Created in COMSOL Multiphysics 6.0

Solar Dish Receiver

Introduction

A paraboloidal dish concentrator can focus incident solar radiation onto a target or cavity receiver, resulting in very high local heat fluxes. This can be used to generate steam, which can be used to power a generator, or hydrogen, which can be used directly as a fuel source. In some applications, such as hydrogen production via the solar thermal gasification of biomass in supercritical condition, the uniformity of the flux on the surface of the cavity receiver has a significant effect on the efficiency of hydrogen production (Ref. 1).

The basic concept behind the paraboloidal dish concentrator is shown in Figure 1. Solar radiation enters from the right and is reflected by the concentrator. The rays converge toward an extremely small area in the focal plane, where a cavity receiver can be positioned.

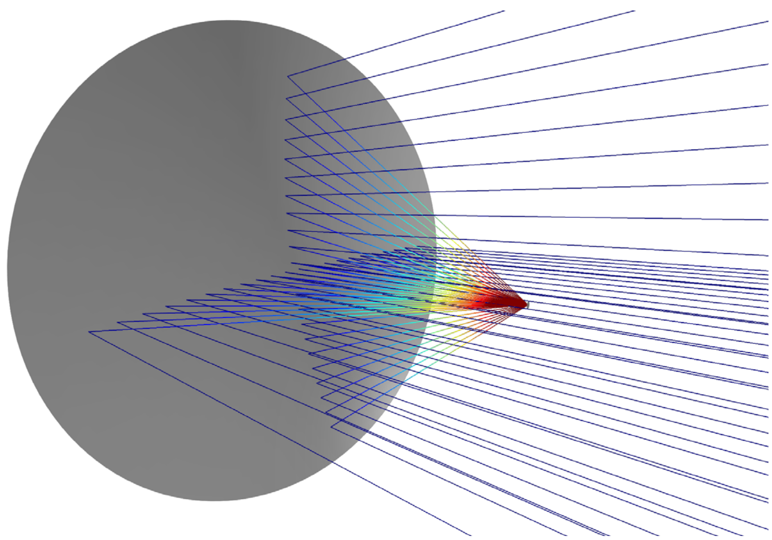

Figure 1: A simple solar concentrator system consisting of a parabolic dish and a small receiver. The color of the incident and focused rays corresponds to the ray intensity.

Of particular interest in evaluating the performance of solar collector-receiver systems is the *concentration ratio*, defined as the ratio of the incident flux to the ambient solar flux. A high concentration ratio usually means that the concentrator is capable of focusing solar radiation efficiently. When computing the concentration ratio, the incident flux can either be measured in the focal plane or on the surface of the cavity receiver.

A variety of computational methods to predict the concentration ratio are available. Shuai et al. (Ref. 1) compared the results of a Monte Carlo ray tracing code to compute the concentration ratios of several different cavity geometries. Jeter (Ref. 2) proposed a semi-analytical method in which the concentration ratio is computed via integration of the intensity distribution over the concentrator surface. A standard practice in many solar energy research institutions is to measure the concentrated solar flux using charge coupled device (CCD) imaging cameras (Ref. 3).

The ideal focusing system consists of a perfectly smooth paraboloidal dish that focuses collimated incident solar radiation onto a point in the focal plane that is infinitesimally small within the limit of the approximations of geometrical optics. However, several imperfections in this system cause the measured concentration ratio to deviate from the ideal case.

To accurately predict the concentration ratio, the finite size of the sun and the intensity distribution over the solar surface must be considered. The intensity profile on the solar disk is referred to as *sunshape*. Solar intensity is greatest at the center of the solar disk and decreases closer to the periphery of the disk, a phenomenon called ***solar limb darkening***.

Integration Method for Ideally Smooth Solar Collectors

A method for computing the concentration ratio in the focal plane in the absence of surface roughness is described by Jeter (Ref. 2). Consider differential area elements on the surface of the concentrator at $\mathbf{r}_c$ and on the focal plane of the receiver at $\mathbf{r}$, as shown in Figure 2.

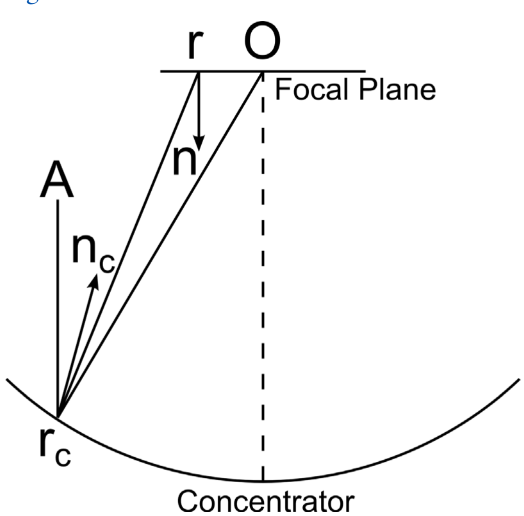

Figure 2: Diagram of the paraboloidal solar concentrator.

where the surface normals at the concentrator and focal plane are $\overline{\mathrm{r_c n_c}}$ and $\overline{\mathrm{rn}}$, respectively, and O is the focus. The following angles are defined:

$$\delta_1 = \angle \mathrm{Or_c r} \qquad \theta_c = \angle \mathrm{rr_c n_c} \qquad \theta = \angle \mathrm{r_c rn}$$

The concentration ratio at **r** is

$$C(\mathbf{r}) = \frac{1}{I_0}\int_{\Omega} \frac{f\cos(\theta)\cos(\theta_c)}{|\mathbf{r}-\mathbf{r}_c|^2} dA_c \tag{1}$$

$$f(\delta) = \begin{cases} I_0/(\pi\sin(\psi_m)^2) & \delta \le \psi_m \\ 0 & \delta > \psi_m \end{cases} \tag{2}$$

where:

- f (SI unit: $W/(m^2$ steradian)) is the radiant intensity,
- Ω denotes surface integration over the collector surface,
- I_0 (SI unit: W/m^2) is the incident solar flux,
- ψ_m is the maximum solar disk angle, and
- dA_c (SI unit: m^2) is a differential area element on the surface of the collector.

