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The Design and Testing of a Solar Autoclave with Broad Spectrum Sterilization Capabilities

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THE DESIGN AND TESTING OF A SOLAR AUTOCLAVE WITH BROAD SPECTRUM STERILIZATION CAPABILITIES

by

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ABSTRACT

Energy is difficult to come by in developing countries and this interferes with the ability of doctors to provide good healthcare to their patients. Without decent sterilization, patients can become infected and diseases can spread throughout hospitals. This study involves designing a solar autoclave for developing countries that is as efficient as electrical autoclaves. The design is intended to not require any electrical input and to be affordable to those who cannot afford advanced medical equipment. Once the solar autoclave is designed, it will be tested to determine if it can sterilize equipment against a variety of different bacteria, including bacteria that are Biosafety level 2. These bacteria are the cause of many deadly outbreaks, making it necessary for an autoclave to be effective in killing these dangerous bacteria. Despite these aims, the design executed in this study was not able to reach the desired temperature and pressure goals. Using data from the experiments conducted in this study, errors in execution and recommendations are discussed. Further research will be needed to design a solar autoclave with the capacity for a full cycle for sterilization.

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ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

Developing countries are challenged by lack of resources that interfere with attempts to improve living conditions for their citizens. Medical care and reliable, clean energy are two of the main challenges for these countries (Heuck et al., 1991).As medical care becomes more advanced, it often leaves behind communities that cannot afford the new life-saving technologies. These advancements that make medical care more efficient usually requires an abundance of energy. An average American hospital of 76,000 square feet uses about $3-4 per square foot per year (UCIrvine, 2007). Because of the difficulty in developing countries to provide the necessary energy, many people are infected with different kinds of communicable diseases because of the difficulty in sanitizing medical equipment (Heuck et al., 1991).

Of special importance, the Clostridium difficile spores present a major problem for the developing countries, often causing rampant hospital infections and closures (Gerding et al., 1995). C. difficile causes gastrointestinal diseases that can vary from severe diarrhea to toxic megacolon to death (Gerding et al., 1995). These spores are not part of the sterilization standard because they are not commonly targeted when equipment is sterilized. They are also Biosafety Level 2, meaning they are more difficult to kill. One of the reasons for the poor sterilization practices and standards is the lack of energy sources, which makes proper sterilization problematic. The search for inexpensive alternate energy options is imperative.

Renewable sources of energy seem the obvious direction in which to devote efforts, since nonrenewable energy can be very expensive and thus of particular concern for developing countries. Dees and Foroudastan (2007) elaborate on a few reasons why developing countries need to focus on the development of renewable energy:

1) The abundance of open spaces allows for many regions with direct sunlight for solar energy devices

2) Conventional energy sources are harmful to human health and destroy ecosystems

3) Since solar panels are cheaper than other forms of renewable energy, it would be perfect to power small families and villages in rural areas

Fossil fuels produce pollution which in turn has been linked to serious health problems. As Dees and Foroudastan noted, "The World Bank estimates that 780 million women and children breathing kerosene fumes inhale the equivalent of smoke from 2 packs of cigarettes a day"'(p. 3). In contrast, solar energy produces no fumes, does not leave any kind of byproduct, and is considerably cheaper than fossil fuels. With fossil fuels being nonrenewable, the need to switch to renewable energy is very important, particularly in the sterilization of medical equipment.

One way to address this problem is to design an affordable autoclave that uses solar energy to sterilize medical equipment that can destroy harmful spores. The design should be easy to maintain and should be as efficient as traditional autoclaves. In order to design a solar autoclave, it is necessary to understand the biology of the bacteria targeted. Understanding how the bacteria protect themselves from heat denaturation will assist in designing a solar autoclave.

To this end, this project sought to design and test a solar autoclave that meets the sterilization standard and could destroy a reasonable number of Clostridium difficile spores. Prior to describing the design and testing methodology, it is imperative to cover the challenges of sterilization.

CHAPTER 2

LITERATURE REVIEW

Sterilization

Any effective design must sterilize equipment with bacteria such as *Bacillus subtilis* spores and *Bacillus stearothermophilus* spores. "To inactivate 100,000 spores of *B. stearothermophilus* in saturated steam at 121 °C requires 12 minutes of exposure, but 1,000,000 spores of *B. subtilis* are inactivated in less than 1 minute at the same temperature" (Block, 2001). This is the standard for any equipment to be deemed "sterilized" and, consequently, this was the goal for the design of this solar autoclave. It needed to be able to compete against commercial autoclaves. The solar autoclave that was designed changed water into steam to sterilize the equipment. Steam sterilization is efficient and is commonly used in many hospitals all over the world. Block (2001) states that:

> Sterilization by steam under pressure is nearly universally applied except where penetration or heat and moisture damage is a problem. Steam sterilization equipment is found in a wide variety of shapes and sizes in hospitals, clinics, microbiologic laboratories, and industrial production facilities. Steam sterilization works better than some other forms of sterilization because steam destroys most resistant bacterial spores in a brief exposure and heats rapidly because of mass heat transfer as it condenses. (Block, 2001)

Steam sterilization is thus the best option for a solar autoclave, since time is also a factor. The sterilization process needs at least 20 minutes, not counting the time needed to heat the water. Electric powered autoclaves can boil water in minutes and the sterilization process is able to begin quickly. The problem with solar autoclaves is their reliance on energy from the sun, which may not be as consistent or reliable as an electrical input. The process of boiling the water

and filling the entire system with steam at the right temperature and pressure can take much longer. Electrical autoclaves can reach the desired temperature and pressure in about ten minutes and the sterilization process is completed within an hour. It is thus necessary to design a solar autoclave that will be able to complete a process within a few hours.

Bacteria Considered for the Sterilization Standard

Of particular importance to this study was to target *C. difficile* spores, as it is very common for this spore to cause hospital infections, especially in third world countries (Balassiano et al., 2012). However, there are no reliable statistics for how common this infection is in developing countries (Garci et al., 2007). The lack of evidence is due to the fact that the types of tests needed to diagnose *C. difficile* infections are not available in developing countries (Garcia et al., 2007).

