FRANCIELE BRAGA MACHADO TULLIO
LUCIO MAURO BRAGA MACHADO
(ORGANIZADORES)

RESULTADOS DAS PESQUISAS E INOVAÇÕES NA ÁREA DAS ENGENHARIAS

Atena Editora
Ano 2020

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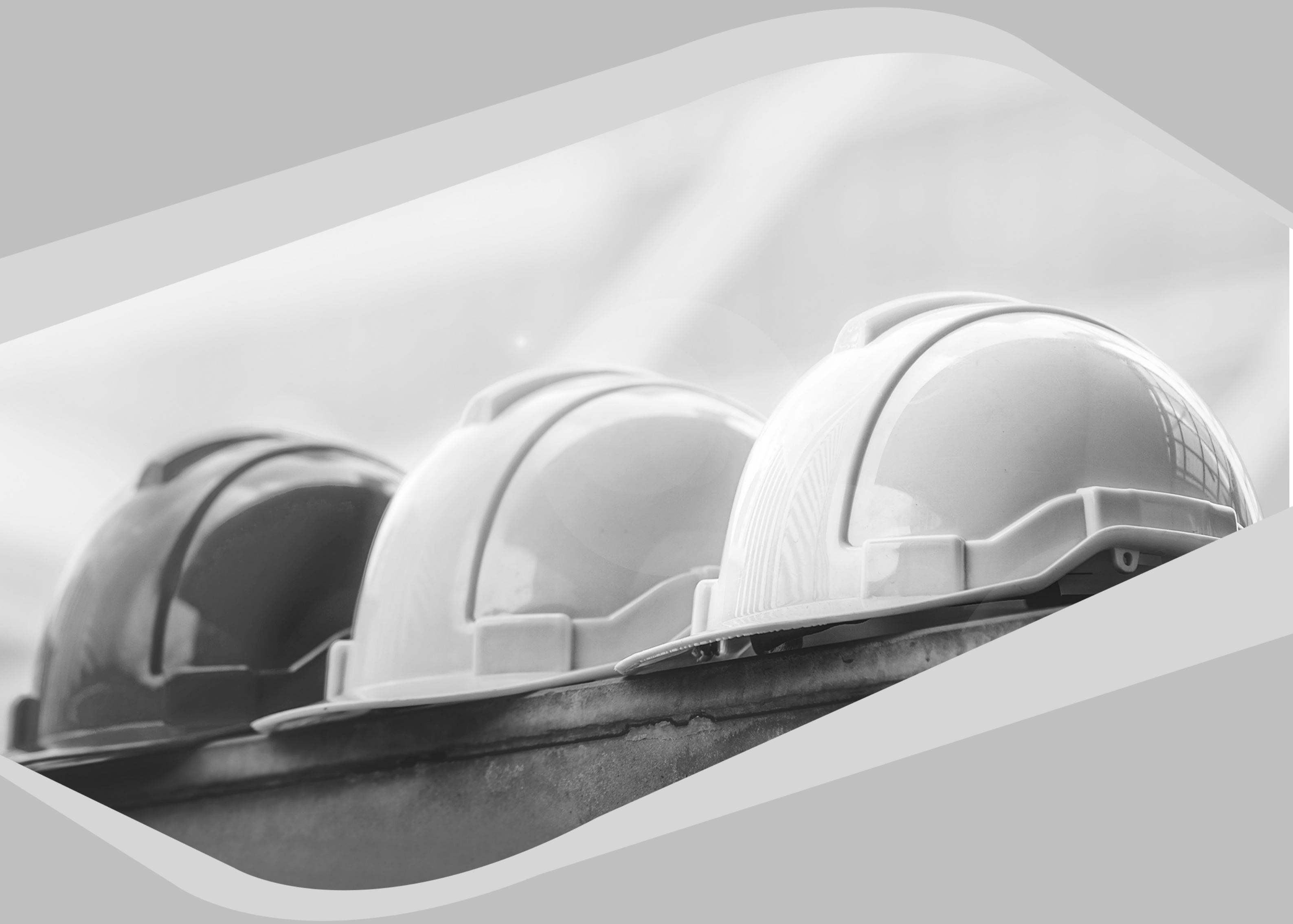

