Solar Autoclave for Rural Areas

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Engineering Analysis

Document

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INTRODUCTION

Certain countries such as the United States are fortunate to have an organized healthcare system with properly sterilized equipment, regulated by imposed hygienic standards. However, many developing areas around the world have limited availability to properly sterilized medical equipment. Unfortunately, patients in these areas are being treated with unsanitary utensils. Not only does this put the patient's life at risk, but also contributes to the spread of diseases. Our team's objective is to create a solar autoclave that can be used at remote health clinics in these developing countries in order to sanitize medical equipment. This device will operate in absence of grid power within medical clinics utilizing only the power of the sun. This report summarizes the engineering analysis of this device. The solar autoclave was divided into subsections, and analysis was done for each section. Sections being analyzed include: thermodynamic properties of water, thermal capture, the thermal resistance circuit for the system, a thin walled pressure vessel, and insulation.

THERMODYNAMIC PROPERTIES OF WATER AT 121°C

In an autoclave, the water needs to be pressurized in order to raise its boiling point to 121°C. In other words, an increase in pressure will result in an increase in the water's boiling point. The heat within the autoclave will cause the water to evaporate and the pressure to rise. After the water is evaporated, the steam used to sterilize the equipment can either be saturated steam or superheated steam. Although superheated steam is hotter than saturated steam and contains more energy, it has a low heat transfer capacity and therefore transfers heat poorly. Saturated steam is preferable because it has a better energy exchange capacity. Figure 1 below shows the comparison between superheated and saturated steam.

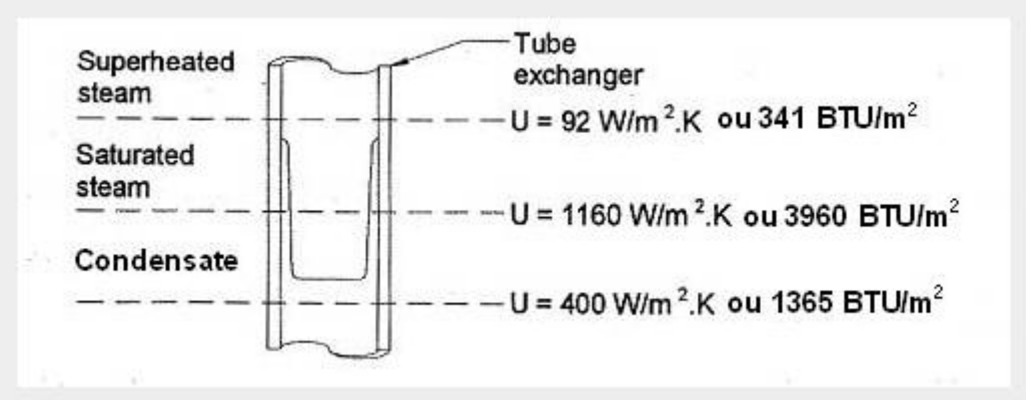


Figure 1: Heat Transfer Capacity (U) for Water

(Source: http://www.systhermique.com/steam-condensate/services/troubleshooting/superheated-steam/)

In order to determine how much energy is required to heat the water, the following equation can be applied:

$$E = m \cdot (u_2 - u_1) \tag{1}$$

Where:

E = Energy, in kJ

m = Mass of water, in kg

u = Internal energy, in $\frac{kJ}{kg}$

For the solar autoclave to properly sterilize the medical equipment, the temperature of the steam will need to be brought from room temperature (20˚C) to 121˚C. After using Shapiro's *Fundamentals of Engineering Thermodynamics* [1], the internal energy values at room temperature and 121°C can be found as shown in the table below. Based on these values and Equation 1 above, the energy, or heat transfer value can then be determined once the mass of water is known. The boiler will use 1 Liter of water to fill a larger pressure vessel. At room temperature, 1 liter of water equates to 1 kilogram. Therefore, the mass of water in the system will be approximately 1 kilogram within the boiler:

