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Thermal performance and biological evaluation of solar water disinfection systems using parabolic trough collectors

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ABSTRACT

Thermal and optical performance of solar water disinfecting systems using parabolic trough collector, PTC, have been investigated experimentally and numerically. Four PTCs systems were designed, manufactured and field tested under the same weather conditions of Cairo 30°N. The four systems were installed to be compared thermally and biologically. Each system consists of a 2-m^2 PTC and line-focus pipe to carry the water sample to be disinfected. In the first system (thermal system), a black painted stainless steel pipe covered by Pyrex glass envelope, to minimize the convective and radiative heat loss, is supported through the line-focus of the PTC. While in the second system (optical system) the contaminated water is used as absorber through a Pyrex glass tube, the two above processes are considered respectively in the third system. In the fourth system, a black tube including and surrounded by the contaminated water are considered as the absorber. The contaminated water is passed through the annular space between the Pyrex glass tube and the collector absorber. The experimental results indicate that the third system has better performance than the other studied systems from the biological point of view with twice area. It has the minimum biological contamination, Spore-former bacteria count, total bacterial counts and total coliforms. While the thermal system is thermally efficient, the optical system is not recommended to use alone. A numerical modeling of the systems was developed and validated by experimental data. The annual performance of the systems is presented. Under the same environmental and technical conditions the third system can be considered as the most efficient one that can produce about Million liter of clean water a year.

Keywords: Thermal disinfection; Optical disinfection; Parabolic trough; Bacteriological examination; Numerical simulation

1. Introduction

A primary concern of people living in developing countries throughout the world is to obtain clean drinking water. In many places this problem is made harder by the fact that many of the available water sources are surface without some forms of treatments. Heating and optical are the most common techniques for disinfecting contaminated water. Consequently solar energy can play a significant role in disinfecting contaminated water in those regions that enjoy hot and sunny climate. Water which treated by heating to 60°C

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in a commercial solar collector system would inactivate enteric bacteria, spore and viruses [1]. They concluded that achieving a sufficiently high temperature (preferably 55°C or higher for several hours) is an important factor for microbial inactivation by solar disinfection systems.

Most efforts using solar energy to kill pathogenic microbes in contaminated water have used transparent containers exposed to direct sunlight [2]. Solar disinfection is one of the simplest and least expensive methods for providing acceptable quality drinking water. It is an ideal method for use when economic and sociocultural conditions in the community are not amenable to other treatment or disinfection alternatives such as filtration or chlorination even though these are also acknowledged to be simple and inexpensive [3]. Solar disinfection is a thermal process consisting of raising water temperature for a long enough period of time in containers that have been prepared to absorb the heat generated by solar radiation [4]. Many variables affect its efficiency parameters that could interfere with perfect disinfection include geographic latitude and altitude, season, number of hours of exposure, time of the day, cloud and temperature, volume and material of vessels containing the water and water turbidity and color [5]. That method can improve the bacteriological quality of water considerably.

High temperatures strongly affect all microorganisms, vegetative cells perish as proteins are denatured and other components undergo hydrolysis [3]. Although some bacteria in the water are capable of forming spore making them particularly heat resistant, most are generally killed off at between 40 and 100°C while algae protozoa and fungi perish at between 40 and 60°C [4].

Solar optical disinfection is an effective water treatment method. Ultra-violet rays from the sun are used to inactivate pathogens present in water. Treatment to control waterborne microbial contaminants by exposure to sunlight in clear vessels that allows the combined germicidal effects of both UV radiation and heat has been developed, evaluated and put into field practice [5–13].

Oates et al. [14] developed a mathematical model (SODIS) based on satellite-derived daily total energies to simulate monthly mean, minimum, and maximum 5-h averaged peak solar radiation intensities with agreement with the measured values. Actual SODIS efficiency in January was tested by the inactivation of total coliform, *E. coli*, and H_2S-producing bacteria. One-day exposure achieved complete bacterial inactivation 52% of the time, while a 2-day exposure period achieved complete microbial inactivation 100% of the time. McLoughlin et al. [15] compared three different collector of compound parabolic, parabolic and V-groove profiles for the disinfection of water heavily contaminated with *Escherichia coli* (K-12). Results have shown that the compound parabolic reflector promoted a more successful inactivation of *E. coli* than the parabolic and V-groove profiles.

