Evaluation of Indigenous Solar Water Disinfection Reactor

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Abstract. Feasibility of enhancing the efficiency of solar disinfection units by utilizing an indigenous solar water disinfection reactor (SWDR), as an alternative and economical mean of disinfecting municipal water, has been studied. Several experiments were performed to investigate the effects of different control parameters on disinfection efficiency of SWDR including material type of containers, exposure time and water turbidity. Temperature of reactor base reached $62 \pm 1^\circ\text{C}$ within 2.5 hours corresponding to the ambient temperature of $28 \pm 1^\circ\text{C}$. Water temperature in transparent polyethylene bag reached $55 \pm 1^\circ\text{C}$ while colored polyethylene bag reached a minimum temperature of $46 \pm 1^\circ\text{C}$ as compared to other tested container materials during the solar exposure of 2.5 hours. Various parameters such as water pH, total Coliform, heterotrophic plate count (HPC) and viral indicator *Coliphage* were investigated before and after the experiment in order to test the water disinfecting efficiency of reactor. It was found that water having turbidity less than 23 NTU can be treated within 2.5 hours with 99.99% efficiency. However, utilizing SWDR one may get similar efficiency even water turbidity reached to 29.5 NTU in similar environmental conditions. Results revealed that SWDR is more efficient and may be used to disinfect water in lesser time.

Keywords: Solar disinfection, Total Coliform, Coliphage, SWDR, Water turbidity.

Introduction

Beyond any shadow of doubt, clean and sterile water is scarce in developing countries and the goal of universal access to safe water and sanitation has not been achieved. A large portion of earth is covered with water but only 0.3% of fresh water is available. In fact the improper use of this fresh water is much more common than its proper use. Owing to these reasons, it becomes difficult task to supply clean drinking water to about 6.8 billion peoples in the world (Hunter *et al.*, 2002). Limited access to safe water supply results in transmitting diseases such as diarrhea, hepatitis, giardiasis, dysentery and gastro intestinal with contaminated water among the people especially in the rural areas of the country where supplied water is polluted with variety of pathogen. It is reported that use of unsafe water cost life of around sixty thousand

children every day worldwide (Tersieva and McFeters, 1991; Spears *et al.*, 2006). Clean water is scarce and at least one third of the population in developing countries has no access to safe and reliable drinking water supplies (Saleem, 2009).

Water suspected to contain pathogens must be treated before its use to protect public health. Disinfection is a process used to eliminate pathogenic microorganisms. Different techniques are adopted by people to purify water including boiling, distillation, reverse osmosis, ozonation, GAC (Granular Activated Carbon), solar disinfection, chlorination, ion exchanger etc. Most of them are capital intensive and some techniques required sophisticated equipment, well skilled operator and burning of fossil fuels (Tersieva and McFeters, 1991; Spears *et al.*, 2006). Solar disinfection technique is one of the cheapest

and more economical methods for disinfection of water, utilizing solar radiation to inactivate and destroy pathogenic bacteria, water borne bacteria, viruses, and parasites and generally it is more useful in regions where other disinfection facilities are not accessible (Jamil *et al.*, 2009). Solar disinfection method or SODIS as it is known is one of the simplest methods for providing acceptable quality of drinking water. Solar disinfection technique is the cheapest and simple enough to be applied by individuals or in households. It is more useful in those areas where accessibility for adopting alternatives methods is difficult (Wegelin *et al.*, 1994; Wegelin and Sommer, 1998; Boyle *et al.*, 2008). The World Health Organization considers SOLDIS to be valid option in those areas where no other means are available (Wegelin and Sommer, 1998). In Pakistan clean water supply is limited in the low income and rural areas. In some areas supply of portable water is available but unreliable due to addition of contaminants during transportation. Furthermore, the storage of this water may increase the chances of microbial growth and consequently water may require disinfection before use. Numerous health complains related to water borne pathogens are reported in the past (Saeed and Behzad, 2006; Qureshi *et al.*, 2011)). Keeping in view the reality in future, supply of safe drinking water to all population seems to be impossible. One approach to provide safe water for all is household water treatment and safe storage, which is promoted globally by the WHO to reduce the global burden of waterborne diseases (WHO, 2012). Use of simple, economical and robust technique of solar disinfection may provide an alternative clean water supply at those sites.