Table 1: Thermodynamic Properties for Saturated Liquid

		Internal Energy, u [$\frac{kJ}{kg}$]
Temperature [°C]	**Pressure [bar]**	**Saturated Liquid**
20	0.02339	83.95
121	2.05050	507.752

Using Equation 1 above, the energy required to heat the water in the autoclave is found to be 423,802 Joules. Once the energy has been transferred to the water within the boiler, the pressure rises, allowing the water to reach 121 ˚C. The pressure will then overcome the stiffness of a spring pressure valve, allowing steam to release into the hose and down to the pressure vessel. With a valve head surface area of $5.07{\bullet}10^{-3}$ square meters, the pressure of 2.05 bar will overcome the spring stiffness of 270 $\frac{kN}{m}$, moving the piston 1 millimeter. An illustration of the concept is shown in Figure 2.

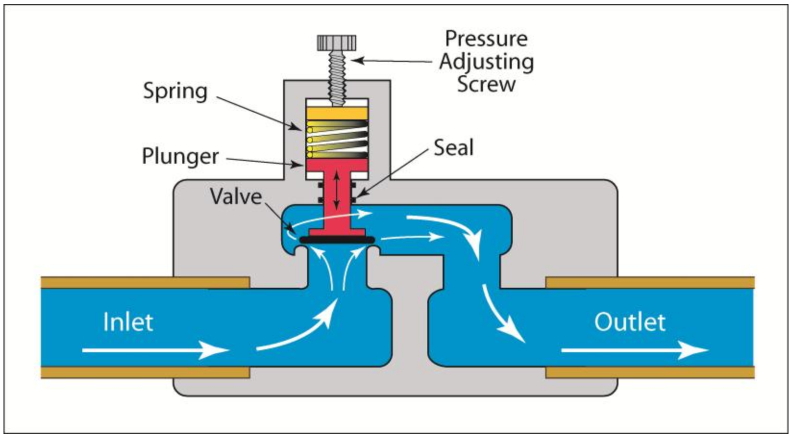


Figure 2: Spring Pressure Valve

(Source: http://www.ctgclean.com/tech-blog/2012/04/valves-backpressure-regulating-valves/)

THERMAL CAPTURE

Thermal capture is determined from the radiation being emitted from the sun. Applying the equations from above, the projected area needed to acquire the necessary power is found from Equation 2 below:

$$q_{rad} = \alpha \cdot \rho \cdot G \cdot A_{proj} \tag{2}$$

Where:

q_{rad} = the incoming power of the sun, in W
α = the absorptivity of the bottom of the pressure vessel
ρ = the reflectivity of the material on parabolic trough
G = the solar irradiance, in $\frac{W}{m^2}$
A_{proj} = the projected area from the trough, in m^2

This equation can then be manipulated to solve for the projected area, shown in Equation 3 below:

$$A_{proj} = \frac{E}{t \cdot \alpha \cdot \rho \cdot \epsilon \cdot G} \tag{3}$$

Where:

E = the energy required to raise the water temperature, in J
t = the time allotted to reach goal temperature, in seconds
ϵ = the estimated efficiency of the trough

Emissivity is a significant factor in how efficient the solar autoclave can be. Emissivity, ε, is equal to absorptivity, α, and directly related to reflectivity, ρ. Therefore, a lower emissivity value results in a higher reflectivity value. For the parabolic trough to effectively collect solar power, reflectivity is very important. Equation 4 below shows the correlation between the two:

$$\rho = 1 - \varepsilon \tag{4}$$

Where:

ε = the emissivity constant

Table 2 below shows the different emissivity and resulting reflectivity values of various materials being considered for the parabolic trough.

