Heat Transfer Optimization of a Solar Radiation Concrete Oven for Rural Areas

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Abstract: Creating healthy food and drinking water typically requires electricity and fuel sources that are not available in rural areas of underdeveloped countries. Many rural areas have an abundance of solar radiation which can be harnessed to create viable heating sources. This work investigates the design of a robust solar radiation concrete oven for cooking food and treating water for viruses. Selection and usage of materials for the oven is optimized through heat transfer parametric studies performed with the commercial FEM software COMSOL. The oven is composed of several interacting material layers including: a) walls composed of concrete, brick, and insulators, b) a steel chamber for water retention, c) a soapstone cooking chamber, d) an oven cap made of glass embedded in concrete, and e) solar reflective panels. Temperature distribution throughout the oven will be examined and discussed, and experimental verification studies for the COMSOL model will be explored.

Keywords: Heat transfer, Solar oven, water treatment.

1. Introduction

The process of creating healthy food and drinking water typically requires electricity and fuel sources that are not available in rural areas. Only 23% of Africa's population, the main focus of this work, has access to electricity [1]. Without electricity rural areas often rely on burning solid fuels (wood, dung, trash, etc.) that emit toxic fumes. Inhalation of these fumes causes millions of deaths per year that could be prevented with proper heating sources. Africa has an abundance of solar radiation which when properly harnessed creates a viable heating source for cooking food and purifying water.

Solar cookers have been developed from a) metals and plastics [2], and b) metalized cardboard [3], but these cookers are often inefficient, lacking in durability, and are susceptible to theft. In addition current solar cookers are not designed to treat viruses in water on a practical scale. The technologies that do address viruses utilize: a) chlorination or iodization, b) the boiling of water, or c) solar water disinfection (SODIS) [4] = water pasteurization. Doses of chloride/iodine have to be carefully monitored for chlorination/iodization to be a safe and effective treatment option, and this is not practical in rural areas. Boiling water to treat viruses is not feasible due to a lack of energy sources, and SODIS methods are underdeveloped for large scale applications. The most common SODIS method is to expose plastics bottles filled with contaminated water to sunlight for several hours.

This work will investigate the design of a prototype solar radiation concrete oven for cooking food and treating water for viruses. This prototype is a 1/3rd scale model of the full size oven, which, can accommodate an entire rural village and will have a life span of 10 – 20 years. Materials and the geometry of the prototype oven are optimized through parametric heat transfer studies using COMSOL.

2. Design

The oven is composed of heating and insulation walls sandwiched between a concrete cap and base as shown in Fig.1. The Styrofoam and Rockwool layers act as insulation while the brick and concrete are used for sustainability and

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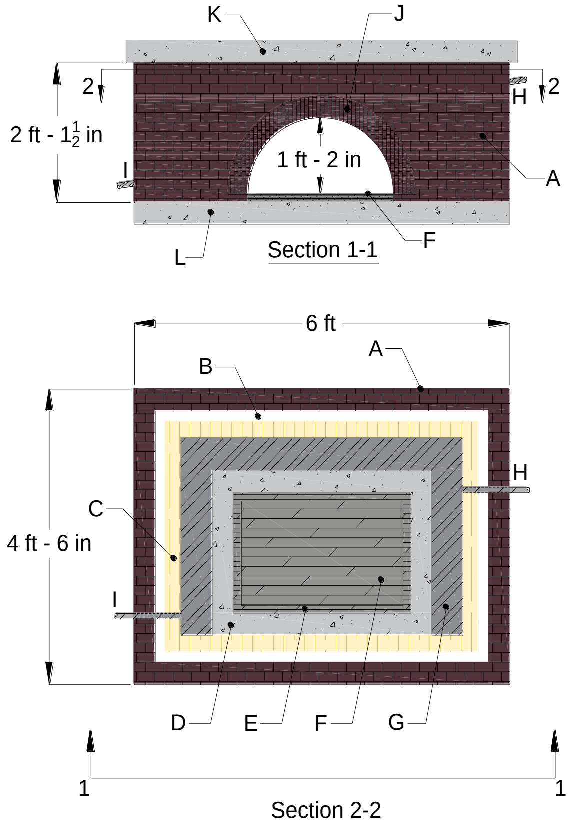

