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DEVELOPMENT OF A SOLAR WATER PASTEURIZER WITH INTEGRAL HEAT EXCHANGER (SPIHX)

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ABSTRACT
There is potential for treating waterborne diseases using a solar pasteurizer with integral heat exchanger in developing countries. The team conceptualized and designed a SPIHX system prototype with auto thermostat valve, using various concept design and selection tools. Testing was done to measure water temperature as a function of solar radiation, and was compared to a heat transfer model. Values for time and temperature were also compared to a safety curve, and tests for coliform bacteria quantities were taken before and after pasteurization. While the system was efficient from a flow rate standpoint, insufficient reduction of pathogens (due to insufficient duration of time at elevated temperature) is the main problem to be fixed in Phase II. There is also room to improve cost and fabrication methods, gain more test date and work directly with Venezuela.

NOMENCLATURE

a_0:	First safety zone coefficient
a_1:	Second safety zone coefficient
a_2:	Third safety zone coefficient
C_p:	Thermal Heat Capacitance
C'_s:	Heat Transfer Model Coefficients
d:	thickness
ε:	Heat exchange Effectiveness
L(T):	Distance traveled above certain temperature
$\dot{m}$:	Mass flow rate of water in the pasteurizer
$M_{thermal}$:	Thermal Mass
ρ:	density
Q'':	Energy(Heat) per area
Δt:	Required time at Temperature
T_a:	Ambient temperature
T_{init}:	Initial temperature
T_{out}:	Outlet temperature
T_{Past}:	Temperature of safe pasteurization
$T(x)_{Past}$:	Temperature at a given Length
T_{valve}:	Temperature at Thermostatic Valve
time(T):	Actual time at Temperature
U_L:	Total heat loss
V_m:	Mean velocity
x:	Distance along Pasteurizer

INTRODUCTION
The MSD team was presented the task of designing a solar water pasteurizer to treat waterborne diseases in unsafe drinking water for low-income families in developing countries. To arrive at this design, research was done to understand the problem at hand.

Background
According to the World Health Organization, there are over one billion people that do not have access to clean water, and every year, over five million people die due to lack of safe and sanitary water [1,2]. At the 2002 World Summit for Sustainability Conference, a target was set to halve the proportion of people without access to clean water [3]. While considerable improvements have been made to get clean water to urban areas, it is the rural areas of the developing world that fall short of providing safe water.

According to UNICEF, 50% of the children in rural areas in the 50 least developed countries do not have access to improved drinking water sources [1].

Currently there are technologies for treating water that include boiling, chemical disinfection via chlorination, slow sand filtration, ultraviolet disinfection, and solar disinfection. Many of these treatment methods are costly to maintain, and are not efficient from a sustainability point of view. Since energy from the sun is readily available in most underdeveloped countries with unsafe water sources, developing a solar water treating technology seemed a more viable and sustainable option.

Solar water treatment, otherwise known as solar pasteurization, works on the principal that protozoa, bacteria and viruses which cause waterborne disease can be killed at elevated, but not boiling temperatures. Quality of pasteurization is a function of temperature versus exposure time, such that the most thermally resistant pathogens are mostly inactivated in less than one minute above 70° C [4]. Parry and Mortimer found that Hepatitis A was fully inactivated within 4 minutes at 70° C and 30 seconds at 75° C [5]. Feachem et. al. proposed a safety zone curve relating temperature versus exposure time to destroy enteroviruses, the most resistant pathogens to heat, which can be seen in Fig. 1 [6]. This curve will be used later to evaluate the quality of the pasteurization system.

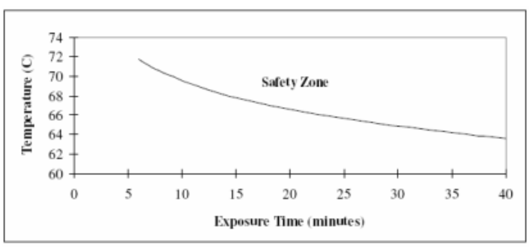

Figure 1: Safety Zone for Inactivation of Enteroviruses

Benchmarking

In the mid 1990's solar pasteurization caught on as a technology filled with potential, and early systems tended to be batch processed. For instance, the Aquapak™ [7] is a low-cost polyethylene bag that costs only about $1 to manufacture (Fig. 2). It heats water up to 67° C and then uses a water pasteurization indicator (WAPI) to find out when the water has been heated sufficiently. It is relatively cheap, but takes a long time to pasteurize, and struggles to pasteurize more than 5 liters/day. As with other batch process pasteurizers, the operator must monitor them and replace water immediately after pasteurizing to optimize performance.

