Model created in COMSOL Multiphysics 6.4

Thermal Controller, Reduced-Order Model

Introduction

This example demonstrates controlling the temperature in a heated metal block using a thermal controller and how to use reduced-order modeling to shorten computing time for additional simulations.

The model studies the controlled temperature response to a sinusoidal variation of the external temperature for two candidate thermostat positions and two temperature setpoints. One candidate location for the thermostat is between the surface with the external temperature variation and the heater, and in the other location both the heater and the surface with the external temperature are located on the same side.

Model Definition

The dynamic system consists of a metal block that exchanges heat with the environment. A heater and a thermostat switch are situated inside the glass-enclosed system. The system works as follows: The thermostat turns the heater on or off when the temperature becomes too low or too high.

The finite-element model of the metal block requires two inputs:

- The state of the heater, which can be On (1) or Off (0)
- The exterior temperature, T_{out}

As its output, the model supplies the temperature at the thermostat's location.

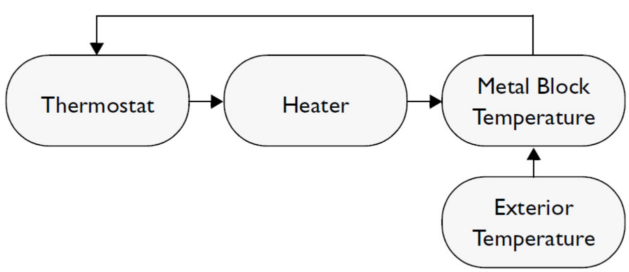


Figure 1: Block diagram for the thermal controller system.

The PDE describes the overall system's temperature distribution given the temperature of the heater and the exterior environment. If the heat transfer is so fast that the heat distribution is more or less constant (in space, not in time), a single state is sufficient.

Otherwise, controlling the temperature requires modeling a space-dependent PDE in COMSOL Multiphysics.

DOMAIN EQUATIONS

The heat equation is

$$\rho C\frac{\partial T}{\partial t} - \nabla \cdot (k\nabla T) = Q$$

BOUNDARY CONDITIONS

The boundary conditions come from the level of insulation around the system. On well-insulated sides the temperature flux is zero, which gives the Neumann boundary condition $n \cdot (k\nabla T) = 0$. The poorly insulated sides involve the Neumann condition $n \cdot (k\nabla T) = (k_G/l_G)(T_{out} - T)$, where k_G and l_G are the thermal conductivity and the thickness of the glass sheet that separates the metal block and the exterior.

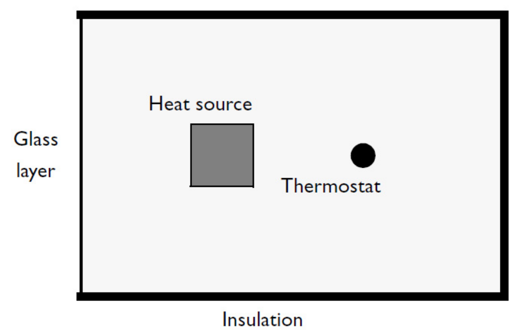


Figure 2: Geometry of the thermal controller system. The figure shows one of the two candidate thermostat positions.

Because only the temperature distribution in the xy-plane is of interest, you can use a 2D model. For the units to make sense, think of the domain as having a depth (z direction) of 1 m.

CONTROLLING TEMPERATURE

The temperature is controlled by switching the heater on and off depending on a temperature measurement (`T`) relative to a temperature setpoint (`Tset`). In order to avoid switching on an off as soon as there is a small deviation, a deadband (+/- `dT`) is often used to define an acceptable deviation from the setpoint before the controller switches its state. Introducing indicator functions (`lowtemp` and `hightemp`) switching signs when the temperature changes to a value outside the acceptable range, events can be used to switch the heater on and off.

```
lowtemp = (Tset – dT) – T
hightemp = T – (Tset + dT)
```

The event triggered when detecting `lowtemp` > 0 switches the heater on and the event triggered when detecting `hightemp` > 0 switches the heater off.

REDUCED-ORDER MODELING (MODEL REDUCTION)

Large finite-element simulations can be costly, and if repeated simulations are needed it can be beneficial to use reduced-order models (ROMs). Reduced-order modeling is a method for reducing a given dynamic finite element model to one with fewer degrees of freedom while maintaining the dynamic characteristics of the system. ROMs are typically valid only in the vicinity of their design conditions and have lower accuracy, but the simulation time is significantly shorter. The objective for model reduction is to provide a sufficiently accurate representation of the input-output dynamics of the unreduced model in a given parameter range with a minimal total computational cost, including the cost of creating the reduced model. The characteristics of the unreduced model as well as the value of the reduced model guide the choice of model-reduction method. Nonlinearities require special treatment, and if the model is to be valid in a large parameter range it can be costly to produce basis functions or input-output samples. Model reduction can, for example, be performed by linearization of the finite-element model and projection of the resulting system matrices onto a limited set of base functions representing the dynamics of significance for the application and defining the relevant inputs and outputs of interest. In this case, the model reduction is performed by projection onto a selected subset of eigenmodes for the system, corresponding to the dominant dynamics.

In the present example the unreduced model as well as the outputs are linear and the dependence on the input parameters has an affine representation. A small number of eigenmodes are used as the basis functions and the inputs represent the exterior temperature (`Tout`) and the fraction of maximum power of the heater (`HeatState`). The outputs are defined as the temperatures in two candidate points for thermostat placement (`T1`, `T2`). The control strategy described in the previous section is, however, clearly nonlinear and not a candidate for model reduction since it only has two states.

Results and Discussion

The tutorial shows how to use a reduced model rather than a full finite-element simulation to evaluate a control strategy. In this case, the controlled system is linear but the controller has nonlinear dynamics. It is also illustrated how increasing the number of basis functions can improve the transient response of the reduced model when compared to a finite-element simulation. The external temperature variation is slow and smooth, but the dynamics of the controller can introduce high-frequency transients. The dynamic response of the reduced model is determined by the eigenmodes included in the basis, and increasing the number of modes extends the dynamic range of the reduced model and improves the accuracy of the transient response. From the comparison with the response of the unreduced model it is clear that an increase from 6 to 40 eigenmodes, which is done in the settings for the eigenvalue study, brings the reduced model response closer to that of the unreduced model. The final comparison is shown in Figure 3.