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Editora Chefe: Profª Drª Antonella Carvalho de Oliveira
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Edição de Arte: Lorena Prestes
Revisão: Os Autores

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Dados Internacionais de Catalogação na Publicação (CIP)
(eDOC BRASIL, Belo Horizonte/MG)

R436 Resultados das pesquisas e inovações na área das engenharias [recurso eletrônico] / Organizadores Franciele Braga Machado Tullio, Lucio Mauro Braga Machado. – Ponta Grossa, PR: Atena, 2020.

Formato: PDF
Requisitos de sistema: Adobe Acrobat Reader
Modo de acesso: World Wide Web
Inclui bibliografia
ISBN 978-65-86002-21-8
DOI 10.22533/at.ed.218200303

1. Engenharia – Pesquisa – Brasil. 2. Inovações tecnológicas. 3. Tecnologia. I. Tullio, Franciele Braga Machado. II. Machado, Lucio Mauro Braga.

CDD 658.5

Elaborado por Maurício Amormino Júnior | CRB6/2422

Atena Editora
Ponta Grossa – Paraná - Brasil
www.atenaeditora.com.br
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Atena Editora
Ano 2020

APRESENTAÇÃO

A obra “Resultados das Pesquisas e Inovações na Área das Engenharias” contempla dezoito capítulos em que os autores abordam as mais recentes pesquisas e inovações aplicadas nas mais diversas áreas da engenharia.

A constante transformação que a sociedade vem sofrendo é produto de um trabalho de desenvolvimento de pesquisas e tecnologia que aplicadas se tornam inovação.

O estudo sobre materiais e seu comportamento auxiliam na compreensão sobre seu uso em estruturas e eventualmente podem determinar o aparecimento ou não de patologias.

As pesquisas sobre a utilização de ferramentas computacionais permitem o aprimoramento da gestão de diversas atividades e processos de produção.

São abordadas também nessa obra as pesquisas sobre a forma de ensinar, utilizando as tecnologias em favor do processo de ensino e aprendizagem.

Diante disso, esperamos que esta obra instigue o leitor a desenvolver ainda mais pesquisas, auxiliando na constante transformação tecnológica que o mundo vem sofrendo, visando a melhoria da qualidade de vida na sociedade. Boa leitura!

Franciele Braga Machado Tullio
Lucio Mauro Braga Machado

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CAPÍTULO 7

LOW-COST SUNLIGHT CONCENTRATORS TO IMPROVE HEAT TRANSFER DURING WATER SOLAR DISINFECTION

Data de aceite: 27/02/2020

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ABSTRACT: Solar disinfection (SODIS) is a method recommended by the World Health Organization to obtain microbiologically safe water. The efficiency of SODIS for disinfection purposes can be improved by concentrating the sunlight with solar concentrators (SOCOs) as also showed previously, however, most SOCOs are expensive to be purchased by low-income people. In this study, low-cost SOCOs built with reflecting surfaces such as foil from beverage cans, aluminized tetra pak packages and mirror were tested to improve heat transfer during water solar disinfection. The increase in water temperature reached the mean values of 13, 10 and 8°C for the SOCOs with mirror, aluminum foil, and aluminized tetra pak packages, respectively, in sunny days. As a consequence, the disinfection efficiency of *Escherichia coli* was significantly improved in the SOCO-aluminum and SOCO-mirror system. Regarding production, the SOCOs used in this study can be produced with inexpensive and relatively easy-to-source parts and do not require special tools or skills, so users in under-resourced areas are able to produce the containers for own use.

KEYWORDS: SODIS, Drinking water, *Escherichia coli, Pseudomonas aeruginosa*, Mirror, Aluminized tetra pak package, Foil from beverage can.

