Optical Analysis of an Evacuated Tube Collector with Built-In Semicircular Concentrator for Process Heat Applications

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Abstract

The aim of this study is to evaluate the optical performance of an Evacuated Tube solar thermal Collector with Semi-Circular concentrator (ETC-SC). An optical simulation model is developed in a ray-tracing software and its consistency is proven through experimental data from the literature. A parametric analysis is then performed to investigate the impact of the absorber's radius, the absorber's position and the acceptance angle of the semi-circular mirror on the optical efficiency of the collector. The results of this study show that the variation of the absorber's radius slightly affects the optical performance of the collector. Regarding the absorber's position, the greatest distance studied presented the best results for all incident angles studied. In terms of acceptance angle, it was shown that for small incident angles, the best performance is shown from the smallest acceptance angle studied, but for greater incident angles, this relationship is reversed. The results of this study are valuable for the design, simulation and performance analysis of the evacuated tube collectors.

Keywords: Evacuated tube collector, ray tracing, optical efficiency.

1. Introduction

To date, insufficient attention has been paid to the potential of renewable energy resources in industrial applications. An analysis (Taibi et al., 2012) suggests that up to 21% of final energy demand and feedstock use in the manufacturing industry sector could be of renewable origin by 2050, a five-fold increase over current levels in absolute terms. In addition, if a 50% share of renewables in power generation is assumed, the share of direct and indirect renewable energy use rises to 31% in 2050. Yet, the substantial potential for solar heat is not reflected to the installations number. While low-temperature solar process heat can reach cost effectiveness today in locations with good radiation as in Mediterranean region, in early 2014 there were only 130 solar thermal plants for industrial process heating worldwide, producing 93 MW_{th} (IEA SHC, 2014).

Process temperatures found in the industrial sector range from low (T<100ºC), medium (100ºC < T < 250ºC) to high (T > 250ºC) level (IRENA, 2015, Horta et al., 2016). Whereas low temperature applications are already addressed by well-established flat plate solar thermal collector technologies, the approach to medium temperature applications relies on a range of more sophisticated thermal collector technologies, such as the evacuated tube collectors (Aguilar-Jiménez et al., 2018). The effectiveness of the evacuated tube collectors and subsequently, their capacity to produce medium temperature level heat is closely related to their optical performance.

In the literature there are many studies discussing the optical and thermal properties of the evacuated tube collectors. Back in 1974, Winston (1974) studied a collector with a trough-like reflecting wall light channel that had a concentration factor of 10 and did not need diurnal sun tracking. More recently, all-glass vacuum tube collector was the objective of the study of Li et al. (2010). They developed a heat transfer model, then validated it with a physical model and found reasonable deviations. Buttinger et al. (2010) developed a new non-tracking, low concentrating collector that aimed specifically at delivering process heat at temperatures 120-150^{o}C. They showed efficiencies around 50% at a temperature of 150^{o}C with a radiation of 1000W/m^2. Nkwetta and Smyth (2012) analyzed two profiles of concentrated evacuated tube heat pipe solar collectors made of single-sided and double sided absorber. The concentrated double-sided absorber evacuated tube heat pipe proved better

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compared to the concentrated single-sided absorber evacuated tube heat pipe solar collector due to higher outlet temperature with greater temperature differential and improved thermal performance. They also evaluated the optical performance of an internal low-concentrating evacuated tube heat pipe solar collector for medium temperature applications. Their raytracing analysis resulted in an optical efficiency of 79.13% for transverse angles 0-20^o. Another study (Kumar et al., 2017) investigated theoretically the performance of heat pipe solar collectors and found that they are sensitive to the solar radiation, the ambient temperature as well as to the length of evaporator. A study targeted at the calculation of the potential of solar process heat to specific industrial sectors in Germany was recently published (Lauterbach et al., 2012). It was found that the theoretical potential of solar heat for industrial processes below 300^{o}C in Germany accounts for 134 TWh per year and the technical potential is 3.4% of the overall industrial heat demand.

The Evacuated Tube solar thermal Collector with Semi-Circular concentrator (ETC-SC) considered in the present study consists of a row of evacuated receiver tubes connected in series. Inside each receiver tube, there is an absorber tube coated with a special absorption layer. In this configuration, a semicircular concentrator is placed inside the evacuated tube and underneath the absorber tube with the scope to direct the solar radiation onto the absorber tube (Fig. 1). This study aims at evaluating the effect of adding the semicircular mirror component on the optical efficiency of the ETC-SC.

