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# Accelerating the solar disinfection process of water using modified compound parabolic concentrators ($CPC_s$) mirror

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ABSTRACT

Solar disinfection can significantly improve the microbiological quality of drinking water. Water samples of 0, 50, and 100 nephelometric turbidity units spiked with fecal coliforms ($10^7$ CFU/mL) were exposed to natural sunshine in 1 L quartz glass tubes fitted with three different design compound parabolic concentrators ($CPC_1$), $CPC_2$, and $CPC_3$, with concentration factor of the solar radiation of 1. On clear days, the complete inactivation times (more than 7-log unit reduction in bacterial population) in the systems with $CPC_1$, $CPC_2$, and $CPC_3$ were 90, 20, and 15 min, respectively. The maximum obtained temperatures in the water samples were 57.9˚C for $CPC_1$, 77.7˚C for $CPC_2$, and 80˚C for $CPC_3$. The use of $CPC_{2–3}$ significantly improved the efficiency of the old $CPC_S$ technique, since these systems shortened the exposure times to solar radiation and also minimized the negative effects of turbidity and also regrowth was zero in the disinfected samples. Overall, this technology has been proved to be a good method enhancement to inactivate micro-organisms under real conditions and represents a good alternative technique to drinking water treatment in developing countries.

*Keywords:* Compound parabolic concentrators ($CPC_s$); Solar disinfection; Drinking water; Fecal coliforms

## 1. Introduction

Lack of safe drinking water is a serious threat in relation to the diseases which are transmitted through contaminated water [1]. Solar disinfection (SODIS) can significantly improve the microbiological quality of drinking water and, thus, protect the public health [2]. On the other hand, laboratory studies have consistently shown that exposing contaminated water to sunlight significantly reduces its microbial loads [3–5]. Since the speed of the disinfection process is a very important issue in the SODIS method it was commonly used to disinfect water for 6–8 h is required. Solar UV water disinfection processes have

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been demonstrated to be effective [6,7]. One of the mechanisms of disinfection in the SODIS technique is that UV sun in the processes of genetic replication of bacteria cell walls interferes and destroys micro-organisms. $UV_A$ can induce cellular membrane damage through the production of reactive oxygen species [8]. Thermal inactivation is attributed to the absorption of red and infrared photons [9]. It has been reported that a temperature range of 12–40℃ has a negligible effect on the rate of SODIS; however, the inactivation of bacterial organisms has been observed at the temperatures of greater than 45℃. Limitations of the conventional SODIS systems have led several groups to use solar concentrators, including compound parabolic collectors (CPCs), in order to amplify spectral irradiance in solar photolytic or photocatalytic applications [10]. At least one group has developed and implemented a continuous-flow solar UV disinfection system [11]. CPCs are the static solar collectors that concentrate all of the incident solar radiation below a certain angle so that the radiation reflected by the surface of the collectors also reaches the lower part of the reactor and the entire surface is irradiated almost homogeneously [12–14].

The aim of this study is to assess the use of modified CPC mirrors to enhance the $CPC_s$ which is conventional in other works. The main aim of this study is to enhance thermal capacity and optical reactors of $CPC_s$ through changes in the physical structure and converted visible sun's energy it into heat energy to increase the temperature of the water to speed up water disinfection.

## 2. Materials and methods

### 2.1. Preparation of bacteria

The contaminated water sample was used for preparing the fecal coliforms. The first sampling was done by sterile containers and transferred to the laboratory. Then the culture lactose broth was used to determine the total coliforms, and incubated at 35℃ for 24 at the next step using a flame-sterilized loop the positive (turbidity and gas in this growth) were used for selecting bacteria and cultivation in culture EC broth (5 g nutrient broth/L of deionized water). After cultivation, the inoculated EC broth was placed in incubator at 44℃ for 24 h [15]. The stock suspension at the stationary phase yielded bacterial concentration $10^9$ CFU/mL. The feed suspension of the bacteria used in reactor testing ($10^7$ CFU/mL) was produced by the dilution of 10 mL of stock into 1 L of distilled water or filtered surface water.

