Illuminating the Design Process

White Paper, August 2010

Solar CPC modeling

Solar Compound Parabolic Concentrator (CPC) Modeling using OptisWorks

OPTIS
Illuminating the Design Process

Solar Compound Parabolic Concentrator (CPC) Modeling using OptisWorks

Part I: Introduction

1. Introduction

Compound Parabolic Concentrator (CPC) is an ideal solar energy collector. Solar concentrators collect and focus a larger area of sun light onto a smaller area with minimum loss. The main purpose of solar concentrators is to reduce the cost of the entire solar system. Solar cells are typically the most expensive components in the entire system. The cost will be prohibitive if a large area has to be covered with solar cells to collect solar energy. The use of solar concentrators reduces the area of expensive solar cell material required and substantially reduces the overall cost. For example, a CPC with a stationary position can typically reduce the required solar cell area by up to four times (4X concentration ratio). Higher concentration ratio can be achieved by seasonally adjusting the CPC orientation or using a sun tracking system.

Illuminating the Design Process

Solar Compound Parabolic Concentrator (CPC) Modeling using OptisWorks

This paper describes the modeling of a classic CPC using OptisWorks. A routine to build a CPC in SolidWorks is introduced, followed by the optical modeling, including concentrator reflective surface property and a real solar source, the sun. Finally, CPC truncation, a practical design concern, is analyzed using the OptisWorks tolerance analysis tool.

The objective of this paper is to provide OptisWorks users a guideline to model any type of solar concentrators or complex solar systems.

Part II: CPC Modeling

2.1 Geometry

The geometry of an ideal CPC 2-D cross-section is shown in Fig. 1. It concentrates the sun radiation within a cone of half angle θ onto a flat absorber on the bottom (AB in Fig. 1), where solar cells are located. As shown in Fig. 1, the cross section of a CPC is symmetric about the vertical axis. Each side of the CPC is a segment of a tilted parabola. For example, the right branch (BC) is a segment of parabola with the focus at point A. The axis of this parabola is tilted counterclockwise by an angle of θ with respect to the CPC vertical axis of symmetry. For an untruncated CPC, two parameters are required to fully constrain the geometry: the width of the flat absorber (AB in Fig. 1) and the acceptance half angle θ. Based on these geometrical features and constraints, the CPC cross-section in Fig. 1 can be sketched in SolidWorks. By sweeping the 2-D SolidWorks sketch along the CPC aperture contour, a 3-D CPC can be modeled.

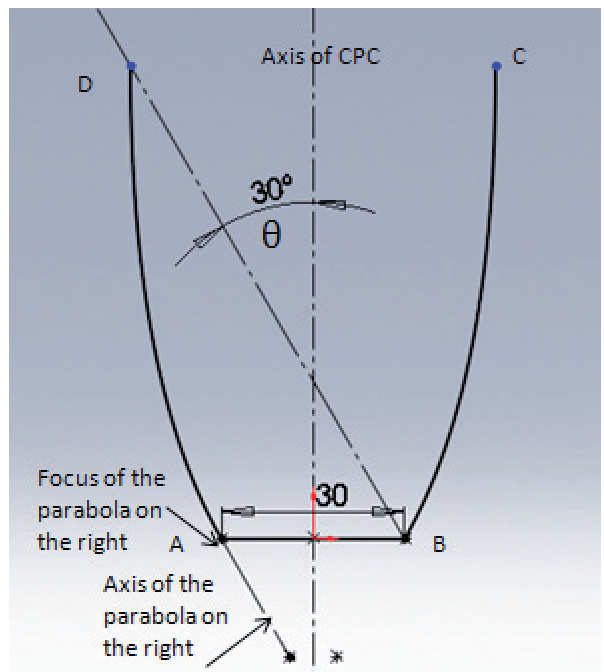


Fig. 1: 2-D cross-section of an ideal Compound Parabolic Concentrator (CPC).

