Model created in COMSOL Multiphysics 6.4

Rotating Microwave Oven with Phase Transition

Introduction

Simulating a rotating microwave oven helps us understand how microwave energy interacts with objects, affecting their internal temperature and cooking results. It also aids in refining microwave oven designs and understanding heat transfer during heating. The example model demonstrates how heat transfers within a potato as it changes from moist to dehydrated, addressing its material properties and microwave absorption rates using the phase change material feature. These factors are essential for accurately modeling cooking or heating processes.

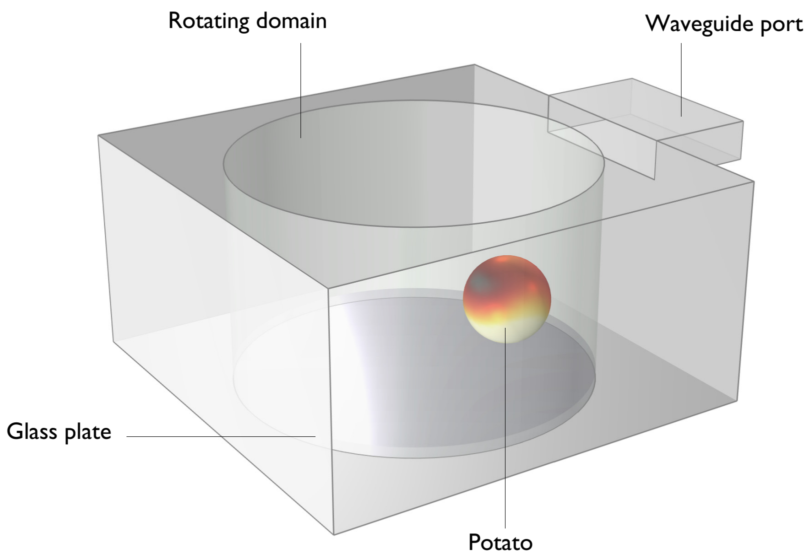


Figure 1: Heated potato inside a rotating domain.

Model Definition

A spherical, water-rich load simulating a potato is placed on a rotating glass tray in a microwave oven, positioned off-center. A 1 kW, 2.45 GHz microwave power is applied through a waveguide feed, and the tray rotates at 9 degrees per second. The heat transfer model addresses the transition from a water-rich to a dehydrated phase, including changes in material properties and microwave losses. The simulation rotates the model in 0.25-second steps, with a mesh adjusted for conformity at each step using the Phase Change

Material feature from the Heat Transfer in Solids interface and the Events interface for step-wise motion.

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN

A Port feature is configured to represent the waveguide boundary with a 1 kW power input and a rectangular port type. The Continuity feature ensures electromagnetic field continuity across boundaries, while the Wave Equation, Electric 2 feature models the lossy behavior of electric waves in the potato. It accounts for dielectric losses with temperature-dependent permittivity values.

HEAT TRANSFER IN SOLIDS

This interface describes thermal behavior within the potato and glass plate domains. The potato domain includes a Phase Change Material feature, crucial for simulating transitions between water-rich and dehydrated states. It is configured with a phase change temperature of 373.15 K and a latent heat of 2.2564×10^6 J/kg. Thermal conductivity values are specified for each direction to model heat conduction accurately.

MOVING MESH

The model utilizes the Moving Mesh functionality to handle rotating domains. The Rotating Domain feature describes rotational motion with a parameter for the rotation angle, enabling dynamic geometry changes during rotation.

EVENTS

The Events interface manages discrete events and state changes. An Explicit Event feature defines time-dependent changes with a period specified by dt, while the Discrete States feature tracks rotation angles and step numbers.

MULTIPHYSICS

The Electromagnetic Heating multiphysics feature couples electromagnetic effects with heat transfer, integrating the impact of electromagnetic fields on thermal processes.

ADDITIONAL SETTINGS

Discretization properties for both electromagnetic and heat transfer physics are set to Linear.

The Model Builder sets up a comprehensive multiphysics simulation integrating electromagnetic wave propagation, heat transfer, and discrete events with rotating domains under Moving Mesh functionality. This setup provides a detailed and interactive simulation of complex physical processes, considering dynamic changes in geometry and the interaction of various physical phenomena.

Results and Discussion

The average temperature in the potato, is shown in Figure 2, gradually approaches 380 K over time.

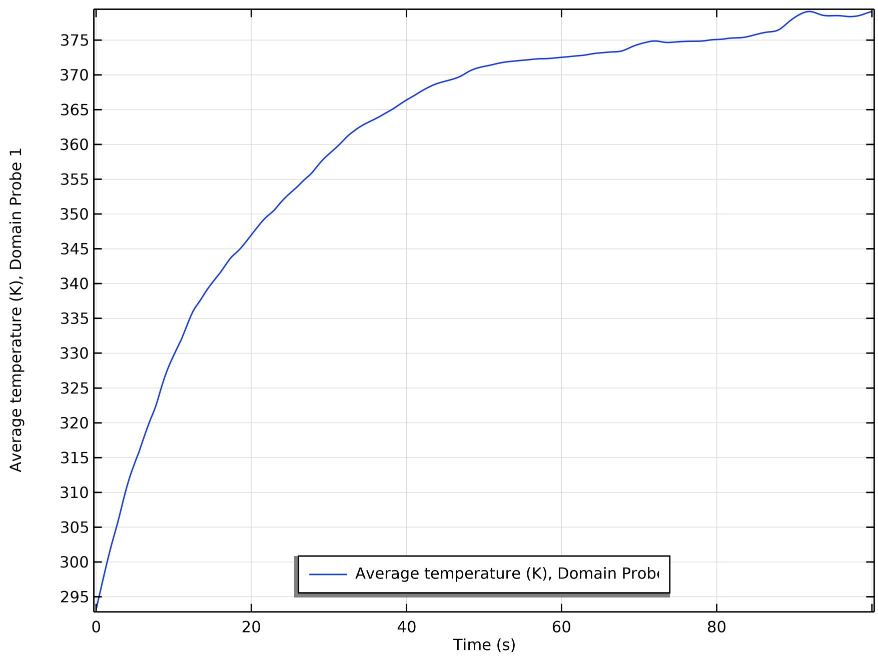


Figure 2: The average temperature in the potato over time

Figure 3 show the initial electric field norm distribution at the bottom of the microwave oven, with a relatively stronger field observed underneath the potato. Temperature distribution in the potato and glass plate domains is shown in Figure 4. The glass plate does not heat up from the electromagnetic waves. However, the area adjacent to the potato is affected due to the temperature increase from the potato.

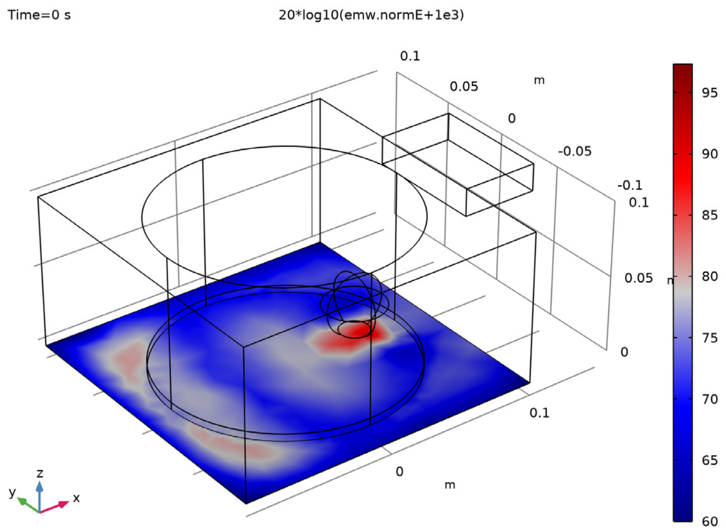


Figure 3: A plot of the electric field norm distribution at the bottom of the microwave oven.

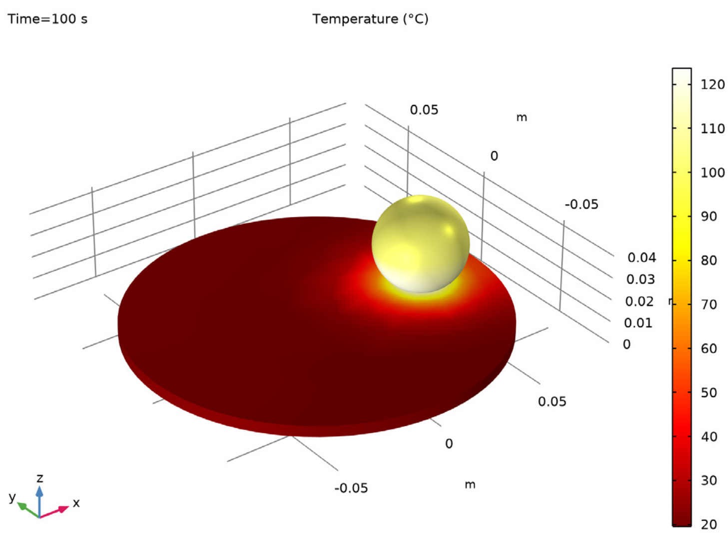


Figure 4: Temperature in the potato and glass domains.