Martin-Dominguez [16] presented the efficiency of the solar energy based water disinfection process for water inside bottles. The use of solar concentrators and bottles partially painted black increases inactivation efficiency, reducing the solar exposure time required for a total disinfection to just 2 h. With the use of solar concentrators and partially blackened bottles, the water temperature reached 65°C, while only 50°C was achieved when using the same concentrators and completely transparent bottles.

Duff and Hodgson [17] tested a new passive solar water pasteurization system based on density difference flow principles with high potential. In addition Rinco'n and Pulgarin [18] carried out experiments using a CPC and natural water spiked with *E. coli* K 12. The addition of TiO_2, TiO_2/Fe^{3+} or Fe^{3+}/H_2O_2 to the water accelerates the bactericidal action of sunlight, leading to total disinfection by solar photocatalysis. Moreover El-Ghetany and Abdel Dayem [19] developed a flat-plate thermal system for water thermal disinfection. The system was successfully numerically simulated demonstrating efficient utilization along the year.

The main objective of the work is to find out the best solar disinfection system from both biological and thermal point of view for both thermal and/or optical effects. In order to achieve higher temperature in a small period of time, a parabolic trough solar collector (PTC) is used to heat the contaminated water. The PTC can concentrate the solar rays on the line focus and consequently can make thermal and/or optical effects of the contaminated water passing in the system to be disinfected. Testing of using non-tracking PTC in water disinfection process can be considered as the second objective of the research work. Biological evaluation before and after disinfection process is considered to find the best system from that point of view. Four systems were installed considering the optical, thermal and both of them. A bacteriological examination was established for each case to find the most efficient system. A validated numerical model demonstrates the annual performance is established.

2. Experimental setup

The experimental test rig consists of four PTCs systems (namely, thermal, optical, optical followed by thermal and optical/thermal in the same collector). Each system consists of 2-m^2 PTC, steel frame,

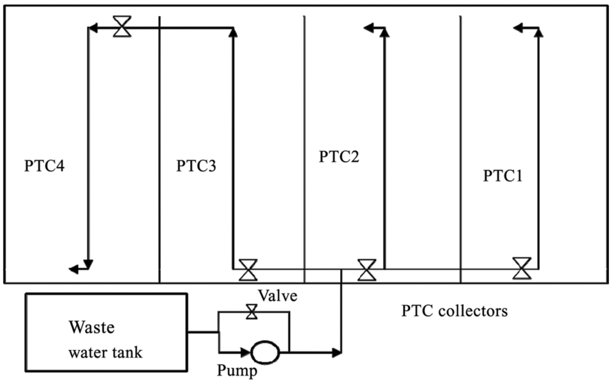

Fig. 1. Layout of the installed solar water disinfecting systems.

connecting tubes and 0.5 hp water pump and main source of contaminated water tank as shown in Figs. 1 and 2. In the optical/thermal system PTC1, the absorber is made of perforated black painted stainless steel pipe covered by Pyrex glass envelope. The contaminated water is passed through the annular space between the Pyrex glass tube and the thermal perforated pipe, so the contaminated water can be exposed to the solar rays (optical effects) as well as heated by the absorbed solar radiation that concentrated on the line focus of the PTC.

In the thermal system PTC2, a black painted stainless steel pipe where the contaminated water is flowing, covered by a Pyrex glass envelope, to minimize the convective and radiative heat loss, is fixed along the line focus of the PTC. However in the optical system PTC3, the contaminated water is passed through a Pyrex glass tube placed in the line focus of the PTC. In the optical followed by thermal system PTC4, the contaminated water is passed through a Pyrex glass tube placed in the line focus of the PTC3 and respectively passed through the black painted stainless steel pipe with Pyrex glass envelope connected in series.

Fig. 2. Photograph of the systems considered.

The layout of the experimental system is presented in Figs. 1 and 2. The PTC collector consists mainly of an Aluminum parabola covered by a reflective sticker (Aluminum foil), which has a reflectivity of about 0.95. The curvature of the concentrator generates a parabola with focal length equals to 0.272 m and the rim angle (φ) of 90°. The receiver of the PTC consists of stainless steel with one inch diameter located at the focal plane through which the fluid inside is heated. It is painted black to improve the absorbitivity of the absorber tube.

The concentrators are oriented to the south and inclined by 30° with the horizontal; they are fixed systems (not tracking) with an average height of 2 m from the ground. The contaminated water is pumped from 100 liter tank by 0.5 hp pump into a pipe that equally distributes water into the four collectors at the same time. The flow rate inside the pipe is adjusted by a gate valve at each pipe.

