AN INVESTIGATION OF A SOLAR PASTERIZER WITH AN INTEGRAL HEAT EXCHANGER (SPIHX)

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ABSTRACT

A steady-state model is developed for a Solar Pasteurizer with an Integral Heat Exchanger (SPIHX). A parametric study is conducted for key system parameters. Increases in the heat exchanger transfer coefficient improve the performance most dramatically for systems with traditional collector parameters. A 0.36 m^2 testbed SPIHX was constructed and tested. A warm-up periods occurs before flow begins. At ambient temperatures around 10°C flow rates ranged from 10 to 55 l/hr-m^2 for solar irradiances in excess of 600 W/m^2. The SPIHX simulated flow rates are compared to measured flow rates for eight days. The model on average over-predicts water treatment by 5.2%. Most of the model discrepancies occur for periods of scattered clouds or high wind speed.

1. INTRODUCTION

Although clean potable water is critical to sustaining human life, according to the World Health Organization there are approximately one billion people without access to safe water (1). Every year more than five million people die because of the lack of safe water and improper sanitation. The most profound impact of unsafe water occurs among children below the age of five. More than 10,000 children die every day from diarrheal diseases, most of which are tied to unsafe water (2).

Some of the illnesses associated with unsafe water are diarrhea, hepatitis, polio, cholera, and typhoid. These illnesses are caused by pathogens found in unsafe water, which include protozoa, viruses, and bacteria. Feacham, et al. (3), Backer (4), and Burch and Thomas (5) summarize the pathogens found in unsafe water, the diseases they cause, and treatment techniques. One potential water treatment technology that has gained recent attention for dispersed populations is solar water pasteurization.

Pasteurization works on the principal that pathogenic protozoan, bacteria and viruses are destroyed as water temperatures are elevated. Water can actually be pasteurized at much lower temperatures than boiling. The pasteurization of water is a function of temperature and exposure-time. Feachem (3) proposes temperature and exposure-time safety zones for the inactivation of pathogens based on several tests conducted over a wide range of conditions. A pasteurization process only has to cross into the safety zone at one point to be effective. Because boiling is not necessary, solar energy can be utilized to heat water to pasteurization temperatures. In the past decade, there has been work done on developing flow-through solar pasteurizers.

A flow-through pasteurizer normally has a thermostatic valve to regulate a continual flow through the system while ensuring pasteurization temperatures are reached. Often systems use a heat exchanger to recover heat from treated water to improve performance. One system of this type is a solar box cooker with an inexpensive external heat exchanger (6). A recent off-the-shelf system uses a traditional solar collector coupled with a shell and tube heat exchanger and has been successfully tested for its effectiveness in disinfecting water (7). If the solar collector and the heat exchanger can be integrated with little sacrifice to system performance, the cost and simplicity of the system could be greatly improved. Anderson and Collier have developed a high technology solar pasteurizer with an integral heat exchanger (SPIHX) using a parabolic-trough concentrating collector (8). This system relies on the direct normal solar flux and utilizes a PV powered pump.

There is a need to investigate a simpler SPIHX system and develop tools that are useful in designing appropriate solar pasteurization systems. A simple SPIHX can be built by attaching a heat exchanger surface on the underside of a thin rectangular channel absorber as shown in Figure 1. This approach would eliminate all the components associated with an external heat exchanger such as insulation, housing, and piping material. Because the water is in full contact with the absorber, other materials besides copper, such as polymers, can be used with little reduction in the collector efficiency factor. The use of polymers could reduce the cost of material and manufacture to less than a system with a traditional hot water collector and an external heat exchanger.

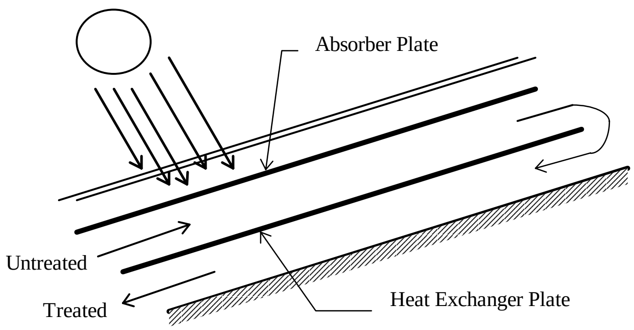

Fig. 1: Solar Pasteurizer with an Integral Heat Exchanger

2. STEADY-STATE SPIHX MODEL

A detailed derivation of the SPIHX model can be found in (9). The SPIHX system is modeled by performing energy balances on a length of fluid in the upper and lower sections of the pasteurizer noted by ① and ② respectively in Figure 2. This leads to a system of differential equations which can be analytically solved. By setting $T_t(L)$ equal to the desired pasteurization temperature, the mass flow rate can be determined for a given set of parameters.