In Equation 2 it is assumed that the incident solar flux does not vary as a function of position on the solar disk; that is, no solar limb darkening is considered. However, it would be possible to extend Equation 2 to account for solar limb darkening by including a term dependent on the angle δ on the right-hand side.

In this model, Equation 1 is implemented using the `dest()` operator. The `dest()` operator evaluates a term in a nonlocal integration coupling on the destination side. For example, including the term `u/((dest(x)-x)^2+(dest(y)-y)^2)` in a nonlocal integration coupling gives the following function of x and y:

$$f(x, y) = \int \frac{u(x', y')}{(x-x')^2 + (y-y')^2} dx'dy'$$

Model Definition

A parabolic solar dish concentrator with a focal length, f, of 3 m is constructed using a built-in Part from the Part Library for the Ray Optics Module. The geometry also includes a small cylinder, one surface of which lies in the focal plane. The incident flux on this surface will be computed, then used to compute the concentration ratio. By adjusting the shape of the cylinder it would be possible to compute the concentration ratios for various cavity geometries, as in Ref. 1, but for the present analysis, only the concentration ratio in the focal plane is computed.

If the dish was a perfect reflector (all of the incoming radiation reflected specularly), the dish was perfectly smooth, and the rays from the sun behaved as planar wavefronts from an infinitely distant point source, all of the incoming rays would be focused on a single point on the collector, at the focus of the paraboloid (within the limits of the geometrical optics approximation). However, in this model, several deviations from this idealized case are considered.

A dedicated boundary condition called **Illuminated Surface** is used to release rays directly from the surface of the dish, initializing their directions as if they were reflected from a distant plane wave source. The direction at which the rays are released from the surface of the dish depends on the incoming ray direction vector $\mathbf{n}_\mathrm{i}$ and the outward surface normal $\mathbf{n}_\mathrm{s}$, according to the formula

$$\mathbf{n}_\mathrm{r} = \mathbf{n}_\mathrm{i} - 2(\mathbf{n}_\mathrm{i} \cdot \mathbf{n}_\mathrm{s})\mathbf{n}_\mathrm{s} \tag{3}$$

The intensity of each individual ray can be computed along its trajectory; the evolution of ray intensity depends heavily on the curvature of the dish. More details on intensity computation can be found in the *Ray Optics Module User's Guide*.

Each ray released is also assigned a fixed power, which is assigned an appropriate value based on the **Source power** setting for the **Illuminated Surface** feature. When the rays reach the surface of the solar collector, they are stopped by the **Wall** feature. The **Deposited Ray Power** subfeature computes the incident heat flux in the focal plane. By taking the ratio of the deposited flux to the incoming solar flux, the concentration ratio on the surface can be computed.

Some of the incoming radiation is absorbed by the dish itself. Even a newly installed dish absorbs a significant fraction of the incident radiation, and parts of the dish can degrade over the course of its lifetime, reducing its efficiency (Ref. 3). In this model, the absorption coefficient is set to 0.1, meaning that 90% of the incoming radiation is reflected.

An additional correction is included due to the finite size of the sun. Not all incident rays will be parallel; instead, the incident rays are sampled from a narrow cone with maximum angle, ψ_m, of 4.65 mrad. In practice, some radiation is also emitted from the *circumsolar region* surrounding the solar disk, instead of the solar disk itself, but this radiation is neglected in the present model; that is, a *circumsolar ratio* (*CSR*) of zero is assumed. When rays are released from points other than the center of the solar dish, their initial intensity can be reduced to account for solar limb darkening effects.

Since the surface of the dish is not perfectly smooth, the reflected rays are not all released at the exact direction given by Equation 3. Instead, the surface normal is perturbed by an additional angle that is sampled from a Rayleigh distribution:

$$P(\phi) = \frac{\phi}{\sigma_\phi^2}\exp\left(-\frac{\phi^2}{2\sigma_\phi^2}\right)$$

where σ_ϕ (SI unit: rad) is the *surface slope error*[1].

The model includes two studies, each corresponding to a separate instance of the **Illuminated Surface** feature. For each study, rays are released from 100,000 distinct points. At each point, the incident ray direction is perturbed by a random angle; the probability density of these perturbations is uniform within a cone of angle ψ_s.

For the first study, no limb darkening model is used and the surface is assumed to be perfectly smooth and reflective. The resulting concentration ratio is compared to the semi-analytical method of Jeter (Ref. 2).

For the second study, a limb darkening model is used to reduce the intensity of solar radiation emitted from the edge of the solar dish. The built-in limb darkening model follows an exponential fit, with wavelength-dependent exponents as described in Ref. 5. The resulting concentration ratio in the focal plane is compared to results in Ref. 1.

For each study, the concentration ratio is computed on a small circular disc, centered at the origin, which lies in the focal plane.

Simply plotting the concentration ratio as a function of the radial distance and azimuthal angle in the focal plane is not sufficient to compare against the data of Refs. 1-2 because there is a significant amount of statistical noise in the model. This is due to the random nature of the incident ray direction vectors at each release point. To smooth some of this statistical noise, the average concentration ratio is taken over all azimuthal angles for each value of the radial coordinate in the focal plane:

$$\bar{C}(\rho) = \frac{1}{2\pi}\int_0^{2\pi} C(\rho, \theta)d\theta \tag{4}$$

Equation 4 is implemented using a General Projection nonlocal coupling. A General Projection nonlocal coupling evaluates a series of line or curve integrals on a source. In

1. The definition of the surface slope error used in the Illuminated Surface feature seems to differ from the definition used by Shuai et al. For the Illuminated Surface, the surface slope error is used to perturb the surface normal direction, not the incident ray direction. As a result, values of the surface slope error used in this model differ from the corresponding results in Ref.1 by a factor of 2.

this example, the **General Projection 1** node integrates the accumulated variable over concentric circles in the focal plane, centered at the origin.

