Journal of Mechanical and Electrical Intelligent System (JMEIS)

Solar disinfection of Escherichia coli: A comparative analysis of 3 types of reactors and TiO2 concentration using a compound parabolic concentrator

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Keywords: photocatalytic disinfection, TiO_2 concentration, compound parabolic concentrator

Abstract. Bacterial disinfection effect on survival of *E.coli* K12 was carried out with the reactor configuration of different solar illuminated areas by 3 types of reactors. Moreover, the objective of this research was to determine the effectiveness of water disinfection by using 3 types of reactor surfaces. The pilot system consisted of a compound parabolic concentrator, which examined water disinfection efficiency. The results reveal that of all the small areas of all 3 reactor surfaces, the catalyst reactor was slightly more effective at dropping bacteria concentration by about 1 log. However, in the experiment with larger areas, the catalyst reactor and black reactor are more effective at dropping bacteria concentration. This result shows the black reactor surface could be applied to water disinfection, which dropped more than 2 logs. Moreover, the catalyst reactor has the most effect on dropping bacteria concentration, to 4 logs. Therefore, TiO_2 has been proven as a water disinfection process for organic contamination. Moreover, the experiments were also carried out using titanium dioxide (TiO_2) by suspension at 0.25, 0.5, 0.75, 1 g/L as a slurry form, which determined the effect of the TiO_2 concentration on bacteria inactivation. The result reveal that the TiO_2 concentration at 1 g/L is the most effect to drop bacteria concentration to 4 logs. The application of this article reveals the black color and photocatalytic disinfection technology in CPC could be applied for water disinfection by global solar radiation.

1. Introduction

In recent years, drinking water has been an enormous problem for people involving both chemical and biological risks. The preparations for clean drinking water have become enormous problems for many countries and efficient solutions have been found to manage the problems. The water disinfection technologies, such as heating, chlorination, and ozonation have been applied for clean drinking water. However, these methods have a negative effect on environment health and incur high operating costs for water disinfection.

Sunlight has been recently applied for water disinfection because this method has been proved for bacteria inactivation [1]. Recently papers showed solar disinfection by determining the UV dose in (kJ/m^2) and UV irradiation (W/m^2). Moreover, most experiments have determined accumulated solar energy in (kJ/L) [2-3]. Furthermore, solar radiation has been applied to enhance bacteria disinfection by adding TiO_2. Therefore, photocatalytic disinfection for drinking water using TiO_2 was used to evaluate the effectiveness against *E.coli* concentration [4-5]. Titanium-dioxide (TiO_2) has been applied to enhance bacteria inactivation by solar radiation [6-8] because the semiconductor (TiO_2) could produce hydroxyl radical ($OH^{\bullet}$) when it was excited by solar radiation of wavelengths near 400 nm [9]. Moreover, TiO_2 has been applied to both disinfection of drinking water and waste water treatment [10]. This oxidation technology has been used not only for water disinfection but also air treatment by using TiO_2. Moreover, TiO_2 is widely known to generate electron/hole pairs (e^-_{CB} / h^+_{VB}) which separated in the conduction band (CB) and the valence band (VB) of semiconductors. The catalytic reaction of TiO_2 photocatalysis involved water and dissolved oxygen [11,12]. They are summarized by equations (1), (2) and (3)

$$TiO_2 + hv \rightarrow TiO_2 + e^-(CB) + h^+(VB) \tag{1}$$

$$H_2O + h^+_{VB} \rightarrow {}^{\bullet}HO + H^+ \tag{2}$$

$$O_2 + e^-_{CB} \rightarrow O_2^{\bullet -} \tag{3}$$

Photocatalytic disinfection agents are commonly used in both drinking water and waste water treatment [13]. Many publications have researched on the application of TiO_2 photocatalytic disinfection on a lab scale [14]. However, the photocatalytic disinfection applications of pilot-plant with natural sunlight also researched on bacteria inactivation [15]. The compound parabolic concentrator has been applied to collect both diffuse and direct solar radiation, which focus on reactor surface for water disinfection. Recent publications have applied CPC and solar radiation to water disinfection [16-17]. Moreover, photocatalytic disinfection using CPC has been publicized which have the effect to drop bacteria concentration [18-19]. Therefore, photocatalytic disinfection has been proved in enhancing public health in developing countries. The proposed scopes of these experiments investigated water disinfection kinetics and efficiency of TiO_2 concentration of different reactor types under global solar radiation. This research has used *E.coli* concentration as an indicator of water disinfection. These experiments used varied parameters such as the 3 types of reactor and the TiO_2 concentration, which were studied at the same time on different sunny days. The goal of this experiment was to evaluate solar radiation in the absence and presence of TiO_2 to assess the effectiveness on bacteria inactivation. The topics studied in this paper are (a) the effect of solar radiation on bacteria disinfection with the presence and absence of TiO_2, (b) the effect of black reactor surface on bacteria disinfection by solar radiation, and (c) the effect of TiO_2 concentration on bacteria disinfection.

