A Importância da Energia Solar para o Desenvolvimento Sustentável

Jaqueline Oliveira Rezende
(Organizadora)

Atena Editora
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APRESENTAÇÃO

A matéria-prima para a geração de energia elétrica, no cenário mundial, ainda é constituída predominantemente pelos combustíveis fósseis, os quais são compostos pelo gás natural, carvão mineral e petróleo. Segundo a Agência Internacional de Energia, em 2016, esses combustíveis foram responsáveis por 65,1% da matriz energética mundial. O emprego desses é notoriamente preocupante, pois são fontes finitas e causam elevados impactos ambientais, como a chuva ácida e a destruição da camada de ozônio, devido liberarem para a atmosfera gás carbônico durante seu processo de queima.

Dessa forma, a energia solar apresenta como principais características a utilização de uma matéria-prima inesgotável, o sol, e não causa impactos ao meio ambiente durante a conversão da energia solar em energia elétrica. Portanto, sendo o desenvolvimento sustentável caracterizado pela utilização dos recursos naturais necessários para o desenvolvimento de diversos setores, como o social, energético e econômico, sem comprometer esses recursos para atender as próximas gerações, a energia solar tem se consolidado como uma fonte de energia alternativa e renovável que contribuí para atender a demanda de eletricidade de modo sustentável.

Nesse contexto, esse *e-book* apresenta artigos que discorrem sobre as principais características da energia solar, destacando suas vantagens e desvantagens, aplicações e desenvolvimento dessa tecnologia no Brasil. Também são descritos estudos sobre a implementação de um sistema de geração de energia solar fotovoltaica e análise de um sistema em operação.

Em seguida, esse exemplar contempla estudos sobre a influência da associação de módulos fotovoltaicos e o sombreamento sobre esses sistemas, é apresentado uma pesquisa sobre um sistema fotovoltaico hibrido e são discutidos os fundamentos e validação de um sistema arrefecedor para usinas fotovoltaicas.

Além disso, são apresentados trabalhos que relatam as características da sujidade acumulada sobre módulos fotovoltaicos, o desenvolvimento de um *software* para projeto e simulação de sistemas solares e a geração de dados de irradiação solar nas condições brasileiras, imprescindíveis nos estudos sobre energia solar fotovoltaica.

Jaqueline Oliveira Rezende

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RESUMO: A análise 2E (energia e exergia) e a metodologia de projeto para um concentrador solar do tipo CPC (Compound Parabolic Collector) sem imagem óptica que, usando apenas radiação solar, alcança um tratamento terciário em águas residuais contendo resíduos orgânicos provenientes de biodigestores anaeróbios. Para o seu projeto, modelos existentes baseados em geometria analítica e cálculo vetorial foram usados para calcular a superfície refletiva. O projeto do sistema de tratamento de água consiste, como nos fornos solares Tolokatsin originais, em um CPC otimizado e truncado com um receptor circular para maximizar o tempo de operação, a irradiância concentrada e otimizar o uso de materiais. Para determinar o desempenho térmico 2E do sistema de tratamento de água, foram calculados os fluxos de calor no sistema, com modelos relevantes, considerando a cidade de Toluca, no México, como referência para as condições de irradiância. O trabalho exposto compreende apenas um elemento de um sistema híbrido do trem de tratamento de resíduos que permite reciclar todo o lixo, o que torna-se um recurso valioso e utilizável.

PALABRAS-CHAVE: Tolokatsin, CPC, tratamento de águas residuais, energia, exergia

2E ANALYSIS OF A SOLAR SYSTEM FOR WATER TREATMENT USING ANIDOLIC OPTICS

ABSTRACT: The 2E analysis (energy and exergy) and the design methodology for a non-imaging optics CPC-type (Compound Parabolic Collector) solar concentrator that, using only solar radiation, achieves a tertiary treatment in waste water containing organic waste coming from an anaerobic biodigester. For its design, existing models based on analytical geometry and vector calculation were used to calculate the reflective surface. The design of the water treatment system consists, as in the original Tolokatsin solar ovens, in an optimally truncated CPC with a circular receiver to maximize the operating time, the concentrated irradiance and optimize the use of materials. To determine the thermal performance 2E of the water treatment system, heat flows in the system were calculated, with relevant models, considering the city of Toluca, Mexico, as a reference for the irradiance conditions. The exposed work comprises only one element of a hybrid system

of the waste treatment train that allows to recycle all the waste, which then becomes a valuable and usable resource.