### 2.2. Turbidity

In the study, three turbidity levels (0, 50, and 100 NTU) were investigated and measured by a TN-100 turbidimeter. Turbid water samples were prepared by adding soil to distilled water. In the phase 50 g of clay was added to 1,000 mL water and the prepared suspension was shaken for 60 min and left to settle for 120 min. The supernatants were collected and the turbidity was determined. Then for the preparing the desired turbidity level it was diluted with distilled water. After preparing the desired concentration of the samples, they were sterilized by autoclaving (for 40 min at 1.0 bar) and stored at 7℃.

### 2.3. Water sample

The tests were performed in a batch system. After the preparing the samples for testing to determine its density (amount of desired bacteria) and turbidity, the samples were placed in the reactors in contact with sunlight. For evaluating the residual number of bacteria in the samples, at first, the sampling was done by a 10 mL sterile pipette in 15 min and then was stored in sterile glass containers and our the laboratory. Then the samples were passed through a membrane filter (0.45 μm Whatman) and then the filter was placed on the EMB agar culture medium and incubated at 35℃ for 24 h. after this time (24 h) the colony counts on plate count method was used to determine the efficiency of disinfection [15]. Regrowth counts of bacteria were determined for all experiments by placing the samples of each reactor at room temperature for 24 and 48 h. After 24 till 48 h the plate count method as described above was used to determine bacterial counts on the EMB agar plates. Endo agar is a selective media, specific for the detection of coliforms and enteric organisms in sources such as drinking water.

### 2.4. CPC mirrors and glass tubes

The quartz glass tubes used in the research had dimensions of 105 cm length, 3.5 cm outer diameter, 1.5 mm wall thickness, and 1.1 L internal volume (Fig. 1). The glass tubes can transmit 93 and 50% of $UV_A$ and $UV_B$ light, respectively. In this study, three types of reactor ($CPC_1$, $CPC_2$, and CPC3) were used. Design of a reactor $CPC_1$ was similar to the old CPCs, with the dimensions of 30 cm width and of 100 cm length, which enables more sunlight to a focal point (F). The $CPC_2$ is similar to the $CPC_1$ with the difference that in $CPC_2$ a black copper metal with dimensions of length, width and thickness of 100, 2.5, and