Another technology used for solar pasteurizing of water was evacuated tubes (ETs), which have a much higher volume output. Also, on a cloudy day an evacuated tube can still produce enough pasteurized water for an entire family to drink. However, it is a complex manufacturing process. An example of price from one such company [8] is quoted at ~$100 per tube, and is comparable in price to other ET systems.

As a result, flow-through systems were developed to use a thermostatic valve or other temperature control to regulate continuous flow through system while ensuring pasteurization temperatures are reached. For instance, the SunRay 1000™ system (Fig. 4) [9] is capable of pasteurizing 1,000 liters per day, but at a cost of ~$8000. For rural families requiring less water, this is not economically feasible. However, by incorporating some form of heat exchanger to recover heat from the treated water, the throughput on any system can be improved by a factor of four or more [10].

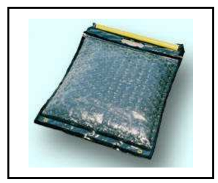

Figure 2: Aquapak™

Figure 3: Evacuated Tube

Figure 4: Sunray 1000™

FORMATION OF NEEDS AND SPECS

There was a noticeable lack of efficient flow-through systems designed for rural family applications. Therefore, the main goal of the project was to conceptualize a solar water pasteurizer, which could be mass produced to treat unsafe water in rural areas. To do this, the multidisciplinary team needed to develop appropriate design specifications necessary to succeed, and use these to rank possible integrated solar pasteurizer concepts.

The main goal of the project was to create a pasteurizer that is economically affordable (low unit cost), effective at reducing pathogens, requires no electricity or added chemicals, and can be fabricated locally in Venezuela. While Venezuela is not ranked as one of the 50 least developed countries, it was a good source of contacts given projects done in solar energy by previous Senior Design teams at RIT. Also, the pasteurizer needed to be functional, and able to successfully pasteurize enough water for a large rural family, without leakage or chemical contamination. The pasteurizer needed to be durable to external forces and able to be integrated anywhere with abundant solar irradiation. Finally, it required that the end user would not need to constantly monitor the system or be expected to perform difficult maintenance procedures.

Using these needs, specifications were formulated. Some main specifications are listed below:

- Total cost for materials to be less than $60 when mass produced
- Output volume to be over 20 Liters per day when averaged monthly throughout the year
- Total coliform bacteria reduction to be greater than log 4 (99.9% inactivation success rate)
- Less than 3 minutes of required hourly maintenance by the end user
- Product must be durable out in the environment and last 5-15 years

These specifications would dictate the success of the prototype.

DESIGN PROCESS

Concept Design

Several designs were initially created, which focused on the heat-exchanger/collector assembly, and were judged using the aforementioned needs. Most of the systems were designed as a solar pasteurizer with integral heat exchanger (SPIHX), as shown in Fig. 5. To explain this diagram, the top sheet is used as the solar collector material. A second sheet acts as a heat exchanger plate. By adding a third sheet at the bottom, a counter-flow heat exchanger with two channels is created.

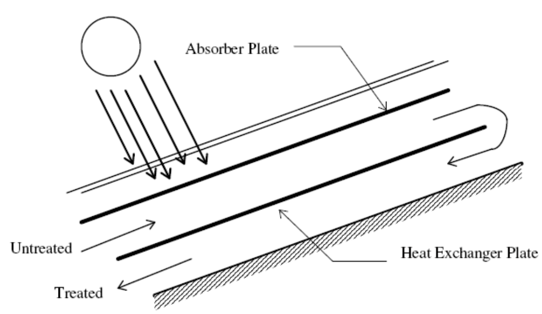

Figure 5: Schematic of solar pasteurizer with integral heat exchanger (SPIHX) assembly.

There were also other designs (smaller evacuated tube, “tube within a tube”) that were considered less feasible. Using a Pugh Chart and a QFD Matrix as concept selection aids, the group decided that the most feasible and effective system would be a SPIHX system that would look similar to Fig. 5, with dimpled aluminum sheets for added structural rigidity.

The materials for the SPIHX plating and the enclosure were researched using the Cambridge Engineering Selector (CES) 2005 program. Figure 6 shows an example of how price and thermal conductivity for different materials were found to select the SPIHX plate material. This helped the group arrive to three metals: aluminum, copper and steel. After further research, it was decided that aluminum (specifically FDA approved 5052 aluminum) was to be used for the three-plate system. CES 2005 also helped the group to conclude fiberglass would be the best insulation material and that plywood would make the best enclosure material.