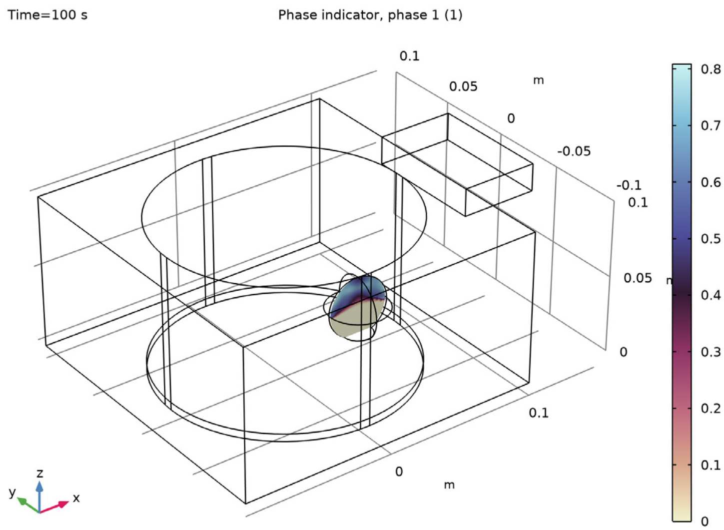


Figure 5: Fraction of water rich state.

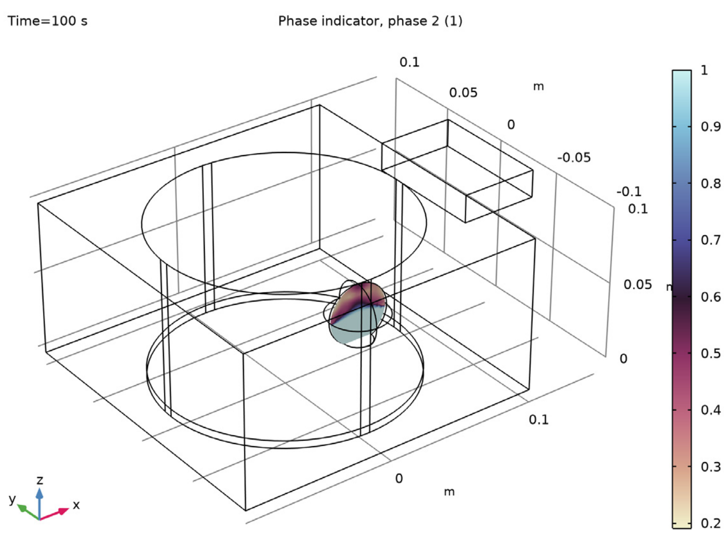


Figure 6: Fraction of dehydrate state.

Figure 5 and Figure 6 describe the fraction of water rich and dehydrate states respectively. Over the time, the bottom part of the potato heat up more than other areas and the water rich state turns into the dehydrate state.

The ratio of the coupled power to the microwave oven can be computed based on the reflection coefficient at the port that provides the excitation. Interestingly, the low coupling is observed periodically in relation to specific position of the potato, particularly when the glass plate is rotated 90 and 270 degrees from its original position (see Figure 7).

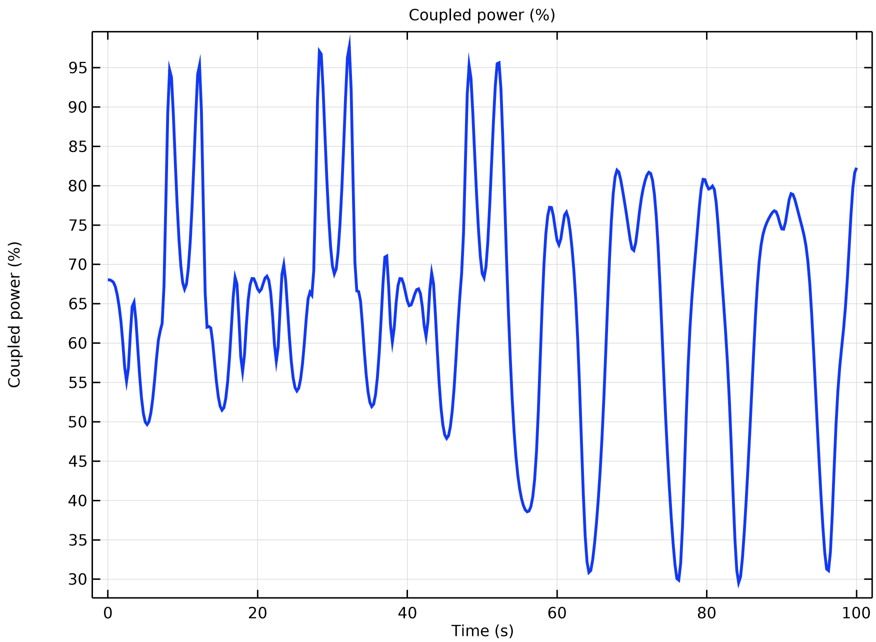


Figure 7: Coupled power to the microwave oven.

Figure 8 illustrates a variety of computed results by combining multiple plots.

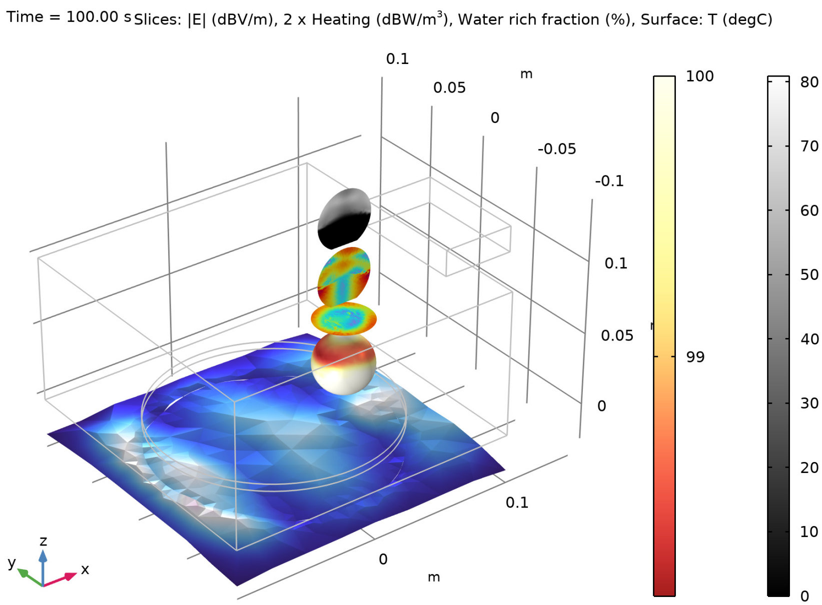


Figure 8: Combination plot of the electric field norm, temperature, and fraction of water-rich state.

Application Library path: `RF_Module/Microwave_Heating/rotating_microwave_oven`

Modeling Instructions

From the **Main Toolbar** 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 **Radio Frequency** > **Electromagnetic Waves, Frequency Domain (emw)**.
3 Click **Add**.
4 In the **Select Physics** tree, select **Heat Transfer** > **Heat Transfer in Solids (ht)**.
5 Click **Add**.
6 In the **Select Physics** tree, select **Mathematics** > **Deformed Mesh** > **Moving Mesh** > **Rotating Domain**.
7 Click **Add**.
8 In the **Select Physics** tree, select **Mathematics** > **ODE and DAE Interfaces** > **Events (ev)**.
9 Click **Add**.
10 Click **Study**.
11 In the **Select Study** tree, select **Empty Study**.
12 Click **Done**.

GLOBAL DEFINITIONS

Geometry Parameters

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.
2 In the **Settings** window for **Parameters**, type `Geometry Parameters` in the **Label** text field.
3 Locate the **Parameters** section. Click **Load from File**.
4 Browse to the model's Application Libraries folder and double-click the file `rotating_microwave_oven_parameters.txt`.

Simulation Parameters

1 In the **Home** toolbar, click **Parameters** and choose **Add** > **Parameters**.
2 In the **Settings** window for **Parameters**, type `Simulation Parameters` in the **Label** text field.
3 Locate the **Parameters** section. In the table, enter the following settings:

Name	Expression	Value	Description
N	20	20	Angular steps over 90 degrees
dt	0.25[s]	0.25 s	Dwell time on each angular position

GEOMETRY 1

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

2 In the **Settings** window for **Geometry**, locate the **Advanced** section.

3 From the **Default repair tolerance** list, choose **Relative**.

Block 1 (blk1)

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

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

3 In the **Width** text field, type `wo`.

4 In the **Depth** text field, type `do`.

5 In the **Height** text field, type `ho`.

6 Locate the **Position** section. In the **x** text field, type `-wo/2`.

7 In the **y** text field, type `-do/2`.

8 Click **Build Selected**.

9 Click the **Wireframe Rendering** button in the **Graphics** toolbar.

Block 2 (blk2)

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

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

3 In the **Width** text field, type `wg`.

4 In the **Depth** text field, type `dg`.

5 In the **Height** text field, type `hg`.

6 Locate the **Position** section. In the **x** text field, type `wo/2`.

7 In the **y** text field, type `-dg/2`.

8 In the **z** text field, type `ho-hg`.

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 `rp`.

4 In the **Height** text field, type `ho`.

5 Click to expand the **Layers** section. In the table, enter the following settings:

Layer name	Thickness (m)
Layer 1	hp

6 Clear the **Layers on side** checkbox.

7 Select the **Layers on bottom** checkbox.

Difference 1 (dif1)

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Difference**.

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

3 Click to select the **Activate Selection** toggle button for **Objects to add**.

4 Select the objects **blk1** and **blk2** only.

5 Click to select the **Activate Selection** toggle button for **Objects to subtract**.

6 Select the object **cyl1** only.

7 From the **Repair tolerance** list, choose **Automatic**.

8 Select the **Keep objects to subtract** checkbox.

9 Click **Build Selected**.

Extract 1 (extract1)

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

2 In the **Settings** window for **Extract**, locate the **Entities or Objects to Extract** section.

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

4 On the object **cyl1**, select Domain 1 only.

5 From the **Input object handling** list, choose **Create remainder object**.

Sphere 1 (sph1)

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

2 In the **Settings** window for **Sphere**, locate the **Size** section.

3 In the **Radius** text field, type `rpot`.

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

5 In the **z** text field, type `hp+0.0175`.

Difference 2 (dif2)

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Difference**.

