COMPOUND PARABOLIC CONCENTRATORS FOR SOLAR WATER HEAT PASTEURIZATION: NUMERICAL SIMULATION

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ABSTRACT

Many people in less developed countries drink water with microbial contamination, which leads to the annual death of 5 million children. Although some people currently boil water, all microbes that cause disease in humans do not survive at temperatures >65ºC, which solar water pasteurizers can easily produce. These pasteurizers are similar to box solar cookers, and typically have a small rectangular reflector. The objective of this work is to calculate the increase in output due to compound parabolic concentrators (CPCs) using numerical simulation. A CPC concentrates the maximum amount of radiation on a planar receiver consistent with the laws of thermodynamics. Since the average water temperature is nearly independent of the solar radiation, the heat losses are nearly constant. Therefore, higher concentration factors yield significantly higher efficiencies. Depending on climate, CPCs increase output by 1,000%-4,000%, while the additional reflector would only ~double the cost and necessitate weekly tilting.

Keywords: compound parabolic concentrators, solar heat pasteurization, numerical simulation, small-scale

1. INTRODUCTION

Many people in less developed countries drink water with microbial contamination, and this is implicated in the annual death of 5 million children (1). Although some people currently boil water, all microbes that cause disease in humans do not survive at temperatures exceeding 65^{o}C, which solar devices can easily produce. A flow-through water pasteurizer contains a thermostatic valve that opens when the water reaches a threshold temperature (indicating pasteurization), and the outgoing hot water warms the incoming cool water in a heat exchanger. The flow is caused by the dirty water reservoir being at a higher elevation than the clean water reservoir. The addition of the heat exchanger and the valve increase the output by a factor of eight or more (1). These pasteurizers are similar to box solar cookers, and typically have a small rectangular reflector. The objective of this work is to optimize the reflector.

Compound parabolic concentrators (CPCs) concentrate the maximum amount of radiation on a planar receiver consistent with the laws of thermodynamics. We have set the CPC acceptance angle such that most of the light is concentrated throughout the day, and then small adjustments of the tilt angle of the device can easily be made, perhaps weekly.

We have found no previous work applying CPCs to solar water heat pasteurizers. However, a CPC was applied to a solar cooker, but since solar cookers cannot in general be tilted, one reflector was removed and the other was tilted differently (2).

2. NUMERICAL SIMULATION OF PASTEURIZER

We have written a computer program in Matlab to calculate the output of this system.

An ideal CPC (no truncation and no reflector scattering or absorption) has:

$$C = \frac{1}{\sin(\theta_a)}$$

(see Tables for notation) within the angular acceptance region, and zero concentration outside this region (see Fig. 1, line 3). Also, the illumination of the receiver is very non-uniform.

Uniform illumination is very important because nonuniform illumination can degrade the performance of a thermostatic pasteurizer. If the thermostat received more light than the average receiver area, the valve would open prematurely, and when cooler water reached the valve, the valve would close, so a full batch would not be pasteurized.

Truncating the reflector reduces C within the acceptance region, and some light from outside the acceptance range can reach the receiver directly, or by reflecting from the reflector on the side from which the light is coming (Fig. 1,line 2). Scattering has the effect of "averaging" C at a given angle with the factor at adjacent angles, and increasing the uniformity of illumination. These two effects have been taken to the extreme in (3) where 95% of the CPC is truncated, and the scattering angle is 10^o, while $?_a$ is only 5^o. The scattering is achieved by introducing sinusoidal distortions into the reflector. This has the result of a nearly constant C out to an incidence angle of 9^o, which is nearly twice the regular acceptance angle. Also, the illumination of the receiver varies only 20%. In the present simulation, we assume that scattering is achieved by using planar facets, which has the further advantage of reducing fabrication cost. First we calculate C the inside and outside of $?_a$ without scattering. C inside is equal to the aperture width adjusted to take into account the reflector losses divided by w_{rec}. The outside C is equal to the direct illumination plus what is reflected off the reflector on the side from which the sun is coming. Finally, the arithmetic mean of the two C's yields the overall C over twice the CPC angular acceptance. This technique correlated well with the raytraced results in (3). The results for different reflector heights are shown in Fig. 2 (the CPC trough is aligned east-west). Notice that the CPC sacrifices C at large incidence angles and gains C at small incidence angles. Since the majority of the light in the north-south direction (near the zenith) for weekly tilted CPCs is at small incidence angles, CPCs perform better. Note that h_{refl}/w_{rec} = 2.5 corresponds to the largest reflector for the solar still (see Pearce and Denkenberger, this conference). Since we are assuming that the pasteurizer receiver is 0.1 m wide, 1 m reflector height corresponds to h_{refl}/w_{rec} = 10.