The 3-D geometry of a CPC may have several variations. This paper models a 3-D CPC with a square aperture as shown in Fig. 2. In theory, an ideal CPC with a half angle cone θ will have a concentration ratio:
For example, an untruncated CPC with a half angle 30° in Fig. 1 has a concentration ratio of 4X.

$$C = (\overline{CD} / \overline{AB})^2 = \frac{1}{\sin^2 \theta}$$

OPTIS
Illuminating the Design Process

Solar Compound Parabolic Concentrator (CPC) Modeling using OptisWorks

To reduce the cost of a CPC, a common practical design change is to truncate the height of the CPC so that less mirror material is needed. Because the mirror portion near the entrance pupil (CD in Fig. 1) is almost parallel to the optical axis, truncation of this part does not reduce entrance pupil area and concentration ratio significantly. The CPC performance at different truncation height will be simulated and analyzed using OptisWorks in a later section.

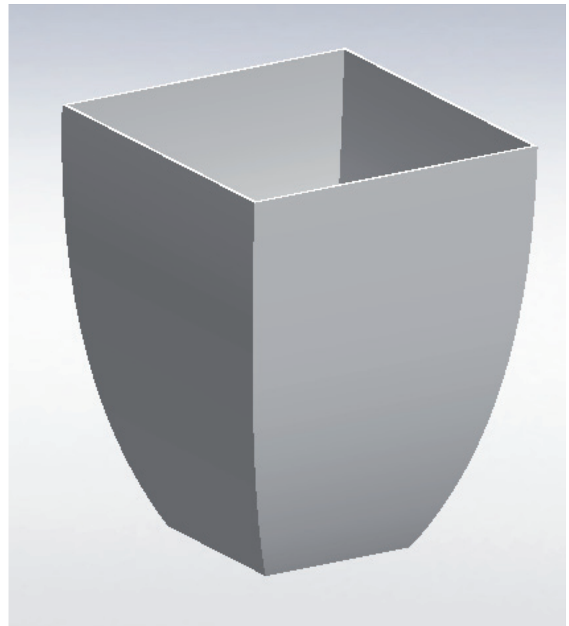
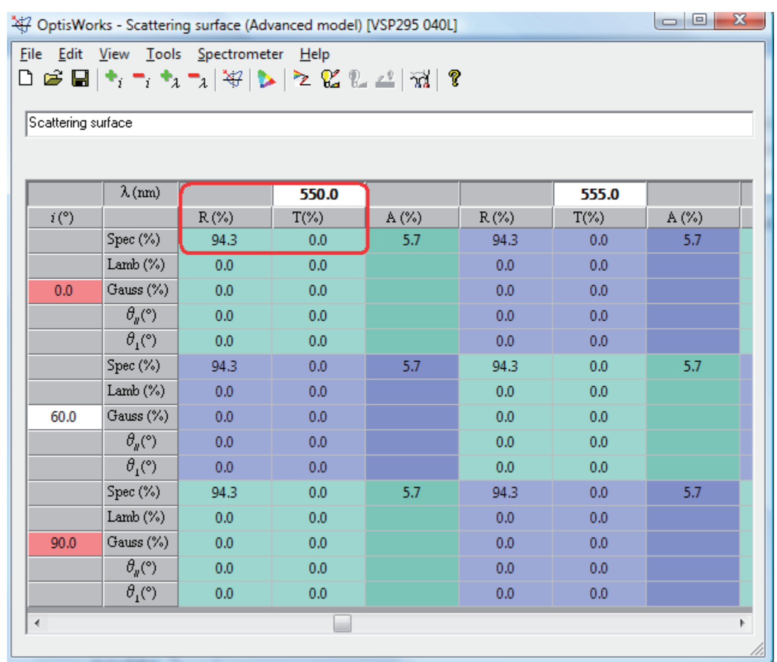


Fig. 2: 3-D geometry of a CPC with a square aperture.

2.2 Surface optical property

The highly reflective mirror surface is a key component of CPC systems. Predefined OptisWorks surface property files from certain major solar material suppliers are available in the OPTIS online library. In this paper, a specular reflection surface manufactured by Almeco-TiNOX (http://www.almeco-tinox.com) is used to model the CPC surface. Users can download this surface property from OPTIS library and directly apply it to the CPC surface.

Fig. 3 shows the content of the surface property file, viewed by OptisWorks surface property editor. The editor shows that the specular reflectivity is modeled as a function of wavelength and light incident angle. For example, the reflectivity at 550nm is 94.3% as highlighted in Fig. 3. These reflectivity data is either provided by suppliers or accurately measured using OPTIS state-of-the-art instrument. The surface property editor also allows users to create any surface property type of their own, provided that the surface property data is known to the users.