The energy balance for ① is:

$$\frac{\dot{m}C_p}{w}\frac{dT_t}{dx} = F'\left(S - U_L\left(T_t - T_a\right)\right) + U_{HX}\left(T_b - T_t\right) \qquad (1)$$

where $\dot{m}$ is the mass flow rate, C_p is specific heat, w is the width, F' is the collector efficiency factor, S is absorbed solar radiation, U_L is the collector loss factor, T_a is ambient temperature, and U_{HX} is the heat exchanger heat transfer coefficient.

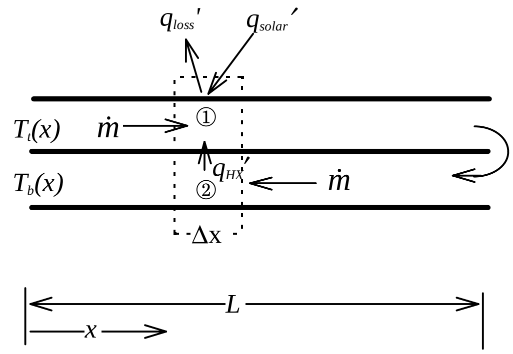

Fig. 2: SPIHX energy balance.

Assuming negligible back losses the energy balance for ② is:

$$\frac{\dot{m}C_p}{w}\frac{dT_b}{dx} = U_{HX}\left(T_b - T_t\right) \qquad (2)$$

Equations (1) and (2) form a system of first order non-homogeneous differential equations. For this particular system the "boundary" conditions are:

$$T_t(0) = T_{fi}$$
$$T_b(L) = T_t(L) \qquad (3)$$

where T_{fi} is the inlet water temperature.

This system of equations can be solved by using matrices and employing a transformation based on diagonalizing the coefficient matrix. The unique solution for the system of equations is:

$$T_t(x) = C_1 b e^{\lambda_1 x} + C_2 b e^{\lambda_2 x} - \frac{c}{a+b}$$
$$T_b(x) = C_1(\lambda_1 - a)e^{\lambda_1 x} + C_2(\lambda_2 - a)e^{\lambda_2 x} - \frac{c}{a+b} \qquad (4)$$

where

$$C_1 = \left(\frac{T_{fi}}{b} + \frac{c}{b(a+b)}\right)\left(\frac{-\lambda_1 e^{\lambda_2 L}}{\lambda_2 e^{\lambda_1 L} - \lambda_1 e^{\lambda_2 L}}\right)$$

$$C_2 = \left(\frac{T_{fi}}{b} + \frac{c}{b(a+b)}\right)\left(\frac{\lambda_2 e^{\lambda_1 L}}{\lambda_2 e^{\lambda_1 L} - \lambda_1 e^{\lambda_2 L}}\right)$$

$$\lambda_{1,2} = \frac{(a+b) \pm \sqrt{(a+b)^2 - 4b(a+b)}}{2} \qquad (5)$$

$$a = \frac{-w\left(U_{HX} + F'U_L\right)}{\dot{m}C_p}$$

$$b = \frac{wU_{HX}}{\dot{m}C_p}$$

$$c = \frac{wF'\left(S + U_L T_a\right)}{\dot{m}C_p}$$

Since the pasteurization temperature is desired at $x=L$, the flow rate can be found by setting $T_1(L) = T_{past}$ in the first part of equation (4). After simplification the mass flow rate for the SPIHX model is:

$$\dot{m} = \frac{C_3}{\ln\left(C_4\left(C_5 - C_6 e^{C_7/\dot{m}}\right)\right)} \quad (6)$$

where

$$C_3 = \frac{-wL}{2C_p}\left(F'U_L + C_8\right)$$

$$C_4 = \frac{T_{past} - T_a - \frac{S}{U_L}}{-2\left(T_{fi} - T_a - \frac{S}{U_L}\right)C_8} \quad (7)$$

$$C_5 = -F'U_L - C_8$$

$$C_6 = -F'U_L + C_8$$

$$C_7 = \frac{-wLC_8}{C_p}$$

$$C_8 = \sqrt{\left(F'U_L\right)^2 + 4F'U_L U_{HX}}$$

The mass flow rate is not in closed form and must be solved by an iterative process. It is critical to note that the model assumes that the system valve perfectly regulates flow to insure maximum flow through the system while maintaining the desired pasteurization temperature.