Results and Discussion

The ray trajectories emanating from the solar dish can be seen in Figure 3. Almost every ray is stopped by the receiver, with only an extremely small number of propagating rays visible above the focal plane.

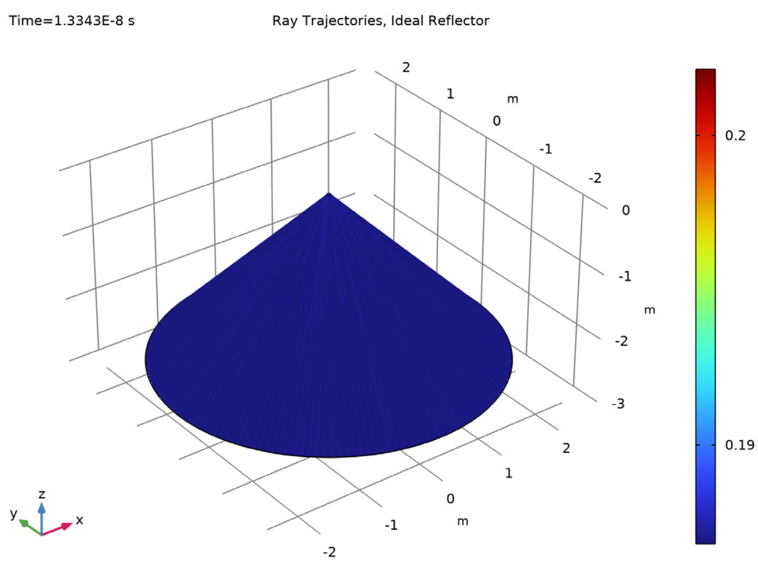

Figure 3: The ray trajectories emanate from the illuminated surface and hit the receiver.

The incident heat flux arriving on the surface of the collector is shown in Figure 4. The heat flux is extremely high, with an average value of about 23 W/mm^2 near the center of the focal plane. The statistical noise is also apparent, since in some boundary mesh elements the incident heat flux exceeds 30 W/mm^2. If smoothing is disabled in the plot, then in a very small number of boundary elements the incident flux is shown to be even greater, as high as 51 W/mm^2. This demonstrates the need for averaging in the azimuthal direction to more consistently compare the concentration ratio to published values.

The azimuthally averaged concentration ratio is plotted in Figure 5 along with the semi-analytical solution of Jeter (Ref. 2). The data are shown to be in close agreement.

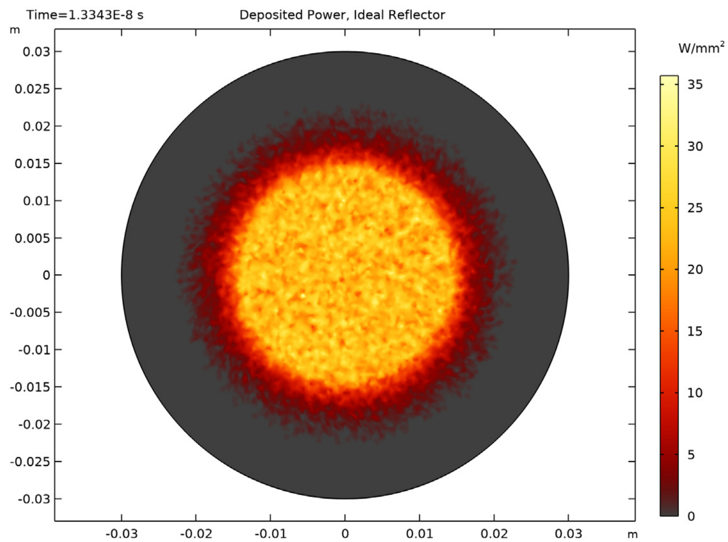

Figure 4: Incident heat flux on the surface of the receiver, resulting from an ideally smooth, non-absorbing paraboloidal reflector. Solar limb darkening effects have also been neglected.

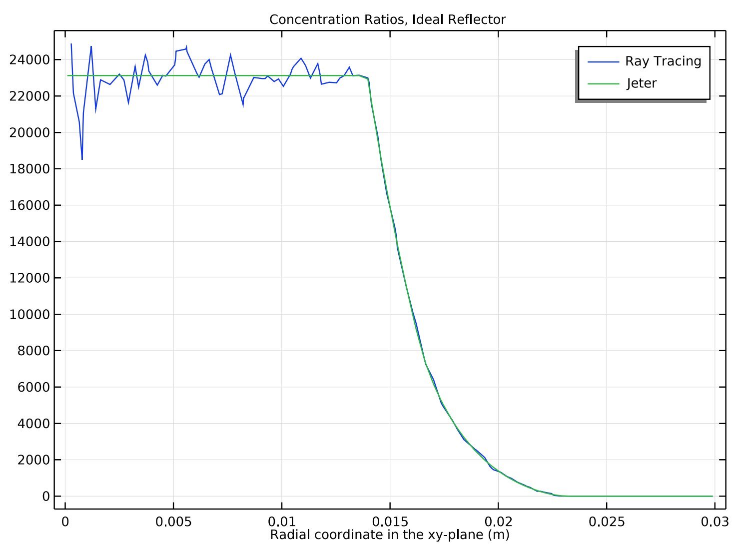

Figure 5: Comparison of the azimuthally averaged, computed concentration ratio in the focal plane to a semi-analytical solution. The two solutions are in close agreement.

The ray trajectories resulting from the second study are shown in Figure 6. Compared to Figure 3, a substantial number of rays now miss the receiver and continue to propagate, reducing the efficiency of the cavity receiver.