Layer	Material	Thickness
A	Brick	4 in
B	Styrofoam	2 in
C	Rockwool	3 in
D	Concrete(walls)	4 in
E	Soapstone(walls)	$1\frac{1}{2}$ in
F	Soapstone(chamber)	$1\frac{1}{2}$ in
G	Retention Channel	6 in
H	Water Entry Pipe	1 in Ø
I	Water Discharge Pipe	1 in Ø
J	Brick(arch)	4 in
K	Concrete(cap)	4 in
L	Concrete (base)	4 in

Figure 1. Concrete Oven Material Layout

stability. A cooking chamber is embedded in the middle of the oven that is composed of a soapstone cooking surface surrounded by soapstone walls.

A stainless steel retention channel (Fig. 2) is embedded between the concrete and Rockwool walls for water treatment. Water is first filtered for bacteria and solids and then poured into the retention channel through a steel entry pipe. The water is treated for viruses via pasteurization from heat that radiates from the cooking chamber. The water must remain in the steel channel for an extended amount of time to eliminate common drinking water viruses. The water temperature and time needed to treat different types of viruses varies [4], but in general the water will need to remain at 40° C (104° F) for a conservative 8 – 12 hours. For the prototype the retention channel is 6 in wide and 24 inches tall, which, will allow the oven to treat around 50 gal of water/day. The retention channel will be sealed on the top and sides with welded steel plates.

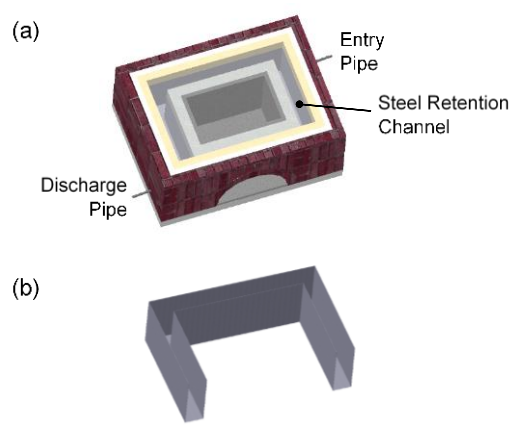

Figure 2. Steel Retention Channel: (a) Embedded in oven, (b) Individual Part (top and front cover plates on channel not shown for clarity).

Once the water has been treated it is released into a storage chamber from the discharge pipe.

Solar reflective panels will be attached to the center of the concrete cap as shown in Fig. 3(a). These panels will reflect sunlight into the cooking chamber via a glass opening embedded in the cap Fig. 3(b)). The panels will be made from FRP that is painted with a reflective paint. Selection of an optimum geometrical design for the panels is currently being investigated. The top of the cap opening is covered with a protective glass layer and the bottom is sealed with an insulation type glass.