2.1. Measurements

The measuring instruments used in the experimental tests, were implemented to measure the various parameters to evaluate the thermal performance of the solar water disinfecting system using PTCs at different operating conditions. A thermopile pyrheliometer is used to measure direct solar radiation of type Actinometer CM 1 (model CM1-780335). It is connected to a voltmeter of type Kaise (model SK-5000K). The output voltage of the pyrheliometer is 5.91×10^{-3} mV/Wm^{-2} for a resistance range of 10 Ohm. The inlet and outlet water temperature of PTC collector and ambient temperature are measured by nickel-chrome/nickel-aluminum thermocouples of 1 mm diameter and insulated with an external binding insulation of plastic. The thermocouple hot junctions are put at the selected positions just at inlet and exit of the pipes. A graduated beaker was used to measure quantity of disinfecting water with an accuracy of 20 ml.

2.2. Microbiological examination

Samples were randomly taken before and after the solar collectors along a day to be biologically tested. The biological tests are described as follows:

2.2.1. Enumeration of classical bacterial indicators

Total and faecal coliforms, faecal streptococci and total bacterial counts at 22 and 37°C were determined according to APHA 1998. The most probable number

(MPN) technique was used to determine the total and faecal coliforms and faecal streptococci in 100 ml sample, while total bacterial counts were counted by using pour plate method as colony forming unit (FU/ml).

2.2.2. Enumeration of supplement indicators of pollution and pathogenic bacteria

MPN technique was used to determine *Pseudomonas aeruginosa* as a new indicator according to APHA 1998, while membrane filtration technique was used to determine the presence of other new indicators of pollution (total yeasts *Candida albicans* and total staphylococci) and selected pathogenic bacteria (salmonellae, total vibrios and listeria group). In this determination 10 ml for raw water and 100 ml treated samples were filtered through nitro-cellulose 0.45 μm membrane. Membranes were transferred onto the specific media for the following parameters:

2.2.3. Enumeration of yeasts

Littman oxgall agar (pH 6.5) supplemented with chloramphenicol (5 mg/l), penicillin (50,000 units/l) and streptomycin (30 mg/l) was used by a surface plate technique.

2.2.4. Enumeration of Candida albicans

Candida Elective Agar (Merk) was used to enumerate and count of *Candida albicans*. Surface inoculated plates were incubated for 2–3 days at 22°C, brown to black, smooth colonies were counted.

2.2.5. Enumeration of Staphyiococci

Baired Parker agar (Merk) was used and the plates were incubated for 48 h at 37°C. Typical Staphyiococci colonies were counted.

2.2.6. Enumeration and identification of salmonellae

Bismuth Sulfite Agar was employed for enumeration of salmonellae according to El-Taweel and Shaban [20]. Biochemical identification of Salmonellae was carried out by the methods of Galton et al. [21].

2.2.7. Enumeration and identification of Vibrios

The TCBS m was used for enumeration of vibrios. Moreover biochemical identification of Vibrios was carried out.

2.2.8. Enumeration and identification of Listeria

Listeria Selective Agar (Merk) supplemented with 0.01% esculin and 0.05% ferric citrate as described by Shaban and El-Taweel [22] was used in enumeration of Listeria group. The plates were incubated for 1–2 days at 37°C and the typical Listeria colonies were counted. Biochemical reactions were carried out Listeria identification.

3. Mathematical model

The considered systems are simple; they consist of a PTC and a controlled pump to force water into the collectors. Therefore the mathematical model contains those three components explained in the following subsections.

3.1. PTC

The collectors receive only the beam (direct) radiation that reflected from the reflectors. Thermal losses from parabolic concentrating collectors occur only from the absorbing surfaces which, while high in temperature, have comparatively small area. The useful energy gain that can be produced from the collector can be estimated as edited in [23]:

$$Q_u = R_1 R_2 N_p [IAM.I_b.A_a F_R \tau\alpha - F_R U_L A_r (T_{ci} - T_a)] \quad (1)$$

For parabolic concentrators, two modifiers (R_1 and R_2) are applied to Eq. (1) in order to correct for other flow rates than under test conditions and to account for more than one collector in a series string. R_1 includes a term called R_{test} as shown in Eq. (2)

$$R_1 = \frac{N_S \dot{m} C_P}{A_a} \left(\frac{1 - e^{\frac{-FU_L A_a}{N_S \dot{m} C_P}}}{R_{test}} \right) \quad (2)$$

$$R_2 = \frac{1 - \left(1 - \frac{R_1 F_R U_L A_r}{\dot{m} C_P N_S}\right)^{N_S}}{\left(\frac{R_1 F_R U_L A_r}{\dot{m} C_P N_S}\right)} \quad (3)$$

and

$$R_{test} = G_{test} C_p \left[1 - e^{-\frac{\acute{F} U_L}{G_{test} C_P}} \right] \quad (4)$$

It is developed a modified loss coefficient called $F'U_L$. $F'U_L$ is based upon the standard collector loss coefficient $F_R U_L$ provided by collector manufacturers and corrects the manufacturer specified loss coefficient for flow rates other than the rated flow rate.