Table 2: Material emissivity and reflectivity

Reflective Material	Emissivity, ε	Reflectivity, ρ
Aluminum - Highly Polished	0.039	0.961
Aluminum - Commercial Sheet	0.090	0.910
425-3M Aluminum Foil	0.030	0.970
Y9360-3M Aluminized Mylar	0.030	0.970

The importance of reflectivity requires a reliable material which can be easily replaced. Mylar is affordable, abundant, and lightweight. The absorptivity of black spray paint was found to be 0.95, which was then lowered to 0.9 in order to be conservative in calculations. The solar irradiance constant is assumed to be 850 $\frac{W}{m^2}$, but may vary between regions. In addition, a half hour of time was estimated to heat the required amount of water, which equates to 1,800 seconds. A 60% efficiency for the homemade trough was estimated. Finally, Equation 3 from above is used to solve for the projected area of the parabolic trough.

$$A_{proj} = \frac{423802\ [J]}{(1800[s])(.9)(.97)(.6)(850\ \left[\frac{W}{m^2}\right])} = .528[m^2]$$

Doubling the projected area will help to ensure the sterilization temperature is reached even if the efficiency of the home made trough is less than 0.6 since the reflective surface will not be perfect. This measurement is on a square meter basis, and can be used to solve for the required dimensions for the trough. The trough will have a length 1.5 meters and width of 0.75 meters.

A parabolic trough functions by reflecting the solar irradiance to a point along the length of the trough, or focal point. To optimize the power reflected by a parabolic trough, the boiler must be placed at the proper location depending on shape and dimensions of the parabola. Using the known length and width needed to obtain goal temperature as well as an arbitrary focal length of 0.15 meters, the depth of the trough can be found. Figure 3 below shows the variables of the parabolic trough.

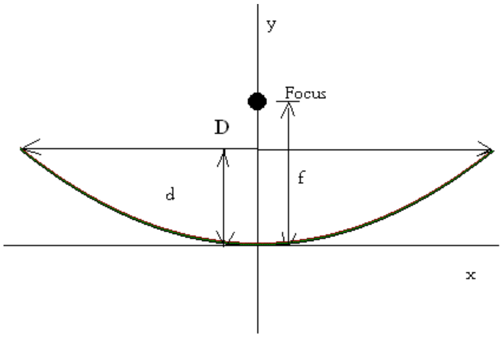


Figure 3: The variables of the solar collector.

(Source: http://www.analyzemath.com/parabola/parabola_focus.html)

Equation 5 can then be used to solve for the depth of the trough.

$$d = \frac{\left(\frac{D}{2}\right)^2}{4f} \tag{5}$$

Where:

d = the depth of the trough, in m
D = the diameter, in m
f = the focal length, in m

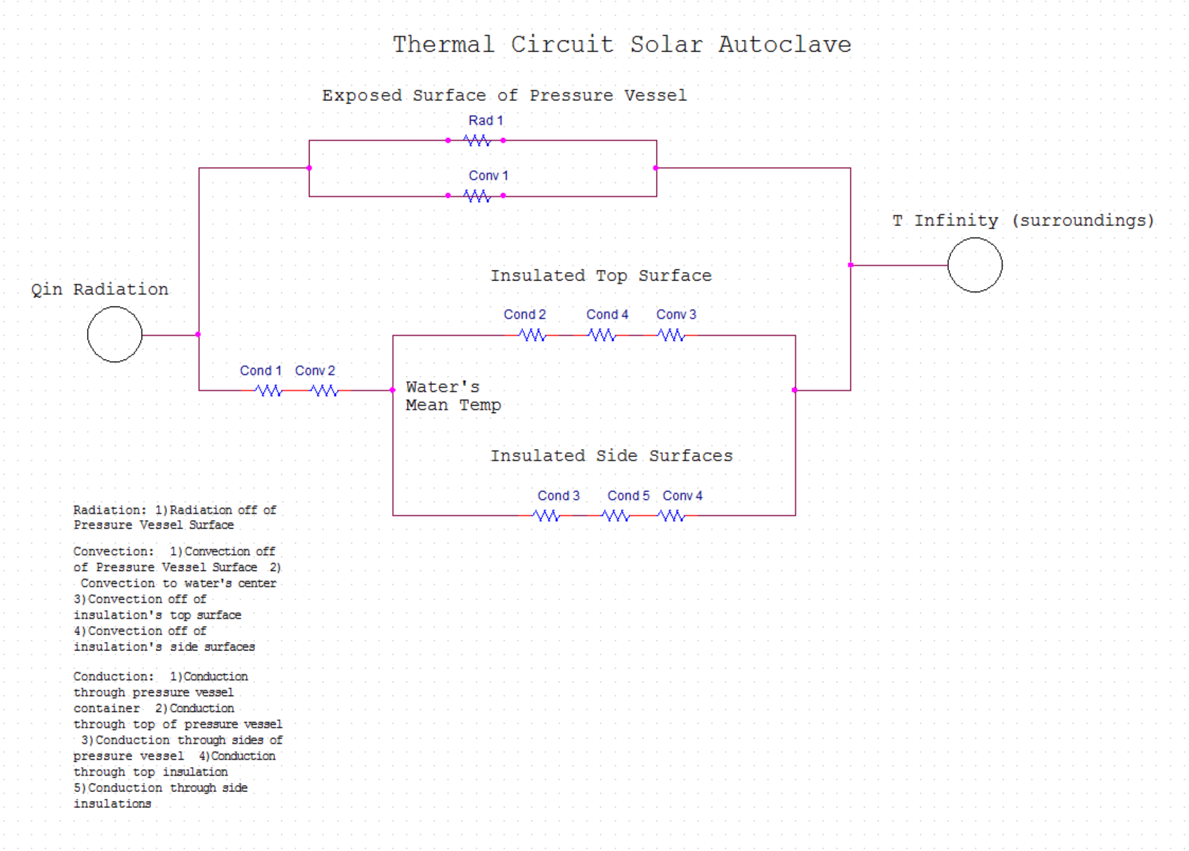
Solving for the depth with the diameter and focal length stated above will be .234 meters. Equation 6 below will then solve for the shape of the parabola of the trough.