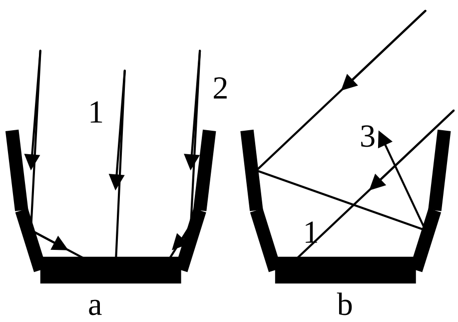

Fig. 1. a. inside $?_a$ and b. outside $?_a$; 1. direct illumination, 2. reflected off side from which sun is coming, and 3. rejected ray.

To maintain uniform illumination, we only include the parts of the infinite trough that actually participate in directing light toward the finite receiver, i.e., the reflectors hang over the ends of the still. The system will have uniform illumination as long as the overhang is sufficient to capture all the incident light headed for the receiver.

We calculated natural convective heat transfer coefficients based on horizontal correlations for pasteurizer tilt < 30°, and vertical adjusted (Rayleigh number with g*cos(tilt) replacing g) for tilt > 30° (4). Also, we considered the tubes to be a flat surface; in reality there would be more area to transfer heat, but the length of air that the heat has to conduct through is greater, so we assumed as a first approximation that these effects cancel. We explore the sensitivity on overall upward heat transfer to account for errors in the above assumptions. For outside convection, we calculated a forced convection heat transfer coefficient, and the greater coefficient of the forced and natural was used (there was assumed to be no wind for the CPC case). The equations for the properties of air were taken from (5), which technically was for humid air, but we believe the error will be relatively small.

We calculated external glass radiation based on an effective sky temperature, regardless of device tilt. In reality, the effective radiation temperature would increase as the glass is tilted from horizontal, because the glass is "looking at" lower elevation air and the ground. However, with a CPC, since the reflectors are generally not very emissive, the glass "looks at" a narrower region of the sky, which would be even colder if the glass is not tilted very much. We assume that these effects cancel.

We treated convection and radiation from the walls very simply, having a total resistance of 0.1°C/(W/m^2). This is reasonable because the thermal resistance of the conduction through the walls (1°C/(W/m^2) for the base case) would dominate the convective and radiative resistance, so an error in the convective and radiative resistance would result in a small overall error.

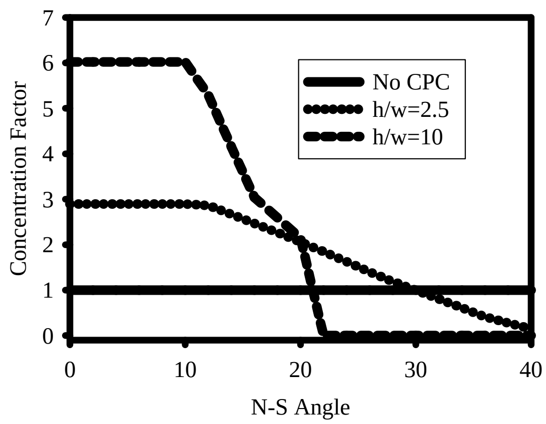

Fig. 2. The Concentration Factor as a function of north-south incidence angle for no CPC, h_{refl}/w_{rec} =2.5 and h_{refl}/w_{rec}=10.