3. PARAMETRIC STUDY OF SPIHX

The mass flow rate defined by equations (6) and (7) is a function of L, w, F', U_L, U_{HX}, T_a, T_{fi}, T_{past}, and S. The effect on flow rate of the heat exchanger heat transfer coefficient can be seen in Figure 3 for four different absorbed solar irradiance levels. The mass flow rate increases as the heat transfer coefficient increases. The most dramatic improvements in performance occur at the lower end of the transfer coefficient scale, 0 to 50 W/m^2-°C. For this particular case, the flow rate more than triples by increasing the heat transfer coefficient from 0 to 100 W/m^2-°C. Although the impact of the transfer coefficient is less pronounced at higher values, its still improves performance significantly.

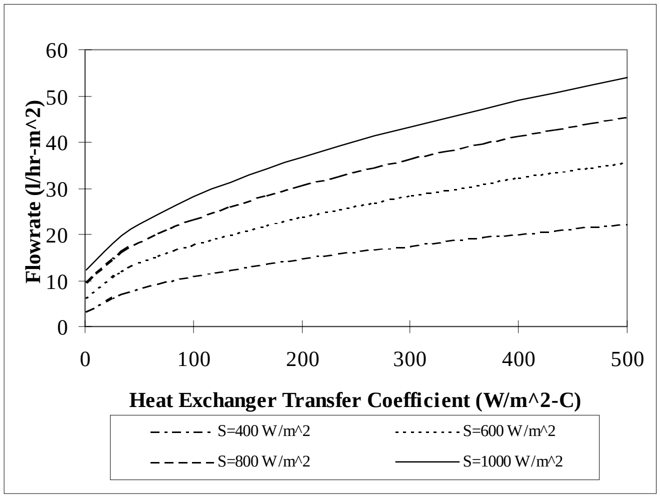

Fig 3: Pasteurizer flow rate versus heat exchanger heat transfer coefficients (L = 2 m, w = 0.3 m, F' = 0.98, U_L = 5 W/m^2-°C, $T_a = T_{fi}$ = 20 °C, and T_{past} = 80 °C).

For small systems with laminar flow, U_{HX} is related to a constant Nusselt number and approximately inversely proportional to channel height. Assuming a Nusselt number of 5.1 in the back channel and 7.9 in the front channel and negligible thermal resistance of the heat exchanger plate, the flow rate relationship to the channel height can be seen in Figure 4.

As seen in Figure 5, the performance of a system decreases as the collector loss factor increases. The system ceases to generate pasteurized water when the losses equal or exceed the absorbed solar radiation. This is of particular concern at lower irradiances and with pasteurizers with high heat loss coefficients. In the particular case shown in Figure 5, a system with a loss factor of 6.43 W/m^2-°C will not pasteurize water below an absorbed radiation of 400 W/m^2.

Figure 6 shows the impact on system performance due to ambient temperature. Flow rate increases significantly as the ambient temperature increases. This indicates that a system will have a better performance during warmer times of the year or in hotter climates. For this particular case, a system located in an ambient temperature of 30°C will perform between 30 to 75% better than a system at an ambient temperature of 10°C for absorbed solar radiation levels of 400 to 1000 W/m^2.

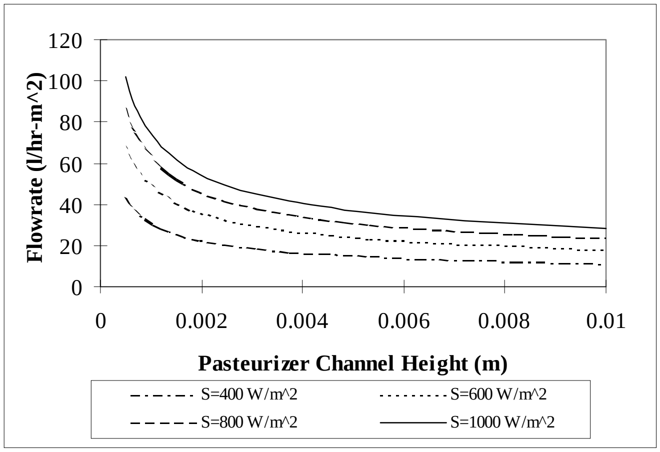

Fig 4: Pasteurizer flow rate versus channel height (L = 2 m, w = 0.3 m, F' = 0.98, U_L = 5 W/m^2-°C, $Ta = T_{fi}$ = 20°C, and T_{past} = 80°C).

