DESIGN AND TESTING OF TWO LOW-COST SOLAR PASTEURIZERS

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ABSTRACT

Four solar water pasteurizer concept designs was examined with the option of three different types of heat exchangers and two different glazing materials. An optimization study to minimize system cost for a desired level of performance (minimum monthly average of 160 liters/day) was conducted by utilizing steady-state TRNSYS models. Based on the optimization study, two prototype systems were built and are in the process of being tested. The first prototype consists of a traditional fin and tube absorber and a shell-and-tube heat exchanger. The second prototype is a fully wetted rigid polymer pasteurizer with integral heat exchanger (SPIHX). The first prototype pasteurized nearly 400 liter per square meter of absorber area during a cool March day in North Carolina. Although polymer systems have potential to reduce system costs, purging and flow distribution have to be improved for narrow channels before they are effective.

1. INTRODUCTION

For the one billion people without access to safe drinking water, most of whom live in rural areas and have minimal levels of income, finding low cost water treatment technologies is vital to their survival. Much attention has recently been placed on water pasteurization as a potentially viable technology to meet this enormous demand. Burch and Thomas (1) provide an overview of the current state of solar pasteurization and a comparison with the alternative technologies.

Solar water pasteurization has particular advantages over many competing technologies such as community based filtration systems, chlorinating, trucking of water supply, and UV treatment. Solar pasteurization is modular, extremely simple, reliable, has only one moving part, and requires little maintenance and no electricity or other energy besides the sun. Pasteurization is not heavily impacted by the turbidity of the water and is able to inactivate cysts, such as giardia. Pasteurizers are especially suited for small applications, while the alternatives mentioned above are for large applications of more then 1000 liters per day. Some of the applications that solar pasteurization would be suitable for are remote residential settings, rural health clinics and small schools, small road-side restaurants and water vendors, where a mobile source of clean water is needed on a continuous basis, and residential buildings in urban areas where the primary source is suspect.

Cobb (2) recently proposed a low cost and simple solar pasteurizer. Fujioka and Rijal (3) tested an off-the-shelf solar pasteurizer. Stevens et al. (4,5) presented a new approach to pasteurizer utilizing an integral heat exchanger (SPIHX) and tested a 0.36 m^2 pasteurizer. In order for solar pasteurization to be successful on a worldwide level, systems must be developed for an appropriate output and the costs must be minimized significantly below current levels.

1.1 Water Requirements

Although the amount of water to be treated varies significantly with climate, culture, and access to water, it is critical to determine a reasonable capacity as the basis for optimization and prototype testing. In order to determine the appropriate capacity for a single-family system, several agencies were contacted that are involved with water supply and treatment for the developing world. Daily water utilization estimates ranged from 3 to 40 liters per person. Joseph Cotruvo (personal communication) at the National Sanitation Foundation (NSF) International recommended a bare minimum of 3-5 liters per person per day (lpd) and that the military standard is 5-7 lpd of drinking water in warm climates. Christian Children's Fund uses a guideline of 5 lpd for refugee camps. Water Partners International specifies 40 lpd in designing their village size water systems (personal communication). When evaluating the percentage of populations having access to safe water, the World Health Organization (WHO) uses the criterion of 20 lpd (6). Based on the WHO criterion and assuming an average family size of 8, a pasteurizer design capacity should be for 160 liters per day.

This paper briefly describes four concept designs, an optimization study, and design of two prototype systems, which may potentially meet the low-cost solar pasteurization emerging market.

2. DESCRIPTION OF FOUR CONCEPT DESIGNS

The four concept designs considered were A) a thin film polymer pasteurizer with an integral heat exchanger (SPIHX), B) a semi-rigid polymer SPIHX, C) a fully wetted copper SPIHX, and D) a traditional fin and tube absorber with an external heat exchanger (SPEHX).

The thin film polymer SPIHX consists of three polymer films heat-sealed together to form two sets of parallel channels. This concept is very similar to film collectors proposed by Thomas at al. (7) and Spears and Tratina (8), but with the addition of a set of back channels for heat recovery and under a slight pressure in the front channel. Because this type system has a strong possibility of being under dry-stagnant conditions, the material considered was polysufone (PSO) with UV stabilizers, carbon black colorant, and 5-mil thickness. Because of the high costs of PSO, polypropylene (PP) was also considered, assuming that a means of preventing dry-stagnant conditions could be incorporated in the design.