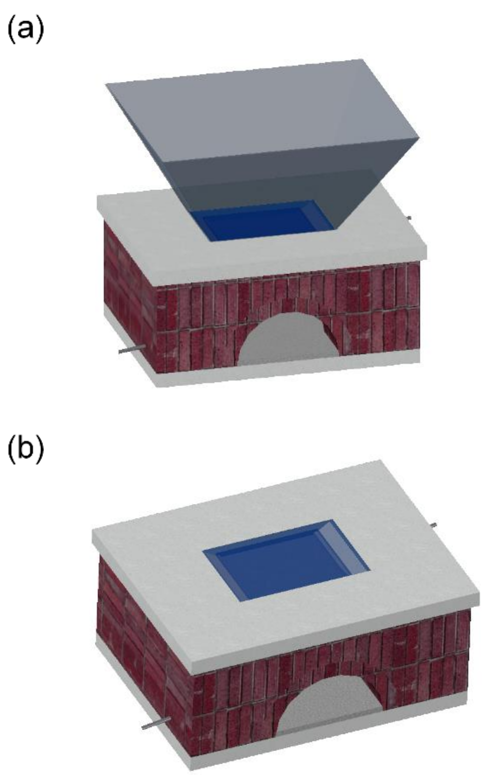

Figure 3. Concrete Cap Design: (a) Solar reflective panels (b) Glass Opening

3. COMSOL Heat Transfer Results and Discussion

COMSOL Multiphysics is used to perform two heat transfer analyses for the solar oven. The first analysis consists of investigating the transfer of heat via thermal conduction to the inside walls of the cooking chamber and into the water inside the steel retention channel. Second, the heat loss from, and therefore cooling of, water is investigated. The objective of this second part is to test the oven capacity to keep the water temperature above or at least at 40^0 C (104^0 F) for a period of eleven hours. Figures 4 and 5 show two composite wall designs I and II. In I a layer of Rockwool (r) is sandwiched between a concrete (c) and Styrofoam (st) layers. This layer of Rockwool is removed in design II (Fig. 5). The oven cooking chamber wall, shown as the left layer, is made of concrete in design I. In design II (Fig. 5) both concrete (c) and soapstone (sp) are adopted for comparison of thermal efficiency. The layers are labeled as follows;
(c) concrete, (w) water, (r) Rockwool, (st) Styrofoam, (b) brick, and (sp) soapstone.

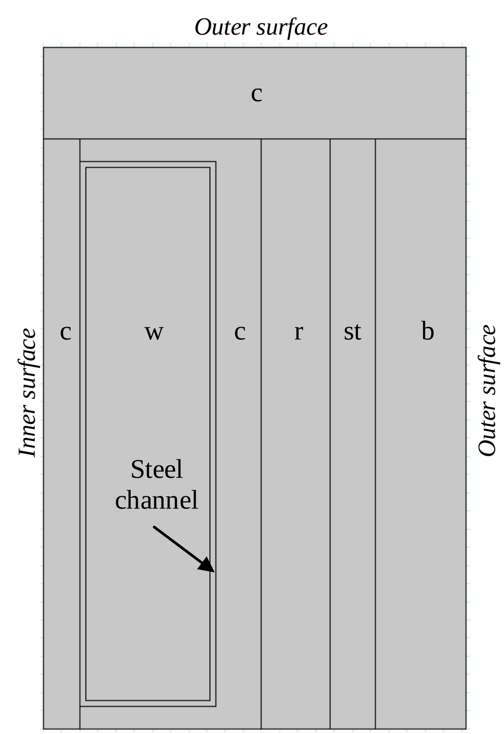

Figure 4. 2D layered section of the oven wall showing design I.

In the first study, the outer surfaces of the oven are kept at 293K while the inner surface is assumed to have reached a maximum cooking temperature of 400 K (120^0 C). The model is run for 11 hours under these conditions and sample results are shown in Fig. 6. It is clear that the heat is conducted efficiently to the water inside the steel retention channel. It can also be observed that the soapstone cooking layer helps in conducting the heat deeper into the composite structure of the oven than the concrete layer does.

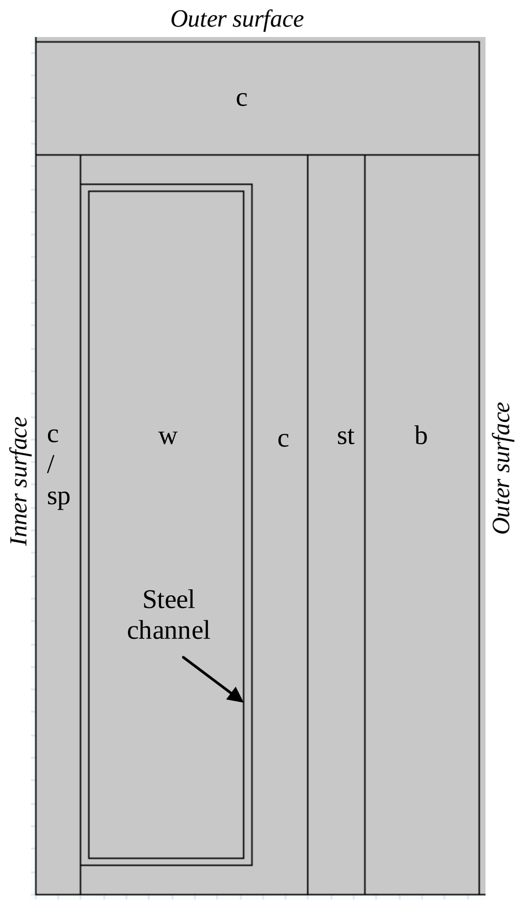

Figure 5. 2D layered section of the oven wall showing design II.