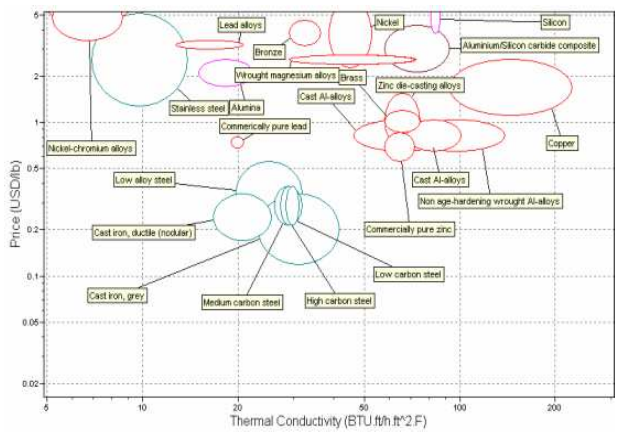

Figure 6: CES 2005 Graph of Thermal Conductivity vs. Price

Other key components, such as the valve regulation, feed water system, air purge control, and enclosure systems were seen to be compatible with any type of heat exchanger. The following determinations were made by the team in terms of cost effectiveness and ease of integration:

- Valve regulation: use an auto-thermostat valve rated at 70-75° C, external to SPIHX for easy access.
- Air purging regulation: An off-the-shelf air-release valve threaded into the thermostat valve housing (highest point of pasteurizer).
- Enclosure: Made out of plywood with notches to hold sides of SPIHX and glass panel. Insulate bottom with fiberglass.
- Solar collection: Absorb solar radiation that passes through 1/8” (3.16 mm) thick glass using a selective black-coated surface for maximized absorption and minimized emittance. Radiation

not absorbed is retained in the enclosure, creating a green house effect.

Flow Rate Model

In order to model the flow of the water through the heat exchanger, an Excel spreadsheet was made to calculate the flow rate of the water based on solar radiation level per hour. The team was able to find hourly solar data for San Juan, Puerto Rico that closely resembled the weather in Venezuela. The equation for the steady-state flow rate was modeled in *An Investigation of a Solar Pasteurizer with an Integral Heat Exchanger* by Stevens [11] and is Eq. 1:

$$m = \frac{C_3}{\ln\left(C_4\left(C_5 - C_6 e^{\frac{C_7}{m}}\right)\right)} \quad (1)$$

These constants are calculated through a series of equations based on many different parameters that account for heat loss, different forms of incoming radiation, and the effects of material properties and sizes on heat transfer. The spreadsheet was set up such that these parameters could be changed in order to reach above the minimum flow rate while keeping the cost of the final system down. The main parameters and their values of the model that affected the output of the pasteurizer are shown in Table 1, resulting in a sufficient output of the system as shown in Figure 7:

Table 1: Parameters Chosen

Width Collector	0.2286	m
Length Collector	0.8128	m
Thickness of Channel	0.0013	m
valve open temperature, T_{past}	71	°C
thickness of collector or bottom plate	0.001	m
thickness of glass	0.00159	m
thickness of air between plate & glass	0.08	m
thickness of heat exchanger	0.001	m
thickness of insulation	0.03	m
total thickness	0.1236	m
Conductivity of plywood	0.13	W/m-K
Emmisivity of collector	0.49	
Emmisivity of glass	0.88	
Tilt angle of collector	10	°
Solar absorptance of collector	0.88	
ρ of plates	7854	Kg/m^3
Cp of plates	434	J/kg-K

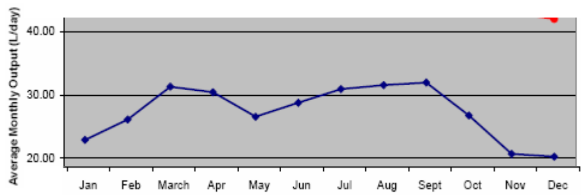

Figure 7: Avg. Monthly Output for Initial Pasteurizer Parameters Above

There was an initial warm up time each day before water reaches pasteurization temperature and begins flowing. The warm-up time that is required each day was found, providing a more realistic value for output. The model of the transient process, used to calculate warm-up time [11], is shown in Eq. 2:

$$Q'' = M_{thermal}\left(T_{final} - T_{initial}\right) + U_L \Delta t\left(\frac{T_{init} + T_{final}}{2} - T_a\right)$$

$$T_{final} = \frac{Q'' + M_{therm} T_{init} - \frac{U_L \Delta t T_{init}}{2} + U_L \Delta t T_a}{\left(M_{therm} + \frac{U_L \Delta t}{2}\right)} \quad (2)$$

where thermal mass is defined in Eq. 3:

$$M_{thermal} = \left(\rho d C_p\right)_{metal} + \left(\rho d C_p\right)_{water} \quad (3)$$

Prototype Phase

It immediately became apparent that the dimple design was not feasible due to stress analysis coupled with the inability to spot weld on an aluminum plated dimple to a middle aluminum plate. Therefore, the first prototype was made without dimples, and was sealed using perimeter welds.

