Created in COMSOL Multiphysics 6.1

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.

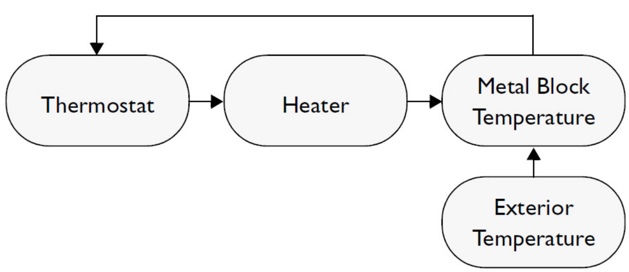


Figure 1: Block diagram for the thermal controller system.

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 $n \cdot (k\nabla T) = (k_G/l_G)(T_{\text{out}} - T)$, 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.

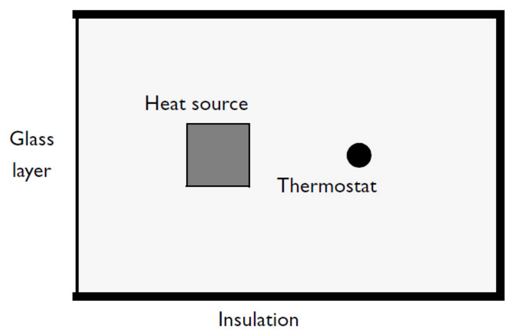


Figure 2: Geometry of the thermal controller system. The figure shows one of the two candidate thermostat positions.

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 30 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.

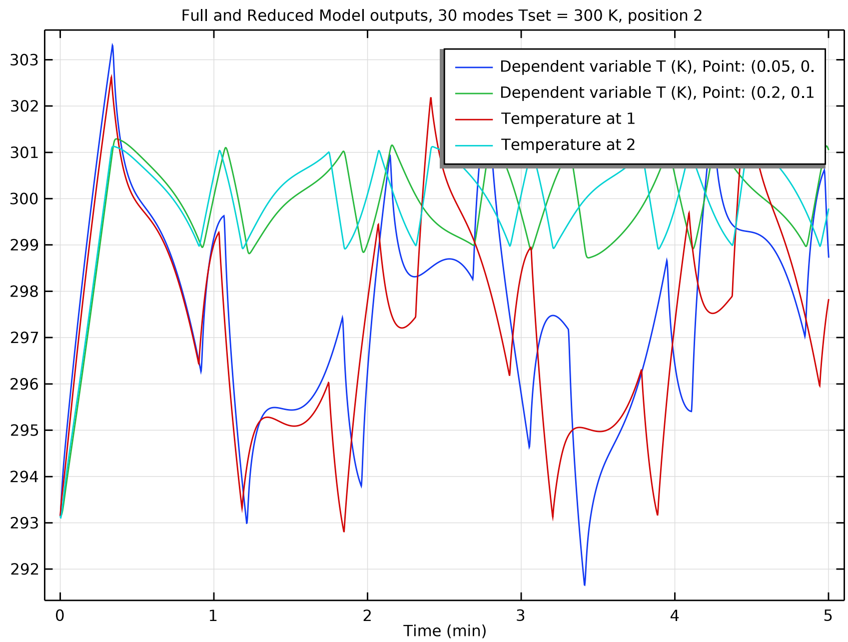


Figure 3: Comparing the reduced model outputs with the temperatures from the FEM model with the thermostat shows good agreement when using 30 eigenmodes, a setpoint of 300 K, and placing the thermostat at position 2.

Application Library path: `COMSOL_Multiphysics/Multiphysics/thermal_controller_rom`

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

NEW

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

ROOT

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

ADD COMPONENT

In the **Home** toolbar, click **Add Component** and choose **2D**.

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**.

Point 1 (pt1)

Add 2 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 `0.05,0.2`.
4. In the **y** text field, type `0.1,0.1`.
5. In the **Geometry** toolbar, click **Build All**.

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>Classical PDEs>Heat Equation (hteq)**.

