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DESIGN AND OPTIMIZATION OF A CONTINUOUS FLOW SYSTEM FOR THE SOLAR DISINFECTION OF WATER, FOR USE IN RURAL COMMUNITIES

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ABSTRACT

The design and optimization of a continuous flow solar water disinfection device is presented.

The design is based on a batch disinfector, previously tested and reported, in which water was exposed to solar radiation in plastic bottles.

In the new device, water flows through a plastic pipe exposed to solar radiation. The flow control is accomplished by using a solenoid valve, which permits the flow of water only when the solar radiation reaches a minimum predetermined value. In the optimization analysis, the tubing's diameter and length-width ratio of the irradiation zone were optimized to obtain the maximum flow at the exposure time required to obtain water disinfection.

External flat reflecting surfaces concentrate the incoming solar radiation over the receiving area, in order to reduce the residence time required to guarantee complete water disinfection.

INTRODUCTION

One of today's most important problems, at the local, national and global level, is the access to water of bacteriological quality appropriate for human consumption. This is especially true of rural zones, in which the limitations for obtaining clean water are greater due to lack of infrastructure and disinfection methods. This need has lead to the development of diverse methods for disinfecting water in these zones. The solar disinfection method is widely known as SODIS, and its application has been promoted in several Latin-American countries, such as Peru, Bolivia and Mexico, as well as in countries of Asia and Africa (1, 2). The process consists of a household-level alternative that uses PET (Polyethylene terephthalate) beverage bottles of a maximum 2 liters capacity (3).

Given the limitations of household-level application, the proposition was made to analyze the possibility of developing equipment capable of producing a continuous flow of solar disinfected water.

NOMENCLATURE

A_i	Tubing internal flow area (m^2)
D_c	Concentrator diameter (m)
d_e	Tubing external diameter (m)
D_{free}	Free diameter at collector's center (m)
δ	Tubing wall thickness (m)
L	Tubing length (m)
num	Number of tubing loops
t	Retention time (h)
V	Flow velocity (m / h)
$\dot{V\!\!\!-}$	Volumetric flow (m^3 / h).
$V\!\!\!-$	Volume (m^3)

System Design Considerations

Diverse factors exist which affect the efficiency of the solar disinfection method, including the minimum time of exposure to radiation with a clear sky, the geographic location, the season and weather conditions, and the intensity of solar radiation with respect to the conditions of each day.

Different studies have reported that through the use of solar concentrators, in controlled laboratory tests, only 3 to 4 hours of intense radiation are needed to disinfect water. The time of the day with the greatest solar radiation is from 11:00 to 15:00 hours (2).

The function of the solar concentrators is to concentrate by optical means the energy from the sun before its transformation into heat or electricity. Thus, the solar radiation that enters the concentrating collector through the area of aperture is reflected or refracted to a smaller surface, the capitation surface, where it is transformed into either thermal or electrical energy (4, 5). The most important advantage of the concentrating collector is that it reduces the heat losses of the radiation absorber. Since it has a smaller surface, the area available for heat transfer with the environment, and thus the liquid flowing through the receptor can heat to greater temperatures and the disinfection efficiency is increased.

Considering the different concentrator designs that exist already, the initial step was the selection of the appropriate construction materials. Tubing was selected first; it had to be of flexible plastic, transparent to UV radiation. This made management easier and made it possible to arrange the tubing in the most space-efficient way that allowed for a flow of 4 liters per day. A spiral arrangement was considered, in order to achieve an adequate flow without strangling the tube and hindering the flow. Considering the placement of the tubing, 2 concentrators were dimensioned (square and hexagonal) in order to triple the obtained radiation.

A mathematical model was developed in order to determine the flow rate in function of: the tube arrangement inside the energy concentration surface, the diameter, thickness, and length of the tube, the number of tubing loops and the dimensions of the adsorption surface. This program was used to optimize the tube diameter to be used, as a function of exposure time, required to ensure disinfection.

The parameters considered for the dimensioning and construction were: a) volumetric flow of 4 liter per test, b) a retention time of 4 hours. Based on a volume of water to be disinfected, the tubing necessary for this flow was calculated, determining the required length and diameter. For this, an algorithm was developed and implemented in the computer program EES (Engineering Equation Solver).

