Radiative Heat Transfer in Finite Cylindrical Media

This model uses the discrete ordinates method (DOM) to solve a 3D radiative transfer problem in an emitting, absorbing, and linearly anisotropic-scattering finite cylindrical medium. Using the S6 quadrature of DOM leads to accurate results, which are needed in combined modes of heat transfer. The calculated incident radiation and heat fluxes agree well with published results obtained by transformed integral methods (see Ref. 1). In addition, the Heat Transfer Module's DOM formulation easily handles the effects of boundary emission and reflection.

Introduction

There are numerous engineering applications of radiative transfer in absorbing, emitting, and anisotropically scattering media with variable radiation properties. Examples include, among others, coal-fired combustion systems, light-weight fibrous insulations, and heat transfer systems containing small scattering particles. Furthermore, the efficiency of radiative transfer depends on the boundary conditions, for example, the temperature and the emissivity of the surrounding walls, and the target where heat transfer is desired. Studies have shown that radiative transfer is highly sensitive to the wall emissivity. In this study you build a validation model representing a cylinder with homogeneous walls. Then you go on to consider walls with space-dependent emissivity and investigate the effects of albedo and scattering.

Model Definition

In this model you validate the DOM formulation in COMSOL Multiphysics by examining three benchmark cases. You investigate the method's efficiency through parametric analyses by changing the single-scattering albedo, wall emissivity, and linear function. In particular, in the final case, you approximate the scattering phase function by a linear function reflecting highly backward, isotropic, and highly forward scattering.

The model geometry, shown in Figure 1, is a cylinder of radius $R = 0.5$ m and height $L = 1$ m.

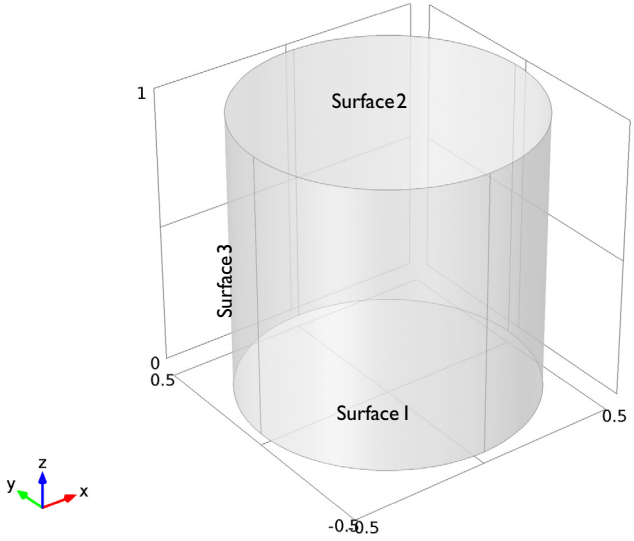


Figure 1: Schematic diagram of the physical model.

These examples use the S6 discrete ordinate method for predicting the heat flux on the enclosure side walls and the incident radiation distribution inside the domain.

VERIFICATION CASE

For the initial study, assume cold boundaries, that is, $I_i = 0$ where $i = 1, 2, 3$ refers to the surface index in Figure 1. Furthermore, assume that the walls diffusively reflect radiation, that is, $\varepsilon_i = 0.5$ for $i = 1, 2, 3$. The medium is at a uniform temperature T such that the blackbody radiation intensity in an arbitrary direction per unit area and solid angle $I_b(T) = \sigma T^4/\pi$ equals 1 W/(m^2·sr).

WALLS WITH VARIABLE EMISSIVITY

Two cases are computed for comparison purposes. These 3D cases represent opaque partial side wall diffuse emission and/or reflection. In both cases, the radiosity on the side walls (Surface 3) varies with the angular coordinate along the full height of the finite cylinder according to $\varepsilon_3 = (1 - y/R)/2$. Both cases also have cold walls at the cylinder top (Surface 1) and bottom (Surface 2).

Case 1 has isotropic scattering function and compares results for different albedos. Case 2 has constant albedo and compares results with highly forward, isotropic, and highly backward scattering function parameterized by the Legendre coefficient a_1.

TABLE 1: NONSTANDARD TEST CASES

CASE	MEDIUM PROPERTIES)
1	albedo = 0.1, 0.5, 0.9 $a_1 = 0$
2	albedo = 0.5 $a_1 = -0.99, 0, 0.99$

THERMAL ANALYSIS

The discrete ordinates method relies on the discrete representation of the directional dependence of the radiation intensity. It involves solving the radiative equation for a set of directions that span the full solid angle range of 4π around a point in space.

The radiation transport equation (RTE) for this type of configuration can be written as

$$\Omega \cdot \nabla I(\Omega, s) = \kappa I_b(T) - \beta I(\Omega, s) + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I(\Omega, \Omega')\phi(\Omega, \Omega')\partial\Omega'$$

where

- $I(\Omega, s)$ is the radiation intensity at a given position s in the direction Ω
- T is the temperature
- κ, β, and σ_s are absorption, extinction, and scattering coefficients, respectively
- $I_b(T)$ is the blackbody radiation intensity
- $\phi(\Omega, \Omega') = 1 + a_1\mu_0$ where $\mu_0 = \Omega \cdot \Omega'$ is the cosine of the scattering angle.

