Asymmetrical compound parabolic concentrator with single flow system: field-test scale, thermal performance parameters, and E. coli inactivation

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Abstract
This work presents a developed field-test scaled asymmetrical compound parabolic concentrator (ACPC) and an investigation of its performance with a single flow system of water on Escherichia coli inactivation. As a function of water flow rate, ability to produce hot water of the ACPC and hence inhibit the growth of bacterial in water is focused to study; the flow rates varied are 0.2, 0.4, and 0.6 l min⁻¹. With a design and choice of material, the constructed ACPC unit with 0.2 l min⁻¹ could produce hot water with maximum temperature of 76.4 °C, with lower flow rates resulting in the lower outlet water temperature and consequently the reduced kinetics of bacteria inactivation. Thermal performance parameters have been described in a correlative view with the particular operation condition and flow rate variables through mathematic calculation. The effect of inlet driving temperature, believed to play a significant role controlling the outlet temperature, on E. coli inactivation has been investigated.

1. Introduction
The efficiency of solar collection system is considered to be dependent upon design of the concentrators and the operation conditions to harvest concentration of the incident solar radiation. Compound parabolic concentrator (CPC), categorized as non-imaging type of concentrator, is a form of solar concentrators capable of reflecting wide-range incident solar radiation to the absorber. The symmetrical version of CPC was initiated with an aim to increase the radiation intensity. With its superior optical collection solarization system; notwithstanding the more idealistic alternative to the asymmetrical compound parabolic concentrator (ACPC) has been further developed enabling solar radiation to concentrate more on the collector when performing at the same acceptance angle; the efficiency of the upgraded ACPC could be up to approximately 3.6 times higher than the symmetrical design [1]. The system operation of ACPC is capable of boiling water, convenient and there is no need to adjust the ACPC unit to accommodate the changing orientation of sunray over the solarization operating time. Yet the non-uniform distribution of solar irradiation on the misaligned collector unit is a significant problem leading to the reduced collection efficiency, as such, a challenge particularly in bacteria disinfection application the heating efficiency of the collector needed to be improved by decreasing the microbes inactivation time closer to the time of the traditionally steam treatment method.

In the CPC system, there are parameters affecting thermal energy output needed to elucidate for more insight. The mathematics and calculation have been studied to obtain the information on how the collector absorb thermal energy, how it loses heat during the operation, and the effect of heat capacity on the performance.
of the collector. The mathematical modeling was applied to predict thermal efficiency of the solar collector in order to enhance the performance of collector and validate with experimental data [2–4]. The collector performance is highly controlled by solar radiation, ambient temperature, and inlet temperature. A particular focus of research studies is mostly on inlet temperature in the comparative range of ambient temperature in the heating system [5, 6]. Fluid flow in terms of uniformity, temperature distribution, mass flow rate, and water flow pattern regimes, has shown significant effect on the increase in thermal efficiency [2, 7, 8].

Solar driven treatment technology has become an increasingly attractive technology due to its high efficient method and cost effective. Solar thermal energy has been known for water disinfection for many decades. Many technical aspects of water disinfection have been studied extensively and developed in many countries, with efforts to produce clean water by reducing contaminants in water [9–12]. Diversity of microbial species varies upon environmental stability of ecosystems such as temperature, light intensity, variability during the day, and relative humidity in the case of humid tropical regions [13]. Having an understanding of the factors to control the dispersion of water borne pathogens is imperative. Escherichia coli is a fecal bacteria indicator to detect waterborne pathogens [14]. Disinfection is defined by reducing the infectious bacteria in a particularly certain area to prevent the initiation point for infection [15]. Traditional disinfectants are chemical, yet risk leading to toxicity and allergy remains a concern, with poor validation of procedures as disadvantage. Further extending the application in soil treatment, solar radiation has been applied and exhibited its effect on fast decomposition of the organic matters and inhibiting the growth of soil microbes [1, 7, 16, 17]. Due to optical and thermal processes, sunlight has a strong synergistic effect on disinfection of bacteria at high temperature [18].

Upgrading the field-test scaled ACPC unit is seen at present little work existing on the improvement of the ACPC heating performance in a reduced time consumption and investigation of its effect on the microbes inhibition [1, 19, 20]. Phitthayarachasak et al [20] reported the ACPC design using copper tubes aligned in a semicircle and fixed them at the back side of the ACPC panel to absorb heat; the ACPC unit could reduce the length of time to inhibit Ralstonia solanacearum in soil from normally 4–6 weeks by solarization process down to 4 h, with temperature of 41.25 °C. A further improvement of the efficiency of solar hot water system via a combination of ACPC, CPC, and flat-plate solar collector (FPSC), it was found that the fabricated system proved hot water with temperature higher than 70 °C, while water dripping rate to soil showed no effect on heat transfer in the soil [19]. This work highlighted that water flow rate and relatively low soil density, designated as the absorber surface, play a significant role determining temperature distribution along the depth; hot water at 50 °C was found not suitable for inhibiting microbes at the 30-cm depth level in 2 h working time. Nonetheless, those attempts that have been made are the particular focus on soil treatment, a simple method for open field burning, and particularly for inhibiting R. solanacearum, the causative agent of wilt in crops leaves in soil.