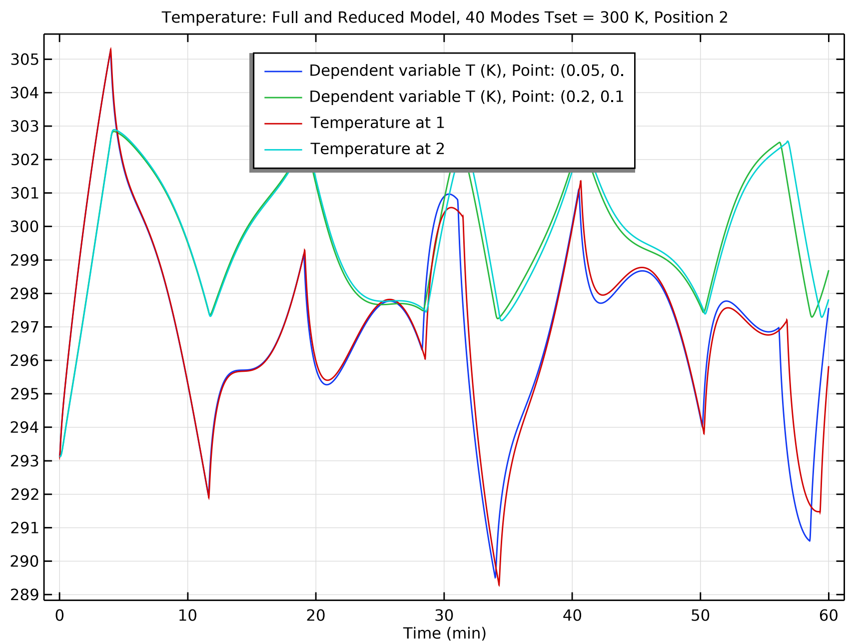


Figure 3: Comparing the reduced model outputs with the temperatures from the finite-element model with the thermostat shows good agreement when using 40 eigenmodes, a setpoint of 300 K, and placing the thermostat at position 2.

Application Library path: `COMSOL_Multiphysics/Multiphysics/thermal_controller_rom`

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 **2D**.

2 In the **Select Physics** tree, select **Mathematics** > **Classical PDEs** > **Heat Equation (hteq)**.

3 Click **Add**.

4 In the **Dependent variable (K)** text field, type `T`.

5 Click **Done**.

GEOMETRY 1

Rectangle 1 (r1)

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

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

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

4 In the **Height** text field, type `0.2`.

Square 1 (sq1)

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

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

3 In the **Side length** text field, type `0.04`.

4 Locate the **Position** section. In the **x** text field, type `0.1`.

5 In the **y** text field, type `0.1`.

6 From the **Base** list, choose **Center**.

7 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

Point 1 (pt1)

Add two points to represent the candidate thermostat positions 1 and 2.

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

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

3 In the **x** text field, type `0.05`.

4 In the **y** text field, type `0.1`.

5 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

Point 2 (pt2)

1 Right-click **Point 1 (pt1)** and choose **Duplicate**.

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

3 In the **x** text field, type `0.2`.

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

Add a 2D component to set up the geometry and use the Heat Transfer in Solids interface in a time-dependent study.

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** > **Copper**.

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.

COMPONENT 1: PHYSICS

In the **Settings** window for **Component**, type `Component 1: Physics` in the **Label** text field.

GLOBAL DEFINITIONS

Add model parameters for the temperature setpoint, thermal conductivity, density, and heat capacity.

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
Tset	293.15[K]	293.15 K	Setpoint temperature
tmax	1[h]	3600 s	Simulation time
outputStep	0.1[min]	6 s	Time interval to output
tstep	0.5[s]	0.5 s	Time step
heatSrc	7.5e6[W/(m^3)]	7.5E6 W/m³	Heat source
cpl	(54/1e-2)[W/(m^2*K)]	5400 W/(m²·K)	Coupling constant
ToutAvg	(293.15[K]-5[K])	288.15 K	Average outside temperature
ToutAmp	10[K]	10 K	Outside temperature variation amplitude
ToutPeriod	20[min]	1200 s	Outside temperature variation period

Define the inputs of the reduced model separately.

ROOT

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

2 In the **Show More Options** dialog, in the tree, select the checkbox for the node **Study** > **Reduced-Order Modeling**.

3 Click **OK**.

GLOBAL DEFINITIONS

Global Reduced-Model Inputs 1

1 In the **Physics** toolbar, click **Reduced-Order Modeling** and choose **Global Reduced-Model Inputs**.

2 In the **Settings** window for **Global Reduced-Model Inputs**, locate the **Reduced-Model Inputs** section.

3 Define the following inputs to use for parameterizing the model:

Control name	Expression
Tout	ToutAvg +(ToutAmp*sin(2*pi*t/ToutPeriod))
HeatState	1

HEAT EQUATION (HTEQ)

Heat Equation 1

1. In the **Model Builder** window, under **Component 1: Physics (comp1)** > **Heat Equation (hteq)** click **Heat Equation 1**.
2. In the **Settings** window for **Heat Equation**, locate the **Diffusion Coefficient** section.
3. In the c text field, type `mat1.def.k_iso`.
4. Locate the **Source Term** section. In the f text field, type `0`.
5. Locate the **Damping or Mass Coefficient** section. In the d_a text field, type `mat1.def.rho*mat1.def.Cp`.

Initial Values 1

1. In the **Model Builder** window, click **Initial Values 1**.
2. In the **Settings** window for **Initial Values**, locate the **Initial Values** section.
3. In the T text field, type `293.15[K]`.

Source 1

1. In the **Physics** toolbar, click **Domains** and choose **Source**.
2. Select Domain 2 only.
3. In the **Settings** window for **Source**, locate the **Source Term** section.
4. In the f text field, type `heatSrc*HeatState`.
5. Locate the **Domain Selection** section. From the **Selection** list, choose **Square 1**.

Flux/Source 1

1. In the **Physics** toolbar, click **Boundaries** and choose **Flux/Source**.
2. Select Boundary 1 only.
3. In the **Settings** window for **Flux/Source**, locate the **Boundary Flux/Source** section.
4. In the g text field, type `cpl*(Tout-T)`.

DEFINITIONS

Introduce point probes for the finite-element model outputs in the positions 1 and 2.

Thermostat position 1: Full Model

1. In the **Definitions** toolbar, click **Probes** and choose **Point Probe**.
2. In the **Settings** window for **Point Probe**, locate the **Source Selection** section.
3. From the **Selection** list, choose **Point 1**.
4. In the **Label** text field, type `Thermostat position 1: Full Model`.

5 In the **Variable name** text field, type `ppb1`.

Thermostat position 2: Full Model

1 Right-click **Thermostat position 1: Full Model** and choose **Duplicate**.

2 In the **Settings** window for **Point Probe**, type `Thermostat position 2: Full Model` in the **Label** text field.

3 In the **Variable name** text field, type `ppb2`.

4 Locate the **Source Selection** section. From the **Selection** list, choose **Point 2**.

Thermostat position 1: Full Model (ppb1), Thermostat position 2: Full Model (ppb2)

1 In the **Model Builder** window, under **Component 1: Physics (comp1)** > **Definitions**, Ctrl-click to select **Thermostat position 1: Full Model (ppb1)** and **Thermostat position 2: Full Model (ppb2)**.

2 Right-click and choose **Group**.

Probes for Full Model

In the **Settings** window for **Group**, type `Probes for Full Model` in the **Label** text field.

ROOT

The thermostat can be modeled by a discrete on/off state that can be described using Events. Add a 0D component to set up appropriate events.

ADD COMPONENT

In the **Model Builder** window, right-click the root node and choose **Add Component** > **0D**.

COMPONENT 2: CONTROLLER EVENTS

In the **Settings** window for **Component**, type `Component 2: Controller Events` in the **Label** text field.

Add a variable that defines the source of the measured temperature from the full model.

DEFINITIONS (COMP2)

Variables 1: Temperature at Position 1 or 2 Using the Full Model

1 In the **Model Builder** window, under **Component 2: Controller Events (comp2)** right-click **Definitions** and choose **Variables**.