The boundary intensities at the cylinder walls are given by the sum of the effective emitted intensity and the reflected incident intensities in the given direction:

$$I_{bnd}(\Omega) = \varepsilon_w I_b(T) + \frac{\rho_d}{\pi} q_{out} \quad \text{for all } \Omega \text{ such that } \mathbf{n} \cdot \Omega < 0$$

where

- ε_w is the surface emissivity, which is in the range $[0, 1]$
- $\rho_d = 1 - \varepsilon_w$ is the diffusive reflectivity
- $\mathbf{n}$ is the outward normal vector

- q_{out} is the heat flux striking the wall:

$$q_{\text{out}} = \int_{\mathbf{n}\cdot\boldsymbol{\Omega}_j > 0} (\mathbf{n}\cdot\Omega) I(\Omega, s)\partial\Omega'$$

The above equations can be discretized in Cartesian coordinates for monochromatic or gray radiation as

$$\Omega_i \cdot \nabla I_i = \kappa I_{\text{b}}(T) - \beta I_i + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I(\Omega, \Omega')\phi(\Omega, \Omega')\partial\Omega'$$

The Sn approximation of the RTE in the direction i can be expressed as

$$\Omega_i \cdot \nabla I_i = \kappa I_{\text{b}}(T) - \beta I_i + \frac{\sigma_s}{4\pi}\sum_{j=1}^{n} w_j I_j \phi(\Omega_j, \Omega_i)$$

For a discrete direction, Ω_i, the values of $\Omega_{i,1}$, $\Omega_{i,2}$, and $\Omega_{i,3}$ define the direction cosines of Ω_i obeying the condition ${\Omega_{i,1}}^2 + {\Omega_{i,2}}^2 + {\Omega_{i,3}}^2 = 1$. The index j in the above equation denotes the direction of incoming radiation contributing to the direction Ω_i.

For a diffuse reflecting surface on a wall boundary, the boundary condition equation is transformed as

$$I_{i,\,\text{bnd}} = \varepsilon_w I_{\text{b}}(T) + \frac{\rho_d}{\pi}\sum_{\mathbf{n}\cdot\boldsymbol{\Omega}_j > 0} w_j I_j \mathbf{n}\cdot\Omega_j \qquad \text{for all } \Omega_i \text{ such that } \mathbf{n}\cdot\Omega_i < 0$$

Results and Discussion

The results demonstrate that the DOM procedure for the prediction of radiation is an elegant and accurate method for modeling multidimensional radiative heat transfer in cylindrical geometries.

VERIFICATION CASE

This case treats the effects of the scattering albedo on the incident radiation and heat fluxes. Figure 2 shows the distribution of the net heat flux $q_{\text{net}}(R, 0, z)$ versus axial optical thickness. There is good overall agreement of the present work with published literature results (Ref. 2, Ref. 3, and Ref. 4).

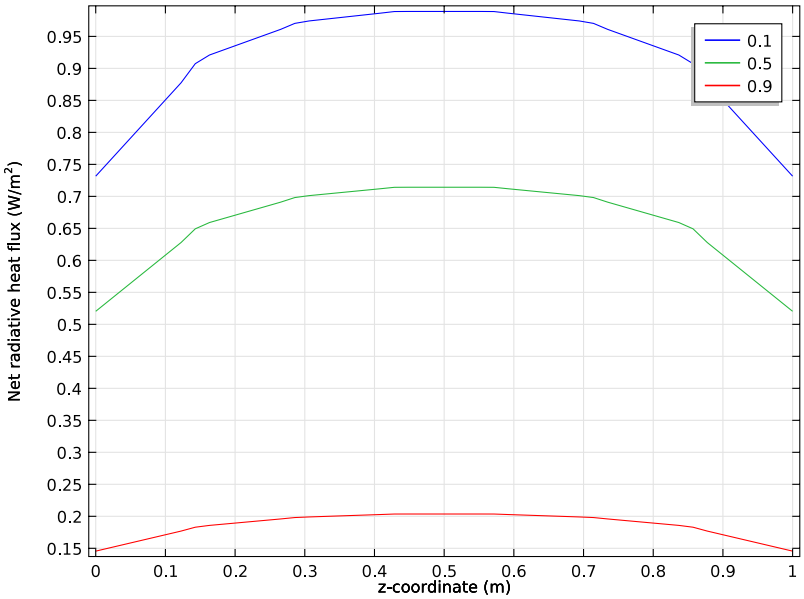


Figure 2: The effects of the scattering albedo on the radial heat flux $q_{\text{net}}(R, 0, z)$*; for a hot cylindrical medium enclosed by cold walls,* $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = 0.5$.

The effects of albedo on the distribution of centerline incident radiation in axial direction are shown in Figure 3. The incident radiation is symmetric with respect to

$z = L/2$ plane and decrease with increasing scattering albedo. Furthermore, results become more uniform with larger scattering albedo.

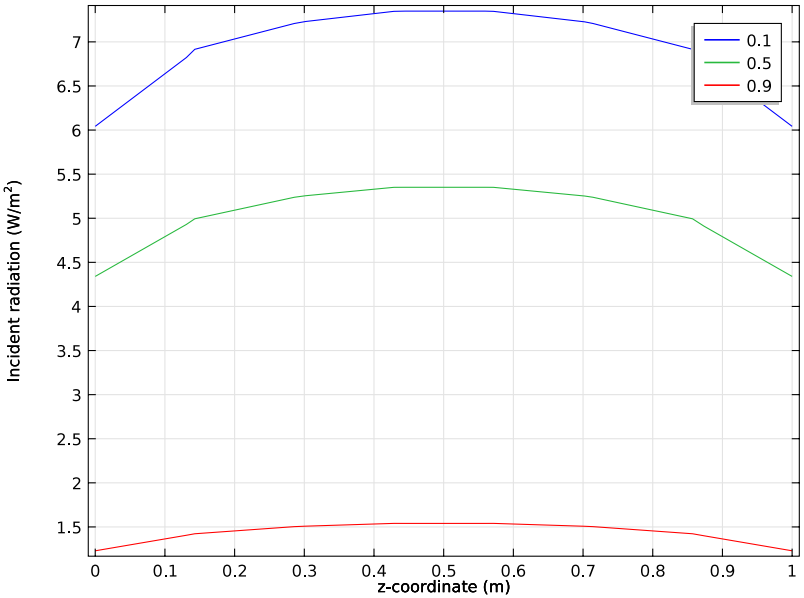


Figure 3: The effects of the scattering albedo on the distribution of centerline incident radiation $G(0, 0, z)$ *for a hot cylindrical medium enclosed by cold walls,* $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = 0.5$.

