The Influence of Some Important Parameters on the Performance Efficiency of the Compound Parabolic Solar Concentrator

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Abstract

The solar concentrator is designed in the form of a compound parabolic concentrator CPC of relatively light metal (aluminum) with a reflective inner surface (coated with a reflective material). Parabola is characterized by a high concentration of incident rays at one point (the focus) of a large radiation field, in other words the design has a relatively large acceptance angle and a small amount of diffusion compared to other concentrators. The CPC of circular cross section has been designed by using (Zemax) optical design program, with a different concentration ratio for each sample (C = 1, 2, 3, 4, 5). The design of the sample should be consistent with the shape of the detector (which is attached to the exit aperture). A plastic cover has been used to cover the entrance aperture to protect against external environmental factors (such as moisture, dust, and rain), made of hard material (PMMA) which has a good thermal expansion coefficient. The number of rays falls to the detector and the optical power and illumination have been read to study the optical efficiency, evaluate them to the optical system according to the angle of inclination of the sun within the range (0o-25o). The technology of truncation of solar concentrator, i.e. cutting part of the concentrator's length, has been adopted to obtain an optimal design that can receive and reflect as much solar radiation as possible. The deductions are used for different values of the design length (100mm, 200mm, 300mm, 400mm, 500mm) taking into account the change in the entrance aperture for each length to accommodate the largest possible amount of radiation as an important factor and has a major influence on the design efficiency. As for the exit aperture, it has a fixed value of the section area (50 mm) for all designs with different concentration ratios to obtain a suitable comparison standard.

Key Words: Zemax, Solar Concentrator, Compound Parabolic Concentrator, Acceptance Angle, Concentration Ratio.

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Introduction

The using of solar concentrators to exploit solar energy is an important technology of our time. Because of the world needs for renewable energies and investment instead of fossil fuels. Solar energy is distinguished from other clean energies by providing it in all countries of the world and almost all times of the year. This energy is divided into thermal and photonic energy. It is divided into two fields according to the type of the used energy [1].

Solar concentrators are used to utilize the maximum amount of solar energy and reduce the effective area to increase efficiency. These solar concentrators are divided into two types: the first is photovoltaic solar concentrators that convert light energy into electrical energy directly through solar cells, and the second is thermal solar concentrators that convert thermal radiation energy into electrical energy indirectly by using of steam engines.

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Also it has other fields of use such as refrigeration, heating and cooking regulators [2].

The compound parabola solar concentrator (CPC) is characterized by concentrate solar radiation with high efficiency and a relatively large acceptance angle. This is very useful in optical designs that specialized in this field, because it does not need to use a solar tracking system that is expensive. Also, this design possesses high dynamics by changing the important parameters such us concentrator length, concentration ratio, acceptance angle and shape of the cross section, while maintaining the basic function of their functions, to appropriate with needs and purposes of the designer. CPC also has advantage of having a large radiation reception field that focuses radiation at one point (focus). That is, non-diffusion of radiation in more than one location, as is the case in most other optical systems [3].

CPC has been designed by simulating in the Zemax optical design programming, using a non-sequential ray tracing mode. The geometry of CPC has the advantage of automatically changing its optical parameters as the design changes. These parameters directly affect the performance of the CPC. The parameters are appropriate for each according to the type and amount of changing. Therefore, these parameters have been studied in this work to know the extent of their influence on each other, and the extent of their influence on the efficiency performance of CPC.

The topic of solar thermal concentrators in general and compound parabolic solar concentrators in particular occupies a large area of study and attention, as it is one of the most important issues of exploiting renewable energies, considering their effective role in modern life and finding appropriate alternatives to fossil fuels for the societies need for them, especially with the increasing demand for clean energy sources. The field of using CPC technology is very wide, because it is important in the field of using solar energy without needing solar tracking system.

J. A. Colinamarques et al. have developed a mathematical model that simulates direct solar radiation reflection on a CPC using geometry analysis and vector calculation. From the results, the center was constructed to show the distribution of the fallen energy on the absorption surface, depending on the surface reflectivity. It was found that the falling energy is greater in the upper part of the absorber at the bottom. Note that the surface reflections at the top are suitable for regular energy distribution [4].

