh other factors like cost per unit volume, weight, longevity and reaction to external conditions.

Secondly, the geometry of the hot plate and the arrangement of fins has an effect on the uniformity of the melting process and the total time it takes for the salt to melt. Because of this, the modeling became critical in determining the geometry of the module which in turn affects the size and weight of the solar cooker.

Thirdly, after coming up with the optimum design, the study also had to show how long the entire melting process would take and ensure the temperature of the salt at any point would still be below the decomposition temperature.

Lastly, there were concerns of thermal stresses that arise result due to the high temperature gradients introduced by the heat source so the software had to be able to provide the thermal effects.

According to [2], taking all these requirements into consideration, the software most capable of achieving all of them was discovered to be Solidworks. Solidworks is a solid modeling CAD (computer-aided-design) which also offers a Finite Element Analysis (FEA) design validation tool that can handle some multiphysics simulations as well as nonlinear studies. The validation tool can handle transient thermal analysis and also derives static
analyses from thermal effects.

Figure 1: Dave Wilson's drawing of the thermal-storage solar cooker.
2 Method

2.1 Modeling the salt and module in Solidworks

Firstly the models were based on the dimensions of the solar cooker Dave Wilson had prototyped.

Figure 2 shows the top of the hot plate with the circular heat target as well as the right, bottom and isometric views of the part. The side view shows the length of the fins as well as the diameter and thickness of the hot plate.

Figure 3 shows the bottom surface of the hot plate where the fins protrude from the surface.

Figure 4 shows the model of the salt with the depressions representing the spaces the fins will fill out once an assembly of the parts is made.

Figure 2: The top of the hot plate where the circular target where the heat will be concentrated on then distributed throughout the module. Units are in mm.
Figure 3: The bottom of the hot plate where fins protrude from the surface. Units are in mm.
Figure 4: Lithium nitrate. The extruded cuts are the spaces to be filled out by the fins when the salt is paired up with the module. Units are in mm.

The dimensions of the hot plate and target area were however altered after initial trial runs to come with the optimum design best suited for the users of the solar cooker and other design considerations.

One the changes included changing the geometry of the target area to a conical depression of diameter 20mm and a height of 20mm.
Figure 5: 3-D CAD of the module with a conical target.

2.2 3-D Assembly of the module and salt

The assembly between the salt and module was supposed to achieve the following conditions:

- A 10mm air gap between the salt and the bottom of the hot plate. This air gap allows for expansion of the salt as it is being heated up.

- A 10mm gap between the bottom of the fins and the bottom of the salt.

Fig 6 shows the engineering drawings for the assembly. The right and bottom views show the 10mm gap requirement.
2.3 Transient-heat-transfer analysis in Solidworks

The following steps were taken to carry out the transient-heat-transfer analysis in Solidworks:

- Open a thermal analysis in Solidworks and under properties select transient study specifying total time and the time step.
- Define initial conditions of the study which was an initial temperature of 25 °C.
- Define the heat power input and select the target area for the power.
- Define material properties for the module and the salt.
- Add temperature sensors on the top of the salt-fin interface at each radius away from the center of the hot plate.
The table below shows the material properties for the four materials used in the thermal studies. The materials are copper, aluminium, cast iron and lithium nitrate. The properties for lithium nitrate were extrapolated from the properties of $LiNO_3-NaNO_3$ [1].

<table>
<thead>
<tr>
<th>Materials</th>
<th>Copper</th>
<th>Aluminium</th>
<th>Cast Iron</th>
<th>Solid lithium nitrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity [W/m.K]</td>
<td>390</td>
<td>170</td>
<td>45</td>
<td>0.53</td>
</tr>
<tr>
<td>Specific Heat [J/(kg.K)]</td>
<td>390</td>
<td>1300</td>
<td>510</td>
<td>1500</td>
</tr>
<tr>
<td>Density [kg/m$^3$]</td>
<td>8900</td>
<td>2700</td>
<td>7200</td>
<td>14000</td>
</tr>
<tr>
<td>Melting Point [°C]</td>
<td>1085</td>
<td>660</td>
<td>1200</td>
<td>255</td>
</tr>
<tr>
<td>Decomposition Temperature [°C]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>600</td>
</tr>
<tr>
<td>Yield Strength [MPa]</td>
<td>258</td>
<td>55</td>
<td>98</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1: Table showing material properties.
2.4 Results from transient-heat-transfer analysis

The transient analysis was carried out under different heat intensity conditions and different module materials to produce the following plots.

