

Radiative Heat Transfer in Finite Cylindrical Media — PI Method

This application uses the P1 approximation to solve a 3D radiative transfer problem in an emitting, absorbing, and linearly anisotropic-scattering finite cylindrical medium. The calculated incident radiation and heat fluxes are compared to the results obtained with the highly accurate S6 discrete ordinates method (see Radiative Heat Transfer in Finite Cylindrical Media). The results obtained with this method show fairly good agreement with published results obtained by transformed integral methods (see Ref. 1) for optically thick media.

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 tutorial you validate the P1 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 results are compared to the results obtained with the DOM formulation as shown in Radiative Heat Transfer in Finite Cylindrical Media.

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

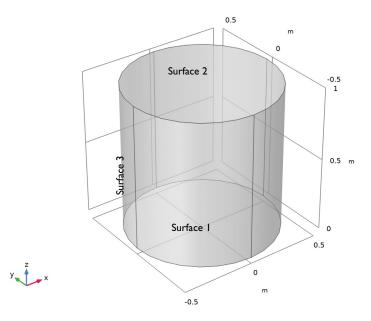


Figure 1: Schematic diagram of the physical model.

These examples use the P1 approximation 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, T = 0K. Furthermore, assume that the walls diffusively reflect radiation, that is, $\varepsilon = 0.5$. The medium is at a uniform temperature *T* such that the blackbody radiation intensity $I_h(T) = \sigma T^4 / \pi$ is equal to 1 W/ m^2 .

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 I: 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 P1 approximation method is the simplest form of the method of spherical harmonics (PN) to describe radiative transport in participating media. 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
- $I_{\rm b}(T)$ is the blackbody radiation intensity
- $\phi(\Omega, \Omega') = 1 + \alpha_1 \mu_0$ where $\mu_0 = \Omega \cdot \Omega'$ is the cosine of the scattering angle.

The RTE (an integro-partial differential equation) is transformed into a set of partial differential equations. The remaining task is to solve an additional equation for

$$G = \int_{0}^{4\pi} I(\Omega) d\Omega$$

which adds a heat source/sink to account for radiative heat transfer.

$$-\nabla \cdot (D_{\rm P1} \nabla G) = Q_{\rm r}$$

where D_{P1} is a diffusion coefficient and Q_r is the radiative heat source. The boundary condition for opaque surfaces then is

Results and Discussion

The results demonstrate that the P1 method provides a fast alternative to the DOM method. The solution time is only a few seconds whereas it is about 4 hours for the DOM method on the same mesh. The results represent the radiation characteristics well. The numerical values show good agreement for small scattering coefficients (omega) and high absorption coefficients (kappa). The relation between both values is $\kappa = \omega/(\omega - 1)$.

VERIFICATION CASE

This case examines the effects of the scattering albedo on the incident radiation and heat fluxes. Figure 2 shows the distribution of the net heat flux $q_{\rm r,\,net}(R,0,z)$ versus axial optical thickness. There is good agreement with the results obtained from the DOM model. The results for the net radiative heat flux (Figure 2) show good agreement with distance to the top and bottom boundary. The relative error for small scattering albedo is below 10% and increases with increasing scattering albedo.

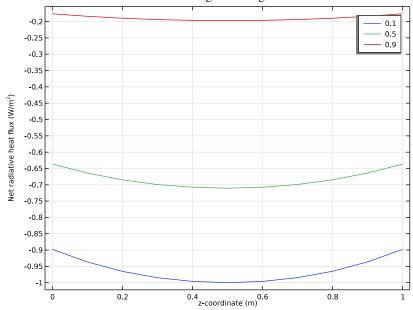


Figure 2: The effects of the scattering albedo on the radial heat flux $q_{r,\, net}(R,\, 0,z)$; for a hot cylindrical medium enclosed by cold walls, $\epsilon_1=\epsilon_2=\epsilon_3=0.5$.

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.