The purpose of the algorithm was to model the water flow through the tubing, as a function of length and diameter. The collector's irradiation area was fixed at certain value, and the computer model calculated the tubing diameter and length that maximize the disinfected volume during the time period allowed. In the following equations the flow model is presented. After its implementation in EES, a flow maximization procedure was carried out, leaving the tubing external diameter as the optimization parameter. The model calculated the length of tubing that would fit in the collector area for different tubing diameters.

$$A_i = \frac{\pi}{4}\left(d_e - 2\delta\right)^2$$

Equation 1, Flow area inside the tubing

$$\dot{\forall} = \mathrm{V} \cdot A_i$$

Equation 2, Volumetric flow

$$\mathrm{V} = \frac{L}{t}$$

Equation 3, Required flow velocity

$$\forall = \dot{\forall} \cdot t$$

Equation 4, Water volume disinfected in the time period

$$num = \frac{D_C - D_{free}}{2 \cdot d_e}$$

Equation 5, Number of loops in the tubing spiral.

$$L = \pi \cdot num \cdot \left(D_C - d_e \cdot num \right)$$

Equation 6, Total tube length of the concentric spirals

Once the dimensions of the bases had been calculated, the next step was to dimension their walls, considering that the required inclination is 60° (2). The next consideration for the dimensions was that the walls should in no direction obstruct the solar radiation to the base of the concentrator; on the contrary, light should be projected from the walls into the concentration surface.

Once the equipment was assembled, it was coated with acrylic paint in order to minimize damage from exposure to weather. The inside of the concentrator was covered with adhesive aluminum foil, and its edges were protected with aluminum tape. Once this was done, each concentrator was instrumented with a needle valve in order to control the entry flow, as well as with digital thermometers to monitor the thermal performance.

Construction Materials

The basic materials used for the construction of the concentrators were:

Base and walls: Since a lightweight, easily manageable material was needed, wood was used.

Coatings: The internal faces of the walls are covered with adhesive aluminum, and the outer part with vinyl paint in order to keep out humidity.

Tubing: Flexible, transparent polyethylene tubing was selected.

Support: A metallic structure was designed for supporting the concentrator.

Figures 1 and 2 show the isometric projection of the concentrators; Figure 3 shows the dimensions of the corresponding prototypes.

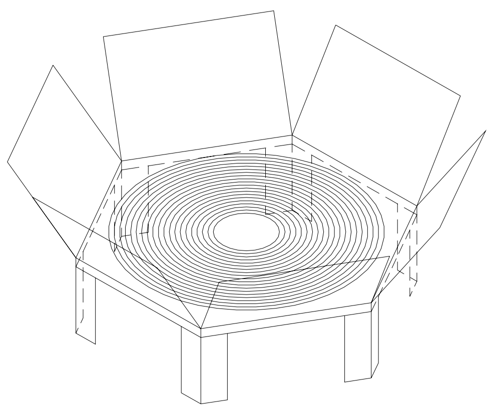

Figure 1.- Isometric projection of the hexagonal concentrator.

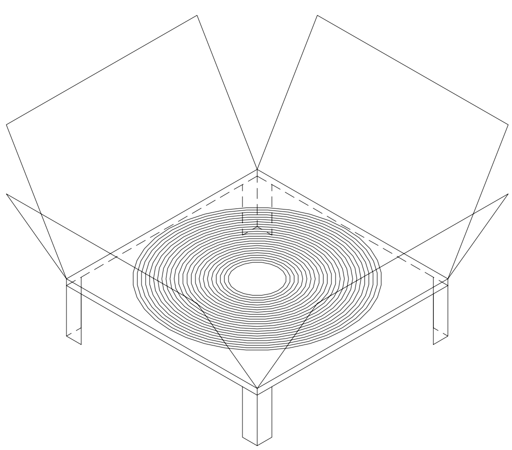

Figure 2.- Isometric projection of the square concentrator.

Water Disinfection

In order to ensure a high concentration of total and fecal coliforms, the disinfection trials were performed with domestic wastewater from the treated effluent of the Chihuahua City Wastewater Treatment Plant. This was done to ensure a high concentration of microorganisms and determine the disinfection efficiency even in critical conditions of bacteriological quality.