TABLE 1. VARIABLES AND PARAMETERS

Parameter	Explanation [Value]
T_{sky}	Effective radiation temperature of sky (emissivity = 1): $0.0552(T_{air})^{1.5}$ [K]
E_{basin}	Tube emissivity (lampblack) [0.95]
E_{gl}	Glass emissivity [0.925]
L_{gl}	Thickness of the glass [4 mm]
w_{rec}	Width of the tube array (receiver)
h_{refl}	Height of the reflector
T_{thermo}	Temperature at which the thermostat opens [80°C]
T_{op}	Average operating (tube) temperature
T_{inlet}	Temperature at inlet to box (after heat exchanger)
?	Heat exchanger effectiveness
C	Concentration factor of the sun
$?_a$	Acceptance half-angle of the CPC

We assumed that there was no air exchange with the outside. The outlet temperature from the pasteurizer is equal to T_{thermo}. The inlet temperature, assuming that the water from the holding tank is at T_{amb} is:

$T_{inlet} = T_{amb} + ?(T_{thermo} - T_{amb})$.

T_{op} is just the average of the inlet and outlet temperatures, assuming that the water warms linearly with time. We neglected the solar flux into the walls, because we are assuming that the receiver is pointed at the sun in the north-south direction. We adjusted the wall area based on the thickness of the walls (because of corners), the tube diameter (assumed to be 1 cm), and the gap between the tubes and glass.

We assumed that it was consistently sunny during our model day; if there were passing clouds, output would fall considerably, but there would be transient effects that the current program cannot model. If the day is completely overcast, a no-CPC unit cannot reach T_{op}, so there is no output. Also, since CPCs cannot concentrate diffuse light, the CPC unit would produce no output.

We calculate the heat transfer coefficients based on estimated temperature differences to find an overall thermal resistance of the device. Then the actual operating temperature and ambient temperatures are used to calculate the loss. If the loss is greater than the input energy, zero output results. The output is the integral of the difference between input energy and loss when the input energy is greater than the loss (see Fig. 4).

The simulation takes into account energy received in both beam (direct sunlight) and diffuse (indirect sunlight) forms. Following the typical assumption, we regard the diffuse light to be isotropically distributed (6). We adjust the beam intensity I_z for atmospheric attenuation as (7):

$$I_z = 1353 e^{-0.357 \sec^{0.678} \theta_z} \quad \text{W/m}^2,$$

where θ_z is the angle of the sun from the vertical.

Since the maximum movement of the zenith of the sun is only 2.8°/wk (during the equinoxes), the total angular acceptance region of 20° would be acceptable for weekly-adjusted CPC systems. Since the primary application for the pasteurization system studied here is for less-developed countries, labor could be substituted in return for a lower-cost system, and since these adjustments could be coordinated with other maintenance, weekly adjustments are reasonable. These adjustments can be made with the aid of a device similar to a sundial (2). The technician would aim directly at the maximum zenith angle near the equinoxes, 5° below the maximum zenith angle in the winter, and 5° above in summer. This acceptance angle is energetically acceptable because the vast majority of the solar radiation influx is contained within ~10° of elevation angle of the zenith (8). We assumed that the tubes take on a discrete temperature value over the entire surface.

We have assumed that the baseline ("no CPC device") has no reflector and is optimally tilted weekly. In reality, the receiver is typically horizontal and there is a reflector approximately the size of the receiver. We assume that the reflector compensates for the receiver being horizontal (the illumination of the receiver will not be uniform unless it is adjusted throughout the day).

We calculated the reflectivity of the glass for parallel and perpendicular polarization, and we took the arithmetic mean of the two, as solar radiation is randomly polarized. The primary reflections are: light reflected off the top of the glass; and transmitted through the top of the glass, reflected off the bottom of the glass, and transmitted through the top of the glass. The secondary reflection is: transmitted through the top of the glass, reflected off the bottom of the glass, reflected off the top of the glass, reflected off the bottom of the glass, and transmitted through the top of the glass. We ignored tertiary reflections.

We used a relative convergence criterion of 0.1% so that all the figures in the sensitivity table below are significant. We reduced the integration time step by a factor 10 each iteration, which indicates that the final result is very close to the actual value. The typical run took a few minutes on a personal computer.