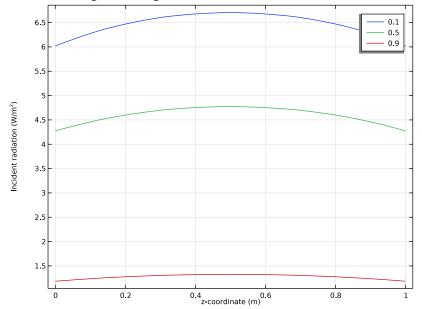


Figure 3: The effects of the scattering albedo on the distribution of centerline incident radiation G(0,0,z) for a hot cylindrical medium enclosed by cold walls, $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = 0.5$.

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

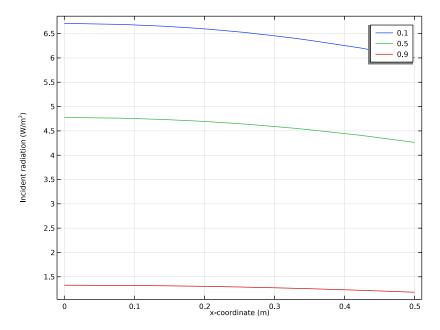


Figure 4: The effects of the scattering albedo on the distributions of the incident radiation G(x, x)0, L/2) with respect to normalized optical thickness x/R for a hot cylindrical medium enclosed by cold walls, $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = 0.5$.

For the validation case the relative error compared to the DOM model is below 20%.

WALLS WITH VARIABLE EMISSIVITY

The incident radiation at the midplane 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. The numerical error for small scattering albedo again is low (around 10%).

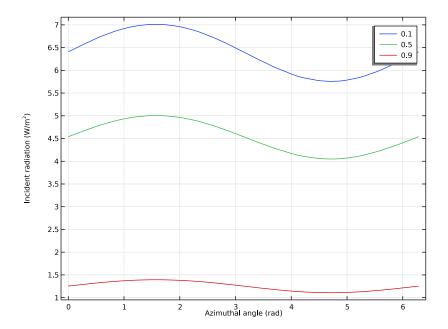


Figure 5: The effects of scattering albedo on the distribution of incident radiation at midplane z=L/2 at R/2 distance from the cylinder axis with respect to an azimuthal coordinate for Case 1.

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.

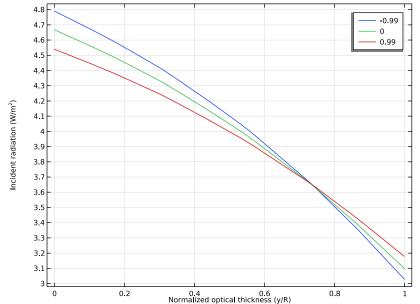


Figure 6: The effects of linear anisotropic scattering coefficient a 1 on the distribution of incident radiation G(0, y, L/2) with respect to normalized optical thickness – y/R for Case 2.

Unlike the discrete ordinates method, the P1 method is computationally inexpensive and gives fast results at the expense of accuracy in most cases. For large optical thickness the results show good agreement with the results obtained from the discrete ordinate method and hence with the results presented in the literature.

References

- 1. X.L. Chen and W.H. Sutton, "Radiative Transfer in Finite Cylindrical Media Using Transformed Integral Equations," J. 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. Quantitative Spectroscopy and Radiative 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," J. Thermophysics and Heat Transfer, vol. 6, no. 1, pp. 180-182, 1992.

Application Library path: Heat Transfer Module/Verification Examples/ cylinder participating media p1

Modeling Instructions — Validation Case

From the File menu, choose New.

NEW

In the New window, click Model Wizard.

MODEL WIZARD

- I In the Model Wizard window, click **3D**.
- 2 In the Select Physics tree, select Heat Transfer>Radiation> Radiation in Participating Media (rpm).
- 3 Click Add.
- 4 Click 🗪 Study.
- 5 In the Select Study tree, select General Studies>Stationary.
- 6 Click **Done**.

GLOBAL DEFINITIONS

Parameters 1

- I In the Model Builder window, under Global Definitions click Parameters I.
- 2 In the Settings window for Parameters, locate the Parameters section.