W. Zheng et al. are designed a new type of concentrator with numerical and experimental research consisting of a quirky parabolic compound which is a mixture of CPC and a collector solar center shaped like a rectangular plate using (mat lab) program. The comparison is consistent with the numerical results in the experimental data, and the maximum deviation was (8.07%), and there appeared compatibility according to the thermal efficiency of (60%). This center is more suitable for obtaining hot water at a lower temperature for heating in cold areas [5].

N. Ortega et al. proposed two engineering designs based on numerical simulations and commercial availability of materials. A radiation tracking analysis was performed to determine the losses due to the truncation of a CPC model. Each has a real concentration rate of (1.8) and an acceptance angle of (30^{o}). The experimental setup construction is designed to choose the different operating conditions of the unit from temperature and flow in addition to that the model contains water tanks and a pump where the results obtained using the Mexican standard showed that this technology is able to provide stable temperatures for industrial processes and improve manufacturing errors discovered in this Experimental tests [6].

Optical Design

The CPC consists of a reflective inner surface (a highly reflective metal material such as silver or chrome) that has a parabolic shape. It contains an aperture for the rays facing the sun. Its mission is to receive the solar rays and reflect them on the reflective inner surface. The process of internal reflections on the inner surface of the center is repeated, until the rays reach the other aperture (exit aperture) in which the receiving surface is located. The receiving surface varies in type and shape according to the type and purpose of the concentrator, as shown in the figure [7].

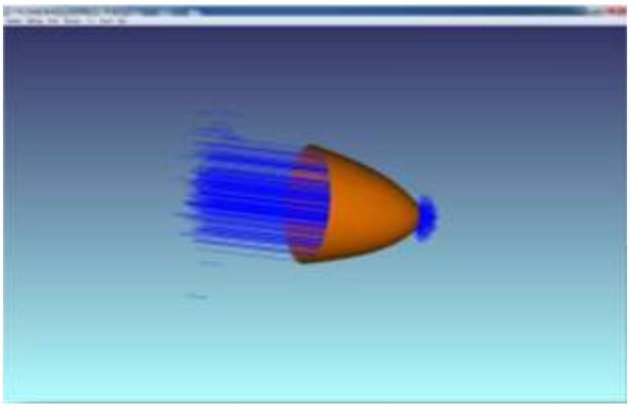


Figure 1. The sample of Compound parabolic concentrator CPC

The CPC sample in the Zimax software has been designed with a fixed value of exit aperture radius (50 mm) outlet. While the value of the entrance aperture changes according to the change in the concentration ratio and the acceptance angle. The length of the concentrator ranges is (100-500mm). Changing the concentrator length has a significant influence on the acceptance angle and concentration ratio.

The truncation of the concentrator length has a positive effect in increasing the design's efficiency, by reducing the area of the reflective inner surface, in line with other parameters to get the maximum amount of radiation on the recipient surface. That is, to reduce the ratio of stray rays to the outside of the concentrator after the reflection inside it [8].

The advantage of the CPC circular cross section is symmetry in all directions. That is, it can be installed in any side facing the sun to give the same results. That is mean not limited to fixing it against the sun, figure (2).

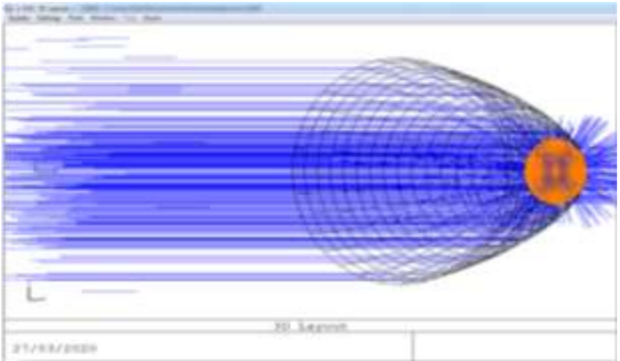


Figure 2. Scheme of the circular cross section CPC in Zemax

A Gaussian radiation source was chosen because it spreads randomly. It is the most appropriate choice for a design where the optical axis is on the axis (z), the number of rays is determined (1000 rays) in the analysis ray field to get the exit aperture. As for the width of the beam reaching the concentrator corresponds to the width of the entrance aperture, which is changed depending on the acceptance angle.

