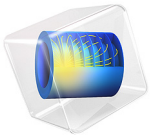

Thermal Distribution in a Pack of Cylindrical Batteries

Introduction

This example demonstrates how to model the temperature distribution in a battery pack during a 4C discharge. The pack is constructed by first coupling two cylindrical batteries in parallel. Six parallel-connected pairs are then connected in series to create the full pack - a configuration also called 6s2p. This configuration for the lithium ion battery pack is quite common in portable devices like skateboards, toys, drones and medical equipments.The symmetry of the problem is used twice so that only the temperature distribution for three batteries needs to be solved for.

Three instances of the Lumped Battery interface are used to generate the appropriate heat sources, which are then coupled to one Heat Transfer interface in a 3D geometry.

For a detailed description of the Lumped Battery interface and the underlying model, see the Parameter Estimation of a Time-Dependent Lumped Battery Model tutorial.

Model Definition

Figure 1 shows the model geometry. Three 21,700 battery cylinders (21 mm in diameter, 70 mm high) are placed adjacent to each other. Small connecting strips of aluminum are located at the top and bottom of the cylinders according to the 6s2p configuration. The whole pack is assumed to be wrapped in plastic, forming a domain filled with air. Assuming a nominal capacity of 4 Ah for each cell and nominal voltage of 3.6 V, the battery pack has a total nominal capacity of approximately 177 Wh.

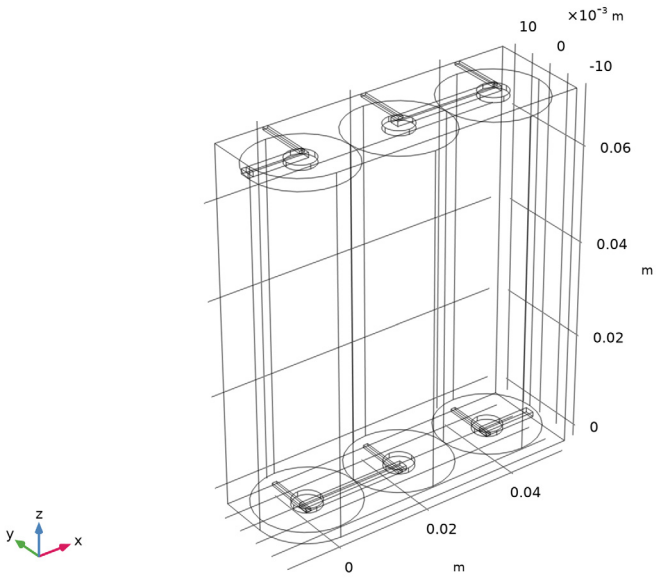

Figure 1: Model geometry.

One Lumped Battery interface is used to model each battery cylinder, with temperature-dependent ohmic, exchange current and diffusion time-constant parameters according to Arrhenius expressions.

The temperature profile is modeled using a Heat Transfer interface, where the heat sources stemming from the battery models are added by the use of an Electrochemical Heating multiphysics nodes. The convection in the air-filled domain enclosing the batteries is neglected, assuming quiescent conditions. The outer boundaries of the pack are cooled using a convective cooling condition. Symmetry (no flux) conditions are used for the interior flat symmetry boundaries facing the rest of the pack.

Anisotropic heat conductivities are used in each battery by the use of individually defined cylindrical coordinate systems for each battery cylinder, with generally lower heat conductivities in the radial direction compared to the angular and z directions - a result of the spirally wound metal foils in the jelly roll design of the batteries.

The pack is discharged from 100% to 20% state-of-charge (SOC) using a 4C rate for 12 minutes.

Results and Discussion

Figure 2 shows the temperature distribution in the pack at the end of the simulation, where the solution data has been mirrored twice to illustrate the temperature of the full 6s2p pack. The innermost parts of the pack experience a temperature about 2°C higher than the outermost parts.