Studies in the past showed successful application of solar disinfection process however, longer solar exposure time and low water turbidity is suggested (Ahmed and

Saleem, 2010; Faisal, 2010). Various solar reactor design had been tested for household disinfection of larger volume of drinking water and inactivation of entropathogen *Cryptosporidium parvum* were investigated however, longer time was required for achieving desired level of disinfection (G-Couso *et al.*, 2012). Research shows that Coliform-free potable waters are not necessarily pathogen-free because some viral pathogens may be present in the water (Ratto *et al.*, 1989). Moreover, *Coliphage* is emerging as a global indicator microorganism for microbiological quality of drinking water (Hijnen, *et al.*, 2006). The previous researchers showed that *Coliphage* assays are practical and although ratios of coliphages to those of other microorganisms tended to fluctuate, the *Coliphage* counts could give a useful estimate of numbers of the microorganisms in sewage-polluted water. (Wentzel, 1982; Grabow *et al.*, 1984).

Based on a preliminary study carried out elsewhere a detailed investigation has been made by using an improved design of solar disinfection unit which provided promising results (Faisal, 2010). Main objective of the present study is to enhancing the efficiency of solar disinfection unit; which substantially kills the pathogens more efficiently. This objective can be achieved by using a simpler SWDR fabricated with indigenously available low cost material. Effect of solar radiation on standard water quality bacterial indicators (total coliform and HPC) will be also investigated along with viral pollution indicator Coliphage. In the literature researchers recommended that UV disinfection is not feasible to use for high turbidity waters which tend to reduce the efficiency of solar disinfection (Davies *et al.*, 2009). As the presence of turbidity in water sample may hinder the solar disinfection process the effect of turbidity on solar water disinfection

processes with and without reactor was also investigated (F-Ibáñez, 2009).

Material and Methods

A rectangular shape solar reactor was used as shown in Figure 1. Reactor was fabricated with bent aluminum sheet (semicircular) which concentrate the solar radiation to the focus point and top of the box was covered with removable glass which enhance greenhouse effect in the reactor. Sides of the reactor are made of wood (insulating material) which help in trapping the heat inside.

The solar water disinfection reactor works on the principle of greenhouse effect. The incoming solar radiation, after passing through the glass cover, is reflected by the aluminum sheet which concentrates the solar energy to the focus. This will rise the temperature of the water contained in the selected material more efficiently during disinfection process. As the solar radiation incident on aluminum sheet, the temperature of the base rises and it emits the thermal radiation which has a longer wavelength and thus thermal radiation is trapped inside the box.

The raw water was collected from a household tap and inoculated with domestic wastewater to obtain significant counts of microorganisms as shown in Table 1. Water samples each 1.5 liters were filled in six different containers namely; Poly Ethylene Terephthalate (PET) transparent and colored bottles, glass transparent and colored bottles, 6mm gauge PET transparent and colored bags and placed separately inside the reactor and exposed to solar radiation at least up to 2.5 hours. Another set of samples kept outside the reactor to see the difference of disinfection with and without reactor. Samples were collected in the sterilized container at 30 minutes interval and promptly analyzed for various water quality parameters such as total

coliform, HPC, *Coliphage* and pH as shown in table 1.

The standard test for the coliform group was carried out by using the multiple tube fermentation technique and Spread Plate Count technique was used to determine the HPC as per the procedure mentioned in Standard Methods for the Examination of Water & Wastewater (Clesceri *et al.*, 2005). Analysis for *Coliphage* was done by following the procedure outlined in (Wentzel *et al.*, 1982). A bench top pH meter manufactured by Thermo Orion (model 550A) was used for the determination of pH. Analysis of samples was carried out at the Department of Environmental Engineering, NED University of Engineering & Technology, Karachi, Pakistan.

Table 1. Analysis result of raw water for selected parameters.