CONCENTRADORES DE LUZ SOLAR DE BAIXO CUSTO PARA MELHORAR A TRANSFERÊNCIA DE CALOR DURANTE A DESINFECÇÃO SOLAR DE ÁGUA

RESUMO: A desinfecção solar (SODIS) é um método recomendado pela Organização Mundial de Saúde para se obter água potável do ponto de vista microbiológico. A eficiência do SODIS para fins de desinfecção pode ser melhorada por meio de concentradores da radiação solar (SOCOs) como já mostrado anteriormente, entretanto, a maioria dos SOCOs são caros para serem adquiridos por pessoas de baixa renda. Neste estudo, SOCOs de baixo custo construídos com superfícies refletoras como latas de bebidas de alumínio, embalagens aluminizadas do tipo tetra pak e espelhos foram testados quanto a capacidade para transferir calor durante a desinfecção solar da água. O aumento médio da temperatura da água alcançou 13, 10 e 8 °C para os SOCOS com espelho, latas de bebidas de alumínio e embalagens aluminizadas do tipo tetra pak, respectivamente, em dias ensolarados. Como conseqüência, a eficiência da desinfecção de *Escherichia coli* foi significativamente melhoradas nos sistemas SOCO-alumínio e SOCO-espelho. Em relação à produção, os SOCOs usados neste estudo podem ser produzidos com peças de baixo custo e relativamente fáceis de serem encontradas, e não requerem ferramentas ou habilidades especiais, de modo que os usuários em áreas com poucos recursos podem produzi-los.

PALAVRAS-CHAVE: SODIS, Água potável, *Escherichia coli*, *Pseudomonas aeruginosa*, Espelho, Embalagem aluminizada tetra pak, Folha de lata de bebida.

1 I INTRODUCTION

Recent data indicate that 844 million people still lack a basic drinking water service and 2.3 billion people did not have access to basic sanitation service (WHO/UNICEF, 2017). This leads to several problems of public health. When water is unsafe and sanitation non-existent, water can kill. Globally, waterborne illnesses are the second leading cause of death for children under five, killing 1,000 children every day (UNICEF/USA, 2017).

In many developing countries, the intermittent supply of water encourage population to look for alternative sources which are generally inappropriate. Even those who have regular supply of water may not have access to microbiologically safe water. Thus, point-of-use water treatment technologies, such as filtration, boiling, chlorination, flocculation/disinfection and solar water disinfection (SODIS) are valuable tools for improving drinking water quality and to reduce the high incidence of diarrheal diseases (GÓMES-COUSO et al. 2012).

SODIS is a simple, low-cost, and sustainable method for disinfecting contaminated water (AMIN & HAN, 2011; DUNLOP et al. 2011). SODIS is a World Health Organization approved method and has been applied mainly in developing countries where people have no access to safe drinking-water (MOSER & MOSLER, 2008; MURINDA &

KRAEMER, 2008; DAWNEY et al, 2014; MAC MAHON & GILL, 2018). The standard method involves at least 6 hours of sunlight exposure to a polyethylene tetraphtalate (PET) bottle filled with no more than 2 to 3 L of contaminated drinking-water (DUNLOP et al. 2011; TEDESCHI et al. 2014). PET bottles are considered safe and adequate for SODIS applications and do not trigger the migration of hazardous contaminants at critical levels (SCHMID et al. 2008). During the solar disinfection, the pathogenic microorganisms are inactivated by the synergic action of two factors: (i) radiation in the UV range (UV-A, wavelength 315-400 nm), and (ii) the increasing temperature which must reach at least 45 °C (MCGUIGAN et al. 1998). The main condition for applying this technique is geographic location. Countries lying in the latitude lines of 30°N and 30°S receive sufficient sunlight to apply SODIS (NAVNTOFT et al. 2008).