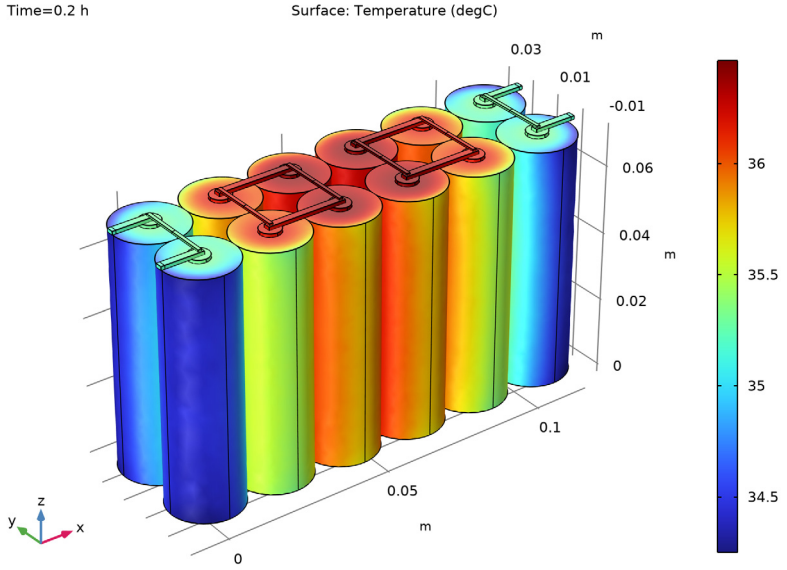

Figure 2: Temperature plot at t= 0.2 h.

Figure 3 shows a plot of the individual cell voltages during the discharge. The outermost cell (Cell 1) exhibits a slightly lower discharge voltage, a result of the ohmic drop and exchange current being slightly lower, and the diffusion time constant slightly higher, for the lower temperature, but the effect is small. The corresponding temperatures are shown in Figure 4.

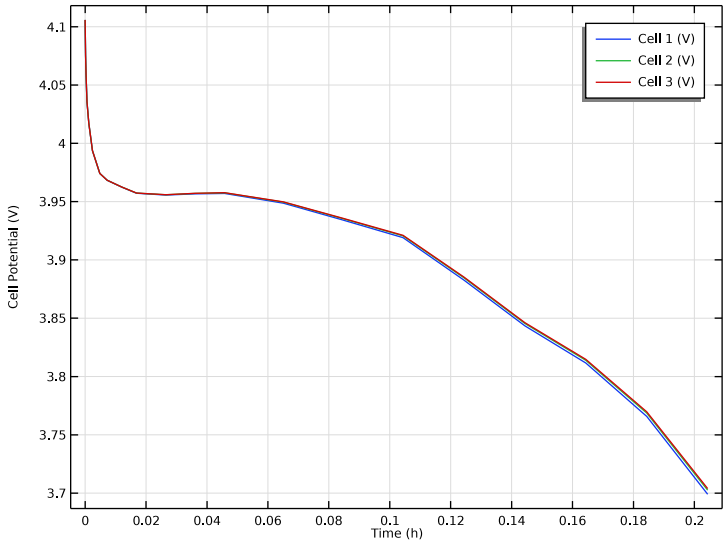

Figure 3: Cell voltages versus time.

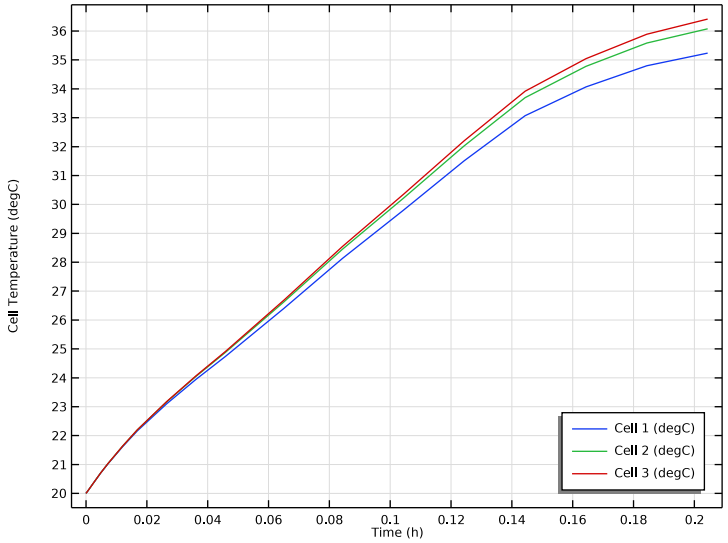

Figure 4: Average cell temperatures versus time.