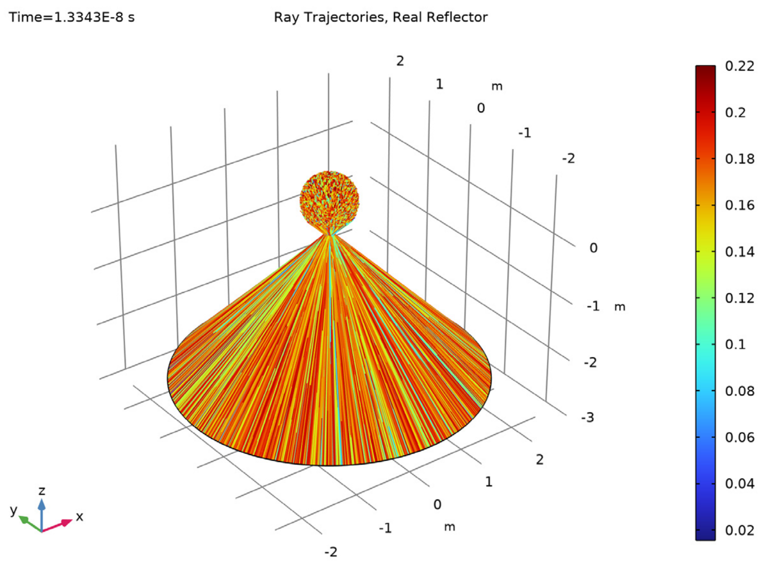

Figure 6: Reflection of solar radiation by a paraboloidal dish. Surface roughness, absorption, and solar limb darkening have all been taken into account.

The flux distribution in the focal plane is shown in Figure 7. Compared to Figure 4, the distribution is much more widespread, lacking any well-defined plateau. The maximum flux has also been considerably reduced.

The comparison of the azimuthally averaged concentration ratio to Ref. 1 is shown in Figure 8. The two solutions are again shown to be in close agreement. Further statistical convergence could be achieved by increasing the number of rays and refining the mesh on the focal plane, at the cost of increased memory usage and solution time.

Finally, the incident heat flux distributions from the two studies are directly compared in Figure 9.

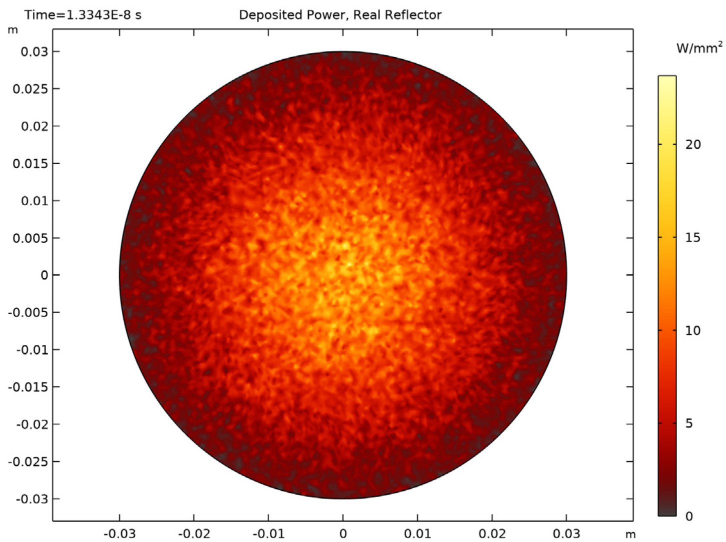

Figure 7: Flux distribution in the focal plane when taking surface roughness, absorption, and solar limb darkening into account.

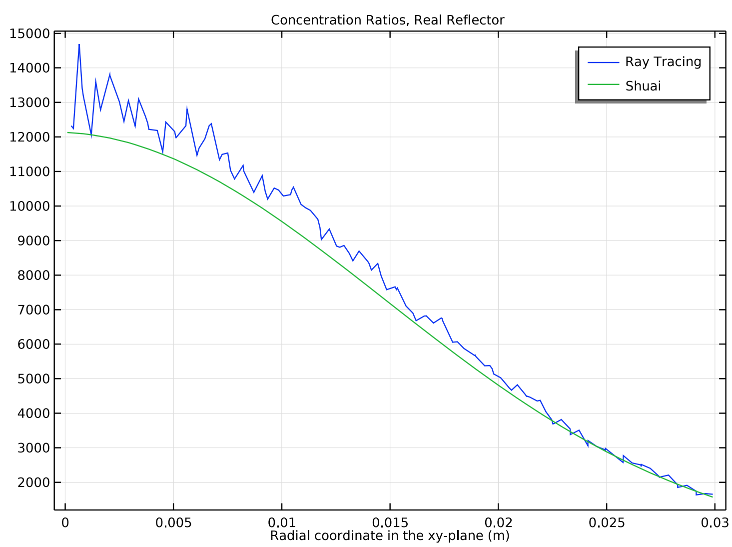

Figure 8: Comparison of the azimuthally averaged concentration ratio to published data.

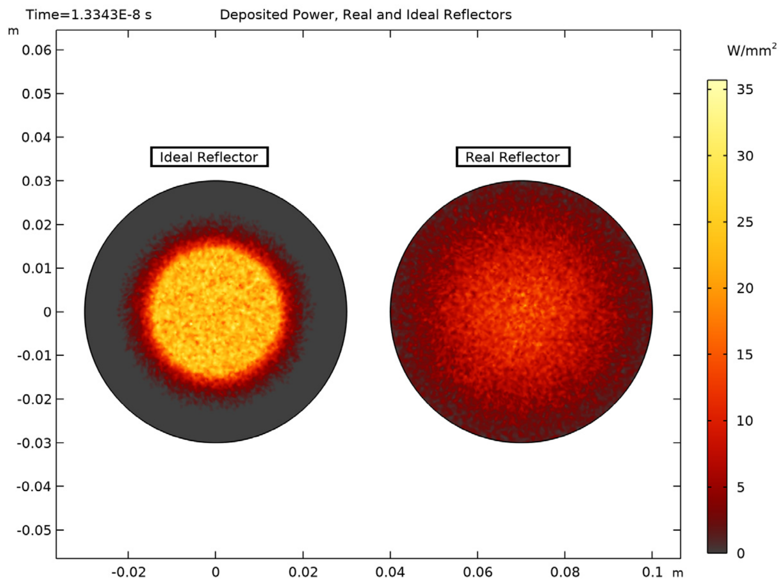

Figure 9: Direct comparison of the flux distributions when including roughness, absorption, and solar limb darkening (the "Real Collector"), and when neglecting these effects (the "Ideal Collector").