3 In the table, enter the following settings:

Name	Expression	Value	Description
Т0	(1[W/m^2]*pi/ sigma_const)^(1/4)	86.275 K	Body temperature
Tw	0[K]	0 K	Wall temperature
ew	0.5	0.5	Wall emissivity
omega	0.5	0.5	Single-scattering albedo
sigma_s	omega	0.5	Scattering coefficient
kappa	sigma_s*(1/omega-1)	0.5	Absorption coefficient
R	0.5[m]	0.5 m	Cylinder radius
L	1 [m]	l m	Cylinder length

GEOMETRY I

Cylinder I (cyl1)

- I 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 R.
- 4 In the Height text field, type L.
- 5 Click **Build All Objects**.

MATERIALS

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

Domain

- I In the Materials toolbar, click Blank Material.
- 2 In the Settings window for Material, type Domain in the Label text field.
- **3** Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Absorption coefficient	kappaR	kappa	I/m	Basic
Scattering coefficient	sigmaS	sigma_s	I/m	Basic

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

Walls

- I In the Materials toolbar, click : Blank Material.
- 2 In the Settings window for Material, type Walls in the Label text field.
- 3 Locate the Geometric Entity Selection section. From the Geometric entity level list, choose Boundary.
- 4 From the Selection list, choose All boundaries.
- **5** Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Surface emissivity	epsilon_rad	ew	I	Basic

RADIATION IN PARTICIPATING MEDIA (RPM)

- I In the Model Builder window, under Component I (compl) click Radiation in Participating Media (rpm).
- 2 In the Settings window for Radiation in Participating Media, locate the Participating Media Settings section.
- 3 Find the Radiation settings subsection. From the Radiation discretization method list, choose PI approximation.

Participating Medium 1

- I In the Model Builder window, under Component I (compl)> Radiation in Participating Media (rpm) click Participating Medium 1.
- 2 In the Settings window for Participating Medium, locate the Model Input section.
- **3** In the *T* text field, type T0.

Opaque Surface I

- I In the Model Builder window, click Opaque Surface I.
- 2 In the Settings window for Opaque Surface, locate the Model Input section.
- **3** In the *T* text field, type Tw.

STUDY I

Parametric Sweep

- I In the Study toolbar, click Parametric Sweep.
- 2 In the Settings window for Parametric Sweep, locate the Study Settings section.
- 3 Click + Add.

4 In the table, enter the following settings:

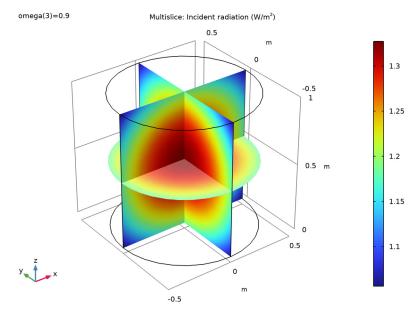
Parameter name	Parameter value list	Parameter unit
omega (Single-scattering albedo)	0.1 0.5 0.9	

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

RESULTS

Incident Radiation (rpm)

The default plot shows a 3D distribution of incident radiation on surface slices.



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

Net Radiative Heat Flux vs. z, ID

- I In the Home toolbar, click Add Plot Group and choose ID Plot Group.
- 2 In the Settings window for ID Plot Group, type Net Radiative Heat Flux vs. z, 1D in the Label text field.

Line Graph 1

I In the Net Radiative Heat Flux vs. z, ID toolbar, click the Line Graph.

- 2 Click the Transparency button in the Graphics toolbar.
- **3** Select Edge 12 only.
- 4 Click the Transparency button in the Graphics toolbar again to return to the original state.
- 5 In the Settings window for Line Graph, click Replace Expression in the upper-right corner of the y-Axis Data section. From the menu, choose Component I (compl)> Radiation in Participating Media>Boundary fluxes>rpm.qr_net - Net radiative heat flux -W/m².
- 6 Click Replace Expression in the upper-right corner of the x-Axis Data section. From the menu, choose Component I (compl)>Geometry>Coordinate>z - z-coordinate.
- 7 Click to expand the **Legends** section. Select the **Show legends** check box.

Finish the plot by adjusting the title and axis labels.