2 Select the object **sph1** only.

3 In the **Settings** window for **Difference**, locate the **Difference** section.

4 Click to select the **Activate Selection** toggle button for **Objects to subtract**.

5 Select the object **extract1(1)** only.

6 Select the **Keep objects to subtract** checkbox.

7 From the **Repair tolerance** list, choose **Automatic**.

Rotate 1 (rot1)

1 In the **Geometry** toolbar, click **Transforms** and choose **Rotate**.

2 Select the objects **dif2**, **extract1(1)**, and **extract1(2)** only.

3 In the **Settings** window for **Rotate**, locate the **Rotation** section.

4 In the **Angle** text field, type `rot`.

Union 1 (uni1)

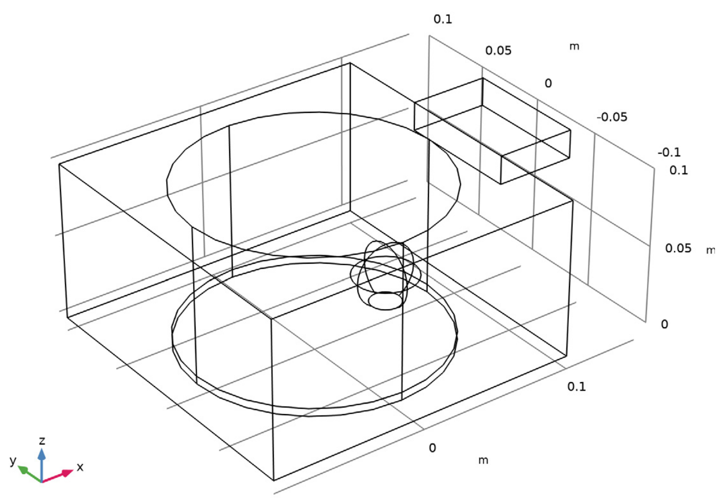
1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Union**.

2 Select the objects **rot1(1)**, **rot1(2)**, and **rot1(3)** only.

3 In the **Settings** window for **Union**, locate the **Union** section.

4 From the **Repair tolerance** list, choose **Automatic**.

5 Click **Build Selected**.



Form Union (fin)

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Geometry 1** click **Form Union (fin)**.

2 In the **Settings** window for **Form Union/Assembly**, locate the **Form Union/Assembly** section.

3 From the **Action** list, choose **Form an assembly**.

4 From the **Repair tolerance** list, choose **Relative**.

5 In the **Geometry** toolbar, click **Build All**.

DEFINITIONS

Global Variable Probe 1 (var1)

1 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Definitions** node.

2 Right-click **Definitions** and choose **Probes** > **Global Variable Probe**.

3 In the **Settings** window for **Global Variable Probe**, locate the **Expression** section.

4 In the **Expression** text field, type `ang/(pi/(2*N))`.

5 Select the **Description** checkbox. In the associated text field, type `Angular step number`.

6 Click to expand the **Table and Window Settings** section. Click **Add Plot Window**.

Global Variable Probe 2 (var2)

1 In the **Definitions** toolbar, click **Probes** and choose **Global Variable Probe**.

2 In the **Settings** window for **Global Variable Probe**, locate the **Expression** section.

3 In the **Expression** text field, type `100[%]*(1-abs(emw.S11)^2)`.

4 In the **Table and plot unit** field, type `%`.

5 Select the **Description** checkbox. In the associated text field, type `Coupled power`.

6 Locate the **Table and Window Settings** section. Click **Add Plot Window**.

Domain Probe 1 (dom1)

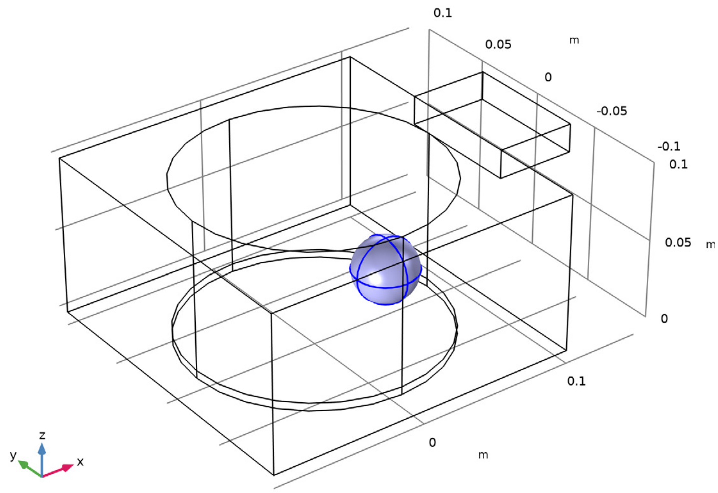
1 In the **Definitions** toolbar, click **Probes** and choose **Domain Probe**.

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

3 From the **Selection** list, choose **Manual**.

4 Click **Clear Selection**.

5 Select Domain 5 only.



6 Locate the **Expression** section. In the **Expression** text field, type `T`.

7 Select the **Description** checkbox. In the associated text field, type `Average temperature`.

8 Click to expand the **Table and Window Settings** section. Click **Add Plot Window**.

Maximum 1 (maxop1)

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

2 Select Domain 5 only.

Integration 1 (intop1)

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

2 Select Domain 5 only.

Identity Boundary Pair 1 (ap1)

1 In the **Model Builder** window, click **Identity Boundary Pair 1 (ap1)**.

2 In the **Settings** window for **Pair**, locate the **Frame** section.

3 Select the **Manual control of frame** checkbox.

Explicit, Data Storing Domain

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

2 In the **Settings** window for **Explicit**, type `Explicit, Data Storing Domain` in the **Label** text field.

3 Select Domains 3 and 5 only.

Explicit, Data Storing Boundary

1 Right-click **Explicit, Data Storing Domain** and choose **Duplicate**.

2 In the **Settings** window for **Explicit**, type `Explicit, Data Storing Boundary` in the **Label** text field.

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

4 Select Boundaries 1–5, 14, 16–20, 23, and 27 only.

MATERIALS

Air

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.

2 In the **Settings** window for **Material**, type `Air` in the **Label** text field.

3 Click to expand the **Material Properties** section. Locate the **Material Contents** section. In the table, enter the following settings:

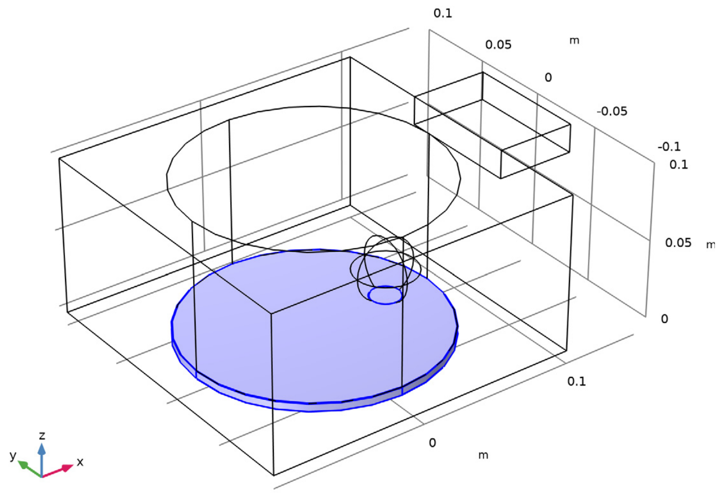
Property	Variable	Value	Unit	Property group
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	1	1	Basic
Relative permeability	mur_iso ; murii = mur_iso, murij = 0	1	1	Basic
Electric conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	0	S/m	Basic

Glass

1 Right-click **Materials** and choose **Blank Material**.

2 In the **Settings** window for **Material**, type `Glass` in the **Label** text field.

3 Select Domain 3 only.



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

Property	Variable	Value	Unit	Property group
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	4.2	1	Basic
Relative permeability	mur_iso ; murii = mur_iso, murij = 0	1	1	Basic
Electric conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	0	S/m	Basic
Thermal conductivity	k_iso ; kii = k_iso, kij = 0	5	W/(m·K)	Basic
Density	rho	2210	kg/m³	Basic
Heat capacity at constant pressure	Cp	1000	J/(kg·K)	Basic

ADD MATERIAL FROM LIBRARY

In the **Home** toolbar, click **Windows** and choose **Add Material from Library**.

ADD MATERIAL

1 Go to the **Add Material** window.

2 In the tree, select **Built-in** > **Water, liquid**.

3 Click the **Add to Component** button in the window toolbar.

MATERIALS

Water rich

1 In the **Settings** window for **Material**, type `Water rich` in the **Label** text field.

2 Select Domain 5 only.

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

Property	Variable	Value	Unit	Property group
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	80	1	Basic
Relative permeability	mur_iso ; murii = mur_iso, murij = 0	1	1	Basic

ADD MATERIAL

1 Go to the **Add Material** window.

2 In the tree, select **Liquids and Gases** > **Gases** > **Steam**.

3 Click the **Add to Component** button in the window toolbar.

4 In the **Home** toolbar, click **Add Material** to close the **Add Material** window.

MATERIALS

Dehydrated

1 In the **Settings** window for **Material**, type `Dehydrated` in the **Label** text field.

Here, the domain selection is empty. However, once you specify the materials for the different phases in the Phase Change Material feature later on, it automatically manages the property assignment to the appropriate domains, reducing the need for manual domain selection.