	λ (nm)		550.0			555.0	
i (°)		R (%)	T(%)	A (%)	R (%)	T(%)	A (%)
	Spec (%)	94.3	0.0	5.7	94.3	0.0	5.7
	Lamb (%)	0.0	0.0		0.0	0.0	
0.0	Gauss (%)	0.0	0.0		0.0	0.0	
	$\theta_{//}$(°)	0.0	0.0		0.0	0.0	
	θ_{1}(°)	0.0	0.0		0.0	0.0	
	Spec (%)	94.3	0.0	5.7	94.3	0.0	5.7
	Lamb (%)	0.0	0.0		0.0	0.0	
60.0	Gauss (%)	0.0	0.0		0.0	0.0	
	$\theta_{//}$(°)	0.0	0.0		0.0	0.0	
	θ_{1}(°)	0.0	0.0		0.0	0.0	
	Spec (%)	94.3	0.0	5.7	94.3	0.0	5.7
	Lamb (%)	0.0	0.0		0.0	0.0	
90.0	Gauss (%)	0.0	0.0		0.0	0.0	
	$\theta_{//}$(°)	0.0	0.0		0.0	0.0	
	θ_{1}(°)	0.0	0.0		0.0	0.0	

Fig. 3 Almeco-TiNOX high specular reflective surface modeled in OPTIS surface property editor.

Part III : Optimization and simulation results

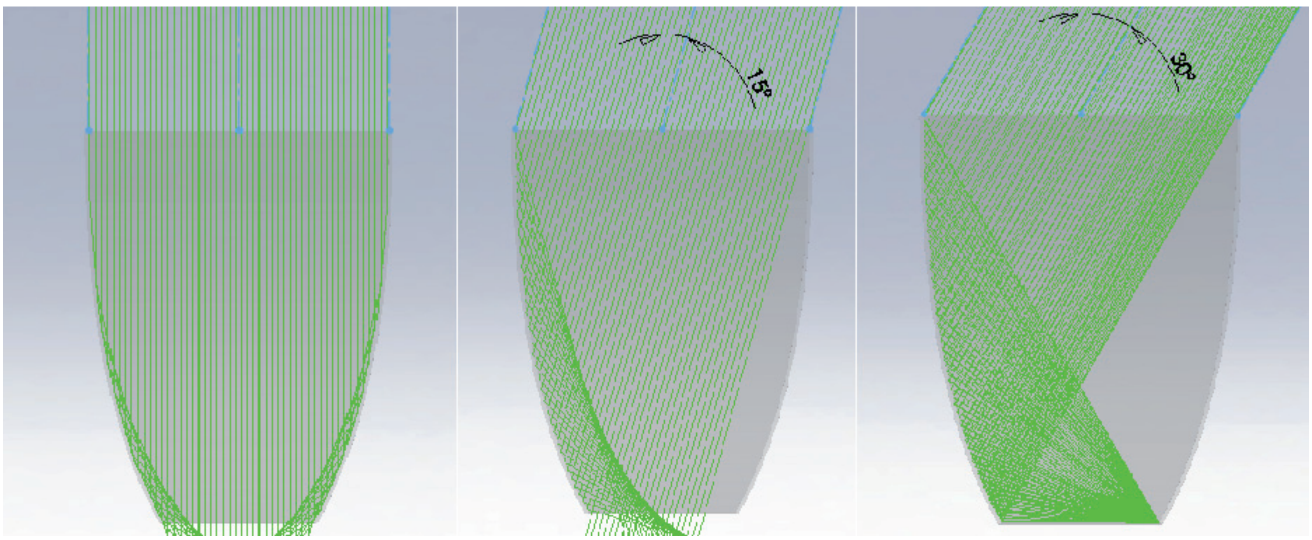


Fig. 4: Sun light concentrated by the CPC from different incident angles (0°, 15° and 30° from left to right).