Table 1
Modifiers (IAM) of the incidence angles

θ	0	10	20	30	40	50	60	70	80	90
Modifier (IAM)	0.9	0.8	0.72	0.63	0.54	0.45	0.36	0.27	0.18	0.09

$$\grave{F}U_L = \begin{cases} F_R U_L \ \ if \dfrac{F_R U_L A_r}{G_{test} C_P A_a} \geq 1 \\ G_{test} C_p [1 - e^{\left(\frac{F_R U_L A_r}{G_{test} C_P A_a}\right)} if \dfrac{F_R U_L A_r}{G_{test} C_P A_a} < 1 \end{cases}. \quad (5)$$

In addition to losses due to the angle of incidence, there are other losses from the collectors that can be correlated to the angle of incidence. These losses occur due to additional reflection and absorption by the glass envelope when the angle of incidence increases. The incidence angle modifier (IAM) [24] corrects for these additional reflection and absorption losses. The incidence angle modifier is given as an empirical fit to experimental data for a given collector type. The corrected data of the incidence angles is shown in Table 1.

Provided that there is flow, the temperature of fluid at the collector outlet is given by the following equation

$$T_{co} = T_{ci} + \frac{Q_u}{\dot{m} C_p} \quad (6)$$

3.2. On/Off controlled pump

The controller generates a control function γ_o that can have values of zero or one. The value of γ_o is chosen as a function of the difference between upper and lower temperatures, T_H and T_L, compared with two dead band temperature differences, ΔT_H (It is taken as 10°C) and ΔT_L (It is taken as 10°C). The new value of γ_o is dependent on whether initial value $\gamma_i = 0$ or 1. The controller is normally used with γ_o connected to γ_i giving a hysteresis effect. For safety considerations, a high limit cut-out is included with the controller. Regardless of the dead band conditions, the control function will be set to zero if the high limit condition is exceeded.

This pump model computes a mass flow rate using a variable control function, which must be between zero and one, and a fixed maximum flow capacity considered in the work.

3.3. Solar radiation model

Due to a shortage in the annual beam radiation measurements it is estimated from the measured horizontal global radiation. In that model it uses the clearness index ($k_T = 1-\theta z$) and the solar altitude angle (α) to estimate the diffuse fraction (I_{dh}/I_{gh}). The correlation developed by Reindl (25) is given by the following equations:

– Interval: $0 \leq k_T \leq 0.3$; Constraint: $I_d/I \leq 1.0$

$$\frac{I_{dh}}{I_{gh}} = 1.02 - 0.254 k_T + 0.0123 \sin(\alpha). \quad (7)$$

– Interval: $0.3 \leq k_T \leq 0.78$; Constraint: $1.0 \leq I_d/I \leq 0.97$

$$\frac{I_{dh}}{I_{gh}} = 1.4 - 1.749 k_T + 0.177 \sin(\alpha). \quad (8)$$

– Interval: $0.78 \leq k_T$; Constraint: $0.1 \leq I_d/I$

$$\frac{I_{dh}}{I_{gh}} = 0.486 k_T + 0.182 \sin(\alpha). \quad (9)$$

The considered angles are estimated based on the latitude of the location, local time and day number as defined in [21]. The beam radiation on a horizontal surface is calculated by the difference between the total radiation and the diffuse component,

$$I_b = I_{gh} - I_{dh} \quad (10)$$

4. Results and discussion

4.1. Experimental performance and biological evaluation

The experiments procedure was developed as allowing a contaminated water (that artificially contaminated by adding one liter of raw waste water to 100 liters of fresh water) to pass through the collectors with a certain flow rate. The water is heated and/or exposed to solar radiation through the line focus PTC solar collectors and then collected in containers along daylight. The inlet and outlet temperature of the collectors were measured and the weather conditions as well. A sample of the inlet and outlet contaminated