To improve SODIS efficiency, several attempts have been carried out in the last decades to increase the radiation reaching the bottles. For this, solar concentrators (SOCOs) with reflecting surfaces such as aluminum foil, mirrors and lenses have been used (HINDIYED & ALI 2010, AMIN & HAN, 2011). However, in many cases, the SOCO production are expensive and bulky to be economically transported to the location where they are required, such as rural areas, and thus they are expensive to be purchased by those who currently use SODIS (DUNLOP et al. 2011). Ubomba-Jaswa et al. (2010) developed a batch reactor fitted with a compound parabolic collector to improve SODIS efficiency at a price of US$200. Despite the attractive price, it is still expensive for low-income people.

In this study, the main goal was to develop low-cost sunlight concentrators (SOCOs) to improve heat transfer during solar water disinfection. The materials used as reflecting surfaces were aluminum foil from beverage cans, aluminized tetra pak packages and mirror. Accordingly, the efficacy of the SOCOs was assessed using well-water contaminated with *Escherichia coli* (ATCC 25922) and *Pseudomonas aeruginosa* (ATCC 9027).

2 I MATERIAL AND METHODS

2.1 Solar energy concentrators

Three solar concentrators (SOCOs) were made using the design proposed by Martín-Dominguez et al. (2005). The SOCOs consisted of a wood fixed base painted black with a rectangular area of 0.45 m x 0.35 m and wood wings of 0.35 m x 0.45 m and 0.35 m x 0.35m, all with the same vertical angle (ϴ) of 30º with respect to the fixed base. Three materials were used to cover the wings: aluminum foil from beverage cans, aluminized tetra pak packages and mirrors (Figure 1). The beverage cans and tetra pak packages were used because they are recyclable materials and can be easily found without cost. The mirror has been traditionally used in SOCOs due its efficacy to improve solar disinfection and was used here as a reference. Each SOCO had a capacity of four bottles. Bottles exposed directly to sunlight (SODIS) always were included as control.

Figure 1. Solar energy concentrators (SOCOs) to improve heat transfer during water solar disinfection. a). SOCO-aluminum foil from beverage cans, b). SOCO-aluminized tetra pak packages, c). SOCO-mirror, and d). SODIS.

2.2 Contaminated well-water

Well-water was collected from an artesian well located in Federal University of Mato Grosso, Cuiabá, Brazil. The water was autoclaved (121 °C, 1 atm, 20 min) and 1.8 L sterile water was transferred to 2-L transparent PET bottles that were previously disinfected with 70% alcohol and subjected to UV irradiation for 15 minutes.

Escherichia coli (ATCC 25922) and *Pseudomonas aeruginosa* (ATCC 9027) were used to contaminate the well-water. Procedures for the preparation of these strains for solar inactivation were identical. Bacteria from stock cultures were sub-cultured in 50 mL Nutrient Broth (g L^{-1}: peptone 5.0, NaCl 5.0, yeast extract 1.5 and beef extract 1.5) and incubated for 24 h at 35 °C on rotary shaker (150 rpm). Bacteria in stationary phase were harvested by centrifugation (3600 g, 10 min) washed and resuspended in sterile saline solution (0.85%). This procedure was repeated three times to obtain bacteria suspension used to contaminate the water. Initial bacteria concentration in well-water ranged from 10^4 and 10^5 CFU mL^{-1} (Colony Forming Unit mL^{-1}).

2.3 Sunlight exposure

PET bottles were typically irradiated from 9 am to 3 pm. All experiments were conducted at Federal University of Mato Grosso located in Mato Grosso State, Midwest Brazil. Observations of weather conditions were recorded at each sampling. Solar radiation data were obtained at 5 min intervals from a meteorological station located approximately 100 m from the site of the experiments. Water temperatures in bottles were recorded using a digital thermometer (Incoterm, model 6132). The solar disinfection experiments were conducted on nine different days to ensure the repeatability of the trends of the results.