$$y = \frac{x^2}{4f} \tag{6}$$

THERMAL CIRCUIT

A thermal circuit is a graphical representation of the various paths of heat flows. Heat will always flow from hot to cold in order to achieve equilibrium in the system. When this occurs, the heat will encounter different resistances. These resistances can be anything in the system trying to resist the flow of heat, whether it is a fluid or solid. Fluids deal with convection resistances while solids involve conduction resistances.

For this form of analysis, we will consider the pressure vessel that holds the actual medical equipment as well as the insulation around it. The heat flow traveling into the system follows several different paths as it makes its way into the water and eventually out of the system. Below is a diagram of the entire system followed by two diagrams of the circuit broken up into separate sections.



Radiation: 1) Radiation off of Pressure Vessel Surface

Convection: 1) Convection off of Pressure Vessel Surface 2) Convection to water's center 3) Convection off of insulation's top surface 4) Convection off of insulation's side surfaces

Conduction: 1) Conduction through pressure vessel container 2) Conduction through top of pressure vessel 3) Conduction through sides of pressure vessel 4) Conduction through top insulation 5) Conduction through side insulations

Figure 4: Thermal circuit for system

Figure 4 above shows the thermal circuit for the entire autoclave system. Initially, heat is transferred into the system in the form of radiation. However, radiation does not turn into heat until it is absorbed somewhere. In this case, the radiation is absorbed into the bottom of the pressure vessel, which will be painted black.

At this point the heat is presented with two paths; either the heat conducts into the vessel, Cond 1, or it is lost in the form of radiation or convection. The parallel circuit at the top represents the heat that could potentially be lost from the bottom surface of the pressure vessel. Rad 1 represents the infrared radiation that would be emitted from the vessel itself. Conv 1 represents the heat that would convect off of the surface, into the surrounding air, $T_{infinity}$.