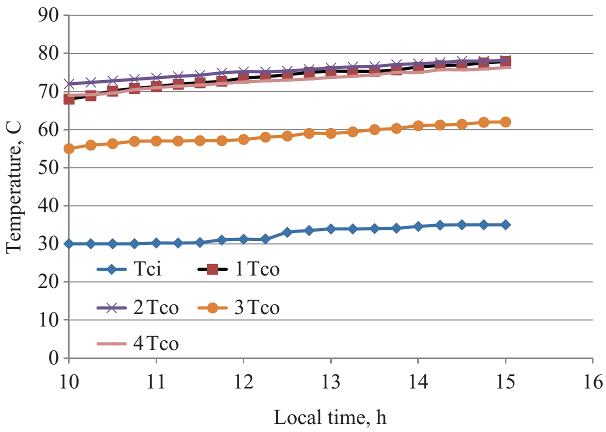

Fig. 3. Temperatures variation of the inlet and outlet flow on 4/7/2007.

water was taken to be tested by microbiological examination. Through the present investigation, different experiments have been carried out on the line-focus parabolic-trough solar collector constituting a solar water disinfecting system under different meteorological conditions of Cairo, Egypt and for different water flow rates during the collectors.

Three different flow rate quantities of (3 l/min), (4.5 l/min) and (6 l/min) were considered to study the collectors performance thermally and biologically under various conditions. That can allow finding the optimal flow rate for each collector. The inlet and outlet temperatures of each collector are observed in Figs. 3 and 4. The weather data of solar radiation and ambient temperature for the experiments days were measured.

As expected the larger flow rate produces lower exit temperature for the four systems with nearly constant inlet and ambient temperatures. All the experiments were carried out around the solar noon where the

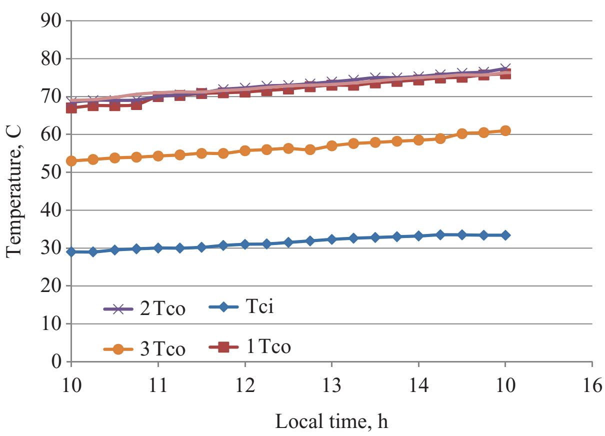

Fig. 4. Inlet and outlet temperatures variation of the concentrators on 5/7/2007.

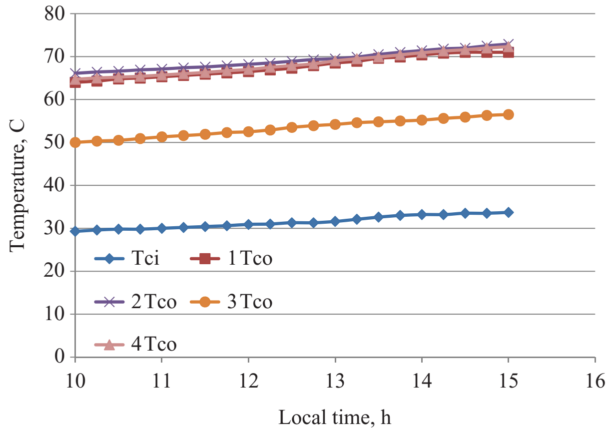

Fig. 5. Inlet and outlet temperatures variation of the concentrators on 7/7/2007.

concentrators can obtain a high gain. That is because they are non-tracked and south facing orientation. Because the experiments were established around the solar noon, the temperatures are linearly increased from 10 AM to 3 PM (summer time) where the solar radiation and ambient temperature have the same behavior.

As shown in Figs. 3–5, the third collector PTC3; the optical system has the lowest exit temperature. It has no absorber; the contaminated water absorbs a part of reflected sun rays. The exit temperature can overcome 60°C in that case. It is lower than the other systems by about 17°C where the contaminated water is heated by about 23°C. For other collectors, it increases by about 40°C. That is a good indicator of higher efficiency of such collectors. The second system PTC2 has the highest exit temperature for all cases. From the thermal loss point of view, it has lower heat loss than PTC1 and PTC4.

For PTC1, the water is passed inside a stainless steel absorber and in between the absorber and optical cover. Therefore, the heat loss is increased. In PTC4, the water is preheated in the optical collector and then heated inside a normal collector. Although this system has twice aperture area of other collectors but the exit temperature is not higher than them. That can be understood as the higher inlet water temperature to the second collector decreases the efficiency.