Parameters	Results	Units
pH	7.28±0.20	-
Water Temperature	28±1	°C
Ambient Temperature	28±1	°C
Total Suspended Solid	394±5	mg/L
Electrical Conductivity	188±4	µ-siemens/cm
Color	Colorless	-
Turbidity	1.1±0.3	NTU
Hardness	123±5	mg/L
Chloride	137±5	mg/L
Calcium	56±06	mg/L
Magnesium	29.2±0.8	mg/L
Sulfate	71.3±0.2	mg/L
Res. Chlorine	<0.2	mg/L
Sodium	112±4	mg/L
Iron	1.6±0.2	mg/L
Total Dissolved Solids	372±5	mg/L
Total Suspended Solids	394±5	mg/L
Total Coliform (MPN)	7850±10	MPN/100ml
Heterotrophic Plate Count (HPC)	83580±20	PFU/100ml
<i>Coliphage</i>	32±1	MPN/100ml

In other set of experiments effect of turbidity on solar water disinfection

performance also investigated by adding turbidity in samples from 5 to 85 NTU using kaolin powder before exposing to solar radiation. Parallel runs were performed using SWDR.

Fig. 1. Solar Water Disinfection Reactor (SWDR): a) dimensional sketch b) fabricated SWDR.

Results and Discussion

This section describes the results obtained during study before and after exposing to solar radiation. Effect of water turbidity on solar disinfection process with and without SWDR also elucidated

Raw Water Characteristics

In order to characterize the inoculated raw water, detailed physical, chemical and microbial analysis were performed and results of these analyses are presented in Table 1. Later water samples were filled in selected bags and bottles and exposed to sunlight with and without solar reactor.

Temperature Measurement inside the Reactor

During solar exposure of 2.5 hours, temperature variation inside the reactor was continuously monitored. Temperature of the base, longitudinal side and lateral side of the reactor were noted at 30 minutes interval using mercury thermometer results obtained are presented in figure 2.

Fig. 2. Temporal variations in ambient, base and side walls temperature in the reactor during study period.

It can be seen from figure 2 that the base of the reactor attain high value of temperature up to $62^{\circ}\text{C} \pm 1^{\circ}\text{C}$ whereas longitudinal side and lateral side reaches to $54^{\circ}\text{C} \pm 1^{\circ}\text{C}$ and $53^{\circ}\text{C} \pm 1^{\circ}\text{C}$ respectively corresponding to time span of 150 minutes. The reactor base attains high temperature which may be due to direct incident of solar radiation on metal sheet having larger surface area.

Water Temperature Variation:

Temperature inside each bag and bottle were measured at 30 minutes interval using mercury thermometer. Water sample temperature was measured by three persons simultaneously as quickly as possible to minimize the loss of reactor temperature. Water temperature variation in different containers is presented in figure 3. Maximum water temperature of $55 \pm 1^{\circ}\text{C}$ was achieved inside the transparent polyethene bag due to its thinner material. Minimum temperature of water ($46 \pm 1^{\circ}\text{C}$) was found to be in colored glass bottles. Relatively high temperatures were observed in transparent material rather than in colored material due to the presence of color in the material which may obstruct some of the solar radiation to penetrate the bottle. Most of the researchers in the past used foiled backed reflector reactor to enhance the solar disinfection efficiency and reported that

addition of either an absorptive or a reflective backing enhanced the reactor performance by achieving higher water temperature in shorter time span (A-Barcelo *et al.*, 2013; Marques *et al.*, 2013). Marques *et al.* was able to get the water temperature up to 50 °C in 3 hours exposure time. Similarly A-Barcelo *et al.* achieved water temperature of 39.8 ± 3.8 °C in 4 hours exposure time.

Results show that the reactor used in current study provided higher temperature (55 ± 1 °C) within 2.5 hour time span.

Analysis of Samples with Constant Turbidity

One set of samples having constant turbidity of 1.1 NTU was exposed to solar radiation. The results obtained for selected chemical and microbiological parameters are discussed in this section. As transparent containers showed significant gain in water temperature bacteriological parameters (TC and HPC) for only transparent containers are discussed below:

pH

It was found that pH of water samples remained almost unchanged in all experimental runs. The maximum change of 0.1 was noted (in transparent PET bottles) which may be due to the breaking and rejoining of H_2O into H^+ and OH^- ions but it hasn't the significant effect on disinfection process. Similar results were reported by some other researchers (Ahmed and Saleem, 2010).