Net Radiative Heat Flux vs. z, ID

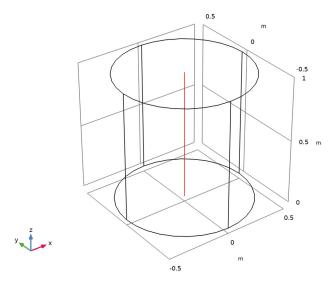
- I In the Model Builder window, click Net Radiative Heat Flux vs. z, ID.
- 2 In the Settings window for ID Plot Group, click to expand the Title section.
- **3** From the **Title type** list, choose **None**.
- 4 Locate the **Plot Settings** section. Select the **x-axis label** check box.
- 5 Select the y-axis label check box.
- 6 In the Net Radiative Heat Flux vs. z, ID toolbar, click Plot.

Cut Line 3D I

- I 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 2, set X to 0, and z to L.

4 Click Plot.

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.

Incident Radiation vs. z, ID

- I In the Results toolbar, click \sim ID Plot Group.
- 2 In the **Settings** window for **ID Plot Group**, type Incident Radiation vs. z, 1D in the **Label** text field.
- 3 Locate the Data section. From the Dataset list, choose Cut Line 3D 1.

Line Graph 1

- I In the Incident Radiation vs. z, ID toolbar, click Line Graph.
- 2 In the Settings window for Line Graph, click Replace Expression in the upper-right corner of the x-Axis Data section. From the menu, choose Component I (compl)>Geometry> Coordinate>z z-coordinate.
- 3 Locate the Legends section. Select the Show legends check box.

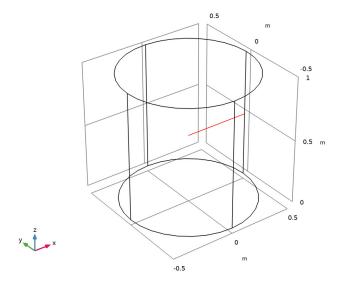
Incident Radiation vs. z, ID

- I In the Model Builder window, click Incident Radiation vs. z, ID.
- 2 In the Settings window for ID Plot Group, locate the Title section.
- **3** From the **Title type** list, choose **None**.

- 4 Locate the Plot Settings section. Select the x-axis label check box.
- 5 Select the y-axis label check box.
- 6 In the Incident Radiation vs. z, ID toolbar, click **Plot**.

Cut Line 3D 2

- I 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 I, set Z to L/2.
- 4 In row Point 2, set X to R, and z to L/2.
- 5 Click Plot.



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

Incident Radiation vs. z, ID

Right-click Incident Radiation vs. z, ID and choose Duplicate.

Incident Radiation vs. x, ID

- I In the Model Builder window, under Results click Incident Radiation vs. z, ID 1.
- 2 In the Settings window for ID Plot Group, type Incident Radiation vs. x, 1D in the Label text field.
- 3 Locate the Data section. From the Dataset list, choose Cut Line 3D 2.

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

Line Graph 1

- I In the Model Builder window, expand the Incident Radiation vs. x, ID node, then click Line Graph 1.
- 2 In the Settings window for Line Graph, click Replace Expression in the upper-right corner of the x-Axis Data section. From the menu, choose Component I (compl)>Geometry> Coordinate>x - x-coordinate.
- 3 In the Incident Radiation vs. x, ID toolbar, click Plot.

Modeling Instructions — Case 1

RADIATION IN PARTICIPATING MEDIA (RPM)

Obaque Surface 2

- I In the Physics toolbar, click **Boundaries** and choose **Opaque Surface**.
- 2 In the Settings window for Opaque Surface, locate the Model Input section.
- **3** In the *T* text field, type Tw.
- 4 Select Boundaries 1, 2, 5, and 6 only.

These are the vertical wall boundaries. To reach all of them, you can rotate the geometry or click either the Transparency button or the Wireframe Rendering button in the Graphics toolbar.

5 Locate the Surface Radiative Properties section. From the ε list, choose User defined. In the associated text field, type ew*(1-y/R).

Now, disable Opaque Surface 2 in Study I to be able to re run the same Study I configuration.

STUDY I

Steb 1: Stationary

- I In the Model Builder window, under Study I click Step I: Stationary.
- 2 In the Settings window for Stationary, locate the Physics and Variables Selection section.
- 3 Select the Modify model configuration for study step check box.
- 4 In the tree, select Component I (compl)>Radiation in Participating Media (rpm)> Opaque Surface 2.
- 5 Click Disable.