Given a clue for the absorber surface seemingly a non-negligible factor on the heating performance, understanding the correlation between unit design and functioning and solar collector performance, behavior of collector parameters relating the operation conditions, and system operation and microbial inhibition in part of target application, these links are prerequisites to applying further the previous findings to other application such as in wastewater treatment. In this study, we report performance of the single-flow asymmetrical compound parabolic concentrator on Escherichia coli inactivation. A design herein is that the size of two reflectors are different, regarding the optimized irradiation orientation and location of the experimental site at which difference of incident angles depending on the latitude and the solar altitude is strongly concerned [21, 22]. Details of the concentrator design, dimension, and the materials constructing the system are described, with an emphasis on an aim to achieve the enhanced efficiency of hot water production. Relating the efficiency of the system to the microbes inhibition ability, a single flow direction of hot water and varied flow rates were setup and experimentally operated to investigate reduction of bacteria. The content of this work is concerned with how the ACPC operations combining with the bacteria inactivation are done and how the test data are presented in a combination way, reflecting the solar system treatment in water. The mathematical calculation has been applied to this work for an understanding of the factors that control the outlet temperature and subsequently the relating bacteria inactivation.

2. Materials and methods

2.1. Asymmetrical compound parabolic concentrator (ACPC) design and fabrication

The use of ACPC is to collect solar energy and then transfer heat to water. The ACPC unit is capable of bringing up the temperature in a certain period to guarantee that the how water could inhibit the bacteria. The constructed ACPC is demonstrated in figure 1(a). The frame base is made of steel to provide the structural strength and painted to prevent rust. The ACPC was designed to include two sizes, large and small, of parabolic solar reflector unit and absorber unit. Stainless steel was used as a reflective surface of the large solar reflector due to high radiation reflectance. Dimension of the large reflector and the small reflector are 1.6 × 1.2 m², and
The curve length of the large reflector is 1.35 m, and 0.6 m of the small reflector. The size of absorber is $1.6 \times 1.0 \text{ m}^2$.

Heat from the reflector and the absorber is transferred to water through the copper tube, with absorptance of 0.95 it was used as solar radiation receiver or absorber tubes [23]. In this study, the heating process is the use of copper tube that was positioned at the back side of the large reflector and underneath the absorber; see figure 1(b). No tubes were installed under the smaller reflector in this case. The copper tube was bent into a semicircle shape and aligned in a serpentine pattern at the back side of the large reflector and the absorber to

Figure 1. (a) Photo of asymmetrical compound parabolic concentrator unit. (b) Back side of the large parabolic reflector with the copper tubes attached with the serpentine arrangement. (c) Schematic drawing showing the major components of the designed ACPC. (d) Experimental setup.
absorb heat. The inner diameter of the copper tube is 8.11 mm and the outer diameter is 9.53 mm. There are 12 rows of the tubes aligned underneath the large reflector, and 8 rows put under the absorber. The length of the tubes under the large reflector is 1.5 m and 1.6 m for the absorber, while distance between the tubes was set constant at 0.1 m. The absorber, with its surface material made of zinc sheet, was sprayed coated with black color coating to enhance efficiency of the heating process. The top of the absorber was covered with a 5-mm thick glass sheet, 1.6 \times 1.0 \text{ m}^2 in size. The glass sheet was designed to place in a suitably minimum spacing of 15 cm over the copper tubes. Since usually convective heat losses from the top cover to the surrounding are significant, reducing the space between the cover and the absorber as possible can diminish such losses. Further, both sides sealed and the bottom of the absorber was insulated to prevent heat loss. The schematic diagram of ACPC after reducing the space between the cover and the absorber as possible can diminish such losses. Further, both sides

The direction of water in this study is a single flow direction through the curled copper tubes, starting from the storage tank (Tank I), the inlet set at the top of the large reflector flowing down level through the absorber and the outlet positioned at the end of the absorber; here water was collected in a container (Tank II). At the end of the reflector, the copper tube was hole punched for inserting a thermocouple to measure the temperature of water coming out of the reflector; this parameter is called herein the outlet water temperature from the large reflector \( T_{fo, p} \). While temperature of water at the end of the absorber is \( T_{fo, ab} \). Valves and the control devices were connected in series; see figure 1(d). The probe of type K thermocouple with capability of measuring the temperature range between 50 °C to 800 °C was connected to the solar water heating system. Rotameter was used to measure water flow rate in a range of 0.2–6 l min⁻¹.