4 Click **Add to Component 1** in the window toolbar.

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

HEAT EQUATION (HTEQ)

1 In the **Settings** window for **Heat Equation**, click to expand the **Dependent Variables** section.

2 In the **Dependent variable** text field, type `T`.

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
kiso	4.92e3[W/(m*K)]	4920 W/(m·K)	Thermal conductivity
rho	7.82e3[kg/m^3]	7820 kg/m³	Density
Cp	449[J/(kg*K)]	449 J/(kg·K)	Heat capacity

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 box, in the tree, select the check box 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 In the table, enter the following settings:

Control name	Expression
Tout	(293.15[K]-5[K])+(10[K]*sin(2*pi*t/120[s]))
HeatState	1

Parameterize the model using the global definitions.

HEAT EQUATION (HTEQ)

Heat Equation 1

1 In the **Model Builder** window, under **Component 1 (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 kiso.

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 rho*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 7.5e7[W/(m^3)]*HeatState.

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 `(54/1e-3)[W/(m^2*K)]*(Tout-T)`.

DEFINITIONS

Introduce probes for the FEM model outputs in the positions 1 and 2.

Thermostat position 1

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

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

3 In row **Coordinates**, set **x** to `0.05`.

4 In row **Coordinates**, set **y** to `0.1`.

5 In the **Label** text field, type `Thermostat position 1`.

Thermostat position 2

1 Right-click **Thermostat position 1** and choose **Duplicate**.

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

3 Locate the **Point Selection** section. In row **Coordinates**, set **x** to `0.2`.

Temperature 1

1 In the **Model Builder** window, expand the **Component 1 (comp1)>Definitions>Thermostat position 1** node, then click **Point Probe Expression 1 (ppb1)**.

2 In the **Settings** window for **Point Probe Expression**, type `Temperature 1` in the **Label** text field.

Temperature 2

1 In the **Model Builder** window, expand the **Component 1 (comp1)>Definitions>Thermostat position 2** node, then click **Point Probe Expression 1 (ppb2)**.

2 In the **Settings** window for **Point Probe Expression**, type `Temperature 2` 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 (COMP2)

Add the variable that defines the source of the measured temperature.

DEFINITIONS (COMP2)

Variables 1

1 In the **Model Builder** window, under **Component 2 (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`	`comp1.ppb1`		

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

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 **Add to Component 2** 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 Right-click **Component 2 (comp2)>Events (ev)** and choose **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-1)-Tmeasured`	`-1`
`hightemp`	`Tmeasured-(Tset+1)`	`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** check box.

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

Variable	**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** check box.

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

Variable	**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

Set up a time-dependent study to compute the FEM model.

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 **General Studies>Time Dependent**.

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

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

STUDY 1

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(0,0.1,5)`.

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

Solution 1 (sol1)

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

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

3 In the **Model Builder** window, under **Study 1>Solver Configurations>Solution 1 (sol1)** 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 `0.1`.

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

RESULTS

Duplicate the probe table and set an appropriate label for the copy for future reference.

Full model outputs Tset = 20 degrees C, position 1

1. In the **Model Builder** window, expand the **Results>Tables** node.
2. Right-click **Probe Table 1** and choose **Duplicate**.
3. In the **Settings** window for **Table**, type `Full model outputs Tset = 20 degrees C, position 1` in the **Label** text field.

Set up an eigenvalue study to compute a basis to be used for model reduction.

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. Right-click and choose **Add Study**.

STUDY 2

1. In the **Model Builder** window, click **Study 2**.
2. In the **Settings** window for **Study**, locate the **Study Settings** section.
3. Clear the **Generate default plots** check box.
4. Clear the **Generate convergence plots** check box.

Eigenvalue

1. In the **Study** toolbar, click **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** check box.
4. In the **Study** toolbar, click **Compute**.

Set up an empty study and then add a Model Reduction study. Configure inputs and outputs using the global inputs and the output probes.

ADD STUDY

1. Go to the **Add Study** window.
2. Find the **Studies** subsection. In the **Select Study** tree, select **Empty Study**.
3. Click **Add Study** in the window toolbar.

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

STUDY 3

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

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

3 Clear the **Generate convergence plots** check box.

Model Reduction

1 In the **Study** toolbar, click **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 2**.

4 From the **Unreduced model study** list, choose **Study 1**.

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

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** check box.

STUDY 1

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

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 **Physics and Variables Selection** section.

3 In the table, clear the **Solve for** check box for **Events (ev)**.

STUDY 3

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

DEFINITIONS (COMP2)

Configure events to run with the Reduced Model output temperature at position 1.