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

3 In the table, enter the following settings:

Name	Expression	Unit	Description
`Tmeasured`	`if(Tset < 294[K], comp1.ppb1, comp1.ppb2)`	K	

4 In the **Label** text field, type `Variables 1: Temperature at Position 1 or 2 Using the Full Model`.

This assigns `Tmeasured` the value of the FEM probe variable corresponding to the measured temperature at Position 1.

Set up an eigenvalue study to compute six bases to be used for model reduction.

ADD STUDY

1. In the **Home** toolbar, click **Add Study** to open the **Add Study** window.
2. Go to the **Add Study** window.
3. Find the **Studies** subsection. In the **Select Study** tree, select **Empty Study**.
4. Click the **Add Study** button in the window toolbar.
5. In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 1: MODEL REDUCTION WITH 6 MODES

1. In the **Settings** window for **Study**, type `Study 1: Model Reduction with 6 Modes` in the **Label** text field.
2. Locate the **Study Settings** section. Clear the **Generate default plots** checkbox.
3. Clear the **Generate convergence plots** checkbox.

Step 1: Eigenvalue

1. In the **Study** toolbar, click **More Study Steps** and choose **Eigenfrequency** > **Eigenvalue**.
2. In the **Settings** window for **Eigenvalue**, locate the **Study Settings** section.
3. Select the **Desired number of eigenvalues** checkbox.
4. Click to expand the **Results While Solving** section. From the **Probes** list, choose **None**.

Add a Model Reduction study step. Configure inputs and outputs using the global inputs and the output probes.

Step 2: Model Reduction

In the **Study** toolbar, click **More Study Extensions** and choose **Model Reduction**.

Time Dependent 1

1 Right-click **Step 2: Model Reduction** and choose **Time Dependent**.

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

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

4 In the **Output times** text field, type `range(0, outputStep, tmax)`.

Step 2: Model Reduction

1 In the **Model Builder** window, click **Step 2: Model Reduction**.

2 In the **Settings** window for **Model Reduction**, locate the **Model Reduction Settings** section.

3 From the **Training study for eigenmodes** list, choose **Study 1: Model Reduction with 6 Modes**.

4 From the **Unreduced model study** list, choose **Study 1: Model Reduction with 6 Modes**.

5 From the **Defined by study step** list, choose **Time Dependent 1**.

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

Variable	Expression	Description
`T1`	`comp1.ppb1`	`Temperature at 1`
`T2`	`comp1.ppb2`	`Temperature at 2`

7 Locate the **Model Control Inputs** section. In the table, set up the training values: change the value of `Tout` to `293.15` and `HeatState` to `1`.

8 Locate the **Model Reduction Settings** section. Clear the **Ensure reconstruction capability** checkbox.

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

ADD PHYSICS

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

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

3 In the tree, select **Mathematics** > **ODE and DAE Interfaces** > **Events (ev)**.

4 Click the **Add to Component 2: Controller Events** button in the window toolbar.

5 In the **Home** toolbar, click **Add Physics** to close the **Add Physics** window.

EVENTS (EV)

Set up a discrete state for the current on/off setting and indicator functions for the temperatures relative to the controller setpoint and deadband. If the temperature is too low, `lowtemp` changes sign and triggers an event to turn the heater on, and if the temperature is too high, `hightemp` changes sign and triggers an event to turn the heater off.

Indicator States 1

1 In the **Events** toolbar, click **Indicator States**.

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

3 In the table, enter the following settings:

Name	g(v,vt,vtt,t)	Initial value (u0)
lowtemp	(Tset-2.5)-Tmeasured	-1
hightemp	Tmeasured-(Tset+2.5)	1

Discrete States 1

1 In the **Events** toolbar, click **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)
relay	if(Tset > 293.15,1,0)

Implicit Event 1

1 In the **Events** toolbar, click **Implicit Event**.

2 In the **Settings** window for **Implicit Event**, locate the **Event Conditions** section.

3 In the **Condition** text field, type `lowtemp > 0`.

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

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

	Expression
relay	1

Implicit Event 2

1 In the **Events** toolbar, click **Implicit Event**.

2 In the **Settings** window for **Implicit Event**, locate the **Event Conditions** section.

3 In the **Condition** text field, type `hightemp > 0`.

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

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

	Expression
relay	0

GLOBAL DEFINITIONS

Assign the modeling state of the thermostat to the heater state.

Global Reduced-Model Inputs 1

1. In the **Model Builder** window, under **Global Definitions** > **Reduced-Order Modeling** click **Global Reduced-Model Inputs 1**.
2. In the **Settings** window for **Global Reduced-Model Inputs**, locate the **Reduced-Model Inputs** section.
3. In the table, enter the following settings:

Control name	**Expression**
HeatState	comp2.relay

STUDY 1: MODEL REDUCTION WITH 6 MODES

The model reduction study retrieves the variables to solve for from the unreduced study settings. Events, in this case, should be deactivated.

Time Dependent 1

1. In the **Model Builder** window, under **Study 1: Model Reduction with 6 Modes** > **Step 2: Model Reduction** click **Time Dependent 1**.
2. In the **Settings** window for **Time Dependent**, locate the **Physics and Variables Selection** section.
3. In the **Solve for** column of the table, clear the checkbox for **Component 2: Controller Events (comp2)**.

ADD STUDY

1. In the **Study** toolbar, click **Add Study** to open the **Add Study** window.
2. Go to the **Add Study** window.
3. Find the **Studies** subsection. In the **Select Study** tree, select **General Studies** > **Time Dependent**.
4. Click the **Add Study** button in the window toolbar.
5. In the **Study** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 2

Step 1: Time Dependent

1 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.
2 From the **Time unit** list, choose **min**.
3 In the **Output times** text field, type `range(0, outputStep, tmax)`.
4 In the **Model Builder** window, click **Study 2**.
5 In the **Settings** window for **Study**, type `Study 2: Controller Full` in the **Label** text field.
6 Locate the **Study Settings** section. Clear the **Generate default plots** checkbox.
7 Clear the **Generate convergence plots** checkbox.

Add a parametric sweep to run the full model with different values of `Tset` and `Tmeasured`.

Parametric Sweep

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

Parameter name	Parameter value list	Parameter unit
Tset (Setpoint temperature)	`293.15[K] 300[K]`	K

5 Locate the **Output While Solving** section. From the **Probes** list, choose **None**.

Solution 3 (sol3)

1 In the **Study** toolbar, click **Show Default Solver**.
2 In the **Model Builder** window, expand the **Solution 3 (sol3)** node.
3 In the **Model Builder** window, under **Study 2: Controller Full** > **Solver Configurations** > **Solution 3 (sol3)** click **Time-Dependent Solver 1**.
4 In the **Settings** window for **Time-Dependent Solver**, click to expand the **Time Stepping** section.
5 From the **Steps taken by solver** list, choose **Manual**.
6 In the **Time step** text field, type `tstep`.

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 2: Controller Full** click **Step 1: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Physics and Variables Selection** section.

3 Select the **Modify model configuration for study step** checkbox.

4 In the tree, select **Global Definitions** > **Reduced-Order Modeling** > **Time Dependent, Modal Reduced-Order Model 1 (rom1)**.