2. The Preparation of Reactor Surface of Experiments

The reactors were designed for 3 types of experiments. The first type was designed to use the glass plate size of 7×20 cm by 7×5 cm with 6 mm of thickness to combination as the reactor. The second type was the same as the first type but this second reactor type was designed to absorb global solar radiation by the matte black acrylic (TOA) sprayed on the bottom of the reactor as in Fig. 1 (a). The third type was designed to analyze the effectiveness of photocatalytic disinfection by coating TiO_2 (AMPERIT) on a stainless plate sized 7×20 cm. with 3 mm of thickness [19]. The stainless plate was coated with TiO_2 by the thermal spray method which tacked the plate onto the bottom as in Fig. 1(b).

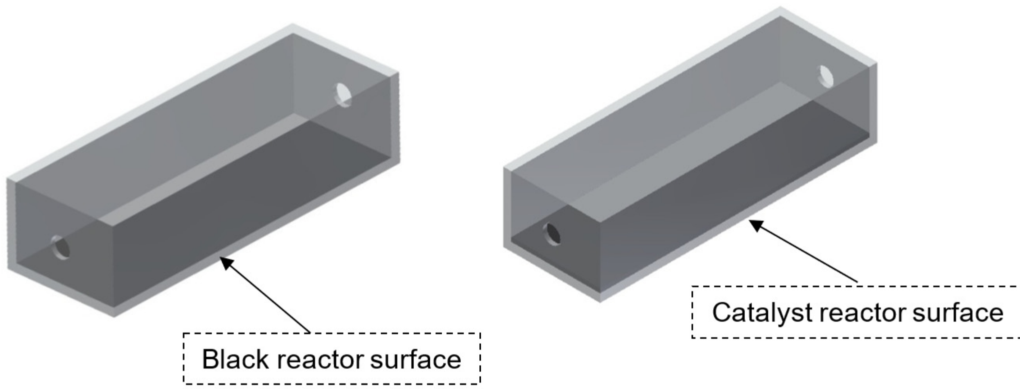

Fig. 1. (a) The black reactor surface and (b) The catalyst reactor surface [19].

The 4 reactors were connected in a series on the compound parabolic concentration (CPC) as non-tracking the reactors aligned in a north- south direction and held on a platform tilded at 14° local latitude as in Fig. 2. The CPC has a flat receiver which applied to water disinfection by focusing solar radiation onto the reactors. The parameter of the CPC can be calculated according to the following condition [20].

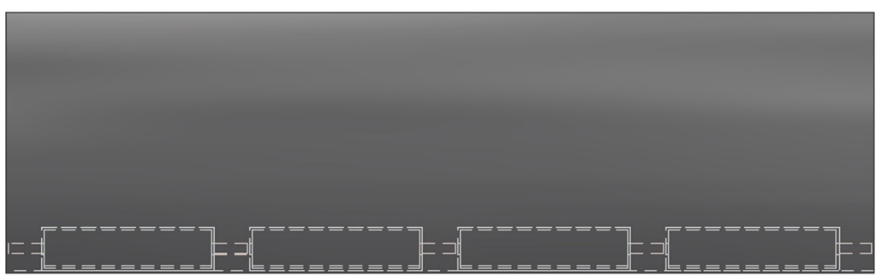

Fig. 2. The reactors connected in a series on CPC.

$$f = \frac{a}{2}(1 + \sin\theta_c) \tag{4}$$

$$H = \frac{a}{2}\left(\frac{1}{\tan\theta_c} + \frac{1}{\tan\theta_c \sin\theta_c}\right) \tag{5}$$

$$x^2 = 4fy \tag{6}$$

Where f is the focus of the parabola, a is the receiver, θ_c is the acceptance half-angle and H is the height of the CPC. This experiment was set up in Bangkok, and so the θ_c was defined to be 21°. The width of the flat receiver was defined to be 12.5 cm. Therefore, the CPC was calculated from the equation (4) – (6). The height of the CPC was 1.234 m, aperture of CPC was 0.696 m, and the focus was 0.092 m. The CPC was designed by the truncated method to lower the cost of material and increase the illumination time by solar radiation.

3. Experiment and Method

3.1 Reactor Setup

The CPC pilot plant consisted of the 4 reactors connected in a series on the CPC, which was designed to be non- tracking. The compound parabolic concentrator (CPC) was developed from solar thermal energy applications to collect global solar radiation on the photoreactor. The de-ionized water was prepared in the reservoir of each test. The total volume of the de-ionized water, 6 liters, was circulated through the sampling valve, regulator valve, flow meter, 4 reactors and then returned to the reservoir as in Fig 3. The experiments were adjusted at a fixed flow rate of 2 liters/min. The characteristics of the experiments are shown in Table 1. The experiments were carried out under global solar radiation at King Mongkut's University of Technology Thonburi, Bangkok (13° 45´ N 100° 31´ E).