Total Coliform

Temporal variation in the total Coliform counts during the study period is presented in figure 4. It is evident from figure 4 that the counts of TC decreases from 7850 MPN/100ml to 0, 12 and 130 in transparent shopping bag, transparent PET and transparent glass respectively during the exposure of 90 minutes. It shows that TC was quickly inactivated in transparent polyethene shopping

bag within 30 minutes and reached to 0 MPN/100ml. However, TC reached to zero counts after exposure of 1.5 hours in all transparent containers.

Fig. 3. Temporal water temperature variation in different containers.

In various solar disinfection studies researchers used indicator microorganism *Escherichia coli* to see the efficiency of the process. All of these studies have achieved different degrees of success (McLoughlin *et al.*, 2004; Mani *et al.*, 2006; Navntoft *et al.*, 2008; Marques *et al.*, 2013; A-Barcelo *et al.*, 2013; Nalwanga *et al.*, 2013). Total Coliform is a group of bacteria consist of various types of rod-shaped Gram-negative non-spore forming and motile bacteria. However, *Escherichia coli* is a less resistant member of TC group (Tersieva *et al.*, 1991; Spears *et al.*, 2006). In the present study one can easily assume that the inactivation of TC means that inactivation of *Escherichia coli* achieved at even lower exposure time.

Fig. 4. Variation in TC with respect to time in various samples during study period.

Heterotrophic Count Plate

It is evident from figure 5 that there is reduction in HPC with exposure time however, it took longer time to inactivate as compared to TC. This may be attributed to the fact that HPC is the measure of all heterotrophic bacteria present naturally and consist of different strains of bacteria among which some may be more resistant as compared to TC. However HPC count reaches to almost zero count within 1.5 hour in transparent shopping bag then in transparent PET bottle within 2 hour. HPC remains present in the sample contained in colored containers even after the exposure of 3 hours.

Coliphage

Based on literature reviewed, *Coliphage*, as a viral indicator microorganism, testing was included to determine the microbiological water quality of drinking water. It can be seen from figure 6 that the removal of *Coliphage* virus in transparent bag is faster and reached to its minimum value to 0MPN/100ml counts up to two hour of solar exposure. It is also evident from this figure that *Coliphage* has been

completely destroyed within exposure of 2.5 hour in all transparent materials. However, solar disinfection plays an insignificant effect in the containers having colored materials. Delayed inactivation of virus as compared to TC and HPC may be attributed to their inherent resistance against solar radiation as compared to bacterial cell similar results are reported by Hijnen and coworkers in their study (Hijnen *et al.*, 2006).

Fig. 5. Variation in TC with respect to time in different material.

Fig. 6. Variation in *Coliphage* with respect to time in different containers.

Comparison of disinfecting efficiencies for SOLDIS process with and without SWDR

In order to examine the change in efficiency of SOLDIS process due to SWDR the results obtained are also compared with those results which were carried out without using any solar reactor.

As previous results showed that solar disinfection process has significant effect on transparent material rather than in colored material, only results of transparent material including transparent polyethene bag, PET and glass bottles with and without reactor are compared with respect to removal percentage of total Coliform. Results based on constant turbidity (1.1 NTU) are presented in figure 7. Furthermore, the results obtained with variable turbidity effect on solar disinfection process with and without reactor also compared in figure 8.

Fig. 7. Temporal variation in TC counts in transparent containers with and without SWDR.

Comparison of disinfection efficiencies with constant turbidity

It is evident from figure 7 that SWDR has given positive effect in boosting the efficiency of SOLDIS process. Total Coliform took almost 1.5 hour for complete inactivation when using SWDR while about 2 hour needed for their complete removal without using SWDR in transparent glass and PET bottles.

However, complete inactivation of total Coliform achieved within half an hour of solar exposure using SWDR whereas it takes about 1.5 hour without using reactor in transparent Polyethene bags. It is found that on the average about 50 to 75% lesser time is required to disinfect the water to same level of treatment while using SWDR.

Effect of turbidity

As turbidity is one of the important factors in disinfection process while using chemical as well as physical methods, effect of turbidity present in water samples also investigated. In this part of the study 15 raw water samples were prepared by adding kaolin powder giving turbidity from 5 NTU to 85 NTU. Each sample was exposed to solar radiation for one hour. Another set of duplicate samples were exposed to the solar radiation at the same time without using SWDR. A comparison of results obtained is presented in figure 8. Results show that a solar disinfection without reactor has disinfecting efficiency between 99.99 % and 98% for samples having turbidity below 23 NTU. While using SWDR similar efficiencies can be achieved in samples having turbidity up to 29.5 NTU. Therefore, an improvement in disinfection efficiency is evident by using SWDR. Although the difference in turbidity is only 28.3% but turbidity is one of the issues in water treatment and need to be considered. Davies and colleagues recommended further detailed investigation to address the

contribution of turbidity alone on the solar disinfection efficiency (Davies *et al.*, 2009).