2.2. Experimental setup and system operation

The experimental setup is shown in figure 1(d). The experiments were conducted in Bangkok, Thailand; thus \( \theta_c \) is 21°. \( \theta_r \) is the acceptance half-angle, which is to be mentioned in the section 2.3. The reactor was normally positioned in north–south axis; the large reflector was aligned to face the south direction thus the small reflector face the north direction. Solar radiation intensity was measured by pyranometer (KIPP&ZONEN, CM11, sensitivity 25.872 \times 10^{-6} \text{ V Wm}^{-2}) and recorded every 10 s. The temperature was recorded by the temperature recorder (Wisco’s Analog Input Module, model AL210). In the operation, temperatures at different positions of the ACPC were monitored: the temperature of water in the storage tank, Tank I \( (T_{s1}) \), the inlet water temperature from the parabolic large reflector \( (T_{in,p}) \), the outlet water temperature from the large reflector \( (T_{fo,p}) \), the outlet water temperature from the absorber unit \( (T_{fo,ab}) \), the ambient air temperature \( (T_a) \), and solar radiation intensity \( (I) \). \( T_{fo, ab} \) was measured at the exit end of the copper tube at the absorber.

There are two parts of experiments for data collection in this study. Part I is to investigate the heating of the collector during the day from the early morning low temperature at 8 a.m. to the final operating temperature in the afternoon at 16:00 p.m.; data collection has been done every one hour. Under a clear sky condition as normally solar intensity is high at noon time, in Part II data were collected every five minutes during a particular period between 12:00 p.m to 12:30 p.m., with a particular concern on the intermittent effects such as sunshine or rapid wind speed not to disturb the collector performance during the operation period.

The experiment was set for water to flow from the storage tank down through the serpentine copper tube installed underneath the large reflector (inlet), and the absorber (outlet). The data of water temperature at different positions of the ACPC system and intensity of sun radiation were collected every hour during the operation period. The efficiency of solar collector is influenced by the water flow rate parameter; the volume flow rates selected in this study were 0.2, 0.4, and 0.6 l min⁻¹ and controlled by the rotameter. Regarding the time frame of operation, suitability for the designed solar system, three flow rates were chosen to try to cover as optimal range as possible for this study in order to obtain a significant difference in the operation output, while keeping the solar irradiation intensity the same for all operation tests. There are a wide range of flow rate adopted and seen in literatures; e.g. usually 0.15–1.01 l min⁻¹ for laminar flow of wastewater [24], 0.18–3.4 l min⁻¹ in solar collector efficiency study [25], 0.04–2.7 l m⁻¹ in E. coli inhibition study [26, 27]. Total volume of water used in this study is 9 L. Water was taken from the tap water, boiled at 100 °C and let it cool down before filling in the storage tank (Tank I) for the measurement.

2.3. Mathematics and calculation

A mathematic model for flat-plate collector has been applied in this study with an aim to understand how the important variables relate and affect the performance of solar collector. In many practical cases, it could be seen that calculations and equations are modified or reduced to the relatively simple form by simplifying a number of assumptions involving the process; those are such as the sheet and tube are constructed in parallel, temperature gradients around the tubes are neglected, temperature gradients in the direction of water flow and between the tubes are considered independently, dust and dirt on the collector surface are negligible. The ACPC was
designed upon the basis of compound parabolic concentrator (CPC), with flat shape solar energy absorber. The key parameters to concern are shown in these following equations [1, 21, 24].

\[
H = \frac{a}{2} \left( \frac{1}{\tan \theta_c} + \frac{1}{\tan \theta_c \sin \theta_i} \right) \\
f = \frac{a}{2} \left( 1 + \sin \theta_i \right) \\
A_a = \frac{a}{\sin \theta_i}
\]

Where \( H \) is the height of ACPC, \( a \) is the flat area of solar energy absorber, \( \theta_c \) is the acceptance half-angle, \( f \) is the focus of parabola, and \( A_a \) is the aperture area of the parabola.

To determine the heat removal factor for the serpentine typed collector, the specifications needed are shown in table 1.

To study thermal performance of collector, the importance of flat-plate energy balance to concern is the distribution of incident solar energy into useful heat gain, thermal losses, and optical losses. As the energy is absorbed by the collector, the temperature of the collector becomes higher and higher than surroundings. The loss of energy from the collector to the surroundings can be in terms of convection and radiation. The convection heat transfer coefficient from the collector panel to surrounding \( (h_{ct}, \text{W m}^{-1} \text{K}^{-1}) \) is expressed by [1, 24]

\[
h_{ct} = 2.8 + 3 \nu
\]

Where \( \nu \) is average wind velocity \( (\text{m s}^{-1}) \). The radiation coefficient from the collector panel to surrounding \( (h_{rt}, \text{W m}^{-1} \text{K}^{-1}) \) is expressed by

\[
h_{rt} = \varepsilon_{\text{steel}} \sigma (T_{\text{steel}}^2 + T_{\text{sky}}^2) (T_{\text{steel}} + T_{\text{sky}})
\]

Where \( \varepsilon \) is plate emissivity, \( \sigma \) is a constant, \( T_{\text{steel}} \) is temperature of large reflector, and \( T_{\text{sky}} \) is sky temperature; \( T_{\text{sky}} = 0.0552 T_a^{0.5} \), when \( T_a \) is ambient temperature.

