Created in COMSOL Multiphysics 6.1

Sun's Radiation Effect on Two Coolers Placed Under a Parasol

Introduction

A warm sunny day at the beach can be more enjoyable with a steady supply of frosty beverages. This example considers two Styrofoam coolers containing cold beverage cans sitting on a sandy beach. A parasol provides partial shade for one of the coolers over the course of the day. The difference in beverage temperature over time is computed. This tutorial demonstrates the usage of the external radiation source boundary condition, as well as how to model structures exposed to ambient conditions.

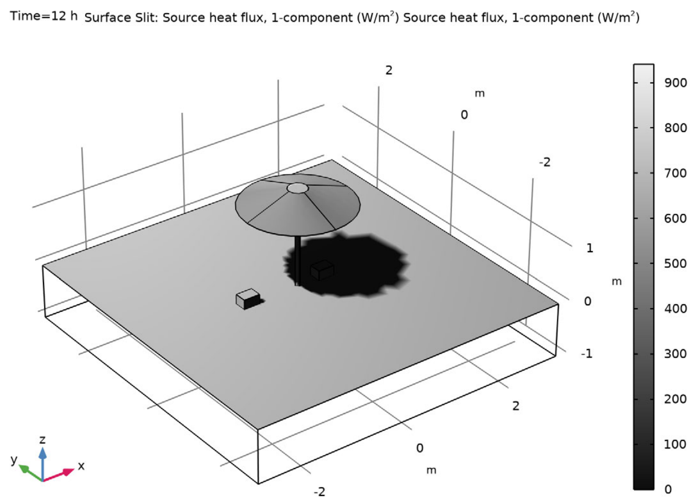


Figure 1: A parasol provides shade on the beach. Two Styrofoam coolers contain beverage cans that should remain as cold as possible.

Model Definition

A system of a parasol and two coolers is modeled as shown in Figure 1. The coolers, made of Styrofoam, contain six beverage cans each. The beverage cans are represented by water-filled cylinders with walls modeled as thermally thick thin layers of aluminum. The choice of the thermally thick option is not motivated by the physics, they are in reality thermally thin. With the thermally thick option a slit is defined for the temperature on the walls, so the temperature can differ between the inner and outer faces. This is used to define initial conditions that are discontinuous between the exterior and interior can surfaces. Because aluminum has higher thermal conductivity than the surrounding materials, the Thin Layer – thermally thick condition behaves like a continuity condition as soon as the initial temperature difference vanishes. The initial cans temperature is 1°C. The spacing between the cans and the cooler walls is small, so the model neglects free convection inside the cooler for simplicity.

The parasol primarily provides shade but otherwise has no significant thermal effect on the beverage temperature. For this reason, it is not too important to have a high fidelity model of the parasol. It is only the shadow cast by the parasol that contributes to the beverage temperature profile. The material used for the parasol is acrylic plastic.

The primary source of heat in this model is the solar irradiation, which is included using the External Radiation Source feature. This feature uses the longitude, latitude, time zone, time of year, and time of day to compute the direction of the incident solar radiation over the simulation time. Sun irradiance and temperature values recorded at Caracas, Venezuela (Meteorological data ASHRAE 2017) are chosen for this analysis. Assuming no cloud cover, the solar flux at the surface is about 1000 W/m^2. All of the ambient surfaces of the model are included in the solar loading calculation, and shadowing effects are included.

The temperature of the sun is about 5800 K, and it emits primarily short-wavelength infrared and visible light at wavelengths shorter than 2.5 microns. The fraction of this short-wavelength solar radiation that is absorbed by the various materials is quantified by the solar absorptivity. Because the surfaces are at a much lower temperature, they reradiate in the long-wavelength infrared band, at wavelengths above 2.5 microns, and the fraction of reradiated energy is quantified by the surface emissivity. The solar and ambient wavelength dependence of emissivity model is used to account for differing emissivities in different wavelength bands.

There are three ambient temperature conditions in this model. First, the ground at 1 m below the sand surface is assumed to be at a constant temperature of 27°C throughout the day, corresponding to the average water temperature at this location.