Application Library path: `Battery_Design_Module/Thermal_Management/lumped_li_battery_pack_6s2p`

Modeling Instructions

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

NEW

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

MODEL WIZARD

1. In the **Model Wizard** window, Start with adding a 3D space dimension along with a Heat Transfer in Fluids and a Lumped Battery interface.
2. click **3D**.
3. In the **Select Physics** tree, select **Heat Transfer>Heat Transfer in Fluids (ht)**.
4. Click **Add**.
5. In the **Select Physics** tree, select **Electrochemistry>Batteries>Lumped Battery (lb)**.
6. Click **Add**.
7. Click **Study**.
8. In the **Select Study** tree, select **General Studies>Time Dependent**.
9. Click **Done**.

DEFINITIONS

Add an analytical function to account for the temperature dependent activation energy using the Arrhenius relation.

Analytic 1 (an1)

1. In the **Home** toolbar, click **Functions** and choose **Local>Analytic**.
2. In the **Settings** window for **Analytic**, type `Arrh` in the **Function name** text field.
3. Locate the **Definition** section. In the **Expression** text field, type `exp(Ea/R_const*(1/Temp-1/T0))`.
4. In the **Arguments** text field, type `Ea, Temp`.

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

Argument	Unit
Ea	J/mol
Temp	K

6 In the **Function** text field, type 1.

E_OCP

Next add interpolation functions to define the SOC dependent equilibrium potential and its temperature dependence.

1 In the **Home** toolbar, click f(x) **Functions** and choose **Local>Interpolation**.

2 In the **Settings** window for **Interpolation**, type E_OCP in the **Label** text field.

3 Locate the **Definition** section. From the **Data source** list, choose **File**.

4 In the **Filename** text field, type lumped_li_battery_pack_6s2p_E_OCP_data.txt.

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

Argument	Unit
Column 1	1

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

Function	Unit
int1	V

dEdT

1 In the **Home** toolbar, click f(x) **Functions** and choose **Local>Interpolation**.

2 In the **Settings** window for **Interpolation**, type dEdT in the **Label** text field.

3 Locate the **Definition** section. From the **Data source** list, choose **File**.

4 In the **Filename** text field, type lumped_li_battery_pack_6s2p_dEdT_data.txt.

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

Argument	Unit
Column 1	1

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

Function	Unit
int2	V/K

GEOMETRY 1

The model geometry is available as a parameterized geometry sequence in a separate MPH-file. If you want to build it from scratch, follow the instructions in the section Appendix — Geometry Modeling Instructions. Otherwise load it from file with the following steps.

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 `lumped_li_battery_pack_6s2p_geom_sequence.mph`.

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

4 Click the **Transparency** button in the **Graphics** toolbar.

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

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.

Battery Parameters

Add the parameter file required for setting up the physics of the lumped battery and heat transfer interfaces.

1 In the **Home** toolbar, click **Parameters** and choose **Add>Parameters**.

2 In the **Settings** window for **Parameters**, type `Battery 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 `lumped_li_battery_pack_6s2p_parameters.txt`.

DEFINITIONS

Add cylindrical coordinate systems to define the rotational symmetry around the batteries. This will be needed when setting material properties for the heat transfer interface.

Cylindrical System 2 (sys2)

In the **Definitions** toolbar, click **Coordinate Systems** and choose **Cylindrical System**.

Cylindrical System 3 (sys3)

1 Right-click **Cylindrical System 2 (sys2)** and choose **Duplicate**.

2 In the **Settings** window for **Cylindrical System**, locate the **Settings** section.

3 Find the **Origin** subsection. In the table, enter the following settings:

x (m)	y (m)	z (m)
d_batt	0	0

Cylindrical System 4 (sys4)

1 Right-click **Cylindrical System 3 (sys3)** and choose **Duplicate**.

2 In the **Settings** window for **Cylindrical System**, locate the **Settings** section.

3 Find the **Origin** subsection. In the table, enter the following settings:

x (m)	y (m)	z (m)
2*d_batt	0	0

MATERIALS

Next, add and define the materials in the different domains: air to the region surrounding the batteries and aluminum to the current collectors.

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>Air**.

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

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

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

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

MATERIALS

Air (mat1)

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** click **Air (mat1)**.

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

3 From the **Selection** list, choose **Air Domain**.

Aluminum (mat2)

1 In the **Model Builder** window, click **Aluminum (mat2)**.

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

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

Active Battery Material

Add a blank material to define the thermal properties of the active battery material manually.