3. RESULTS AND DISCUSSION

The power that passes through the glass and the losses are shown in Fig. 4. The no CPC case shows a roughly sinusoidal behavior of the light entering the pasteurizer. During the middle of the day (~7 hr), the reflectors concentrate about six times as much light onto the receiver (C = 6), and about five times as much light enters the pasteurizers (because the light reflected off the reflectors is more oblique, so it suffers greater reflection losses from the glass). During the morning and evening, C is smaller, so the advantage of the CPC is less. Finally, near sunrise and sunset, the light the pasteurizer receives is actually less for the CPC, but there is very little total light at these times, so the penalty is small. The integral of the entering power minus the losses when the losses are smaller than the entering power is the useful energy, i.e. the energy that goes to heating the water. The CPC directs more total energy onto the tubes, and that energy is also used much more efficiently because losses are a smaller fraction, so the output is much greater. Fig. 3 shows the tropics case, where the output is approximately 10 times as much with the CPC. If we had plotted the winter desert case with a 40 times increase in output, the output of with no CPC would have been difficult to see because it is relatively so small. Fig. 3b. shows how the losses decrease as the ambient temperature increases towards the maximum t_{delay} hours after solar noon. Also, the losses are less for the CPC because it is assumed to block the baseline 2 m/s wind.

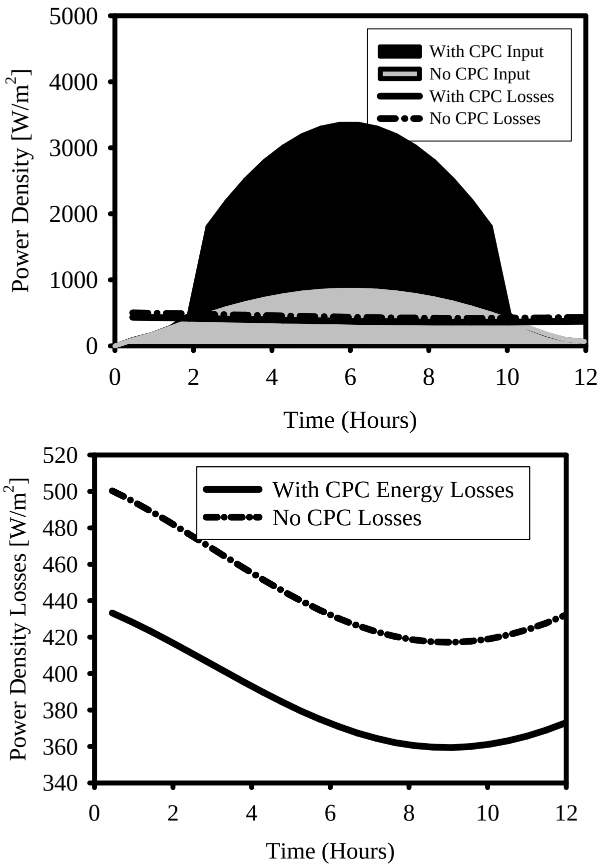

Fig. 3. a. The power density input (shaded areas) and losses (lines) as a function of time with and without a CPC. A detail of the losses is shown in b.

The output is shown in Fig. 4: no CPC is 19.9, 168, and 142 L/day/m^2 for winter desert, tropics, and summer desert, respectively. This is smaller than claimed in (1): 80-100 L/day for 0.28 m^2, so 290-360 L/day/m^2. This may be due to their better insulation or lower convective heat loss. The output for h_{refl}/w_{rec} = 10 is 816, 1530, and 1430 L/day/m^2 for winter desert, tropics, and summer desert, respectively.