In addition, the variations in the incidence angle of solar radiation are simulated by the tilt of the x-axis of the coordinates of the optical source that simulates the source of the sun by instructing (tilt about x) as it was determined from the angles within the range (0^{o}-25^{o}).

Regarding radial aperture installed for all samples with a exit aperture radius of (50mm), the model was chosen with different concentration ratios (C) to show its effect on the efficiency which in turn has a special acceptance angle for each concentration ratio.

The Detector

A detector was put in place of receiving surface inside the concentrator, to detect the rays falling on it. As a result is knowledge the amount of radiation received, and to calculate the performance efficiency of the CPC. The surface of the detector was chosen to match the shape of the exit aperture that is means it covers all the area of the aperture to ensure receipt of all rays connected to it (figure 2).

Zemax Program

It is one of the modern design programs for optical systems of both types (imaging system and non-imaging system) used for optical design and assessment of efficiency through various methods of analyzing the results, as well as the program provides optimal values for the balance of parameters (optimum balance) for design to obtain the ideal design . The program is used to design and analyze optical systems such as lenses, camera, mirrors, optical fibers and lighting systems using numerical analysis methods in matrix presentation with a sequential and non-sequential ray tracing mode [9].

The program is characterized by its high ability in analysis and simulation in addition to allowing other programs to establish a link with it to work in design flexibility. Data can be exchanged to and from the program using Dynamic Data Exchange (DDE). The purpose of this is that external applications can use Zemax to calculate the radiation through an optical system and then more analysis information and accounts, and this is an important feature that allows users to expand the calculation of capabilities and design of optical systems that do not exist in Zemax from other programs [10].

This program is easy to use because it contains many windows. The main window is through which the data for design to be opened, closed and preserved. As for the input window, it is easier for the designer to enter information such as lens thickness, lens radius, type of surface, type and sources of the entrance aperture. It is also possible to enter other influences such as temperature, pressure, humidity, wavelength, field of vision and angle of incidence of radiation. The program contains a large library of different types of lenses and materials manufactured for them, providing the designer with a wide field for the most appropriate choice for the design.
Zemax provides information about design efficiency with assessment tools such as Spot diagram, ray fan aberration, optical transfer function, encircled energy, point spread function and the detector viewer window.

Ray Tracing Mode in Zemax

The mathematical model that used in Zemax program is a ray tracing mode by mathematical treatment of the laws of reflection, refraction, absorption, and scattering of light. This is done through the use of numerical analysis methods in mathematics through the matrix presentation operations, which determines the optical characteristics of the system, such as the shape of the image formed and the amount of continuous radiation. The ray tracing mode includes two types, sequential and non-sequential, depending on the type of system designed.
Non sequential ray tracing is often used in non-visual optical systems such as lighting systems, concentrators, and stray light analysis. The rays can fall on several surfaces without sequence. The non-sequential ray tracing mode provides a set of tools for assessing design efficiency, for example illumination distribution, encircled energy and detector viewer.
Figure (3) shows the item component editor window for this style. The first column represents the object type, which means the source type used, then the x-axis coordinate columns. y. z. Likewise, the inclination of each surface with respect to the three axes through the columns Tilt about x, y, z, and then the type of material for the body and the dimension columns for length, width, height and radius, in addition to other parameters related to the surface type. This mode provides the design of many optical systems with high flexibility in terms of shape, dimensions and other details, whether small or large.

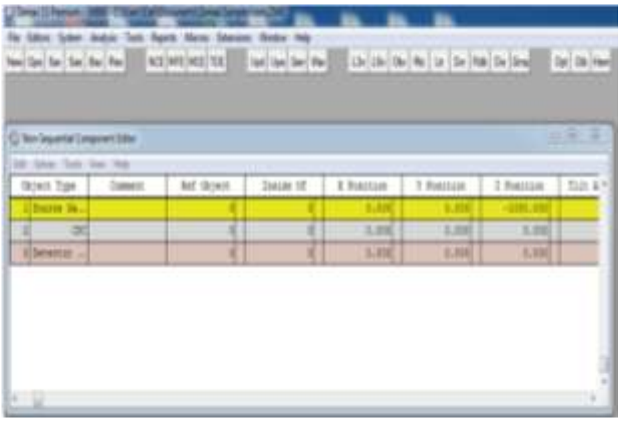


Figure 3. Non sequential component editor window in Zemax

Parameters for Samples

There are many factors that influence the geometric design of the CPC that can be controlled via the Zemax program. Affect the shape, size and efficiency of the design. In this work, these parameters were changed successively with certain values, note the difference in the efficiency of the design at each value, and make a comparison between them to reach the best design for certain values of these parameters. The most important of these parameters are:

1. Truncation of Concentrator Length

The CPC shape geometry is close to ideal for high efficiency and concentration at a good acceptance angle compared to other concentrators, but its disadvantage is that it is long compared to the diameter of the exit aperture that should be considered in a wide application for economic and light weight purposes. Therefore, it was necessary to make truncates to length to obtain the best optical efficiency by determining the number of internal reflections of the solar radiation. The lower length of the concentrator, due to the greater angle of acceptance of the concentrator and less area of the insertion hole according to the following relationship, the length of which is determined by the appropriate form of it.

$$L = \frac{a(1+sin\theta_i)cos\theta_i}{sin^2\theta_i} \qquad (1)$$

Where is (θ_i) represents the acceptance angle, (a) the radius of the entrance aperture and (L) is the concentrator length. Equation (1) is important in determining the appropriate design for CPC as it links the most important design parameters in a single relationship. The designer needs to find a perfect balance of the equation values to find the most appropriate design for the highest efficiency.

2. Concentration Ratio

It is defined as the ratio between the radius of the entrance aperture and the radius of the exit aperture (receiving surface) and is calculated by the relationship:

$$C = \frac{a}{a'} = \frac{n^2}{\sin\theta_i^2} \qquad (2)$$

Where (C) represents the concentration ratio, (a') the radius of the exit aperture, (n) the refractive index of the concentrator's inner cavity. By knowing the engineering design of the concentrator, we notice that the concentration ratio carries a value (C ≥1). Equation (2) shows the inverse relationship between the concentration ratio and the acceptance angle, that is, the higher concentration ratio, leads to the lower acceptance angle and vice versa. Increasing the acceptance angle and concentration ratio is an important factor in increasing the efficiency of the concentrator, but equation (2) for the design of the equivalent CPC requires finding optimum values for these parameters to reach the highest design efficiency.
The concentration ratio is important in the design of non-visual optics. The ideal concentration means that all the radiation within the CPC for a certain acceptance angle will not bounce out back, but rather fall on the exit aperture. For example, the percentage of concentration is affected by the input aperture, according to the context used to calculate the optical efficiency. The relationship is direct, that is, the greater entrance aperture, lead to the greater concentration ratio.

3. Acceptance Angle

The CPC must have a sufficient acceptance angle to receive the largest possible amount of solar radiation with the change in the angle of radiation fall with the movement of the sun during the daylight hours. Therefore, it is important to design the CPC with the widest possible of acceptance angle (taking into account other engineering parameters such as length and concentration ratio). As mentioned previously, the most desirable feature of a CPC is long-term work without the need for a tracking system. This design has the ability to reflect all the radiation falling on the entrance aperture at different angles, but with certain limits to obtain a suitable efficiency (80%). These limits are known as the acceptance angle of the CPC. If all the rays are within the range of the acceptance angle, they will be reflected on the inner surfaces of the CPC, up to the receiver in an amount that allows the efficiency to remain at an acceptable degree (Figure 22).
Through equation (2) it was found that the acceptance angle is inversely proportional to the concentration ratio. Equation (2) can be expressed as follows:

$$CAP = \sqrt{C}\sin\theta \leq n \qquad (3)$$

Whereas, the CAP represents the product of the concentration ratio in the acceptance angle, or what is known as the optical etendue, which represents the characteristic of the optical system of the spread of the optical beam through a certain area and angle. The higher CAP, means greater the acceptance angle and concentration ratio.