2.4 Bacterial enumeration

Enumeration of bacteria in well-water exposed to sunlight was conducted through the Spread Plate Method (APHA, 2012). The detection limit for this method of quantification is 10 CFU mL^{-1}. Aliquots of 1 mL water were collected from the PET reactors and transported in sterile tubes on ice to the laboratory. The analysis was carried out within 2 hours of sample collection. The aliquots were serially diluted in sterile saline solution (0.85% w/v) and 0.1 mL was plated on media Luria-Bertani Agar (g L^{-1}: tryptone 10.0, NaCl 10.0, yeast extract 5.0, agar 15.0) and Cetrimide Agar (g L^{-1}: gelatin peptone 20.0, magnesium chloride 1.4, potassium sulfate 10.0, cetrimide 0.3, agar 15.0) to count *E. coli* and *P. aeruginosa*, respectively. These bacteria were measured each 1 h, during 6 h exposure. As control, bottles with well-water contaminated always were kept in the dark at room temperature in the laboratory. All bacteria enumerations were performed in duplicate.

2.5 Data analysis

The behavior of inactivation curves on experimental data of SODIS and SOCOs was investigated with Geeraerd and Van Impe Inactivation Model Fitting Tool (GInaFit) using Geeraerd Log-linear model (GEERAERD et al. 2005). Geeraerd model has been widely used for the fitting of solar disinfection studies (BOYLE et al. 2008; AMIN & HAN, 2009; AMIN et al. 2014; LAWRIE et al. 2015). $T_{99.9}$ values (time to reduce plate counts by 99.9%) also were calculated using Geeraerd Log-linear model. Results were analyzed by one-way analysis of variance when it was assumed normality and homogeneity of variance of data. Otherwise, the nonparametric Kruskall-Wallis test was used. Differences were considered significant at $p<0.05$ for both tests.

3 I RESULTS AND DISCUSSION

3.1 Weather conditions

The weather conditions during solar disinfection experiments were sunny. A sunny day was defined by Nalwanga et al. (2014) as zero cloud cover with strong sunshine for at least three quarters of the day. Mean values of global radiation during the solar exposure ranged from 676.1 W m^{-2} (06/01/2015) to 789.4 W m^{-2} (16/01/2015) (Table 1). These values were appropriate for SODIS application, which should receive 3–5 h solar radiation above 500 W m^{-2} (WEGELIN et al. 1994).

Exposure date (DD/MM/YY)	Irradiance (W m^{-2})		
	Mean ± Standard Deviation	Minimum	Maximum
28/12/2014	683.3 ± 103.6	445.2	894.3
29/12/2014	715.3 ± 87.8	508.1	840.6
31/12/2014	687.7 ± 115.4	328.1	898.1
06/01/2015	676.1 ± 79.5	521.9	844.9
13/01/2015	734.6 ± 88.3	555.6	900.9
14/01/2015	699.4 ± 103.8	516.1	851.3
15/01/2015	679.1 ± 150.6	238.1	875.5
16/01/2015	789.4 ± 132.1	468.4	981.3
17/01/2015	705.4 ± 104.5	505.6	876.9

Table 1**.** Average global radiation (9 am to 3 pm) during the application of solar disinfection.

3.2 Thermal performance

Water temperature is affected by weather conditions and is directly proportional to irradiance (AMIN et al. 2014). The water temperature was measured at 1 h intervals and results (mean of 9 different dates) are shown in Figure 2. There was almost an exponential rise in water temperature between 9-12 am reaching maximum values at 1-2 pm. These maximum values were higher than 45 ºC, which is the minimum temperature required for microbial inactivation by SODIS (MCGUIGAN et al. 1998). A maximum difference of 13, 10 and 8 ºC was observed between SODIS and SOCO-Mirror, SOCO-Aluminum and SOCO-Tetra pak, respectively. These results are greater than those obtained in other studies. Amim & Han (2009) made a solar collection system using aluminum foils as reflecting surface and observed that, in sunny weather, the temperature of water in the SOCO system was 2-4 °C greater than temperature in the SODIS system. As consequence, it was found a 20-30% increase in the disinfection efficiency due to the concentrated effects of sunlight radiation. Amin et al. (2014) evaluated the solar disinfection of *P. aeruginosa* contaminated harvested rainwater by the SODIS and SOCO systems. At mild and weak conditions, the solar concentrator increased the water temperature by up to 2-3 °C. However, the SOCO system was efficient only under mild weather conditions. Increase in water temperature in our study indicated that the reflecting materials associated with the open wings from SOCOs were adequate to improve heat transfer during water solar disinfection. Moreover, additional solar radiation input to the PET bottles not only increase the heat but also increase the incident UV radiation on the water contributing for the optical inactivation. Kruskal-Wallis multiple comparisons of mean ranks showed a statistically significant difference between the temperatures found in SOCOs and SODIS (p<0.01).