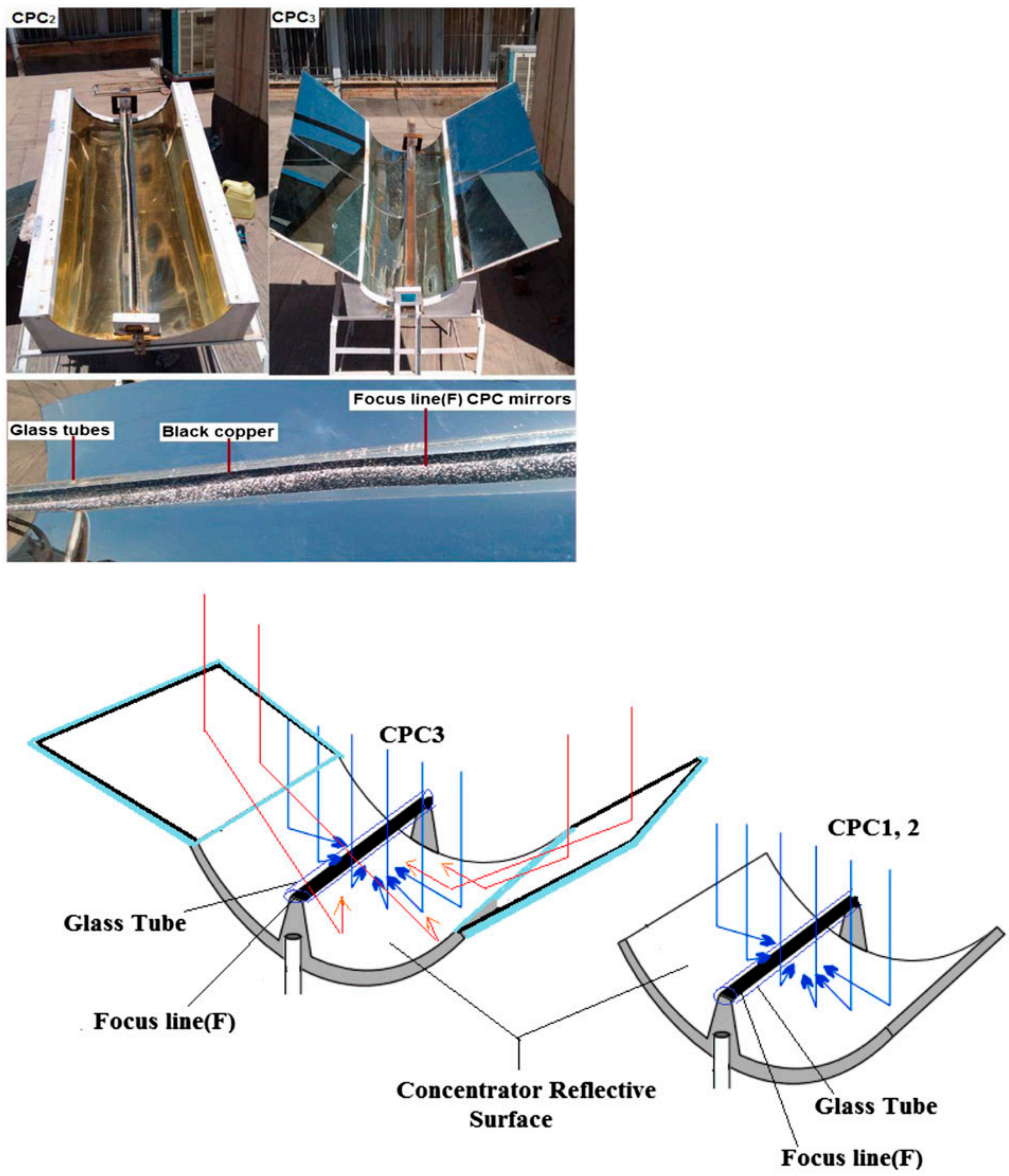


Fig. 1. Photographs showing the quartz glass tube fitted with black copper in the reactors CPCs filled with samples of water experimentally contaminated with fecal coliforms during real sunlight exposure.

0.2 cm, respectively, has been fixed vertically at the center of glass tube to absorb more light (Fig. 1). The $CPC_3$ is similar to the $CPC_2$ with the difference that two flat mirrors with a 45° angle to the vertical dimension of 30 cm and a length of 100 cm were placed in both sides of the $CPC_3$ to increase the light area in the reactor (Fig. 1). As previous research has found that high temperature of 45˚C has strong synergy between optical and thermal inactivation. A number of methods to enhance temperature and accelerate the rate of thermal inactivation of organisms through the use of absorptive materials and painting PET bottles black in order to aid in the absorption of solar radiation [16,17]. In this study, we used the reflective surface of the CPCs comprises mirrors with thickness 1 mm, which reflects 86% of UV radiation and 96% of other types of solar radiation. The dimensions and properties of the glass tubes and each of the CPCs reactors are shown in Table 1.

### 2.5. Solar experiment

All experiments were performed under natural solar radiation in Tehran-Iran that geographical location, 3 min at 25°–39° and 47 min north latitude and 44, 63, 18 min east longitude 5 min which had a very good position to use solar energy. All the experiments were conducted in duplicate on twin systems (tube + CPC) under the same meteorological conditions, and to ensure reproducibility of results each sample was done three times. Tests started at 11 am and finished at 15 pm local time. Samples were taken after 15, 30, 60, 75, 90,105, 120, 135, 150, 180, 240, and 300 min of solar exposure. As seen in Fig. 1 reactors were placed to the N–S and at an angle of 35°–15° considering region and the season and then were sampled. Solar and UV irradiance was measured with a global UV radiometer (295–385 nm UV and 400–1500 nm Solar, Model HAGNER, Sweden). The initial temperature of all samples was about 20°C. To calculate the amount of absorbed heat energy for rising the temperature of the water the following (Eq. (1)):

$$Q = mc\,(T_f - T_i) \tag{1}$$

In this equation $Q$ (heat equivalent absorption of thermal energy) is the amount of thermal energy increased in terms of (J), $m$ is the mass of water in terms of (kg), $c$ is the heat capacity of water at normal temperature (0–100°C), it can be considered fixed the amount of which will be considered in the equation 4190 J/kg K, $T_i$ initial temperature in terms of (K), $T_f$ final temperature in terms of (K).