Variables 1

1 In the **Model Builder** window, under **Component 2 (comp2)>Definitions** click **Variables 1**.

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

3 In the table, change the expression of `Tmeasured` to `rom1.T1`.

DEFINITIONS (COMP1)

Add global variable probes for the outputs of the Reduced Model.

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

Global Variable Probe 1 (var1)

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`.

Global Variable Probe 2 (var2)

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

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

3 In the **Expression** text field, type `rom1.T2`.

Set up a time-dependent study to perform simulations using the Reduced Model.

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 **General Studies> Time Dependent**.

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

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

STUDY 4

Step 1: Time Dependent

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

2 In the table, clear the **Solve for** check box 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(0,0.1,5)`.

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

6 In the **Probes** list, select **Thermostat position 1**.

7 Under **Probes**, click **Delete**.

8 Click **Delete** again to remove **Thermostat position 2** as well.

9 In the **Model Builder** window, click **Study 4**.

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

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

12 Clear the **Generate convergence plots** check box.

Solution 4 (sol4)

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

2 In the **Model Builder** window, expand the **Solution 4 (sol4)** node, then click **Time-Dependent Solver 1**.

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

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

5 In the **Time step** text field, type `0.1`.

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

RESULTS

Reduced Model outputs, 6 modes Tset = 20 degrees C, position 1

1 In the **Model Builder** window, right-click **Probe Table 1** and choose **Duplicate**.

2 In the **Settings** window for **Table**, type `Reduced Model outputs, 6 modes Tset = 20 degrees C, position 1` in the **Label** text field.

Full and Reduced Model outputs, 6 modes Tset = 20 degrees C, position 1

1 In the **Model Builder** window, right-click **Probe Plot Group 2** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `Full and Reduced Model outputs, 6 modes Tset = 20 degrees C, position 1` in the **Label** text field.

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

4 In the **Title** text area, type `Full and Reduced Model outputs, 6 modes Tset = 20 degrees C, position 1`.

Full model output table graph

1. In the **Model Builder** window, expand the **Full and Reduced Model outputs, 6 modes Tset = 20 degrees C, position 1** node, then click **Probe Table Graph 1**.
2. In the **Settings** window for **Table Graph**, type `Full model output table graph` in the **Label** text field.
3. Locate the **Data** section. From the **Table** list, choose **Full model outputs Tset = 20 degrees C, position 1**.

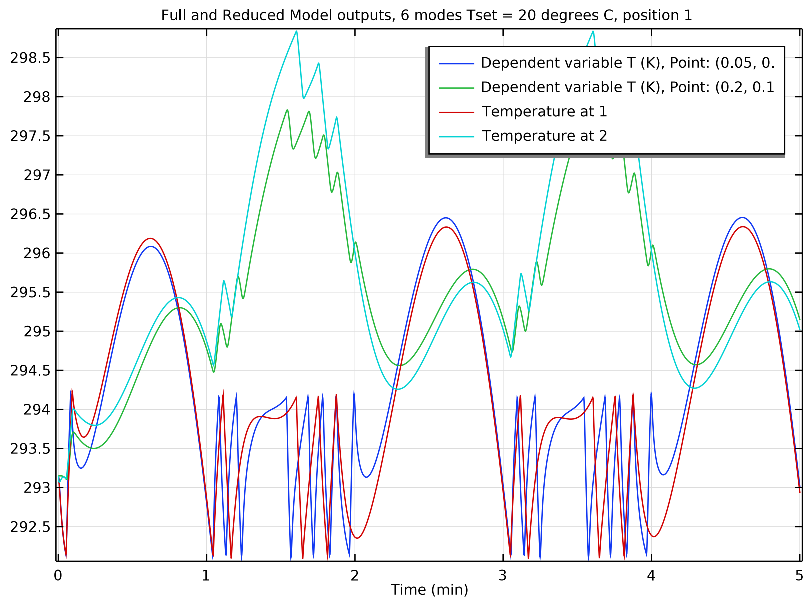
Reduced model output table graph

1. Right-click **Full model output table graph** and choose **Duplicate**.
2. In the **Settings** window for **Table Graph**, type `Reduced model output table graph` in the **Label** text field.
3. Locate the **Data** section. From the **Table** list, choose **Reduced Model outputs, 6 modes Tset = 20 degrees C, position 1**.