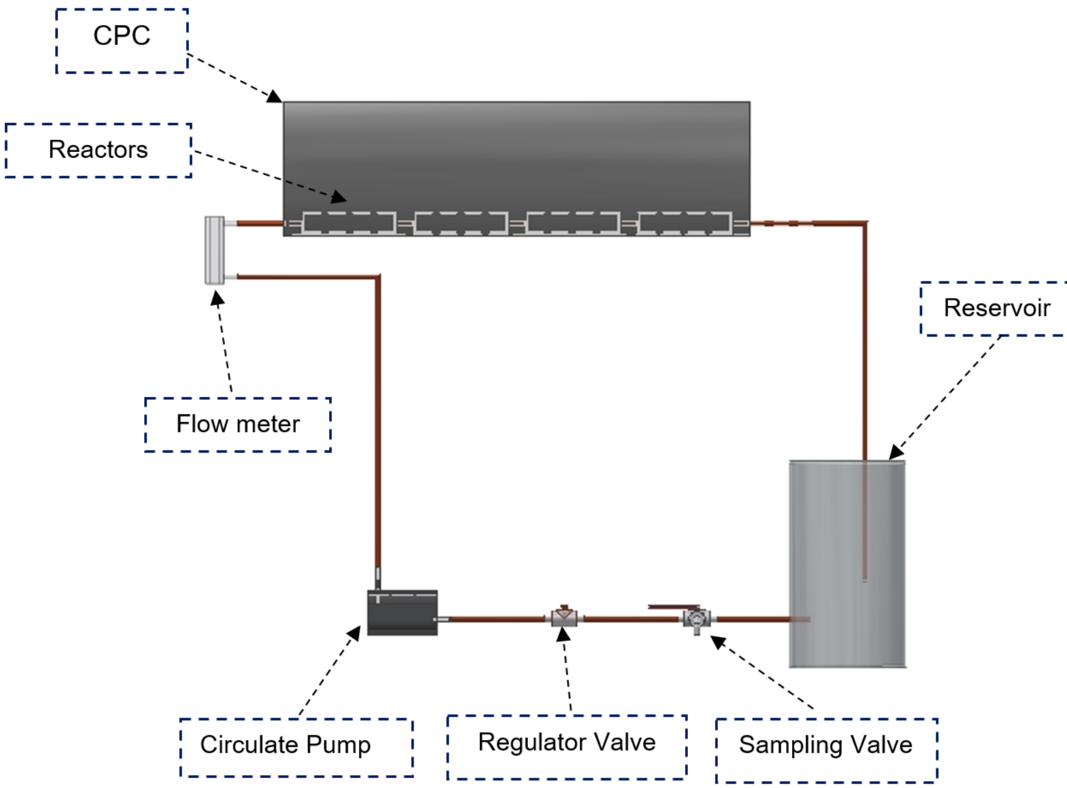

Fig. 3. Flow diagram of the solar disinfection in the CPC.

Table 1. The characteristics of bacteria inactivation.

Illuminated reactor surface	0.014 m^2	0.056 m^2
Number of reactors	1	4
Total volume of water	6 liters	
Flow rate	2 liters/min	
Experimental time	90 min	

3.2 Experimental Procedure

The bacteria disinfection was evaluated on the bacteria concentration decreasing under reactor on the CPC. Bacteria concentration was determined by measuring *E.coli* cells under solar radiation every 15 minutes. The experiments were designed to quantify bacteria concentration against the experimental time. The bacteria concentration was suspended in a reservoir which contained 6.0 liters of an autoclave sterilized de-ionized water. The initial bacteria concentration counts were 10^7 CFU/mL. The bacteria disinfection was monitored by sampling at 15 min intervals. A 10 mL sampling was collected in a sterilized tube by releasing from the sampling valve. The experiment was started at 10:45 A.M and continued until 12:15 P.M. which involved sampling every 15 minutes staring at 11:00 A.M. until 12:15 P.M

3.3 *E.coli* analysis

Bacteria concentration suspensions were diluted and plated on LB-agar. The colony counts were taken after 24 hours after incubation and the plates were incubated at 37 °C. A bacteria culture determined the bacteria concentration and tested suspensions were diluted to a suitable concentration by Rigger solution and then disseminated uniformly on to a nutrient agar plate. After an overnight incubation at 37 °C, and colonies were counted and the initial of bacteria was calculated which all experiments were counted for at least three plates.