Figure 4 displays the distributions of the incident radiation across the mid-plan radius $G(x, 0, L/2)$ with respect to normalized optical thickness x/R.

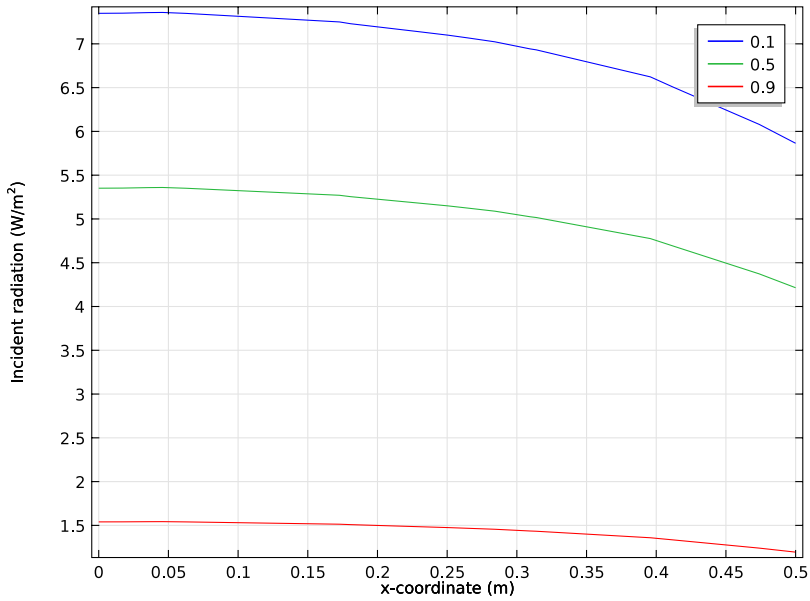


Figure 4: The effects of the scattering albedo on the distributions of the incident radiation $G(x, 0, L/2)$ *with respect to normalized optical thickness* x/R *for a hot cylindrical medium enclosed by cold walls,* $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = 0.5$.

WALLS WITH VARIABLE EMISSIVITY

The incident radiation at the mid-plane $z = L/2$ at the radial position $R/2$ is shown in Figure 5. At the side surface $R/2$ distance from the cylinder axis, $G(R, 0, L/2)$ changes with the azimuthal angle. The changes in scattering albedo are also illustrated. The smallest albedo makes the biggest change around the azimuthal angle.

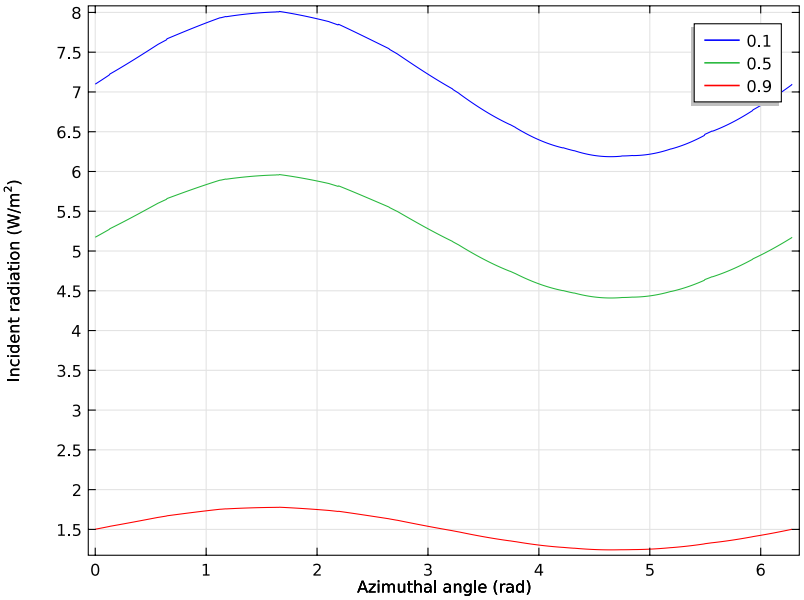


Figure 5: The effects of scattering albedo on the distribution of incident radiation at mid-plane $z = L/2$ at $R/2$ distance from the cylinder axis with respect to an azimuthal coordinate for Case 1.

Figure 6 shows the effect of a nonzero linear anisotropic scattering coefficient a_1. As expected, the differences between isotropic scattering, forward scattering, and backward scattering are most accentuated far from the boundary.

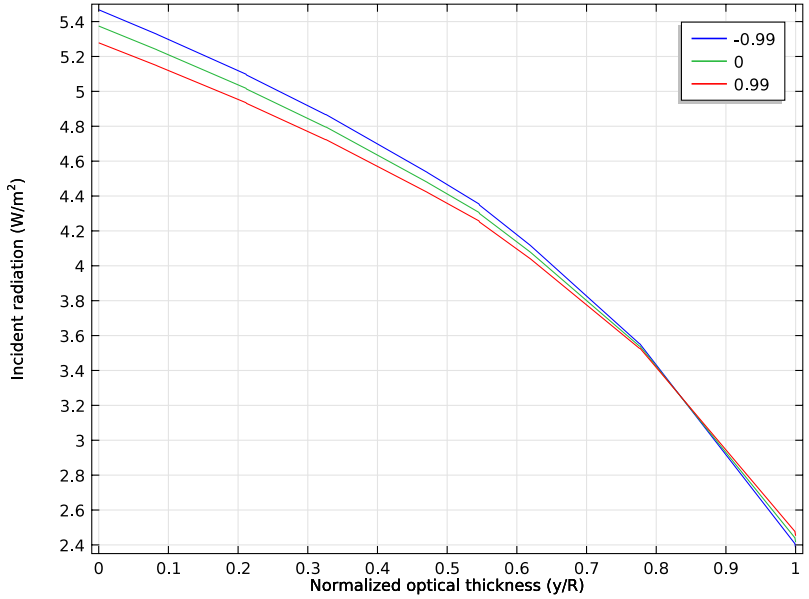


Figure 6: The effects of linear anisotropic scattering coefficient a_1 on the distribution of incident radiation $G(0, y, L/2)$ with respect to normalized optical thickness $-y/R$ for Case 2.