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

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

3 Locate the **Geometric Entity Selection** section. From the **Selection** list, choose **Batteries**.

4 In the **Model Builder** window, expand the **Component 1 (comp1)>Materials> Active Battery Material (mat3)** node, then click **Basic (def)**.

5 In the **Settings** window for **Basic**, locate the **Output Properties** section.

6 Click + **Select Quantity**.

7 In the **Physical Quantity** dialog box, select **General>Density (kg/m^3)** in the tree.

8 Click **OK**.

9 In the **Settings** window for **Basic**, locate the **Output Properties** section.

10 In the table, enter the following settings:

Property	Variable	Expression	Unit	Size
Density	rho	`rho_batt`	kg/m³	1x1

11 Click + **Select Quantity**.

12 In the **Physical Quantity** dialog box, select **Transport> Heat capacity at constant pressure (J/(kg*K))** in the tree.

13 Click **OK**.

14 In the **Settings** window for **Basic**, locate the **Output Properties** section.

15 In the table, enter the following settings:

Property	Variable	Expression	Unit	Size
Heat capacity at constant pressure	Cp	`Cp_batt`	J/(kg·K)	1x1

HEAT TRANSFER IN FLUIDS (HT)

Now define the heat transfer in the battery pack.

Initial Values 1

1. In the **Model Builder** window, under **Component 1 (comp1)>Heat Transfer in Fluids (ht)** click **Initial Values 1**.
2. In the **Settings** window for **Initial Values**, locate the **Initial Values** section.
3. In the T text field, type `T_init`.

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 **Heat Flux Boundaries**.
4. Locate the **Heat Flux** section. From the **Flux type** list, choose **Convective heat flux**.
5. In the h text field, type `ht`.
6. In the T_{ext} text field, type `T_init`.

Solid 1

1. In the **Physics** toolbar, click **Domains** and choose **Solid**.
2. In the **Settings** window for **Solid**, locate the **Domain Selection** section.
3. From the **Selection** list, choose **Battery 1**.
4. Locate the **Coordinate System Selection** section. From the **Coordinate system** list, choose **Cylindrical System 2 (sys2)**.
5. Locate the **Heat Conduction, Solid** section. From the k list, choose **User defined**. From the list, choose **Diagonal**.
6. In the k table, enter the following settings:

kT_batt_r	0	0
0	kT_batt_ang	0
0	0	kT_batt_ang

Solid 2

1. Right-click **Solid 1** and choose **Duplicate**.
2. In the **Settings** window for **Solid**, locate the **Domain Selection** section.
3. From the **Selection** list, choose **Battery 2**.

4 Locate the **Coordinate System Selection** section. From the **Coordinate system** list, choose **Cylindrical System 3 (sys3)**.

Solid 3

1 In the **Model Builder** window, under **Component 1 (comp1)>Heat Transfer in Fluids (ht)** right-click **Solid 1** and choose **Duplicate**.

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

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

4 Locate the **Coordinate System Selection** section. From the **Coordinate system** list, choose **Cylindrical System 4 (sys4)**.

Solid 4

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

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

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

LUMPED BATTERY (LB)

Now define the battery characteristics in the lumped battery interface.

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Lumped Battery (lb)**.

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

3 From the **Selection** list, choose **Battery 1**.

4 Locate the **Operation Mode** section. In the I_{app} text field, type `-I_1C*C_rate`.

5 Locate the **Battery Settings** section. In the $Q_{\text{cell},0}$ text field, type `Q_cell`.

6 In the $\text{SOC}_{\text{cell},0}$ text field, type `1`.

Cell Equilibrium Potential 1

1 In the **Model Builder** window, under **Component 1 (comp1)>Lumped Battery (lb)** click **Cell Equilibrium Potential 1**.

2 In the **Settings** window for **Cell Equilibrium Potential**, locate the **Open Circuit Voltage** section.

3 From the **Open circuit voltage input** list, choose **From definitions**.

4 From the $E_{\text{OCV,ref}}$ list, choose **E_OCP (int1)**.

5 From the dE_{OCV}/dT list, choose **dEdT (int2)**.

Voltage Losses 1

1 In the **Model Builder** window, click **Voltage Losses 1**.

2 In the **Settings** window for **Voltage Losses**, locate the **Ohmic Overpotential** section.

3 In the $\eta_{IR,1C}$ text field, type `eta_1C*Arrh(Ea_eta1C, lb.Temp)`.

4 Locate the **Activation Overpotential** section. In the J_0 text field, type `J0_0*Arrh(Ea_J0,lb.Temp)`.

5 Locate the **Concentration Overpotential** section. Select the **Include concentration overpotential** check box.

6 In the τ text field, type `tau_0*Arrh(Ea_Tau,lb.Temp)`.

Copy the lumped battery interface node, and then modify the settings of the copy, to define the second battery in the pack.