There were conceptual problems with the prototype, in that it couldn't handle the water pressure without external support. This addition was cumbersome, adding incentive to have the SPIHX assembly with built-in rigidity. There was also incentive to eliminate the welding process, which required a skilled welder and resulted in significant warping of metal. There were two alternative prototypes that were developed and judged for advantages and disadvantages: A bolt-and-spacer SPIHX using silicone to seal the perimeter, and an Alumaloy™-welded SPIHX requiring lower welding temperatures and less skill.

While the bolt-and-spacer design had the longest critical path to build, the dimensional rigidity, simple labor requirements, good sealing and aesthetic positives convinced the team that it was the best prototype to continue onto the final design.

FINAL DESIGN

Heat Exchanger Design

The heat exchanger was the core piece of the overall pasteurizer. The component must provide a high rate of heat transfer, and handle operating pressures required to drive water through the system, be leak proof, and be easy to manufacture. Material selection and fabrication processes were two key design areas taken into consideration.

Figure 8 shows a detailed view of the heat exchanger. The design consists of three 32" (81.28 cm) x 9" (22.86 cm) 18 gauge (1mm thick) aluminum sheets. All three plates were fastened by seventy-six 4-40 screws. Two 1 mm gaps were created through the placement of two 4-40 washers in each gap along the length of the heat exchanger for water to travel through. Silicone sealant was used along the perimeter of the plates to prevent leakage along the sides.

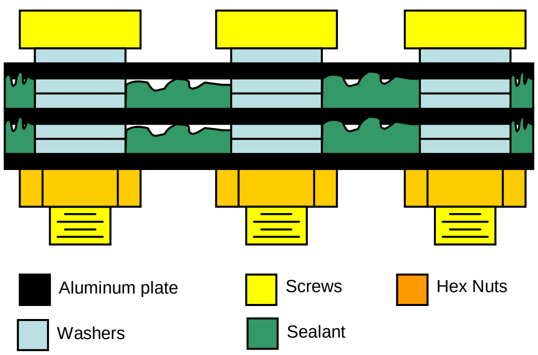

Figure 8: Detailed cross-sectional view of heat exchanger

Figure 9 shows a flanged piece that was fastened at the inlet and outlet sections of the SPIHX. The inside diameter was threaded for a ¼" NPT connection, through which couplings could connect to external features.

Figure 9: Flanged piece for ¼" NPT connection

The heat exchanger was further fastened along the mid-section to prevent a 'ballooning' effect caused by the water pressure. Ballooning would increase the gap height and initial warm up time to reach pasteurization temperatures. Figure 10 shows the final assembly of the heat exchanger.

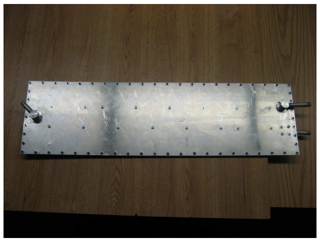

Figure 10: Assembled heat exchanger

The top plate was painted with a single selective coating (not shown above) to enhance solar absorptivity and retard emissivity.

Enclosure Design

Plywood was used as the enclosure material. Figure 11 shows a schematic of the enclosure.

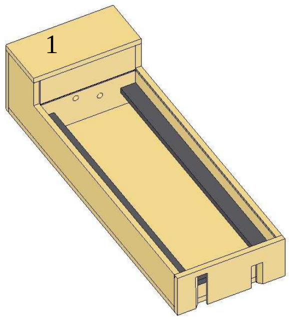

Figure 11: Assembled enclosure

The enclosure was designed so that the assembled heat exchanger can be dropped in. There are notches fitted along the perimeter to hold an installed glass panel. Any piping or tubing was fitted through holes and slots at either end of the enclosure.

The enclosure also provided for a separate compartment (1) to enclose the valve housing. This allowed the operator to change out a valve in case of failure without tampering with the rest of the system.

