Energy Conversion and Management 123 (2016) 549–558

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

The performance and applicability study of a fixed photovoltaic-solar water disinfection system

Yanchao Jin [a], Yiping Wang [a,b], Qunwu Huang [a,*], Li Zhu [b], Yong Cui [c], Lingyun Cui [a]

[a] School of Chemical Engineering and Technology, Tianjin University, Tianjin 300072, China
[b] School of Architecture, Tianjin University, Tianjin 300072, China
[c] Tianjin University Research Institute of Architectural Design, Tianjin 300072, China

ARTICLE INFO

Article history:
Received 15 April 2016
Received in revised form 28 June 2016
Accepted 29 June 2016
Available online 6 July 2016

Keywords:
Photovoltaic
SODIS
Temperature
Lhasa
Chennai

ABSTRACT

The objective of the study is to construct and evaluate a fixed PV (photovoltaic) cell integrated with SODIS (solar water disinfection) system to treat drinking water and generate electricity under different climate through experimental and simulation methods. The photovoltaic and disinfection performances of the hybrid system were studied by the disinfection of *Escherichia coli*. The applicability of the system in Lhasa and Chennai was evaluated by analyzing the daily radiation and predicting the daily water temperature and the system electricity output. The results confirm that the temperature would dramatically enhance the SODIS process and shorten the disinfection time, when the water temperature was above 45 °C. The PV cell in the hybrid system could work under low temperature because of the water layer and the generated electricity was much more than the system consumption. The simulation results show that the days with maximum water temperature above 45 °C were more than 60% of whole year in Chennai. The generated electricity of the hybrid system was 49682.3 W h and 45615.9 W h a year in Lhasa and Chennai respectively. It was sufficient to drive the system of whole year. The number of days which realized drinking water treatment was 324 days in Lhasa and 315 days in Chennai a year.

1. Introduction

The problems of drinking water still plague human beings, especially for whom living in remote areas. Throughout the world, there are approximate one million children younger than five years old dying of contaminated drinking water every year [1]. Due to poor sanitation and source water, the main contaminations were caused by microorganisms [2]. SODIS (solar water disinfection) had been proven to be effective of treating various waterborne pathogens, for example, *Escherichia coli*, *Salmonella typhimurium*, *Vibrio cholera* etc. [3,4]. It was mainly attributed to the UV (ultraviolet spectrum) in the sun light [5].

More than 70% people live in rural communities in India. Due to the water contamination, especially the bacterial contamination, water crisis will still be a national issue by 2020. Besides India, in China there are also large amounts of people living in remote areas who have to face the problem of drinking water. For example, Tibet, China, because of the over 4000 m average altitude and very low population density (about 2 persons km^{-2}), it is quite expensive and difficult to install pipe network of drinking water there [6]. Fortunately, solar radiations are abundant in many areas of India and China, where SODIS is applicable to treat drinking water there.

1 L-2 L PET (polyethylene terephthalate) bottles were always used as water containers for SODIS. However, it was difficult to meet the demands of portable water consumption of a family. In order to increase the water treatment volume, borosilicate glass tubes were widely used in researches and practices [3,7,8]. Most of these instruments required pumps to recycle water and the pumps needed electricity. However, electricity was also a shortage for people in remote areas.

Another factor that is preventing the application of SODIS is long treatment time. It is about 6 h exposure for SODIS when it is sunny, and 2 or 3 days when it is cloudy [9]. A lot of measurements have been taken to enhance the SODIS process and shorten the treatment time. The method of attaching aluminum foil to the backs of bottles or simply painting them black had been demonstrated to increase disinfection rate by increasing the radiation into the bottles [10]. Optical concentrators were also commonly used to strengthen the light intensity. McLoughlin et al. [3] demonstrated that compound parabolic (CPC), V-groove and parabolic could all improve *E. coli* disinfection rate. In the subsequent studies, different volumes with CPC concentrators all achieved faster disinfection

* Corresponding author.
E-mail address: huangqw@tju.edu.cn (Q. Huang).

http://dx.doi.org/10.1016/j.enconman.2016.06.073
0196-8904/

Nomenclature

CFU	colony-forming unit, a single colony on culture media
LB	Luria-Bertani
PET	polyethylene terephthalate
SODIS	solar water disinfection
ROS	reactive oxygen species
DL	detection limit
P_m	the maximum output power (W)
I_{sc}	short-circuit current (A)
A	area (m^2)
F	view factor
G	solar radiation intensity (W/m^2)
h	heat transfer coefficient (W/m^2 K)
m	mass (kg)
T	temperature (K)
Nu	Nusselt number

Subscripts

a	ambient
b	insulation cotton
c	PV cell
$g-1$	the water layer covering glass
$g-2$	the PV cell covering glass
wt	water tank
w	water

rate than that of PET bottles [9,11,12]. Although using aluminum foil or concentrators had significantly enhanced the process, the cost was also increased.