The second ambient condition is the surrounding air temperature. There exists a combination of free and forced convection, due to wind, from all exposed surfaces to the ambient air, the temperature of which is assumed to vary sinusoidally through the day. In this application, the Convective Heat Flux boundary condition uses a bulk heat transfer coefficient of 20 W/(m^2·K) for all exposed surfaces.

The third boundary condition is the radiative view factor to ambient. The graybody radiative view factors are computed between all exposed faces in the model, and radiative heat transfer is computed between these faces. However, these computed view factors do not sum to unity. There is a significant view factor to surrounding regions that is not modeled; this is the residual view factor. The temperature of the ambient is the same as the ambient air temperature.

Results and Discussion

Figure 2 plots the temperature profile at 4 p.m. Notice the decrease of temperature where the parasol shade stands.

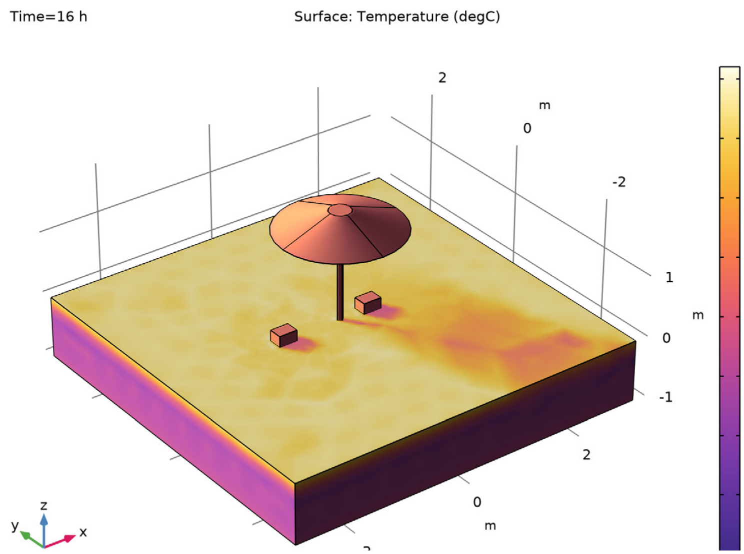


Figure 2: Temperature distribution.

Figure 3 plots the temperature of the beverage inside two of the cans. This shows clearly the advantage of placing the cooler in the shade. At 2 p.m., the parasol shade starts to leave the cooler corresponding to the green curve, which is responsible for the sudden variation in the temperature increase at that moment.

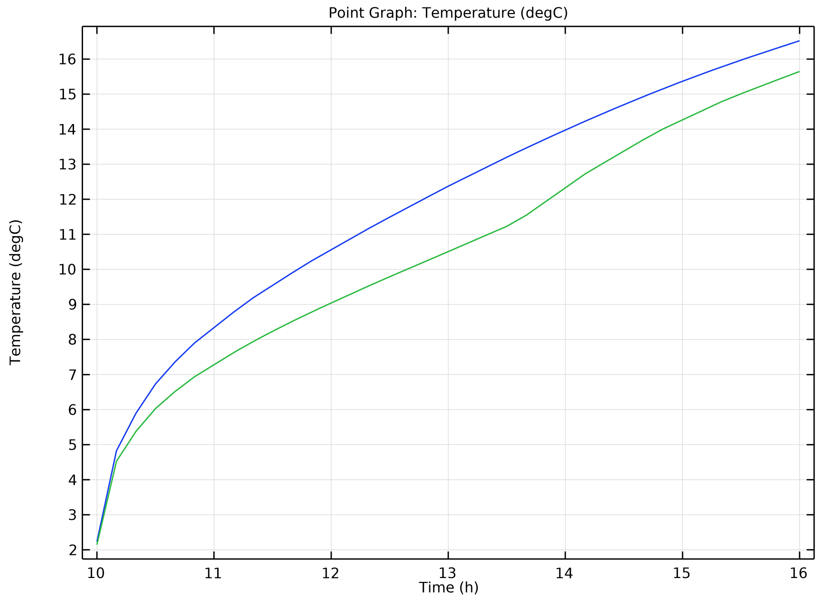


Figure 3: Beverage temperature over time inside of the two coolers at the left side of the parasol (blue curve) and at the right side (green curve).