1. This analysis was run using copper as the module material. The power input was 1000W and the diameter of the target was 10mm. As a result, the power intensity was found to 3.19MW/m².

![Heat Transfer Plot](image)

Figure 8: 25 copper rods configuration with a power input of 1000W.

2. This analysis was run using copper as the module material. The power input was 500W and the diameter of the target was 10mm. As a result, the power intensity was found to 0.8MW/m².
3. This analysis was run using copper as the module material. The power input was 500W and the diameter of the target was 20mm. As a result, the power intensity was found to be 0.8MW/m².

4. This analysis was run using copper as the module material. The power input was 500W but the geometry of the target area was changed to a conical depression of 20mm in diameter and a depth of 20mm. As a result, the power intensity was found to be 0.8MW/m².
Figure 11: 25 copper rods configuration with a power input of 500W and a conical target.

5. This analysis was run using copper as the module material. The power input was 1000W and the diameter of the target was 10mm. As a result the power intensity was found to 3.19MW/m². However for this analysis the fin at the center of the hot plate was removed to observe how that would affect the uniformity of the temperature.

Figure 12: 24 copper rods configuration with a power input of 1000W.

6. This analysis was run using copper as the module material. The power input was 500W and the diameter of the target was 10mm. As a result
the power intensity was found to $0.8\text{MW/m}^2$. However for this analysis the fin at the center of the hot plate was removed to observe how that would affect the uniformity of the temperature.

Figure 13: 24 copper rods configuration with a power input of 500W.

7. This analysis was run using aluminium as the module material. The power input was 1000W and the diameter of the target was 10mm. As a result, the power intensity was found to $3.19\text{MW/m}^2$.

Figure 14: 25 aluminium rods configuration with a power input of 1000W.

8. This analysis was run using aluminium as the module material. The
power input was 500W and the diameter of the target was 10mm. As a result the power intensity was found to 0.8MW/m².

Figure 15: 25 aluminium rods configuration with a power input of 500W.

9. This analysis was run using aluminium as the module material. The power input was 500W and the diameter of the target was 20mm. As a result the power intensity was found to 0.8MW/m².

Figure 16: 25 aluminium rods configuration with a power input of 500W.

10. This analysis was run using aluminium as the module material. The power input was 1000W and the diameter of the target was 10mm. As
a result the power intensity was found to be 3.19MW/m². However for this analysis the fin at the center of the hot plate was removed to observe how that would affect the uniformity of the temperature.

Figure 17: 24 aluminium rods configuration with a power input of 1000W.

11. This analysis was run using cast iron as the module material. The power input was 500W and the diameter of the target was 10mm. As a result the power intensity was found to 0.8MW/m².

Figure 18: 25 cast iron rods configuration with a power input of 500W and 20mm target area diameter.
2.5 Conclusions: Transient-heat-transfer analysis

From the transient plots obtained from the study, the following conclusions were made:

1. Lithium nitrate heats more uniformly under a smaller power intensity. This can be observed from comparing figure 7 temperature curves which are more identical to figure 6 temperature curves which are more separated.

2. The temperature is more uniformly distributed throughout the salt when the salt is paired up with a module material of a higher thermal conductivity. This can be seen from comparing figure 7 to figure 15. Amongst the three metals, cast iron has the lowest conductivity and figure 15 shows that it also has the highest temperature gradients within the salt. The thermal performances of copper and aluminium is quite similar.

3. The size or geometry of the target area does not affect the temperature distribution through the salt. Instead the only the magnitude of the heat power affects the temperature curves. This is can be seen from Figure 7, Figure 8 and Figure 9 where the temperature curves are the same although the target area and geometry were different.

4. There are higher temperature gradients in the salt if the salt is paired with a 24 rods configuration module. This means that configuration is less favorable for uniform temperature distribution.