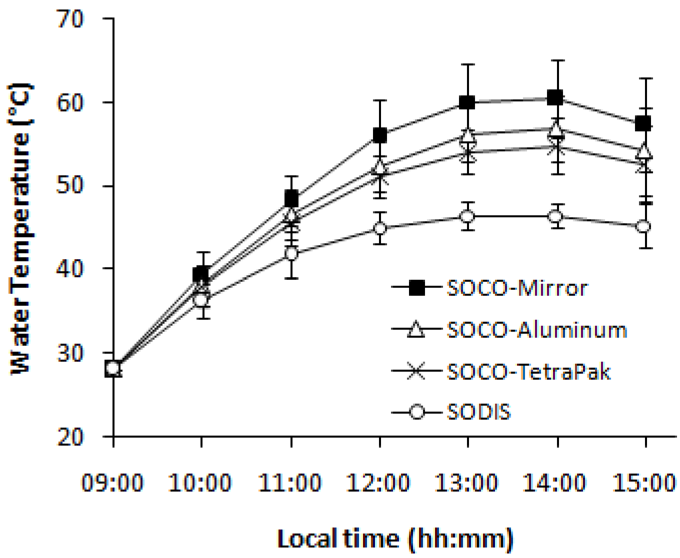

Figure 2. Effects of SOCOs and SODIS in water temperature.

3.3 Disinfection performance

The sensitivity to solar disinfection by SODIS and SOCOs of the two bacterial species reported in this study is illustrated in Figure 3. No reduction in population was detected for control samples of the species examined kept in the dark (data not shown). *P. aeruginosa* (ATCC 9027) is more sensitive to solar disinfection than *E. coli* (ATCC 25922). Complete inactivation (when the bacterial concentration decreased below the detection limit (DL = 10 CFU mL^{-1})) of *P. aeruginosa* was reached after 1-2 hours of solar exposure while 2-4 hours were necessary to complete inactivation of *E. coli* (Figure 3). The two bacteria failed to regrow at room conditions after two days in dark storage indicating that the inactivation process was irreversible.