2. Methodology

2.1. Description of the Evacuated Tube solar thermal Collector with Semi-Circular concentrator

The components and the design features of the ETC-SC are shown in Fig. 1. This ETC-SC collector converts energy from the sun into usable heat under solar thermal technology principles. The heat produced can be then used for sanitary hot water use and for industrial process heat. The ETC SC composed of three main parts: a)The evacuated tubes, that consist of two glass tubes, one inside the other. The inner tube, in which the heat transfer fluid flows, is coated with a selective paint on its external surface. There is vacuum in the annulus space to minimize heat losses. In the inner side of the outer glass tube, a semicircular mirror is positioned facing the sun to direct the radiation into the inner glass tube. b) The manifold that is an insulated box containing the header pipe. c) The mounting frame. It is out of the scope of this study to evaluate the manifold and the frame, since this study focuses on the optical performance of the evacuated tubes.

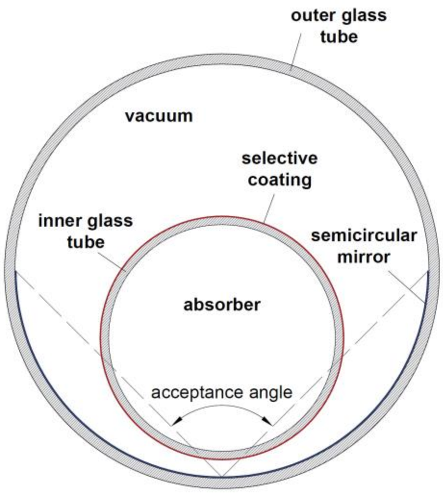

Fig. 1: ETC-SC design configuration

The optical analysis of the ETC SC is performed using the Tonatiuh ray-tracing software developed by CENER (Tonatiuh, 2012). Considering that all tubes comprising the solar collector are identical, the optical analysis was performed for one tube only, with an indicative length of 1m. Fig. 2 depicts the developed model that consists of three elements; outer glass, absorber and mirror. The glass envelope is built as two concentric surfaces, but it is not clearly shown due to its transparency feature.

The optical analysis is implemented in terms of the Incidence Angle Modifier (IAM). When the Sun rays hit the collector from an angle the performance changes and this is what the IAM provides; an angular performance factor. A value of 1 is achieved when the collector receives the maximum radiation. For evacuated tube collectors that employ reflective components and are affected by reflection off neighboring tubes, the IAM may exceed 1. The two types of IAMs are:

- Transversal IAM, that measures the change in performance as the Sun angle changes in relation to the collector, through the day.
- Longitudinal IAM, that measures the change in performance as the Sun angle changes in relation to the collector, through the year.

The value of most concern for fixed collectors is the transversal IAM, as this reflects the change in performance throughout the day. Therefore, in this study the transversal IAM is calculated and evaluated.

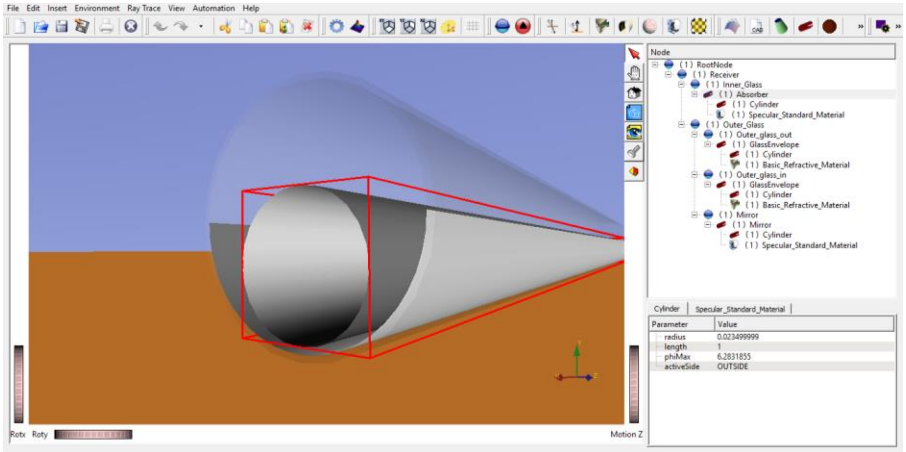

Fig. 2: Print screen of the optical model developed in Tonatiuh.

The geometrical and material properties of the elements of the tube that were used to the Tonatiuh model are shown in Table 1.