3.4 Solar Radiation Measurement

The solar radiation was measured by a pyranometer (Model.CM11,KIPP&ZONEN). The pyranometer was adhered at the same angle with the CPC as 14°. Moreover, the solar energy was evaluated in terms of solar irradiance, which is defined as the rate of incidence on a surface per unit area (W/m^2) and solar energy dose on the illuminated reactor surface (J/m^2) and the accumulated solar energy per unit of water volume (J/L^{-1}), which is used for solar disinfection in a reactor.

3.5 The Experiments of Reactor Surface by Solar Energy

The experiment demonstrated water disinfection on different number of reactors. The experiments were set for 1 reactor (0.014 m^2) and 4 reactors (0.056 m^2) to compare the effectiveness on bacteria inactivation. Moreover, the experiments were set for the 4 reactors' configuration in a series where all reactors had the same as area in Fig 4.

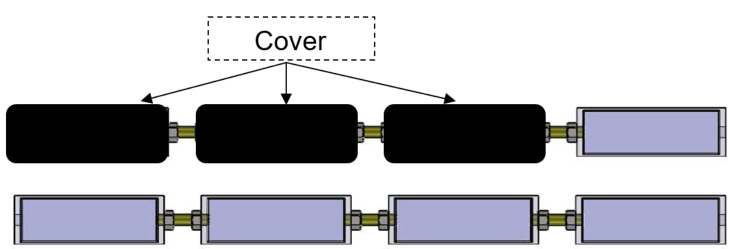

Fig. 4. Reactor's surface exposed to solar radiation

In the experiment, 1 reactor was set to receive solar radiation and other 3 reactors were covered by black plate to conceal solar radiation. Moreover, the 4 reactors were set to be exposed to solar radiation. All cases of experiments tested both 1 reactor and 4 reactors to determine the effective of water disinfection. Therefore, the first experiment set the reactor surface to determine the effectiveness of solar radiation. Moreover, the second experiment was applied to set the black reactor surface to determine the effect of black surface impacted by solar radiation and the third experiment was applied to set the catalyst reactor surface to determine the effect of photocatalytic disinfection. Moreover, the experiments were also set to assess the efficiency of TiO_2 concentration which was tested on the 4 reactors to receive solar radiation. The experiment evaluated the effect on bacteria disinfection by adding TiO_2 in slurry form in the reservoir for 0.25, 0.5, 0.75 and 1 g/L of concentration. Therefore, the systems can be developed by the low-cost method of using TiO_2 concentration.

4. Results and Discussion

4.1 The Effect of 3 Types of Reactor Surfaces on Bacteria Inactivation with 1 Reactor Exposed to Global Solar Radiation

These experiments assessed the effects of a reactor, black reactor, and catalyst reactor on bacteria disinfection. This experiment was set to evaluate a small area on bacteria inactivation. Moreover, water disinfection of *E.coli* concentration suspension in sterile de-ionized water ranged from 10^7-10^8 CFU/mL in the bactericidal effect of solar radiation. The experiment has been observed on the 3 types of reactor surfaces, which set the 1 reactor to receive solar radiation to determine water disinfection within 90 minutes experimental time.

All the results in Fig. 5(a) show the bacteria concentration was very slowly dropped at the first 30 min of exposure to solar radiation. This result shows the flowing of photons or generated $OH^{\bullet}$ radicals is not sufficience to damage bacteria membrane. However, bacteria inactivation acceleration was dropped in the period of 30-60 min of all cases. These results reveal that the anti-stress enzymes are not able to protect the bacteria membrane. Moreover, after 60 min, bacteria inactivation was not more effective at dropping all 3 types of reactors. The result shows the flowing of photons was absorbed on a reactor surface to attack bacteria cells which dropped almost 2 logs within 90 min experimental time. Moreover, the flowing of photons was absorbed on a black reactor surface which had a slightly more effect to drop the bacteria concentration than other reactor surfaces. This result could be explained that a black reactor surface is more effective on bacteria inactivation, which shows the properties of black color could be applied to absorb solar radiation on water disinfection. Moreover, the catalyst reactor surface is the most efficient for bacteria inactivation because it has a synergistic relationship of $OH^{\bullet}$ radicals and flowing of photons to overcome bacteria membranes. However, these results reveal the catalyst reactor surface is slightly more effective than the black reactor and non-black reactor, which show similar bacteria inactivation kinetics because there is a small area to absorb solar radiation to generate $OH^{\bullet}$ radicals. However, all 3 types of reactors including the 1 reactor exposed to solar radiation did not significantly drop different bacteria concentrations within 90 min.

The results also show bacteria inactivation as a function of accumulated solar energy per unit of water volume (J/L^{-1}), which is used for solar disinfection in the reactor.

$$Q = \sum_n \bar{Q}_{n-1} \frac{Ar}{Vt} (t_n - t_{n-1}) \tag{7}$$

Where $\boldsymbol{Q}$ accumulated solar energy, t_n is the experimental time for sampling, $\boldsymbol{Q_{n-1}}$ is the average solar radiation during the period (t_n-t_{n-1}), Ar is the illuminated surface, and Vt is the total volume of water.