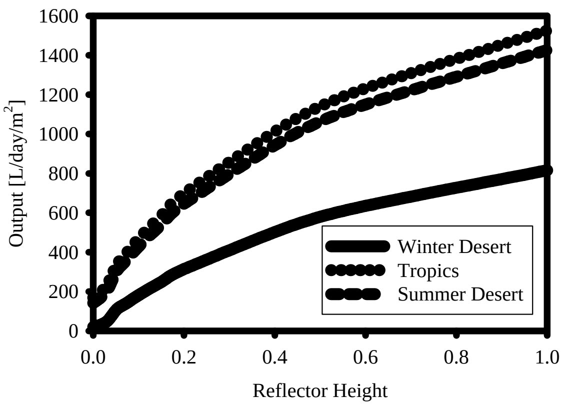

Fig. 4. Output in L/day/m^2 as a function of reflector height

We performed a sensitivity on all of the input parameters, the CPC case corresponding to h_{refl}/w_{rec} = 10, or h_{refl} = 1 m (see Table 2). In general, no CPC is much more sensitive to small changes in losses or incoming energy. A smaller L_{gap} increases convective losses to the glass, but it decreases losses through the walls because the walls can be made shorter. This is actually an optimization problem, but this sensitivity shows that there is worse performance for both doubling and halving the gap, so the baseline value is close to the optimum. L_{ins} and k_{ins} must be explored separately because increasing L_{ins} increases the area that heat can conduct through. This is why halving k_{ins} increases output more than doubling the L_{ins}. Lower V reduces the losses for no CPC (the CPC is assumed to block wind, so there is no effect) and increases output dramatically. The zero wind velocity basically isolates the advantage of the CPC blocking wind, which is 113.9% for winter desert, and 22.8% for tropics. As can be seen in Fig. 4, the advantage of a tall CPC is much greater than these percentages, so blocking of the wind is a relatively small factor overall. Changing n_{gl} results in approximately a 3% change in light delivered, so this is roughly the effect on the CPC. Glass absorption behaves similarly. Increasing T_{amb} has a greater effect than increasing T_{var} by twice the amount even though the peak temperature is the same. Decreasing t_{delay} means that the air is warmer for a greater portion of the operating time (see Fig. 3b), so the losses are less. Increasing I_{dif} increases no CPC output more than it increases CPC output because CPC is less sensitive to increases in light, but also the CPC cannot concentrate diffuse light. For CPC, the change in output is similar to the change in F_{tub}. Changing the upward (through the glass) heat transfer has a dramatic effect on output, and warrants further refinement. No CPC is obviously insensitive to reflector reflectivity, and the CPC output changes proportionally to reflectivity (lower is stainless steel, upper is silver).

A very important sensitivity is that of the heat exchanger effectiveness, ? (the fraction of heat reclaimed). Neglecting the change in T_{op}, ? = 0.8 means that the water only has to be heated up 20% as much as with no heat exchanger, so output should be 5X. Similarly, the output should be 10X if ? = 0.9, or double that of the base case (? = 0.8). Fig. 5 shows the output multiplier from the base case for different ?. For large CPC, the multiplier approaches the above values. However, for no CPC, the result is very different. This is because when ? is greater, it means that T_{op} is higher, meaning greater losses, which are very important for no CPC. Therefore, there is a greater incentive for the CPC to have higher ?. Even without this effect, going from ? = 0.8 to 0.9 doubles output, which basically means one only has to build one device instead of two, saving the cost of the additional device. Since the cost of the additional device in the case of the CPC is greater (because of the cost of the reflectors), the incentive to increase ? is greater, for instance by building a longer heat exchanger. Both of these effects will result in higher optimal ?, further increasing output and decreasing cost of water. Further research should be done on this topic.

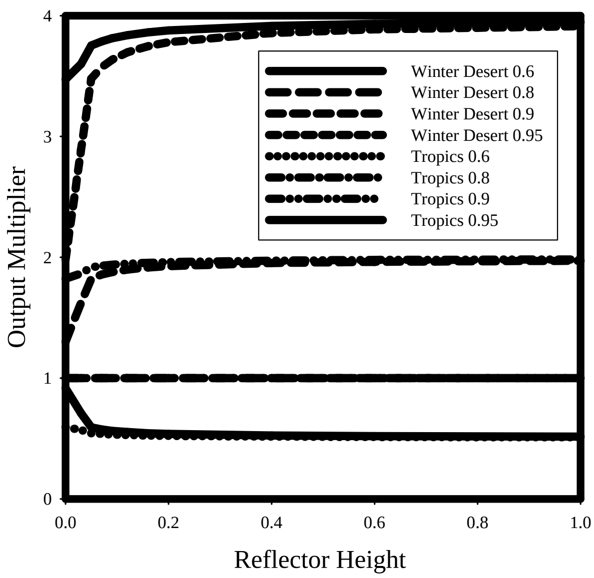

Fig. 5 The output multiplier as a function of reflector height (m) for tropics and winter desert conditions of ? = 0.6, 0.8, 0.9 and 0.95

A flow-through pasteurizer costs approximately $60 for a receiver of 0.25 m^2, or $\$240/m^2$ (1), and inexpensive reflectors cost ~$\$4/m^2$ (9). For reflectors that are 10X as tall as the width of the still and for a receiver 2.5 m long (same 0.25 m^2 receiver area) with overlap on both ends equal to the receiver length, this yields a doubling in cost due to the reflectors. Therefore, the cost of water in the tropics is roughly 1/5, and it is ~1/20 in the winter desert.