References

1. Y. Shuai, X-L. Xia, and H-P. Tan, "Radiation performance of dish solar concentrator/cavity receiver systems," *Solar Energy*, vol. 82, pp. 13–21, 2008.

2. S.M. Jeter, "The distribution of concentrated solar radiation in paraboloidal collectors", *Journal of Solar Energy Engineering*, vol. 108, pp. 219–225, 1986.

3. G. Johnston, "Focal region measurements of the 20 m^2 tiled dish at the Australian national university," *Solar Energy*, Vol. 63, No. 2, pp. 117-124, 1998.

4. M. Schubnell, "Sunshape and its influence on the flux distribution in imaging solar concentrators," *Journal of Solar Energy Engineering*, vol. 114, pp. 260–266, 1992.

5. D. Hestroffer and C. Magnan, "Wavelength dependency of the Solar limb darkening," Astron. Astrophysl, vol. 333, pp. 338–342, 1998.

Application Library path: `Ray_Optics_Module/Solar_Radiation/solar_dish_receiver`

Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **3D**.

2 In the **Select Physics** tree, select **Optics>Ray Optics>Geometrical Optics (gop)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces>Ray Tracing**.

6 Click **Done**.

GEOMETRY 1

Define some parameters for the geometry setup.

GLOBAL DEFINITIONS

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, locate the **Parameters** section.

3 In the table, enter the following settings:

Name	Expression	Value	Description
f	3[m]	3 m	Focal length
phi	45[deg]	0.7854 rad	Rim angle
d	4*f*(csc(phi)-cot(phi))	4.9706 m	Dish diameter
A	pi*d^2/4	19.404 m²	Dish projected surface area

Name	Expression	Value	Description
psim	4.65[mrad]	0.00465 rad	Maximum solar disc angle
sig	1.75[mrad]	0.00175 rad	Surface slope error
I0	1[kW/m^2]	1000 W/m²	Solar irradiance

GEOMETRY 1

Cylinder 1 (cyl1)

1 In the **Geometry** toolbar, click **Cylinder**.

2 In the **Settings** window for **Cylinder**, locate the **Size and Shape** section.

3 In the **Radius** text field, type 30[mm].

4 In the **Height** text field, type 100[mm].

5 Click **Build All Objects**.

PART LIBRARIES

1 In the **Geometry** toolbar, click **Parts** and choose **Part Libraries**.

2 In the **Model Builder** window, click **Geometry 1**.

3 In the **Part Libraries** window, select **Ray Optics Module>3D>Mirrors> paraboloidal_reflector_shell_3d** in the tree.

4 Click **Add to Geometry**.

5 In the **Select Part Variant** dialog box, select **Specify rim angle** in the **Select part variant** list.

6 Click **OK**.

GEOMETRY 1

Paraboloidal Reflector Shell 3D 1 (pi1)

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **Paraboloidal Reflector Shell 3D 1 (pi1)**.

2 In the **Settings** window for **Part Instance**, locate the **Input Parameters** section.

3 In the table, enter the following settings:

Name	Expression	Value	Description
phi	phi	45 °	Rim angle
d2	0	0 m	Center hole diameter
F	3[m]	3 m	Focal length

Name	Expression	Value	Description
nix	0	0	Incident ray direction, x component
niz	-1	-1	Incident ray direction, z component

4 Locate the **Position and Orientation of Output** section. Find the **Displacement** subsection. In the **zw** text field, type `-f`.

5 Click to expand the **Boundary Selections** section. In the table, select the **Keep** check box for **All**.

GLOBAL DEFINITIONS

In the **Model Builder** window, collapse the **Global Definitions** node.

GEOMETRY 1

In the **Model Builder** window, collapse the **Component 1 (comp1)>Geometry 1** node.

DEFINITIONS

Integration 1 (intop1)

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Integration**.

2 In the **Settings** window for **Integration**, locate the **Source Selection** section.

3 From the **Geometric entity level** list, choose **Boundary**.

4 From the **Selection** list, choose **All (Paraboloidal Reflector Shell 3D 1)**.

Interpolation 1 (int1)

1 In the **Definitions** toolbar, click **Interpolation**.

Load the expected solution data from Ref. 1.

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 From the **Data source** list, choose **File**.

4 Click **Browse**.

5 Browse to the model's Application Libraries folder and double-click the file `solar_dish_receiver_reference.txt`.

6 Click **Import**.

7 Locate the **Units** section. In the **Argument** table, enter the following settings:

Argument	Unit
t	mm

8 In the **Function** table, enter the following settings:

Function	Unit
int1	W/mm^2

Add a selection for the surface of the paraboloidal dish, where the reflected rays are released.

Focal Plane

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `Focal Plane` in the **Label** text field.

3 Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Boundary**.

4 Select Boundary 5 only.

Variables 1

1 In the **Model Builder** window, right-click **Definitions** and choose **Variables**.

Define variables to compute the concentration ratio for an ideal parabolic solar concentrator, following Jeter (Ref. 2). To save time, these variables can be loaded from a file.

2 In the **Settings** window for **Variables**, locate the **Variables** section.

3 Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `solar_dish_receiver_variables.txt`.

General Projection 1 (genproj1)

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **General Projection**.