Table 1: Geometrical and material properties used in Tonatiuh

	Glass outer	**Glass inner**	**Absorber**	**Mirror**
Geometry	Radius 0.042m Length 1m	Radius 0.040m Length 1m	Radius 0.0245m Length 1m	Radius 0.0396m Length 1m
Material	Basic refractive material Transmissivity 0.96	Basic refractive material Transmissivity 0.96	Specular standard material Reflectivity 0	Specular standard material Reflectivity 0.96

Fig. 3 shows the raytracing analysis implemented for the ETC-SC solar collector, under various Sun deviations from the transversal plane.

When looking at the tubes from above (0^o) each tube's surface is exposed to the maximum amount of sunlight with no gaps between them and no overlap. At this angle, the amount of rays lost between the tubes is neglected and therefore this angle is used as the reference point for the IAM value of 1. Indeed, with 500 rays selected to be showed, at 0^o Sun deviation, most of the sun rays actually hit the absorber and the concentrator produces 787W per m^2 of absorber's aperture area. For greater Sun angles, the tubes start to overlap, shading each other. They are still facing the Sun, but the actual surface area of the receiver exposed to the sunlight is reduced. For the collector under investigation and at 20^o zenith angle, the production is reduced by only 1% (778W/m^2). For zenith angles beyond 40^o (early morning or late afternoon), only a small amount of rays reaches the tubes and so, this period has minimal influence on the total daily energy output of the collector. At 40^o, the loss in power production becomes evident at 17% with the concentrator now producing 651W/m^2. Fig. 4 shows the incidence flux distribution in the surface of the absorber, at zenith 0^o.

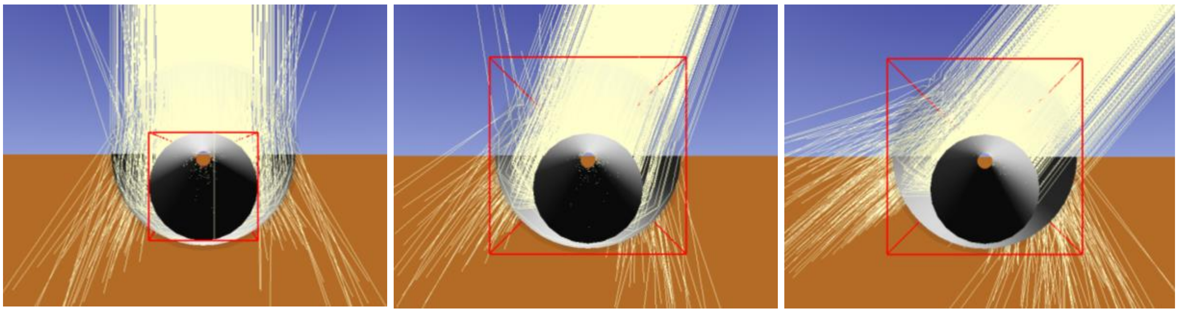

Fig. 3: Ray tracing figures for the ETC-SC collector under investigation, zenith 0° (left), 20° (middle) and 40° (right).

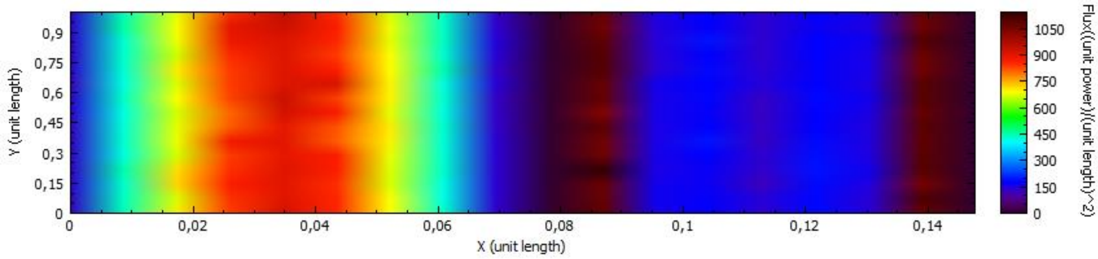

Fig. 4: Incidence flux distribution in the surface of the ETC-SC absorber, with zenith 0°.

2.2. Validation of optical model

The model is validated towards accredited performance data, taken from the Solar Rating and Certification Corporation SRCC (SRCC, 2017). Sun angles beyond 40° are not considered in the model validation, since the solar radiation is very low at that period (early morning and late afternoon) and the impact on the total daily energy output of the collector is negligible. As such, the deviation between the optical model and experimental data from the literature does not exceed 11% and the average deviation of all cases considered is 2.8%, so the model is considered as valid and consistent.