Full and Reduced Model outputs, 6 modes Tset = 20 degrees C, position 1

1. In the **Model Builder** window, click **Full and Reduced Model outputs, 6 modes Tset = 20 degrees C, position 1**.

2 In the **Full and Reduced Model outputs, 6 modes Tset = 20 degrees C, position 1** toolbar, click **Plot**.



Comparing the reduced model with 6 eigenmodes and the full model shows some disagreement.

STUDY 2

Increase the number of eigenmodes to produce a more complete basis for the Reduced Model.

Step 1: Eigenvalue

1 In the **Model Builder** window, under **Study 2** click **Step 1: Eigenvalue**.

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

3 In the **Desired number of eigenvalues** text field, type 30.

STUDY 3

Recompute the Model Reduction study with the new set of eigenmodes.

Step 1: Model Reduction

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

STUDY 4

Recompute the Reduced Model dependent study.

Click **Compute**.

RESULTS

Reduced Model outputs, 30 modes Tset = 20 degrees C, position 1

1. In the **Model Builder** window, right-click **Probe Table 1** and choose **Duplicate**.
2. In the **Settings** window for **Table**, type `Reduced Model outputs, 30 modes Tset = 20 degrees C, position 1` in the **Label** text field.

Full and Reduced Model outputs, 30 modes Tset = 20 degrees C, position 1

1. In the **Model Builder** window, right-click **Probe Plot Group 2** and choose **Duplicate**.
2. In the **Settings** window for **1D Plot Group**, type `Full and Reduced Model outputs, 30 modes Tset = 20 degrees C, position 1` in the **Label** text field.
3. Locate the **Title** section. From the **Title type** list, choose **Manual**.
4. In the **Title** text area, type `Full and Reduced Model outputs, 30 modes Tset = 20 degrees C, position 1`.

Full model output table graph

1. In the **Model Builder** window, expand the **Full and Reduced Model outputs, 30 modes Tset = 20 degrees C, position 1** node, then click **Probe Table Graph 1**.
2. In the **Settings** window for **Table Graph**, type `Full model output table graph` in the **Label** text field.
3. Locate the **Data** section. From the **Table** list, choose **Full model outputs Tset = 20 degrees C, position 1**.

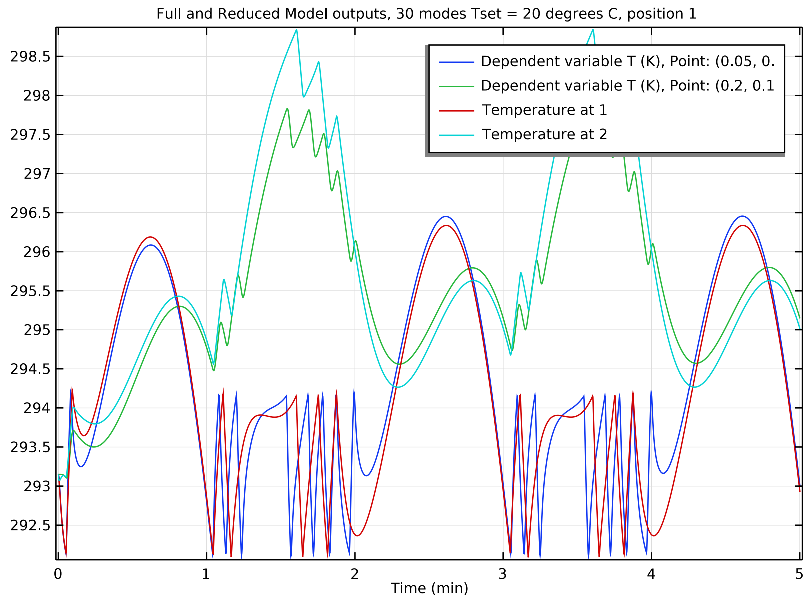
Reduced model output table graph

1. Right-click **Full model output table graph** and choose **Duplicate**.
2. In the **Settings** window for **Table Graph**, type `Reduced model output table graph` in the **Label** text field.
3. Locate the **Data** section. From the **Table** list, choose **Reduced Model outputs, 30 modes Tset = 20 degrees C, position 1**.