The second concept design (see figure 2), semi-rigid polymer SPIHX, makes use of off-the-shelf corrugated signage material made from a polypropylene co-polymer with channel sizes ranging from 2-6 mm. The material is inexpensive and readily available in carbon black. The glazing could either be glass or a horticulture grade polymer rigid glazing. The absorber assembly will be backed with 1-inch isocyanurate insulation. Additional heat exchanger area can be added to the system by using two more corrugated PP sheets bonded together and placed behind the absorber assembly.

The copper SPHIX concept design consists of a fully wetted absorber plate with an attached heat exchanger on the underside. The absorber surface can be coated with a selective surface. The channels will have an average height of 2mm designed to minimize thermal mass while utilizing an optimal collection area. A selective coating to maximize heating and minimize losses will cover the collection surface. Water will travel between the absorber and preheat channels via an external valve attachment.

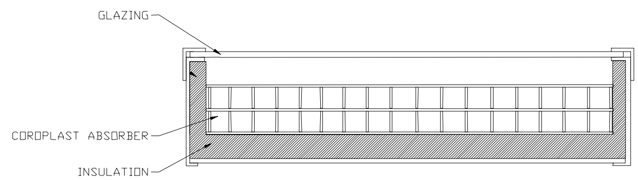

Fig. 1: Semi-rigid polymer SPIHX

The copper SPEHX D concept design consists of a traditional tube-and-fin absorber with external counter-flow heat exchanger (see figure 2). The top header will have a valve housing attached directly to one end, which is different than the three previous concept designs.

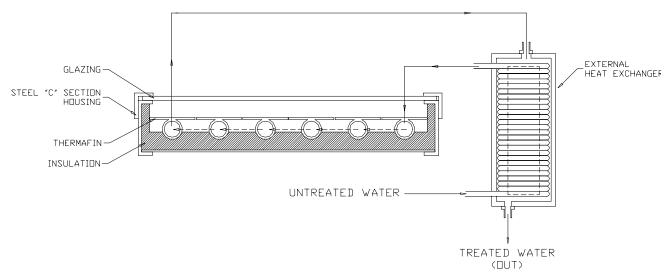

Fig. 2: Copper SPEHX

Although there are numerous heat exchangers available on the market today, there are few low-cost ones, and even fewer that are suitable for the low flows of solar water pasteurizers. Two concept designs were considered for external heat exchangers. The first was a traditional shell-and-tube heat exchanger such that turbulent flow exists in the tube at desired flow rates between 30 and 60 liters per hour (lph). This concept relies on a high heat transfer coefficient and can be achieved by twisting ¼" type L copper tubing around 1 ½" pipe with acceptable pressure drops. Smaller diameter tubes will lead to unacceptable pressure drops for desired overall heat transfer coefficients, while larger diameter tubes will not permit flow in the turbulent regime.

The second external heat exchanger considered consisted of layering corrugated polypropylene sheets to create a counter-flow heat exchanger. This concept relies on large surface areas to obtain a high overall heat transfer.

3. MODELING AND OPTIMIZATION

3.1 Costing Functions

The goal of the optimization was to minimize the initial cost for a system to pasteurize an average of 160 liters per day during the worst month of a year. Costing functions were derived for each concept design and variations of the design (heat exchanger and glazing options). The function assumed some fix cost (thermostatic valve, interconnection, and fixed labor), cost per unit collection area (absorber plate, housing, insulation, and labor), and cost per unit of heat exchanger area. It was assumed that most construction would take place in developing countries, where the systems would be most likely used.

The cost functions did not include the cost of storage tanks or mounting hardware, which will be required for normal operation of systems. It was anticipated that this would be provided locally. The costs also did not account for profit, shipping, or international tariffs. Since these cost will most likely be some multiple of the fabrication cost, they will not impact the relative costs between concepts and the locale of the minimum cost of each concept.

3.2 TRNSYS Model

A steady-state pasteurizer component module was developed for the TRNSYS environment based on models developed by the author (4,5). The pasteurizer module is slightly different than flat plate collector models in that the mass flow rate is treated as an output rather than an input. In addition, the outlet temperature at the valve housing is an input to the component module.

The pasteurizer module has three modes: 1) SPIHX, 2) SPEHX, and 3) no heat exchanger mode. Because the solutions derived in Stevens et. al. (4) are not in closed form, the module employs a simple iterative loop to calculate pasteurizer mass flow rates for modes 1 and 2. Mode 1 for the pasteurizer component can be used in conjunction with the heat exchanger (Type 5) component to simulate the addition of external heat exchanger to a SPIHX type system.