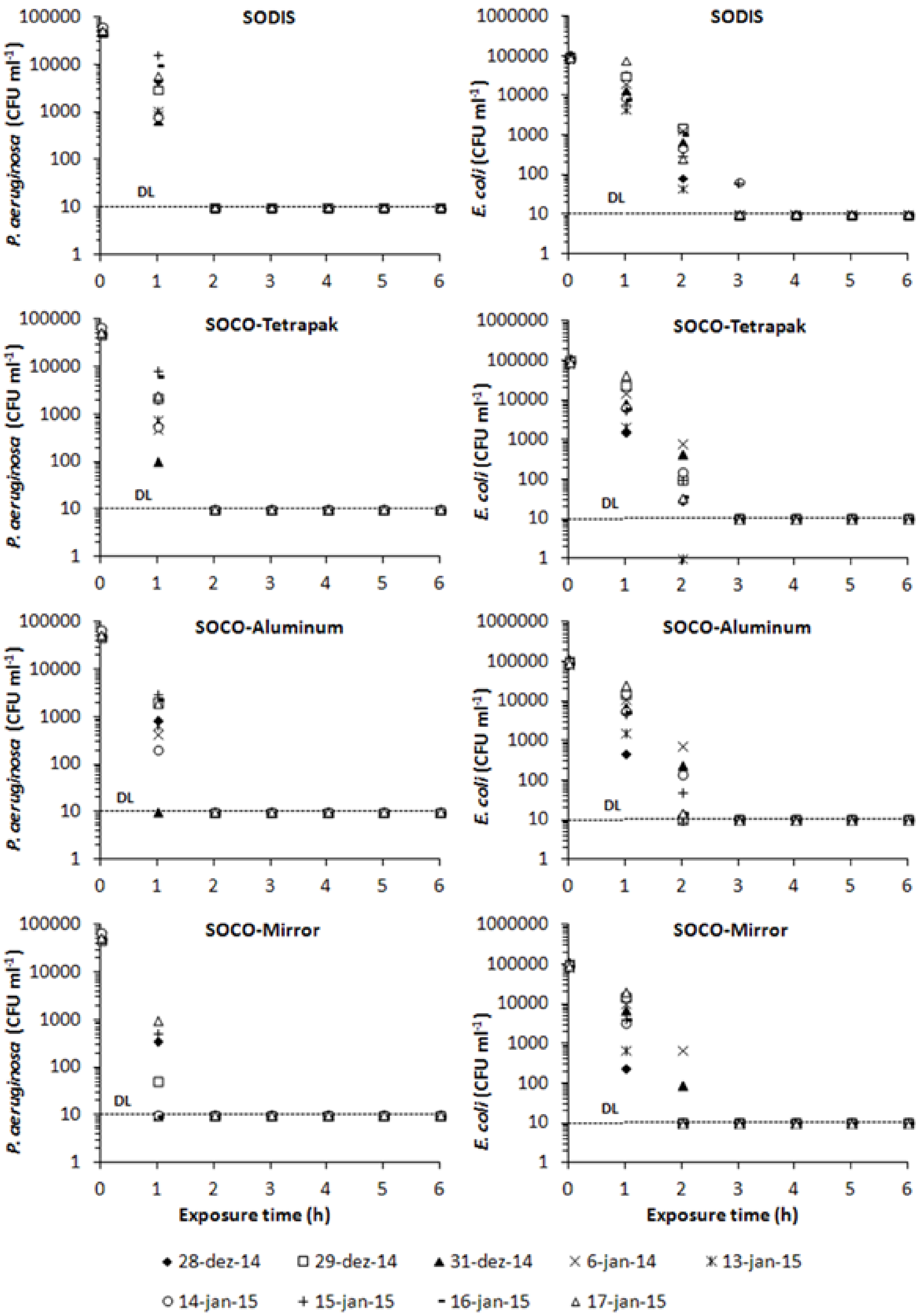

Figure 3. Inactivation curves of *P. aeruginosa* and *E. coli* during 6-h solar exposure (9 am to 3 pm) with SODIS and SOCOs in nine different dates. Dashed line indicates the detection limit (DL).

The inactivation curves in our experiments, with rare exceptions, showed no lag phase and all curves were well described by a Log-linear model ($0.87 < r^2 < 0.99$ for *E. coli* and $0.86 < r^2 < 0.99$ for *P. aeruginosa*). In some cases, during the solar inactivation of *P. aeruginosa* in SOCO-aluminum and SOCO-mirror, a relatively small number of data points collected made the use of the Log-linear model impractical. Bacterial inactivation rates, k (min^{-1}), at SODIS and SOCOs systems calculated using the Geeraerd Log-linear model are compared in Table 2. Inactivation rates obtained for *P. aeruginosa* in SODIS and SOCOs are practically identical. On the order hand, inactivation rates for *E. coli* obtained for SOCO-aluminum and SOCO-mirror were statistically higher than that obtained for SODIS (p=0.0259 and p=0.0002, respectively).