Valve Housing Design

The valve housing encloses an auto thermostat valve used to regulate flow and ensure that no flow occurs before the rated temperature of 71°C has been reached. The thermostat valve is a typical thermostat used in the radiator of automobiles. Because these thermostats are designed to allow some leakage even when fully closed, the exterior casing was modified.

Figure 12 shows an exploded view of the valve housing with the thermostat valve.

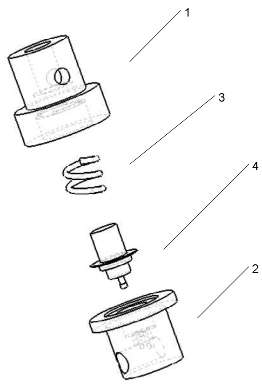

Figure 12: Exploded view of valve housing

The housing consists of a top (1) and a bottom half (2). The top housing (1) must allow enough room for the thermostat valve (4) to expand at a rated temperature of 71°C. When temperatures are below the rated temperature, the spring (3) keeps the valve in a closed position. The bottom half (2) is fitted with a gasket in the grooved section to ensure that there are no leaks past the valve when fully closed. Both halves of the housing had threaded holes for piping and smaller taps for connection of thermocouples during testing. Both halves of the housing have threaded ¼" NPT holes for piping. The assembly is held together by four 6/32" (0.476 cm) socket head bolts that are ¾" (1.905 cm) long.

The valve housing also incorporates an air vent. A natural property of water is its tendency to release air as it warms up. If enough air is released upon heating, pockets of air form, which have a high probability of blocking flow.

Feed Water Design

The feed water system consisted of an inlet bucket fitted with a filter, which addressed sediment issues, and UV resistant, high-temperature hosing. Hose clamps were used to connect the hose from the buckets to a double-threaded ¼" NPT pipe coupling which were then fitted onto the pasteurizer.

The inlet bucket was placed above the pasteurizer to provide enough pressure for the water to travel through the pasteurizer. The outlet bucket was placed below the inlet bucket but above the highest point of the pasteurizer to ensure that the bottom channel of the heat exchanger is flooded at all times. Hence, once in operation, the bottom channel should be empty only during the initial warm up period. Flooding the heat exchanger is necessary in order to enhance the heat transfer.

System Integration

Figure 13 shows the final pasteurizer assembly. The various subsystems mentioned above work in conjunction to provide operating pressures, feed and extract water from the heat exchanger, regulate flow via a thermostat valve, and minimize heat loss via the enclosure with insulation and glass.

Figure 13: Exploded view of valve housing

EXPERIMENTAL SETUP

After the SPIHX model was constructed, outdoor testing was done for a total of 10 days, between the months of April and May. During this time the test conditions were mostly favorable with minimal cloud cover and abundant sunshine. The pasteurizer was put out in the sun each morning and allowed to operate throughout the day. Using a data acquisition system, temperatures were monitored throughout the system using T-type thermocouples, which were placed in locations specified in Table 2:

Table 2: Thermocouple Setup

Thermocouple	Description
Valve	Fluid temperature near the thermostat valve
Inlet	Water temperature entering the pasteurizer
Outlet	Water temperature near the thermostat valve
FP 1	Front plate thermocouple 1, located 9.5" (24.13 cm) above the inlet
FP 2	Front plate thermocouple 2, located 13.75" (34.925 cm) above the inlet
BP 1	Back plate thermocouple 1, located 9.5" (above the outlet
BP 2	Back plate thermocouple 2, located 13.75" (34.925 cm) above the outlet

Along with the temperatures, solar data was logged as well as the flow rate of the system. Solar radiation was collected using a Li-Cor LI-200SZ light sensor, displaying the W/m^2 of solar energy from the sun. Flow rate of the system was calculated by monitoring the pressure rise of the outlet water tank, using a Freescale Semiconductor MPX2010 DP pressure transducer. The pressure transducer was calibrated for the specific tank used and a curve was fitted for the water level within the tank. From this curve, the change in water level inside the tank was measured. Due to noise levels associated with the pressure transducer, the tank level was averaged over a 10 minute time period, which was used to calculate the flow rate. Therefore, instantaneous flow rate was not measured, and instead an average flow rate of the system was monitored.