In this research, to calculate, the cumulative dose of irradiation in a period of sunlight shines into the reactor per unit time is calculated. This was calculated by integrating the average solar global irradiance measured at any time during the different exposure times, as shown in the following (Eq. (2)):

$$D = \int_{t2}^{t1} I\,dt \tag{2}$$

where $D$ is cumulative dose of irradiation in terms of (J/m$^2$), $I$ is the irradiation solar energy in terms of (W/m$^2$).

## 3. Results and discussion

The study was carried out in Tehran in spring. The essays were carried out on sunny days without cloud cover. Fig. 2 shows the peak sun hours of 12–14, so tests were done at the same time. The maximum sunlight and UV radiations in three reactors ($CPC_1$, $CPC_2$, and $CPC_3$) were 1270.2 and 36.4 W/m$^2$, respectively (Fig. 2). Another tube was kept as a controller in the dark under the same field conditions to guarantee the viability of the cells in the tube in the absence of solar radiation.

The water temperature of the systems was monitored for each sample in all the experiments. The maximum temperatures reached in water samples with turbidity levels of 0, 50, and 100 NTU were 47.1, 53.6 and 57.9°C, respectively, for $CPC_1$, and 71.7, 75.6, and 77.1°C, respectively, for $CPC_2$ and 76.7, 78.2, and 80°C, respectively, for $CPC_3$ (Fig. 3). Increasing the temperature reached 28°C in the control sample at the dark (and without CPC). According to Fig. 3 percent increase to the maximum temperature in all three reactors relative to maximum temperature in the dark (and without CPC), were 45, 63, and 65%, respectively. Significant water samples reached to the higher

Table 1
Dimensions and properties of the quartz glass tube fitted with reactors $CPC_1$, $CPC_2$, and $CPC_3$

| | Length (cm) | Width (cm) | Aperture area (m$^2$) | Thickness (mm) | Diameter (cm) | Treated volume (l) |
|---|---|---|---|---|---|---|
| $CPC_1$ | 100 | 30 | 0.38 | 2 | 30 | 1 |
| $CPC_2$ | 100 | 30 | 0.38 | 2 | 30 | 1 |
| $CPC_3$ | 100 | 30 | 0.38 + 0.3 | 2 | 30 | 1 |
| Glass tubes | 105 | | | 1.5 | 3.6 | |
| Black copper | 100 | 3 | 0.03 | 1 | | |