MOVING MESH

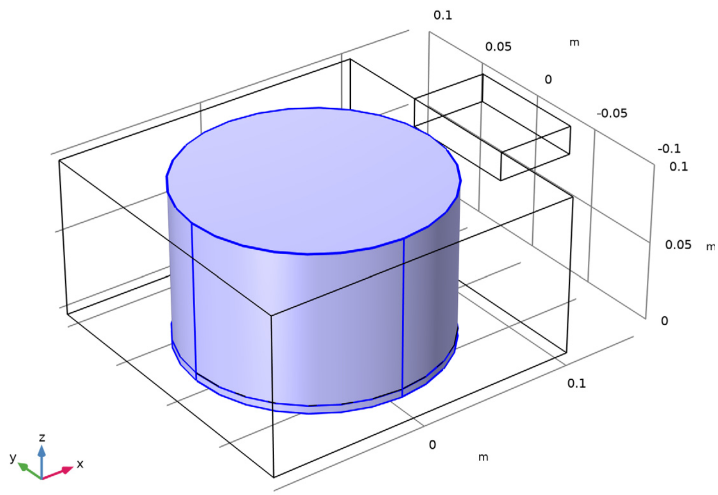
Rotating Domain 1

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

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

3 Click **Remove from Selection**.

4 Select Domains 3–5 only.



5 Locate the **Rotation** section. In the α text field, type ang.

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EMW)

1 Click the **Show More Options** button in the **Model Builder** toolbar.

2 In the **Show More Options** dialog, click **Select All**.

3 Click **OK**.

4 In the **Model Builder** window, under **Component 1 (comp1)** click **Electromagnetic Waves, Frequency Domain (emw)**.

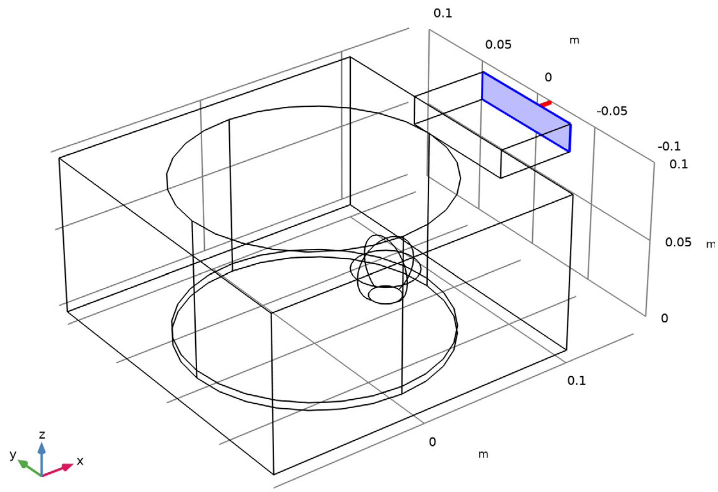
5 In the **Settings** window for **Electromagnetic Waves, Frequency Domain**, click to expand the **Discretization** section.

6 From the **Electric field** list, choose **Linear**.

Port 1

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

2 Select Boundary 20 only.



3 In the **Settings** window for **Port**, locate the **Port Properties** section.

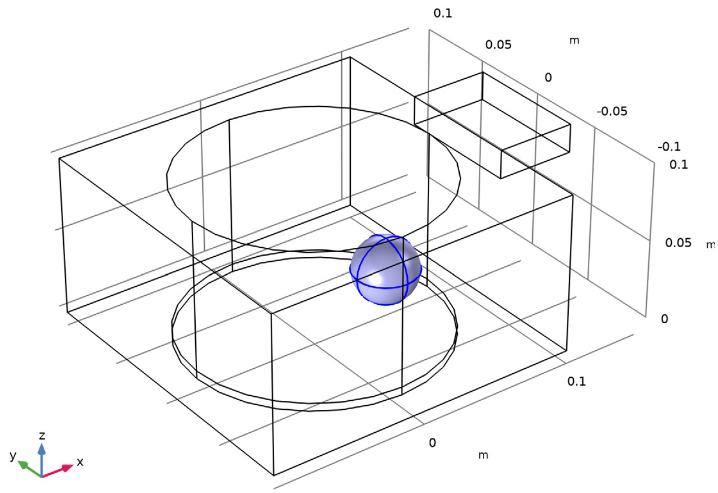
4 From the **Type of port** list, choose **Rectangular**.

5 In the P_{in} text field, type `1e3[W]`.

Wave Equation, Electric 2

1 In the **Physics** toolbar, click **Domains** and choose **Wave Equation, Electric**.

2 Select Domain 5 only.



3 In the **Settings** window for **Wave Equation, Electric**, locate the **Electric Displacement Field** section.

4 From the **Electric displacement field model** list, choose **Dielectric loss**.

5 From the ε′ list, choose **User defined**. In the associated text field, type `64*ht.theta1+1`.

6 From the ε″ list, choose **User defined**. In the associated text field, type `19*ht.theta1+1`.

MULTIPHYSICS

Electromagnetic Heating 1 (emh1)

In the **Physics** toolbar, click **Multiphysics Couplings** and choose **Domain > Electromagnetic Heating**.

HEAT TRANSFER IN SOLIDS (HT)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Heat Transfer in Solids (ht)**.

2 Select Domains 3 and 5 only.

3 In the **Settings** window for **Heat Transfer in Solids**, click to expand the **Discretization** section.

4 From the **Temperature** list, choose **Linear**.

Continuity 1

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Heat Transfer in Solids (ht)** click **Continuity 1**.

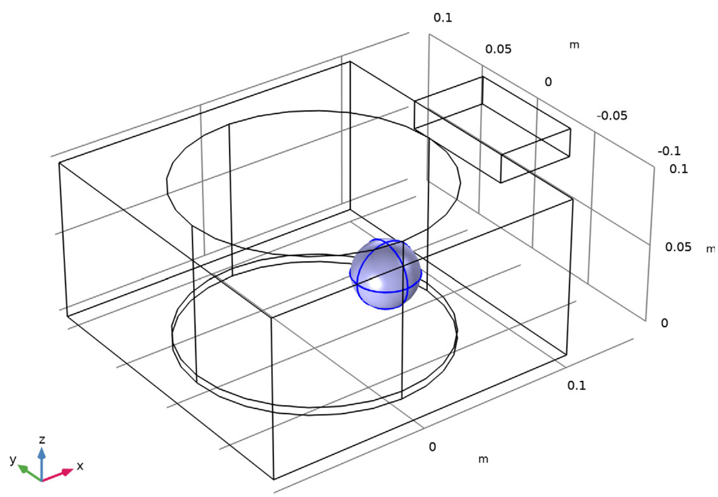
2 In the **Settings** window for **Continuity**, locate the **Advanced** section.

3 Select the **Disconnect pair** checkbox.

Solid 2

1 In the **Physics** toolbar, click **Domains** and choose **Solid**.

2 Select Domain 5 only.



Phase Change Material 1

1 In the **Physics** toolbar, click **Attributes** and choose **Phase Change Material**.

2 In the **Settings** window for **Phase Change Material**, locate the **Phase Change** section.

3 In the $T_{1 \rightarrow 2}$ text field, type `373.15[K]`.

4 In the $L_{1 \rightarrow 2}$ text field, type `2.2564E6[J/kg]`.

5 Locate the **Phase 1** section. From the **Material, phase 1** list, choose **Water rich (mat3)**.

6 Locate the **Phase 2** section. From the **Material, phase 2** list, choose **Dehydrated (mat4)**.

7 From the k_2 list, choose **User defined**. In the associated text field, type `1e2`.

EVENTS (EV)

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

Explicit Event 1

1 In the **Physics** toolbar, click **Global** and choose **Explicit Event**.

2 In the **Settings** window for **Explicit Event**, locate the **Event Timings** section.

3 In the T text field, type dt.

4 Clear the **Use consistent initialization** checkbox.

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

Variable	Expression
ang	step*(pi[rad]/(2*N))
step	step+1

Discrete States 1

1 In the **Physics** toolbar, click **Global** and choose **Discrete States**.

2 In the **Settings** window for **Discrete States**, locate the **Discrete States** section.

3 In the table, enter the following settings:

Name	Initial value (u0)	Description
ang	0	rotation angle
step	0	angular step no

MESH 1

Mapped 1

In the **Mesh** toolbar, click **More Generators** and choose **Mapped**.

Size

1 In the **Model Builder** window, click **Size**.

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 Click the **Custom** button.

4 Locate the **Element Size Parameters** section. In the **Maximum element size** text field, type c_const/2.45[GHz]/5.

5 In the **Minimum element size** text field, type c_const/2.45[GHz]/6.

6 In the **Maximum element growth rate** text field, type 2.

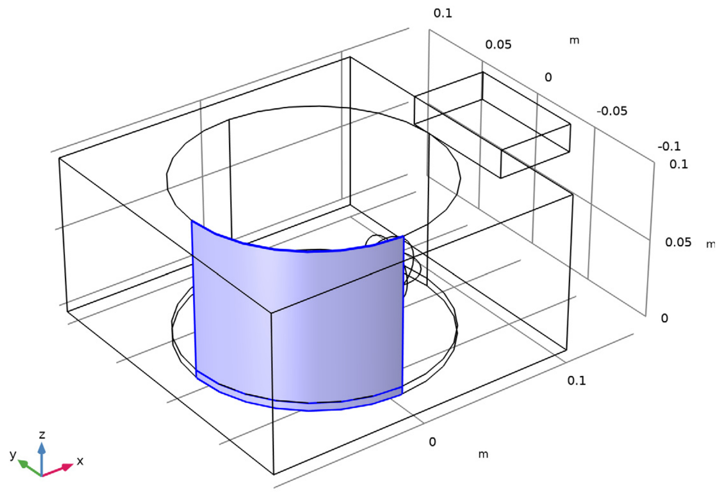
7 In the **Curvature factor** text field, type 1.