Results

Through the practical results obtained from the Zemax program, the study focused on analyzing the performance of the CPC and the effect of some important parameters on the performance of the CPC, such as the concentration length and incidence angles, and its relationship to the acceptance angles and the difference in concentrations depending on the change in the radius of the entrance aperture that including this CPC receives radiation from one side. In order to analyze the number of incidence rays and their reflection towards the receiver and their influence on the performance, appropriate tools have been used that give a clear picture of the design efficiency. The detector is the most important tool that possesses this feature, which can give the number of rays that reach it for different locations of the sun without tracking system.
The efficiency of the CPC was calculated for different incidence angles (0^o-25^o) of the solar radiation as a simulation of its inclination during the daylight period, and to know the effect of its position on the efficiency of the concentrator. Also, a variable concentration length (100-500 mm) was adopted because of the importance of length truncation of the CPC in order to obtain a relatively high efficiency design.
The instrument that used in this work is the detector reading tool, as it is the most important tool for the non sequential ray tracing mode, through which the number of rays that reach the detector can be read as shown in figure (4), as well as the illumination distribution pattern of the detector surface. The primary purpose of using the

analysis tools is to assess the quality of the performance of the designed optical system and to determine the number of rays that can reach the detector to perform its function in transferring the radiation energy to the receiver for the purpose of heating the thermal warehouse and thus benefit from it for multiple purposes such as generating electricity, heating or cooking.

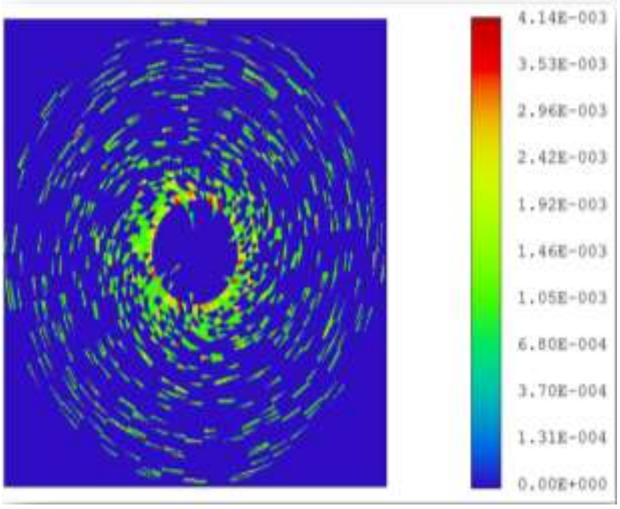


Figure 4. Number of received rays on the Detector viewer window in Zemax

Acceptance Angle

The CPC is designed with different Concentration ratios to compare them (C=1, 2, 3, 4, 5) represented by circular cross section, segmented by the relationship between the entrance aperture area to the exit aperture area approved by Zimax. The relationship between the concentration ratios for the sample is inversely proportional to the solar acceptance angle (figure 5). The results showed that the efficiency of the system depends on the concentration ratio, acceptance angle, and concentrator length.

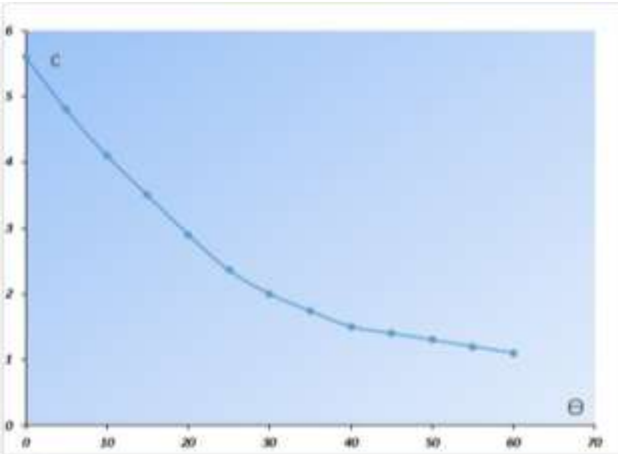


Figure 5. Relation between Concentration Ratio and Acceptance Angle

Concentration Ratio

Figure (6) illustrates the variation in the CPC efficiency, according to the incidence angles for each concentration, so that all the curves are sloped from the maximum value at a incidence angle of zero, where the received incidence angles for the sun's rotation movement were taken (0° - 25°), and by determining the acceptance angles that represent the largest possible from the radiation reaching the detector for each concentration ratio.

When measuring the optical efficiency of the solar radiation in the CPC sensed by the detector, it was found that the greatest optical efficiency was recorded at the concentration ratio (C=2) at an acceptance angle (25°), taking into account that the sun's tilt angles (0°-25°), by observing all the incidence angles within the range of the acceptance angle, it gives an acceptable efficiency, unlike the rest of the concentration ratios, which give a certain range of incidence angles, as in the concentration ratio (C=1) where the acceptance angle is (15°), meaning that the acceptable range of the incidence angles, i.e. the sun's tilt movement that can reach The detector is (0-15°) with neglecting incidence angles greater than (15°) with unacceptable efficiency.