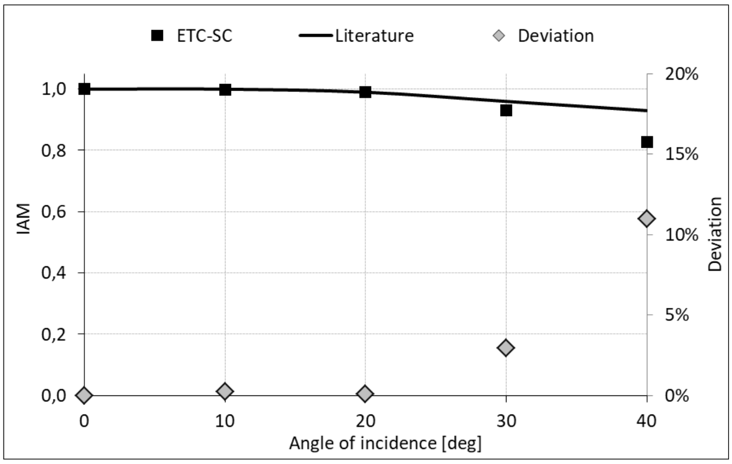

Fig. 5: Left axis: IAM points (black points) of ETC-SC collector under investigation, IAM curve (black line) of the reference collector in the literature. Right axis (grey points): % deviation between those two values.

Following the validation of the optical model, the transversal IAM curve of the ETC-SC collector under investigation is drawn (Fig. 6), by varying the angle of incidence, from 0° to 70°, with a step of 5°.

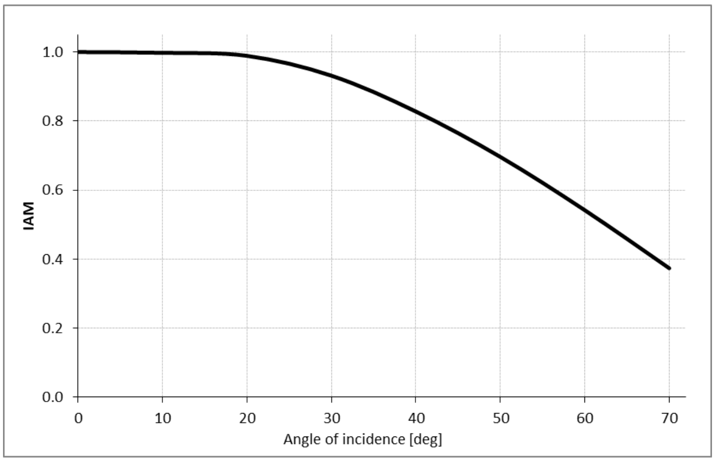

Fig. 6: IAM curve of ETC-SC collector under investigation.

The shape of the transversal IAM curve is due to the cylindrical absorber area and the presence of the semicircular mirror, which passively tracks the sun throughout the day. The IAM values drop away from 1, as the angle increases and as such, solar conversion efficiency is maximum at midday. For angles of incidence higher than 50^o, there are rays lost between the tubes, tube overlap and reflection of neighboring tubes, hence the IAM drops at a faster pace. These angles correspond to early morning or late afternoon, when solar radiation levels are already very low, so this efficiency drop is of minor importance.

3. Parametric analysis

3.1. Absorber radius

Three different values for the absorber radius, namely 0.0235m, 0.021m and 0.0185m, are compared towards the IAM curve (Fig. 7). In general, this study shows that the variation of the absorber radius has a marginal effect on the collector performance. More specifically, reducing the absorber radius by 12% and 14% reduces the power production by 0.6% and 0.9%, respectively. This is owned to the limited range of change; possibly, a greater change in the radius is expected to have a greater effect on the collector performance.