KEYWORDS: Tolokatsin, CPC, waste water treatment, energy, exergy

1 I INTRODUCTION

The anidolic optics - or nonimaging optics - arises in the middle of 1960 as a result of the developments carried out independently by Baranov in the USSR, Ploke in Germany and Winston in the USA, with the development of the compound parabolic concentrator (CPC) (GONZÁLEZ-MORA; RINCÓN-MEJÍA, 2018; TAPIA S.; DEL RÍO P., 2009).

Compound parabolic collectors (CPCs) are made up of mirrors designed to redistribute solar radiation, both diffuse and direct, in a localized area. The geometry of the concentrator depends on several parameters in order to increase the use of radiation (WINSTON; MIÑANO; BENÍTEZ, 2005). Initially, CPCs were devised for applications detecting Cherenkov radiation in high-energy physics; However, due to its characteristics, its use has been extended to different sectors, such as solar concentration for wastewater treatment.

From the technical and economic point of view, it is plausible to think about thermo-photochemical processes for the elimination of different persistent residues such as antibiotics and bacteria with devices that use only concentrated solar energy. This statement is the result of old experiences in the field of research in which some photochemical prototypes focused on the treatment of wastewater have been successfully developed (ALMAZÁN-SÁNCHEZ et al., 2017; COLLARES-PEREIRA, 2005; TSYDENOVA; BATOEV; BATOEVA, 2015)the UV radiation source was the sunlight collected by a compound parabolic concentrator (CPC-2D, as well as in the theoretical analysis of a novel geometry to achieve similar results (GONZÁLEZ-MORA, 2017), also because the specific process to eliminate this type of waste requires a temperature higher than , with a variable power of depending on the exposure time (RAM; ANDREESCU; DING, 2011; TCHOBANOGLOUS, G., BURTON, F.L., STENSEL, 2003); thus, it is attractive to think of a hybrid system that allows producing energy and with a low environmental impact, minimizing the waste generated (ISLAS-ESPINOZA; DE LAS HERAS, 2018).

However, to propose a functional prototype, it is necessary to make a proposal validated by theoretical models in order to ensure the thermal conditions that allow effective treatment of wastewater, so that its coupling to a hybrid system can be beneficial and operational.

2 I CONCENTRATOR DESIGN: OPTOGEOMETRIC DESCRIPTION

The main objective of anidolic optics is the transfer of radiation in an efficient and controlled manner, so this type of optics is used for the design of concentrators and illuminators where image formation is not strictly necessary, although it cannot be discarded, and where Aberrations are not strictly aberrations since image formation is not prioritized. Instead of having an object, you have a light source and instead of an image you have a receiver where an irradiance map from the source will be produced. There are two fundamental aspects in the design of concentrators for the solar area, one is to maximize the transfer of flow and the other is to create controlled distributions of the irradiance (FERNÁNDEZ-BALBUENA, 2011).

The most important parameter of a solar concentrator is the concentration coefficient, which allows directly relating the amount of energy that will be redirected to the receiver. Considering Fig. 1, which shows a generic solar concentrator that allows to collect the flow of solar energy over an area of capture or opening () concentrating it in another surface of smaller size, called receiver or exit (); the geometric concentration coefficient is defined in eq. (1); where defines the acceptance half-angle, within which the light is captured in the opening area and redirected to the receiver. The radiation is said to be accepted through an acceptance angle because the incident radiation within this angle reaches the receiver after passing through the opening area. The acceptance angles in practice range from the minimum of the solar disc subtension (around) to (DUFFIE; BECKMAN, 2013; KALOGIROU, 2014).

$$C_g = \frac{A}{A'} = \frac{1}{\sin\theta_0} \qquad (1)$$

According to the Second Law of Thermodynamics and the Stefan-Boltzmann Law (or through the concept of etendué conservation), the maximum ideal concentration of a solar concentrator can be determined with ease. The maximum value that can reach a solar concentrator is of the order of using only curved mirrors (GONZÁLEZ-MORA; RINCÓN-MEJÍA, 2018). Although the geometric concentration coefficient () for CPCs theoretically reaches the maximum thermodynamic limit, CPCs are designed for low concentration applications having values between with different temperature ranges in the receiver (KALOGIROU, 2007).