It is important to understand that spores are the dormant stage of bacteria, when no nutrients are present.

> Fully formed spores, recognized as the most resistant form of life on the planet, protect the bacterial genome against heat, desiccation, radiation, and oxidation... As soon as environmental conditions become favorable for vegetative growth, however, it is critical that B. subtilis quickly exits from the dormant state. This process is referred to as spore germination and is triggered by the presence of nutrients in the environment. The nutrients are sensed by specific spore membrane receptors and, within minutes, the spore core rehydrates, the cortex is hydrolyzed, and the coat is shed. (de Hoon et al., 2010).

The sporulation process involves numerous stages that the bacteria go through in order to create a spore. The process takes about 8 hours, while cell division takes only 30 minutes (de Hoon et

al., 2010). To be able to protect itself from "heat, desiccation, radiation, and oxidation," the cell creates many layers that are not present in the vegetative state (Madiga et al., 2012).

> The outermost layer is the *exosporium*, a thin protein covering. Within this are the *spore coats*, composed of layers of spore-specific proteins. Below the spore coat is the *cortex*, which consists of loosely cross-linked peptidoglycan, and inside the cortex is the *core*, which contains the core wall, cytoplasmic membrane, cytoplasm, nucleoid, ribosomes, and other cellular essentials. (Madigan et al., 2012)

All of the layers listed above work together to protect the cell while it is in dormant state. This is illustrated below in Figure 1. "The complex intercalates (insert between bases) in DNA, which stabilizes DNA against heat denaturation" (Madigan et al., 2012).

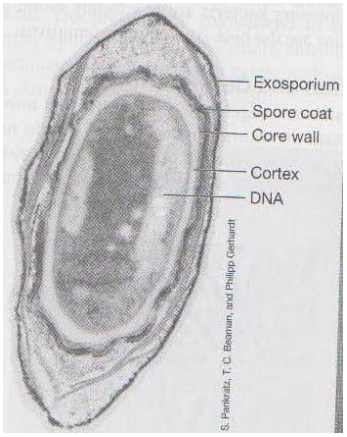

Figure 1: Spore Diagram

These spores, though very resistant, can be destroyed by the use of autoclaving. With the information given above, the goal for designing the autoclave will be to destroy a large percentage of the *C. difficile* spores.

CHAPTER 3

METHODOLOGY

Design of the Solar Autoclave

After much research and contemplation, the final design that was chosen involved the heat pipes. The heat pipes, collector header, and frame were purchased from SEA Groups Ltd. The model number is SEA-FZ58-12 and holds 12 heat pipes. All 12 heat pipes were installed for this design. The autoclave was purchased from All American. This company makes both pressure cookers and sterilizers. The autoclave chosen does not have an electrical input and is meant to be put over a heat source, such as a flame or a hot plate. It is made out of aluminum and has a capacity of 25 quarts. This particular model was chosen because it is able to hold a basic surgical set. The largest tool is about 14 in and can fit in the autoclave slanted. The copper piping used to connect the collector header to the autoclave is Type M 3/4" diameter copper piping, which can be purchased at any home improvement store. The insulation for the copper piping is Armacell 1/2" thick self seal pipe wrap. To ensure that the insulation sealed around the piping, black zip ties were used at certain points. The insulation casing for the autoclave and the lid was made from Foil back wrap insulation that is 1.5" thick.

Since one of the goals was to have no electrical input, pumps were out of the question. It was necessary to have each of the components at certain heights so that gravity could assist in creating the circulation. The autoclave was set up at the highest point, since steam rises. The collector header where the heat pipes are attached was at the lowest point. The water was poured directly into the autoclave, where it would drain down into the collector header to be heated. It was expected that the steam would rise into the autoclave and when it lost energy and cooled down, it would fall back down to the collector header to be reheated. The final design is shown

in Figure 2. The pipes were copper covered in insulation. The steam was allowed to flow freely throughout the system. It was directed by the slight slant of the collector header, pushing the steam into the direction towards the autoclave (shown in Figure 3).

Figure 2: Final Design

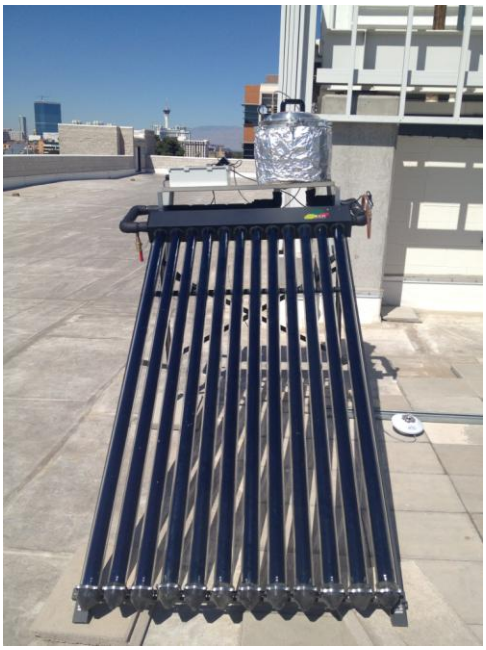

Figure 3: Final Design

Testing Procedure

In order to track events during the experiments, a data logger and many different sensors were used throughout the system. The data logger used was a Campbell Scienctific CR 1000, which comes equipped with a computer program that assists in writing the program to read and collect all of the data from the different sensors. The program is easily written and can be imported to Excel to be analyzed. A laptop can be connected while an experiment is run and the data points can be plotted so that the user can see the changes. This feature makes it easy to see if the cycle is working during the experiment. There are thermocouples at the inlet and outlet of the collector header, for the ambient air, reference temperature (within the data logger and an additional one added to the data logger), and a final one that goes into the top of the lid of the autoclave to record internal the temperature (Model Number: CF-000-T-2-60-1). All of the thermocouples were purchased from Omega. The thermocouple that was in the autoclave reaches about a 1/4" into the autoclave. The thermocouples for the inlet and outlet were placed on the outside of the piping beneath the insulation, before the collector header and after. A pyranometer is an Eppley PSP used to measure the incident radiation of the sun (Figure 4). This was placed at the same angle as the heat pipes so that the pyranometer would be receiving the same amount of radiation as the heat pipes. A pressure transducer (Model Number PX309-100A5V), purchased from Omega, was added near the outlet of the collector header to keep track of the pressure changes throughout the experiment (Figure 5). It has a pressure range from 0-100 psia and a working temperature range of 4 to 185°F.