RESULTS AND INTERPRETATION

Safety Zone Consideration:

A critical assessment of the system was whether or not the water within the system has reached the pasteurization temperature and remained there for an appropriate amount of time. The conservative upper boundary for destruction of most thermally resistant pathogens, as used for the Feachem Safety Curve, can be approximately represented by Eq. 4 [11]:

$$T_{Past} = -9.851°C * \log(\Delta t) + 61.9°C \qquad (4)$$

Using the temperature distribution from the data within the system, the temperature profile was across the SPIHX system was fitted for a representative day, May 4 at 12:00pm. This profile is represented below.

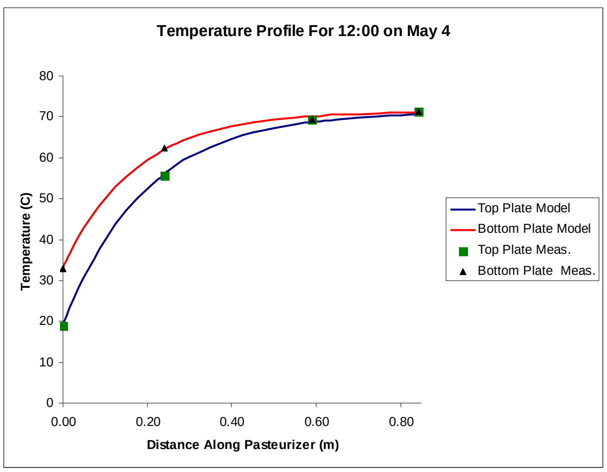

Figure 14: Temperature Profile across SPIHX on May 4 at 12:00, steady state operation.

The distance that the water travels when it is above a certain temperature can be obtained by solving Eq. 5 for x, which represents the temperature profile along the plate [11].

$$T(x)_{Past} = a_0 + a_1 e^{a_2 2x} \qquad (5)$$

Since the maximum velocity inside the system is approximately 50% greater than the mean velocity, the time above a specific temperature is represented by Eq. 6[11].

$$\text{time(T)} = \text{L(T)} / 1.5\ \text{V} \cdot \text{m} \qquad (6)$$

Using multiple data points from representative days, the exposure curve was graphed and compared to the safety zone.

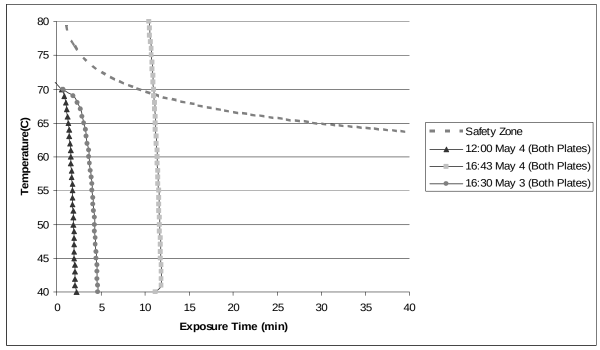

Figure 15: Temperature vs. Time Exposure Curve for Representative Days.

In order for pasteurization to be successful, the exposure curve needs to fall within in the safety zone at any point. It can be seen from the graph, that the safety zone was not reached for two of the three curves represented. After some investigation, it has been determined that the flow rate of the system was too high at certain times, not allowing the water to remain above a critical temperature for a sufficient amount of time. During May 4 at 16:43, the safety zone was in fact reached, due to lower flow rates obtained within the system. The high flow rates of the system would need to be better controlled and kept constant to ensure the safety zone is reached at all times. It is important to note that the safety zone curve is an extremely conservative approach, not taking into account the time the water is traveling in and out of the system and inside the valve.

Total Coliform Reduction:

In order to verify the effectiveness of the pasteurizer with regards to bacterial reduction, contaminated water was used within the system and a total coliform test was performed. The total coliform test 9221C is a standard EPA-approved test for potable water testing, found in Standard Methods for Water and Wastewater [12].

Water was extracted from two different locations to be biologically tested, pasteurized using the SPIHX system, and tested again to find the reduction of coliform. The first location was a small stream located at Scottsville Road, in Rochester, NY. The initial test resulted in 500 organisms per 100 ml. After pasteurizing the contaminated water sample the test resulted in 4 organisms per 100 ml. The second sample was taken from another small stream located on the RIT campus. The initial test came back with 80 organisms per 100 ml. After pasteurizing the test came back with 0 organisms per 100 ml. Table 3 below summarizes the findings.