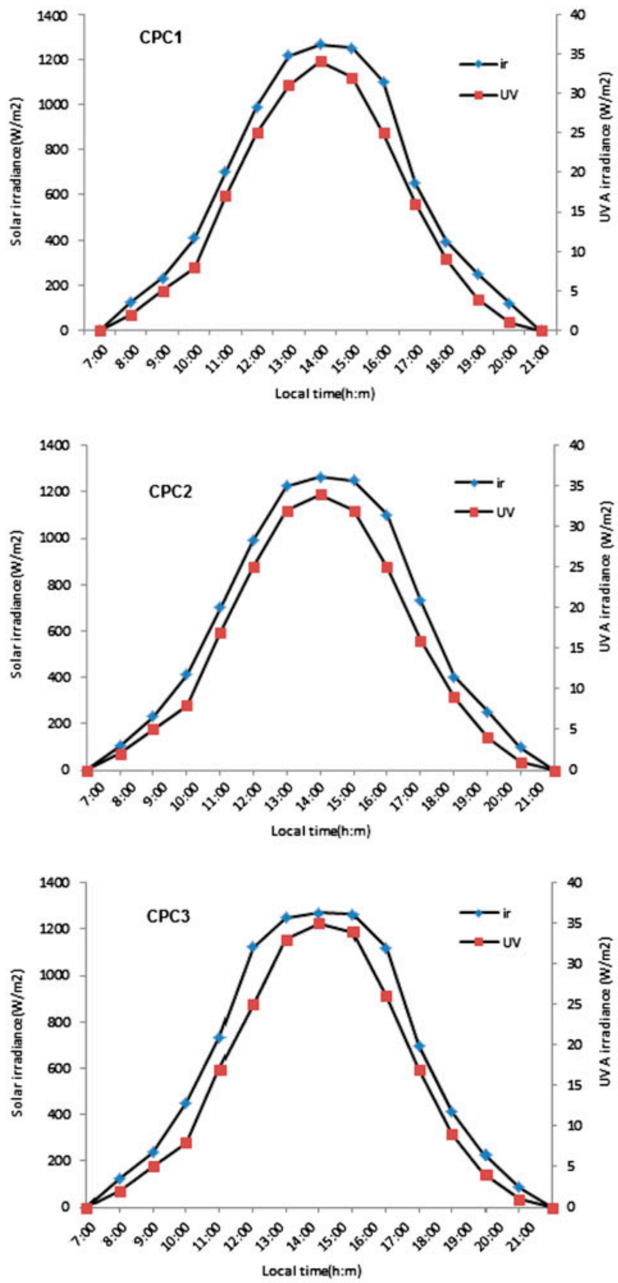


Fig. 2. Graphic representations of the values of solar irradiance and UV radiations registered during the solar disinfection studies carried out the quartz glass tube fitted with reactors $CPC_1$, $CPC_2$, and $CPC_3$.

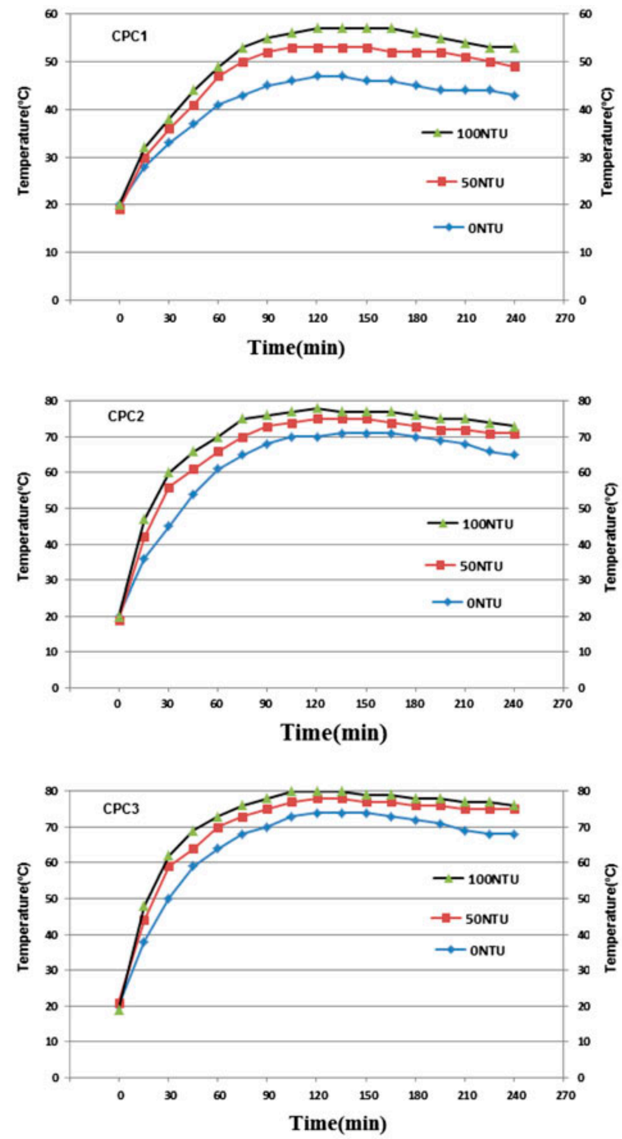


Fig. 3. Profiles of the average temperatures of the water recorded within the quartz glass tube fitted with reactors $CPC_1$, $CPC_2$, and $CPC_3$ containing water samples of different levels of turbidity.

temperature in the reactors $CPC_2$ and $CPC_3$ than in the other water samples in the reactor $CPC_1$ ($p < 0.005$) for exposure periods of 15–240 min. All maximum temperatures were always recorded after120–180 min of exposure (13:00–14:00 h, local time). However, according to Fig. 3 higher water samples temperature were significant in the turbidity 0 NTU than 50 and 100 NTU ($p < 0.05$).