References

1. X.L. Chen and W.H. Sutton, "Radiative Transfer in Finite Cylindrical Media Using Transformed Integral Equations," *Journal of Quantitative Spectroscopy and Radiative Transfer*, vol. 77, pp. 233–271, 2003.

2. X. Chen, *Transformed Integral Equations of Radiative Transfer and Combined Convection-radiation Heat Transfer Enhancement with Porous Insert*, Doctoral Thesis, University of Oklahoma, 2003.

3. S. T. Thynell and M. N. Ozisik, "Radiation Transfer in Absorbing, Emitting, Isotropically Scattering, Homogeneous Cylindrical Media," *J. Quant. Spectrosc. Radiat. Transfer*, vol. 38, no. 6, pp. 413–426, 1987.

4. H. Y. Li, M. N. Ozisik, and J. R. Tsai, "Two-dimensional radiation in a cylinder with spatially varying albedo," *Journal of Thermophysics and Heat Transfer*, vol. 6, no. 1, pp. 180–182, 1992.

Model Library path: `Heat_Transfer_Module/Tutorial_Models/cylinder_participating_media`

Modeling Instructions—Validation Case

MODEL WIZARD

1 Go to the **Model Wizard** window.

2 Click **Next**.

3 In the **Add physics** tree, select **Heat Transfer>Radiation>Radiation in Participating Media (rpm)**.

4 Click **Add Selected**.

5 Find the **Dependent variables** subsection. From the **Discrete ordinates method** list, choose **S6**.

6 Click **Next**.

7 Find the **Studies** subsection. In the tree, select **Preset Studies>Stationary**.

8 Click **Finish**.

GLOBAL DEFINITIONS

Parameters

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

2 In the **Parameters** settings window, locate the **Parameters** section.

3 In the table, enter the following settings:

Name	Expression	Description
T0	(1[W/m^2]*pi/sigma_const)^(1/4)	Body temperature
Tw	0[K]	Wall temperature
ew	0.5	Wall emissivity
omega	0.9	Single-scattering albedo

Name	Expression	Description
sigma_s	omega	Scattering coefficient
kappa	sigma_s*(1/omega-1)	Absorption coefficient
R	0.5[m]	Cylinder radius
L	1[m]	Cylinder length

GEOMETRY 1

Cylinder 1

1 In the **Model Builder** window, under **Model 1** right-click **Geometry 1** and choose **Cylinder**.

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

3 In the **Radius** edit field, type R.

4 In the **Height** edit field, type L.

5 Click the **Build All** button.

MATERIALS

Add a material to specify the absorption and scattering coefficients inside the cylinder.

Material 1

1 In the **Model Builder** window, under **Model 1** right-click **Materials** and choose **Material**.

2 Right-click **Material 1** and choose **Rename**.

3 Go to the **Rename Material** dialog box and type Domain in the **New name** edit field.

4 Click **OK**.

5 In the **Material** settings window, locate the **Material Contents** section.

6 In the table, enter the following settings:

Property	Name	Value
Absorption coefficient	kappaR	kappa
Scattering coefficient	sigmaS	sigma_s

Analogously, specify the emissivity of the walls using a material.

Material 2

1 In the **Model Builder** window, right-click **Materials** and choose **Material**.

2 Right-click **Material 2** and choose **Rename**.

3 Go to the **Rename Material** dialog box and type Walls in the **New name** edit field.

4 Click **OK**.

5 In the **Material** settings window, locate the **Geometric Entity Selection** section.

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

7 From the **Selection** list, choose **All boundaries**.

8 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Name	Value
Surface emissivity	epsilon_rad	ew

RADIATION IN PARTICIPATING MEDIA

1 In the **Model Builder** window's toolbar, click the **Show** button and select **Advanced Physics Options** in the menu.

2 In the **Radiation in Participating Media** settings window, click to expand the **Advanced Settings** section.

3 From the P_{index} list, choose **0.3**.

With this performance index value, solving the model requires roughly 2 GB of RAM. If your computer has less available memory than that, try a value in the range 0.5--1.

Radiation in Participating Media 1

1 In the **Model Builder** window, expand the **Radiation in Participating Media** node, then click **Radiation in Participating Media 1**.

2 In the **Radiation in Participating Media** settings window, locate the **Model Inputs** section.

3 In the T edit field, type `T0`.

Opaque Surface 1

1 In the **Model Builder** window, under **Model 1>Radiation in Participating Media** click **Opaque Surface 1**.

2 In the **Opaque Surface** settings window, locate the **Model Inputs** section.

3 In the T edit field, type `Tw`.

MESH 1

1 In the **Model Builder** window, under **Model 1** click **Mesh 1**.

2 In the **Mesh** settings window, locate the **Mesh Settings** section.

3 From the **Element size** list, choose **Coarse**.

Free Triangular 1

1 Right-click **Model 1>Mesh 1** and choose **Free Triangular**.

2 Select Boundary 4 only.

Swept 1

1 In the **Model Builder** window, right-click **Mesh 1** and choose **Swept**.

2 In the **Settings** window, click **Build All**.

STUDY 1

Parametric Sweep

1 In the **Model Builder** window, right-click **Study 1** and choose **Parametric Sweep**.

2 In the **Parametric Sweep** settings window, locate the **Study Settings** section.

3 Click **Add**.

4 In the table, enter the following settings:

Parameter names	Parameter value list
omega	0.1 0.5 0.9

Before solving, switch to an iterative solver to reduce memory consumption.