The collector overall heat loss coefficient (\( U_L \)) can be determined by this following equation [28].

\[
U_L = U_t + U_b
\]

\( U_t \) is the loss coefficient at the top, \( U_b \) is the loss coefficient at the bottom; \( U_b = 0 \). The convection heat transfer coefficient from the collector panel to surrounding \( h_{ct} \) and radiation coefficient from the collector panel to surrounding \( h_{rt} \) is the key parameters determining the loss coefficient at the top part of the collector (\( U_t \));

\[
U_t = h_{ct} + h_{rt}
\]

| Parameters                              | Values | Unit  |
|-----------------------------------------|--------|-------|
| Plate thickness (\( \delta \))         | 0.0006 | m     |
| Area of collector (\( A_c \))          | 1.6    | m\(^2\) |
| Area of aperture (\( A_a \))           | 3.52   | m\(^2\) |
| Outer diameter of copper tube (\( D_o \)) | 0.0093 | m   |
| Inner diameter of copper tube (\( D_i \)) | 0.0081 | m   |
| Serpentine tube length                  | 30.72  | m     |
| Tube spacing (\( w \))                 | 0.1    | m     |
| Water mass flow rate (\( m \))         | 0.0033 | kg s\(^{-1}\) |

| Collector specification                 |        |
|----------------------------------------|--------|
| Plate emissivity (\( \varepsilon \))  | 0.22   |
| Transmittance–absorption product (\( \tau \)) | 0.56   |
| Thermal conductivity (\( k_t \))      | 15.1   | W m\(^{-1}\) K\(^{-1}\) |
| Stefan–Boltzmann constant (\( \sigma \)) | 5.67 \( \times \) 10\(^{-8}\) | W m\(^{-2}\) K\(^{-4}\) |
| Thermal conductivity of copper tube (\( k_t \)) | 385     | W m\(^{-1}\) K\(^{-1}\) |
| Solar radiation intensity (\( I_l \))  | 632\(^a\) | W m\(^{-2}\) |
| Temperature of the stainless steel sheet (\( T_s \)) | 56.13\(^a\) | °C |
| Ambient air temperature (\( T_a \))   | 34\(^a\) | °C |

\(^a\) The example values measured at 10:00 a.m.
The useful heat gain in water or the energy extracted by the collector ($Q_{w,o}$) is thermal energy that water removes from the collector. This parameter is assumed to be considered under steady state condition, which is proportional to the useful heat absorbed by collector, nonetheless believed to be lesser amount lost by the collector to the surroundings [28].

$$Q_{w,o} = mC_{pw}(T_o - T_i) \quad (7)$$

The net useful heat gain ($Q_{u,\text{net}}$) is determined by

$$Q_{u,\text{net}} = Q_u - Q_{w,o} \quad (8)$$

Where $Q_u$ is actual useful heat gain, dependent upon the collector heat removal factor ($F_R$) multiplying the maximum possible useful heat gain in the collector, occurring when the temperature of whole collector is at the inlet temperature and heat losses to the surroundings are at a minimum. Equation (9) to determine $Q_u$, known as the Hottel-Whillier-Bliss equation, is the generalized form of relationship developed for the basic design configuration of collector sheet and tube [29]. The equation for $Q_u$ has been employed in many design and applications of parabolic collector [30].

$$Q_u = A_dF_R \left[ L(\tau\alpha) - U_l \frac{A_d}{A_r} (T_f - T_a) \right] \quad (9)$$

Where $\tau$ is transmission coefficient, $\alpha$ is absorption coefficient.

$$F_R = F_1F_2F_3 \left\{ \frac{2F_3}{F_6 \exp\left[\frac{-(1 - F_2)^{1/2}}{F_3} + F_5 \right]} + 1 \right\} \quad (10)$$

$$F_1 = \frac{K}{U_lW} \left[ \frac{KR(1 + \gamma)^2 - 1 - \gamma - KR}{(KR(1 + \gamma) + 1)^2 - (KR)^2} \right] \quad (11)$$

$$F_2 = \frac{1}{KR(1 + \gamma)^2 - 1 - \gamma - KR} \quad (12)$$

$$F_3 = \frac{mC_p}{F_1U_lA_c} \quad (13)$$

$$F_4 = \frac{1}{F_2} \quad (14)$$

$$F_5 = \frac{1}{F_2} + F_4 - 1 \quad (15)$$

$$F_6 = 1 - \frac{1}{F_2} + F_4 \quad (16)$$

The quantity of $F_R$ in a simplified form is defined as follows [28].

$$F_R = \frac{mC_{pw}(T_o - T_i)}{A[I\tau\alpha - U_l(T_f - T_a)]} \quad (17)$$

The collector heat removal factor $F_R$ is a dimensionless quantity relating the actual useful heat gain of the collector to the useful gain if the temperature of whole collector surface were at the fluid inlet temperature. For the design of a sheet and tube solar water heater with the tubes attached on the back of the solar plate in parallel position, an appropriate form of the collector efficiency factor needed to be derived, with its effect to reduce the useful heat gain from to the actual one that had the whole collector been at the inlet fluid temperature.

The net useful heat gain is further taken to calculate the outlet water temperature from the collector ($T_{fo}$), the increase in temperature of fluid at the exit.

$$T_{fo} = \frac{Q_{u,\text{net}}}{mC_{pw}} + T_f \quad (18)$$

Where $C_{pw}$ is specific heat capacity of water, $T_f$ is inlet water temperature.