The assumptions for the component module are:

- No thermal mass, steady-state,
- Heat loss model is identical to mode 3 of Type 1 Collector component,
- Theoretical incidence angle modifier model as used in mode 3 of Type 1 Collector component,
- Inlet temperature and ambient temperatures are equal for modes 2 and 3,
- Constant fluid properties,
- Absorber plate temperature is the average of inlet temperature and temperature at valve of pasteurizer. The absorber plate temperature is used in the heat loss calculations, and
- Heat exchanger transfer coefficient is constant across entire surface and throughout the simulation time.

Besides areas, the model requires the several system parameters. Table 1 shows the key parameters used for simulations for all the concept designs. The high collector efficiency factors for the SPIHX systems are due to the absorber surfaces being fully wetted. Selective surfaces were assumed for both copper systems, concepts C and D, while the polymer based systems were assumed to have emittance and absorptances of 0.8.

TABLE 1 PARAMETERS FOR SIMULATIONS

Concept	*HX*	*F'*	ε	α	U_{HX}	$U_{HX,2}$
					kJ/hr-m²-°C	*kJ/hr-m²-°C*
A	1	0.99	0.8	0.8	1116	803
A2	1	0.99	0.8	0.8	925	803
B	2	0.99	0.8	0.8	905	905
C	3	1.00	0.39	0.91	1814	1552
C	4	1.00	0.39	0.91	1814	2372
D	2	0.93	0.39	0.91	905	N/A
D	3	0.93	0.1	0.93	1552	N/A
D	4	0.93	0.1	0.93	2372	N/A

Notes:

F' Collector efficiency factor
ε Emittance of absorber plate
α Absorptance of absorber plate
U_{HX} Heat transfer coefficient for integral heat exchanger of SPIHX and external of SPEHX
$U_{HX,2}$ Heat transfer coefficient for additional external heat exchanger of SPIHX systems
A PSO film SPIHX
A2 PP film SPIHX
B PP corrugated SPIHX
C Copper SPIHX

D Fin and tube SPEHX

HX Options:
1 Polymer thin film heat exchanger
2 PP corrugated heat exchanger
3 Flat plate copper heat exchanger
4 Shell-and-tube heat exchanger

The heat transfer coefficient for the SPIHX and heat exchangers were calculated based on laminar flow and the geometry of each system. The shell-and-tube heat exchanger, option 4, is the only heat transfer coefficient that was based on turbulent flow in the tube and natural convection in the shell.

3.3 Optimization

Annual simulations using Miami and Phoenix TMY data were conducted using the developed TRNSYS module. Figure 3 shows a sample of the TRNSYS simulation of concept C, copper SPIHX, for four days in January.

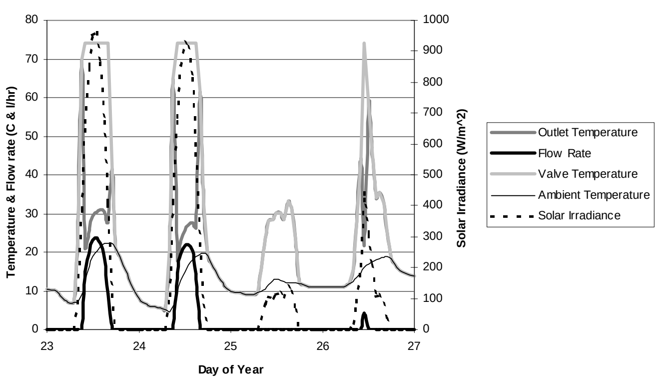

Fig. 3 SPEHX modeled performance for four days in January in Phoenix, AZ.

An optimization study was done initially to determine the ideal fixed slope for each concept. Since system daily throughput is a function of both ambient temperatures and solar irradiance, the cooler months of December and January will require more solar irradiance than required in June. The goal of this portion of the study was to determine optimal fixed slope to maximize average daily throughput for the worst month of the year. Based on the TMY weather data, the optimum slope for Phoenix is 53° and for Miami fell between 40° and 48° depending on system concept.

Simulations were conducted over a range of heat exchanger to collection area ratios and for all variations of the four concept designs. Figure 4 shows the cost function versus heat exchanger to collection area ratio for concept D with heat exchanger option 4. For this concept, the optimum ratio between heat exchanger area and collection area is 1.75. The cost function is relatively flat between 1 and 5. For the assumed costing function, the optimum system contains an absorber plate area of 0.38 m^2 and heat exchanger area 0.66 m^2.