One important factor in using SODIS is using the sun's thermal energy. In earlier studies, the changes in CPCs structure to increase the temperature of the water samples effectively increased the efficiency of the disinfection. The results of the research showed that the use of 1 L glass tube solar in the system with the modified $CPC_2$ and $CPC_3$ (black copper superconductor and flat mirrors) greatly improved the efficiency of the SODIS technique for disinfecting drinking water contaminated with forms of total coliforms, that are waterborne index and are commonly used in disinfections. Thus, in comparison to old CPCs the use of these systems led to total inactivation of the bacteria in some cases, reduce the exposure time to sunlight, and minimize the negative effect of turbidity [18]. There were a number of previous studies that had tried to enhance disinfection using some kind of solar thermal system. In the study with black water bottle caused increase in the surface to absorb sunlight and convert it into heat energy that was causing the temperature increase and improve the efficiency of disinfection [16]. In previous SODIS experiments it was established that the minimum temperature at which a synergy effect can be observed is around 45–50 for *Escherichia coli* [16,19].

As seen in Table 2 in terms sampling of each kg of water in the reactor $CPC_1$ for reaching the maximum temperature 57℃, after the time 170 min and received 155.2 kJ of *Q*(heat equivalent absorption of thermal energy), and 53 MJ/m$^2$ of *D* (cumulative dose of energy) (to rise temperature of 37℃) while that for $CPC_2$ reaching the maximum temperature 77℃, after the time 105 min and received 239 kJ of *Q*, and 11.2 MJ of *D* (to rise temperature of 57℃), for $CPC_3$ reaching the maximum temperature 80℃, after the time 100 min 252 kJ of *Q*, and 9.5 MJ of *D* (to rise temperature of 60℃). In this study, rising temperature has been modified in reactors ($CPC_2$ and $CPC_3$) relative to the old CPCs ($CPC_1$) 15 and 20℃, respectively, as well as the disinfection time was reduced to one-third. Considering the wavelengths of sunlight that reaches the earth surface in the wavelength was maximum range of 300–1,600 nm. However, the range of wavelengths of the sun's energy passes through the water, absorption rate was low and the majority of the light passes through water [16]. In this research for maximum use of the solar visible light wavelength range of 300–1,600 nm, we used a black copper metal which was a strong absorbent of solar visible light. Overall, the study showed that the use of adsorbents that were closer to absolute black body efficiently absorb sunlight and increase the rate of temperature at *F* of the CPCs mirror. The results in (Table 2) shows by placing a sunlight absorbent and receiving radiation dose of in $CPC_2$ 9.8 MJ, the temperature of the sample increased 71℃, which is equivalent to 216 kJ of thermal energy. This change in the structure reduces the disinfection time from 180 min to less than 30 min. In addition to the synergistic effect of temperature on parameters such as solar UV to increase disinfection rate, the water itself at temperatures above 65℃ for 30 min and at 80℃ for a few seconds causes the water pasteurization, even in the presence of turbidity and organic matter. We could say that one of the most effective ways to increase the efficiency of SODIS methods is to enhance the efficiency of light absorption of sunlight and convert it into heat energy.