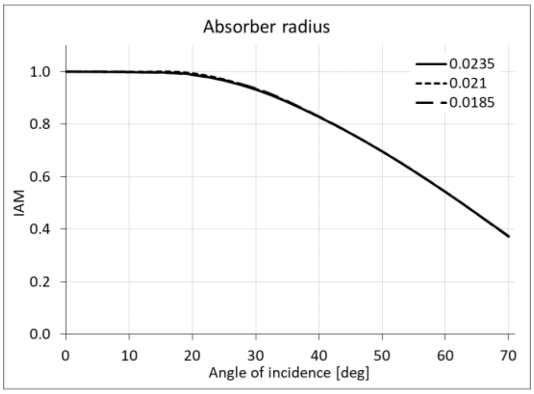

Fig. 7: IAM curve of the ETC-SC collector, for three absorber radiuses

3.2. Absorber position

The second investigated parameter is the position of the absorber tube, in relation to the outer glass tube. Three different positions are studied, namely 0.007m, 0.005m and 0.003m distance between the lower part of the absorber and the lower part of the semicircular mirror. Fig. 8 shows the results of this analysis and reveals that at the 0.007m distance the absorber has a better performance, for all incident angles up to 70^o. Fig. 9 shows the effect of the absorber's position on the intercept factor of the solar collector; the intercept factor of the 0.003m distance is 13.6% greater than that of the 0.007m. At this point, it should be noted that the zero distance option was not studied, due to the practical and construction limitations that this option would have.

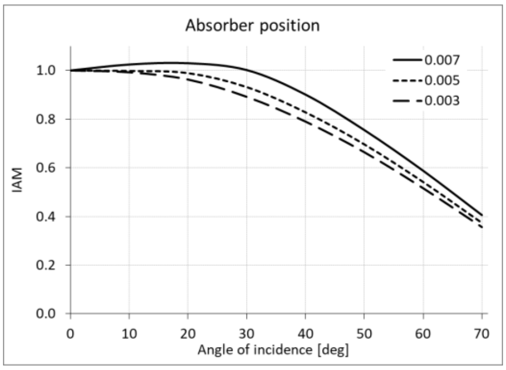

Fig. 8: IAM curve of the ETC-SC collector, for three absorber positions

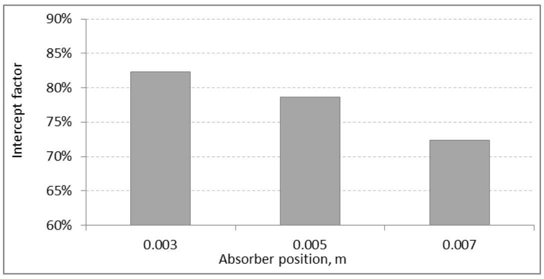

Fig. 9: Intercept factor of the ETC-SC collector, for three absorber positions

3.3. Acceptance angle

Three different acceptance angles were investigated, namely 90^o, 105^o and 120^o. Fig. 10 depicts the IAM curve towards the angle of incidence for the three acceptance angles studied. The results show that for incident angles up to 40^o, the best performance is shown from 90^o acceptance angle. This is relationship is also reflected in the power production curve. For greater incident angles, there is the reverse phenomenon; the solar collector with 120^o acceptance angle shows better IAM curve. This is owned to the fact that for greater incident angles, the 120^o acceptance angle allows more rays to reach the absorber and has less blocking losses.

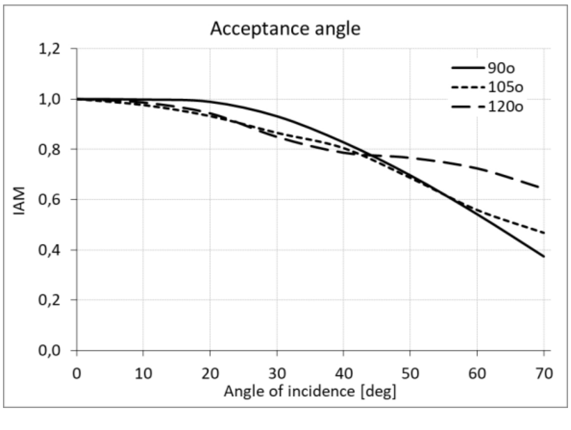

Fig. 10: IAM curve of the ETC-SC collector, for three acceptance angles

4. Conclusions

The optical performance of an Evacuated Tube Collector with Semi-circular Concentrator was investigated, in terms of transversal IAM curve. An optical simulation model was initially developed and validated with literature data. The impact of the absorber's radius, absorber's position and acceptance angle on the optical efficiency were evaluated, in the range of 0.0185m-0.0235m, 0.003m-0.007m, and 90^o-120^o respectively. It was found that the variation of the absorber radius at the selected range had marginal effect on the IAM. In terms of distance between the absorber tube and the glass tube, the greatest distance studied (0.007m) presented the best outcome throughout all day. Finally, the parametric analysis of the acceptance angle showed that for incident angles up to 40^o, the best outcome is shown from the 90^o acceptance angle. For greater incident angles though, the best performance was shown from the 120^o acceptance angle. This study revealed the importance of considering the IAM effect when calculating the performance of solar collectors. The results are valuable for the design and performance analysis of evacuated tube collectors.

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