As shown in Figs. 3-5, PTC4 has the lowest instantaneous efficiency due to twice aperture area used in it with relatively the same exit temperature. Moreover, the system PTC2 has the maximum efficiency along the day for all flow rates due to minimum heat loss that it has.

5. Biological evaluation

The above biological tests are developed for the different random samples for the different explained

Table 2
Biological results of the test run on 4/7/2007

Biological examination	TBC 22°C	Sporeformer	TBC 37°C	Total Coliform
Raw contaminated water sample	200,000	100,000	300,000	700,000
Optical and thermal PTC	1,300	5	8,000	23
Thermal PTC	1,700	4	5,000	20
Optical PTC	28,000	7	22,000	25
Thermal after Optical PTC	2,100	1	1,700	3

systems. The biological tests of total bacterial counts (TBC) at 22°C followed by Spore-former bacteria count and the TBC at 37°C followed by total coliforms. Two samples are taken before and at the end of the experiments of each system for two days. The remained number of bacteria is presented in Tables 2 and 3 before and after the experiments.

In general it is shown that the tests of spore former and total coliform are relatively eliminated for all considered systems. The total bacterial account for 22 and 37°C are individuals for the different systems. It is higher for 37°C than in 22°C for the first and second systems where those systems produce higher temperature. For the third and fourth systems the temperatures are lowered and that raises the TBC at 37°C than at 22°C. From the bacteriological examination, the fourth PTC is the best system that has the minimum number of bacteria for all tests. That is because it has both optical and thermal effects at high temperature. Perhaps, the first PTC has also both effects but that is partially occurred. Where a part of water is exposed to the direct sun rays, other parts are not exposed. Also the temperature is lowered inside the absorber due to high heat losses.

From the experimental data shown in Tables 1 and 2, the fourth system which provides both higher temperature and sun-rays exposure has the minimum TBC and total caliform. That approved the thermal and optical effects for the water disinfection. Those results are in close agreement with the results provided by [1-4].

In all systems relatively high temperature and sun rays exposure are provided. Therefore the bacteria is denatured for all cases as indicated by [3] and [4] in the temperature range of 40°C and 100°C. In addition in optical systems ultra-violet rays from the sun can inactivate pathogens present in water as concluded in [6].

5.1. Validation of collector characteristics

The outlet temperatures of the collectors are estimated for the same inlet temperatures, area, and mass flow-rate. They are estimated under the same weather conditions of solar radiation and ambient temperature. The characteristics of each collector are modified to obtain a good agreement between the estimated and corresponding measured data as possible. Those characteristics include intercept efficiency ($F_R\tau\alpha$) and efficiency slope (F_RU_L). The estimated values of those parameters are indicated in Table 4.

The estimated temperatures are compared with the measured ones for each disinfection system as presented in Fig. 6 where Fig. 7 illustrates the beam radiation and the ambient temperature as well. As clearly in the two figures the variation of the estimated temperatures is similar to the beam radiation variation. That is completely true because the beam radiation is the energy source to the collectors. Therefore the difference between the measured and estimated temperatures is obtained from that variation. Therefore the difference between the measured and simulated temperature can be understood.

The estimated temperatures are higher than the measured ones in general unless at about 11.5 AM. In that time the beam radiation is dropped due to drop in the global horizontal radiation. That largely affects the estimated temperatures. For the measured

Table 3
Biological results of the test run on 5/7/2007

Biological examination	TBC 22°C	Sporeformer	TBC 37°C	Total Coliform
Raw contaminated water sample	210,000,000	700,000	3,000,000,000	700,000
Optical and Thermal PTC	130,000	5	120,000	23
Thermal PTC	24,000	4	90,000	20
Optical PTC	32,000	5	92,000	25
Thermal after Optical TC	710	1	800	3

Table 4
Characteristics of the collectors

Collector	$F_R\tau\alpha$	F_RU_L, W/m^2.K
PTC1	0.5	15
PTC2	0.52	15
PTC3	0.3	15
PTC4	0.25	15

temperatures they are not affected by that drop in solar radiation. Perhaps that drop is occurred instantaneously. Moreover the ambient temperature is also dropped and that affects also in the collector performance. From 10 to 11 AM the temperatures are relatively high although the beam radiation is not high. That is because the ambient temperature is relatively high during that period as clearly presented in Fig. 7.