5 Right-click **Study 1** and choose **Show Default Solver**.

6 In the **Model Builder** window, expand the **Study 1>Solver Configurations** node.

Solver 1

1 In the **Model Builder** window, expand the **Study 1>Solver Configurations>Solver 1** node.

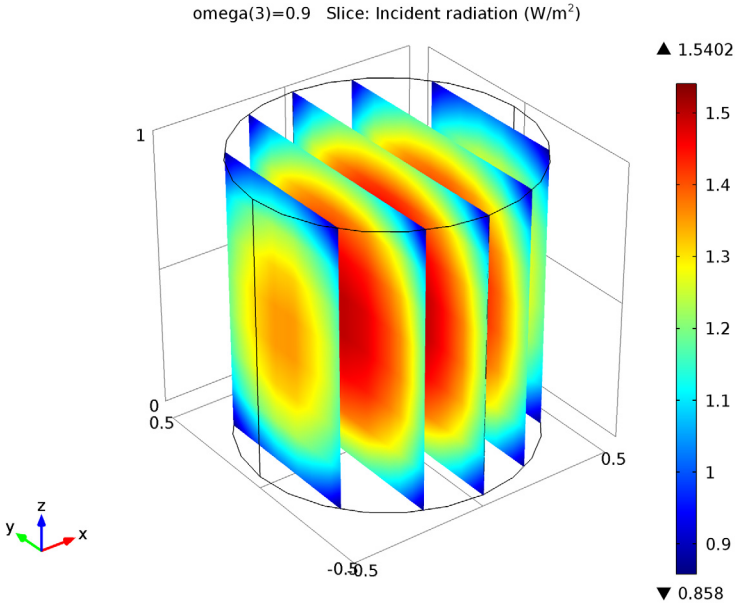
2 Right-click **Stationary Solver 1** and choose **Iterative**.

3 Right-click **Study 1>Solver Configurations>Solver 1>Stationary Solver 1>Iterative 1** and choose **Enable**.

4 Right-click **Study 1** and choose **Compute**.

RESULTS

The first default plot shows the incident radiation distribution in 3D and the second default plot represents the net radiative heat flux distribution in 3D, see figure below.



Add a new 1D Plot to represent the net radiative heat flux along the z-coordinate and compare with Figure 2.

1D Plot Group 3

1. In the **Model Builder** window, right-click **Results** and choose **1D Plot Group**.
2. Right-click **1D Plot Group 3** and choose **Line Graph**.
3. Click the **Transparency** button on the Graphics toolbar.
4. Select Edge 12 only.
5. Click the **Transparency** button on the Graphics toolbar again to return to the original state.
6. In the **Line Graph** settings window, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Radiation in Participating Media>Net radiative heat flux (rpm.qw)**.
7. Click **Replace Expression** in the upper-right corner of the **x-Axis Data** section. From the menu, choose **Geometry and Mesh>Coordinate>z-coordinate (z)**.

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

Finish the plot by adjusting the title and axis labels.

9 In the **Model Builder** window, click **1D Plot Group 3**.

10 In the **1D Plot Group** settings window, click to expand the **Title** section.

11 From the **Title type** list, choose **None**.

12 Locate the **Plot Settings** section. Select the **x-axis label** check box.

13 In the associated edit field, type `z-coordinate (m)`.

14 Select the **y-axis label** check box.

15 In the associated edit field, type `Net radiative heat flux (W/m<sup>2</sup>)`.

16 Click the **Plot** button.

17 Right-click **1D Plot Group 3** and choose **Rename**.

18 Go to the **Rename 1D Plot Group** dialog box and type `Net Radiative Heat flux vs z, 1D` in the **New name** edit field.

19 Click **OK**.

Data Sets

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

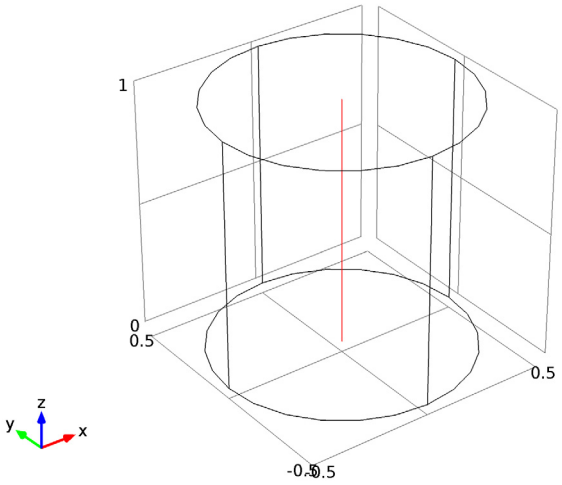
2 In the **Cut Line 3D** settings window, locate the **Line Data** section.

3 In row **Point 2**, set **x** to `0`.

4 In row **Point 2**, set **z** to `L`.

5 Click the **Plot** button.

The Graphics window shows the location of the line in the model geometry.



Add a new 1D Plot to represent the incident radiation along the z-coordinate and compare with Figure 3.

1D Plot Group 4

1 In the **Model Builder** window, right-click **Results** and choose **1D Plot Group**.

2 In the **1D Plot Group** settings window, locate the **Data** section.

3 From the **Data set** list, choose **Cut Line 3D 1**.

4 Right-click **Results>1D Plot Group 4** and choose **Line Graph**.

5 In the **Line Graph** settings window, click **Replace Expression** in the upper-right corner of the **x-Axis Data** section. From the menu, choose **Geometry and Mesh>Coordinate>z-coordinate (z)**.