3.1 Ray tracing with interactive source

Interactive source is a type of light source that can be modeled in OptisWorks. It is defined using simple reference geometries in SolidWorks such as points, curves and faces. Ray tracing by interactive sources is generated in synchronized with CAD geometry change. For concentrator design, this feature allows users to quickly validate and optimize the reflector geometry for each specific angular field of incident light.

For the purpose of proof of concept, an interactive source ray tracing is used to simulate how the light from different sun directions gets concentrated by the CPC. A collimated line source is defined to model the sun light in a 2-D cross section. The ray tracing in Fig. 4 shows how the CPC concentrates the sun light from three different angles (0°, 15° and 30°). At 30° incident angle, which is the limit of the CPC angular field of view, the light gets focused at the boundary of the CPC bottom surface. At a smaller incident angle such as 0° and 15°, the light distribution on the CPC bottom surface is a contribution of both direct incidence and reflection by the CPC, thus more uniform. The analysis from interactive source ray tracing can assist the users to validate the CPC design and estimate of the light distribution pattern on the solar cells.

3.2 Sun Source Modeling

To model a complete solar source, the sun, optical parameters including sun power, spectrum and intensity angle are required. By defining a photometric "surface source" in OptisWorks, these parameters can be input into the model for ray tracing and simulation.

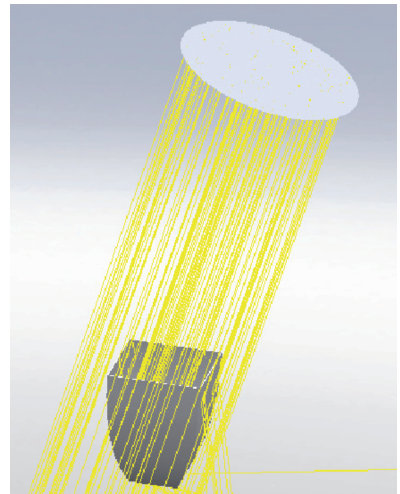


Fig. 5 Ray tracing from a solar source with real optical parameters including power, intensity and spectrum.

A practical way to define the size and shape of the solar source in OptisWorks is to define the source on a planar surface. To ensure accurate simulation results, the size of the planar surface should be large enough to cover the largest dimension of the optics in the model. Fig. 5 shows the ray tracing from the sun source modeled on a circular planar surface. The diameter of the circular planar surface should be large enough that rays emitting from the surface covers the entire CPC aperture.

The appropriate average irradiance is assumed to be about 1000 W/m2. This value varies due to many factors such as weather conditions, latitude, longitude and time of the year. Since OptisWorks only allows Watts values as an input to model the sun irradiance, a conversion from irradiance (Watts/m2) to power unit (Watts) is required. The equation below shows how to convert from irradiance to power:

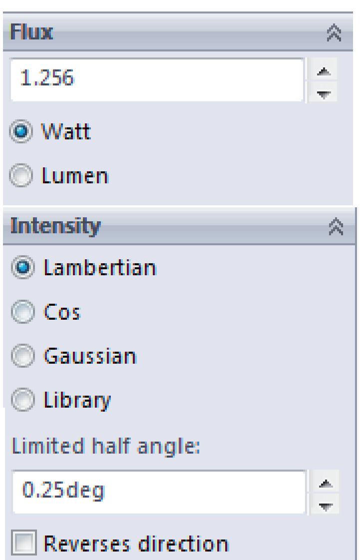


Fig. 6 Flux and intensity angle used in OptisWorks "Surface Source definition" to model the sun.

$$\Phi = E \cdot A$$

where E is the irradiance and A is the area of the planar surface on which the sun source is defined. Φ is the calculated incident solar power (flux) from that area in the unit of Watts. For example, the planar surface area shown in Fig. 6 is about 1.256x10-3 m2. We have assumed the sun irradiance to be 1000W/m2. Using the equation above, the calculated solar power emitted from the surface is 1.256 Watts, which is input into the flux box in OptisWorks "surface source" definition as shown in Fig.6.

The light emitting from the sun surface is Lambertian. Based on the sun diameter and the average distance between the sun and the earth, the divergent angle of the sun light incident on earth is calculated to be approximately 0.5 degrees. Therefore, a "Lambertian" intensity type and a half-angle 0.25° are used as input in the "surface source" definition as shown in Fig. 6.