As for the third concentration ratio (C=3) in which the entrance aperture is three times the exit aperture, the values, as we can see from figure (6) the efficiency values to descend as the incidence angle increases to an angle (15°) which is the most acceptable range for the third concentration ratio, while the rest of the values are not sufficiently acceptable enough to descend to zero at an angle of incidence (25°).

The slope of values at the concentration ratio (C=4) with a difference from the rest of the concentration ratios, because the acceptance angle of the acceptable optical efficiency is within the range (0°-10°) from within the incidence angles, which records the highest optical efficiency that the detector can sense within the fourth concentration ratio .

As for the fifth concentration ratio (C=5), the entrance aperture area is five times greater than the exit aperture area. Where we note the recording of the lowest optical efficiency at the vertical incidence at an acceptance angle equal to (Θ=0°), unlike the other concentrations because the amount of solar radiation reaching the detector is small in relation to the rest of the radiation reflected inside the CPC, which is reflected in more than one direction leading to its return from the entrance aperture.

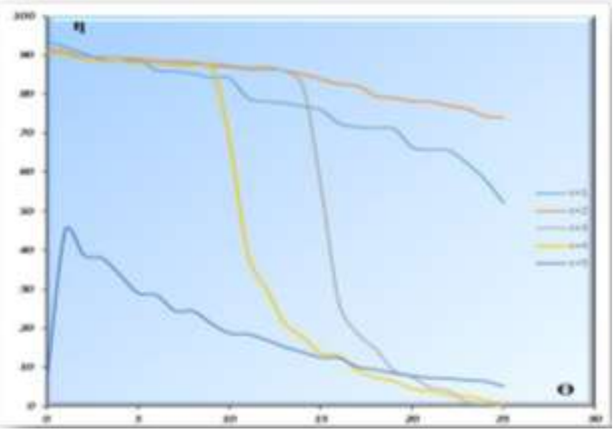


Figure 6. Relation between optical efficiency and incidence angle of different concentration ratio of CPC

Length of Concentrator

The process of truncating a portion of the concentrator’s length is useful for obtaining an optimal balance between the concentration ratio and the acceptance angle, which is illustrates the performance of CPC. The truncation had to be done to reduce the area of the reflecting surface, thereby reducing the radius of the entrance aperture. The sample with a concentration ratio (C=3) was chosen for being the best of rest of the models, due to its preference in grading the efficiency values with the difference in the incidence angle as shown in Figure (6). So the truncation of the length was gradual by (100 mm) for each case, as a result, five samples of CPC were considered with different lengths (L = 500, 400, 300, 200, 100 mm), which represents the efficiency of CPC for different values from the incidence angle of the rays for five samples of the concentrator's lengths.

From the noticeable comparison of the optical efficiency provided by the Zemax detector viewer, it is observed that the optical efficiency is close within the acceptance angle range (15°) as shown in figure (7), while variation appears as the incidence angle exceeds (15°) in lengths (500, 400, 300 mm). The values are approximately equal, i.e. the efficiency declines and unacceptable values approximate. As for the two lengths (100, 200 mm), they give an acceptable efficiency of the incidence angle (20°). As is evident at the length (100mm), the design gives good efficiency for a range up to the angle (25°). This is very important because the design without of tracking system.