Reference

1. F.P. Incropera, D.P. DeWitt, T.L. Bergman, and A.S. Lavine, *Fundamentals of Heat and Mass Transfer*, 6th ed., John Wiley & Sons, 2006.

Application Library path: `Heat_Transfer_Module/Thermal_Radiation/parasol`

Modeling Instructions

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

NEW

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

MODEL WIZARD

1 In the **Model Wizard** window, click **3D**.
2 In the **Select Physics** tree, select **Heat Transfer>Radiation>Heat Transfer with Surface-to-Surface Radiation**.
3 Click **Add**.
4 Click **Study**.
5 In the **Select Study** tree, select **General Studies>Time Dependent**.
6 Click **Done**.

GEOMETRY 1

Define an analytic function for the time-dependent ambient temperature.

GLOBAL DEFINITIONS

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.
2 In the **Settings** window for **Parameters**, locate the **Parameters** section.
3 In the table, enter the following settings:

Name	Expression	Value	Description
Tavg	27[degC]	300.15 K	Average ambient temperature
dT	3[K]	3 K	Half diurnal temperature variation
dateDay	1	1	Day
dateMonth	1	1	Month
dateYear	2012	2012	Year

Ambient Temperature

1 In the **Home** toolbar, click f(x) **Functions** and choose **Global>Analytic**.
2 In the **Settings** window for **Analytic**, type `T_ambient` in the **Function name** text field.
3 Locate the **Definition** section. In the **Expression** text field, type `Tavg+dT*cos(2*pi*(x-14)/24)`.
4 Locate the **Units** section. In the table, enter the following settings:

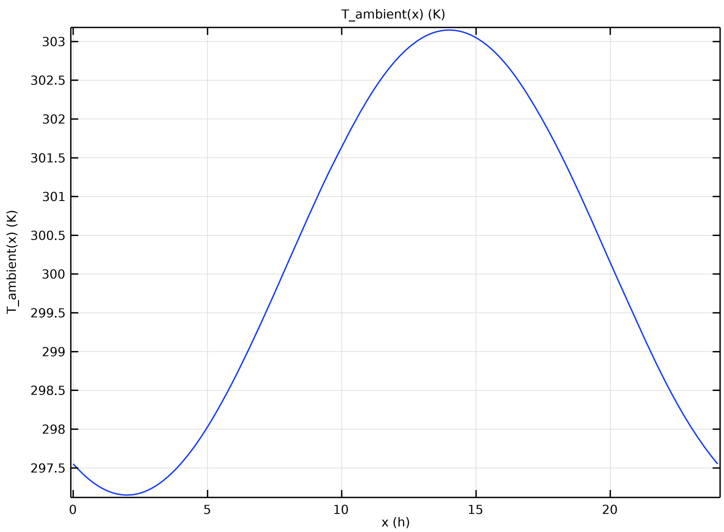
Argument	Unit
x	h

5 In the **Function** text field, type `K`.

6 Locate the **Plot Parameters** section. In the table, enter the following settings:

Argument	Lower limit	Upper limit	Unit
x	0	24*3600	s

7 Click **Plot**.



8 In the **Label** text field, type `Ambient Temperature`.

GEOMETRY 1

The geometry sequence for the model is available in a file. If you want to create it from scratch yourself, you can follow the instructions in the Geometry Modeling Instructions section. Otherwise, insert the geometry sequence as follows:

1 In the **Geometry** toolbar, click **Insert Sequence** and choose **Insert Sequence**.

2 Browse to the model's Application Libraries folder and double-click the file `parasol_geom_sequence.mph`.

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

4 Click the **Zoom Extents** button in the **Graphics** toolbar.

DEFINITIONS

The following selection gathers the boundaries of the twelve cans.