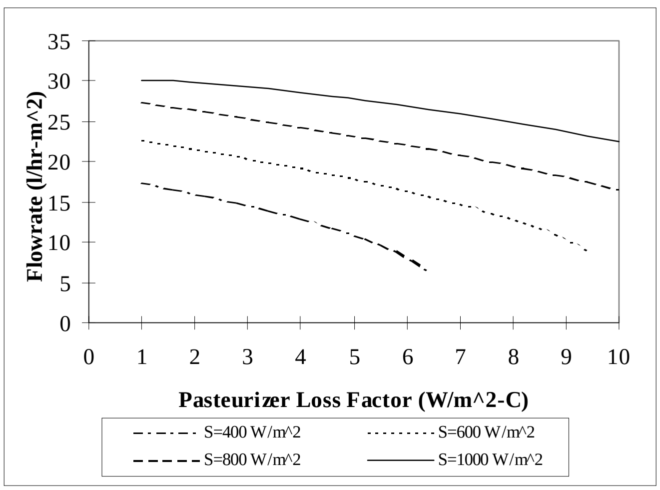

Fig. 5: Pasteurizer flow rate versus heat loss factor (L = 2 m, w = 0.3 m, h = 0.01 m, F' = 0.98, U_{HX} = 100 W/m^2-°C, $Ta = T_{fi}$ = 20°C, and T_{past} = 80°C).

4. EXPERIMENTAL TESTBED

A 1.78 m x .20 m SPIHX system was built out of sheets of galvanized steel and framing. The system's average channel heights were 7.9 mm. The absorber had a flat-black paint surface. A stock cartridge for an automobile thermostat valve was placed in a special casing with a gasket to prevent leakage. The SPIHX was housed in an insulated box with a single sheet of glazing. The system was supplied with water from a 55 gallon HDPE drum. The treated water leaving the SPIHX was stored in a 120 liter HDPE tank. A constant head of 30 cm of water was kept on the system.

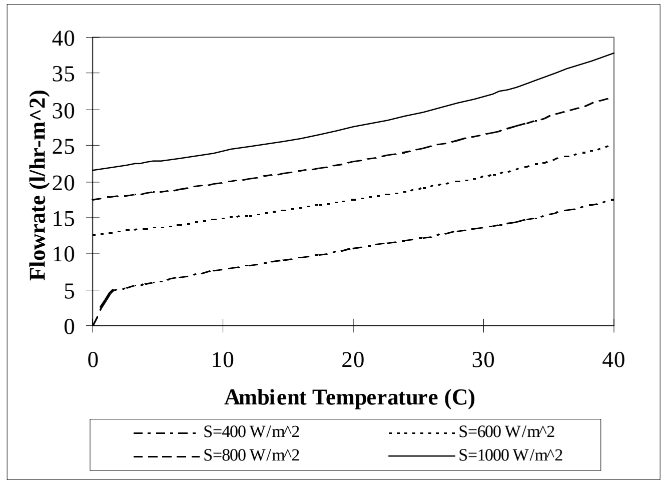

Fig. 6: Pasteurizer flow rate versus ambient temperature. The parameters used for this plot are as follows: L = 2 m, w = 0.3 m, h = 0.01 m, F' = 0.98, U_{HX} = 100 W/m^2-°C, U_L = 5 W/m^2-°C, T_{past} = 80°C and $Ta = T_{fi}$.

Eighteen thermocouples were placed along the length of the front and back plate, in the inlet and outlet flow stream, and in the valve housing. A pressure gauge was used to measure the water level in the treated tank. Flow rates were calculated by differentiating the water level. Solar irradiance was measured using a LICOR pyranometer. Data was collected every five seconds and was averaged every one to three minutes, depending on the test day.

The collector parameters were determined by operating the system in a collector mode when the back channel was bypassed. The collector parameters were approximately:

$$F'U_L = 6.17 \text{ W/m}^2\text{-°C}$$

$$F'(\tau\alpha)_n = 0.81 \tag{8}$$

$$b_o = -0.39$$

where $(\tau\alpha)_n$ is the transmittance-absorptance product near normal and b_o is the incidence angle modifier coefficient. The system does have a high b_o because it is a narrow collector.