6 Locate the **Legends** section. Select the **Show legends** check box.

7 In the **Model Builder** window, click **1D Plot Group 4**.

8 In the **1D Plot Group** settings window, locate the **Title** section.

9 From the **Title type** list, choose **None**.

10 Locate the **Plot Settings** section. Select the **x-axis label** check box.

11 In the associated edit field, type `z-coordinate (m)`.

12 Select the **y-axis label** check box.

13 In the associated edit field, type `Incident radiation (W/m<sup>2</sup>)`.

14 Click the **Plot** button.

15 Right-click **1D Plot Group 4** and choose **Rename**.

16 Go to the **Rename 1D Plot Group** dialog box and type `Incident radiation vs z, 1D` in the **New name** edit field.

17 Click **OK**.

Data Sets

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

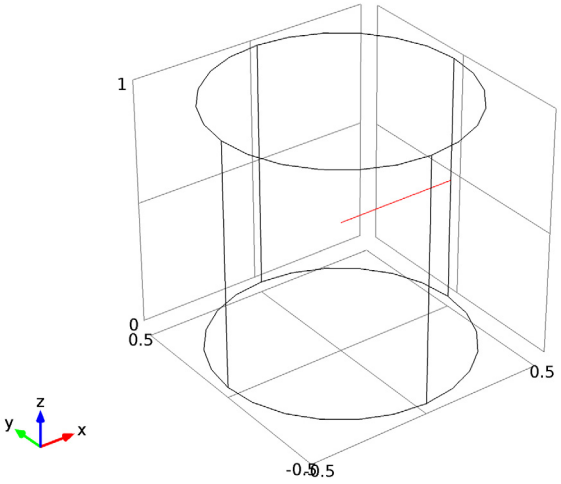
2 In the **Cut Line 3D** settings window, locate the **Line Data** section.

3 In row **Point 1**, set **z** to `L/2`.

4 In row **Point 2**, set **x** to `R`.

5 In row **Point 2**, set **z** to `L/2`.

6 Click the **Plot** button.



Add a new 1D Plot to represent the incident radiation along the x-coordinate and compare with Figure 4.

Incident radiation vs z, 1D 1

1 In the **Model Builder** window, under **Results** right-click **Incident radiation vs z, 1D** and choose **Duplicate**.

2 In the **1D Plot Group** settings window, locate the **Data** section.

3 From the **Data set** list, choose **Cut Line 3D 2**.

4 Locate the **Plot Settings** section. In the **x-axis label** edit field, type `x-coordinate (m)`.

5 In the **Model Builder** window, expand the **Incident radiation vs z, 1D 1** node, then click **Line Graph 1**.

6 In the **Line Graph** settings window, click **Replace Expression** in the upper-right corner of the **x-Axis Data** section. From the menu, choose **Geometry and Mesh>Coordinate>x-coordinate (x)**.

7 Click the **Plot** button.

8 In the **Model Builder** window, right-click **Incident radiation vs z, 1D 1** and choose **Rename**.

9 Go to the **Rename 1D Plot Group** dialog box and type `Incident radiation vs x, 1D` in the **New name** edit field.

10 Click **OK**.

Modeling Instructions—Case 1

RADIATION IN PARTICIPATING MEDIA

Opaque Surface 2

1 In the **Model Builder** window, under **Model 1** right-click **Radiation in Participating Media** and choose **Opaque Surface**.

2 In the **Opaque Surface** settings window, locate the **Model Inputs** section.

3 In the T edit field, type `Tw`.

4 Select Boundaries 1, 2, 5, and 6 only.

These are the vertical wall boundaries. To be able to reach them all you can rotate the geometry or click either the **Transparency** button or the **Wireframe Rendering** button on the **Graphics** toolbar.

5 Locate the **Wall Settings** section. From the ε list, choose **User defined**. In the associated edit field, type `ew*(1-y/R)`.

ROOT

In the **Model Builder** window, right-click the root node and choose **Add Study**.

MODEL WIZARD

1 Go to the **Model Wizard** window.

2 Find the **Studies** subsection. In the tree, select **Preset Studies>Stationary**.

3 Click **Finish**.

STUDY 2

Parametric Sweep

1 In the **Model Builder** window, right-click **Study 2** and choose **Parametric Sweep**.

2 In the **Parametric Sweep** settings window, locate the **Study Settings** section.

3 Click **Add**.

4 In the table, enter the following settings:

Parameter names	Parameter value list
omega	0.1 0.5 0.9

5 Right-click **Study 2** and choose **Show Default Solver**.

6 In the **Model Builder** window, expand the **Study 2>Solver Configurations** node.

Solver 2

1 In the **Model Builder** window, expand the **Study 2>Solver Configurations>Solver 2** node, then click **Dependent Variables 1**.

2 In the **Dependent Variables** settings window, locate the **General** section.

3 From the **Defined by study step** list, choose **User defined**.

4 Locate the **Initial Values of Variables Solved For** section. From the **Method** list, choose **Solution**.

5 From the **Solution** list, choose **Solver 1**.

6 In the **Model Builder** window, under **Study 2>Solver Configurations>Solver 2** right-click **Stationary Solver 1** and choose **Iterative**.