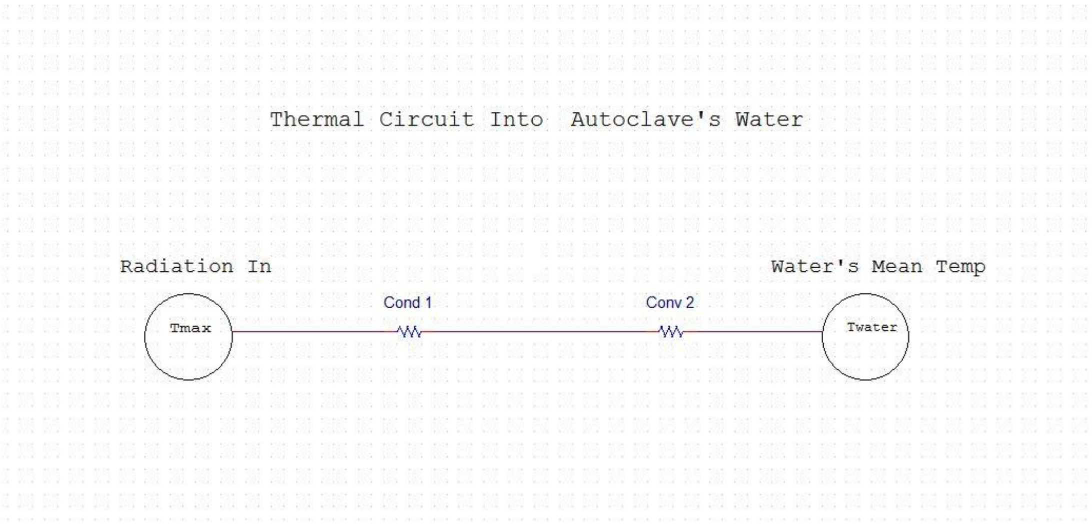


Figure 5: Thermal circuit of heat entering pressure vessel

Figure 5 above shows a closer look at the thermal circuit of the heat transfer into the pressure vessel once the radiation is absorbed. As mentioned before, the heat will conduct through the bottom surface of the pressure vessel, and then convect through the water inside of the vessel.

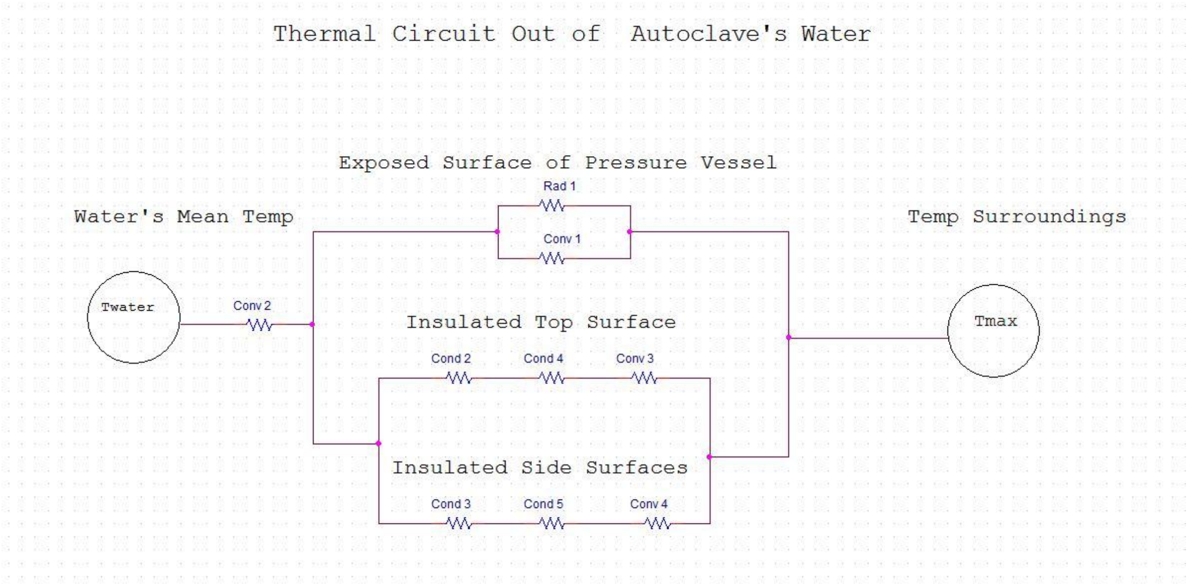


Figure 6: Thermal circuit of heat leaving pressure vessel

Figure 6 above shows a closer look at the thermal circuit of the heat transfer out of the pressure vessel. The T_{water} that starts the circuit in this figure continues from the end of Figure 5.