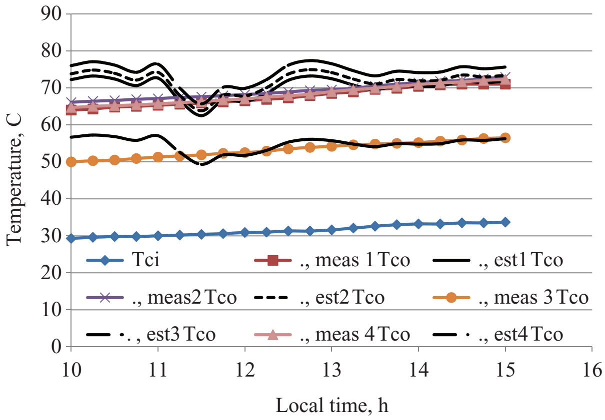

Fig. 6. Validation of the numerical modeling.

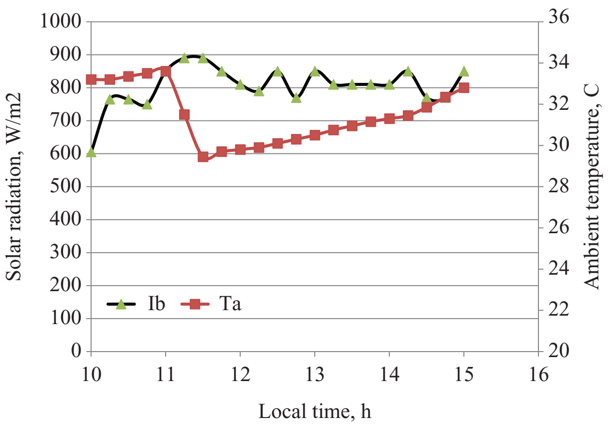

Fig. 7. Weather condition of the corresponding validation day.

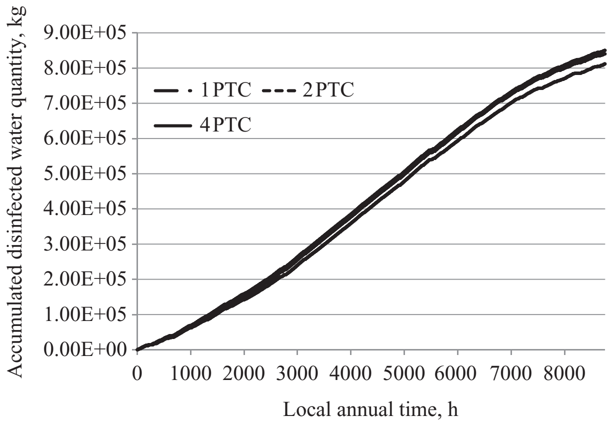

Fig. 8. Annual accumulated disinfected water.

5.2. Annual performance of the systems

Regarding the results of the experimental subsection the mass flow rate of 4.5 l/min (270 kg/h) is more efficient from biological point of view. Therefore it is used to demonstrate the annual performance of the systems. In addition the same specifications of the systems are used. The systems are controlled to produce outlet temperature of 73°C as indicated in the measurement data. That means the pump is switched off if the temperature is less than 73°C. Even the outlet temperature is relatively high for the PTC3 where it has not an absorber it is not considered in that subsection. Under the measured weather data of a year the numerical simulation is running for a year.

The annual accumulated of clean water is presented in Fig. 8 for the three systems PTC1, PTC2 and PTC4. The systems PTC1 and PTC4 have almost the same quantity of clean water in a year. They have about 840,240, 811,890 and 850,230 liter, respectively. That is corresponding to 420,120, 405,945 and 212,557.5 liter/m^2. PTC4 has the lowest productivity per square meter but it has the lowest bacteria account. That conclusion agrees with the conclusion of the experimental data. The productivity is increased during the summer months as expected but the annual performance for that level of temperature is accepted. By that water production the systems considered are highly recommended for the waste water disinfection purposes.