ADD STUDY

- I 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 General Studies>Stationary.
- 4 Click Add Study in the window toolbar.
- 5 In the Home toolbar, click $\stackrel{\frown}{\sim}$ Add Study to close the Add Study window.

STUDY 2

Parametric Sweep

- I In the Study toolbar, click Parametric Sweep.
- 2 In the Settings window for Parametric Sweep, locate the Study Settings section.
- 3 Click + Add.
- **4** In the table, enter the following settings:

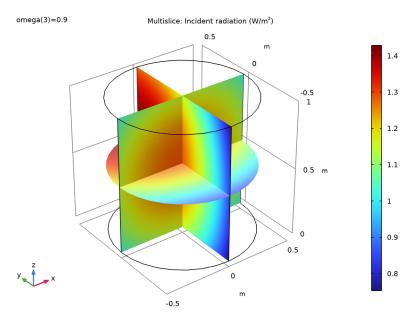
Parameter name	Parameter value list	Parameter unit
omega (Single-scattering albedo)	0.1 0.5 0.9	

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

RESULTS

Incident Radiation (rpm) I

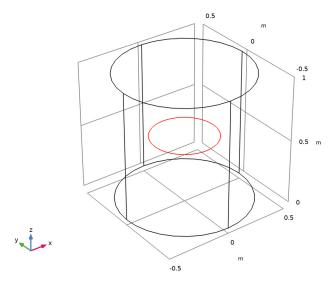
The default plot shows a 3D distribution of incident radiation on surface slices.



Parameterized Curve 3D I

- I In the Results toolbar, click More Datasets and choose Parameterized Curve 3D.
- 2 In the Settings window for Parameterized Curve 3D, locate the Data section.
- 3 From the Dataset list, choose Study 2/Solution 2 (sol2).
- 4 Locate the Parameter section. In the Name text field, type phi.
- 5 In the Maximum text field, type 2*pi.
- 6 Locate the Expressions section. In the x text field, type R*cos(phi)/2.
- 7 In the y text field, type R*sin(phi)/2.
- 8 In the z text field, type L/2.

9 Click Plot.



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

Incident Radiation vs. Azimuthal Angle, ID

- I In the Results toolbar, click \to ID Plot Group.
- 2 In the Settings window for ID Plot Group, type Incident Radiation vs. Azimuthal Angle, 1D in the Label text field.
- 3 Locate the Data section. From the Dataset list, choose Parameterized Curve 3D 1.

Line Graph 1

- I In the Incident Radiation vs. Azimuthal Angle, ID toolbar, click the Graph.
- 2 In the Settings window for Line Graph, locate the Legends section.
- 3 Select the Show legends check box.

Incident Radiation vs. Azimuthal Angle, ID

- I In the Model Builder window, click Incident Radiation vs. Azimuthal Angle, ID.
- 2 In the Settings window for ID Plot Group, locate the Title section.
- **3** From the **Title type** list, choose **None**.
- 4 Locate the Plot Settings section.

- 5 Select the x-axis label check box. In the associated text field, type Azimuthal angle (rad).
- 6 Select the y-axis label check box.

Line Graph 1

- I In the Model Builder window, click Line Graph I.
- 2 In the Settings window for Line Graph, locate the x-Axis Data section.
- 3 From the Parameter list, choose Expression.
- 4 In the Expression text field, type phi.
- 5 In the Incident Radiation vs. Azimuthal Angle, ID toolbar, click **Plot**.

Modeling Instructions — Case 2

GLOBAL DEFINITIONS

Parameters 1

For case 2, you need to add a parameter for the Legendre coefficient a1 in the scattering phase function.

- I In the Model Builder window, under Global Definitions click Parameters I.
- 2 In the Settings window for Parameters, locate the Parameters section.
- **3** In the table, enter the following settings:

Name	Expression	Value	Description
a1	0.99	0.99	Legendre coefficient

RADIATION IN PARTICIPATING MEDIA (RPM)

Add a new Radiation in Participating Media node for Study 3 only.

Participating Medium 2

- I In the Physics toolbar, click **Domains** and choose Participating Medium.
- **2** Select Domain 1 only.
- 3 In the Settings window for Participating Medium, locate the Model Input section.
- **4** In the *T* text field, type T0.
- 5 Locate the Scattering section. From the Scattering type list, choose Linear anisotropic.
- **6** In the a_1 text field, type a1.