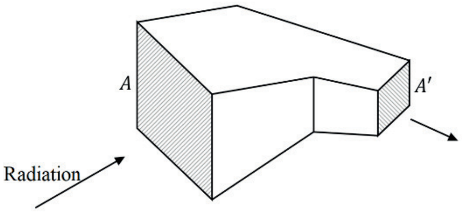


Fig. 1. Schematic diagram of a concentrator. Adapted from (WINSTON; MIÑANO; BENÍTEZ, 2005).

Very ideally, considering only radiation as a transport phenomenon, the temperature that can be reached with a solar concentrator can be related to the concentration of the device through (GONZÁLEZ-MORA; RINCÓN-MEJÍA, 2018):

$$T_r \propto \left(\frac{C_g}{C_{g,max}}\right)^{1/4} \qquad (2)$$

Within the entire available geometries of solar concentrators, the design of a symmetrical compound parabolic concentrator (CPC) with a circular section receiver was chosen, in order to be able to easily handle the residual water.

Regardless of the type of receiver that the CPC may have, the rays that enter the concentrator with a maximum acceptance semi-angle (extreme rays) must be reflected by the mirror so that they tangentially reaches the receiver; while all the rays that enter with an angle less than the maximum semi-angle (i.e. inside the total angular acceptance angle), are directed to the receiver after passing through the internal optics of the CPC (reflection or refraction) The description for a CPC with cylindrical receiver, is obtained for the coordinate axes , whose reflecting surface is generated considering the characteristic that every ray entering inside the angular acceptance angle is intercepted by the receiver; but, if the rays of light enter parallel to the focal axis, at any point where a ray of light strikes, the normal to the reflector bisects the incoming angle between the tangent and the receiver passing through , and the incident ray (GONZÁLEZ-MORA; RINCÓN-MEJÍA, 2018).

Taking into consideration the above, the geometry of the mirrors for the CPC with circular receiver of radius are formed by two symmetrical curves, as shown in the Fig. 2. The first curve (and) is called involute whose parametric equations are described in (3), while the second curve (and) corresponds to a curve called antiaustics or macrofocal parabola (CHAVES, 2017) with parametric equations (4).

$$ED:\begin{cases} x(t) = a(\sin t - t\cos t) \\ y(t) = -a(\cos t + t\sin t) \end{cases}; \quad 0 \leq t \leq \frac{\pi}{2} + \theta_0 \tag{3}$$

$$DF:\begin{cases} x(t) = a\left[\dfrac{\sin\theta_0\cos(t-\theta_0) - \left(\frac{\pi}{2} + t + \theta_0\right)\cos t}{1+\sin(t-\theta_0)} + \cos\theta_0\right] \\ y(t) = -a\left[\dfrac{\cos\theta_0\cos(t-\theta_0) + \left(\frac{\pi}{2} + t + \theta_0\right)\sin t}{1+\sin(t-\theta_0)} - \sin\theta_0\right] \end{cases}; \frac{\pi}{2} + \theta_0 \leq t \leq \frac{3\pi}{2} - \theta_0 \tag{4}$$

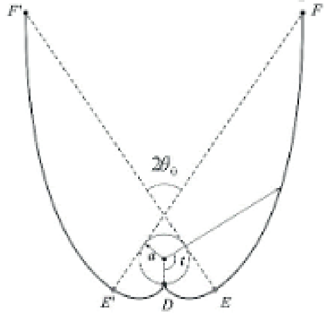


Fig. 2. Geometry for the CPC with circular receiver (GONZÁLEZ-MORA; RINCÓN-MEJÍA, 2018).

However, in practice it is common to truncate the height of the CPC to an established angle in order to save material. At present, there are several criteria and methodologies to truncate the CPC-2D; several authors, based on the works described by Winston and Rabl in the 1970s, state that truncating the height of the CPC will not have a great impact on the opening of the entrance (the curve that should be truncated will be the antiaustic). Thus, truncating the CPC, a considerable decrease in the height of the CPC can be achieved with very little reduction in the concentration factor, which has a favourable effect on the economy and manufacture of the same, since the amount of mirror to be used is reduced (NILSSON, 2005).

Within the various truncation criteria is the Rincón criterion, which establishes that the CPC-2D must be truncated in such a way that none of the rays parallel to the angle of incidence that are directed towards the receiver are blocked by the mirrors of the CPC-2D, which results in an optimized anidic optical concentrator (RINCÓN MEJÍA; DURÁN GARCÍA; LENTZ HERRERA, 2009).