The contour lines, presented for the 11 hr. case in Fig. 6, show how effective is the Styrofoam layer in insulating and keeping the heat inside the oven wall structure.

The ability of the design to hold the water at temperatures above 313K (≈ 40^o C) for a period of 11 is also investigated. Figure 7 shows sample COMSOL results for designs I (left) and II (right). It is evident that the water temperature satisfies and exceeds the minimum requirement to eliminate common drinking water viruses during the 11 hours and beyond. After 11 hours, the simulation suggests that the water temperature is around 330K (≈ 57^o C) when starting from 370K (≈ 95^0 C) at time 0. It is also suggested that removing the Rockwool layer does not have negative influence on holding the water temperature at desired values.

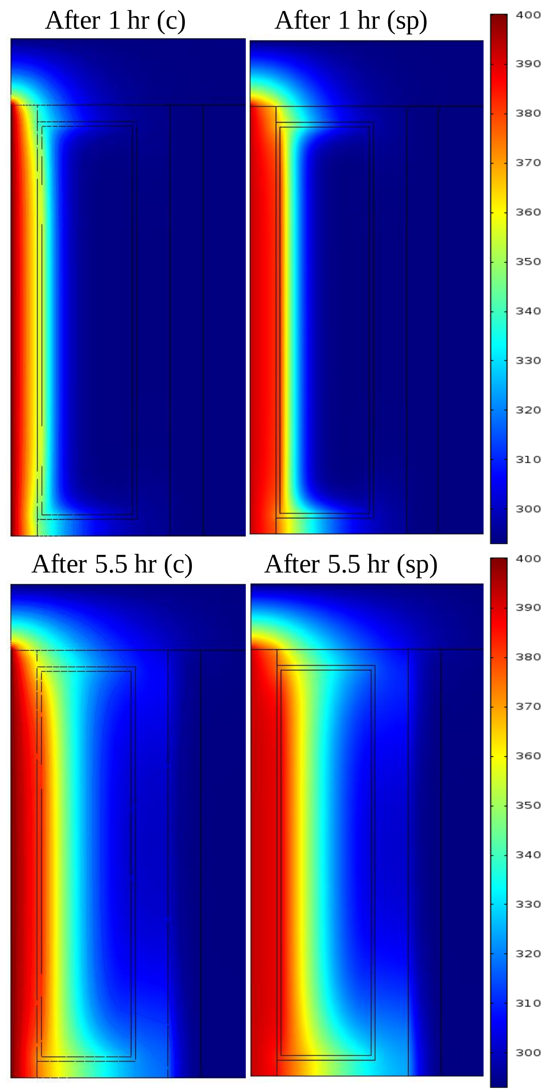

Figure 6. 2D layered section of the oven wall showing temperature distribution for design II with a concrete (c) wall (left) and soapstone (sp) wall (right).