5 Right-click and choose **Disable**.

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

Add global variable probes for the outputs of the Reduced Model with six eigenmodes.

DEFINITIONS (COMP1)

In the **Model Builder** window, under **Component 1: Physics (comp1)** click **Definitions**.

Thermostat position 1: Reduced Model 1

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 `rom1.T1`.

4 In the **Label** text field, type `Thermostat position 1: Reduced Model 1`.

Thermostat position 2: Reduced Model 1

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 `rom1.T2`.

4 In the **Label** text field, type `Thermostat position 2: Reduced Model 1`.

Thermostat position 1: Reduced Model 1 (var1), Thermostat position 2: Reduced Model 1 (var2)

1 In the **Model Builder** window, under **Component 1: Physics (comp1)** > **Definitions**, Ctrl-click to select **Thermostat position 1: Reduced Model 1 (var1)** and **Thermostat position 2: Reduced Model 1 (var2)**.

2 Right-click and choose **Group**.

Probes for Reduced Model 1

In the **Settings** window for **Group**, type `Probes for Reduced Model 1` in the **Label** text field.

Add a new variable and configure events to run with the Reduced Model 1's output temperature at position 1 or 2.

DEFINITIONS (COMP2)

Variables 2: Temperature at Position 1 or 2 Using the Reduced Model 1

1 In the **Model Builder** window, under **Component 2: Controller Events (comp2)** right-click **Definitions** and choose **Variables**.

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

3 In the table, enter the following settings:

Name	Expression	Unit	Description
Tmeasured	if(Tset < 294[K], rom1.T1, rom1.T2)		

4 In the **Label** text field, type `Variables 2: Temperature at Position 1 or 2 Using the Reduced Model 1`.

Disable Variable 2 in the full model.

STUDY 2: CONTROLLER FULL

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 2: Controller Full** click **Step 1: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Physics and Variables Selection** section.

3 In the tree, select **Component 2: Controller Events (comp2)** > **Definitions** > **Variables 2: Temperature at Position 1 or 2 Using the Reduced Model 1**.

4 Right-click and choose **Disable**.

Set up a time-dependent study to perform simulations using the reduced model with six eigenmodes.

ADD STUDY

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

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

3 Find the **Studies** subsection. In the **Select Study** tree, select **Empty Study**.

4 Click the **Add Study** button in the window toolbar.

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

STUDY 3: CONTROLLER ROM WITH 6 MODES

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

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

3 Clear the **Generate convergence plots** checkbox.

4 In the **Label** text field, type `Study 3: Controller ROM with 6 Modes`.

5 In the **Study** toolbar, click **Time Dependent**.

1 In the **Settings** window for **Time Dependent**, locate the **Physics and Variables Selection** section.

2 In the **Solve for** column of the table, under **Component 1: Physics (comp1)**, clear the checkbox for **Heat Equation (hteq)**.

3 Locate the **Study Settings** section. From the **Time unit** list, choose **min**.

4 In the **Output times** text field, type `range(0, outputStep, tmax)`.

5 Locate the **Physics and Variables Selection** section. Select the **Modify model configuration for study step** checkbox.

6 In the tree, select **Component 2: Controller Events (comp2)** > **Definitions** > **Variables 1: Temperature at Position 1 or 2 Using the Full Model**.

7 Right-click and choose **Disable**.

8 Click to expand the **Results While Solving** section. From the **Probes** list, choose **Manual**.

9 In the **Probes** list, choose **Thermostat position 1: Full Model (ppb1)** and **Thermostat position 2: Full Model (ppb2)**.

10 Under **Probes**, click **Delete**.

Add a parametric sweep to run the Reduced Model 1 with different values of `Tset` and `Tmeasured`.

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

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

3 Click **Add**.

4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
Tset (Setpoint temperature)	`293.15[K] 300[K]`	K

5 Locate the **Output While Solving** section. From the **Probes** list, choose **None**.

Solution 7 (sol7)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 7 (sol7)** node.

3 In the **Model Builder** window, under **Study 3: Controller ROM with 6 Modes** > **Solver Configurations** > **Solution 7 (sol7)** click **Time-Dependent Solver 1**.

4 In the **Settings** window for **Time-Dependent Solver**, locate the **Time Stepping** section.

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

6 In the **Time step** text field, type `tstep`.

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

Comparing the reduced model with six eigenmodes and the full model at Position 1 and Position 2. Here, global plots are used but probe table can be used instead if the temporal resolution of the solution is poor.

RESULTS

Temperature: Full and Reduced Model, 6 Modes, Tset = 20°C, Position 1

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

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

3 From the **Position** list, choose **Upper left**.

4 In the **Label** text field, type `Temperature: Full and Reduced Model, 6 Modes, Tset = 20°C, Position 1`.

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

6 In the **Title** text area, type `Temperature: Full and Reduced Model, 6 Modes Tset = 20°C, Position 1`.

7 Locate the **Data** section. From the **Dataset** list, choose **None**.

Temperature: Full Model

1 Right-click **Temperature: Full and Reduced Model, 6 Modes, Tset = 20°C, Position 1** and choose **Global**.

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

3 From the **Dataset** list, choose **Study 2: Controller Full/Parametric Solutions 1 (6) (sol4)**.

4 From the **Parameter selection (Tset)** list, choose **From list**.

5 In the **Parameter values (Tset (K))** list box, select **293.15**.

6 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
`comp1.ppb1`	`K`	`Thermostat position 1: Full Model`
`comp1.ppb2`	`K`	`Thermostat position 2: Full Model`

7 In the **Label** text field, type `Temperature: Full Model`.

8 Locate the **x-Axis Data** section. From the **Axis source data** list, choose **Time**.

9 Click to expand the **Legends** section. Find the **Include** subsection. Clear the **Solution** checkbox.

Temperature: Reduced Model with 6 Modes

1 In the **Model Builder** window, right-click **Temperature: Full and Reduced Model, 6 Modes, Tset = 20°C, Position 1** and choose **Global**.

2 In the **Settings** window for **Global**, type `Temperature: Reduced Model with 6 Modes` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 3: Controller ROM with 6 Modes/Parametric Solutions 2 (11) (sol8)**.

4 From the **Parameter selection (Tset)** list, choose **From list**.

5 In the **Parameter values (Tset (K))** list box, select **293.15**.

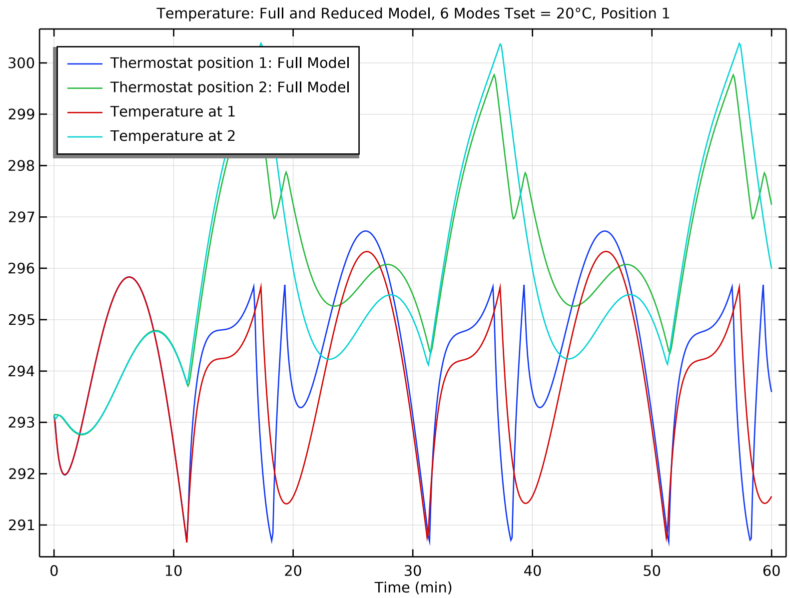
6 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
`rom1.T1`		`Temperature at 1`
`rom1.T2`		`Temperature at 2`