The system was operated as a pasteurizer for eight days over a two month period in the late fall of 1997. The heat exchanger transfer coefficient was determined by integrating equation (2) over the entire length of the SPIHX and solving for U_{HX}. It was assumed that the losses through the back insulation are negligible. The heat transfer coefficient is:

$$U_{HX} = \frac{\dot{m}C_p(T_{past} - T_{fo})}{w\int_0^L \left(T_b(x) - T_t(x)\right)dx} \quad (9)$$

where T_{past} is the valve housing temperature and T_{fo} is outlet of the back channel temperature. The top and back fluid temperature functions are approximated by performing an exponential curve fit on the temperature measurements taken along the length of the channels. Using data from 10/30/97, the U_{HX} for the testbed was 471 W/m^2-°C.

5. PERFORMANCE AND MODEL RESULTS

Figure 7 shows the solar irradiance and system performance for October 30, 1997, which is typical performance for sunny test days. The valve opened shortly before noon and continued to pasteurize water until 16:00. The valve appears to be adequate at regulating the flow rate. The late start was because of the large thermal mass of the system. Minimizing the mass is critical in designing an optimal SPIHX. Also of interest is a slight cycling of the valve shortly before 13:00. This did not occur on other test days except under cloudy conditions.

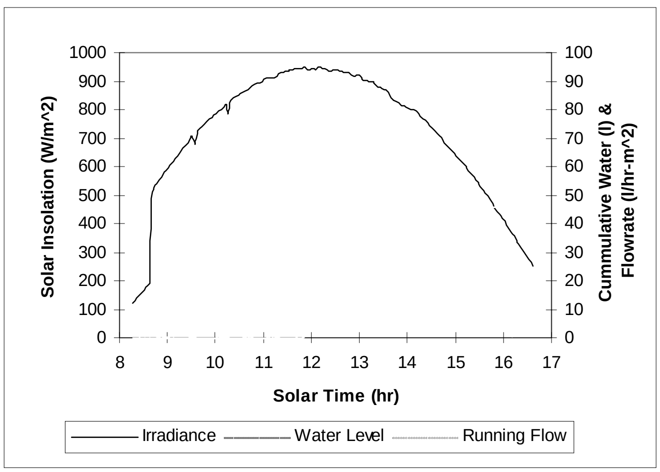

Fig 7: SPIHX testbed performance for 10/30/97.

For the eight test days, the flow rates after system warm-up were between 10-55 l/hr-m^2 for solar irradiance levels above 600 W/m^2. The average ambient temperature was around 10°C. The flow rates for the test days are compared to the SPIHX model. Figure 8 shows modeled and measured data for times of flow rates on 10/30/97. The model predicts the average flow for this day as 3.2% higher than the average measured flow. The lower prediction shortly after noon is because the model does not account for stored energy in the system when the flow began. The higher prediction after 12:30 is due to valve cycling.

The model predicted flow rates for the eight test days 5.2% higher than the average measured flow rate. The main discrepancies occur on days when the average wind speed was high or when there were scattered clouds. Under other conditions the model predicts system performance well once the system is heated to desired temperatures.

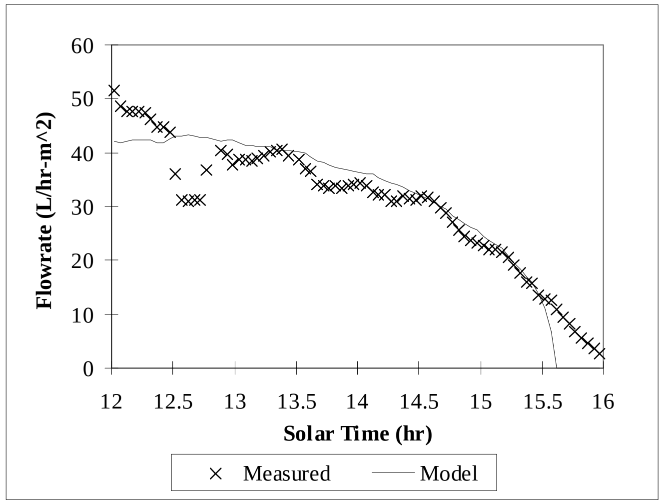

Fig. 8: Modeled versus measured flow rates for 10/30/97.