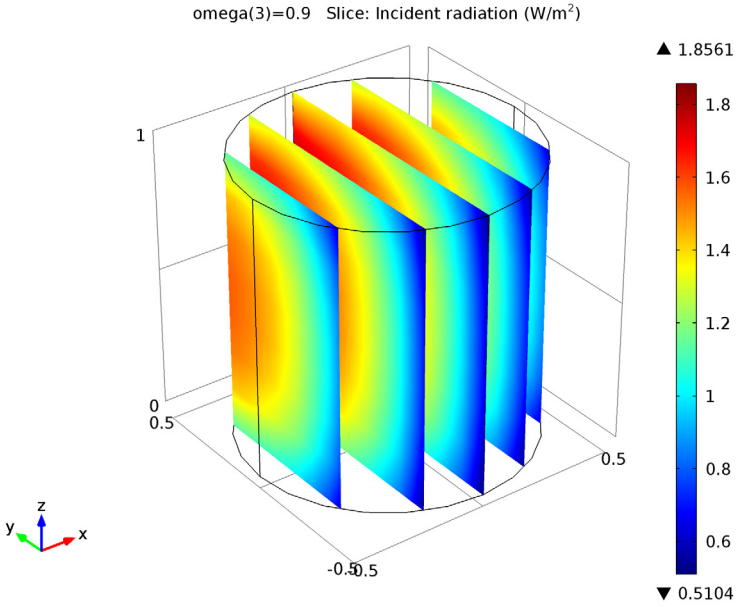
7 Right-click **Study 2>Solver Configurations>Solver 2>Stationary Solver 1>Iterative 1** and choose **Enable**.

8 Right-click **Study 2** and choose **Compute**.

RESULTS

Incident Radiation (rpm) 1

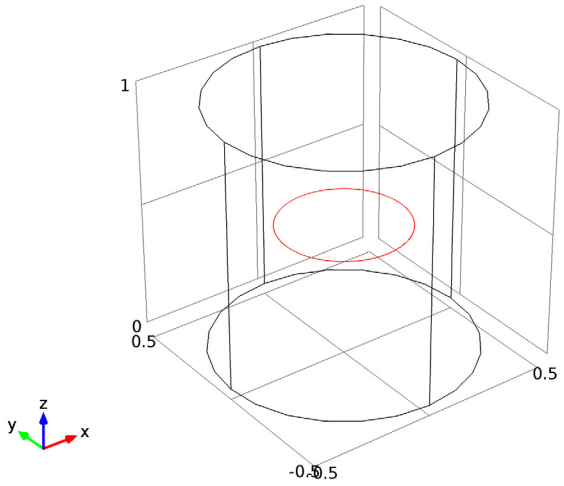
The first default plot shows the incident radiation distribution in 3D and the second default plot represents the net radiative heat flux distribution in 3D, see figure below.



Data Sets

1. In the **Model Builder** window, under **Results** right-click **Data Sets** and choose **More Data Sets>Parameterized Curve 3D**.
2. In the **Parameterized Curve 3D** settings window, locate the **Data** section.
3. From the **Data set** list, choose **Solution 2**.
4. Locate the **Parameter** section. In the **Name** edit field, type `phi`.
5. In the **Maximum** edit field, type `2*pi`.
6. Locate the **Expressions** section. In the **x** edit field, type `R*cos(phi)/2`.
7. In the **y** edit field, type `R*sin(phi)/2`.
8. In the **z** edit field, type `L/2`.
9. In the **Model Builder** window, under **Results>Data Sets** click **Parameterized Curve 3D 1**.

10 In the **Settings** window, click **Plot**.



Add a new 1D Plot to represent the incident radiation in function of the azimuthal angle and compare with Figure 5.

1D Plot Group 8

1 In the **Model Builder** window, right-click **Results** and choose **1D Plot Group**.

2 In the **1D Plot Group** settings window, locate the **Data** section.

3 From the **Data set** list, choose **Parameterized Curve 3D 1**.

4 Right-click **Results>1D Plot Group 8** and choose **Line Graph**.

5 In the **Line Graph** settings window, click to expand the **Legends** section.

6 Select the **Show legends** check box.

7 In the **Model Builder** window, click **1D Plot Group 8**.

8 In the **1D Plot Group** settings window, locate the **Title** section.

9 From the **Title type** list, choose **None**.

10 Locate the **Plot Settings** section. Select the **x-axis label** check box.

11 In the associated edit field, type `Azimuthal angle (rad)`.

12 Select the **y-axis label** check box.

13 In the associated edit field, type `Incident radiation (W/m<sup>2</sup>)`.

14 Click the **Plot** button.

15 Right-click **1D Plot Group 8** and choose **Rename**.

16 Go to the **Rename 1D Plot Group** dialog box and type `Incident radiation vs azimuthal angle, 1D` in the **New name** edit field.

17 Click **OK**.

Modeling Instructions—Case 2

GLOBAL DEFINITIONS

Parameters

For Case 2, you need to modify the value of the single-scattering albedo that you defined previuosly and add a parameter for the Legendre coefficent `a1` in the scattering phase function.

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

2 In the **Parameters** settings window, locate the **Parameters** section.

3 In the table, enter the following settings:

Name	Expression	Description
omega	0.5	Single-scattering albedo
a1	0.99	Legendre coefficient

RADIATION IN PARTICIPATING MEDIA

Radiation in Participating Media 1

1 In the **Model Builder** window, under **Model 1>Radiation in Participating Media** click **Radiation in Participating Media 1**.

2 In the **Radiation in Participating Media** settings window, locate the **Scattering** section.

3 From the **Scattering type** list, choose **Linear anisotropic**.

4 In the a_1 edit field, type `a1`.

ROOT

In the **Model Builder** window, right-click the root node and choose **Add Study**.

MODEL WIZARD

1 Go to the **Model Wizard** window.

2 Find the **Studies** subsection. In the tree, select **Preset Studies>Stationary**.

3 Click **Finish**.

STUDY 3

Parametric Sweep

1 In the **Model Builder** window, right-click **Study 3** and choose **Parametric Sweep**.

2 In the **Parametric Sweep** settings window, locate the **Study Settings** section.

3 Click **Add**.

4 In the table, enter the following settings:

Parameter names	Parameter value list
a1	-0.99 0 0.99

Note that the value a1 = 0 gives the same solution as for omega = 0.5 in Case 1.