Equations:

The following equations determine the resistances of the thermal circuits, and can be applied to Figures 4, 5, and 6 above.

For two or more paths of heat transfer in parallel we use the three following equations:

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n} \tag{7}$$

$$R_{eq} = \frac{R_1 R_2}{R_1 + R_2} \tag{8}$$

$$R_{eq} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}} \tag{9}$$

Each of these equations allow for different ways to solve for the equivalent resistance of the parallel sections of the circuit.

For two or more heat transfer resistances in series we use the equation:

$$R_{eq} = R_1 + R_2 + \cdots R_n \tag{10}$$

Convection resistances are defined as:

$$R_{convection} = \frac{1}{h_{convection} A_{surface}} \tag{11}$$

Conduction resistances are defined as:

$$R_{conduction} = \frac{L}{k_{conduction} A_{surface}} \tag{12}$$

Thus using these equations we are able to define the thermal resistance into the water, as seen in Figures 4 and 5, as:

$$R_{eq} = R_{cond\ 1} + R_{conv\ 2} \tag{13}$$

$$R_{eq} = \frac{L}{k_{conduction} A_{surface}} + \frac{1}{h_{convection} A_{surface}} \tag{14}$$

These resistances will allow for a full analysis of the entire system.

THIN WALLED PRESSURE VESSEL

For the sterilization chamber of the medical equipment as well as the boiler, a thin walled pressure vessel can be modeled. A thin-walled pressure vessel is defined as a pressure vessel which has a radius, *r*, larger than 10 times its wall thickness, *t*. The pressure vessel experiences stress in three directions: longitudinal, tangential, and radial. However, the radial stress is much smaller than the other two, and can be considered negligible. If failure were to occur, it would happen due to either the longitudinal or tangential stresses. Both the longitudinal and the tangential stresses are due to an internal gage pressure given to us by the resultant pressure after the water has reached a final temperature of 121ºC.

The maximum tangential stress, or hoop stress, accumulated inside the cylinder is given to us by the following diagram and equation:

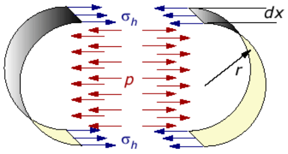


Figure 7: Hoop Stress inside of Cylinder

(Source: http://www.efunda.com/formulae/solid_mechanics/mat_mechanics/pressure_vessel.cfm)

$$(\sigma_h)_{max} = \frac{pr}{t} \tag{15}$$

The maximum longitudinal stress accumulated inside the cylinder is then given to us by the following diagram and equation:

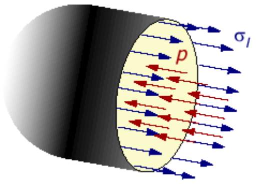


Figure 8: Longitudinal Stress inside of Cylinder

(Source: http://www.efunda.com/formulae/solid_mechanics/mat_mechanics/pressure_vessel.cfm)

$$(\sigma_l)_{max} = \frac{pr}{2t} \tag{16}$$

Where, for both equations:

p = pressure inside vessel, in Pa
r = inner radius of vessel, in m
t = wall thickness, in m

The hoop stress for a pressure vessel of this geometry is half as large as the longitudinal stress. This is a good explanation as to why overcooked hot dogs break at the seam as opposed to at the ends. From this comparison, we can conclude that we want the accumulated hoop stress to be no more than half the stress of the material, giving us a factor of safety greater than 2.