STUDY I

Step 1: Stationary

Now, disable Radiation in Participating Media 2 in Study 1 and Study 2 to be able to re run the same configurations for these studies.

- I In the Model Builder window, under Study I click Step I: Stationary.
- 2 In the Settings window for Stationary, locate the Physics and Variables Selection section.
- 3 In the tree, select Component I (compl)>Radiation in Participating Media (rpm)> Participating Medium 2.
- 4 Right-click and choose **Disable**.

STUDY 2

- I In the Model Builder window, under Study 2 click Step 1: Stationary.
- 2 In the Settings window for Stationary, locate the Physics and Variables Selection section.
- 3 Select the Modify model configuration for study step check box.
- 4 In the tree, select Component I (compl)>Radiation in Participating Media (rpm)> Participating Medium 2.
- 5 Right-click and choose Disable.

ADD STUDY

- I 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 General Studies>Stationary.
- 4 Click Add Study in the window toolbar.
- 5 In the Home toolbar, click Add Study to close the Add Study window.

STUDY 3

Parametric Sweep

- I In the Study toolbar, click Parametric Sweep.
- 2 In the Settings window for Parametric Sweep, locate the Study Settings section.
- 3 Click + Add.

4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
al (Legendre coefficient)	-0.99 0 0.99	

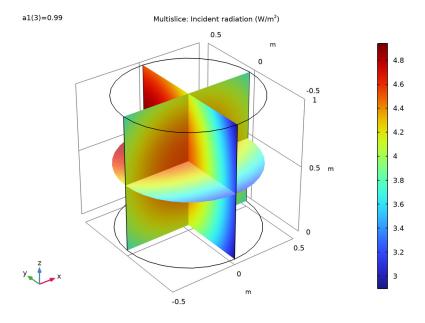
Note that the value $a_1 = 0$ gives the same solution as for $\omega = 0.5$ in case 1.

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

RESULTS

Incident Radiation (rpm) 2

The default plot shows a 3D distribution of incident radiation on surface slices.



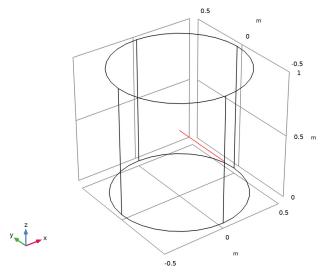
Parameterized Curve 3D 2

- I In the Results toolbar, click More Datasets and choose Parameterized Curve 3D.
- 2 In the Settings window for Parameterized Curve 3D, locate the Data section.
- 3 From the Dataset list, choose Study 3/Solution 3 (sol3).
- **4** Locate the **Expressions** section. In the **y** text field, type s*R.

5 In the z text field, type L/2.

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

6 Click Plot.



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

Incident Radiation vs. Normalized Optical Thickness, ID

- I In the Results toolbar, click \(\subseteq ID Plot Group. \)
- 2 In the Settings window for ID Plot Group, type Incident Radiation vs. Normalized Optical Thickness, 1D in the Label text field.
- 3 Locate the Data section. From the Dataset list, choose Parameterized Curve 3D 2.

Line Graph I

- I In the Incident Radiation vs. Normalized Optical Thickness, ID toolbar, click Line Graph.
- 2 In the Settings window for Line Graph, locate the x-Axis Data section.
- 3 From the Parameter list, choose Expression.
- 4 In the Expression text field, type s.
- **5** Locate the **Legends** section. Select the **Show legends** check box.

Incident Radiation vs. Normalized Optical Thickness, ID

- I In the Model Builder window, click Incident Radiation vs. Normalized Optical Thickness, ID.
- 2 In the Settings window for ID Plot Group, locate the Title section.
- 3 From the Title type list, choose None.
- 4 Locate the Plot Settings section.
- 5 Select the x-axis label check box. In the associated text field, type Normalized optical thickness (y/R).
- **6** Select the **y-axis label** check box.
- 7 In the Incident Radiation vs. Normalized Optical Thickness, ID toolbar, click Plot.