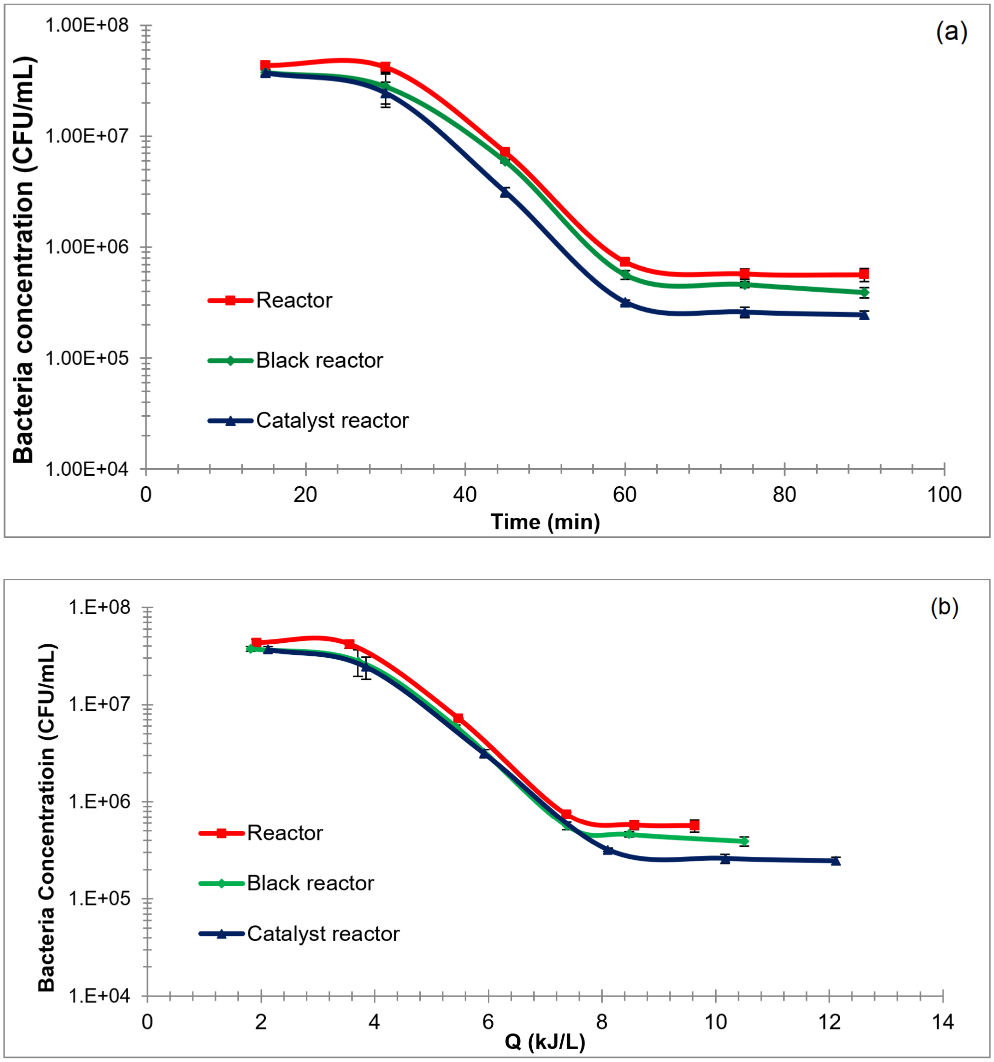

Fig. 5 Bacteria inactivation of *E.coli* (log (CFU/mL)) during real sunlight exposure under reactor (—□—), black reactor (—◊—), catalyst reactor (—Δ—) against (a) experimental time, (b) accumulated solar energy per liters of 3 types of reactor surfaces.

Table 2. Bacteria inactivation on 3 types of 1 reactor surface exposed to solar radiation.

The reactor types	Reactor	Black reactor	Catalyst reactor
Temperature rang (◦C)	34.51-39.26	34.15-41.04	38.26-44.7
Initial bacteria concentration (CFU/mL)	4.78×10^{7}	4.67×10^{7}	4.72×10^{7}
Final bacteria concentration (CFU/mL)	5.65×10^{5}	3.9×10^{5}	2.45×10^{5}
Solar radiation average (W/m^2)	754.81	814.24	952.32
Accumulated solar energy (kJ/L)	9.632	10.506	12.117

The results in Fig. 5(b) show the graph dropped almost the same bacteria inactivation until accumulation of solar energy as 7 kJ/L. Moreover, the experiments show that the catalyst and black reactor surface require an accumulated solar energy more than 7 kJ/L which was more effect on bacteria inactivation. This result could be explained that the low accumulated solar energy is not more effective at dropping bacteria inactivation. Moreover, these results could be explained that the properties of black color on reactor surface are not more effective at dropping bacteria concentration with the low accumulated solar energy where the photons are not enough to damage the bacteria membrane. Moreover, the catalyst reactor is drop bacteria concentration more slightly than the black reactor and non-black reactor. This result shows the $OH^{\bullet}$ radicals and incoming of photons need to accumulate to damage bacteria membranes. The results of the bacteria inactivation in the 1 reactor surface are summarized in Table 2.