7 Locate the **x-Axis Data** section. From the **Axis source data** list, choose **Time**.

8 Locate the **Legends** section. Find the **Include** subsection. Clear the **Solution** checkbox.

9 In the **Temperature: Full and Reduced Model, 6 Modes, Tset = 20°C, Position 1** toolbar, click  **Plot**.



Comparing the reduced model with six eigenmodes and the full model shows some disagreement.

Temperature: Full and Reduced Model, 6 Modes, Tset = 300 K, Position 2

1 Right-click **Temperature: Full and Reduced Model, 6 Modes, Tset = 20°C, Position 1** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `Temperature: Full and Reduced Model, 6 Modes, Tset = 300 K, Position 2` in the **Label** text field.

Temperature: Full Model

1 In the **Model Builder** window, expand the **Temperature: Full and Reduced Model, 6 Modes, Tset = 300 K, Position 2** node, then click **Temperature: Full Model**.

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

3 In the **Parameter values (Tset (K))** list box, select **300**.

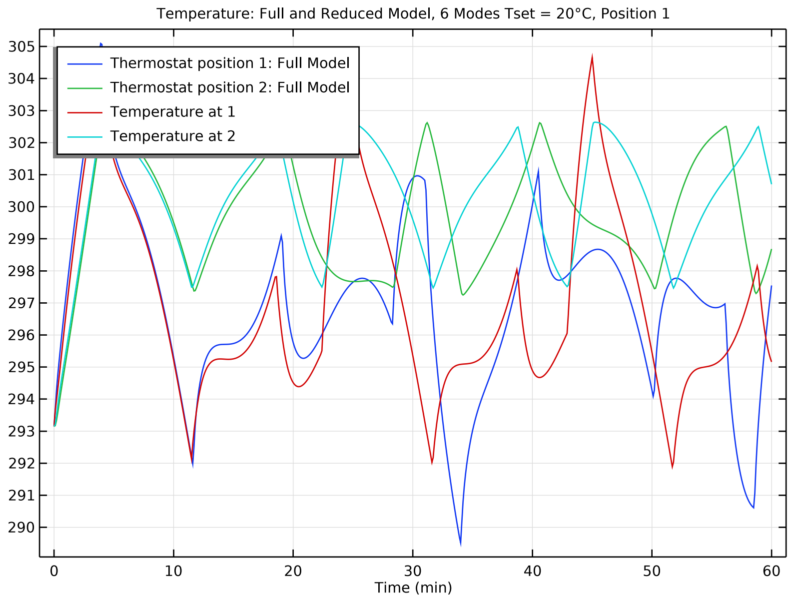
Temperature: Reduced Model with 6 Modes

1 In the **Model Builder** window, click **Temperature: Reduced Model with 6 Modes**.

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

3 In the **Parameter values (Tset (K))** list box, select **300**.

4 In the **Temperature: Full and Reduced Model, 6 Modes, Tset = 300 K, Position 2** toolbar, click **Plot**.



The agreement between the reduced model with six eigenmodes and the full model is poor also at Position 2.

Temperature: Full and Reduced Model, 6 Modes, Tset = 300 K, Position 2

1 In the **Model Builder** window, click **Temperature: Full and Reduced Model, 6 Modes, Tset = 300 K, Position 2**.

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

3 In the **Title** text area, type `Temperature: Full and Reduced Model, 6 Modes Tset = 300K, Position 2`.

ADD STUDY

Increase the number of eigenmodes to produce a more complete basis for the Reduced Model, and recompute the Model Reduction study with the new set of eigenmodes.

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

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

3 Find the **Studies** subsection. In the **Select Study** tree, select **Empty Study**.

4 Click the **Add Study** button in the window toolbar.

5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 4: MODEL REDUCTION WITH 40 MODES

1 In the **Settings** window for **Study**, type `Study 4: Model Reduction with 40 Modes` in the **Label** text field.

2 Locate the **Study Settings** section. Clear the **Generate default plots** checkbox.

3 Clear the **Generate convergence plots** checkbox.

Step 1: Eigenvalue

1 In the **Study** toolbar, click **More Study Steps** and choose **Eigenfrequency** > **Eigenvalue**.

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

3 Select the **Desired number of eigenvalues** checkbox. In the associated text field, type `40`.

Add a Model Reduction study step. Configure inputs and outputs using the global inputs and the output probes.

Step 2: Model Reduction

In the **Study** toolbar, click **More Study Extensions** and choose **Model Reduction**.

Time Dependent 1

1 Right-click **Step 2: Model Reduction** and choose **Time Dependent**.

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

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

4 In the **Output times** text field, type `range(0, outputStep, tmax)`.

Step 2: Model Reduction

1 In the **Model Builder** window, click **Step 2: Model Reduction**.

2 In the **Settings** window for **Model Reduction**, locate the **Model Reduction Settings** section.

3 From the **Training study for eigenmodes** list, choose **Study 4: Model Reduction with 40 Modes**.

4 From the **Unreduced model study** list, choose **Study 4: Model Reduction with 40 Modes**.

5 From the **Defined by study step** list, choose **Time Dependent 1**.

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

Variable	Expression	Description
T1	comp1.ppb1	Temperature at 1
T2	comp1.ppb2	Temperature at 2

7 Locate the **Model Control Inputs** section. In the table, set up the training values: change the value of Tout to 293.15 and HeatState to 1.

8 Locate the **Model Reduction Settings** section. Clear the **Ensure reconstruction capability** checkbox.

Step 1: Eigenvalue

Disable variables and deactivate events when building the ROM.

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

2 In the **Settings** window for **Eigenvalue**, locate the **Physics and Variables Selection** section.

3 Select the **Modify model configuration for study step** checkbox.

4 In the tree, select **Global Definitions** > **Reduced-Order Modeling** > **Time Dependent, Modal Reduced-Order Model 1 (rom1)**.

5 Right-click and choose **Disable**.

6 In the tree, select **Component 2: Controller Events (comp2)** > **Definitions** > **Variables 1: Temperature at Position 1 or 2 Using the Full Model** and **Component 2: Controller Events (comp2)** > **Definitions** > **Variables 2: Temperature at Position 1 or 2 Using the Reduced Model 1**.

7 Right-click and choose **Disable**.

8 Locate the **Results While Solving** section. From the **Probes** list, choose **None**.

Time Dependent 1

1 In the **Model Builder** window, under **Study 4: Model Reduction with 40 Modes** > **Step 2: Model Reduction** click **Time Dependent 1**.