Figure 4: Pyranometer

Figure 5: Pressure Transducer

First, the solar autoclave was tested to see if it was able to reach a temperature of at least 121°C and a pressure of 15 psi consistently for at least 30 minutes after reaching this state. This

was done by adding a measured amount of deionized water into the autoclave and then it was sealed. The system was monitored using many sensors throughout and left to reach at least 17 or 18 psi. Once this was achieved, the air would be purged from the system and the autoclave would be left to go through the sterilization process. The system needs to be able to perform this process multiple times before bacterial testing can begin.

Next, the success of sterilization and efficiency of the solar autoclave was tested. The first test involved the use of an autoclave strip. This is a small strip of paper that changes color if it has been "sterilized." If this test is successful, then actual bacterial testing would be conducted. The first test would be conducted with *B. subtilis* and *B. stearothermophilus*. They would be plated on small squares of stainless steel to imitate medical equipment. The plated square would be placed into the solar autoclave and, in theory, sterilized. The sterilized plate would then be compared to a control plate (a plate that also has the bacteria). If it passed the conditions in the sterilization standard, then it is possible to move forward to test with *C. difficile*. The process would be repeated for *C. difficile*.

CHAPTER 4

RESULTS

The initial testing first involved finding the correct amount of water to work with. If too much water is added, the system, including the water reaches a steady state and is not able to produce superheated steam. Too little water and the system will not have enough steam to fill the whole system and be able to purge.

The first test used 1 liter of deionized water. This was too much for the system and it was not able to reach the goal temperature or pressure. Figure 6 shows all of the temperatures throughout the system. It should be noted that there are two reference temperature lines. One is from the data logger itself and the other is an additional thermocouple that was added. They are basically the same temperature, which shows that the data from the thermocouples is accurate. Figure 7 displays the radiation for the time that the experiment was done. For ease of analyzing the data, Figure 8 includes both the temperature and the pressure of the autoclave. It can be seen that the autoclave reaches just above 60℃, but because the pressure is not able to keep increasing, the steam loses its energy and falls back down to the collector header, dropping the temperature of the autoclave. With this information, the amount of water had to be reduced in order for the system to reach 15 psi and 121°C.