8 In the **Resolution of narrow regions** text field, type 0.1.

Mapped 1

1 In the **Model Builder** window, click **Mapped 1**.

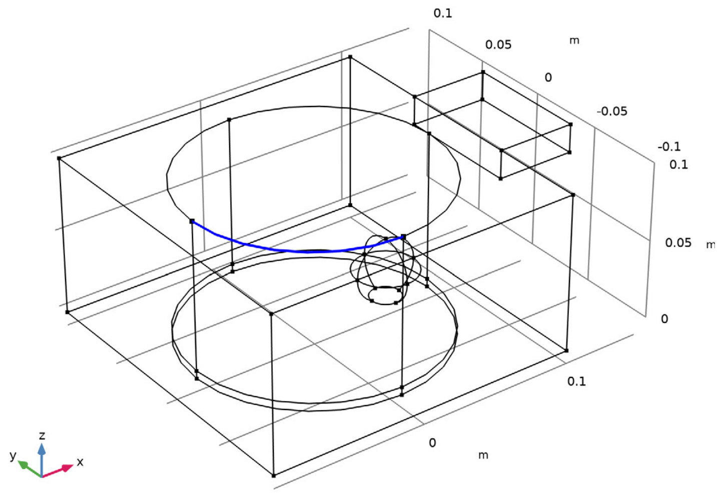
2 Select Boundaries 6 and 8 only.



Distribution 1

1 Right-click **Mapped 1** and choose **Distribution**.

2 Select Edge 15 only.



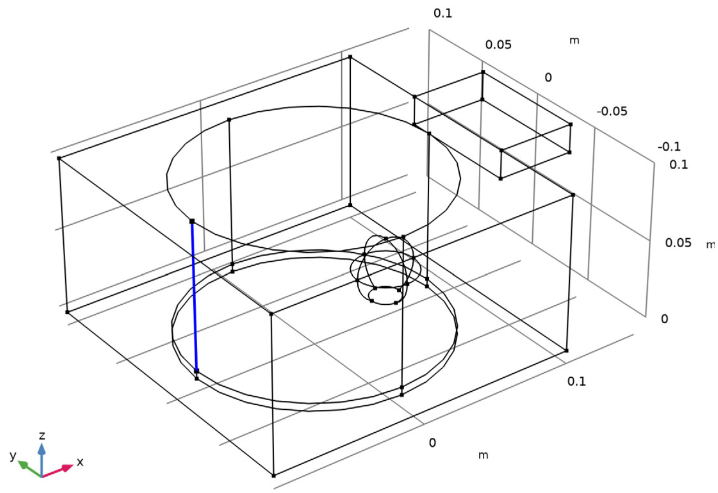
3 In the **Settings** window for **Distribution**, locate the **Distribution** section.

4 In the **Number of elements** text field, type `N`.

Distribution 2

1 Right-click **Mapped 1** and choose **Distribution**.

2 Select Edge 12 only.



3 In the **Settings** window for **Distribution**, locate the **Distribution** section.

4 In the **Number of elements** text field, type `floor(N*0.8)`.

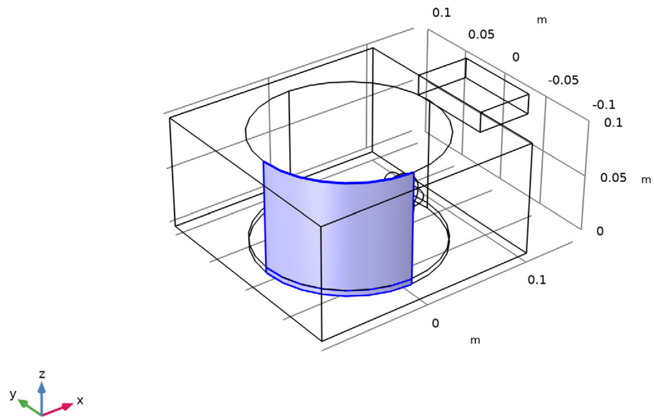
Copy 1

1 In the **Mesh** toolbar, click **Copy** and choose **Copy**.

2 In the **Settings** window for **Copy**, locate the **Dimension** section.

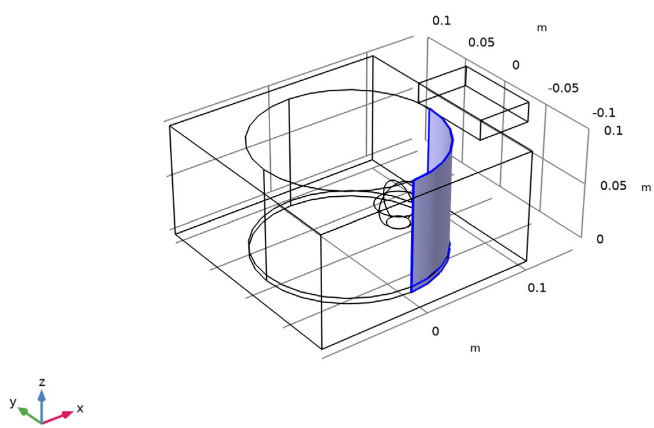
3 From the **Geometric entity level** list, choose **Boundary**.

4 Select Boundaries 6 and 8 only.



5 Locate the **Destination Entities** section. Click to select the **Activate Selection** toggle button.

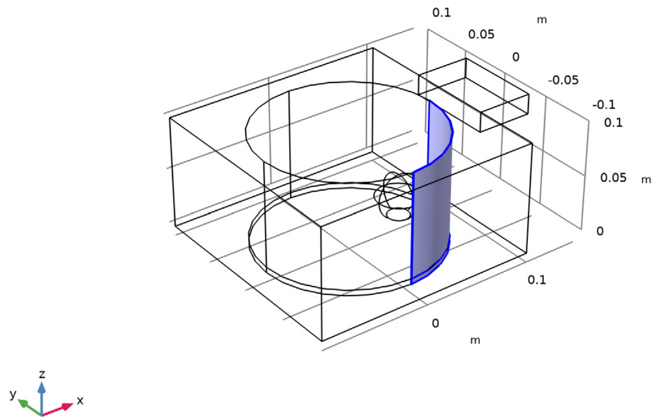
6 Select Boundaries 10 and 11 only.



Copy 2

1 In the **Mesh** toolbar, click **Copy** and choose **Copy**.

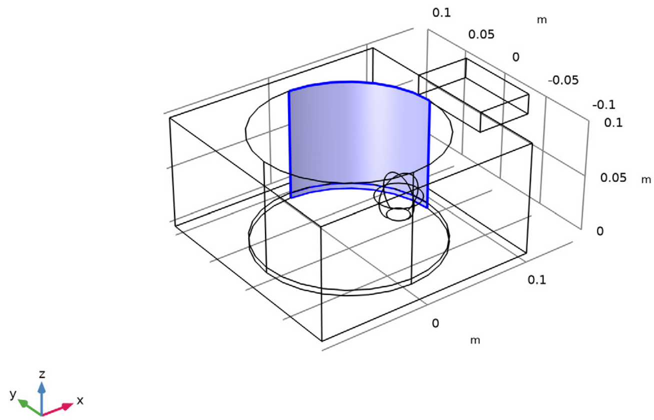
2 Select Boundaries 10 and 11 only.



3 In the **Settings** window for **Copy**, locate the **Destination Entities** section.

4 Click to select the **Activate Selection** toggle button.

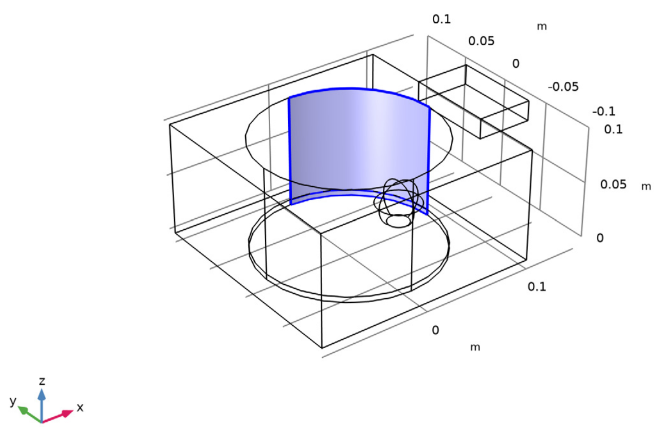
5 Select Boundaries 12 and 13 only.



Copy 3

1 In the **Mesh** toolbar, click **Copy** and choose **Copy**.

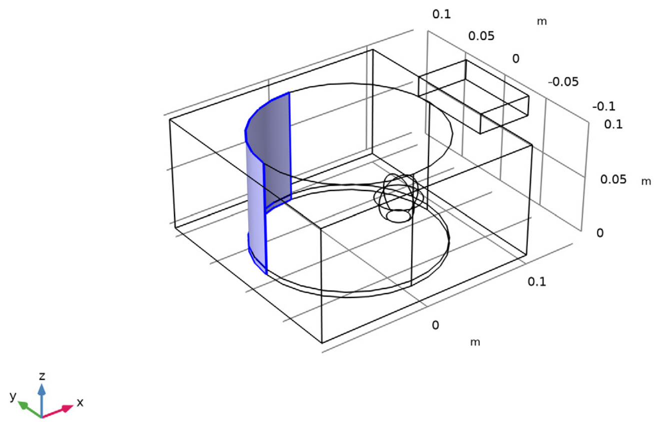
2 Select Boundaries 12 and 13 only.