From these observations, the module materials can be narrowed to two; copper and aluminium. As a result the following factors will also be taken into consideration when making the final decision:

- The cost of the material per unit volume.
- The weight of the material.
- There is literature claiming aluminium is reactive to lithium nitrate.
- The longevity of the material and its resistance to wear and tear
- Aluminium has a lower melting point which is dangerously closer to temperatures that some sections of the salt will need to reach in order for the entire salt to be melted.
With all these factors in mind, copper became the best material to use. The optimum heat power is 500W with the optimum number of fins being 25. At this configuration all the salt melts around 15000 seconds or 4.17 hours as shown by figure 8. The choice of the target area and geometry would be determined by the thermal stress analysis.

2.6 Thermal stress analysis

Due to the high heat intensity introduced to a very small target area, a very important component of the analysis was to study the magnitude of the thermal stress the target area experiences during heating. These stresses should be less than the yield strength of the material to avoid failure of the module. This analysis was carried out using two different study methods in SolidWorks:

1. Nonlinear analysis.
   This is a transient study that exports the temperature profile from the transient thermal study and produces a curve showing how the von Mises stresses change in time. The following graphs were obtained from the nonlinear analysis of the target area.
   (a) This analysis was carried out using transient thermal results from the copper hot plate with 25 fins and power input of 500W. The diameter of the circular target was 10mm.

![Graph](image)

Figure 19: Nonlinear study of the 25 copper rods configuration with a power input of 500W. Diameter of target is 10mm.
This analysis was carried out using transient thermal results from the copper hot plate with 25 fins and power input of 500W. The diameter of the circular target was 20mm.

![Graph](image_url)

Figure 20: Nonlinear study of the 25 copper rods configuration with a power input of 500W. Diameter of target is 20mm.

This analysis was carried out using transient thermal results from the copper hot plate with 25 fins and power input of 500W. The diameter of the circular target was 30mm.

![Graph](image_url)

Figure 21: Nonlinear study of the 25 Copper rods configuration with a power input of 500W. Diameter of target is 30mm.
(d) This analysis was carried out using the transient thermal results from the copper hot plate with 25 fins and power input of 500W. The target area was a conical depression.

![Graph showing Von Mises Stress vs Time](image)

Figure 22: Figure of the 25 copper rods configuration with a power input of 500W. The target area was a conical depression.

2. Static Analysis.
   This study exports individual temperature points from the transient study and evaluates them one at a time to obtain the thermal effects. This study was used as a confirmation of result obtained from nonlinear study.

(a) This analysis was carried out using transient thermal results from the copper hot plate with 25 fins and power input of 500W. The diameter of the circular target was 20mm.
2.7 Conclusions: Thermal stress analysis

The following conclusions were drawn from the thermal stress study:

1. Increasing the target area reduces the initial von mises stress. The initial stress level is 8MPa for the 30mm diameter target, 12.5MPa for the 20mm diameter and 45MPa for the 10mm diameter.

2. Although the conical target increases the target area it has less of an effect on the initial stress level as compared to increasing the circular target area to the same area as Figure 20 shows. The total surface area of the conical target is \(1.02 \times 10^{-3} \text{ m}^2\) and initial stress level was 14MPa. For the circular target of radius 15mm the surface area is \(7.07 \times 10^{-4} \text{ m}^2\), the initial stress level is 8MPa.

3. The stress level asymptotes to a value that is dependent on the temperature dynamics of the study and the surface area of the target area. The steady state stress level is believed to mainly due to material expansion.

From these studies thermal stresses on the target area although present will never go above the yield strength of copper hence making it safe to use the module.
3 Recommendations and future work

Although the von mises stresses were found to be less than the yield stress of copper, they might become significant as cyclic loads. As a result it would be beneficial to do a study detailing how the cyclic loading affect the module as this determines the life of the product.

Secondly the thermal stress analysis was more specifically for the target area but during the course of the study, it was discovered that the fins could also be points of failure as the temperature rises. Lastly it would beneficial to test out a physical model based on these suggestio inorder to observe its performance and compare it to the expected performance.

4 Bibliography

References

[1] Omotani and A. Nagashima. Thermal Conductivity of Molten Salts, HTS and the LiN0$_3$-NaNO$_2$ System Using a Modified Transient Hot-wire Method.

[2] Author unknown. COSMOS/FFE.