2 In the **Settings** window for **General Projection**, locate the **Source Selection** section.

3 From the **Geometric entity level** list, choose **Boundary**.

4 From the **Selection** list, choose **Focal Plane**.

5 Click the **Go to Default View** button in the **Graphics** toolbar.

6 Locate the **Source Map** section. In the **x-expression** text field, type `r`.

7 In the **y-expression** text field, type `theta`.

8 Locate the **Destination Map** section. In the **x-expression** text field, type `r`.

9 In the **Model Builder** window, collapse the **Definitions** node.

GEOMETRICAL OPTICS (GOP)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometrical Optics (gop)**.

2 In the **Settings** window for **Geometrical Optics**, locate the **Domain Selection** section.

3 Click **Clear Selection**.

4 Locate the **Intensity Computation** section. From the **Intensity computation** list, choose **Compute power**.

5 Locate the **Ray Release and Propagation** section. In the **Maximum number of secondary rays** text field, type `0`.

Add two instances of the **Illuminated Surface** release feature. One of these features will include surface roughness and solar limb darkening. One release feature will be used in each of the two studies in this model.

Ideal Illuminated Surface

1 In the **Physics** toolbar, click **Boundaries** and choose **Illuminated Surface**.

2 In the **Settings** window for **Illuminated Surface**, type `Ideal Illuminated Surface` in the **Label** text field.

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **All (Paraboloidal Reflector Shell 3D 1)**.

4 Locate the **Initial Position** section. From the **Initial position** list, choose **Density**.

5 In the N text field, type `100000`.

6 Locate the **Ray Direction Vector** section. Specify the $\mathbf{L}_i$ vector as

0	x
0	y
-1	z

7 Locate the **Angular Perturbations** section. From the **Corrections for finite source diameter** list, choose **Sample from conical distribution**.

8 Locate the **Total Source Power** section. In the P_{src} text field, type `A*I0`.

9 Locate the **Angular Perturbations** section. In the ψ_m text field, type `psim`.

Real Illuminated Surface

1 In the **Physics** toolbar, click **Boundaries** and choose **Illuminated Surface**.

2 In the **Settings** window for **Illuminated Surface**, type `Real Illuminated Surface` in the **Label** text field.

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **All (Paraboloidal Reflector Shell 3D 1)**.

4 Locate the **Initial Position** section. From the **Initial position** list, choose **Density**.

5 In the N text field, type 100000.

6 Locate the **Ray Direction Vector** section. Specify the $\mathbf{L}_i$ vector as

0	x
0	y
-1	z

7 In the α text field, type 0.1.

8 Locate the **Angular Perturbations** section. From the **Corrections for finite source diameter** list, choose **Sample from conical distribution**.

9 In the ψ_m text field, type psim.

10 From the **Limb darkening model** list, choose **Empirical power law**.

11 Select the **Include surface roughness** check box.

12 In the σ text field, type sig.

13 Locate the **Total Source Power** section. In the P_{src} text field, type A*I0.

14 Locate the **Incident Ray Polarization** section. From the **Initial polarization type** list, choose **Unpolarized**.

Focal Plane

1 In the **Physics** toolbar, click **Boundaries** and choose **Wall**.

2 In the **Settings** window for **Wall**, type Focal Plane in the **Label** text field.

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Focal Plane**.

4 Click the **Go to Default View** button in the **Graphics** toolbar.

Use the **Deposited Ray Power** node to compute the incident heat flux in the focal plane.

Deposited Ray Power 1

1 In the **Physics** toolbar, click **Attributes** and choose **Deposited Ray Power**.

2 In the **Model Builder** window, collapse the **Geometrical Optics (gop)** node.

MESH 1

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.

2 In the **Settings** window for **Mesh**, locate the **Physics-Controlled Mesh** section.

3 From the **Element size** list, choose **Extremely fine**.

4 Locate the **Sequence Type** section. From the list, choose **User-controlled mesh**.

Size 1

1 In the **Model Builder** window, right-click **Free Triangular 1** and choose **Size**.
2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.
3 Click **Clear Selection**.
4 Select Boundary 5 only.
5 Locate the **Element Size** section. Click the **Custom** button.

   Use an extremely fine mesh on the focal plane to improve the resolution of the deposited ray power.

6 Locate the **Element Size Parameters** section. Select the **Maximum element size** check box.
7 In the associated text field, type `5E-4`.
8 Select the **Minimum element size** check box.
9 In the associated text field, type `2E-4`.
10 In the **Model Builder** window, collapse the **Mesh 1** node.
11 In the **Model Builder** window, right-click **Mesh 1** and choose **Build All**.

STUDY 1

Step 1: Ray Tracing

1 In the **Model Builder** window, under **Study 1** click **Step 1: Ray Tracing**.
2 In the **Settings** window for **Ray Tracing**, locate the **Study Settings** section.
3 From the **Time-step specification** list, choose **Specify maximum path length**.
4 In the **Lengths** text field, type `0 4`.
5 Locate the **Physics and Variables Selection** section. Select the **Modify model configuration for study step** check box.
6 In the tree, select **Component 1 (Comp1)>Geometrical Optics (Gop)>Real Illuminated Surface**.
7 Right-click and choose **Disable**.

Solution 1 (sol1)

1 In the **Study** toolbar, click **Show Default Solver**.

   Specify a manual time step size to speed up the computation and reduce the file size.

2 In the **Model Builder** window, expand the **Solution 1 (sol1)** node, then click **Time-Dependent Solver 1**.
3 In the **Settings** window for **Time-Dependent Solver**, click to expand the **Time Stepping** section.

4 From the **Steps taken by solver** list, choose **Manual**.

5 In the **Time step** text field, type `4[m]/c_const`.

6 In the **Model Builder** window, collapse the **Study 1** node.

7 In the **Study** toolbar, click **Compute**.

RESULTS

Ray Trajectories, Ideal Reflector

1 In the **Settings** window for **3D Plot Group**, type `Ray Trajectories, Ideal Reflector` in the **Label** text field.

2 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.