7 In the **Model Builder** window, right-click **Lumped Battery (lb)** and choose **Copy**.

LUMPED BATTERY 2 (LB2)

1 In the **Model Builder** window, right-click **Component 1 (comp1)** and choose **Paste Lumped Battery**.

2 In the **Messages from Paste** dialog box, click **OK**.

3 In the **Settings** window for **Lumped Battery**, locate the **Domain Selection** section.

4 From the **Selection** list, choose **Battery 2**.

Voltage Losses 1

1 In the **Model Builder** window, expand the **Lumped Battery 2 (lb2)** node, then click **Voltage Losses 1**.

2 In the **Settings** window for **Voltage Losses**, locate the **Ohmic Overpotential** section.

3 In the $\eta_{IR,1C}$ text field, type `eta_1C*Arrh(Ea_eta1C, lb2.Temp)`.

4 Locate the **Activation Overpotential** section. In the J_0 text field, type `J0_0*Arrh(Ea_J0,lb2.Temp)`.

5 Locate the **Concentration Overpotential** section. In the τ text field, type `tau_0*Arrh(Ea_Tau,lb2.Temp)`.

LUMPED BATTERY (LB)

In the **Model Builder** window, under **Component 1 (comp1)** right-click **Lumped Battery (lb)** and choose **Copy**.

LUMPED BATTERY 3 (LB3)

1 In the **Model Builder** window, right-click **Component 1 (comp1)** and choose **Paste Lumped Battery**.

2 In the **Messages from Paste** dialog box, click **OK**.

3 In the **Settings** window for **Lumped Battery**, locate the **Domain Selection** section.

4 From the **Selection** list, choose **Battery 3**.

Voltage Losses 1

1 In the **Model Builder** window, expand the **Lumped Battery 3 (lb3)** node, then click **Voltage Losses 1**.

2 In the **Settings** window for **Voltage Losses**, locate the **Ohmic Overpotential** section.

3 In the $\eta_{IR,1C}$ text field, type `eta_1C*Arrh(Ea_eta1C, lb3.Temp)`.

4 Locate the **Activation Overpotential** section. In the J_0 text field, type `J0_0*Arrh(Ea_J0,lb3.Temp)`.

5 Locate the **Concentration Overpotential** section. In the τ text field, type `tau_0*Arrh(Ea_Tau,lb3.Temp)`.

MULTIPHYSICS

Electrochemical Heating 1 (ech1)

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

Electrochemical Heating 2 (ech2)

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

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

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

4 Locate the **Coupled Interfaces** section. From the **Electrochemical** list, choose **Lumped Battery 2 (lb2)**.

Electrochemical Heating 3 (ech3)

1 Right-click **Electrochemical Heating 2 (ech2)** and choose **Duplicate**.

2 In the **Settings** window for **Electrochemical Heating**, locate the **Coupled Interfaces** section.

3 From the **Electrochemical** list, choose **Lumped Battery 3 (lb3)**.

DEFINITIONS (COMP1)

Adding probes for Temperature and Cell Potential for different cells would allow to visualize results while solving.