Given that, for the application to be developed, a temperature lower than is desired, which is the main limiting factor, with the aim of achieving the elimination of persistent waste in water, with eq. (2) we can obtain a approximate concentration coefficient for the concentrator; However, this equation only models a phenomenon purely governed by radiation, so the geometric concentration must be greater than that obtained directly, this with the purpose that, when considering losses by thermal and optical, the conditions are met of design without major problem.

Thus, a geometric concentration of is considered for an optimally truncated CPC, so that global losses are not a limitation to achieve the elimination of waste. When applying the Rincón's criterion, we have the equations for the CPC, which can be seen graphically in Fig. 3; while in eq. (5) and eq. (6) the parametric equations that describe the curve are shown.

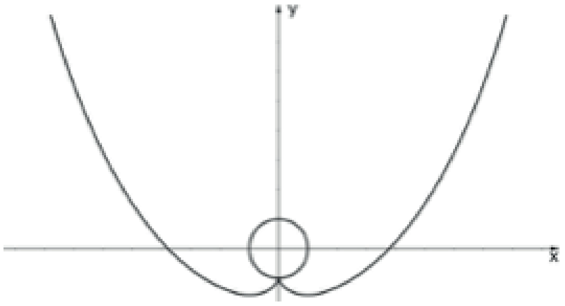


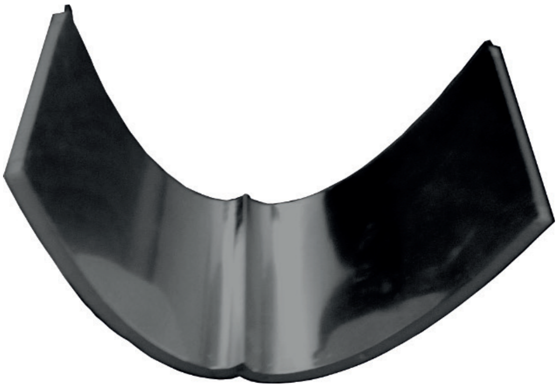
Fig. 2. Geometry for the designed CPC(GONZÁLEZ-MORA; RINCÓN-MEJÍA, 2018).

$$\begin{cases} x(t) = \sin t - t\cos t \\ y(t) = -\left(\cos t + t\sin t\right) \end{cases}; \quad 0 \leq t \leq 1.8606 \tag{5}$$

$$\begin{cases} x(t) = \dfrac{0.2857\cos(t-0.9583) - (1.8606+t)\cos t}{1+\sin(t-0.2898)} + 0.9583 \\ y(t) = -\left[\dfrac{0.9583\cos(t-0.9583) + (1.8606+t)\sin t}{1+\sin(t-0.2898)} - 0.2857\right] \end{cases}; \quad 1.8606 \leq t \leq 3.8431 \tag{6}$$

The equations described in (5) and (6) are in their dimensionless form, which allows scaling the curves to any radius. For the prototype it is considered that the receiver will consist of a test tube of radius and long, so that the receiver can contain , in Fig. 4. (a) the 3D prototype is shown, and in (b) an arrangement with 6 concentrators that will allow several tests to be carried out simultaneously; while in (c) a photograph of the real prototype can be seen.

(a) (b)



(c)

Fig. 4. CPC prototype for water treatment. (a) 3D model of a CPC. (b) Arrangement of the CPC provision. (C) Photograph of the prototype, where the back and previous parts have been omitted to appreciate the curvature of the mirror.

3 I ANALYSIS 2E OF THE CONCENTRATOR

The thermal analysis was carried out taking as reference the conditions of the city of Toluca, Mexico (), considering that the prototype will be oriented in the N-S direction. Next, we describe the methodology with the results for any typical day n. To determine the amount of energy that will be captured by each CPC, it is necessary to determine the solar angles for an inclined surface , such as the declination , the solar time and the zenith angle using eqs. (7) to (9). In this description, several standard calculations related to the Earth-Sun geometry are omitted, since they are available in the literature and can be determined without major complications knowing the location and the number of the day (DUFFIE; BECKMAN, 2013; GOSWAMI, 2015; KALOGIROU, 2009)

$$\delta_s = 23.45^\circ \sin\left(360\frac{240+n}{365}\right) \qquad (7)$$

$$\theta_z = \tan^{-1}\frac{\tan\beta_s}{\left|\cos\left(\gamma_s - \gamma\right)\right|} \qquad (8)$$

$$\alpha_s = 90^\circ - \theta_z \qquad (9)$$

To determine the values of direct and diffuse radiation, the values of the atmospheric transmission must be determined, according to the Hottel model (DUFFIE; BECKMAN, 2013), eqs. (10) and (11), where the factors , and vary according to the geographical altitude, as well as the climate of the region. Thus, direct and diffuse solar radiation at ground level is determined using (10) and (11).