3 In the **Settings** window for **Copy**, locate the **Destination Entities** section.

4 Click to select the **Activate Selection** toggle button.

5 Select Boundaries 7 and 9 only.



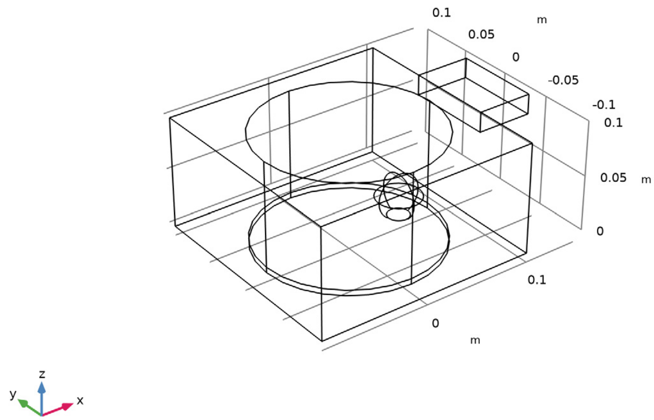
Copy 4

1 In the **Mesh** toolbar, click **Copy** and choose **Copy**.

2 In the **Settings** window for **Copy**, locate the **Source Entities** section.

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog, type `6-13` in the **Selection** text field.



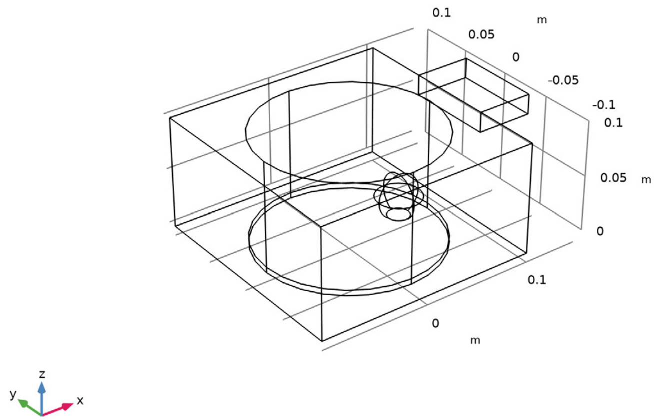
5 Click **OK**.

6 In the **Settings** window for **Copy**, locate the **Destination Entities** section.

7 Click to select the **Activate Selection** toggle button.

8 Click **Paste Selection**.

9 In the **Paste Selection** dialog, type `21, 22, 24, 25, 28-31` in the **Selection** text field.



10 Click **OK**.

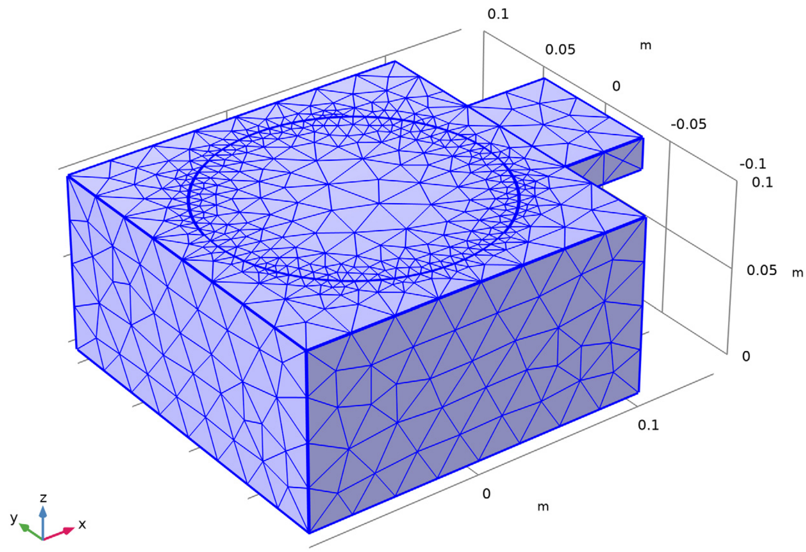
Size 1

1. In the **Model Builder** window, right-click **Mesh 1** and choose **Size**.
2. In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.
3. From the **Geometric entity level** list, choose **Domain**.
4. Select Domain 5 only.
5. Locate the **Element Size** section. Click the **Custom** button.
6. Locate the **Element Size Parameters** section.
7. Select the **Maximum element size** checkbox. In the associated text field, type `c_const/2.45[GHz]/sqrt(65)/5`.
8. Select the **Minimum element size** checkbox. In the associated text field, type `c_const/2.45[GHz]/sqrt(65)/6`.

Free Tetrahedral 1

1. In the **Mesh** toolbar, click **Free Tetrahedral**.
2. In the **Settings** window for **Free Tetrahedral**, click to expand the **Element Quality Optimization** section.
3. Find the **Accept lower element quality to** subsection. Clear the **Avoid inverted curved elements** checkbox.

4 Click **Build All**.



STUDY 1

Step 1: Frequency–Transient

1 In the **Study** toolbar, click **More Study Steps** and choose **Time Dependent** > **Frequency–Transient**.

2 In the **Settings** window for **Frequency–Transient**, locate the **Study Settings** section.

3 In the **Output times** text field, type `range(0,0.25,100)`.

4 In the **Frequency** text field, type `2.45[GHz]`.

5 Click to expand the **Store in Output** section. In the table, enter the following settings:

Interface	Output	Selection
Electromagnetic Waves, Frequency Domain (emw)	Selection	

6 Under **Selections**, click **Add**.

7 In the **Add** dialog, in the **Selections** list, choose **Explicit, Data Storing Domain (Domain)** and **Explicit, Data Storing Boundary (Boundary)**.

8 Click **OK**.

Solution 1 (sol1)

1 In the **Model Builder** window, right-click **Solver Configurations** and choose **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 1 (sol1)** node, then click **Dependent Variables 1**.

3 In the **Settings** window for **Dependent Variables**, locate the **Residual Scaling** section.

4 From the **Method** list, choose **Automatic**.

5 In the **Model Builder** window, expand the **Study 1** > **Solver Configurations** > **Solution 1 (sol1)** > **Dependent Variables 1** node, then click **Study 1** > **Solver Configurations** > **Solution 1 (sol1)** > **Time-Dependent Solver 1**.

6 In the **Settings** window for **Time-Dependent Solver**, click to expand the **Time Stepping** section.

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

8 In the **Time step** text field, type `0.25`.

9 In the **Event tolerance** text field, type `0.001`.

10 Right-click **Time-Dependent Solver 1** and choose **Fully Coupled**.

11 In the **Settings** window for **Fully Coupled**, locate the **General** section.

12 From the **Linear solver** list, choose **Direct**.

13 Click to expand the **Method and Termination** section. From the **Nonlinear method** list, choose **Automatic (Newton)**.

14 In the **Maximum number of iterations** text field, type `25`.

15 In the **Model Builder** window, click **Direct**.

16 In the **Settings** window for **Direct**, locate the **General** section.

17 From the **Solver** list, choose **PARDISO**.

18 In the **Model Builder** window, click **Study 1**.

19 In the **Settings** window for **Study**, locate the **Study Settings** section.

20 Clear the **Generate default plots** checkbox.

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

RESULTS

Probe Plot Group 2

1 In the **Model Builder** window, under **Results** click **Probe Plot Group 2**.

2 In the **Settings** window for **1D Plot Group**, locate the **Legend** section.

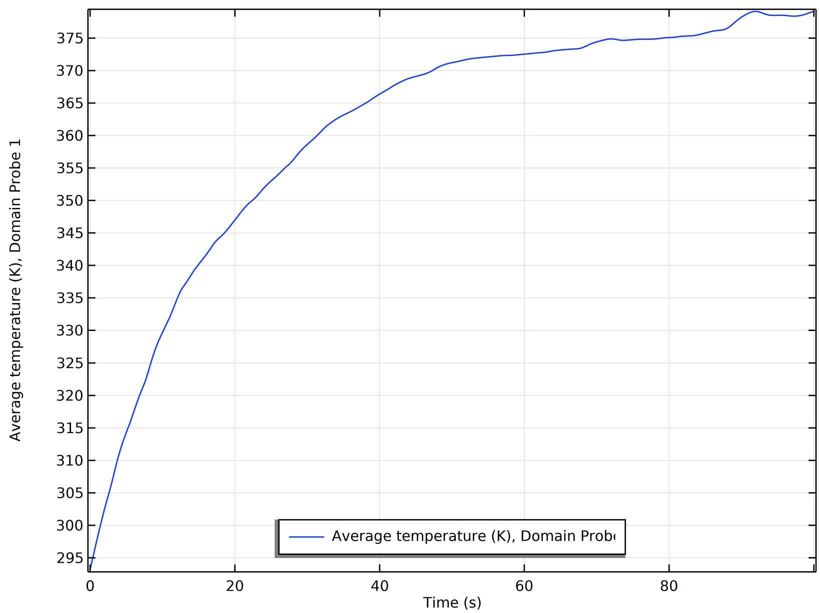
3 From the **Position** list, choose **Lower middle**.

Probe Plot Group 3

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

2 In the **Settings** window for **1D Plot Group**, locate the **Legend** section.

3 From the **Position** list, choose **Lower middle**.



Probe Plot Group 4

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

2 In the **Settings** window for **1D Plot Group**, locate the **Legend** section.

3 From the **Position** list, choose **Lower middle**.

Electric Field (emw)

1 In the **Results** toolbar, click **3D Plot Group**.

2 In the **Settings** window for **3D Plot Group**, type `Electric Field (emw)` in the **Label** text field.

3 Locate the **Data** section. From the **Time (s)** list, choose **0**.

4 Locate the **Plot Settings** section. From the **View** list, choose **New view**.

5 From the **Frame** list, choose **Spatial (x, y, z)**.

Slice 1

1 Right-click **Electric Field (emw)** and choose **Slice**.

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

3 In the **Expression** text field, type `20*log10(emw.normE+1e3)`.

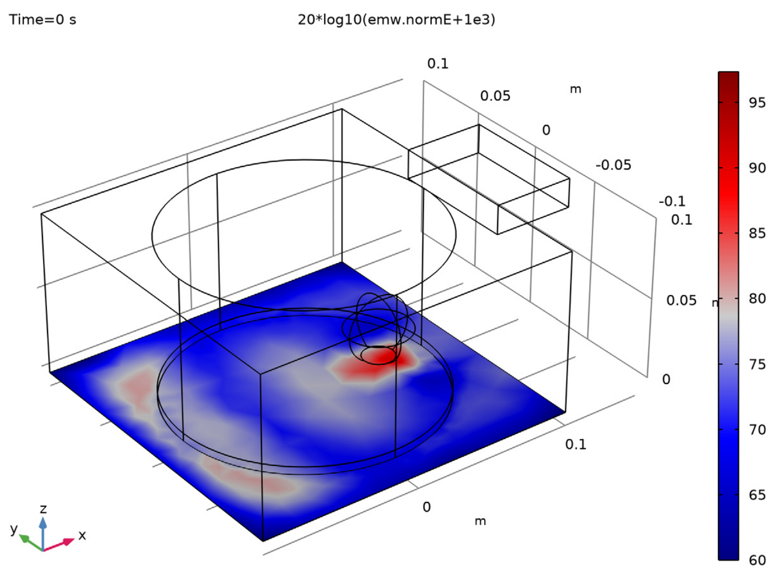
4 Locate the **Plane Data** section. From the **Plane** list, choose **xy-planes**.