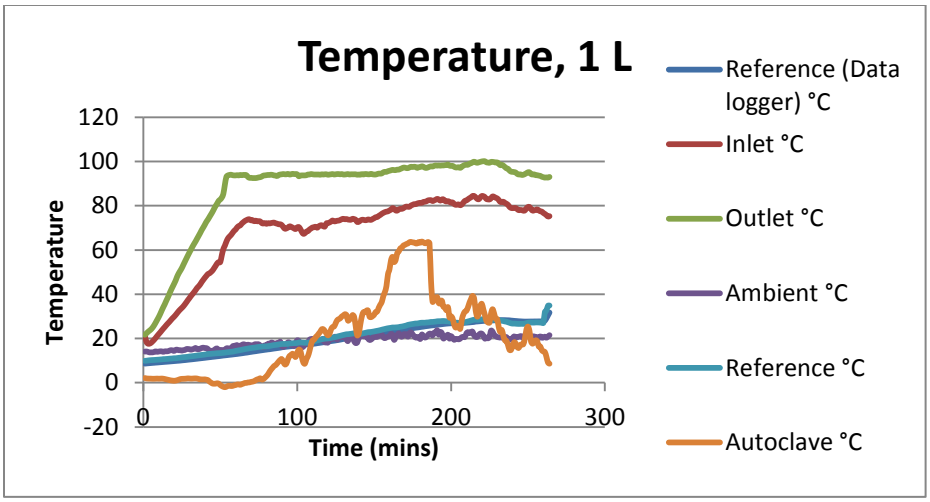

Figure 6: 1 L, Temperatures

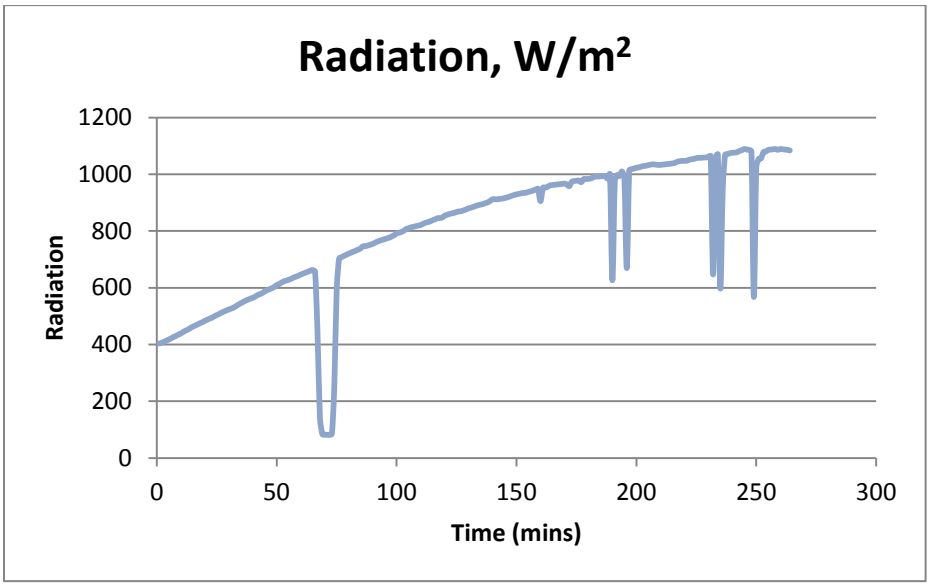

Figure 7: 1 L, Radiation

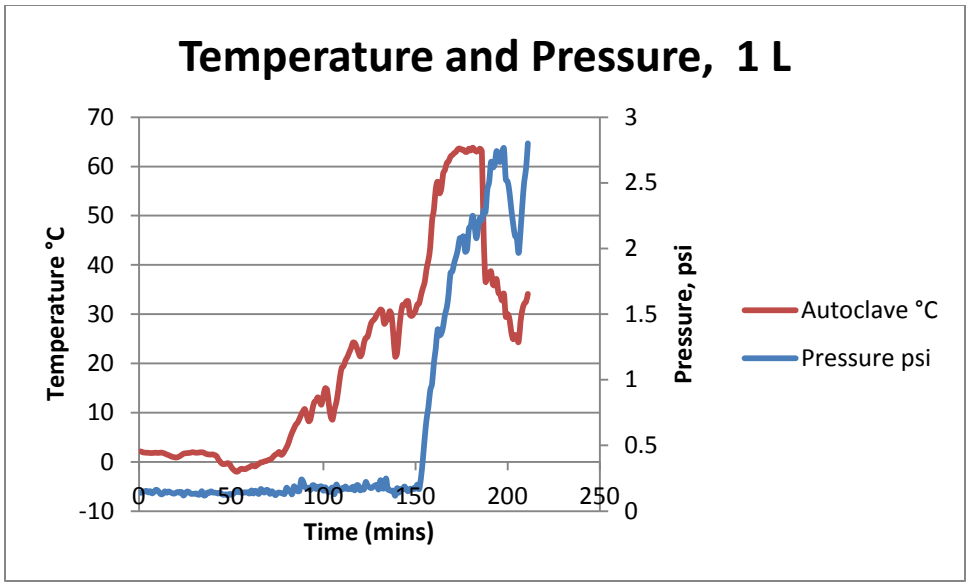

Figure 8: 1 L, Temperature vs. Pressure

The amount of water was reduced to 300mL and the system was run again. The temperatures throughout the system are shown in Figure 9. The radiation from that time period is in Figure 10. The temperature versus pressure graph (Figure 11) shows that the system did work; not only was the autoclave able to reach a pressure of about 17 psi, but the air was purged and the system was able to rebuild the pressure. The autoclave was at a temperature of above 121°C for over 50 minutes. This trial shows that the solar autoclave can reach the goals requisite for sterilization. The experiment was repeated again with the same amount of water and it was successful yet again. For this trial, the temperatures throughout the system, radiation from the time the trial was run, and the temperature versus pressure graphs are shown in Figures 12, 13, and 14, respectively. In this trial, the autoclave was able to reach a pressure 17 psi and the system was purged of its air. From the graph, it can be seen that the pressure was steadily increasing back up to 17 psi. One thing to note is that the temperature of the autoclave in this trial did not reach the goal of 121ºC. The maximum temperature reached 118.77ºC. However, there may have been some error with the thermocouple used. Using a more accurate

thermocouple, the temperature may actually have reached our goal. Another note to make is the differences in radiation on the two days. The two days are compared in Figure 15. Though Trial 1 probably had a partly cloudy day because of all the drops in radiation, it didn't begin to decrease until over 100 minutes. Trial 2 reached its peak at about 50 minutes and began to decrease. The autoclave was given more time to be exposed to higher levels of radiation in Trial 1 than in Trial 2. This difference could be why the autoclave was not able to reach the goal temperature. Though there were two successful trials, the system should be able to run through the cycle multiple times consistently before bacterial testing can be performed.