$$\tau_b = a_0 + a_1 e^{-\frac{k}{\cos\theta_z}} \qquad (10)$$

$$\tau_d = 0.271 - 0.294\tau_b \qquad (11)$$

$$G_b = G_{on}\tau_b\cos\theta_z \qquad (12)$$

$$G_d = G_{on}\tau_b \qquad (13)$$

To calculate the irradiance that captures and concentrates any concentrator (GONZÁLEZ-MORA; RINCÓN-MEJÍA, 2018), we consider a virtual angle that will be the difference of the angle of inclination () and the acceptance half-angle (); this virtual angle will define the direct radiation capture factor by:

$$F_C = \left| \begin{array}{ll} C_g & \text{if} \quad \theta_C \leq tan^{-1}\left(tan\theta_z cos\gamma\right) \leq \beta + \theta_0 \\ 0 & \text{if} \quad \theta_C \geq tan^{-1}\left(tan\theta_z cos\gamma\right) \geq \beta + \theta_0 \end{array} \right. \qquad (14)$$

So the direct irradiance that enters the concentrator will be:

$$G_{b,C} = G_{b,\beta}F_C\cos\theta_0 \qquad (15)$$

To calculate the diffuse radiation that can enter the concentrator, it is considered:

$$G_{d,C} = \left| \begin{array}{ll} \frac{G_{d,\beta}}{C_g} & \text{si} \quad \beta + \theta_0 < 90^\circ \\ \frac{G_{d,\beta}}{2}\left(\frac{1}{C_g} + \cos\beta\right) & \text{si} \quad \beta + \theta_0 > 90^\circ \end{array} \right. \qquad (16)$$

The radiation collected by the concentrator will then be the contribution of direct and diffuse radiation:

$$G_C = G_{b,C} + G_{d,C} \tag{17}$$

Thus, the thermal power concentrated in the receiver is

$$\dot{Q}_C = A\eta_o G_C \tag{18}$$

Where is the optical performance, defined by the optical properties of the materials to be used (reflectance, absorptance and transmittance). Considering that a MIRO-SUN® sheet, a Pyrex® glass receiver, will be used, the optical performance is estimated at. 0.6319.

The thermal loss model encompasses the three phenomena of heat transport (conduction, convection and radiation) considering the climatological conditions of Toluca (CONAGUA, 2000). For the conduction phenomenon, the Fourier's Law is used, eq. (19). For convection, the Adiutori's approach is used instead of the Newton's law of cooling, eq. (20). Finally, the Stefan-Boltzmann law models the heat losses by radiation, eq. (21) (ADIUTORI, 2017; BERGMAN et al., 2011).

$$\dot{Q}_{l-cond} = -\kappa \nabla T \tag{19}$$

$$\dot{Q}_{l-conv} = A_r f(\Delta T) \tag{20}$$

$$\dot{Q}_{l-r} = \varepsilon_r \sigma \left(T_r^4 - T_{sky}^4\right) \tag{21}$$

Where is the thermal conductivity of the elements that support the receiver, is the infrared emittance of the receiver and is the effective temperature of the sky, which can be determined if the dew point temperature of the environment is known (DUFFIE; BECKMAN, 2013). Thus, the total heat losses in the receiver will be the contribution of the three phenomena in an additive manner, as seen in equation (22).

$$\dot{Q}_{l-t} = \dot{Q}_{l-cond} + \dot{Q}_{l-conv} + \dot{Q}_{l-r} \tag{22}$$

In this way, the useful thermal power of the concentration system will be the difference of the concentrated thermal power and the heat losses, as stated in (23), while the energy efficiency according to the first law of thermodynamics can be determined by (24), where is the temperature of the environment.