According to Fig. 3 we can say that the temperature in the reactors $CPC_2$ and $CPC_3$ increased rapidly than to $CPC_1$. The reactors $CPC_2$ and $CPC_3$ after 30 min with receiving energy flux 1.5 MJ/m$^2$ reached temperatures above 60℃, while $CPC_1$ after 180 min with receiving energy flux 70 MJ/m$^2$ reached approximately temperatures 60℃. The water samples' higher temperature was significant in the reactors $CPC_2$ and $CPC_3$ than $CPC_1$ ($p < 0.005$). This represents that the system with $CPC_1$ reached complete inactivation time maximum after 120 min (100 NTU) and for reactors $CPC_2$ and $CPC_3$ this time was less than 30 min (100 NTU). An increase in solar exposure time was required to achieve bacterial inactivation in the system with the $CPC_1$ and reached the complete inactivation time with increasing turbidity (Table 2). The addition of the reflective insert (Black copper metal and flat mirrors) resulted in increased rates of inactivation, however an exposure time less than 15 min was required to reach complete inactivation (7log). Kehoe et al. believed that the volume of water used in SODIS efficiency was affected [20]. This subject can be investigated from two aspects: at first, with increasing water films solar

Table 2
Main results of the tests presented in the experimental section

| | Turbidity (NTU) | DOS (MJ/m$^2$) | Q (kJ) | Max temperatures (℃) | Time inactivation (min) |
|---|---|---|---|---|---|
| $CPC_1$ | 0 | 37 | 115.1 | 47.4 | 90 |
| | 50 | 48 | 138.6 | 53.2 | 150 |
| | 100 | 53 | 155.2 | 57.1 | 180 |
| $CPC_2$ | 0 | 9.8 | 216.3 | 71.5 | 20 |
| | 50 | 10.1 | 230.6 | 74.9 | 25 |
| | 100 | 11.2 | 239.8 | 77.1 | 30 |
| $CPC_3$ | 0 | 7.5 | 229.3 | 74.6 | 15 |
| | 50 | 9.1 | 244.4 | 78.2 | 20 |
| | 100 | 9.5 | 252 | 80.0 | 20 |

disinfecting methods the UV sun penetration and its effectiveness was reduced, according to Eq. (1) by increasing the volume of water sample temperature is reduced and therefore reduced rate of water disinfection. According to previous studies on CPCs by a concentrate factor of different volume of water disinfection was an important factor in increasing the volume level of depth of film contact UV increases and thus reduced the efficiency of the disinfection [21].

Turbidity was a limiting factor in the SODIS methods. One of the effects of turbidity was that it created a shield for organisms that in direct contact with UV disinfection reduces efficiency [22]. In Table 2, the complete inactivation time of bacteria and the required energy in all the three different types of reactors was shown. In the sample controller, without CPC (in the dark), the rate of removing bacteria reached less than one log. As seen, the systems required time reaching the complete inactivation at the turbidity levels of 0, 50, and 100 NTU were 90, 150, and 170 min, respectively, for the $CPC_1$, and 20, 25, and 30 min, respectively, for the $CPC_2$and 15, 20, and 20 min, respectively, for the $CPC_3$ (Fig. 4). As shown in Table 2, the complete inactivation time of bacteria was significant in the reactors $CPC_2$ and $CPC_3$ (modified with Black copper metal and flat mirrors) than in the other water samples in the reactor $CPC_1$ ($p < 0.0001$). Solar techniques used to inactivate *E. coli* with increasing water turbidity from 5 to 50 and inactivation time from 150 min to 180 min. The inactivation *oocyst* by $CPC_{2.5}$ was shown with increasing turbidity to influence UV reduces the efficiency of *oocyst* is inactive. It can be said UV influence will affect turbidity [23]. However, with increasing turbidity in $CPC_{2.5}$ 5–100 NTU UV effect on *oocyst* inactivation was reduced but due to the temperature increase caused by the absorption of sunlight, effect turbidity significantly reduced [24]. In this study, it was also shown that the effect of turbidity in $CPC_1$, with the lowest maximum temperature was more than $CPC_2$ and $CPC_3$. In general, temperatures above 65˚C in addition to its synergistic effect with UV for water pasteurization can reduce the effect of turbidity. Regrowth counts of bacteria were determined for all experiments. In none of samples with certain conditions being there was no growth after cultivation. Due to two simultaneous effects of high temperatures and UV, regrowth in most ways of SODIS was not seen in these examples.