Understanding the temperature distribution, some of the solar energy absorbed by the solar plate is conducted along the plate to the region of the tubes; the temperature midway between the tubes will be higher than the temperature in the vicinity of the tubes [28]. The thermal energy transferred to fluid will heat the fluid, causing fluid to increase its temperature. The heat transfer coefficient ($h_f$) can be determined by this equation;

$$h_f = \frac{1.86Re^{1/3}Pr^{1/3}}{m} \left( \frac{D_t}{T} \right)^{1/3} \left( \frac{m}{\mu_c} \right)^{0.14} k_f \quad (19)$$
Where Re is Reynold number, Pr is Prandtl number, $D_{hi}$ is hydraulic inner diameter, L is length of the tube, $\mu$ is dynamic viscosity of inlet water, $\mu_{fi}$ is absolute viscosity of water, $k_f$ is thermal conductivity of fluid. For laminar flow; $Re < 2300$ and $290 \text{ K} < T_f < 340 \text{ K}$ when $T_f$ is fluid temperature inside the tube. $Re$, $Pr$, $D_{hi}$, $\mu$, and $k_f$ can be calculated as follows.

$$Re = \frac{4m}{\pi D_{hi} \mu}$$

(20)

$$Pr = 0.0022T_f^2 - 1.4762T_f + 250.74$$

(21)

$$D_{hi} = 4 \left[ \frac{\left( \pi D^2 \right)}{\left( D + \frac{\pi D}{2} \right)} \right]$$

(22)

$$\mu = 0.3566e^{-0.02T_f}$$

(23)

$$k_f = 0.47061 \ln T_f - 2.0745$$

(24)

The thermal conductivity ($K; \text{ W m}^{-1} \text{ K}^{-1}$) between the plate and the tube is calculated by this equation.

$$K = \frac{(k_f D_{hi} U_f)^{1/2}}{\sin \left( \frac{W - D_{hi}}{h_{fi}} \right)^{1/2}}$$

(25)

Thermal resistance ($R$) is calculated by this expression.

$$R = \frac{1}{C_b} + \frac{1}{\pi D_{hi} h_{fi}}$$

(26)

Bond conductance ($C_b$) was assumed to be $\infty$ for simplification.

The instantaneous thermal efficiency ($\eta$) of the solar collector is a ratio of the useful heat gain to the incident solar energy [28].

$$\eta = \frac{Q_{useful}}{I_f A_c} \times 100$$

(27)

2.4. Test for $E. coli$ inactivation and cell measurement

*Escherichia coli* (ATCC® 25922™, Thailand Institute of Scientific and Technological Research) was conducted to this study, cultured in Nutrient Broth (NB) for 24 h and stored in refrigerator at 4 °C. The initial bacteria concentration was prepared at $2 \times 10^6$ colony-forming units per ml, (CFU)/ml. at each running flow rate, 25 ml water sample was collected every 10 min at the exit of the absorber unit, or at Tank II. The water samples were subject to the $E. coli$ measurement for counting the numbers of living cells. The count of cultivable cells was determined by a standard plate count method. One ml of the water sample was taken and subject to dilution using sterile water. The water samples were incubated with eosin methylene blue (EMB) Agar (Levine) about 35 °C–37 °C for 18–24 h in which the cells were cultivated and suspended in appropriate dilution. After incubation, the count of total colonies of $E. coli$ that show metallic green sheen color was measured. The number of $E. coli$ as colony forming unit per ml was calculated by multiplying the number of colonies with 10 and a dilution factor. The reduction of $E. coli$ was calculated by means of % reduction = (a-b) × 100/a; where a is number of viable cell (CFU ml$^{-1}$) in the control and b is number of viable cell (CFU/ml) in the sample.

3. Results and discussion

3.1. Heating ability of ACPC as a function of water flow rate

Part I is the focus on studying the ACPC ability to produce hot water with single flow system during the operation process from 8:00 a.m. to 4:00 p.m. Water is heated by the energy transferred from the tube to water, causing the increase in temperature along the direction of the flow. The outlet water temperatures from the large parabola sheet and from the absorber were measured in comparison to the inlet water temperature. The water temperatures, both inlet and outlet, and solar radiation were plotted as a function of operation time are shown in figures 2(a)–(c) at water flow rates of 0.2, 0.4, and 0.6 l min$^{-1}$, respectively. The inlet temperature was about 31 to 38 °C.