$$\dot{Q}_u = \dot{Q}_C - \dot{Q}_{l-t} \tag{23}$$

$$\eta_I = \frac{\dot{Q}_u}{\dot{Q}_C} = \eta_o - \frac{U_l\left(T_r - T_a\right)}{C_g G_C} \tag{24}$$

To perform an exergy analysis, it is necessary to define the input exergy as the exergy from the Sun. While there are several models that allow quantifying the amount of solar exergy (BEJAN, 2016; PARROTT, 1978; PETELA, 2010), all depart from the assumption that the Sun is a black body with effective temperature T_S , and is referenced to a reference temperature T_0. The Petela model (PETELA, 1964, 2010) considers the exergy of the radiation emitted by the Sun towards space; whereas the Parrot model (PARROTT, 1978) quantifies the exergy of solar radiation on the Earth's surface; that is, consider the transfer of radiative exergy between the surface of the Sun and the Earth's surface. The Parrot model is stated in eq. (25).

$$\dot{B}_G = A\left(G_b + G_d\right)\left[1 - \frac{4}{3}\frac{T_0}{T_s}\left(1 - \cos\theta_s\right)^{\frac{1}{4}} + \frac{1}{3}\left(\frac{T_0}{T_s}\right)^4\right] \tag{25}$$

Where θ_s is the measurement of the solar disk $(0°16')$, T_s , is the effective temperature of the Sun (5777k) and T_0 is the reference temperature (). The exergy balance of a thermal system is defined in (26).

$$\dot{B}_d = \left(1 - \frac{T_0}{T_r}\right)\dot{Q}_u \tag{26}$$

Thus, exergy performance is calculated by:

$$\eta_{II} = 1 - \frac{\dot{B}_d}{\dot{B}_{DNI}} \tag{27}$$

4 I RESULTS

Using the methodology described in the previous section, Table 1 shows the results for the representative days of each month, and Fig. 5 shows the thermal performance of the system, result of graphing eq. (24).

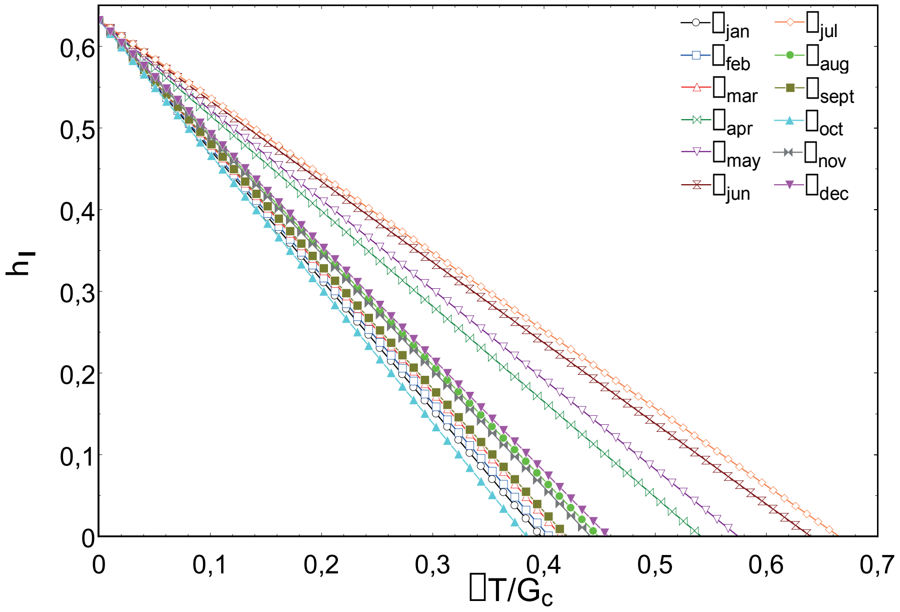
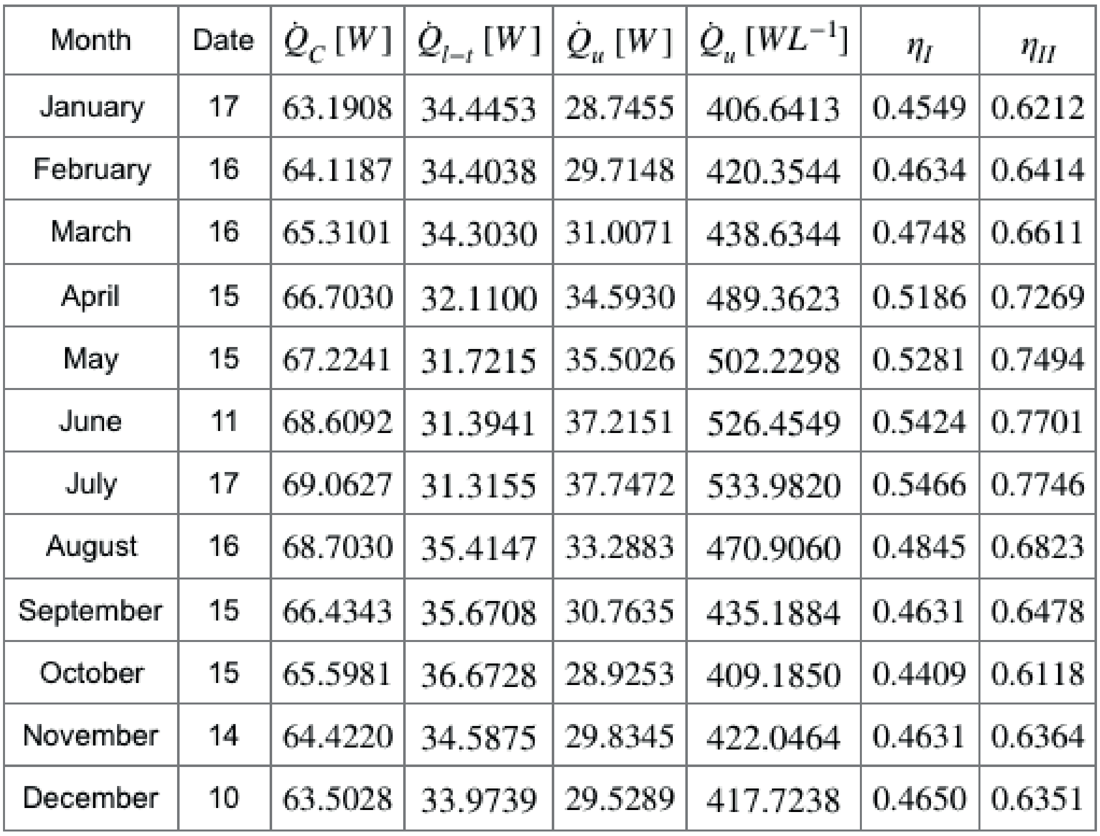