5 Right-click **Study 3** and choose **Show Default Solver**.

6 In the **Model Builder** window, expand the **Study 3>Solver Configurations** node.

Solver 3

1 In the **Model Builder** window, expand the **Study 3>Solver Configurations>Solver 3** node, then click **Dependent Variables 1**.

2 In the **Dependent Variables** settings window, locate the **General** section.

3 From the **Defined by study step** list, choose **User defined**.

4 Locate the **Initial Values of Variables Solved For** section. From the **Method** list, choose **Solution**.

5 From the **Solution** list, choose **Solver 2**.

6 In the **Model Builder** window, under **Study 3>Solver Configurations>Solver 3** right-click **Stationary Solver 1** and choose **Iterative**.

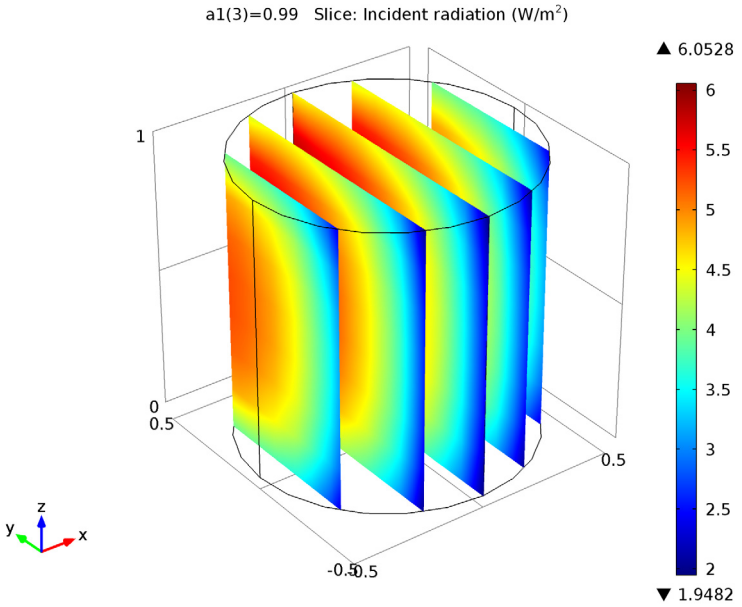
7 Right-click **Study 3>Solver Configurations>Solver 3>Stationary Solver 1>Iterative 1** and choose **Enable**.

8 Right-click **Study 3** and choose **Compute**.

RESULTS

Incident Radiation (rpm) 2

The first default plot shows the incident radiation distribution in 3D and the second default plot represents the net radiative heat flux distribution in 3D, see figure below.

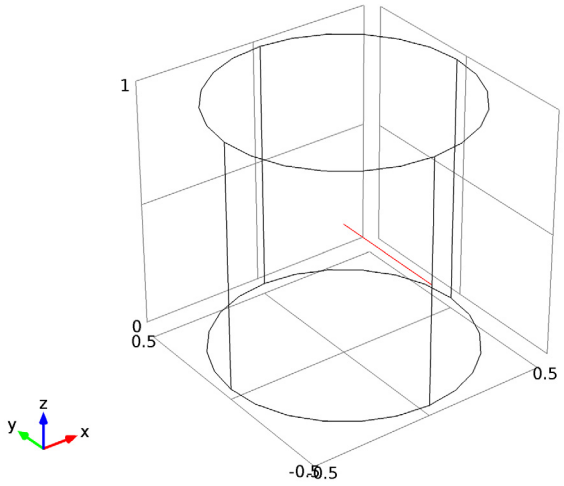


Data Sets

1. In the **Model Builder** window, under **Results** right-click **Data Sets** and choose **More Data Sets>Parameterized Curve 3D**.
2. In the **Parameterized Curve 3D** settings window, locate the **Data** section.
3. From the **Data set** list, choose **Solution 3**.
4. Locate the **Parameter** section. In the **Maximum** edit field, type `1`.
5. Locate the **Expressions** section. In the **y** edit field, type `-s*R`.
6. In the **z** edit field, type `L/2`.

   With the above definition, `s = -y/R` equals the optical thickness along the negative y-axis for the given constant values of x and z.

7 Click the **Plot** button.



Add a new 1D Plot to represent the incident radiation in function of the normalized optical thickness and compare with Figure 6.

1D Plot Group 11

1 In the **Model Builder** window, right-click **Results** and choose **1D Plot Group**.

2 In the **1D Plot Group** settings window, locate the **Data** section.

3 From the **Data set** list, choose **Parameterized Curve 3D 2**.

4 Right-click **Results>1D Plot Group 11** and choose **Line Graph**.

5 In the **Line Graph** settings window, locate the **x-Axis Data** section.

6 From the **Parameter** list, choose **Expression**.

7 In the **Expression** edit field, type `s`.

8 Locate the **Legends** section. Select the **Show legends** check box.

9 In the **Model Builder** window, click **1D Plot Group 11**.

10 In the **1D Plot Group** settings window, locate the **Title** section.

11 From the **Title type** list, choose **None**.

12 Locate the **Plot Settings** section. Select the **x-axis label** check box.

13 In the associated edit field, type `Normalized optical thickness (y/R)`.

14 Select the **y-axis label** check box.

15 In the associated edit field, type `Incident radiation (W/m<sup>2</sup>)`.

16 Click the **Plot** button.

17 Right-click **1D Plot Group 11** and choose **Rename**.

18 Go to the **Rename 1D Plot Group** dialog box and type `Incident radiation vs normalized optical thickness, 1D` in the **New name** edit field.

19 Click **OK**.