Beverage Cans

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

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

3 Select Domains 4–7, 9, 10, and 14–19 only.

These domains are the cans.

Beverage Can Walls

1 Right-click **Beverage Cans** and choose **Duplicate**.

2 In the **Settings** window for **Explicit**, type `Beverage Can Walls` in the **Label** text field.

3 Locate the **Output Entities** section. From the **Output entities** list, choose **Adjacent boundaries**.

The next selection is for the irradiated surfaces.

Irradiated Surfaces

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

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

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

4 Select Boundaries 4, 6, 7, 9, 10, 38–40, 56–62, 65–72, 74, 75, and 118 only.

These are the exterior surfaces of the sand, coolers, and parasol.

ADD MATERIAL

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

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

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

4 Click **Add to Component** in the window toolbar.

5 In the tree, select **Built-in>Air**.

6 Click **Add to Component** in the window toolbar.

7 In the tree, select **Built-in>Acrylic plastic**.

8 Click **Add to Component** in the window toolbar.

9 In the tree, select **Built-in>Aluminum**.

10 Click **Add to Component** in the window toolbar.

MATERIALS

Air (mat2)

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** click **Air (mat2)**.

2 Select Domains 3 and 13 only.

These domains are air between the coolers and the cans.

Acrylic plastic (mat3)

1 In the **Model Builder** window, click **Acrylic plastic (mat3)**.

2 Select Domains 8 and 11 only.

These domains make up the parasol.

Can Walls

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** click **Aluminum (mat4)**.

2 In the **Settings** window for **Material**, type `Can 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 **Beverage Can Walls**.

Extruded polystyrene foam

1 In the **Materials** toolbar, click **Blank Material**.

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

3 Select Domains 2 and 12 only.

These domains are the foams.

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

Property	**Variable**	**Value**	**Unit**	**Property group**
Thermal conductivity	k_iso ; kii = k_iso, kij = 0	0.05	W/(m·K)	Basic
Density	rho	200	kg/m³	Basic
Heat capacity at constant pressure	Cp	1300	J/(kg·K)	Basic

Sand

1 In the **Materials** toolbar, click **Blank Material**.

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

3 Select Domain 1 only.

This domain is the sand.

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

Property	**Variable**	**Value**	**Unit**	**Property group**
Thermal conductivity	k_iso ; kii = k_iso, kij = 0	0.3	W/(m·K)	Basic
Density	rho	1500	kg/m³	Basic
Heat capacity at constant pressure	Cp	800	J/(kg·K)	Basic

5 In the **Materials** toolbar, click **Add Material** to close the **Add Material** window.

HEAT TRANSFER IN SOLIDS (HT)

Initial Values 1

1 In the **Settings** window for **Initial Values**, locate the **Initial Values** section.

2 In the T text field, type `T_ambient(t)`.

Initial Values 2

1 In the **Model Builder** window, right-click **Heat Transfer in Solids (ht)** and choose **Initial Values**.

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

3 From the **Selection** list, choose **Beverage Cans**.

4 Locate the **Initial Values** section. In the T text field, type `1[degC]`.

Temperature 1

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

2 Select Boundary 3 only.

This is the bottom surface of the sand domain.

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

4 In the T_0 text field, type `27[degC]`.

Thin Layer 1

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

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

3 From the **Selection** list, choose **Beverage Can Walls**.

MATERIALS

Can Walls (mat4)

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** click **Can Walls (mat4)**.

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

3 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Thickness	lth	`300[um]`	m	Shell

HEAT TRANSFER IN SOLIDS (HT)

Heat Flux 1

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

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

3 From the **Selection** list, choose **Irradiated Surfaces**.

4 Locate the **Heat Flux** section. From the **Flux type** list, choose **Convective heat flux**.

5 In the h text field, type `20`.

6 In the T_{ext} text field, type `T_ambient(t)`.

SURFACE-TO-SURFACE RADIATION (RAD)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Surface-to-Surface Radiation (rad)**.