5 In the **Planes** text field, type `1`.

6 Select the **Interactive** checkbox.

7 In the **Shift** text field, type `-0.05`.

8 Locate the **Coloring and Style** section. From the **Color table** list, choose **WaveClassic**.



Temperature (ht)

1 In the **Results** toolbar, click **3D Plot Group**.

2 In the **Settings** window for **3D Plot Group**, type `Temperature (ht)` in the **Label** text field.

3 Locate the **Data** section. From the **Time (s)** list, choose **0**.

4 Locate the **Plot Settings** section. Clear the **Plot dataset edges** checkbox.

Surface 1

1 Right-click **Temperature (ht)** and choose **Surface**.

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

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

4 From the **Unit** list, choose **°C**.

5 Locate the **Coloring and Style** section. From the **Color table** list, choose **ThermalLightClassic**.

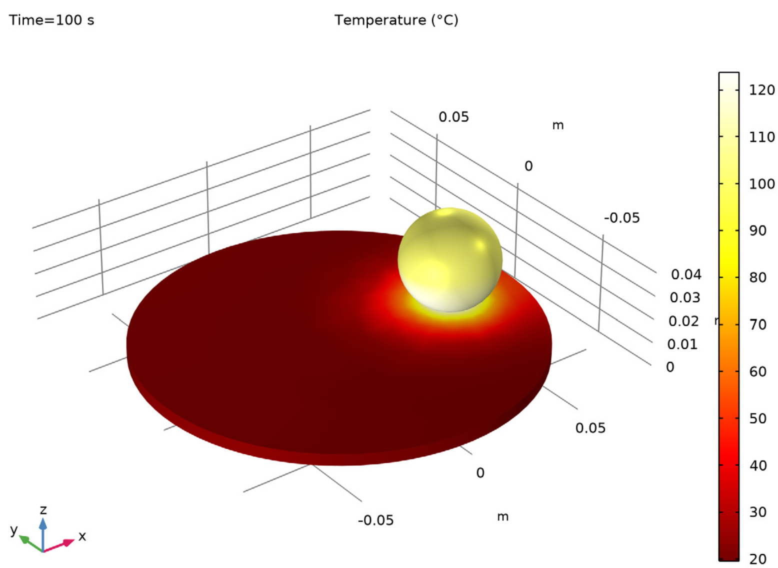
Temperature (ht)

1 In the **Model Builder** window, click **Temperature (ht)**.

2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.

3 From the **Time (s)** list, choose **Last (100)**.

4 In the **Temperature (ht)** toolbar, click **Plot**.



Mesh 1

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

Mesh

1 In the **Results** toolbar, click **3D Plot Group**.

2 In the **Settings** window for **3D Plot Group**, type `Mesh` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Mesh 1**.

4 Locate the **Plot Settings** section. Select the **Propagate hiding to lower dimensions** checkbox.

Mesh 1

1 Right-click **Mesh** and choose **Mesh**.

2 In the **Settings** window for **Mesh**, locate the **Coloring and Style** section.

3 From the **Element color** list, choose **Size**.

4 From the **Color table** list, choose **TrafficLightClassic**.

5 From the **Color table transformation** list, choose **Reverse**.

Selection 1

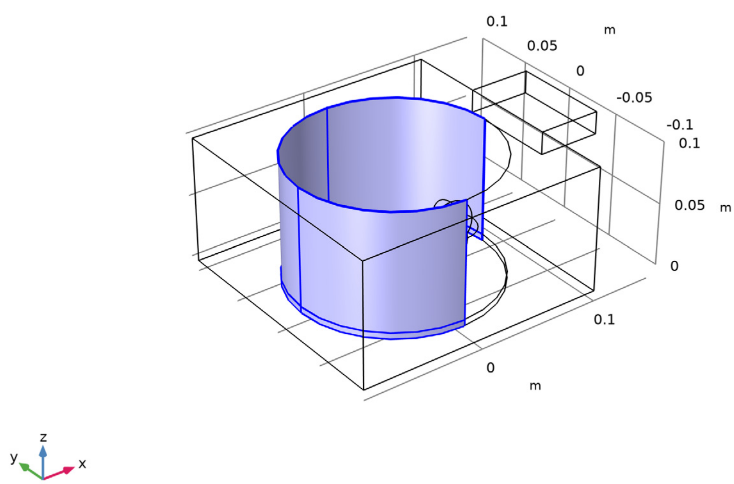
1 Right-click **Mesh 1** and choose **Selection**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog, type `6-9, 12, 13, 21, 22, 24, 25, 30, 31` in the **Selection** text field.

5 Click **OK**.



Qh, Total Power Dissipation Density

1 In the **Results** toolbar, click **3D Plot Group**.

2 In the **Settings** window for **3D Plot Group**, type `Qh, Total Power Dissipation Density` in the **Label** text field.

3 Locate the **Data** section. From the **Time (s)** list, choose **0**.

4 Locate the **Plot Settings** section. From the **Frame** list, choose **Spatial (x, y, z)**.

Slice 1

1 Right-click **Qh, Total Power Dissipation Density** and choose **Slice**.

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

3 In the **Expression** text field, type `log10(emw.Qh)`.

4 Locate the **Plane Data** section. From the **Plane** list, choose **xy-planes**.

5 From the **Entry method** list, choose **Coordinates**.

6 Select the **Interactive** checkbox.

7 In the **Shift** text field, type `0.024`.

8 Locate the **Coloring and Style** section. From the **Color table** list, choose **Opadometa**.

Selection 1

1 Right-click **Slice 1** and choose **Selection**.

2 Select Domain 5 only.

Slice 2

1 In the **Model Builder** window, right-click **Qh, Total Power Dissipation Density** and choose **Slice**.

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

3 In the **Expression** text field, type `log10(emw.Qh)`.

4 Locate the **Plane Data** section. From the **Plane** list, choose **zx-planes**.

5 In the **Planes** text field, type `1`.

6 Select the **Interactive** checkbox.

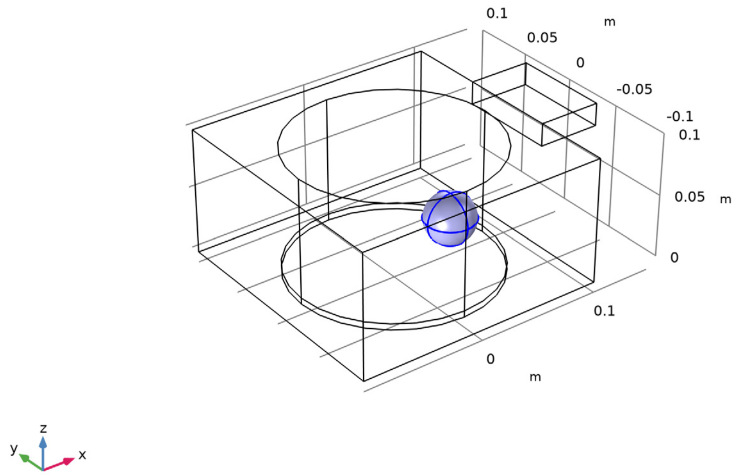
7 In the **Shift** text field, type `-5.0E-4`.

8 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Slice 1**.

Selection 1

1 Right-click **Slice 2** and choose **Selection**.

2 Select Domain 5 only.



Phase Fraction, Water rich

1 In the **Results** toolbar, click **3D Plot Group**.

2 In the **Settings** window for **3D Plot Group**, type `Phase Fraction, Water rich` in the **Label** text field.

3 Locate the **Data** section. From the **Time (s)** list, choose **Last (100)**.

4 Locate the **Plot Settings** section. From the **Frame** list, choose **Spatial (x, y, z)**.

Slice 1

1 Right-click **Phase Fraction, Water rich** and choose **Slice**.

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

3 In the **Expression** text field, type `ht.theta1`.

4 Locate the **Plane Data** section. From the **Plane** list, choose **zx-planes**.

5 In the **Planes** text field, type `1`.

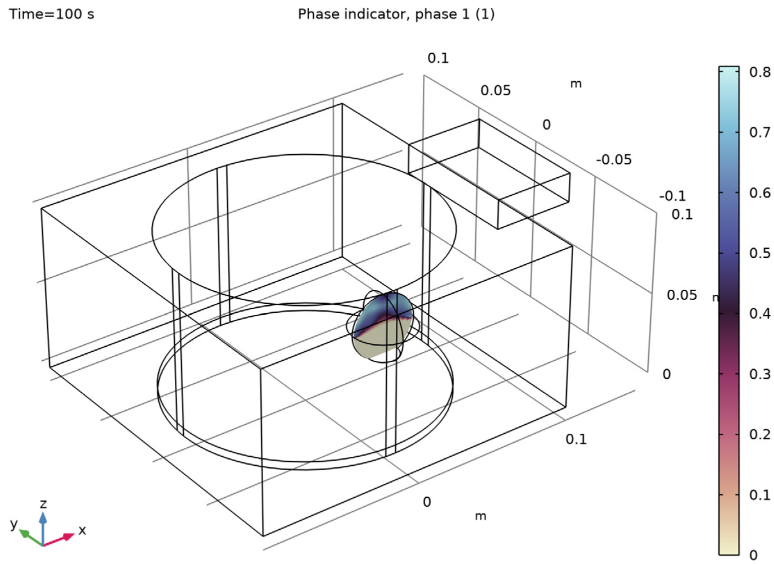
6 Locate the **Coloring and Style** section. From the **Color table** list, choose **Avicularia**.