OPTIS
Illuminating the Design Process

Solar Compound Parabolic Concentrator (CPC) Modeling using OptisWorks

The spectrum of the sun represents the solar power distribution at different wavelengths. CIE standard Illuminant D65 spectrum is commonly used to model the sun spectrum in mid-day. Users can download this spectrum file from OPTIS online library and apply to the solar source. Fig. 7 shows the D65 spectrum curve viewed in the OptisWorks spectrum editor.

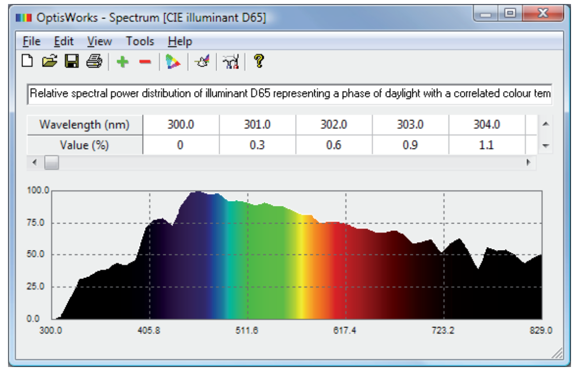


Fig. 7 CIE standard illuminant D65 used in OptisWorks to model the sun spectrum.

3.3 Solar detector modeling

Typical solar power collection systems located behind the concentrators include photovoltaic or thermal collectors. These collection systems themselves are complex optical and mechanical components. Since this paper is targeted at the modeling and analysis of the CPC, an irradiance detector is defined directly at the bottom exit aperture of the CPC to represent an ideal solar energy collector, as shown in Fig. 7. Solar power and irradiance collected by this virtual detector will be simulated and analyzed in the next section.

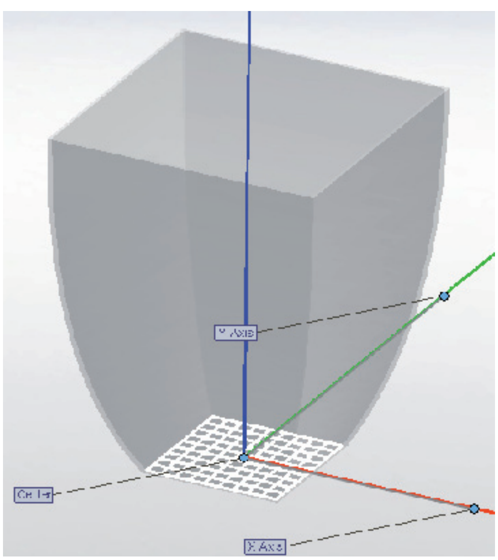


Fig. 8: An irradiance detector (white grids) defined on the bottom exit aperture of the CPC to model an ideal solar energy collector.