The hourly variation of the collector outlet temperatures along a year are estimated in Figs. 9–11. The temperature is switched to 73°C so the maximum indicated temperature is limited to that temperature. As indicated in the figures the temperature reaches the maximum temperature almost along the year. The solar radiation is not enough to raise the temperature in few hours during the winter months. Perhaps that is clearly appeared in Fig. 11 for PTC4 than in Figs. 9 and 10 for

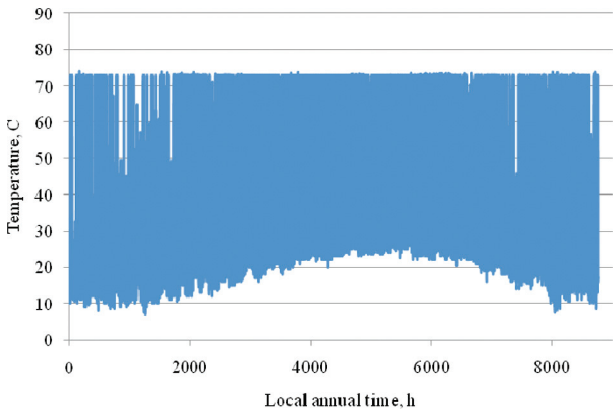

Fig. 9. Hourly variation of the collector outlet temperature of PTC1.

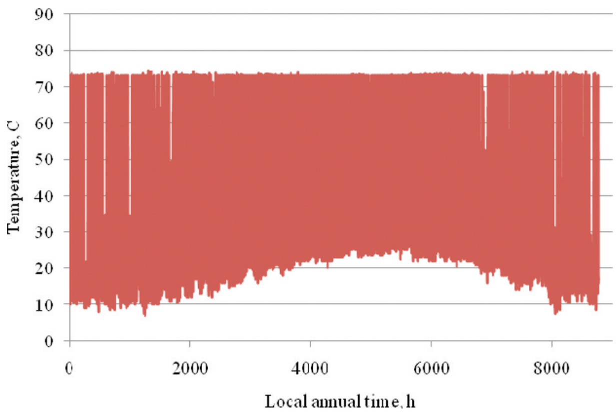

Fig. 10. Hourly variation of the collector outlet temperature of PTC2.

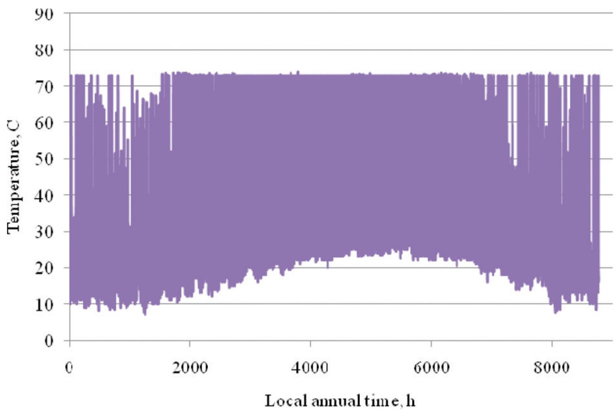

Fig. 11. Hourly variation of the collector outlet temperature of PTC4.

PTC1 and PTC2 respectively. As shown in the figures the considered systems can be efficiently used for the disinfection process.

5. Conclusion

Four parabolic-trough systems were experimentally installed and tested for water disinfection and numerically simulated. Thermal and biological examinations were developed for each system under the same flow rate and weather conditions. Disinfection by optical, thermal, thermal after optical and mixing of them is considered in the study. The numerical simulation was experimentally validated and the annual performance of the systems was investigated. It is obtained that the thermal disinfection is the most thermally efficient for different flow rates with lower cost. The system that has the thermal effect that follows the optical effect has the cleanest water from the biological point of view. Water disinfection by the considered systems has a great potential in that manner.

Nomenclature

A_a	collector aperture area, m^2
A_r	receiver surface area, m^2
C_P	specific heat of the collector fluid, kJ/kg.C
$F_R\tau\alpha$	intercept of collector efficiency vs. $(Ti - Ta)/IT$
F_RU_L	negative of the first-order coefficient of collector efficiency vs. $(Ti - Ta)/IT$ first and second-order coefficients of collector efficiency vs. $(Ti - Ta)/IT$
G_{test}	collector test mass flow rate per unit area, $kg/m^2.s$
IAM	incidence angle modifier
I_b	beam radiation, W/m^2
I_{dh}	horizontal diffuse radiation, W/m^2
I_{gh}	horizontal total radiation, W/m^2
k_T	sky clear index
mass	flow rate of the collectors, kg/s
N_p	number of collectors in parallel
N_s	number of collectors in series
Q_u	useful energy rate of the collector array, W
R_1 and R_2	correction factors, see Eq. 3&4
R_{test}	correction factor due to using mass flow rate rather than the test one
T_a	ambient temperature,°C
T_{ci}	collector inlet temperature,°C
T_{co}	collector outlet temperature,°C

Symbols

α	solar altitude angle, degrees
θz	Incidence angle, degrees

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