Full and Reduced Model outputs, 30 modes Tset = 20 degrees C, position 1

1. In the **Model Builder** window, click **Full and Reduced Model outputs, 30 modes Tset = 20 degrees C, position 1**.

2 In the **Full and Reduced Model outputs, 30 modes Tset = 20 degrees C, position 1** toolbar, click **Plot**.



Comparing the reduced model with 30 eigenmodes and the full model shows better agreement.

Change the temperature setpoint and recompute the Reduced Model dependent study.

GLOBAL DEFINITIONS

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

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

3 In the table, change the expression of `Tset` to `300[K]`.

STUDY 4

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

RESULTS

Reduced Model outputs, 30 modes Tset = 300 K, position 1

1 In the **Model Builder** window, right-click **Probe Table 1** and choose **Duplicate**.

2 In the **Settings** window for **Table**, type `Reduced Model outputs, 30 modes Tset = 300 K, position 1` in the **Label** text field.

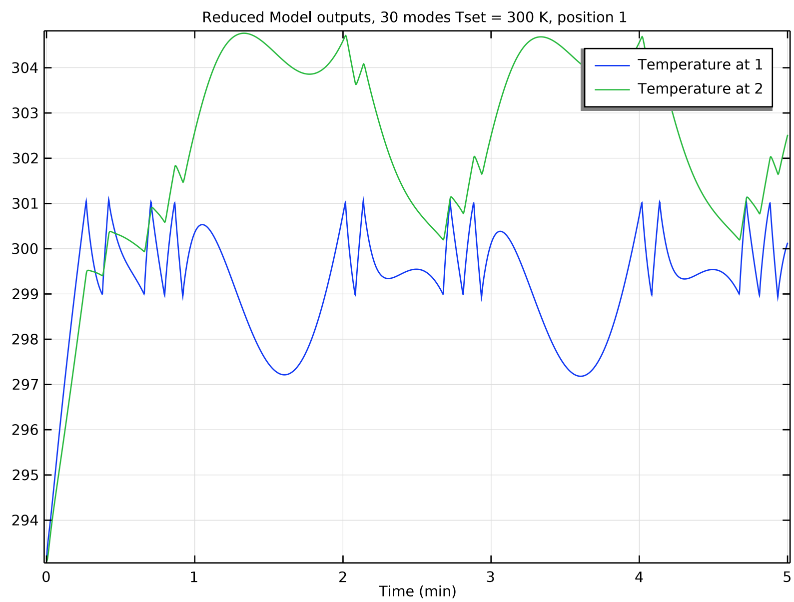
Reduced Model outputs, 30 modes Tset = 300 K, position 1

1 In the **Model Builder** window, right-click **Probe Plot Group 2** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `Reduced Model outputs, 30 modes Tset = 300 K, position 1` in the **Label** text field.

3 Locate the **Title** section. From the **Title type** list, choose **Manual**.

4 In the **Title** text area, type `Reduced Model outputs, 30 modes Tset = 300 K, position 1`.



With the temperature setpoint at 300 K, the heater is active a larger fraction of the time span.

Probe Table Graph 1

1 In the **Model Builder** window, expand the **Reduced Model outputs, 30 modes Tset = 300 K, position 1** node, then click **Probe Table Graph 1**.

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

3 From the **Table** list, choose **Reduced Model outputs, 30 modes Tset = 300 K, position 1**.

Change the thermostat location to position 2 and recompute the Reduced Model dependent study.

DEFINITIONS (COMP2)

Variables 1

1 In the **Model Builder** window, under **Component 2 (comp2)>Definitions** click **Variables 1**.

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

3 In the table, change the expression of `Tmeasured` to `rom1.T2`.

STUDY 4

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

RESULTS

Reduced Model outputs, 30 modes Tset = 300 K, position 2

1 In the **Model Builder** window, right-click **Probe Table 1** and choose **Duplicate**.

2 In the **Settings** window for **Table**, type `Reduced Model outputs, 30 modes Tset = 300 K, position 2` in the **Label** text field.