Temperature Cell 1

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

2 In the **Settings** window for **Global Variable Probe**, type `Temp1` in the **Variable name** text field.

3 In the **Label** text field, type `Temperature Cell 1`.

4 Locate the **Expression** section. In the **Expression** text field, type `lb.Temp`.

5 From the **Table and plot unit** list, choose **degC**.

6 Select the **Description** check box.

7 In the associated text field, type `Cell 1`.

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

9 From the **Plot window** list, choose **New window**.

10 Click + **Add Plot Window**.

Temperature Cell 2

1 Right-click **Temperature Cell 1** and choose **Duplicate**.

2 In the **Settings** window for **Global Variable Probe**, type `Temperature Cell 2` in the **Label** text field.

3 In the **Variable name** text field, type `Temp2`.

4 Locate the **Expression** section. In the **Expression** text field, type `lb2.Temp`.

5 In the **Description** text field, type `Cell 2`.

Temperature Cell 3

1 Right-click **Temperature Cell 2** and choose **Duplicate**.

2 In the **Settings** window for **Global Variable Probe**, type `Temperature Cell 3` in the **Label** text field.

3 In the **Variable name** text field, type `Temp3`.

4 Locate the **Expression** section. In the **Expression** text field, type `lb3.Temp`.

5 In the **Description** text field, type `Cell 3`.

Cell Potential 1

1 Right-click **Temperature Cell 3** and choose **Duplicate**.

2 In the **Settings** window for **Global Variable Probe**, type `Cell Potential 1` in the **Label** text field.

3 In the **Variable name** text field, type `Ecell1`.

4 Locate the **Expression** section. In the **Expression** text field, type `lb.Ecell`.

5 Click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Lumped Battery>lb.E_cell - Cell potential - V**.

6 Locate the **Expression** section. In the **Description** text field, type `Cell 1`.

7 Locate the **Table and Window Settings** section. Click **+ Add Table**.

8 From the **Plot window** list, choose **New window**.

9 Click **+ Add Plot Window**.

Cell Potential 2

1 Right-click **Cell Potential 1** and choose **Duplicate**.

2 In the **Settings** window for **Global Variable Probe**, type `Cell Potential 2` in the **Label** text field.

3 In the **Variable name** text field, type `Ecell2`.

4 Locate the **Expression** section. In the **Expression** text field, type `lb2.Ecell`.

5 Click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Lumped Battery 2>lb2.E_cell - Cell potential - V**.

6 Locate the **Expression** section. In the **Description** text field, type `Cell 2`.

Cell Potential 3

1 Right-click **Cell Potential 2** and choose **Duplicate**.

2 In the **Settings** window for **Global Variable Probe**, type `Cell Potential 3` in the **Label** text field.

3 In the **Variable name** text field, type `Ecell3`.

4 Locate the **Expression** section. In the **Expression** text field, type `lb3.Ecell`.

5 Click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Lumped Battery 3>lb3.E_cell - Cell potential - V**.

6 Locate the **Expression** section. In the **Description** text field, type `Cell 3`.

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 In the **Output times** text field, type `0 0.8/C_rate`.

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

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

7 Clear the **Generate default plots** check box.

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

RESULTS

Add a dataset with a selection and mirror it twice in order to visualize the temperature of the full 6s2p configuration.

Study 1/Solution 1 (3) (sol1)

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

Selection

1 In the **Results** toolbar, click **Attributes** and choose **Selection**.

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

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

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog box, type `1 3-21` in the **Selection** text field.

6 Click **OK**.

Mirror 3D 1

1 In the **Results** toolbar, click **More Datasets** and choose **Mirror 3D**.

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

3 From the **Dataset** list, choose **Study 1/Solution 1 (3) (sol1)**.

4 Locate the **Plane Data** section. In the **X-coordinate** text field, type `2.5*(d_batt)`.

Mirror 3D 2

1 Right-click **Mirror 3D 1** and choose **Duplicate**.

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

3 From the **Dataset** list, choose **Mirror 3D 1**.

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

5 In the **y-coordinate** text field, type `d_batt/2`.

6 Click **Plot**.

STUDY 1

Step 1: Time Dependent

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

2 Drag and drop below **Step 1: Time Dependent**.

RESULTS

Cell Temperatures vs. Time

1 In the **Model Builder** window, expand the **Results>Probe Plot Group 1** node, then click **Probe Plot Group 1**.

2 In the **Settings** window for **1D Plot Group**, type `Cell Temperatures vs. Time` in the **Label** text field.

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

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

5 In the associated text field, type `Cell Temperature (degC)`.

6 Locate the **Legend** section. From the **Position** list, choose **Lower right**.

7 In the **Cell Temperatures vs. Time** toolbar, click **Plot**.

Cell Potential vs. Time

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

2 In the **Settings** window for **1D Plot Group**, type `Cell Potential vs. Time` in the **Label** text field.

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

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

5 In the associated text field, type `Cell Potential (V)`.

6 In the **Cell Potential vs. Time** toolbar, click **Plot**.

Temperature

1 In the **Home** toolbar, click **Add Plot Group** and choose **3D Plot Group**.

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

3 From the **Dataset** list, choose **Mirror 3D 2**.

4 In the **Label** text field, type `Temperature`.

Surface 1

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

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

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

4 In the **Temperature** toolbar, click **Plot**.

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

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. 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 `lumped_li_battery_pack_6s2p_geom_sequence_parameters.txt`.