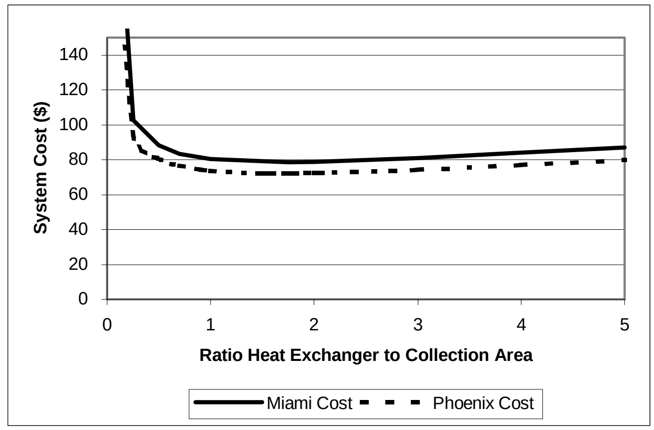

Fig. 4 Cost function for traditional absorber with external shell-and-tube heat exchanger

Similar plots were developed for ten different combinations of concepts and configurations. Table 2 shows the optimal ratios for each configuration for the Phoenix climate and the system costs as defined earlier. Miami costs are slightly higher, but the minimum costs occur at same heat exchanger to collection area ratios.

TABLE 2 OPTIMAL RATIOS

Concept	*HX*	*Glazing*	A_C	A_{HX}	*Area Ratio*	*System Cost*
			m^2	m^2		*$*
A	1	1	0.86	1.71	2	90.30
A	1	2	1.26	1.26	1	89.51
A2	1	2	1.75	0.00	0	51.95
B	2	1	1.04	1.04	1	74.89
B	2	2	1.77	0.00	0	58.54
C	3	1	0.78	0.00	0	88.60
C	4	1	0.47	0.47	1	79.49
D	2	1	0.40	1.62	4	73.43
D	3	1	0.60	0.60	1	108.69
D	4	1	0.38	0.66	1.75	72.15

Notes:

A_c Collector area
A_{HX} Additional heat exchanger area

Glazing Options:
1 Tempered glass
2 Corrugated transparent PP glazing
The lowest cost system is a thin-film system fabricated with PP with a PP glazing panel. Because there were some technical concerns about pressurizing a thin film system, it was decided to pursue the semi-rigid PP SPIHX over the thin-film system. The third lowest cost system is for a SPEHX made from a traditional fin-and-tube absorber with a custom heat exchanger. It is anticipated that the D concept would have a much longer life, if scaling is not a major issue. It was decided to further develop this system for the desired level of output.

4. TWO PROTOTYPES AND INITIAL TESTING

Based on the optimization study, the two prototype systems to be developed and tested were the semi-rigid polymer SPIHX and traditional fin and tube absorber with a shell-and-tube heat exchanger.

4.1 Copper SPEHX

A 71 cm x 46 cm Black Crystal Thermafin absorber plate was tested independently of the system to determine collector parameters as spelled out in ASHRAE 93-1986. Initially a small shell-and-tube heat exchanger was built and tested. The flow rate used for testing purposes was approximately 30 lph, expected normal operating conditions. Heat exchanger testing consisted of measuring overall UA values at different orientations, flow rates, and hot fluid in the tube and then in the shell. The highest UA values occurred for vertical or 45° orientations, while the UA dropped off sharply for horizontal orientation. The UA values were similar regardless of whether the hot flow was in the tube or the shell.

An automobile thermostatic valve was retrofitted using standard copper pipe fittings and a gasket to prevent leakage. The valve housing was fabricated so the valve could easy be swapped out. The valve was attached directly to the top header of the absorber. The heat exchanger was added to the absorber and valve to create a pasteurizer system.

The entire system was assembled and operated over a few days in February to gain better insight into cycling, purging, and performance. Much attention had to be paid to purging air from the system. Initially the system must be purged of most air. Air in the system will lengthen the time the valve takes to open in the morning or even prevent opening altogether. During normal operations air continuously is expelled from the heated water in the heat exchanger and collector.

Although cycling was not an issue for previous work conducted by the authors (4,5) on a SPIHX, cycling can be a significant problem for a SPEHX, where the thermostatic valve is located further away from the absorber and the external heat exchanger is cool when the thermostatic valve first opens. Cycling was noted in all configurations of the SPEHX tested. Effort was made to move the thermostatic valve as close to the absorber as possible. By doing so the valve responded quicker and was able to maintain lower absorber plate temperatures during initial start-up, increasing overall performance.