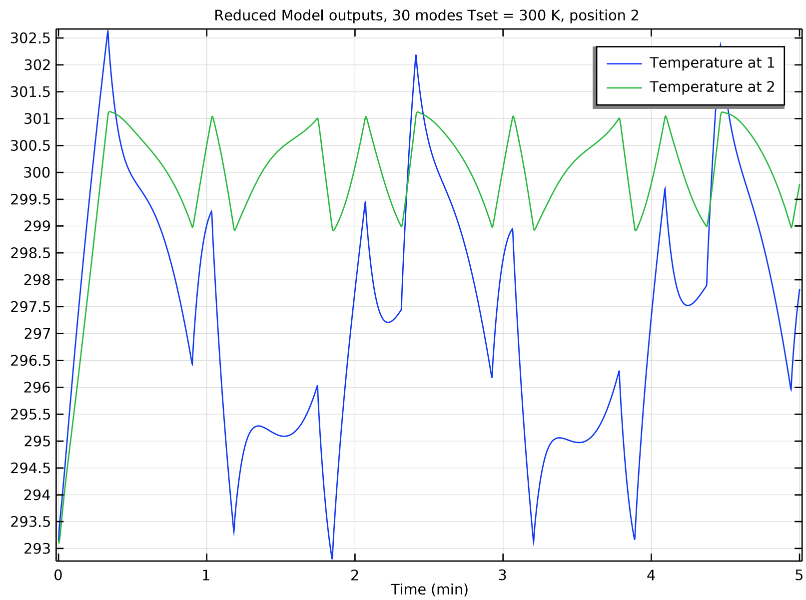
Reduced Model outputs, 30 modes Tset = 300 K, position 2

1 In the **Model Builder** window, right-click **Probe Plot Group 2** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `Reduced Model outputs, 30 modes Tset = 300 K, position 2` in the **Label** text field.

3 Locate the **Title** section. From the **Title type** list, choose **Manual**.

4 In the **Title** text area, type `Reduced Model outputs, 30 modes Tset = 300 K, position 2`.



With the thermostat at position 2, the temperature at 2 rather than that at 1 has an approximate average value of 300 K.

Probe Table Graph 1

1 In the **Model Builder** window, expand the **Reduced Model outputs, 30 modes Tset = 300 K, position 2** node, then click **Probe Table Graph 1**.

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

3 From the **Table** list, choose **Reduced Model outputs, 30 modes Tset = 300 K, position 2**.

Compute the FEM model with the thermostat set at position 2 and perform a comparison.

DEFINITIONS (COMP2)

Variables 1

1 In the **Model Builder** window, under **Component 2 (comp2)>Definitions** click **Variables 1**.

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

3 In the table, change the expression of `Tmeasured` to `comp1.ppb2`.

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 **Physics and Variables Selection** section.

3 In the table, select the **Solve for** check box for **Events (ev)**.

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

5 In the **Probes** list, select **Global Variable Probe 1 (var1)**.

6 Under **Probes**, click **Delete**.

7 In the **Probes** list, select **Global Variable Probe 2 (var2)**.

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

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

RESULTS

Full Model outputs, Tset = 300 K, position 2

1 In the **Model Builder** window, right-click **Probe Table 1** and choose **Duplicate**.

2 In the **Settings** window for **Table**, type `Full Model outputs, Tset = 300 K, position 2` in the **Label** text field.

Full and Reduced Model outputs, 30 modes Tset = 300 K, position 2

1 In the **Model Builder** window, right-click **Probe Plot Group 2** and choose **Duplicate**.

2 In the **Model Builder** window, click **Probe Plot Group 2.1**.

3 In the **Settings** window for **1D Plot Group**, type `Full and Reduced Model outputs, 30 modes Tset = 300 K, position 2` in the **Label** text field.

4 Locate the **Title** section. From the **Title type** list, choose **Manual**.

5 In the **Title** text area, type `Full and Reduced Model outputs, 30 modes Tset = 300 K, position 2`.

Full model output table graph

1 In the **Model Builder** window, under **Results>Full and Reduced Model outputs, 30 modes Tset = 300 K, position 2** click **Probe Table Graph 1**.

2 In the **Settings** window for **Table Graph**, type `Full model output table graph` in the **Label** text field.

3 Locate the **Data** section. From the **Table** list, choose **Full Model outputs, Tset = 300 K, position 2**.

Reduced model output table graph

1 Right-click **Full model output table graph** and choose **Duplicate**.

2 In the **Settings** window for **Table Graph**, type `Reduced model output table graph` in the **Label** text field.

3 Locate the **Data** section. From the **Table** list, choose **Reduced Model outputs, 30 modes Tset = 300 K, position 2**.