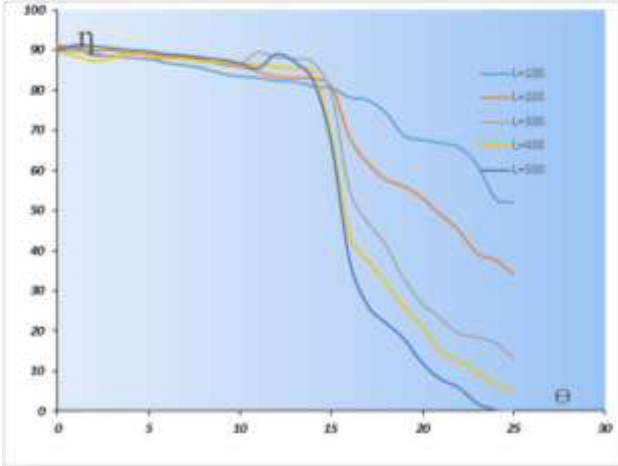


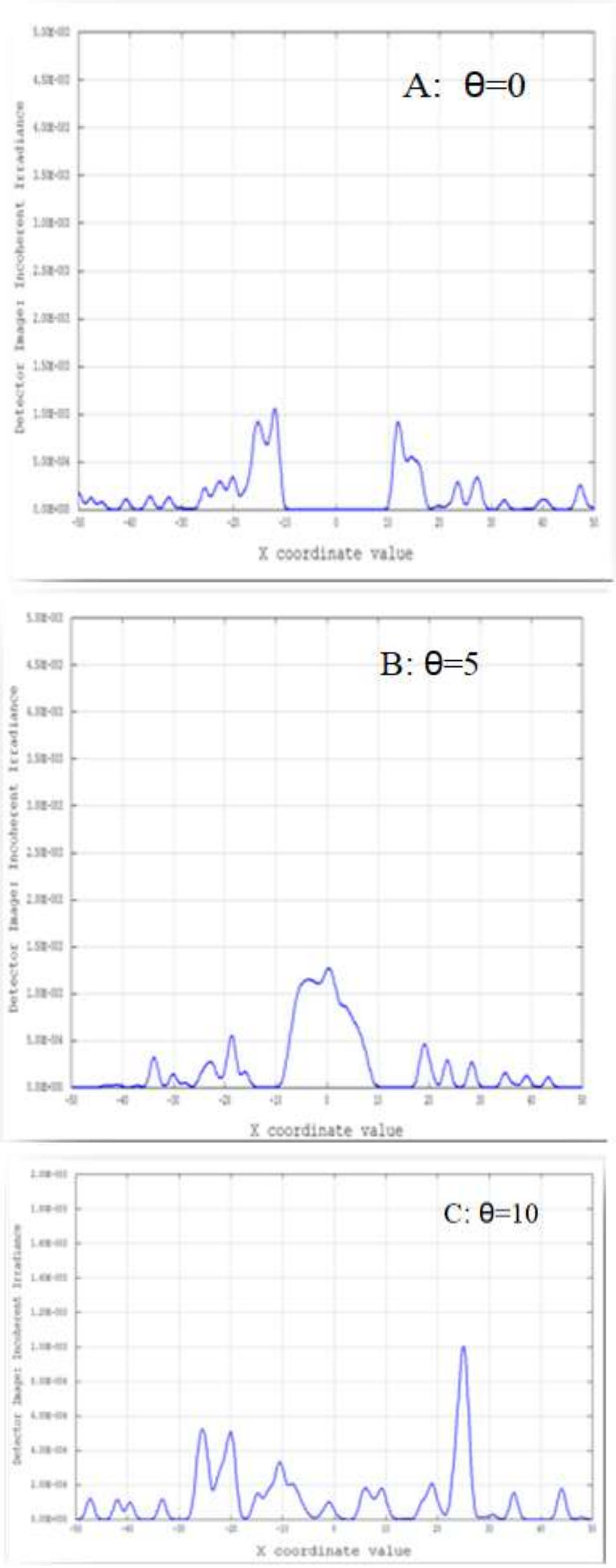
Figure 7. Relation between optical efficiency and incidence angle of different concentrator's length of CPC

Distribution of Illumination

The distribution of the radiation fall on the receiving surface (the detector) can be illustrated by the distribution of illumination, which is defined as how the light flux of a surface is distributed, as is also called the specific power. This tool was used through the detector window in Zemax program to know what the effect of changing the angles of incidence of rays and the number of rays connected to the detector resulting from the reflections within CPC.

The use of the illumination distribution is important for assessing the efficiency of CPC. Considering that the illumination distribution on a regular basis on the surface of the detector shows the ability of the recipient's surface to receive the radiation and the engineering distribution of the radiation on its surface.