Figure 5 shows the daily performance of the pasteurizer with a 0.68 m^2 heat exchanger for March 3, 1999. The flow rates are for 15 minute averages. The average ambient temperature for the testing period was 12.5 °C and total daily solar flux of slightly over 7 kWh/m^2. The system pasteurized 130 liters over the course of the day. The system was operated with a slightly lower thermostatic valve temperature (72 °C) to simulate operations in warmer climates. The system was also manually purged of air throughout testing.

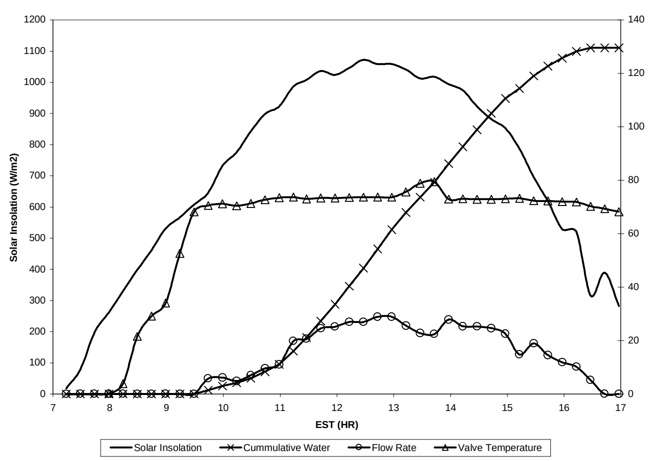

Fig. 5: SPIHX performance for 3/2/99.

Flow rates approached 30 l/hr during peak performance hours or just under 100 $l/hr\text{-}m^2$ of collection area. During steady conditions the effectiveness of the heat exchanger exceeded 0.9 with an overall UA value of approximately 320 W/°C, slightly lower than modeled.

Flow did not start until after 9:30 at which time the system went through a series of cycles, before reaching quasi-steady state conditions around 11:00. The dip in flow rate after 13:00 was caused by failing to purge the system for an extended period of time. The decrease in flow rate increased valve temperatures as can been seen in the figure.

Because there is a warm-up period and losses during cycling, the quasi-steady state model used for optimization tends to over-predict system performance. Although it was not the intent of this paper to compare the measured data to the model, it is apparent that a larger system would be required to meet the desired level of 160 liters/day.

4.1 Corrugated PP SPIHX

Initial testing of a corrugated PP SPIHX focused on design of a header and understanding flow patterns through PP sheets. Because heat transfer coefficients are greatest and thermal mass is minimized for narrow channels, 2 mm channel heights were first investigated. Two sheets (56 cm x 112 cm) were laminated together and two headers fabricated on both ends of both sheets. Early versions of headers were fabricated by using a router to create 2 cm channels. A 0.6 cm thick strip of PP was adhered over the channels with an inlet or outlet nipple.

Upon investigation of the flow by injection of dies and operating as a solar collector, it was discovered that flow was not evenly distributed through channels and purging of air was extremely difficult. Because the poor flow distribution would greatly reduce performance, the header size was increased and 4 mm channel thickness were employed. The new header was made from a 1.3 cm pipe attached to the end of each sheet, much like a traditional absorber plate. This newer system allowed for easy purging and the flow pattern appear to be acceptable for the low flows of solar pasteurizers. The larger channel height will reduce overall performance. Testing of the laminated corrugated PP sheets will be tested as a heat exchanger and SPIHX over several months during the spring of 1999.

5. CONCLUSIONS

An optimization study and initial testing on two systems have been conducted in order to develop a low-cost solar water pasteurizer adequate for a large rural family need for clean water. Four different concepts and several heat exchanger configurations were considered. Based on the optimization, it appears polymer based pasteurizers have great potential to reduce initial system costs.

Two systems were selected for further design and testing. The first makes use of a traditional fin-and-tube absorber with specially designed shell-and-tube heat exchanger (SPEHX). The heat exchanger was designed to be turbulent at the low flows of the solar pasteurizers without generating unreasonable pressure drops. The SPEHX generated nearly 400 liter/m^2 in a day during March. Cycling occurred during initial start-up and continued until system was completely heated. Because of the cycling, the steady-state models presented in [4,5] tend to over-predict overall performance.

The second system selected was a polymer SPIHX made from sheets of corrugated polypropylene. Testing was conducted to qualitatively understand flow patterns in sheets for a few header options. Testing as a pasteurizer is continuing.

6. ACKNOWLEDGEMENTS

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