The ACPC has shown its performance on heating water as seen from those outlet water temperatures lying in the higher region compared to the inlet water temperature. The temperature kept increasing with the operation time and reached the maximum around noon, then continually dropped down until the end of the experiment. At noon time, solar radiation intensities measured for all conditions are less than 900 W m$^{-2}$. The hourly variation of ambient temperature is seen over the operating period. For all water flow rates, the similar pattern of water temperatures and solar radiation can be observed. The solar collector experiences daily variations in light...
intensity, with the incident power from the sun varying across the day from 250–950 W m$^{-2}$. Thus, the result obtained each day is based on the large temperature variation from case to case and directly affected the heating performance of collector and hence the outlet temperatures to be fluctuated. Additionally, airflow rate and weather conditions are the main factors affecting the collector performance. In this work, a number of experiments were operated for different flow rates under the similar working conditions as possible in order to minimize the fluctuation due to the varied conditions. The high radiation intensity in the clear sky, sunny day was found to enhance the solar collector performance and its heating ability. Aiming to report on the collector operation with highest performance achieved, the maximum outlet water temperatures from the absorber measured for the 0.2, 0.4, and 0.6 l min$^{-1}$ are 76.4$^\circ$C (@12:00 p.m., 867 W m$^{-2}$), 64.2$^\circ$C (@13:00 p.m., 862 W m$^{-2}$), and 55.4$^\circ$C (@12:00 p.m., 892 W m$^{-2}$). Relatively higher water temperatures could be obtained when operating at relatively lower water flow rate. To this point of view, the developed field-test scaled ACPC has shown its satisfactory result in producing hot water up to 76.4$^\circ$C in 4 h comparing to the previous works in soil treatment application using hot water from the up-scaled ACPC to inhibit the growth of *Ralstonia solanacearum*; that is, 41.25$^\circ$C in 4 h [20] and recently even greater than 70$^\circ$C in 2 h, but for the system including ACPC + CPC + FPSC [19].

Figure 2. Plots of solar radiation intensity ($I$, $\square$), inlet water temperature ($T_{in}$, $\square$), outlet water temperature from large parabolic reflector ($T_{fo, p}$, $\triangle$), and outlet water temperature from absorber ($T_{fo, ab}$), measured from 8 a.m. – 16 p.m. for the flow rates of (a) 0.2 l min$^{-1}$ ($\bigcirc$), (b) 0.41 l min$^{-1}$ ($\triangle$), and (c) 0.61 in min$^{-1}$ ($\bigcirc$).
The outlet water temperatures, both from the parabola sheet and from the absorber, lie in the higher range than the inlet water temperatures over the 8 hour-operation period. The outlet water temperatures from the absorber are obviously higher than the temperatures measured from the parabola sheet. The absorber unit received water from the reflector, combining with the great ability to absorb heat of the absorber surface, hot water passing through the reflector absorbed more heat from the absorber unit leading to such increased temperatures of water. For all flow rate conditions, the graphs in figure 2 show that $T_{fo}$ increased gradually with time, similar tendency to the temperatures in the storage tank that also increased during the operation period.

The study of heating rate of the designed ACPC was evaluated by means of the slopes of heating temperature and time. The overlay plots of $T_{fo,ab}$ are shown in figure 3 and the slopes determined are in table 2. For the first operating period from 8 a.m.–12 p.m., the highest rate of increase in temperature is 8.32 °C h$^{-1}$ from using the lowest flow rate of 0.2 l min$^{-1}$. While from time 13:00–16:00, the slope of all flow rates was found in the nearly range. When temperature drop during the afternoon time, the decline kinetics for the rates of 0.2 and 0.4 l min$^{-1}$ are about the same.

In Part II, the ACPC was tested at its high temperature operation; data were collected every five minutes, more frequently than Part I during a specific period from 12:00 p.m. to 12:30 p.m. This part was set to investigate the effectiveness of the collector and develop an understanding on how the particular component functions when the operation of collector was presumed to perform at the steady-state high temperature level condition. The plots of outlet water temperatures $T_{fo}$ from the parabolic reflector $T_{fo,p}$ and the absorber $T_{fo,ab}$ and solar radiation intensity I as a function of time are demonstrated in figure 4. These data were further taken to determine the average values (shown in table 3) and then plotted as a function of flow rate; see figure 5.

At high temperature operation, the collector with slow flow rate is capable of producing hot water with the temperature up to the maximum average 76.4 °C. The percentage increase in temperature for $T_{fo,ab}$ comparing to $T_{fo,p}$ is 69.40%, 49.27%, and 37.03%, for the flow rates of 0.2, 0.4, and 0.6 l min$^{-1}$, respectively. This indicates that the absorber has shown its pronounced ability in transferring heat and subsequently producing hot water after receiving water from the reflector. The inlet driven temperature for the absorber part is in the range of 40 to 43 °C. The temperature rise increased by reducing the water flow rate for a given collector as the operation

![Figure 3. Overlay plots of the outlet water temperatures from absorber ($T_{fo,ab}$), measured from 8 a.m.–16 p.m. using different flow rate conditions, with lines indicating different kinetic behavior relating heating performance of the collector for the periods of before and after noon time.](image-url)

| Slope obtained from the plots in figure 3 determined as a function of flow rate. | Slope (°C h$^{-1}$) |
|---|---|
| Flow rate (l min$^{-1}$) | Hour 8:00–12:00 | Hour 13:00–16:00 |
| 0.2 | +8.32 | −4.80 |
| 0.4 | +6.37 | −4.81 |
| 0.6 | +5.07 | −3.32 |
parameter plays its typical role in controlling the outlet temperature. Increasing the flow rate by the factor of two, difference of water temperature rising through the collector ($\Delta T_{fo, ab}$) reduces from 14.9°C between 0.2–0.4 l min$^{-1}$ to 7.1°C between 0.4–0.6 l min$^{-1}$. This temperature rise by the reduced flow rate will reflect the reduced useful heat gain $Q_{u}$, to be mentioned in the section 3.2. It could be ascribed from this view point that water flow rate is the predominant factor controlling the heating performance of the collector and consequently the outlet
temperature. The thermal efficiency of the collector operating at different flow rates was examined and showed in the section 3.2.