4.2 The Effect of 3 Types of Reactor Surfaces on Bacteria Disinfection with 4 Reactors Exposed to Solar Radiation.

The experiments set the 4 reactors to receive solar radiation, which were determined to have more area to receive more solar radiation. All experiments assessed the efficiency of bacteria inactivation of each type of reactor surface.

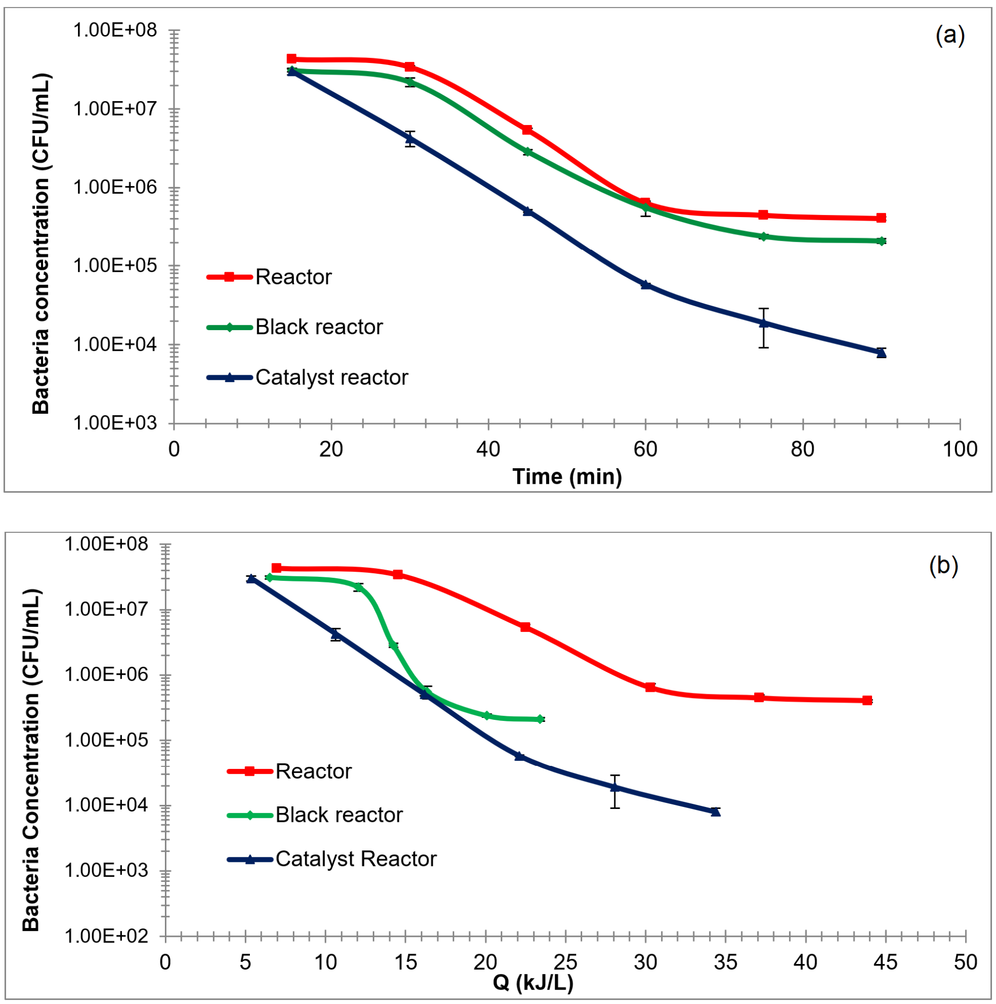

Fig. 6 Bacteria disinfection of *E.coli* (log (CFU/mL)) during real sunlight exposure under reactor (—□—), black reactor (—◊—), catalyst reactor (—∆—) against (a) experimental time (b) accumulated solar energy per liters of 3 types of reactor surfaces.