2 In the **Settings** window for **Time Dependent**, locate the **Physics and Variables Selection** section.

3 Select the **Modify model configuration for study step** checkbox.

4 In the tree, select **Global Definitions** > **Reduced-Order Modeling** > **Time Dependent, Modal Reduced-Order Model 1 (rom1)**.

5 Right-click and choose **Disable**.

6 In the tree, select **Component 2: Controller Events (comp2)**.

7 Right-click and choose **Disable in Solvers**.

8 In the tree, select **Component 2: Controller Events (comp2)** > **Definitions** > **Variables 1: Temperature at Position 1 or 2 Using the Full Model** and **Component 2: Controller Events (comp2)** > **Definitions** > **Variables 2: Temperature at Position 1 or 2 Using the Reduced Model 1**.

9 Right-click and choose **Disable**.

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

GLOBAL DEFINITIONS

Time Dependent, Modal Reduced-Order Model 1: 6 Modes

1 In the **Model Builder** window, under **Global Definitions** > **Reduced-Order Modeling** click **Time Dependent, Modal Reduced-Order Model 1 (rom1)**.

2 In the **Settings** window for **Time Dependent, Modal Reduced-Order Model**, type `Time Dependent, Modal Reduced-Order Model 1: 6 Modes` in the **Label** text field.

Time Dependent, Modal Reduced-Order Model 2: 40 Modes

1 In the **Model Builder** window, under **Global Definitions** > **Reduced-Order Modeling** click **Time Dependent, Modal Reduced-Order Model 2 (rom2)**.

2 In the **Settings** window for **Time Dependent, Modal Reduced-Order Model**, type `Time Dependent, Modal Reduced-Order Model 2: 40 Modes` in the **Label** text field.

Add global variable probes for the outputs of the Reduced Model with 40 eigenmodes.

DEFINITIONS (COMP1)

In the **Model Builder** window, under **Component 1: Physics (comp1)** click **Definitions**.

Thermostat Position 1: Reduced Model 2

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

2 In the **Settings** window for **Global Variable Probe**, type `Thermostat Position 1: Reduced Model 2` in the **Label** text field.

3 Locate the **Expression** section. In the **Expression** text field, type `rom2.T1`.

Thermostat Position 2: Reduced Model 2

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

2 In the **Settings** window for **Global Variable Probe**, type `Thermostat Position 2: Reduced Model 2` in the **Label** text field.

3 Locate the **Expression** section. In the **Expression** text field, type `rom2.T2`.

Thermostat Position 1: Reduced Model 2 (var3), Thermostat Position 2: Reduced Model 2 (var4)

1 In the **Model Builder** window, under **Component 1: Physics (comp1)** > **Definitions**, Ctrl-click to select **Thermostat Position 1: Reduced Model 2 (var3)** and **Thermostat Position 2: Reduced Model 2 (var4)**.

2 Right-click and choose **Group**.

Probes for Reduced Model 2

In the **Settings** window for **Group**, type `Probes for Reduced Model 2` in the **Label** text field.

Add a new variable and configure events to run with the Reduced Model 2's output temperature at position 1 or 2.

DEFINITIONS (COMP2)

Variables 3: Temperature at Position 1 or 2 Using the Reduced Model 2

1 In the **Model Builder** window, under **Component 2: Controller Events (comp2)** right-click **Definitions** and choose **Variables**.

2 In the **Settings** window for **Variables**, type `Variables 3: Temperature at Position 1 or 2 Using the Reduced Model 2` in the **Label** text field.

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

Name	Expression	Unit	Description
`Tmeasured`	`if(Tset < 294[K], rom2.T1, rom2.T2)`		

STUDY 1: MODEL REDUCTION WITH 6 MODES

Modify the settings for the existing studies to match current state.

Step 1: Eigenvalue

1 In the **Model Builder** window, under **Study 1: Model Reduction with 6 Modes** click **Step 1: Eigenvalue**.

2 In the **Settings** window for **Eigenvalue**, locate the **Physics and Variables Selection** section.

3 Select the **Modify model configuration for study step** checkbox.

4 In the tree, select **Component 2: Controller Events (comp2)** > **Definitions** > **Variables 1: Temperature at Position 1 or 2 Using the Full Model**, **Component 2: Controller Events (comp2)** > **Definitions** > **Variables 2: Temperature at Position 1 or 2 Using the Reduced Model 1**, and

Component 2: Controller Events (comp2) > **Definitions** >
Variables 3: Temperature at Position 1 or 2 Using the Reduced Model 2.

5 Right-click and choose **Disable**.

6 In the tree, select **Global Definitions** > **Reduced-Order Modeling** > **Time Dependent, Modal Reduced-Order Model 1: 6 Modes (rom1)** and **Global Definitions** > **Reduced-Order Modeling** > **Time Dependent, Modal Reduced-Order Model 2: 40 Modes (rom2)**.

7 Right-click and choose **Disable**.

Time Dependent 1

1 In the **Model Builder** window, under **Study 1: Model Reduction with 6 Modes** > **Step 2: Model Reduction** click **Time Dependent 1**.

2 In the **Settings** window for **Time Dependent**, locate the **Physics and Variables Selection** section.

3 Select the **Modify model configuration for study step** checkbox.

4 In the tree, select **Component 2: Controller Events (comp2)** > **Definitions** >
Variables 1: Temperature at Position 1 or 2 Using the Full Model,
Component 2: Controller Events (comp2) > **Definitions** >
Variables 2: Temperature at Position 1 or 2 Using the Reduced Model 1, and
Component 2: Controller Events (comp2) > **Definitions** >
Variables 3: Temperature at Position 1 or 2 Using the Reduced Model 2.

5 Right-click and choose **Disable**.

6 In the tree, select **Global Definitions** > **Reduced-Order Modeling** > **Time Dependent, Modal Reduced-Order Model 1: 6 Modes (rom1)**, **Global Definitions** > **Reduced-Order Modeling** > **Time Dependent, Modal Reduced-Order Model 2: 40 Modes (rom2)**,
Component 2: Controller Events (comp2) > **Definitions** >
Variables 1: Temperature at Position 1 or 2 Using the Full Model,
Component 2: Controller Events (comp2) > **Definitions** >
Variables 2: Temperature at Position 1 or 2 Using the Reduced Model 1, and
Component 2: Controller Events (comp2) > **Definitions** >
Variables 3: Temperature at Position 1 or 2 Using the Reduced Model 2.

7 Right-click and choose **Disable**.

STUDY 2: CONTROLLER FULL

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 2: Controller Full** click **Step 1: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Physics and Variables Selection** section.

3 In the tree, select **Global Definitions** > **Reduced-Order Modeling** > **Time Dependent, Modal Reduced-Order Model 2: 40 Modes (rom2)**.

4 Right-click and choose **Disable**.

5 In the tree, select **Global Definitions** > **Reduced-Order Modeling** > **Time Dependent, Modal Reduced-Order Model 2: 40 Modes (rom2)** and **Component 2: Controller Events (comp2)** > **Definitions** > **Variables 3: Temperature at Position 1 or 2 Using the Reduced Model 2**.