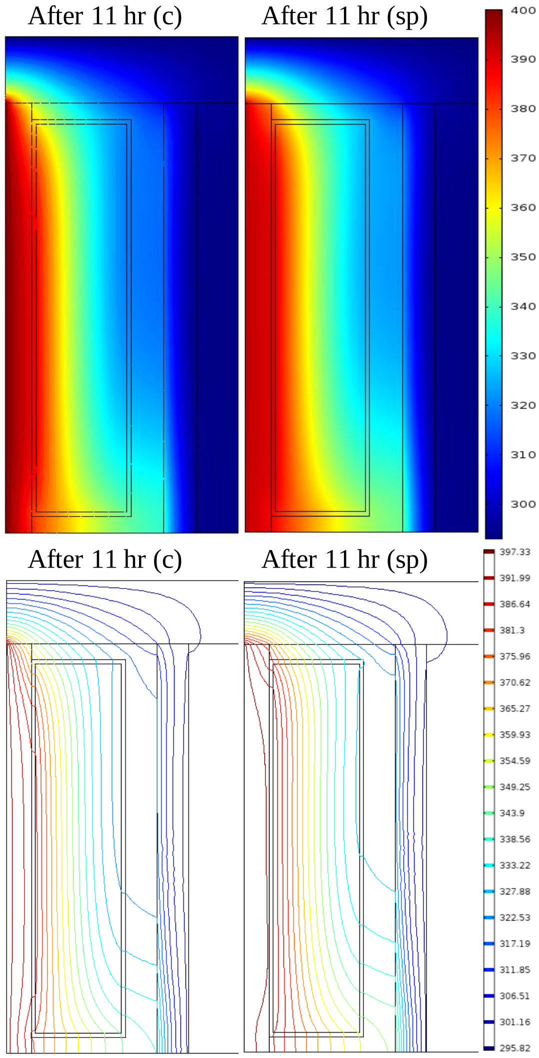

Figure 6. (*Continued*).

4. Conclusions

The heat transfer results show that some layers of insulation can be removed (i.e., the Rockwool layer) and the oven will still meet its target heat range. It is also found that although the soapstone layer is more effective in heat conduction, the oven can still warm up the water using a concrete wall for the cooking surface.

Currently a prototype solar oven is being constructed based on these results and further optimization techniques such as the ‘COMSOL

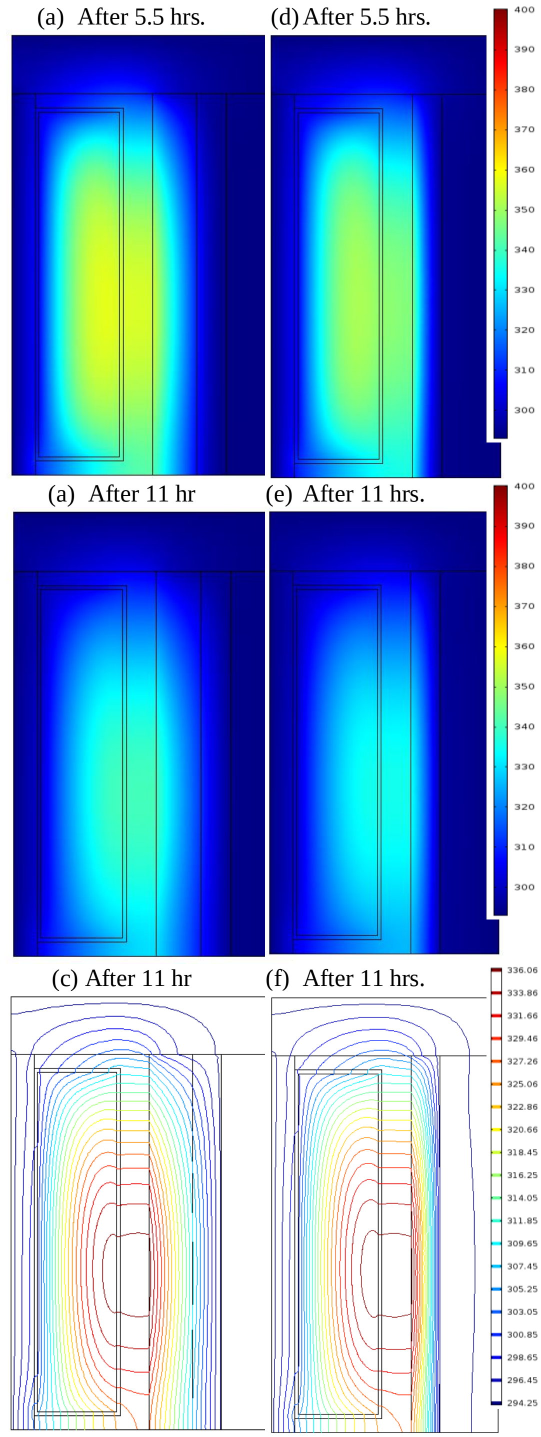

Figure 7. 2D layered section of the oven wall showing cooling over time for design I (left) and design II (right).

Optimization Module' will be used to further enhance the design of this solar oven. Instrumentation such as using thermocouples to measure the temperatures of the cooking surface and the water over time will be implemented for model validation. In addition, the effect of heat loss due to convection by moving air (wind) at the outer surfaces of the oven is currently being simulated using COMSOL.

5. References

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