2 In the **Settings** window for **Surface-to-Surface Radiation**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Irradiated Surfaces**.

4 Locate the **Radiation Settings** section. Find the **Wavelength dependence** subsection. From the **Wavelength dependence of radiative properties** list, choose **Solar and ambient**.

Diffuse Surface 1

1 In the **Model Builder** window, under **Component 1 (comp1)>Surface-to-Surface Radiation (rad)** click **Diffuse Surface 1**.

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

3 In the T_{amb} text field, type `T_ambient(t)`.

4 Locate the **Surface Emissivity** section. From the ε list, choose **User defined for each band**.

5 In the table, enter the following settings:

Spectral band	Emissivity (1)
Solar: [0, 2.5[um][	0.2
Ambient: [2.5[um], +infinity[	0.8

Diffuse Surface 2

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

2 Select Boundary 4 only.

This is the top surface of the sand domain.

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

4 In the T_{amb} text field, type `T_ambient(t)`.

5 Locate the **Surface Emissivity** section. From the ε list, choose **User defined for each band**.

6 In the table, enter the following settings:

Spectral band	Emissivity (1)
Solar: [0, 2.5[um][	0.94
Ambient: [2.5[um], +infinity[	0.76

External Radiation Source 1

1 In the **Physics** toolbar, click **Global** and choose **External Radiation Source**.

2 In the **Settings** window for **External Radiation Source**, locate the **External Radiation Source** section.

3 From the **Source position** list, choose **Solar position**.

4 From the **Location defined by** list, choose **City**.

5 From the list, choose **Caracas, Venezuela**.

6 In the **Date** table, enter the following settings:

Day (1)	Month (1)	Year (1)
dateDay	dateMonth	dateYear

7 In the **Local time** table, enter the following settings:

Hour (1)	Minute (1)	Second (1)
0	0	0

STUDY 1

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 1** click **Step 1: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

3 From the **Time unit** list, choose **h**.

4 Click **Range**.

5 In the **Range** dialog box, type `10` in the **Start** text field.

6 In the **Step** text field, type `10[min]`.

7 In the **Stop** text field, type `16`.

8 Click **Replace**.

   The study starts at 10 a.m. and ends at 4 p.m. with time steps of 10 minutes.

9 In the **Home** toolbar, click **Compute**.

RESULTS

Surface 2

1 In the **Model Builder** window, expand the **Temperature (ht)** node, then click **Surface 2**.

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

3 From the **Solution parameters** list, choose **From parent**.

4 Locate the **Expression** section. From the **Unit** list, choose **degC**.

Surface 1

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

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

3 From the **Unit** list, choose **degC**.

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

5 Click the **Zoom Extents** button in the **Graphics** toolbar.

The first default plot shows the temperature distribution as in Figure 2.

Isothermal Contours (ht)

The second default plot shows the isothermal contours.

Surface Radiosity (rad)

The third default plot shows the surface radiosity. Proceed to plot the surface radiosity at 12 p.m.

1 In the **Model Builder** window, click **Surface Radiosity (rad)**.
2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.
3 From the **Time (h)** list, choose **12**.

Now add a plot showing the solar irradiation at 12 p.m. and see the parasol shade as in Figure 1.

Solar heat flux

1 In the **Model Builder** window, expand the **Surface Radiosity (rad)** node.
2 Right-click **Results** and choose **3D Plot Group**.
3 In the **Settings** window for **3D Plot Group**, type `Solar heat flux` in the **Label** text field.
4 Locate the **Data** section. From the **Time (h)** list, choose **12**.

Surface Slit 1

1 In the **Solar heat flux** toolbar, click **More Plots** and choose **Surface Slit**.
2 In the **Settings** window for **Surface Slit**, locate the **Expression on the Upside** section.
3 In the **Expression** text field, type `rad.q0su1`.
4 Locate the **Expression on the Downside** section. In the **Expression** text field, type `rad.q0sd1`.
5 Locate the **Coloring and Style** section. Click **Change Color Table**.
6 In the **Color Table** dialog box, select **Linear>GrayPrint** in the tree.
7 Click **OK**.
8 In the **Solar heat flux** toolbar, click **Plot**.