One of the major issues discussed in relation to the cost of making SODIS methods and other methods was performance evaluation. According to the study areas between latitude 15˚ north and 35˚ south, where

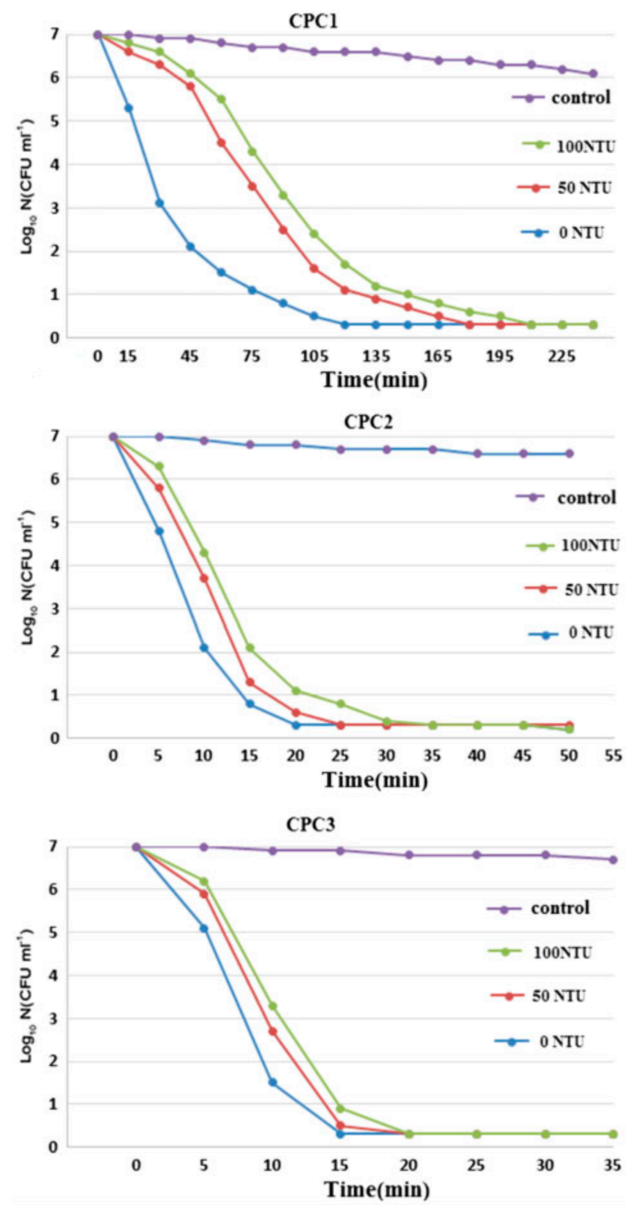


Fig. 4. Inactivation curves of fecal coliforms in the quartz glass tube fitted with reactors $CPC_1$, $CPC_2$, and $CPC_3$ during natural solar radiation exposure on clear days.

there is at least 3,000 h of sunshine a year, Iran is one of the best regions to use the SODIS system. In this research with changes in the structure of the optical reactors CPCs the efficiency and disinfection time has been improved. In this study, cost of the CPCs reactors in Iran is 100 US dollars. The average age of the CPCs reactors, which was estimated to be about 12 years and the cost of disinfection of per liter water in this way is about 0.0025 US dollars while the cost is similar to that involved in setting up sand filters and was cheaper than the use of coagulation/chlorination treatment (>0.01 US dollar per liter water treated) which was lower and quite affordable [25–27]. Considering water crisis in many regions of the world, especially in the Middle East, using all water resources potential is a solution for dealing with the crisis in these countries. Considering average precipitation 260 mm per year in Iran which in most areas is the season precipitation, we can solve the water crisis by collecting precipitation and using SODIS with for rural and urban areas. Modifying the investigated methods this study can be used for disinfecting wastewater treatment even with high density of bacteria.

## 4. Conclusion

The use of $CPC_{2–3}$ significantly improved the efficiency of the old $CPC_S$ technique, since these systems shortened the exposure times to solar radiation and also minimized the negative effects of turbidity and also regrowth was zero in the disinfected samples. This technology has been proved to be a good method enhancement to inactivate micro-organisms under real conditions and represents a good alternative technique to drinking water treatment in developing countries.

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