For practical applications, it is useful to consider the time until the initial number of bacteria is inactivated to a fraction of 10^{-p}. If p = 3, for example, this is the time to reduce plate counts by 99.9% ($t_{99.9\%}$) or three-log inactivation. Table 3 reported $t_{99.99\%}$ values for SODIS and SOCOs experiments with *E. coli* and *P. aeruginosa*. Significant statistical differences were only detected for *E. coli* when SOCO-aluminum and SOCO-mirror were compared to SODIS (p=0.0001 and p=0.0011, respectively).

Although the SOCOs have increased the water temperature, the required time to reach complete inactivation was reduced only for *E. coli* in SOCO-aluminum and SOCO-mirror. During *P. aeruginosa* inactivation, no differences were observed for inactivation rate constants and three-log inactivation times obtained for SODIS and SOCOs. This fact may suggest that UV may also played a significant role in solar inactivation of bacteria. Some researchers have already related the importance of UVA during solar disinfection (KEHOE et al. 2001; MARTÍN-DOMINGUEZ et al. 2005; LAWRIE et al. 2015), once transmittance of most PET bottles is around 85–90% (NAVNTOFT et al. 2008). This situation is more evident when it is noted the inactivation of *P. aeruginosa* in SODIS experiments within two hours even without the temperature water reaches 45 °C (Figures 2 and 3).

The use of laboratory-cultured bacteria in this study may have influenced the rapid solar inactivation observed (between 1-4 h). Comparative trials have shown that bacteria and viruses found in the environment may take longer to inactivate compared with laboratory-cultured test organisms (FISHER et al. 2012). One potential reason for this difference could be growth conditions. In laboratory, cultures grow on rich media under aerobic conditions, while microorganisms in the environment generally grow under nutrient-scarce condition, which may induce resistance to stress, including resistance to heat (JENKINS, et al. 1988).

Solar concentrators	First-order inactivation rate constants (k) (min^{-1})$^{+}$	
	E. coli	*P. aeruginosa*
SODIS	0.056 (± 0.009)	0.091 (± 0.001)
SOCO-Tetra pak	0.067 (± 0.010)	0.091 (± 0.001)
SOCO-Aluminum	0.074 (± 0.017)*	0.091 (± 0.001)

SOCO-Mirror	0.091 (± 0.015)**	0.091 (± 0.001)

Table 2. Inactivation rate constants (k) (min^{-1}) for all solar concentrators, determined from linear regressions of inactivation over time.

+ Data tested by one-way analysis of variance (ANOVA) followed by Tukey multiple comparisons test. * and ** indicate values that are significantly higher than the SODIS value (control) at the 95 and 99% confidence levels, respectively.

Solar concentrators	Three-log inactivation times (min)+	
	E. coli	*P. aeruginosa*
SODIS	127.1 (± 24.94)	75.9 (± 0.83)
SOCO-Tetra pak	104.3 (± 12.42)	75.9 (± 0.91)
SOCO-Aluminum	95.9 (± 17.43)*	75.8 (± 0.90)
SOCO-Mirror	81.6 (± 16.97)*	76.0 (± 1.03)

Table 3. Three-log inactivation times (min) for all solar concentrators.

+ Data tested by one-way analysis of variance (ANOVA) followed by Tukey multiple comparisons test. * indicates values that are significantly lower than the SODIS value (control) at the 99% confidence levels.

4 I CONCLUSSIONS

The SOCOs used in the present study improved heat transference during water solar disinfection when compared to SODIS system. The increase in temperature reached the mean values of 13, 10 and 8 °C for the SOCOs with mirror, aluminum foil from beverage cans, and aluminized tetra pak packages in sunny days. As a consequence, the disinfection efficiency of *E. coli* in the SOCO-aluminum and SOCO-mirror system was significantly improved. The SOCOs used in the present study are simple, low-cost and the materials used to construct them are easily found. These characteristics enable anyone to use the solar disinfection to gain access to safe drinking water, especially those people in under-resourced areas. Additional research is needed to understand the impact of the SOCOs on the inactivation of other microorganisms as well as on the disinfection efficiency under moderate and weak sunlight radiation.

ACKNOWLEDGEMENTS

This study was supported by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) under grant 455007/2012-8.

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2020