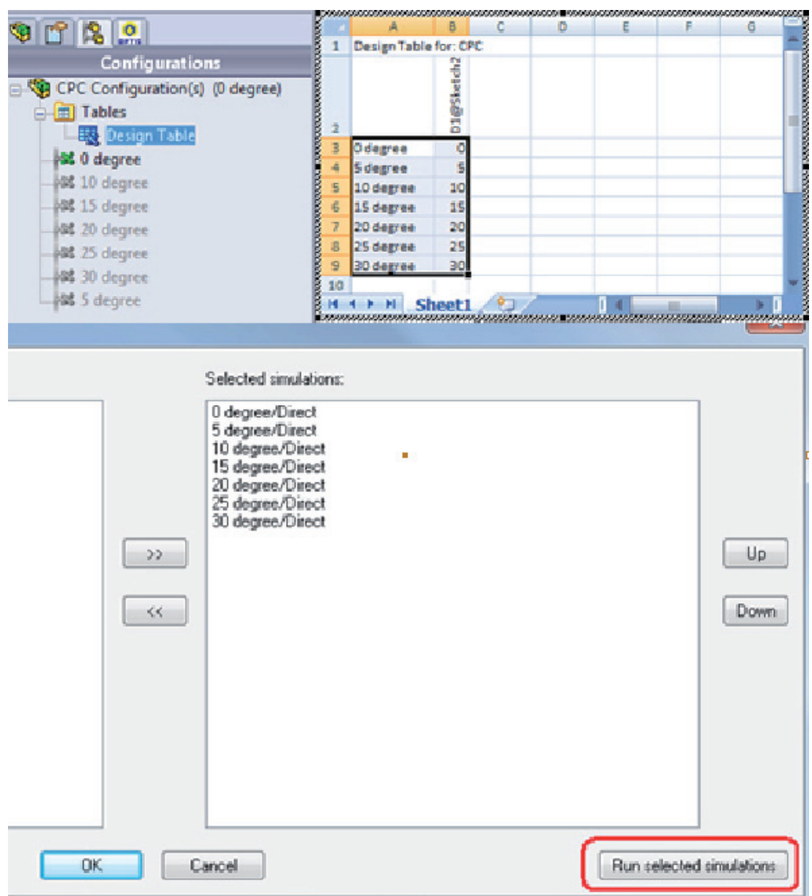


Fig. 9: OptisWorks multi-configuration simulation (bottom) associated with SolidWorks design table (top) allows simulations from different sun positions launch in one mouse-click.

OPTIS
Illuminating the Design Process

Solar Compound Parabolic Concentrator (CPC) Modeling using OptisWorks

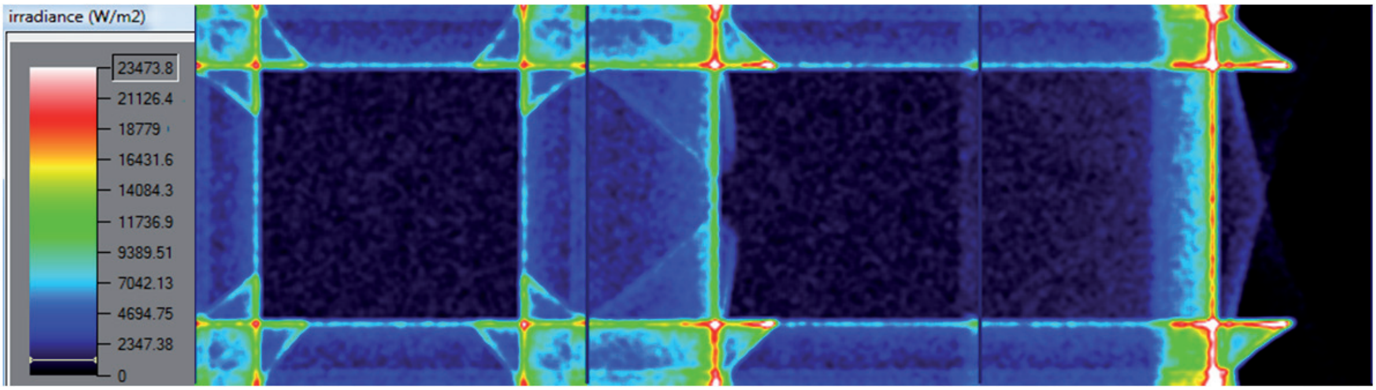


Fig. 10: Simulation results of irradiance concentrated by the CPC on the detector (Fig. 8) with the sun position at 0°, 10° and 20° from the zenith (left to right).

3.4 Simulation of irradiance at different sun positions

The sun changes its positions relative to a static CPC throughout the day. The integration of OptisWorks inside SolidWorks allows users to take advantage of the SolidWorks design table and run optical simulation at different sun positions in a batch processing. Fig. 9 (top) shows that seven incident angles of the sun are configured using the SolidWorks deign table. These angles are referenced to the zenith direction, varying from 0° to 30° with 5° interval. OptisWorks can link to these configurations (Fig. 9 bottom) and simulate the solar energy collected by the irradiance detector in one mouse click.

Fig. 10 shows the irradiance pattern at 0°, 10° and 20°. The false color in these results represents different irradiance levels. Users can take quantitative measurement directly from these simulation results, such as 1-D cross section and 2-D total flux and average irradiance. Fig. 11 shows a 1-D cross section at the center of the detector with the sun at the zenith. Other information such as total flux and average irradiance can be measured directly from these 2-D irradiance maps. Fig. 12 shows a plot of the total flux concentrated by the CPC at different sun positions.