The bacteriological quality of the water was determined in function of the most probable number (MPN) of total and fecal coliforms, which are the indicator microorganisms considered by the Mexican norm (NOM-127-SSA1-1994) to determine the bacteriological quality of water for human consumption. The determination technique used was the Colilert method (Quanti-Tray 2000, IDEXX), approved and validated by the United States Environmental Protection Agency (7).

The results obtained in the different tests performed show that with a retention time inside the concentrator of 4 hours, a total and fecal coliforms inactivation of 100% was achieved (Table 1). Table one also shows that the temperature rose during that time between 4 to 20 C° in the hexagonal concentrator in cloudy and sunny days, respectively.

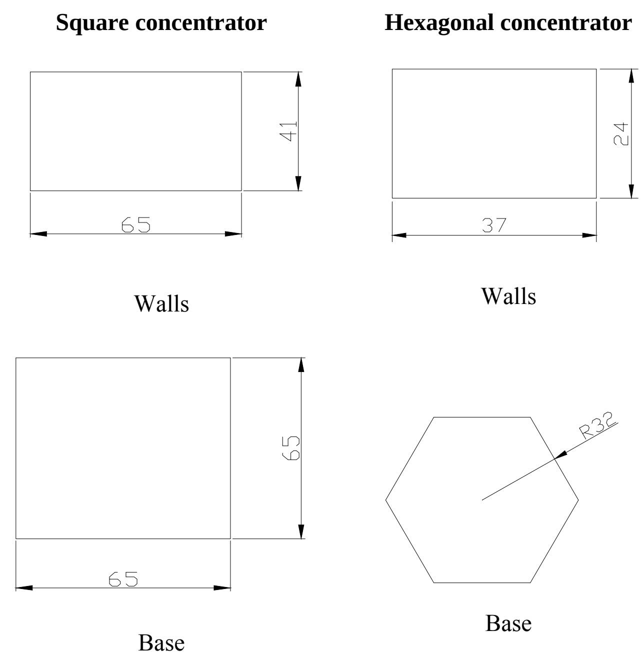

Figure 3.- Dimensions of the base and walls of the square concentrator (cm).

Table 2 presents the disinfection results for exposure times of 1, 2 and 3 hours. The initial concentration of total coliforms in the equipment's entry water was 25,994 MPN/100 mL. After an hour of exposure, the measured disinfection efficiency had reached 99.98%. The 2 hour exposure time trial rendered a microorganism reduction efficiency of 100%, which shows that bacteriologically disinfected water can be obtained after a disinfection time of 2 hours.

The obtained results are within the disinfection efficiencies obtained in other studies performed with plastic bottles and flat concentrators; in these studies, the first hour of exposure rendered a coliform inactivation of 98% (2)

CONCLUSIONS

The equipment designed and built for the disinfection of water worked with a 100% efficiency in the disinfection of water with high concentrations of total and fecal coliforms, with exposure times to radiation of 2 hours.

The capacity of the equipment, with respect to the volume of treated water, can be doubled by varying the times of exposure to solar radiation.

The analyzed disinfection system is efficient, practical and easily manageable, and so it constitutes a water disinfection alternative particularly appropriate for (but not restricted to) rural communities where there is no electric power or water of quality appropriate for human consumption.

REFERENCES

1. Moser S., Heri S., Mosler H.J. (2005): Determinants of the diffusion of SODIS. A quantitative field study in Bolivia. Summary Report. EAWAG, Dübendorf.

2. Martín-Domínguez, A., Alarcón-Herrera, M., Martín-Domínguez, I.R., González-Herrera, A., (2005). Efficiency in the disinfection of water for human consumption in rural communities using solar radiation. Solar Energy. v.78, pp.31-40. Elsevier.

3. Sommer B., Mariño A., Solarte Y., Salas M.L., Dierolf C., Valiente C., Mora D., Rechsteiner R., Setter P., Wirojanagud W., Ajarmeh H., Al-Hassan A., Wegelin M. (1997). SODIS - an emerging water treatment process. J. Water SRT, Aqua v.46, n.3.