3 In the **Title** text area, type `Ray Trajectories, Ideal Reflector`.

4 In the **Model Builder** window, expand the **Ray Trajectories, Ideal Reflector** node.

Color Expression 1

1 In the **Model Builder** window, expand the **Results>Ray Trajectories, Ideal Reflector> Ray Trajectories 1** node, then click **Color Expression 1**.

2 In the **Settings** window for **Color Expression**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)> Geometrical Optics>Intensity and polarization>gop.Q - Ray power - W**.

3 In the **Ray Trajectories, Ideal Reflector** toolbar, click **Plot**.

4 Click the **Zoom Extents** button in the **Graphics** toolbar. Compare the resulting plot with Figure 3.

Ray Trajectories, Ideal Reflector

In the **Model Builder** window, collapse the **Results>Ray Trajectories, Ideal Reflector** node.

Surface 1

1 In the **Results** toolbar, click **More Datasets** and choose **Surface**.

2 In the **Settings** window for **Surface**, locate the **Parameterization** section.

3 From the **x- and y-axes** list, choose **XY-plane**.

4 Locate the **Selection** section. From the **Selection** list, choose **Focal Plane**.

5 Click the **Go to Default View** button in the **Graphics** toolbar.

Deposited Power, Ideal Reflector

1 In the **Results** toolbar, click **2D Plot Group**.

2 In the **Settings** window for **2D Plot Group**, type `Deposited Power, Ideal Reflector` in the **Label** text field.

3 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.

4 In the **Title** text area, type `Deposited Power, Ideal Reflector`.

5 Locate the **Data** section. From the **Dataset** list, choose **Surface 1**.

6 Locate the **Color Legend** section. Select the **Show units** check box.

Surface 1

1 Right-click **Deposited Power, Ideal Reflector** and choose **Surface**.

2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)> Geometrical Optics>Accumulated variables> Boundary heat source comp1.gop.wall1.bsrc1.Qp>gop.wall1.bsrc1.Qp - Boundary heat source - W/m²**.

3 Locate the **Expression** section. In the **Unit** field, type `W/mm^2`.

4 Locate the **Coloring and Style** section. From the **Color table** list, choose **GrayBody**.

5 Click to expand the **Quality** section. From the **Resolution** list, choose **No refinement**.

6 In the **Deposited Power, Ideal Reflector** toolbar, click **Plot**.

7 Click the **Zoom Extents** button in the **Graphics** toolbar. Compare the resulting plot with Figure 4.

Cut Line 3D 1

1 In the **Results** toolbar, click **Cut Line 3D**.

2 In the **Settings** window for **Cut Line 3D**, locate the **Line Data** section.

3 In row **Point 1**, set **X** to `1E-4`.

4 In row **Point 2**, set **X** to `0.03-1E-4`.

5 From the **Snapping** list, choose **Snap to closest boundary**.

Concentration Ratios, Ideal Reflector

1 In the **Results** toolbar, click **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Concentration Ratios, Ideal Reflector` in the **Label** text field.

3 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.

4 In the **Title** text area, type `Concentration Ratios, Ideal Reflector`.

5 Locate the **Data** section. From the **Dataset** list, choose **Cut Line 3D 1**.

6 From the **Time selection** list, choose **Last**.

Line Graph 1

1 Right-click **Concentration Ratios, Ideal Reflector** and choose **Line Graph**.

Plot the azimuthally averaged, smoothed heat source on the cylinder using the nonlocal projection coupling previously defined.

2 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.

3 In the **Expression** text field, type `genproj1(gop.wall1.bsrc1.Qp)/genproj1(I0)`.

4 Click to expand the **Quality** section. From the **Resolution** list, choose **No refinement**.

5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

6 In the **Expression** text field, type `r`.

7 Click to expand the **Legends** section. Select the **Show legends** check box.

8 From the **Legends** list, choose **Manual**.

9 In the table, enter the following settings:

Legends
Ray Tracing

10 In the **Concentration Ratios, Ideal Reflector** toolbar, click **Plot**.

Line Graph 2

1 Right-click **Line Graph 1** and choose **Duplicate**.

2 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.

3 In the **Expression** text field, type `cr`.

4 Click to expand the **Title** section. From the **Title type** list, choose **None**.

5 Locate the **Legends** section. In the table, enter the following settings:

Legends
Jeter

6 In the **Concentration Ratios, Ideal Reflector** toolbar, click **Plot**. Compare the resulting plot with Figure 5. This figure shows the radial variation in the idealized concentration ratio. Now create a second study in which roughness, absorption, and limb darkening effects are considered.

ADD STUDY

1 In the **Home** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Studies** subsection. In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces>Ray Tracing**.

4 Click **Add Study** in the window toolbar.

5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 2

Step 1: Ray Tracing

1 In the **Settings** window for **Ray Tracing**, locate the **Study Settings** section.

2 From the **Time-step specification** list, choose **Specify maximum path length**.

3 In the **Lengths** text field, type `0 4`.

4 Locate the **Physics and Variables Selection** section. Select the **Modify model configuration for study step** check box.

5 In the tree, select **Component 1 (Comp1)>Geometrical Optics (Gop)> Ideal Illuminated Surface**.

6 Right-click and choose **Disable**.

Solution 2 (sol2)

1 In the **Study** toolbar, click **Show Default Solver**.

Specify a manual time step size to speed up the computation and reduce the file size.

2 In the **Model Builder** window, expand the **Solution 2 (sol2)** node, then click **Time-Dependent Solver 1**.

3 In the **Settings** window for **Time-Dependent Solver**, locate the **Time Stepping** section.

4 From the **Steps taken by solver** list, choose **Manual**.

5 In the **Time step** text field, type `4[m]/c_const`.

6 In the **Model Builder** window, collapse the **Study 2** node.

7 In the **Study** toolbar, click **Compute**.

RESULTS

Ray Trajectories, Real Reflector

1 In the **Settings** window for **3D Plot Group**, type `Ray Trajectories, Real Reflector` in the **Label** text field.

2 Locate the **Title** section. From the **Title type** list, choose **Manual**.

3 In the **Title** text area, type `Ray Trajectories, Real Reflector`.

4 In the **Model Builder** window, expand the **Ray Trajectories, Real Reflector** node.

Color Expression 1

1 In the **Model Builder** window, expand the **Results>Ray Trajectories, Real Reflector>Ray Trajectories 1** node, then click **Color Expression 1**.