6 Right-click and choose **Disable**.

7 Locate the **Results While Solving** section. From the **Probes** list, choose **Manual**.

8 In the **Probes** list, choose **Thermostat position 1: Reduced Model 1 (var1)**, **Thermostat position 2: Reduced Model 1 (var2)**, **Thermostat Position 1: Reduced Model 2 (var3)**, and **Thermostat Position 2: Reduced Model 2 (var4)**.

9 Under **Probes**, click **Delete**.

STUDY 3: CONTROLLER ROM WITH 6 MODES

1 In the **Model Builder** window, under **Study 3: Controller ROM with 6 Modes** click **Step 1: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Physics and Variables Selection** section.

3 In the tree, select **Global Definitions** > **Reduced-Order Modeling** > **Time Dependent, Modal Reduced-Order Model 2: 40 Modes (rom2)**.

4 Right-click and choose **Disable**.

5 In the tree, select **Component 2: Controller Events (comp2)** > **Definitions** > **Variables 3: Temperature at Position 1 or 2 Using the Reduced Model 2**.

6 Right-click and choose **Disable**.

7 Locate the **Results While Solving** section. In the **Probes** list, choose **Thermostat Position 1: Reduced Model 2 (var3)** and **Thermostat Position 2: Reduced Model 2 (var4)**.

8 Under **Probes**, click **Delete**.

STUDY 4: MODEL REDUCTION WITH 40 MODES

Step 1: Eigenvalue

1 In the **Model Builder** window, under **Study 4: Model Reduction with 40 Modes** click **Step 1: Eigenvalue**.

2 In the **Settings** window for **Eigenvalue**, locate the **Physics and Variables Selection** section.

3 In the tree, select **Global Definitions** > **Reduced-Order Modeling** > **Time Dependent, Modal Reduced-Order Model 1: 6 Modes (rom1)** and **Global Definitions** > **Reduced-Order Modeling** > **Time Dependent, Modal Reduced-Order Model 2: 40 Modes (rom2)**.

4 Right-click and choose **Disable**.

5 In the tree, select **Component 2: Controller Events (comp2)** > **Definitions** > **Variables 3: Temperature at Position 1 or 2 Using the Reduced Model 2**.

6 Right-click and choose **Disable**.

Time Dependent 1

1 In the **Model Builder** window, under **Study 4: Model Reduction with 40 Modes** > **Step 2: Model Reduction** click **Time Dependent 1**.

2 In the **Settings** window for **Time Dependent**, locate the **Physics and Variables Selection** section.

3 In the tree, select **Global Definitions** > **Reduced-Order Modeling** > **Time Dependent, Modal Reduced-Order Model 1: 6 Modes (rom1)**, **Global Definitions** > **Reduced-Order Modeling** > **Time Dependent, Modal Reduced-Order Model 2: 40 Modes (rom2)**, **Component 2: Controller Events (comp2)** > **Definitions** > **Variables 1: Temperature at Position 1 or 2 Using the Full Model**, **Component 2: Controller Events (comp2)** > **Definitions** > **Variables 2: Temperature at Position 1 or 2 Using the Reduced Model 1**, and **Component 2: Controller Events (comp2)** > **Definitions** > **Variables 3: Temperature at Position 1 or 2 Using the Reduced Model 2**.

4 Right-click and choose **Disable**.

Set up a time-dependent study to perform simulations using the reduced model with 40 eigenmodes.

ADD STUDY

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

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

3 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies** > **Time Dependent**.

4 Click the **Add Study** button in the window toolbar.

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

STUDY 5: CONTROLLER ROM WITH 40 MODES

1 In the **Settings** window for **Study**, type `Study 5: Controller ROM with 40 Modes` in the **Label** text field.

2 Locate the **Study Settings** section. Clear the **Generate default plots** checkbox.

3 Clear the **Generate convergence plots** checkbox.

Step 1: Time Dependent

Disable variables and deactivate events when build ROM.

1 In the **Model Builder** window, under **Study 5: Controller ROM with 40 Modes** 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 **min**.

4 In the **Output times** text field, type `range(0, outputStep, tmax)`.

5 Locate the **Physics and Variables Selection** section. Select the **Modify model configuration for study step** checkbox.

6 In the tree, select **Global Definitions** > **Reduced-Order Modeling** > **Time Dependent, Modal Reduced-Order Model 1: 6 Modes (rom1)**.

7 Right-click and choose **Disable**.

8 In the tree, select **Component 1: Physics (comp1)** > **Heat Equation (hteq)**.

9 Right-click and choose **Disable in Solvers**.

10 In the tree, select **Component 2: Controller Events (comp2)** > **Definitions** > **Variables 1: Temperature at Position 1 or 2 Using the Full Model** and **Component 2: Controller Events (comp2)** > **Definitions** > **Variables 2: Temperature at Position 1 or 2 Using the Reduced Model 1**.

11 Right-click and choose **Disable**.

12 Locate the **Results While Solving** section. From the **Probes** list, choose **Manual**.

13 In the **Probes** list, choose **Thermostat position 1: Full Model (ppb1)**, **Thermostat position 2: Full Model (ppb2)**, **Thermostat position 1: Reduced Model 1 (var1)**, and **Thermostat position 2: Reduced Model 1 (var2)**.

14 Under **Probes**, click **Delete**.

Add a parametric sweep to run the Reduced Model 2 with different values of `Tset` and `Tmeasured`.

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

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

3 Click **Add**.

4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
Tset (Setpoint temperature)	293.15[K] 300[K]	K

5 Locate the **Output While Solving** section. From the **Probes** list, choose **None**.

Solution 13 (sol13)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 13 (sol13)** node.

3 In the **Model Builder** window, under **Study 5: Controller ROM with 40 Modes** > **Solver Configurations** > **Solution 13 (sol13)** click **Time-Dependent Solver 1**.

4 In the **Settings** window for **Time-Dependent Solver**, locate the **Time Stepping** section.

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

6 In the **Time step** text field, type `tstep`.

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

RESULTS

Thermostat position 1: Full Model

Compare the reduced model with 40 eigenmodes and the full model at Position 1 and Position 2.

RESULTS

Temperature: Full and Reduced Model, 40 Modes, Tset = 20°C, Position 1

1 In the **Model Builder** window, expand the **Study 5: Controller ROM with 40 Modes** > **Solver Configurations** > **Parametric Solutions 3 (sol14)** node.

2 Right-click **Temperature: Full and Reduced Model, 6 Modes, Tset = 20°C, Position 1** and choose **Duplicate**.

3 In the **Settings** window for **1D Plot Group**, type `Temperature: Full and Reduced Model, 40 Modes, Tset = 20°C, Position 1` in the **Label** text field.

4 Locate the **Title** section. In the **Title** text area, type `Temperature: Full and Reduced Model, 40 Modes, Tset = 20°C, Position 1`.

Temperature: Reduced Model with 40 Modes

1 In the **Model Builder** window, expand the **Temperature: Full and Reduced Model, 40 Modes, Tset = 20°C, Position 1** node, then click **Temperature: Reduced Model with 6 Modes**.