GEOMETRY 1

Cylinder 1 (cyl1)

1. In the **Geometry** toolbar, click **Cylinder**.
2. In the **Settings** window for **Cylinder**, locate the **Size and Shape** section.
3. In the **Radius** text field, type `r_batt`.
4. In the **Height** text field, type `h_batt`.

Cylinder 2 (cyl2)

1. Right-click **Cylinder 1 (cyl1)** and choose **Duplicate**.
2. In the **Settings** window for **Cylinder**, locate the **Size and Shape** section.
3. In the **Radius** text field, type `r_term`.
4. In the **Height** text field, type `h_term`.
5. Locate the **Position** section. In the **z** text field, type `-h_term`.

Array 1 (arr1)

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

2 In the **Settings** window for **Array**, locate the **Input** section.

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type `cyl2` in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **Array**, click to collapse the **Displacement** section.

7 Locate the **Size** section. In the **z size** text field, type `2`.

8 Click to expand the **Displacement** section. In the **z** text field, type `h_batt+h_term`.

Array 2 (arr2)

1 Right-click **Array 1 (arr1)** and choose **Duplicate**.

2 In the **Settings** window for **Array**, locate the **Input** section.

3 Find the **Input objects** subsection. Click to select the **Activate Selection** toggle button.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog box, type `cyl1` in the **Selection** text field.

6 Click **OK**.

7 In the **Settings** window for **Array**, locate the **Input** section.

8 Click **Paste Selection**.

9 In the **Paste Selection** dialog box, type `arr1(1,1,1)` in the **Selection** text field.

10 Click **OK**.

11 In the **Settings** window for **Array**, locate the **Input** section.

12 Click **Paste Selection**.

13 In the **Paste Selection** dialog box, type `arr1(1,1,2)` in the **Selection** text field.

14 Click **OK**.

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

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

17 Locate the **Displacement** section. In the **x** text field, type `d_batt`.

18 In the **z** text field, type `0`.

19 Click **Build Selected**.

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 `d_batt+d_sc`.

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

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

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

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

8 In the **z** text field, type `-h_sc-h_term`.

9 Click **Build Selected**.

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 `(d_batt+d_sc)/2`.

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

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

6 Locate the **Position** section. In the **x** text field, type `-d_sc/2+(d_batt)*2`.

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

8 In the **z** text field, type `-h_term-h_sc`.

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 `(d_batt)/2+d_sc`.

4 Locate the **Position** section. In the **x** text field, type `-d_sc/2-d_batt/2`.

5 In the **z** text field, type `h_batt+h_term`.

Block 4 (blk4)

1 Right-click **Block 3 (blk3)** and choose **Duplicate**.

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

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

4 In the **Depth** text field, type `d_batt/2+w_pc/2`.

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

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

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

8 In the **z** text field, type `-h_term-h_sc-h_pc`.

9 Click **Build Selected**.

Move 1 (mov1)

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

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

3 Click the **Transparency** button in the **Graphics** toolbar.

4 In the **Settings** window for **Move**, locate the **Input** section.

5 Click **Paste Selection**.

6 In the **Paste Selection** dialog box, type `blk1` in the **Selection** text field.

7 Click **OK**.

8 In the **Settings** window for **Move**, locate the **Input** section.

9 Select the **Keep input objects** check box.

10 Locate the **Displacement** section. In the **x** text field, type `d_batt`.

11 In the **z** text field, type `h_batt+h_term*2+h_sc`.

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

Array 3 (arr3)

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

2 In the **Settings** window for **Array**, locate the **Input** section.

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type `blk4` in the **Selection** text field.

5 Click **OK**.

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

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

8 In the **z size** text field, type `2`.

9 Locate the **Displacement** section. In the **x** text field, type `d_batt`.

10 In the **z** text field, type `h_batt+2*(h_term+h_sc)+h_pc`.

11 Click **Build Selected**.

Move 1 (mov1)

1 In the **Model Builder** window, click **Move 1 (mov1)**.

2 In the **Settings** window for **Move**, click **Build Selected**.

3 Click **Build All Objects**.

Work Plane 1 (wp1)

1 In the **Geometry** toolbar, click  **Work Plane**.

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

3 In the **z-coordinate** text field, type `-(h_term+h_sc+h_pc)`.

Work Plane 1 (wp1)>Plane Geometry

In the **Model Builder** window, click **Plane Geometry**.