4. Duffie, J.A.; Beckman, W.A. (1991) Solar Engineering of Thermal Processes. John Wiley & Sons, New York.

5. Goswami, Y.D. (2000) Principles of Solar Engineering, 2nd Edit. Taylor and Francis, U. S. A., pp.23-36.

6. NOM-127-SSA1-1994, Norma Oficial Mexicana, "Salud ambiental, agua para uso y consumo humano-limites permisibles de calidad y tratamientos a que debe someterse el agua para su potabilizacion". Mexican Health Ministry

7. US EPA, 1996 Approval, Colilert®-18 and Quanti-Tray®/2000, 9/96

Table 1. Results of the disinfection trials with respect to time and Coliform concentration.

Date	Weather	Temperature °C input	Temperature °C output	Coliforms (MPN/100mL) Total Initial	Total Final	Fecal Initial	Fecal Final	Concentrator
27/03/06		24.88	28.67	4013	N.D.	220	N.D	hexagonal
28/03/06		21.72	26.61	1003	N.D	45	N.D	square
29/03/06		24	36.61	2006	N.D	9	N.D	square
30/03/06		23.2	43.7	602	N.D	1	N.D	hexagonal
18/04/06		28.1	46.8	2871.3	N.D.	N.D.	N.D.	hexagonal
20/04/06		25.5	43.9	86645	N.D.	35298.3	N.D.	hexagonal

N.D. = Not detectable

Table 2. Results of disinfection trials with respect to time and total Coliform concentration.

Weather	Trial concentrator	Retention time hours	Temperature °C Initial	Temperature °C Final	Total Coliforms MPN/100 mL Initial	Total Coliforms MPN/100 mL Final
	HEXAGONAL	**1**	27.5	41.8	25994	4
		2	31.6	37.2	25994	0
		3	35.3	38.3	25994	0

N.D. = Not detectable

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PREFACE

The Solar Joint Meeting between the Asociación Nacional de Energía Solar (ANES) de México and the Solar Energy Division of the American Solar Energy Society (ASME) marks a culminating point in years of planning for stretching collaborative ties between ASME and Solar Energy Organizations across the Americas. In 2004, a joint technical session was held at the International Solar Energy Conference in Portland, Oregon with the Caribbean Solar Energy Society. This year, the ANES extended an invitation to ASME to join their XXX National Meeting in Veracruz, México, October 3-6, 2006. These joint meetings are paving the way to needed collaboration across borders that we hope will accelerate the deployment of renewables across our Hemisphere.

Energy has become a mainstream topic worldwide, and renewables are part of this dialogue. The world has major challenges posted by the rapid changing global and regional climate, due to increases in green house gases and land cover conversion, along with a significant reduction of oil as main conventional energy resource. This is making it obvious that a rapid deployment of renewable energy technologies into the market places is part of the solution. While this situation post challenges to the academic community — by pressing the rapid development of lab based technologies — it represents a unique opportunity for bringing renewables into the market place. Solar, wind, biomass, hydrogen, and energy efficiency technologies and approaches are rapidly becoming part of the solution to the major global problems, probably more than ever before. Hemispherical cooperation is more than essential to take advantage of these new opportunities.

The Solar Energy Division of ASME is extremely pleased with the response of the community to this first joint meeting ANES/ASME. This proceeding contains 20 full peer-reviewed papers in a variety of topics in solar energy and other renewable energy technologies. The topics included are; resource assessment, climate change and renewables, biogas production, solar cooling and refrigeration by absorption and adsorption, energy efficient buildings, solar concentrating power, solar dryer of agricultural products, wind energy, among others. The Proceeding also includes the key-note address by Dr. Frank Kreith, *A Global Perspective of Solar Technologies*. All ASME 20 contributions were organized into four technical sessions within the ANES meeting. The compilation represents an expanded range of applications of solar, wind, and biomass, a reflection of the North/South contributions.

We thank all authors who contributed to this first joint meeting. Our special thanks to the reviewers who anonymously participated in improving the final manuscripts, and to ANES and ASME Solar Energy Division leadership for their support in facilitating this first meeting, which we hope is the first one of many to come.

Sincerely,

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