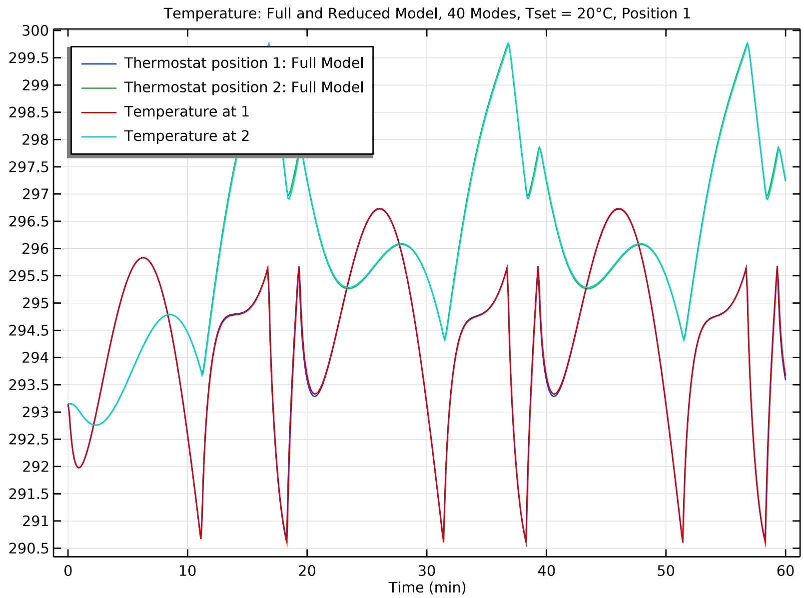
2 In the **Settings** window for **Global**, type `Temperature: Reduced Model with 40 Modes` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 5: Controller ROM with 40 Modes/Parametric Solutions 3 (21) (sol14)**.

4 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
rom2.T1		Temperature at 1
rom2.T2		Temperature at 2

5 In the **Temperature: Full and Reduced Model, 40 Modes, Tset = 20°C, Position 1** toolbar, click **Plot**.



Comparing the reduced model with 40 eigenmodes and the full model shows better agreement.

Temperature: Full and Reduced Model, 40 Modes, Tset = 300 K, Position 2

1 In the **Model Builder** window, right-click **Temperature: Full and Reduced Model, 6 Modes, Tset = 300 K, Position 2** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `Temperature: Full and Reduced Model, 40 Modes, Tset = 300 K, Position 2` in the **Label** text field.

3 Locate the **Title** section. In the **Title** text area, type `Temperature: Full and Reduced Model, 40 Modes, Tset = 300 K, Position 2`.

4 Locate the **Legend** section. From the **Position** list, choose **Upper middle**.

Temperature: Reduced Model with 40 Modes

1 In the **Model Builder** window, expand the **Temperature: Full and Reduced Model, 40 Modes, Tset = 300 K, Position 2** node, then click **Temperature: Reduced Model with 6 Modes**.

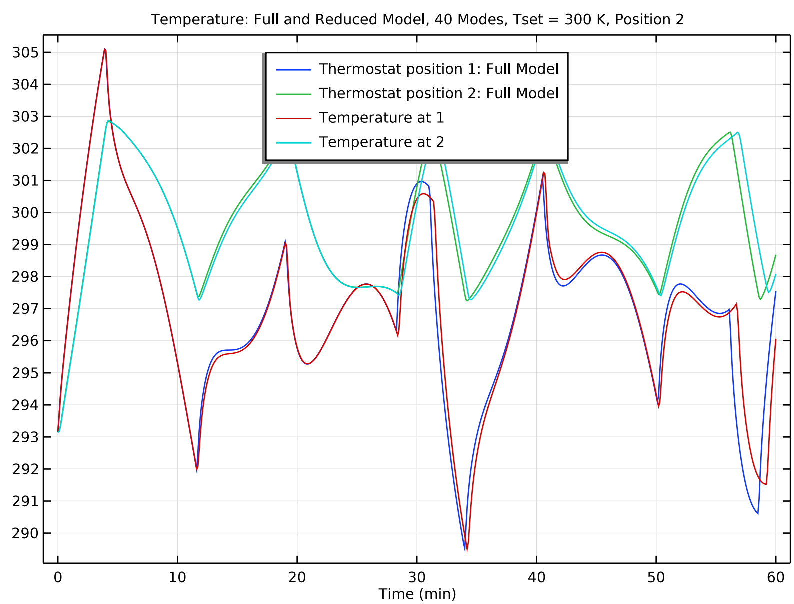
2 In the **Settings** window for **Global**, type `Temperature: Reduced Model with 40 Modes` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 5: Controller ROM with 40 Modes/Parametric Solutions 3 (21) (sol14)**.

4 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
rom2.T1		Temperature at 1
rom2.T2		Temperature at 2

5 In the **Temperature: Full and Reduced Model, 40 Modes, Tset = 300 K, Position 2** toolbar, click **Plot**.



Again, the agreement between the reduced model with 40 eigenmodes and the full model is good.

Create a study for running all the other studies.

ADD STUDY

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

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

3 Find the **Studies** subsection. In the **Select Study** tree, select **Empty Study**.

4 Click the **Add Study** button in the window toolbar.

5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 6: ALL STUDIES

1 In the **Settings** window for **Study**, type `Study 6: All Studies` in the **Label** text field.

2 Locate the **Study Settings** section. Clear the **Generate default plots** checkbox.

3 Clear the **Generate convergence plots** checkbox.

No Study

1 In the **Study** toolbar, click **More Study Extensions** and choose **Study Reference**.

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

3 From the **Study reference** list, choose **Study 1: Model Reduction with 6 Modes**.

4 In the **Study** toolbar, click **More Study Extensions** and choose **Study Reference**.

1 In the **Settings** window for **Study Reference**, locate the **Study Reference** section.

2 From the **Study reference** list, choose **Study 2: Controller Full**.

3 In the **Study** toolbar, click **More Study Extensions** and choose **Study Reference**.

1 In the **Settings** window for **Study Reference**, locate the **Study Reference** section.

2 From the **Study reference** list, choose **Study 3: Controller ROM with 6 Modes**.

3 In the **Study** toolbar, click **More Study Extensions** and choose **Study Reference**.

1 In the **Settings** window for **Study Reference**, locate the **Study Reference** section.

2 From the **Study reference** list, choose **Study 4: Model Reduction with 40 Modes**.

3 In the **Study** toolbar, click **More Study Extensions** and choose **Study Reference**.

1 In the **Settings** window for **Study Reference**, locate the **Study Reference** section.

2 From the **Study reference** list, choose **Study 5: Controller ROM with 40 Modes**.

STUDY 1: MODEL REDUCTION WITH 6 MODES

In the **Model Builder** window, collapse the **Study 1: Model Reduction with 6 Modes** node.

STUDY 2: CONTROLLER FULL

In the **Model Builder** window, collapse the **Study 2: Controller Full** node.

STUDY 3: CONTROLLER ROM WITH 6 MODES

In the **Model Builder** window, collapse the **Study 3: Controller ROM with 6 Modes** node.

STUDY 4: MODEL REDUCTION WITH 40 MODES

In the **Model Builder** window, collapse the **Study 4: Model Reduction with 40 Modes** node.

STUDY 5: CONTROLLER ROM WITH 40 MODES

In the **Model Builder** window, collapse the **Study 5: Controller ROM with 40 Modes** node.

STUDY 6: ALL STUDIES

In the **Model Builder** window, collapse the **Study 6: All Studies** node.