Below is a prototype model of a thin-walled pressure vessel we are considering using for our solar autoclave:

Figure 9: Prototype of Thin-Walled Pressure Vessel

As one can tell from the figure above, there are also bolts connecting and tightening the lid and the vessel. These bolts undergo a deflection stress when the gage pressure is created inside the vessel. This can potentially force the lid to rise to an unsafe level if a high enough factor of safety is not used when choosing the bolt material and geometry. The equation used to calculate the deflection of the bolts is modeled as:

$$\delta_b = \frac{F_b L}{A_b E_b} \tag{17}$$

F_b is the force applied to each bolt due to the gage pressure, calculated by the equation:

$$F_b = \frac{p(\pi r^2)}{N} \tag{18}$$

Where:

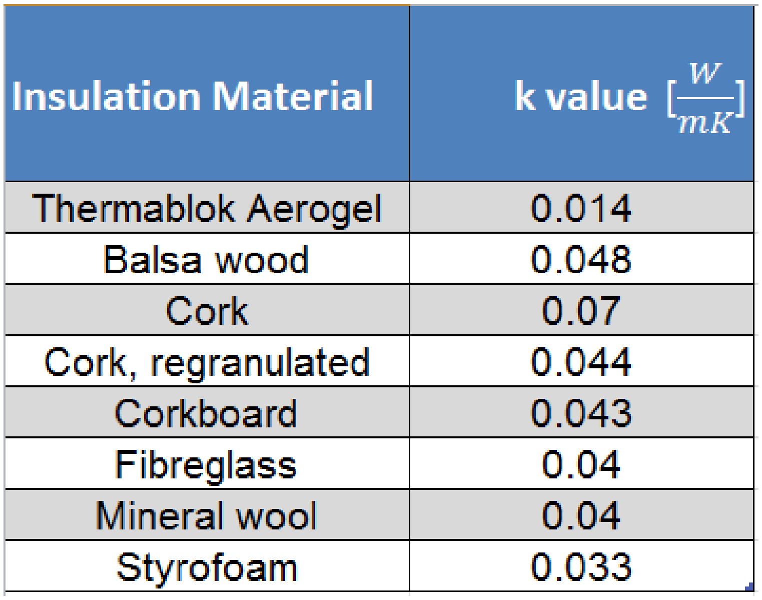
L = overall length of the cylinder, in m
A_b = area of each screw, in m
E_b = modulus of elasticity, in Pa
r = inner radius of the vessel, in m
N = number of bolts used

In conclusion, the most important analysis inside the pressure vessel is the gage pressure built up due to the heating of the water and creation of the steam. In turn, this gage pressure creates a longitudinal stress as well as a hoop stress inside the cylinder. It is helpful to know and understand these stresses when selecting the material and dimensions of the pressure vessel.

INSULATION

Reaching 121 ˚C is the goal for obtaining sterility, but this temperature must be maintained for a certain time span in order to guarantee every piece of equipment is clean and safe to use. Using insulation can help to retain heat and minimize heat loss. The thin walls of the pressure vessel and the hose are two crucial places where heat will try to escape. The boiler will remain exposed as this is portion of the system where the radiation will be absorbed. The table below lists a variety of materials with low thermal conductivity. Materials with a low thermal conductivity will maximize the thermal resistance preventing heat loss.

Table 3: Thermal conductivity values of insulation materials



Insulation Material	k value $[\frac{W}{mK}]$
Thermablok Aerogel	0.014
Balsa wood	0.048
Cork	0.07
Cork, regranulated	0.044
Corkboard	0.043
Fibreglass	0.04
Mineral wool	0.04
Styrofoam	0.033

Thermablok Aerogel is clearly the best choice, but unfortunately Thermablok Aerogel is very expensive and hard to obtain. The next best material for insulation was chosen as Styrofoam, which has both a lower thermal conductivity than other materials and is readily available.

Styrofoam was considered to be readily available because of its common use in shipping and packaging. Another large benefit is the cost, Styrofoam is cheap and in many occasions free, so if the insulation was damaged, it could easily be repaired or replaced.

CONCLUSION

In conclusion, there are several different sections that make up the solar autoclave. The thermodynamic properties of water, thermal capture, thermal circuit, pressure vessel, and insulation are all vital components and processes of the autoclave. In addition, it is important to understand how each segment of the solar autoclave works in order to analyze the entire system. More analysis will continue as our team comes closer to reaching a final design.

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Dr. Brent Nelson
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