Figure (8) shows the pattern of illumination distribution of CPC with a concentration ratio (C=3) for different fallout angles, note that in case (A), the distribution of the solar rays on the surface of the detector in a manner that covers almost all the area of the detector due to the vertical incidence of the rays from the sun at incidence angle (θ=0°), that reach to the detector surface. It is almost similar to the case at incidence angle (θ=5°) in Figure (B). While the illumination distribution changes randomly at the angles (θ=10°, 15°, 20°) in Figure (C, D, E) due to the change in the position of the solar rays that reaches the surface of the detector in the rest of the parts, due to the change in the angle of inclination of the source with respect to the solar concentrator leading to the lack of sensitivity of the detector is in the state (θ=5) in Figure (F).



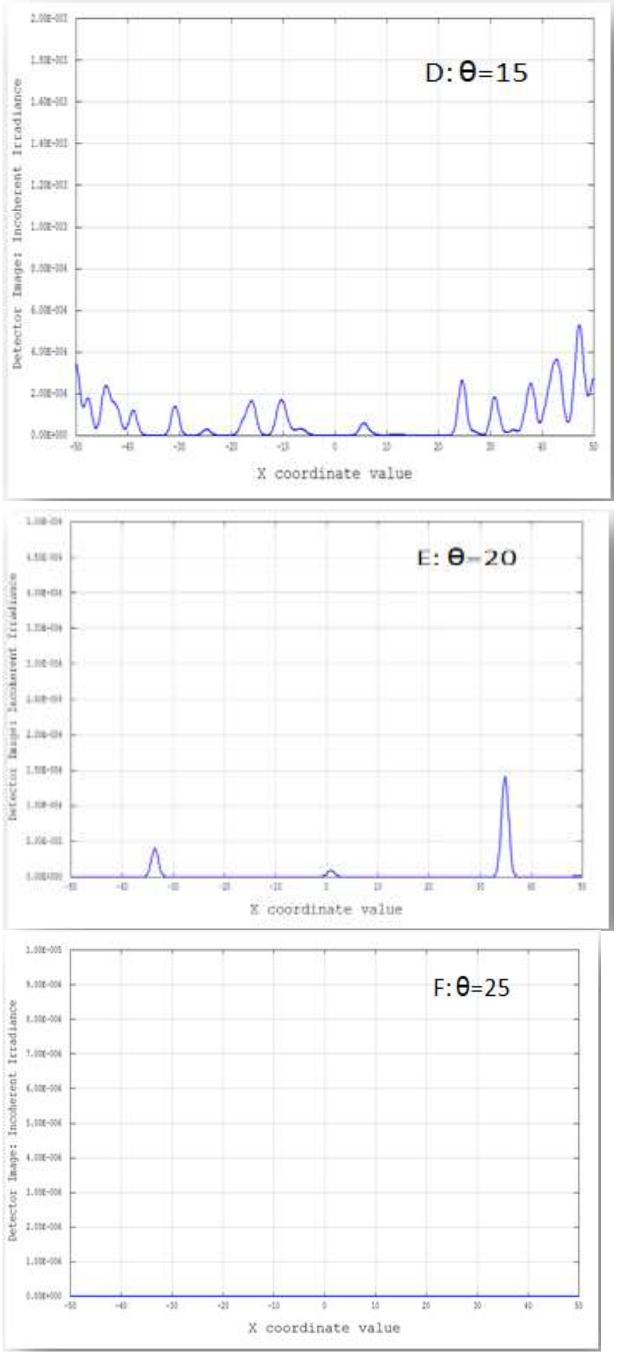


Figure 8. Irradiance Distribution in Detector Surface of CPC for different Incidence Angle

Conclusion

There are five designs were used for CPC with different concentration ratios (C = 1, 2, 3, 4, 5), and length truncation (100,200,300,400,500mm) were made for each sample at a concentration ratio (C=3) in order to obtain the best optical efficiency through determine the number of reflections that occur within the concentrator. The incidence angle of the incoming solar radiation has been changed to the range (0°-25°). Efficiency was measured based on the detector viewer. This tool provides a dot-ray distribution scheme that shows the number of rays connected to the detector, which is a criterion for determining the best performance according to the change in design parameters.

The results indicated the high flexibility in changing its parameters to obtain a high efficiency. Generally, the efficiency decreases with increasing incidence angle and consequently with increasing acceptance angle. As for the concentrator length, the results showed that the process of truncation of the concentrator length has a positive effect in increasing the acceptance angle for all used samples.

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