The experiments in Fig 6(a) show the 4 reactors' surfaces could decrease bacteria inactivation for 2 logs, which shows the effect by solar radiation in 90 min. Moreover, bacteria concentration was dropped over 2 logs by the black reactor surface, which had more effect on bacteria inactivation than the reactor. Therefore, this result could be explained that the black reactor could absorb global solar energy to affect bacteria inactivation. Moreover, bacteria concentration was dropped by the catalyst reactor surface over 4 logs which was the most effect on bacteria inactivation in 90 min. These results show the synergic effect of photons and oxidative species generated from photoactivation by solar radiation. Moreover, this experiment also discussed the effect of accumulated solar energy on bacteria inactivation. The reactors received accumulated solar energy of 45 kJ/L, which decreased bacteria concentration over 2 logs. However, the black reactor received lower accumulated solar energy of only 25 kJ/L but the result shows that properties of a black surface could decrease bacteria concentration more than 2 logs. Whereas, the catalyst reactor dropped bacteria concentration of 3 logs by accumulated solar energy 25 kJ/L. However, in this experiment, the catalyst reactor received accumulated solar energy of 37 kJ/L, which dropped the bacteria concentration over 4 logs. The catalyst reactor is the most effective in bacteria inactivation because it received more accumulated solar energy to generated $OH^{\bullet}$ radicals. The comparison of the 3 types of reactor surfaces in the CPC shows the catalyst reactor was the most efficient in water disinfection. The results of the experiment with the 4 reactors are summarized in Table 3.

Table 3. Bacteria inactivation on 3 types of 4 reactor surfaces exposed to solar radiation.

The reactor types	Reactor	Black reactor	Catalyst reactor
Temperature rang (◦C)	35.21-44.46	37.75-39.07	30.97-38.45
Initial bacteria concentration (CFU/mL)	4.70×10^{7}	4.77×10^{7}	4.79×10^{7}
Final bacteria concentration (CFU/mL)	4.05×10^{5}	2.1×10^{5}	1.06×10^{3}
Solar radiation average (W/m^2)	862.04	456.10	657.55
Accumulated solar energy (kJ/L)	43.87	23.395	34.382

4.3 The Effect of TiO_2 Concentration on Bacteria Inactivation.

TiO_2 has been tested in a photoreactor in CPC, which was performed by using the total bacteria deactivation in de-ionized water. The experiments were carried out using a TiO_2 concentration which was investigated as 0.25, 0.5, 0.75, 1 g/L. The experiments determined the effect of TiO_2 on bacteria inactivation. The experiment sets were evaluated to enhance the process by adding TiO_2. This experiment was carried out using 4 reactors' surfaces exposed to solar radiation.

The results in Fig. 7(a) show bacteria concentration (log (CFU/mL)) against experimental time (a) and accumulated solar energy (kJ/L) (b). All tests of TiO_2 concentration show bacteria concentration dropped rapidly within the 90 min experimental time. The results reveal that the bacteria concentration dropped over 3 logs by 0.25 g/L and 0.5 g/L of TiO_2 concentration in 90 min with similar inactivation kinetics. This result shows TiO_2 is not sufficient to absorb all photons to attack bacteria cells. Moreover, these experiments show bacteria concentration protected cells by self defense mechanisms of bacteria concentration against $OH^{\bullet}$ radicals and incoming photon. However, the experiment which suspended 0.75 g/L and 1 g/L of TiO_2 concentration was slightly more effective in bacteria inactivation than both 0.25 g/L and 0.5 g/L of TiO_2 concentration, which show bacteria concentration was dropped over 4 logs. The trend of bacteria inactivation shows the self-defense and auto repair mechanisms of bacteria are sufficient to protect bacteria cells.