3.2. Mathematic calculation and thermal performance parameters study
Measuring the fluid inlet and outlet temperatures and the fluid flow rate is the basic method of measuring the collector performance, when this difference in temperature is accounted for by the collector efficiency factor. The data obtained in the section 3.1 were subsequently used as the input parameters in the mathematic calculation for the performance parameters study; the results obtained are shown in figures 6(a)–(e).

For a given flow rate of water passing through the tubes, the temperature rise from the inlet to the outlet normally decreases, and decreases toward zero on further increasing the flow rate or when the flow rate becoming very large. This phenomenon typically occurs even when the absorbing surface temperature is still higher than the water temperature. As the mass flow rate of fluid passing through the tubes increases, the temperature rise through the whole collector decreases. Since the average temperature of the collector becomes lower, then this causes the lower losses and the corresponding increase in the useful heat gain $Q_{u,o}$. This increase is reflected by the increase in $F_R$ when the flow rate increases. With these relationships, the result obtained in figure 6(a) has indicated good agreement regarding the equation (17). It could be understandable from the equation (8) for the net useful heat gain $Q_{u,net}$, the maximum $Q_{u,net}$ could be obtained by a reduction of useful gain $Q_{u,o}$ to a minimum, which can be done by bringing the collector temperature to its initial operating temperature; hereby $(T_o-T_i)$ becoming a minimum.

The variation tendency in useful heat gain seems to follow the variation path of solar intensity. The useful heat gain was found to be affected by the design of the absorber and the number of twist that intensifies the swirling and turbulence; as a consequences, with this combination effect, heat transfer time and the rate of heat transfer from the absorber tube to the circulating water tend to increase [23]. $Q_{u}$ is a relationship widely used to measure the collector heat gain and known depending upon the collector heat removal factor $F_R$. Regarding the equation (9), the actual heat gain $Q_{u}$ has been determined in figure 6(b). For a given collector and flow rate, if $\tau$, $\alpha$, $U_L$, and $F_R$ are assumed constant, the collector efficiency is to be in a linear relation to solar radiation $I$, inlet water temperature $T_{i,o}$, and ambient temperature $T_a$. Obtained from the calculation in this study, $F_R$ and $U_L$, in figures 6(a) and (c), were found to vary during the test experiment; thereby presumably the collector efficiency might not be measured directly and accounted for by this assumption. Particularly considering figure 6(c), the collector overall heat loss coefficient $U_L$ of all flow rates appears to fluctuate in the range of 6−15, but seems in a constant pattern over the operation period. One typically concerned in practice possibly applying to such illustration is that; $U_L$ is not constant because heat losses increase as the collector temperature increases above the ambient temperature [28]. Another view of the useful heat gain equation to predict the storage tank
Figure 6. Values obtained from the calculation plotted as a function of time, including (a) $F_R$, (b) $Q_w$, (c) $U_L$, (d) $K$, and (e) $h_f$, with the overlays demonstrated for different flow rates.
temperature in each season, it could be done by putting the known average temperature data, for example the year-round weather data, and the parameters of effective absorptance $\tau_a$ and the overall heat loss coefficient $U_L$, in equation (9) [31].

Taking into account a design configuration of the collector affecting the heat removal factor, type and number of tube bend in the collector are necessary to concern in the calculation. Considering equation (13), for a single bend type, if the group $n_1 \cdot C_p / F_1 \cdot U_1 \cdot A_c$, or $F_3$, is greater than about 1.0, equation of $F_R$ is valid for any number of bends. For smaller values of $F_3$, this concept cannot provide to this case [28]. The result of $F_3$ values, not shown here, measured from time 8:00 to 16:00 were found constant approximately 0.5, 1.4, and 1.6, respectively for each flow rate of 0.2, 0.4, and 0.6 l min$^{-1}$. Applying such defined condition to this study, one may assume for a given flow rate of 0.21 min$^{-1}$ that the equation to determine $F_R$ could not apply suitably to this low flow rate condition. This is because the number of bends might probably become a predominant factor contributing its effect on the collector heat removal factor $F_R$. Thus as a consequence, the curve of calculated $Q_a$ for the flow rate of 0.21 min$^{-1}$ in figure 6(b) might be considered not the well representation of its actual useful heat gain over this operating conditions. In addition, the relatively low flow rate could somehow lead to the reduced $T_4$ of the remaining water in the storage tank, hence possibly reflecting the increased $Q_a$ (in equation (9)); see $Q_a$ of 0.41 l min$^{-1}$ comparing to those of 0.61 l min$^{-1}$ during time 13:00–16:00. The average instantaneous thermal efficiency was also examined for the collector operating at the steady-state high temperature level condition; 38.45 ± 0.30 for 0.21 min$^{-1}$, 53.09 ± 2.91 for 0.41 min$^{-1}$, and 58.33 ± 2.90 for 0.61 l min$^{-1}$. The low efficiency of the lower flow rate condition indicates the smaller useful heat gain in the collector for a given incident solar energy.