Fig. 8. Effect of water turbidity on the solar disinfection efficiency with and without SWDR.

Conclusions and Recommendations

Following specific conclusions derived based on the results obtained during this study:

1. SWDR made up of indigenous low cost material showed significant temperature rise (up to $62 \pm 1^\circ\text{C}$) at the reactor base and enhanced the disinfection efficiency.
2. Transparent polyethene bag is found to be the best container for solar disinfection due to its thinner material and having large surface area for exposure to sunlight. Transparent PET and transparent glass come in the next order of priority followed by colored bottles and bags.
3. Solar disinfection has no significant effect on water pH and remained almost constant during all experimental runs
4. Complete inactivation of TC achieved in all transparent containers within two hours of exposure. Only 30 minutes are required

to inactivate TC when using transparent polyethylene bag and making it a suitable container for solar disinfection.

5. Similar results obtained in case of HPC however, HPC required more time to reach value of zero which may be attributed to the fact that HPC is the measure of all heterotrophic bacteria present naturally and consist of different strains of bacteria among which some may be more resistant as compared to TC.
6. *Coliphage* as a viral indicator showed more resistance against solar radiation than bacterial indicators and its counts reached to zero in 2 hours of exposure in transparent polythene bags. However, counts reached to zero within 2.5 hours in case of all other transparent containers.
7. A comparison of solar disinfection experiments results with and without SWDR showed that about 50 to 75% lesser time is required to disinfect the water to same level of treatment while using SWDR.
8. Turbidity has negative effect on solar water disinfection efficiency. Only water samples having turbidity less than 23 NTU can be treated by solar disinfection method. However, samples having turbidity up to 29.5 NTU can be treated by using SWDR in similar environmental conditions.

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تقييم مفاعل شمسي جديد لتطهير المياه

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المستخلص. تمت دراسة جدوى تعزيز كفاءة التعقيم الشمسي من خلال الاستفادة من مفاعل تطهير المياه بالطاقة الشمسية (SWDR) باعتبارها المتوسط البديل والاقتصادي لتعقيم المياه المحلية. حيث أجريت العديد من التجارب لدراسة تأثير المواد المختلفة للحاويات، وزمن التعرض وتعكر الماء على كفاءة التطهير SWDR. وصلت درجة حرارة قاعدة المفاعل إلى 62 ± 1 ° درجة مئوية خلال ساعتين ونصف بالمقابل لدرجة حرارة المحيط 28 ± 1 ° درجة مئوية. حيث وصلت درجة حرارة الماء في حاوية البولي إيثيلين الشفافة إلى 55 ± 1 درجة مئوية في حين كسبت الحاوية الملونة من البولي إيثيلين الحد الأدنى من درجة حرارة (46 ± 1) ° درجة مئوية بالمقارنة مع غيرها من مواد الحاويات التي تم اختبارها من خلال التعرض الشمسي لساعتين ونصف. وقد تم التحقق من المعايير المختلفة مثل الرقم الهيدروجيني للمياه، ومجموع القولونية، العدد (HPC) والمؤشر الفيروسي عاثية العصية القولونية قبل وبعد الاختبار للتحقق من كفاءة تطهير المياه من المفاعل. حيث وجد أن الماء العكر بأقل من 23 NTU يمكن علاجه خلال ساعتين ونصف بكفاءة تصل إلى 99,99%. ومع ذلك، قد نحصل على كفاءة مماثلة باستخدام SWDR لمياه ذات تعكر يصل إلى 29,5 NTU في ظروف بيئية مماثلة. وكشفت النتائج أن SWDR هو أكثر كفاءة، ويمكن استخدامه لتطهير المياه في وقت أقل.

الكلمات المفتاحية: تطهير شمسي، الكوليفورم الكلية، الكوليفيج، تعكر. المياه.