Table 3: Full Coliform Bacterial Data

BEFORE TREATMENT-Perkins Stream				MPN Index	95% Confidence Limits	
					Lower	Upper
	2XLT (10ml)	1XLT (1ml)	1XLT (0.1ml)			
24 hr	5	3	0	80	30	250
48 hr	5	3	0	80	30	250
80 coliforms/100 ml sample (80 organisms/100ml)						
AFTER TREATMENT-Perkins Stream						
	2XLT (10ml)	1XLT (1ml)	1XLT (0.1ml)			
24 hr	0	0	0	<2	-	-
48 hr	0	0	0	<2	-	-
<2 coliforms/100 ml sample (<2 organisms/100ml)						
More than 98% Coliform Reduction						

BEFORE TREATMENT-Scottsville Pond				MPN Index	95% Confidence Limits	
					Lower	Upper
	2XLT (10ml)	1XLT (1ml)	1XLT (0.1ml)			
24 hr	5	5	2	500	200	2000
48 hr	5	5	2	500	200	2000
500 coliforms/100 ml sample (500 organisms/100ml)						
AFTER TREATMENT-Scottsville Pond						
	2XLT (10ml)	1XLT (1ml)	1XLT (0.1ml)			
24 hr	0	0	0	<2	-	-
48 hr	2	0	0	4	1	17
4 coliforms/100 ml sample (4 organisms/100ml)						
More than 99% Coliform Reduction						

It can be seen from the results that significant reduction was obtained through the use of the SPIHX system. However, a full scale log reduction was not able to be obtained, due to the nature of the test performed. A more specific test would need to be performed, in order to get the full scale log reduction obtained.

Pasteurizer Testing

The data collected during testing was compared to the aforementioned model in Excel. The solar radiation that was observed during testing with a light sensor was placed in the model in order to simulate the expected performance. The actual performance was then compared to the expected performance for the valve temperature and the volumetric flow-rate. These comparisons are shown in Figures 16 and 17, respectively.

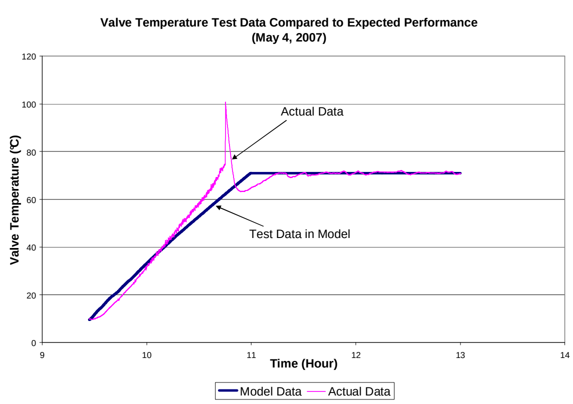

Figure 16: Valve temperature, transient and steady-state, for testing on May 4, 2007 compared to the expected performance

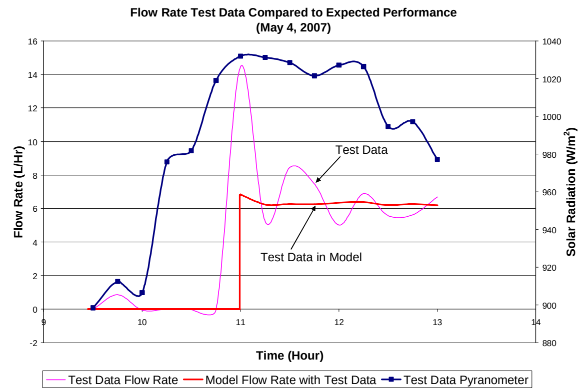

Figure 17: Volumetric flow rate for testing on May 4, 2007 compared to the expected performance

The warm-up rate that was predicted with the model closely resembled what was seen during testing, as shown in Figure 16. This comparison of the test warm-up period with the model prediction shows that the transient portion of the model was relatively accurate and slightly conservative in predicting this portion of the pasteurization. During the testing, the pasteurizer was angled directly at the sun, accounting for the increased warm-up rate, while the model only predicted for when the pasteurizer was faced due south for the entire day.

The average flow-rate from the test data was very similar to the expected flow-rate from the model. The sinusoidal curve in the test data seen in Figure 17 can be attributed to the thermostat valve cycling during testing. Cycling was caused by high pressure forcing cold water forward after the pasteurized water has passed through the thermostat valve. This colder water comes in contact with the valve and causes the valve to fully or partially close.

The model successfully predicted the performance of the pasteurizer. Therefore, this model could be used to implement the pasteurizer in Venezuela.

Output and Efficiency

Once the pasteurizer warmed up, the steady state flow of the water was observed. On May 3 and May 4, 2007, the steady-state flow results can be seen in Figure 18 and 19, respectively. When the solar radiation was steady, the valve stayed open and at a steady temperature, and the amount of pasteurized water increased at a relatively constant rate.