Fig. 5. Thermal performance of the system for each of the representative days of each month.



Month	Date	$\dot{Q}_C\,[W]$	$\dot{Q}_{l-t}\,[W]$	$\dot{Q}_u\,[W]$	$\dot{Q}_u\,[WL^{-1}]$	η_I	η_{II}
January	17	63.1908	34.4453	28.7455	406.6413	0.4549	0.6212
February	16	64.1187	34.4038	29.7148	420.3544	0.4634	0.6414
March	16	65.3101	34.3030	31.0071	438.6344	0.4748	0.6611
April	15	66.7030	32.1100	34.5930	489.3623	0.5186	0.7269
May	15	67.2241	31.7215	35.5026	502.2298	0.5281	0.7494
June	11	68.6092	31.3941	37.2151	526.4549	0.5424	0.7701
July	17	69.0627	31.3155	37.7472	533.9820	0.5466	0.7746
August	16	68.7030	35.4147	33.2883	470.9060	0.4845	0.6823
September	15	66.4343	35.6708	30.7635	435.1884	0.4631	0.6478
October	15	65.5981	36.6728	28.9253	409.1850	0.4409	0.6118
November	14	64.4220	34.5875	29.8345	422.0464	0.4631	0.6364
December	10	63.5028	33.9739	29.5289	417.7238	0.4650	0.6351

Table 1. Thermal performance of the system for the representative days of each month.

During the year, each CPC will deliver a useful average power of $453{,}9530\ WL^{-1}$, , with an energy yield 0.4859 of and an exergetic yield of 0.6775.

5 I CONCLUSIONS

The objective was to optimally design a wastewater treatment prototype, using an anidolic optical system. Based on the theoretical results of Table 1, the system design complies with the energy density restriction of $400-600\ W\ L^{-1}$, so the system will be expected to achieve the design objective.

The energetic and exergy performance have values that are more than acceptable for a concentration system that does not minimize convection losses; so that, if a glass cover is used, the heat transfer process by convection will be minimized, resulting in a noticeable improvement in both energy efficiency and exergy.

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