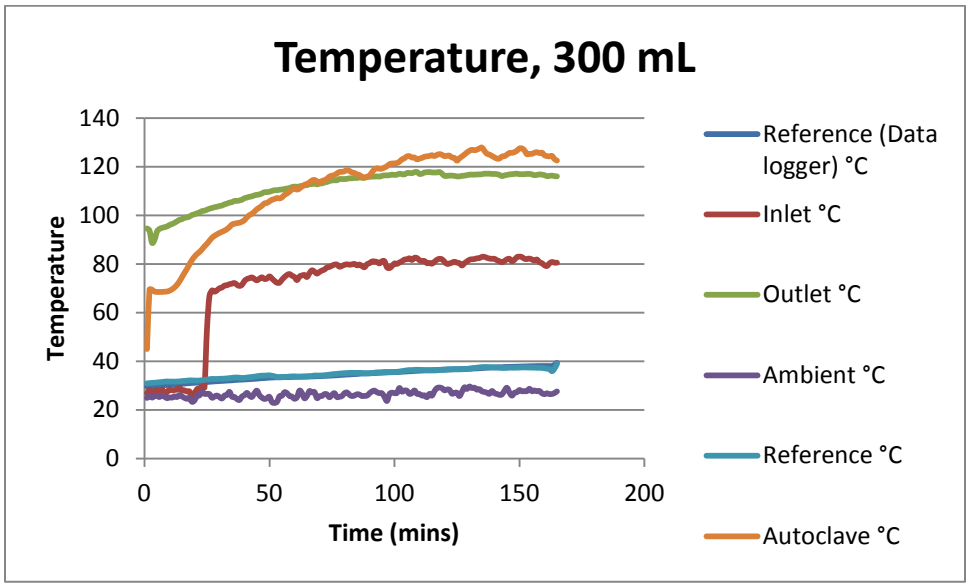

Figure 9: 300 mL, Temperatures, Trial 1

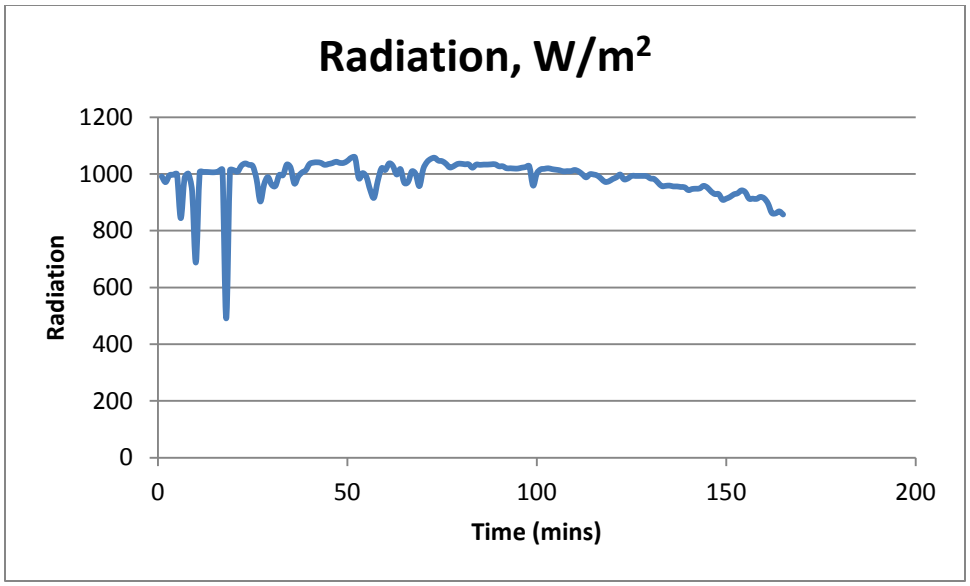

Figure 10: 300 mL, Radiation, Trial 1

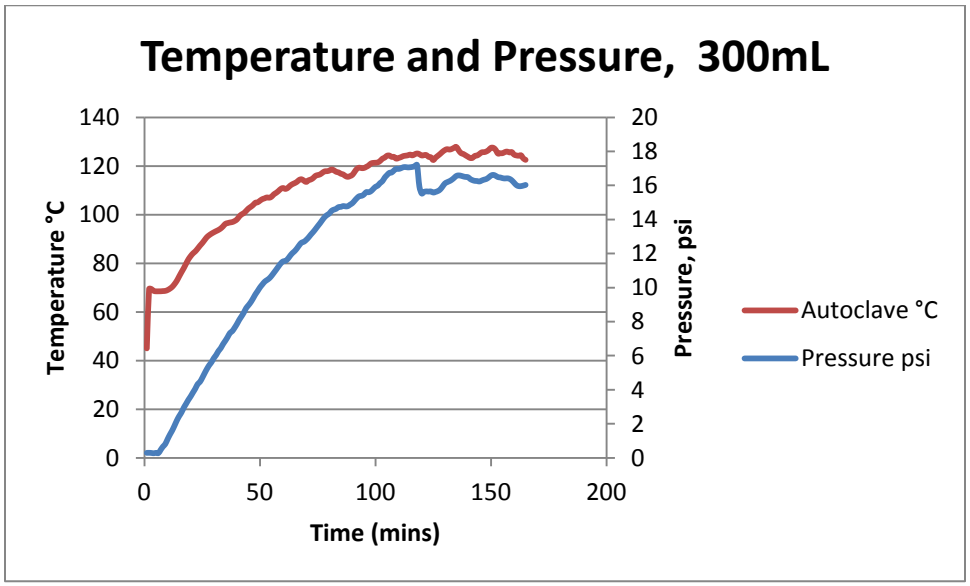

Figure 11: 300 mL, Temperature vs. Pressure, Trial 1

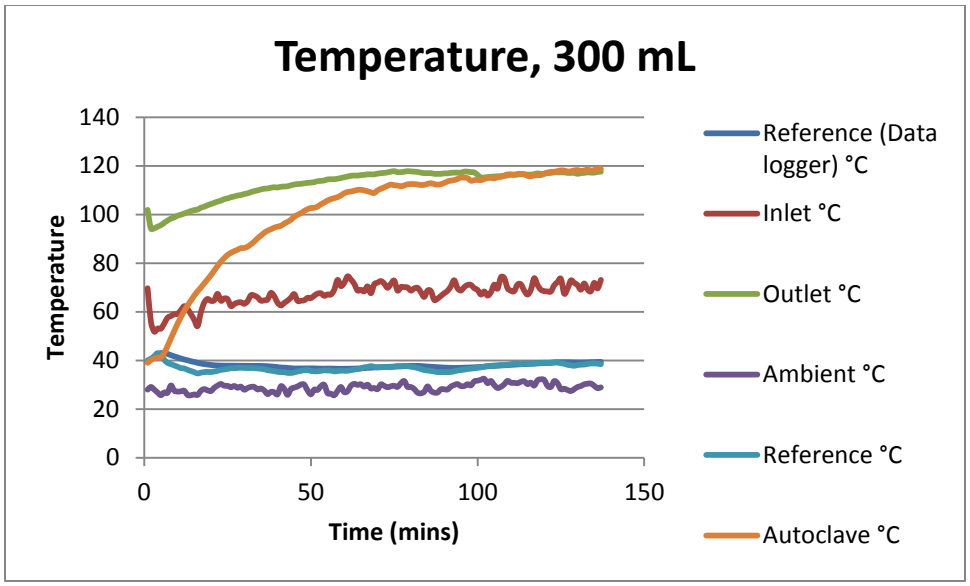

Figure 12: Temperatures, 300 mL, Trial 2

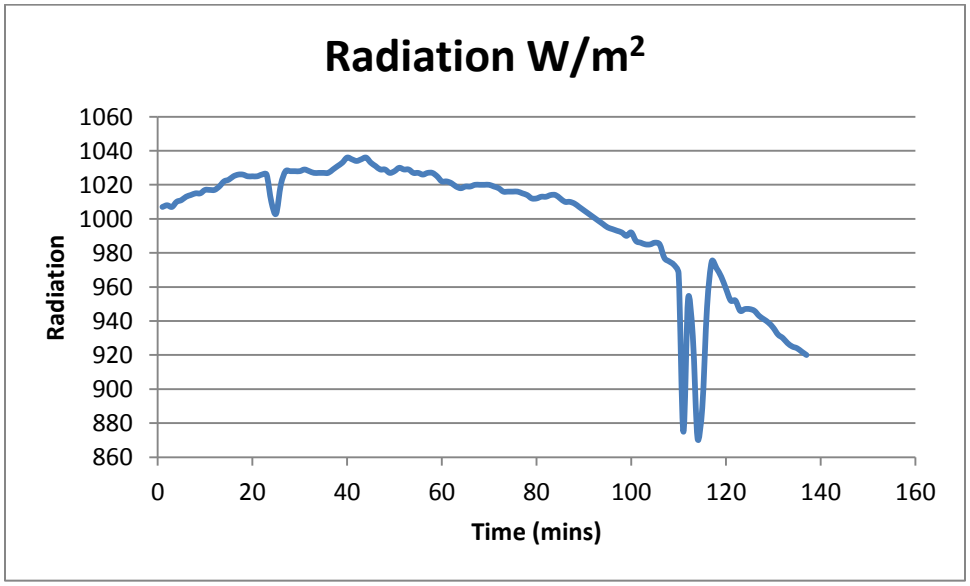

Figure 13: Radiation, 300 mL, Trial 2

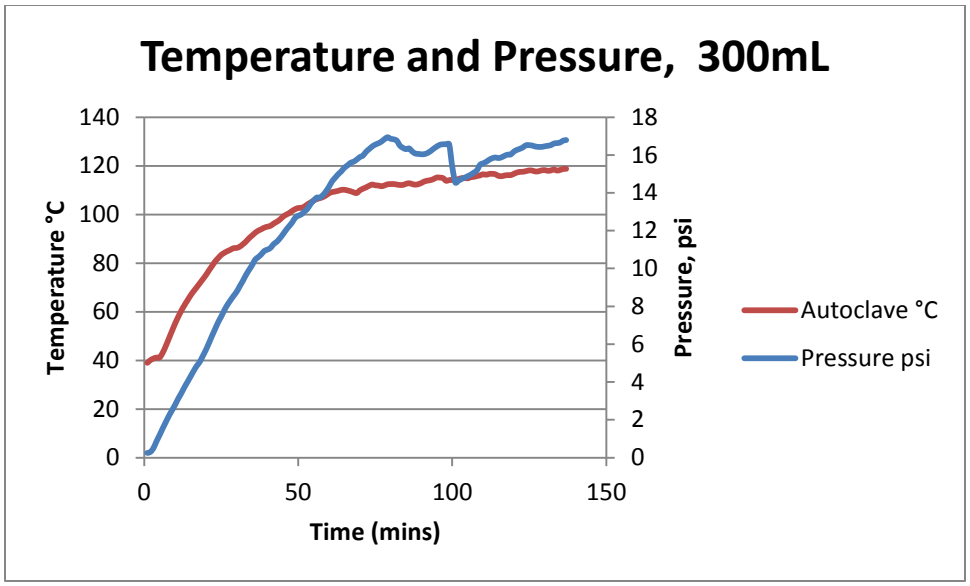

Figure 14: 300 mL, Temperature vs. Pressure, Trial 2

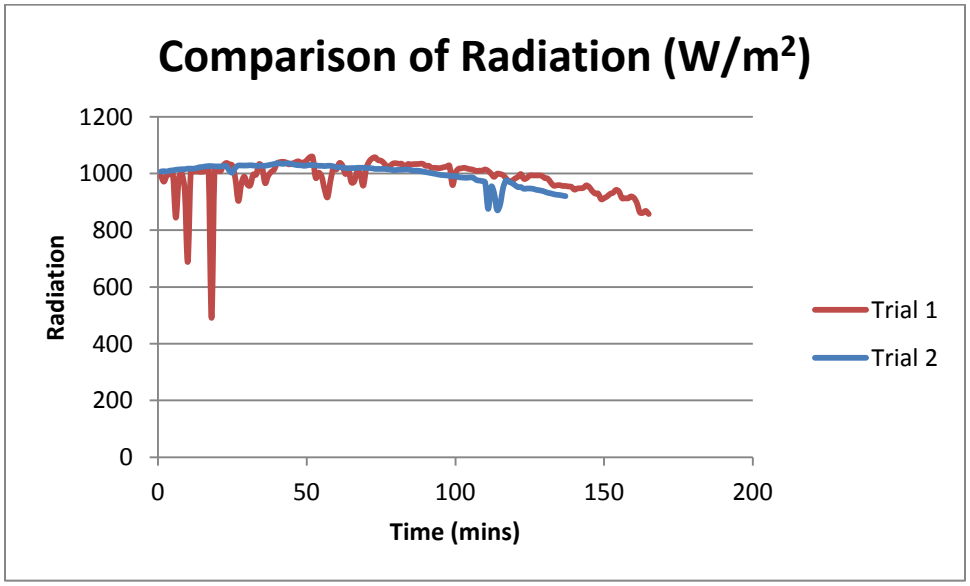

Figure 15: Trial 1 vs. Trial 2 Radiation

When the system was run again, it was not able to hold pressure at all. There was a leak at the seal of the autoclave. It was not possible for the autoclave to build up pressure, thus making it impossible for the system to reach the goal temperature and pressure. To fix this, a groove for an O-ring was machined (Figure 16). This would allow for a full seal and assure that the lid of the autoclave would close level. Once this was done, the system was run again.

However, it again was not able to reach at least 15 psi. After inspection, it seemed as though there was another leak at the point where the thermocouple and pressure gauge are inserted into the lid of the autoclave.