Additives were also used in many studies. Photo catalysts, especially TiO_2 (titanium dioxide), absorbed radiation shorter than 390 nm UVA (ultraviolet A) and created ROS (reactive oxygen species) which could damage bacteria [13,14]. However, if TiO_2 was suspended, it required post treatment. If it was immobilized on the reactors, it was less efficient than suspension and more expensive. Low concentration of hydrogen peroxide (H_2O_2) had been proven that it could efficiently improve the disinfection rate during SODIS process, which liked photo-Fenton [15,16]. Except H_2O_2, lemon and vinegar could also be used as catalysts for solar disinfection [17]. No matter which additives, H_2O_2 or the others, have brought new problems that have been identified, such as storage, transportation, taste and odor.

When the temperature of the water was above 45 °C, a strong synergistic effect was detected [18,19]. It is different with adding chemical components the enhancement of temperature has no residues generation. The ambient temperature is relatively higher in most of the developing countries located near the equator [20]. Besides UV spectrum, temperature would play an important role there.

In order to improve the utilization efficiency of solar energy, hybrid devices with combination of photovoltaic and other applications have been investigated in previous studies. For example, photovoltaic-thermal (PVT) systems that consist of hybrid photovoltaic-thermal systems which simultaneously produce electricity and hot air/water [21,22]. Regarding the use of the solar spectrum, Vivar et al. [23–26] built hybrid systems that integrate photocatalysis with photovoltaic to treat dye polluting water. TiO_2 photocatalysis mainly uses UV and near UV spectrum, which is only accounted for about 4% in the solar spectrum. At the same time, visible and near infrared light is preferred by solar cells.

SODIS also mainly uses UV and near UV spectrum. If the water temperature is above 45 °C as it absorbs far infrared spectrum, it can combine UV light and thermal pasteurization for disinfection. When SODIS was integrated with photovoltaic in a single unit, the water layers have less impact on the PV modules, as catalysts are not essential for SODIS. The electricity generated by solar cells can be used for the system and other household application. However, the studies about hybrid SODIS and solar cells are very few.

Fixed hybrid systems for degradation of dye wastewater could produce purified water and electricity simultaneously in previous studies [24,25]. The main goal of this work is to construct a fixed hybrid system which can disinfect microorganisms for drinking water and generate electricity at the same time. We not only investigate the performance of the system but also identify whether the system is applicable. The solar radiation of Lhasa, China and Chennai, India was analyzed. A computational model for the system was created and used for evaluating daily water temperature and electricity output.

2. Materials and methods

2.1. System and materials

The main part of the system is the absorber which is fabricated by joining a flow channel with a dimension of 515 × 459 × 16 mm up solar cell as Fig. 1 shows. Mono-crystalline cells were commonly used and efficient, which were chosen during the study [27,28]. The parameters under standard condition are listed in Table 1. Insulation cotton with thickness of 5 mm was used for thermal insulation at the back of the absorber. Considering the transmittance, borosilicate glass with a thickness of 4 mm was chosen as the water layer covering glass, which can transmit about 83% of UV and about 90% of visible and near-infrared spectrums.

In order to study the influence of the water channel on the PV cell, a PV module, same as what for the absorber, was used as reference. If without other impacts, the disinfection effect was directly associated with the irradiation energy, which has been determined in previous studies [29,30]. To determine solar energy needed for complete disinfection of 8 L water, a heat exchanger (300 W, accuracy: ±2 °C, Jiale Ltd., China) was used to avoid the influence of the temperature on SODIS process in some of the experiments as shown in Fig. 1(a). A pump (2.5 L min^{-1}, 6 W consumption, RS Components Ltd., China) was chosen to circulate water. The different parts of the system were connected by pipes.

2.2. Environmental conditions and systems monitoring

A data acquisition and recording system had been built to study the photovoltaic and disinfection performance of the system. A global radiometer (Model PSP; sensitivity, 8.43 μV/W m^{-2}, 300–3000 nm) manufactured by the Eppley Laboratory, Inc. was fixed on the system. Eight temperature sensors (Pt 100, range: −50 to 300 °C, accuracy: ±0.5 °C, Heraeus Group Ltd., Germany) were used to record the temperatures of three PV modules (the reference PV module, the systems with and without a heat exchanger) and two water tanks. Two liquid flow sensors (range: 40–250 L/h, accuracy: ±0.5%, LWGY-DN6, Tianjin Instrument Group Co., Ltd., China) recorded the cycle flow rate. All the parameters were recorded by a data logger (DI-710, Quatronix Company).

The ambient temperature and wind speed were recorded by a meteorological station at the interval of 5 min. I-V curves instrument (accuracy: ±0.5%, DS-100C, Daystar, Inc.) was used for measuring I-V curves of the three PV modules at the interval of 5 min.