Next, observe the temperature of the beverages as in Figure 3.

Temperature in the Coolers

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.
2 In the **Settings** window for **1D Plot Group**, type `Temperature in the Coolers` in the **Label** text field.

Point Graph 1

1 In the **Temperature in the Coolers** toolbar, click **Point Graph**.
2 Select Points 41 and 126 only.

For more convenience, you can click the **Paste Selection** button and paste the point numbers.

3 In the **Settings** window for **Point Graph**, locate the **y-Axis Data** section.
4 From the **Unit** list, choose **degC**.

5 In the **Temperature in the Coolers** toolbar, click **Plot**.

Geometry Modeling Instructions

If you want to create the geometry yourself, follow these steps.

GEOMETRY 1

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 `6`.

4 In the **Depth** text field, type `6`.

5 Locate the **Position** section. From the **Base** list, choose **Center**.

6 In the **z** text field, type `-0.5`.

7 Click **Build Selected**.

This first block corresponds to a large region of sand. The next two blocks are the foam coolers on the sand.

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 `0.3`.

4 In the **Depth** text field, type `0.22`.

5 In the **Height** text field, type `0.18`.

6 Locate the **Position** section. From the **Base** list, choose **Center**.

7 In the **x** text field, type `0.5`.

8 In the **z** text field, type `0.09`.

9 Click **Build Selected**.

Block 3 (blk3)

1 Right-click **Block 2 (blk2)** and choose **Duplicate**.

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

3 In the **Width** text field, type `0.26`.

4 In the **Depth** text field, type `0.18`.

5 In the **Height** text field, type `0.14`.

6 Click **Build Selected**.

In the next few steps, you create two six-pack cans by building one cylinder that is duplicated in two 3x2 arrays. Because the cans are located inside the two foam coolers, you need to enable the **Wireframe Rendering** option to see them.

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

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 `0.03`.

4 In the **Height** text field, type `0.125`.

5 Locate the **Position** section. In the **x** text field, type `0.42`.

6 In the **y** text field, type `0.04`.

7 In the **z** text field, type `0.02`.

8 Click **Build Selected**.

Array 1 (arr1)

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

2 Select the object **cyl1** only.

3 In the **Settings** window for **Array**, locate the **Size** section.

4 In the **x size** text field, type `3`.

5 In the **y size** text field, type `2`.

6 Locate the **Displacement** section. In the **x** text field, type `0.08`.

7 In the **y** text field, type `-0.08`.

8 Click **Build Selected**.

Copy 1 (copy1)

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

2 Select the objects **arr1(1,1,1)**, **arr1(1,2,1)**, **arr1(2,1,1)**, **arr1(2,2,1)**, **arr1(3,1,1)**, **arr1(3,2,1)**, **blk2**, and **blk3** only.

For more convenience, use the **Select Box** button to select the abovementioned objects.

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

4 In the **x** text field, type `-1.5`.

5 Click **Build Selected**.

Now, create the parasol.

Cone 1 (cone1)

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

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

3 In the **Height** text field, type `0.3`.

4 From the **Specify top size using** list, choose **Angle**.

5 In the **Semiangle** text field, type `70`.

6 Locate the **Position** section. In the **z** text field, type `1.5`.

7 Click **Build Selected**.

Cone 2 (cone2)

1 Right-click **Cone 1 (cone1)** and choose **Duplicate**.

2 In the **Settings** window for **Cone**, locate the **Position** section.

3 In the **z** text field, type `1.4`.

4 Click **Build Selected**.

Difference 1 (dif1)

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

2 Select the object **cone1** only.

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

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

5 Select the object **cone2** only.

6 Click **Build Selected**.

Cylinder 2 (cyl2)

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 `0.05`.

4 In the **Height** text field, type `1.7`.

5 Click **Build Selected**.

Form Union (fin)

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

2 Click the **Zoom Extents** button in the **Graphics** toolbar.