Figure 16: Machined groove for O-ring

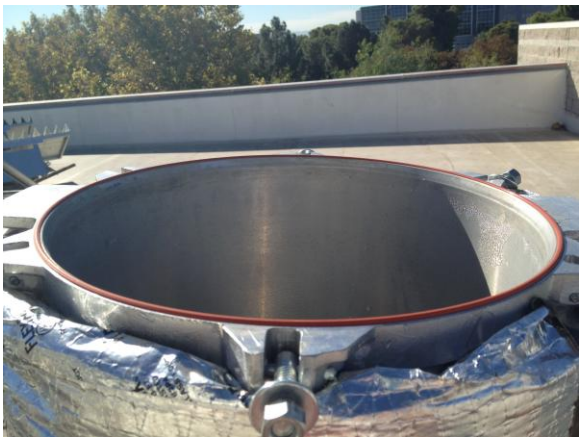

Figure 17: Autoclave with O-ring

The last trial graphs are shown below in Figures 18, 19, and 20. From the temperature versus pressure graph, it can be seen that the autoclave was not able to reach the goal temperature and pressure. The system was left to run for the day, but it was still not able to build up pressure above 9 psi and the temperature did not cross about 70°C. This means that there was a constant leak in pressure somewhere in the system. Because of this leak, it made it impossible for

a sterilization cycle to occur. It will be necessary to either redesign the solar autoclave or to find where it is leaking.