The total heat transfer rate for pasteurization is shown in Figure 9 for 10/30/97. The rate of heat transfer is broken down into the two system components. As expected the heat exchanger was the key energy provider for the process. The heat exchanger provided 75 to 90% of the energy for pasteurization, while the collector useful energy gain provided the remaining 10 to 25%.

With the measured temperature profiles in the SPIHX a curve is created for the minimum temperature-time exposure of the flow. Figure 10 compares three such curves to the conservative enterovirus safety zone proposed by Feachem (3). If any point on the curve lies in the safety zone, then pasteurization has occurred. The system clearly pasteurizes water for the times later in the afternoon. According to the Feachem's safety zone, the temperatures were too low during the early afternoon. It is important to note that both the safety zone and time-temperature curve are conservative. The curve indicates the minimum amount of time an element of water is above a specific temperature. For example, at 13.04, the water will always be above 70°C for at least five minutes. For at least two of those minutes, the water will be above 73°C.

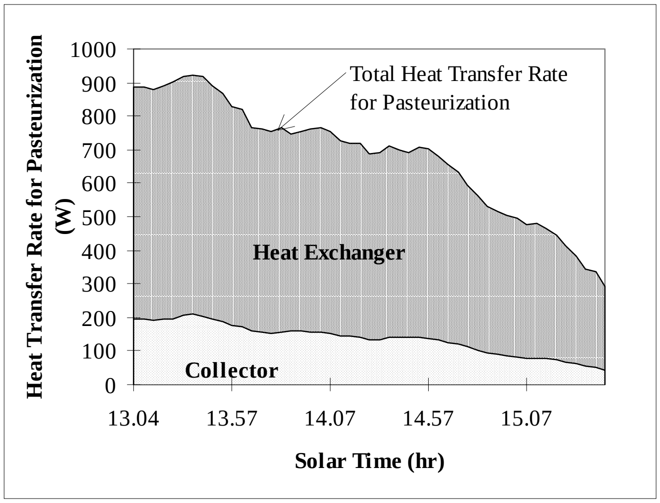

Fig. 9: Total SPIHX heat transfer rate for 10/30/97.

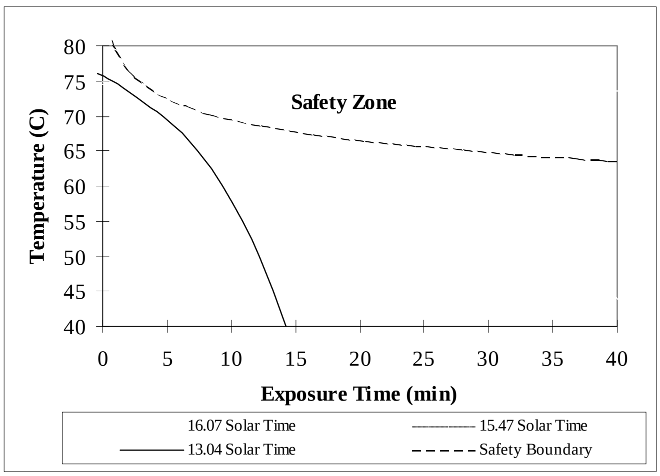

Fig. 10: Temperature vs. exposure time for 10/30/97.

6. CONCLUSIONS

The SPIHX model presented in this paper and developed in (9) is a useful tool in evaluating solar pasteurizers with integral heat exchangers. The parametric analysis indicates that the key system parameters are the heat exchanger heat transfer coefficient, the collector loss coefficient, and the absorbed solar radiation. The testbed did have a much higher U_{HX} than expected. The cause for the higher U_{HX} should be investigated in future studies with the goal of developing an appropriate model to be used for design purposes.

The model did not account for the thermal mass of a SPIHX, which is more of an issue for SPIHX systems than pasteurizers with external heat exchangers. The thermal mass should be added to future SPIHX models to account for warm-up periods and days with scattered clouds. The automobile thermostatic valve used in the testbed appears to have regulated flow adequately as the model assumed.

Slight modifications to the SPIHX model could be made to model evacuated tube systems, concentrating systems, and hybrid systems with external heat exchangers. The model can be used to determine the optimal balance of system parameters in order to minimize system costs for a desired daily performance. The use of alternative materials, such as polymers, may further reduce system costs.

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