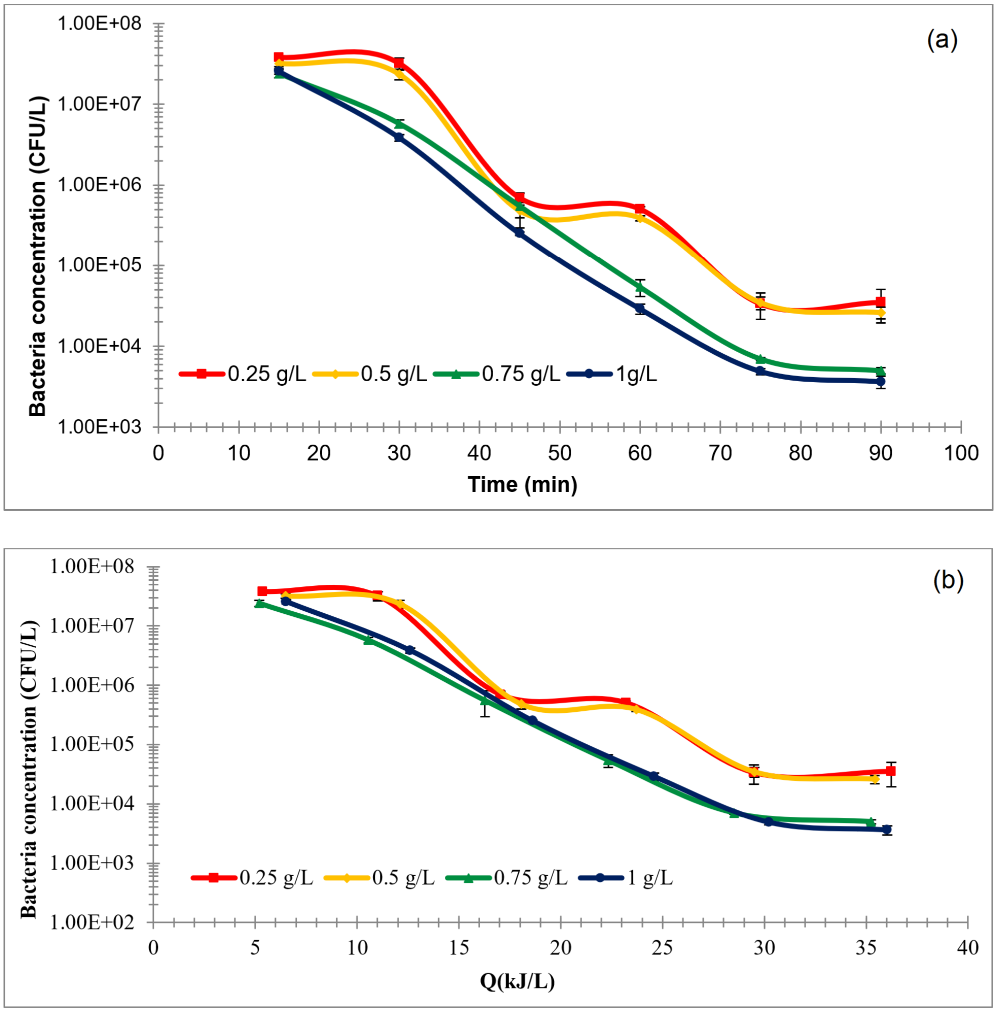

Fig. 7. Bacteria disinfection of *E.coli* (log (CFU/mL)) during real sunlight exposure under TiO_2 concentration as 0.25 g/L (—□—), 0.5 g/L (—◊—), 0.75 g/L (—Δ—), 1 g/L (—●—) against (a) experimental time (b) accumulated solar energy per liter.

This experiment shows a high TiO_2 concentration of catalyst is more available to drop bacteria concentration on the black reactor and reactor surfaces because OH radical will immediately self-recombine to form H_2O_2 equation (5) which produces $HO^{\bullet}_2$ through the synergy of other $OH^{\bullet}$ radicals equation (6). The results of TiO_2 concentration on bacteria inactivation are summarized in Table 4.

$$OH^{\bullet} + OH^{\bullet} \rightarrow H_2O_2 \tag{8}$$

$$H_2O_2 + OH^{\bullet} \rightarrow H_2O + HO_2^{\bullet} \tag{9}$$

However, some authors indicated a higher TiO_2 concentration is not more efficient at dropping bacteria concentration [2]. However, these experiments do not have the same TiO_2 concentration range.

Table 4. Bacteria inactivation by different quantity of TiO_2 concentration.

TiO_2 Concentration (g/L)	0.25	0.5	0.75	1
Initial bacteria concentration (CFU/mL)	4.71×10^7	4.75×10^7	4.77×10^7	4.79×10^7
Final bacteria concentration (CFU/mL)	3.52×10^4	2.6×10^4	5.0×10^3	3.65×10^3
Solar radiation average (W/m^2)	710.47	697.10	676.93	706.89
Accumulated solar energy (kJ/L)	36.22	35.424	35.241	36.03

5. Conclusion

A CPC pilot plant has demonstrated bacteria inactivation by solar energy with 3 types of reactors. The effects of bacteria inactivation on reactors by sunlight reveal which reactor dropped bacteria concentration. Moreover, the performance dropped more when increasing solar radiation exposure on different types of reactors. Additionally, the black reactor application reveals that it could have the effect to drop bacteria more than the reactor surface of both 1 reactor and 4 reactors. Therefore, the properties of black color could absorb incoming photons to damage bacteria cells. Moreover, the catalyst reactor has the most effect at dropping bacteria concentration. These results show the solar photocatalysis process is very useful to apply with solar energy. Moreover, a TiO_2 concentration suspended at 0.25-1 g/L was enough to enhance the bacteria inactivation of *E.coli* contamination. Moreover, the experiment also showed a higher TiO_2 concentration is more effective at dropping bacteria concentration.

Acknowledgements

The authors would like to thank the Division of Electrical Engineering, school of Industry and Technology Rajamangala University of Technology Isan Sakon Nakhon Campus for the financial support for this article. The authors are also grateful to the Division of Biochemical Technology, School of Bioresources and Technology, King Mongkut's University of Technology, Thonburi, for help with analysis of bacteria inactivation.

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