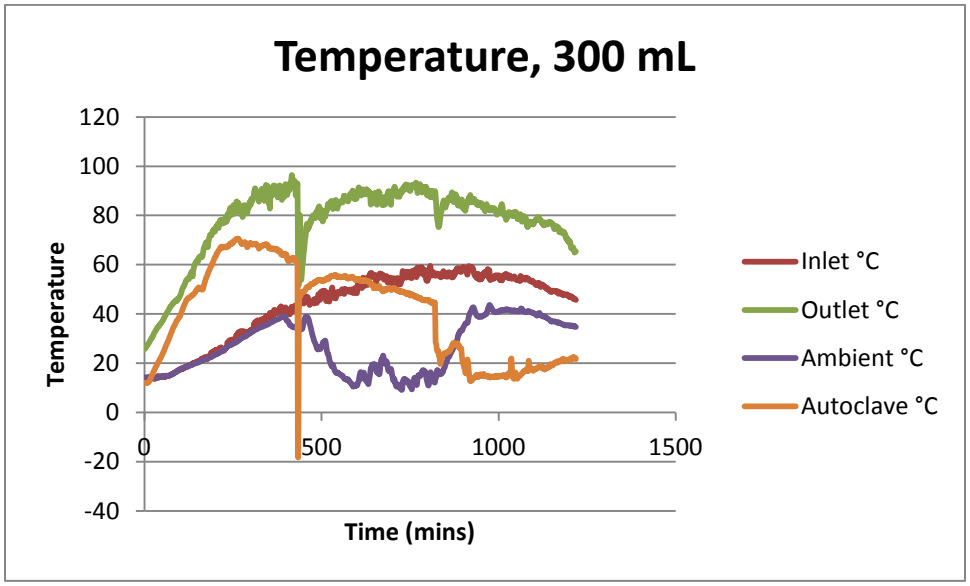

Figure 18: Temperatures, Last Trial

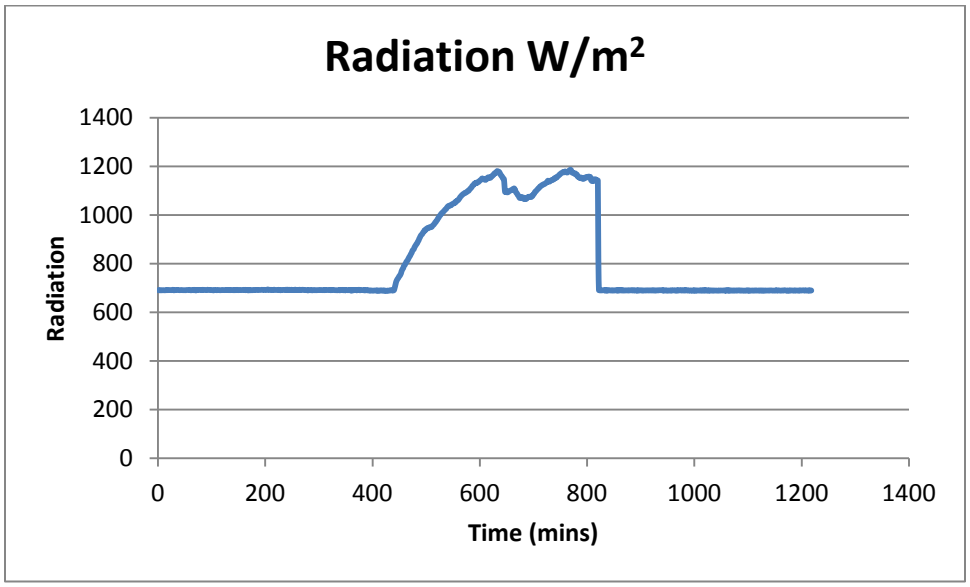

Figure 19: Radiation, Last Trial

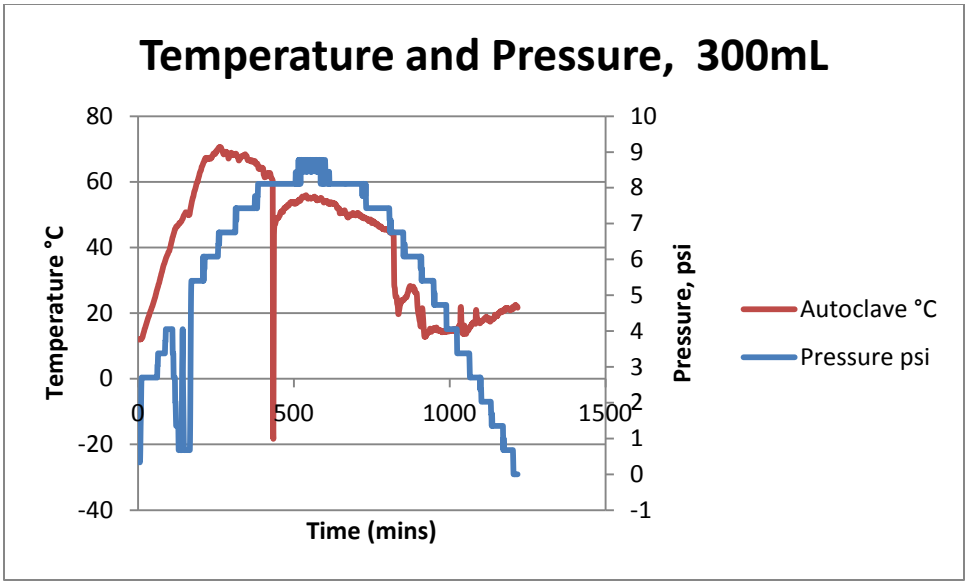

Figure 20: Temperature vs. Pressure, Last Trial

CHAPTER 5

DISCUSSION

From the results shown above, it can be seen that a solar autoclave can be designed, but further research and redesign is needed. In order to fix the pressure leak issue, it will be necessary to find where it is leaking from. There are many possible leakage points. The seal on the autoclave had been resolved by adding the O-ring. The main points that need to be looked at would be where the thermocouple and pressure gauge are connected to the lid of the autoclave (Figure 21). It would need to be taken apart and cleaned with acetone to remove any dirt that may have collected over the time the autoclave was sitting outside. Teflon tape and a sealant could be added to help those points from leaking. If it is not the threads where it is leaking, it may be that the pressure gauge itself is leaking. After months of exposure to the sun, the materials in the pressure gauge may have weakened and cracked. This would have to be replaced before another test is run. Another place where it could be leaking pressure is from the points where the copper piping attaches to the autoclave (Figure 22). This can be fixed the same way as the previous issue. Once these are both taken apart, cleaned, and put together again with a new layer of Teflon tape and sealant, the system could be run as if it was being tested, then the points where it was thought there was pressure leaking could be applied with a solution that begins to bubble if there is air leaking. This would help in finding if these points are still an issue. Once this is resolved, it would be possible to begin testing again.

Figure 21: Piping where the thermocouple and pressure gauge connect to the lid

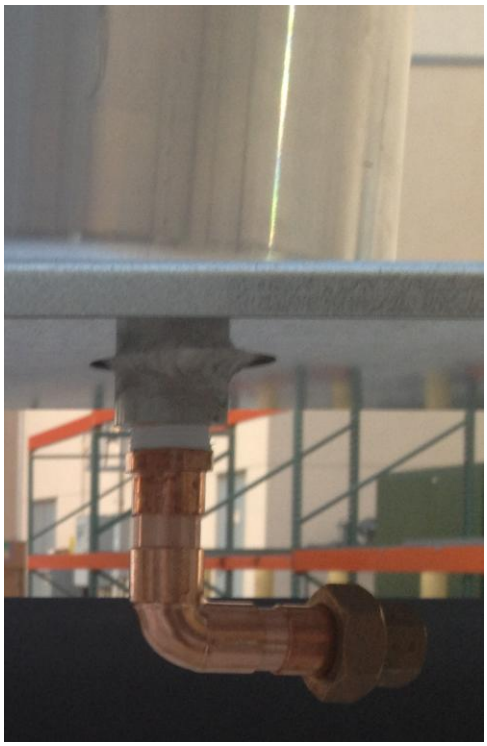

Figure 22: Copper piping that attaches to autoclave

Another issue that arose during testing was a lack of energy to produce steam to fill the system. SEA, the company the heat pipes and collector header were purchased from, sells multiple sizes in collector headers. Their largest can hold up to 24 heat pipes. This would increase the amount of energy brought to the system. It may also help in speeding up the process of producing steam. On a partly cloudy day, the additional heat pipes would assist in making up for the lost radiation from the clouds. The only negative aspect of this would be that it would take up much more room than the original design. It would also make it less portable, since transporting heat pipes is extremely difficult. They need to be moved vertically and are very fragile since they are made of glass. To determine how much additional energy is brought to the system, the larger collector header would need to be tested. This would involve having to cut up new copper piping and weld it together and attach the autoclave to it. New sensors and a data logger would be attached to the system to record all of the data throughout the experiments.

There are a few other issues that should be dealt with before continuing experimentation. The autoclave itself may need to be replaced if it still causes issues. The one purchased needed many modifications for issues that should not have been present. Other options may be looked into if they are better designed. The insulation on the copper piping should be replaced with something similar to the insulation on the autoclave. The current insulation is beginning to fall apart from the exposure to the sun. It would need to be covered in some kind of foil to help protect the insulation from deteriorating. This would also help the pipes keep all of the heat and not lose it to the environment. The more heat the system is able to transfer to the autoclave, the faster the autoclave would reach the goal temperature and pressure.

All of these improvements in design will most likely increase the price of the solar autoclave. It should be kept in mind, however, that the goal of this study was to be able to design

an affordable autoclave that is still as efficient as those run by electricity. The improvements and the cost will have to be compared to see which is imperative to have. As long as the solar autoclave's price stays below $3,000, it will still be more affordable than the electric autoclaves.

Though the study was not successful in designing a reliable solar autoclave, the results indicate that it is still possible to do so. The lessons learned from the tests in this study will aid in the further development of a solar autoclave that will constitute a feasible option for the medical needs of developing countries. They will be able to save money on both energy and water with this type of design as it does not need a large amount of water or any energy input other than that provided by the sun. Once a solar autoclave is successfully designed, it will need to undergo bacterial testing and then further redesign may be needed to raise its efficiency, depending on the results. This study is an attempt to move the research further toward the design of an effective solar autoclave that will meet the urgent need of efficient health care in developing countries.

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