Selection 1

1 Right-click **Slice 1** and choose **Selection**.

2 Select Domain 5 only.

3 In the **Phase Fraction, Water rich** toolbar, click **Plot**.



Phase Fraction, Dehydrated

1 In the **Model Builder** window, right-click **Phase Fraction, Water rich** and choose **Duplicate**.

2 In the **Settings** window for **3D Plot Group**, type `Phase Fraction, Dehydrated` in the **Label** text field.

3 Locate the **Data** section. From the **Time (s)** list, choose **Last (100)**.

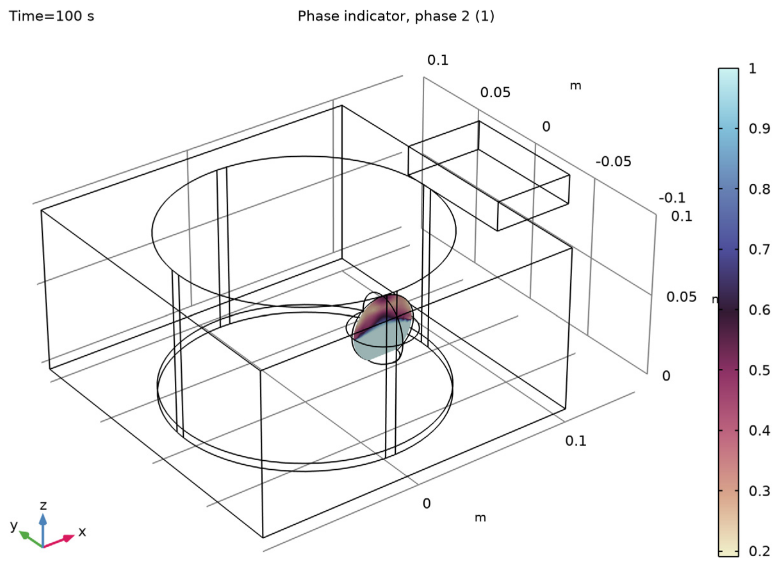
Slice 1

1 In the **Model Builder** window, expand the **Phase Fraction, Dehydrated** node, then click **Slice 1**.

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

3 In the **Expression** text field, type `ht.theta2`.

4 In the **Phase Fraction, Dehydrated** toolbar, click **Plot**.



Q, Coupled Power

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

2 In the **Settings** window for **1D Plot Group**, type `Q, Coupled Power` in the **Label** text field.

3 Locate the **Legend** section. Clear the **Show legends** checkbox.

Global 1

1 Right-click **Q, Coupled Power** and choose **Global**.

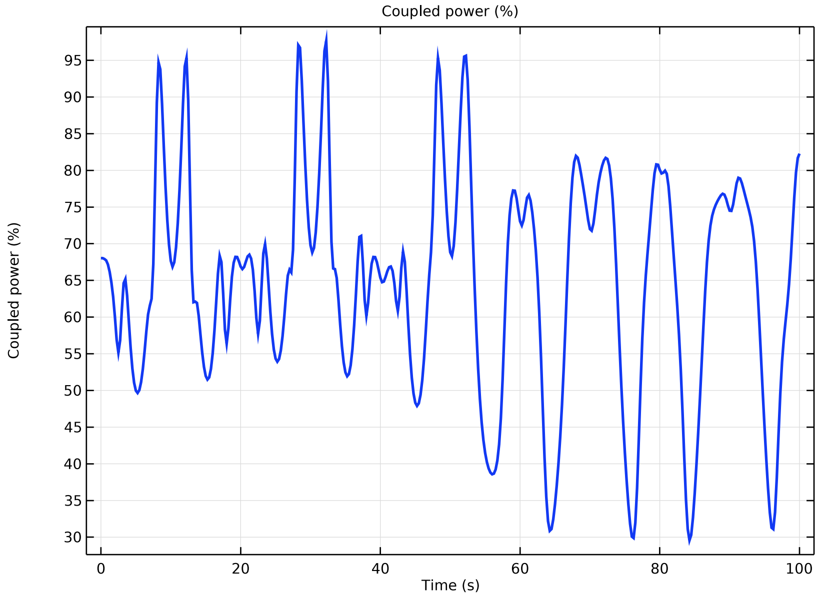
2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 In the table, enter the following settings:

Expression	Unit	Description
`100[%]*(1-abs(emw.S11)^2)`	%	`Coupled power`

4 Click to expand the **Coloring and Style** section. From the **Width** list, choose **2**.

5 In the **Q, Coupled Power** toolbar, click **Plot**.



Combined Plot

1 In the **Results** toolbar, click **3D Plot Group**.

2 In the **Settings** window for **3D Plot Group**, type `Combined Plot` in the **Label** text field.

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

4 From the **Number format** list, choose **Stopwatch**.

5 In the **Number of integer digits** text field, type `2`.

6 In the **Title** text area, type `Slices: |E| (dBV/m), 2 x Heating (dBW/m<sup>3</sup>), Water rich fraction (%), Surface: T (degC)`.

7 In the **Parameter indicator** text field, type `Time = eval(t) s`.

8 Locate the **Plot Settings** section. Clear the **Plot dataset edges** checkbox.

Slice 1

1 Right-click **Combined Plot** and choose **Slice**.

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

3 In the **Expression** text field, type `20*log10(emw.normE+1e3)`.

4 Locate the **Plane Data** section. From the **Plane** list, choose **xy-planes**.

5 In the **Planes** text field, type `1`.

6 Select the **Interactive** checkbox.

7 In the **Shift** text field, type `-0.05`.

8 Locate the **Coloring and Style** section. From the **Color table** list, choose **Wave**.

9 Clear the **Color legend** checkbox.

Selection 1

1 Right-click **Slice 1** and choose **Selection**.

2 Select Domains 1–4 only.

Deformation 1

1 In the **Model Builder** window, right-click **Slice 1** and choose **Deformation**.

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

3 In the **x-component** text field, type `0`.

4 In the **y-component** text field, type `0`.

5 In the **z-component** text field, type `20*log10(emw.normE+1e3)-110`.

6 Locate the **Scale** section.

7 Select the **Scale factor** checkbox. In the associated text field, type `5E-4`.

Surface 1

1 In the **Model Builder** window, right-click **Combined Plot** and choose **Surface**.

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

3 In the **Expression** text field, type `min(T,100[degC])`.

4 From the **Unit** list, choose **°C**.

5 Locate the **Coloring and Style** section. From the **Color table** list, choose **ThermalLight**.

Selection 1

1 Right-click **Surface 1** and choose **Selection**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog, type `32-35, 37-40` in the **Selection** text field.

5 Click **OK**.

Line 1

1 In the **Model Builder** window, right-click **Combined Plot** and choose **Line**.

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

3 In the **Expression** text field, type `1`.

4 Locate the **Coloring and Style** section. From the **Coloring** list, choose **Uniform**.

5 From the **Color** list, choose **Gray**.

Selection 1

1 Right-click **Line 1** and choose **Selection**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog, type `1-8, 10, 11, 13, 14, 18, 20, 23, 25, 29-45, 47, 48, 50, 51, 55, 57, 60, 62` in the **Selection** text field.

5 Click **OK**.

Slice 2

1 In the **Model Builder** window, right-click **Combined Plot** and choose **Slice**.

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

3 In the **Expression** text field, type `log10(emw.Qh)`.

4 Locate the **Plane Data** section. From the **Plane** list, choose **xy-planes**.

5 In the **Planes** text field, type `1`.

6 Locate the **Coloring and Style** section. From the **Color table** list, choose **Prism**.

7 Clear the **Color legend** checkbox.

Selection 1

1 Right-click **Slice 2** and choose **Selection**.

2 Select Domain 5 only.

Transformation 1

1 In the **Model Builder** window, right-click **Slice 2** and choose **Transformation**.

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

3 In the **z** text field, type `0.03`.

Slice 3

1 Right-click **Slice 2** and choose **Duplicate**.

2 In the **Model Builder** window, click **Slice 3**.

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

4 From the **Plane** list, choose **zx-planes**.

5 In the **Planes** text field, type `1`.

6 Locate the **Inherit Style** section. From the **Plot** list, choose **Slice 2**.

Transformation 1

1 In the **Model Builder** window, click **Transformation 1**.

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

3 In the **z** text field, type `0.06`.

Slice 4

1 In the **Model Builder** window, under **Results** > **Combined Plot** right-click **Slice 2** and choose **Duplicate**.

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

3 In the **Expression** text field, type `ht.theta1`.

4 From the **Unit** list, choose **%**.

5 Locate the **Plane Data** section. From the **Plane** list, choose **zx-planes**.

6 In the **Planes** text field, type `1`.

7 Locate the **Coloring and Style** section. From the **Color table** list, choose **GrayScale**.

8 Select the **Color legend** checkbox.

Transformation 1

1 In the **Model Builder** window, expand the **Slice 4** node, then click **Transformation 1**.

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

3 In the **z** text field, type `0.1`.

4 Clear the **Apply to dataset edges** checkbox.