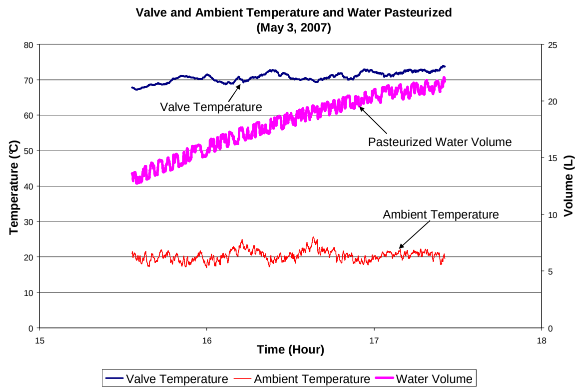

Figure 18: Steady-state flow of pasteurizer on May 3, 2007.

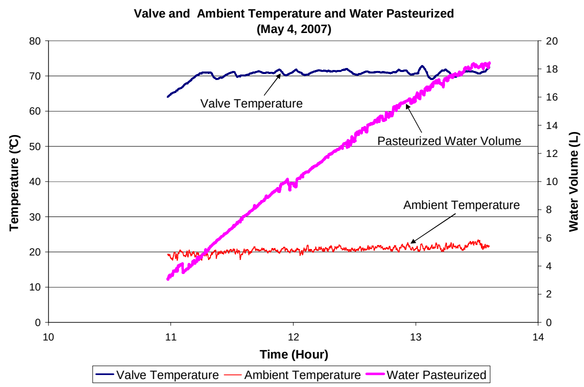

Figure 19: Steady-state flow of pasteurizer on May 4, 2007.

Heat Exchanger Effectiveness

The effectiveness of the heat exchanger can be shown by comparing the difference between the valve temperature and the outlet temperature, to the difference in the valve temperature and the ambient temperature. The outlet temperature was 37°C and the valve temperature was 71°C. With this data, the effectiveness was 66% using Equation 7 [11].

$$\varepsilon = \frac{T_{valve} - T_{out}}{T_{valve} - T_{a}} = 66\% \qquad (7)$$

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Betterment of Design

Many aspects of the prototype could be enhanced. The team had great difficulty in getting temperatures up to the rated valve temperature while testing in the winter months and uncooperative weather of Rochester, NY. Useful data was not recorded until late April. Under such circumstances the team did not have adequate time to revisit the design issues such as valve cycling, low flow, more precise testing techniques for pathogen reduction, and assurance that the temperature distribution falls within the safety zone. A greater focus should be made on:

- comparing actual test data to the engineering model to see if the safety zone has been reached
- better flow regulation via redesign of valve housing, pressure regulation, or redesigning heat exchanger
- reduced cost through revisited materials selection, bettered design, and faster fabrication and assembly methods
- elimination of chemical contaminants through material selection (i.e. replacing silicone sealant with a high-temperature gasket)

The team also did not focus greatly on the design of the feed water system. Better filtration or method to remove sediments should be sought out in order to remove objects that can coagulate inside the pasteurizer. Also the hoses used during testing are not ideal for a final product since they were not necessarily UV resistant or rated for high temperatures. Although the team paid greater attention to the heat exchanger/collector system, the feed water mechanism must be integrated along with all other design considerations when considering the SPIHX as a complete system.

Sponsorship and Partnership

The ultimate goal of this project is to mass produce the system at a reduced cost for the end user, while still being profitable to the manufacturer. Mass production analysis proved to be troubling due to the numerous uncertainties and assumptions the team had to make in order to get a cost estimate. Greater focus should be made in the following areas in order to demonstrate the marketability of the SPIHX:

- finding faster and cheaper ways to machine and fabricate the SPIHX
- determining actual labor rates and material costs in Venezuela or other developing countries
- developing a mass production model from a business standpoint

The team should also seek outside sponsorships or corporate partnerships once mass production seems more probable.

Site Testing

Since communication with members of rural Venezuela was minimal, the ease of integration of the SPIHX is still unknown. Language, educational, and cultural barriers must be explored to make the SPIHX a ready-to-use product.

To test in Venezuela, this creates a need for greater funding, and the team should strive for an established point of contact with an NGO or local organization.

If enough funding is available the team should send a few, if not all, members of the team to test in Venezuela. Also, steps must be done to observe the fabrication methods and materials available in Venezuela to see if mass production within Venezuela could be profitable.

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