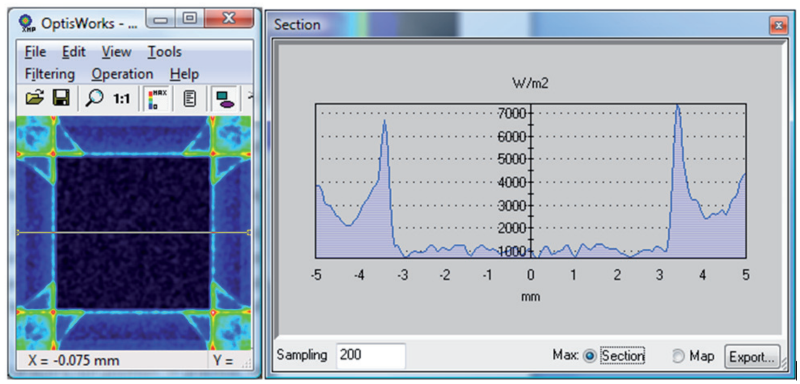


Fig. 11: 1-D irradiance plot (right) across the center of the 2-D irradiance map (left) with the sun located at the zenith.

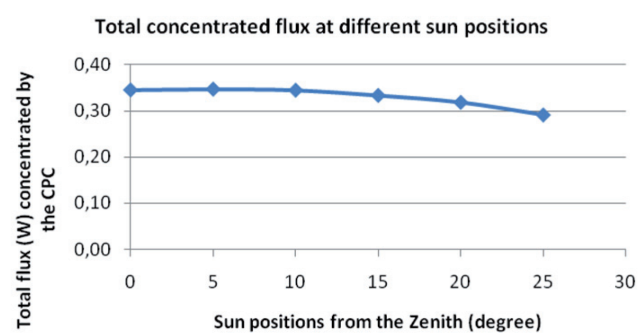


Fig. 12: Flux measured by the detector at different sun positions. The flux is measured from 2-D irradiance simulation results on the detector as shown in Fig. 10.

It is noticed that irradiance hot spots exist in the result of every sun position. In practice, high irradiance hot spots on a photovoltaic solar cell reduce the energy collection efficiency. Thus, to design a CPC with good uniformity is desired. However, it is less an issue for a solar thermal collection system. An advanced analysis tool in OptisWorks named "Light Path Finder" allows these hot spots to be traced back to the source. Users can find the ray paths that only contribute to the hot spots, from the source through the geometry to the final detector. It assists the user to understand where the hot spots come from and enable them to find a way to resolve it. Fig. 13 shows that the hot spot when the sun is located at 10° from the zenith comes from the perfect focus of the CPC geometry. Using the same feature, it is validated that hot spots from other sun positions in Fig. 10 are all caused by the CPC focus. This information allows methods to be developed to reduce the size and magnitude of those hot spots.

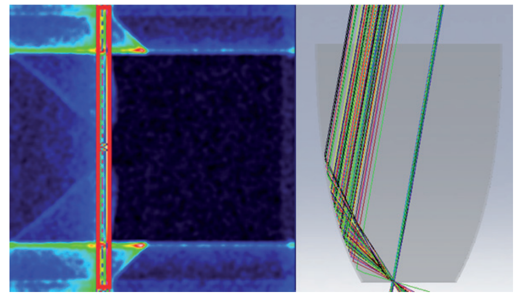


Fig. 13: OptisWorks "Light Path Finder" shows that the highlighted hot spot (left) is caused by the focus of the CPC.

For example, diffusers can be placed on top of the solar cells to scatter the incident light angles and make the irradiance more uniform. Fig. 14 shows that the hot spot can be reduced by applying two diffusers in stack on top of the detector. The irradiance is more uniform with the diffusers (right) than without the diffuser (Left). The type of

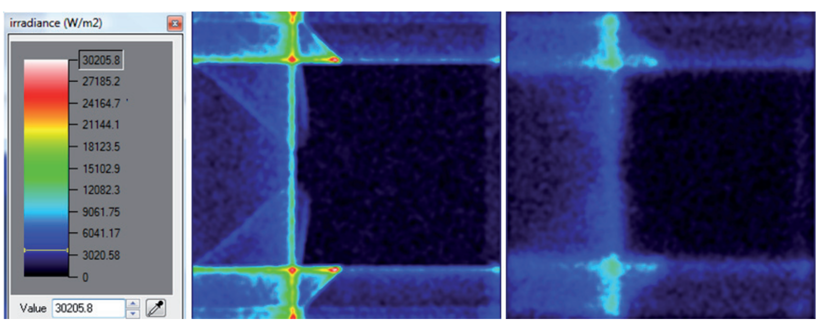


Fig. 14: Irradiance uniformity comparison. Left: without diffuser; Right: with two diffusers.