We have calculated the output when there is no glass cover. Preliminary results indicate that the output with no CPC is small or zero. However, with a large CPC, the output suffers a small loss or even increases. Because of the cost and breakage risk of glass, it may be optimal for CPCs to not use glass, but further analysis is required, as it is sensitive to the heat transfer coefficients.

4. <u>CONCLUSIONS</u>

We performed an extensive sensitivity analysis on passive solar pasteurizers, showing that the output of the device with no CPC is quite sensitive to a number of assumptions, but the CPC device is less sensitive. Since the average water temperature is nearly independent of the solar radiation, the heat losses are nearly constant. Therefore, the reflectors yield significantly higher efficiencies. Adding a CPC that has a height of 10 times the width of the receiver to solar heat pasteurizers increases the amount of water pasteurized by 1000% to 4000%, while only ~doubling costs. This is due to an increase in solar radiation of about 4X, and an increase in efficiency of 2.5X for tropics, and 10X for winter desert conditions.

5. <u>REFERENCES</u>

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TABLE 2. PHYSICAL INPUT PARAMETERS AND SENSITIVITIES

Para-Meter	**Explanation**	**Assumed value [range]**	**Units**	**?% Output No CPC winter desert**	**? % Output CPC winter desert**	**? % Output No CPC tropics**	**? % Output CPC tropics**
L_{gap}	Gap between the tubes & glass	0.01 [0.005, 2]	m	-62.1 -5.3	-1.7 -0.5	-13.1 -2.5	-0.9 -0.4
k_{ins}	Thermal conductivity of insulation layer	0.05 [0.025,0.1]	W/(mK)	92.4 -99.2	4.4 -7.7	19.2 -30.6	2.4 -4.1
L_{ins}	Thickness of insulation layer	0.05 [0.025,0.1]	m	-63.8 43.1	-4.0 2.2	-16.2 9.3	-2.1 1.2
V	Average wind velocity	2 [0,10]	m/s	113.9 -62.3	0.0 0.0	22.8 -17.6	0.0 0.0
n_g	Glass index of refraction	1.5 [1.4-1.6]		22.9 -19.9	3.5 -3.4	6.8 -6.8	3.1 -3.1
F_g	Glass solar absorptivity	0.06 [0.02,0.10]		34.4 -31.6	5.5 -5.5	11.2 -11.0	5.0 -5.0
T_{amb}	Average ambient surface temperature	8 winter [-2,18]; 28 tropics [18,38]	°C	-79.5 145	-15.5 20.8	-43.5 73.3	-19.2 28.9
T_{var}	Daily T_{amb} variation	10 winter [20, 30] 10 tropics [0, 20]	°C	41.7 88.2	1.4 2.8	-11.4 12.1	-1.2 1.2
t_{delay}	Delay from solar noon to maximum T_{amb}	3 [1,5]	hr	13.6 -22.6	0.5 -0.9	4.0 -6.9	0.4 -0.7
I_{dif}	Diffuse intensity	100 [50, 150]	W/m^2	-35.6 40.4	-1.9 1.9	-11.9 12.4	-1.5 1.5
F_{tub}	Tubes solar absorptivity (black matte)	0.97 [0.94,1.00]		-23.3 24.8	-4.0 4.0	-8.0 8.1	-3.6 3.6
m_{HT}	Upward heat transfer multiplier	1.0 [0.75, 1.5]		150.8 -100.0	4.9 -9.8	32.0 -53.7	3.0 -5.9
R_{ref}	Reflector solar reflectivity	0.85 [0.8,0.93]		0.0 0.0	-5.8 9.2	0.0 0.0	-5.1 8.1