Thermal conductivity $K$ of the collector was also investigated in this work. Over the test period from time 8:00 to 16:00, $K$ values by means of thermal conductivity between the plate and the tube were examined by equation (25) and plotted against flow rate; see figure 6(d). The less fluctuation of $K$ in the approximate range of 0.09–0.1 W mK$^{-1}$ was observed for the low flow rate condition of 0.21 min$^{-1}$. This observation is attributed to an influencing effect of $U_1$ reflecting such fluctuation seen for the low flow rate, as $K$ is a function of $U_1$ as shown in equation (25). $K$ of the collector constructed materials, basically varying with temperature, is directly influenced by the component parameters including the material dimension and configuration such as plate thickness, tube diameter and tube spacing, and the overall heat loss coefficient $U_L$.

Exhibited in figure 6(e), the heat transfer coefficient $h$, calculated by using equation (19) was found to be constant over the whole operating period for each flow rate, seen for the $h_0$ of larger flow rates lying in the higher region. Flow rate has a significant effect on the heat transfer parameter. For a given flow rate, $h_0$ depends on the predominant factors of $Re$, $Pr$, tube diameter $D_{hi}$ and length $L$. As shown in equation (20), $Re$ is directly proportional to the mass flow rate of fluid passing through the collector $(\dot{m})$; the low flow rate, the small $Re$ is obtained. The result obtained in figure 6(e) appears to indicate well agreement to those relationships described above.

3.3. Effect of temperature and flow rate on E. coli inactivation

Effect of temperature of hot water, produced from the single-flow ACPC operating at the steady-state high temperature level condition, on inhibiting E. coli has been investigated. Figure 7 shows the overlay plots of total number of E. coli living cells against time measured for different flow rate conditions. As seen the accelerating inactivation rate in the first 10-minute operation period, the dramatically decrease in the number of E. coli is seen for the flow rate of 0.21 min$^{-1}$, clearly confirming that hot water with temperature above 70 °C could inhibit the microbes effectively, agreeing well with those previous mentions [19, 21]. While for the higher flow rates of 0.4 and 0.6 l min$^{-1}$, the bacterial inactivation kinetic was found to reduce in that order, with the temperatures approximately 62 °Cand 54 °C regarding the result in table 3, considered efficient to reflect 77% and 40% of E. coli reduction in ten minutes. Solar disinfection was found to be effective at water temperatures above 45 °C under strong sunshine condition at which the strong synergy between optical and thermal inactivation processes is observed [32, 33]. For the latter 20 min in figure 7, the number of living cells was considered to remain unchanged; only for the 0.6 l min$^{-1}$ flow rate a slight increase was observed after 10 min. This is presumably because of the pasteurizing effect involved but not adequate for coliform bacterial deactivation under this single-flow through system. The pasteurizing effect was found strongly effective when continuously maintaining water temperature in the range of 60 °C to 70 °C for more than one hour [34]. In addition, sunlight is an important factor controlling bacteria inactivation in terms of penetration level of light into water [35]. A design of the process and collecting tank having high light penetration depth may be put into perspective for the enhanced effectiveness in bacteria inactivation. In addition, due to climate change or seasons with low solar radiation intensities, survival of bacteria could possibly increase at low light levels [36].
4. Conclusions

This work presented a detailed design of field-test scaled asymmetrical compound parabolic concentrator, fabricated to produce hot water. With a single flow system focused in this study, the experiments were conducted under solar radiation for eight hours during the day time from local time 8:00–16:00. The heating performance of the solar collector in terms of thermal heating kinetics was evaluated by means of the increase temperature per time. The inlet temperature of water was in the range of 33 to 38 °C. We highlighted the maximum temperature for the designed ACPC is up to a satisfactory level of 76.4 °C obtained using the lowest flow rate of 0.2 l min\(^{-1}\), with this flow rate condition resulting in the fastest heating rate for the operating time before noon. Further investigation of the produced hot water affecting the \(E.\ coli\) inactivation was carried out. The result revealed the efficiency of hot water that the temperatures from 62 °C–74 °C could drastically inhibit the number of \(E.\ coli\) by over 77% microbe reduction in ten minutes at the particular operating time around noon. Resulted from this work, it is anticipated to provide some interesting viewpoints of manipulating and up-scaling process and further appropriate method for bacterial inhibition in contaminated water treatment application. Applying the mathematic calculation into this work, the thermal performance parameters including \(F_P, Q_\omega, U_L, K,\) and \(h_f\) was found to indicate a satisfactory agreement to the relationship of the collector design and property parameters and the operating conditions. Flow rate and inlet driving temperature were believed to play a significant role determining the outlet temperature of the collector.

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