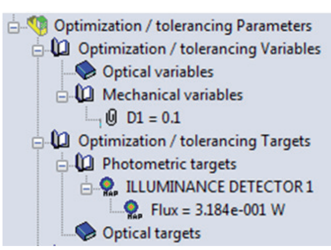
diffuser used in this example is Bayer Makrofol® DP 1243 with a thickness of 150µm. This diffuser is available in the OPTIS online library for users to download and use directly. One side-effect of using the diffusers is that they reduce the total flux collected by the detector, due to light absorption and reflectivity by the diffusers. However, irradiance uniformity is usually a more critical factor that affects overall energy efficiency than the total flux, especially when photovoltaic solar cells are used in the collection system.

OPTIS
Illuminating the Design Process

Solar Compound Parabolic Concentrator (CPC) Modeling using OptisWorks

3.5 Tolerance analysis of the CPC height

A practical concentrator design change to reduce cost is to truncate the CPC height and reduce the CPC material to be used. However, a truncated CPC collects less solar power and has less concentration ratio due to reduced aperture size. Thus, it is a trade-off between manufacturing cost and energy collection efficiency. OptisWorks tolerance analysis provides a tool to help the designers to make a balanced decision. Fig. 15 (left) shows that the truncated CPC height is defined as the tolerance variable and the total flux on the detector is defined as tolerance analysis target. The analysis process will automatically sample a user-defined variable range and simulate the total flux at each sample point. Fig. 15 (right) shows the impact of relative CPC height on the flux measured by the detector, with the sun position at 0° (blue curve) and 20° (red curve) from the zenith. The flux attenuation percentage and the truncation percentage are both referenced to the original untruncated CPC. The similarity between the two curves in Fig. 15 indicates that the impact of CPC height on flux is consistent over different sun positions within the CPC designed acceptance angle. Designers can make a trade-off decision using the information provided by Fig. 15 in combination with their own specifications. For example, if 15% flux reduction is acceptable, the CPC can be truncated as much as 50% of its original height.



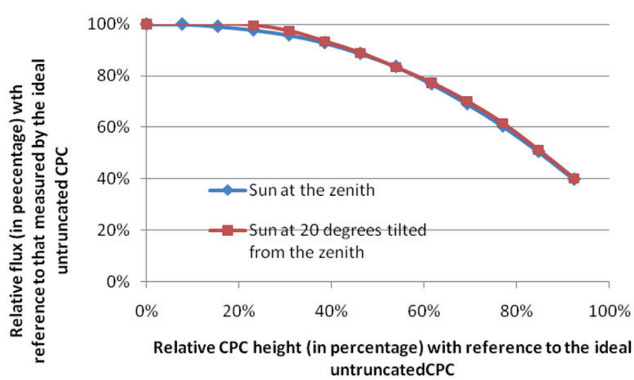


Fig. 15: Impact of CPC height on the flux collection efficiency. Left: OptisWorks tolerance analysis setup; Right: Simulated flux on the detector for CPCs of different height, with the sun at zenith (blue curve) and the sun at 20° from zenith (red curve).

Part IV : Summary

This paper presents a routine to model and analyze a solar concentration system using OptisWorks. A perfect Compound Parabolic Concentrator (CPC) is used as a template. OptisWorks features including interactive ray tracing simulation, light path finder and tolerance analysis are demonstrated. These features assist designers at different levels from design, proof of concept, virtual solar power measurement, hot spot tracking to optimization. Other solar concentrators such as Compound Elliptical Concentrator (CEC) or trumpet concentrator can be modeled and analyzed using the same process.

Written by Joe Wang PhD, OPTIS North America.