2 In the **Settings** window for **Color Expression**, locate the **Expression** section.

3 In the **Expression** text field, type `gop.Q`.

4 In the **Ray Trajectories, Real Reflector** toolbar, click **Plot**.

5 Click the **Go to Default View** button in the **Graphics** toolbar. Compare the resulting plot with Figure 6.

Ray Trajectories, Real Reflector

In the **Model Builder** window, collapse the **Results>Ray Trajectories, Real Reflector** node.

Surface 1

Create duplicates of the **Surface** and **Cut Line 3D** datasets that point to **Solution 2**.

Surface 2

1 In the **Model Builder** window, under **Results>Datasets** right-click **Surface 1** and choose **Duplicate**.

2 In the **Settings** window for **Surface**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 2/Solution 2 (sol2)**.

Cut Line 3D 2

1 In the **Model Builder** window, under **Results>Datasets** right-click **Cut Line 3D 1** and choose **Duplicate**.

2 In the **Settings** window for **Cut Line 3D**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 2/Solution 2 (sol2)**.

Deposited Power, Real Reflector

1 In the **Model Builder** window, right-click **Deposited Power, Ideal Reflector** and choose **Duplicate**.

2 In the **Settings** window for **2D Plot Group**, type `Deposited Power, Real Reflector` in the **Label** text field.

3 Locate the **Title** section. In the **Title** text area, type `Deposited Power, Real Reflector`.

4 Locate the **Data** section. From the **Dataset** list, choose **Surface 2**.

5 In the **Deposited Power, Real Reflector** toolbar, click **Plot**.

6 Click the Zoom Extents button in the **Graphics** toolbar. Compare the resulting plot with Figure 7.

Concentration Ratios, Real Reflector

1 In the **Model Builder** window, right-click **Concentration Ratios, Ideal Reflector** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `Concentration Ratios, Real Reflector` in the **Label** text field.

3 Locate the **Title** section. In the **Title** text area, type `Concentration Ratios, Real Reflector`.

4 Locate the **Data** section. From the **Dataset** list, choose **Cut Line 3D 2**.

Line Graph 1

1 In the **Model Builder** window, expand the **Concentration Ratios, Real Reflector** node, then click **Line Graph 1**.

2 In the **Settings** window for **Line Graph**, locate the **Legends** section.

3 In the table, enter the following settings:

Legends
`Ray Tracing`

Line Graph 2

1 In the **Model Builder** window, click **Line Graph 2**.

2 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.

3 In the **Expression** text field, type `int1(r)/I0`.

4 Locate the **Legends** section. In the table, enter the following settings:

Legends
`Shuai`

5 In the **Concentration Ratios, Real Reflector** toolbar, click **Plot**. Compare the resulting plot with Figure 8.

Create another plot group to directly compare the flux distributions in the focal plane for the two solutions.

Deposited Power, Real and Ideal Reflectors

1 In the **Model Builder** window, right-click **Deposited Power, Ideal Reflector** and choose **Duplicate**.

2 In the **Settings** window for **2D Plot Group**, type `Deposited Power, Real and Ideal Reflectors` in the **Label** text field.

3 Locate the **Title** section. In the **Title** text area, type `Deposited Power, Real and Ideal Reflectors`.

Surface 1

1 In the **Model Builder** window, expand the **Results>Deposited Power, Real Reflector** node.

2 Right-click **Surface 1** and choose **Copy**.

Surface 2

1 In the **Model Builder** window, expand the **Results>Deposited Power, Real and Ideal Reflectors** node.

2 Right-click **Deposited Power, Real and Ideal Reflectors** and choose **Paste Surface**.

3 In the **Settings** window for **Surface**, locate the **Data** section.

4 From the **Dataset** list, choose **Surface 2**.

5 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Surface 1**.

Translation 1

1 Right-click **Surface 2** and choose **Translation**.

2 In the **Settings** window for **Translation**, locate the **Translation** section.

3 In the **x** text field, type `0.07[m]`.

4 In the **Deposited Power, Real and Ideal Reflectors** toolbar, click **Plot**.

Deposited Power, Real and Ideal Reflectors

Create two **Annotation** features to identify the two plots in the **Graphics** window.

Annotation 1

1 In the **Model Builder** window, right-click **Deposited Power, Real and Ideal Reflectors** and choose **Annotation**.

2 In the **Settings** window for **Annotation**, locate the **Annotation** section.

3 In the **Text** text field, type `Ideal Reflector`.

Enter the coordinates for the annotations. The exact coordinates may vary depending on the aspect ratio of the **Graphics** window.

4 Locate the **Position** section. In the **x** text field, type `-0.015`.

5 In the **y** text field, type `0.038`.

6 Locate the **Coloring and Style** section. Clear the **Show point** check box.

7 Select the **Show frame** check box.

Annotation 2

1 Right-click **Deposited Power, Real and Ideal Reflectors** and choose **Annotation**.
2 In the **Settings** window for **Annotation**, locate the **Annotation** section.
3 In the **Text** text field, type `Real Reflector`.
4 Locate the **Position** section. In the **x** text field, type `0.055`.
5 In the **y** text field, type `0.038`.
6 Locate the **Coloring and Style** section. Clear the **Show point** check box.
7 Select the **Show frame** check box.
8 In the **Deposited Power, Real and Ideal Reflectors** toolbar, click **Plot**.
9 Click the **Zoom Extents** button in the **Graphics** toolbar. Compare the resulting plot with Figure 9.