Work Plane 1 (wp1)>Circle 1 (c1)

1 In the **Work Plane** toolbar, click  **Circle**.

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

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

4 In the **Sector angle** text field, type `90`.

5 Locate the **Rotation Angle** section. In the **Rotation** text field, type `180`.

Work Plane 1 (wp1)>Square 1 (sq1)

1 In the **Work Plane** toolbar, click  **Square**.

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

3 In the **Side length** text field, type `r_batt`.

4 Locate the **Position** section. In the **xw** text field, type `-r_batt`.

5 In the **yw** text field, type `-r_batt`.

Work Plane 1 (wp1)>Difference 1 (dif1)

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

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

3 Select the object **sq1** only.

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

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

6 Click  **Paste Selection**.

7 In the **Paste Selection** dialog box, type `c1` in the **Selection** text field.

8 Click **OK**.

9 In the **Settings** window for **Difference**, click  **Build Selected**.

Work Plane 1 (wp1)>Rectangle 1 (r1)

1 In the **Work Plane** toolbar, click  **Rectangle**.

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

3 In the **Width** text field, type `3*(d_batt)`.

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

5 Click **Build Selected**.

6 Locate the **Position** section. In the **xw** text field, type `-r_batt`.

7 In the **yw** text field, type `-r_batt`.

Work Plane 1 (wp1)>Difference 2 (dif2)

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

2 Select the object **r1** 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 Click the **Zoom Extents** button in the **Graphics** toolbar.

6 Select the object **dif1** only.

7 Click **Build Selected**.

Extrude 1 (ext1)

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

2 In the **Settings** window for **Extrude**, locate the **Distances** section.

3 In the table, enter the following settings:

Distances (m)
`h_batt+2*(h_term+h_sc+h_pc)`

4 Click **Build Selected**.

Form Union (fin)

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

Battery 1

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 On the object **fin**, select Domain 3 only.

3 In the **Settings** window for **Explicit Selection**, type `Battery 1` in the **Label** text field.

Battery 2

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 On the object **fin**, select Domain 10 only.

3 In the **Settings** window for **Explicit Selection**, type `Battery 2` in the **Label** text field.

Battery 3

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 On the object **fin**, select Domain 16 only.

3 In the **Settings** window for **Explicit Selection**, type `Battery 3` in the **Label** text field.

Air Domain

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 On the object **fin**, select Domain 2 only.

3 In the **Settings** window for **Explicit Selection**, type `Air Domain` in the **Label** text field.

Connectors

1 In the **Geometry** toolbar, click **Selections** and choose **Complement Selection**.

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

3 Click **Add**.

4 In the **Add** dialog box, in the **Selections to invert** list, choose **Battery 1**, **Battery 2**, **Battery 3**, and **Air Domain**.

5 Click **OK**.

6 In the **Settings** window for **Complement Selection**, type `Connectors` in the **Label** text field.

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

Batteries

1 In the **Geometry** toolbar, click **Selections** and choose **Union Selection**.

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

3 Click **Add**.

4 In the **Add** dialog box, in the **Selections to add** list, choose **Battery 1**, **Battery 2**, and **Battery 3**.

5 Click **OK**.

6 In the **Settings** window for **Union Selection**, type `Batteries` in the **Label** text field.

Batteries and Connectors

1 In the **Geometry** toolbar, click **Selections** and choose **Union Selection**.

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

3 Click **Add**.

4 In the **Add** dialog box, in the **Selections to add** list, choose **Connectors** and **Batteries**.

5 Click **OK**.

6 In the **Settings** window for **Union Selection**, type `Batteries and Connectors` in the **Label** text field.

Heat Flux Boundaries

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, locate the **Entities to Select** section.

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

4 In the **Label** text field, type `Heat Flux Boundaries`.

5 Locate the **Entities to Select** section. Click **Paste Selection**.

6 In the **Paste Selection** dialog box, type `fin: 1-7, 9, 12, 14, 15, 48` in the **Selection** text field.

7 Click **OK**.

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

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

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