



Model created in COMSOL Multiphysics 6.4

Minimizing the Drying Time of a Wood Particle

Introduction

This model is inspired by the [Superheated Steam Drying of a Wood Particle](#) model. In this example, optimization is applied to find the optimal temperature control that minimizes the drying time.

Model Definition

A **Control Function** feature is used to allow a time-varying inlet temperature. The average temperature is constrained to be below 150°C, while the final moisture content should be below 4%.

Results and Discussion

Figure 1 shows the optimized control function.

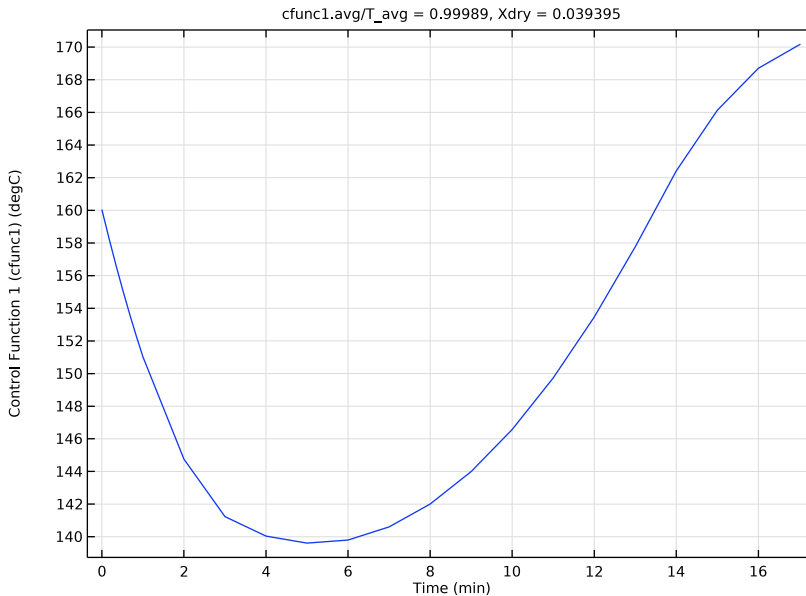


Figure 1: The optimal temperature control is nontrivial in the sense that it has a minimum.

Figure 2 shows the moisture content as a function of time. It can be concluded that the time-varying temperature saves around 10% of the processing time. The assumptions made during the optimization matter for the intermediate times, but the effect is marginal for the final time..

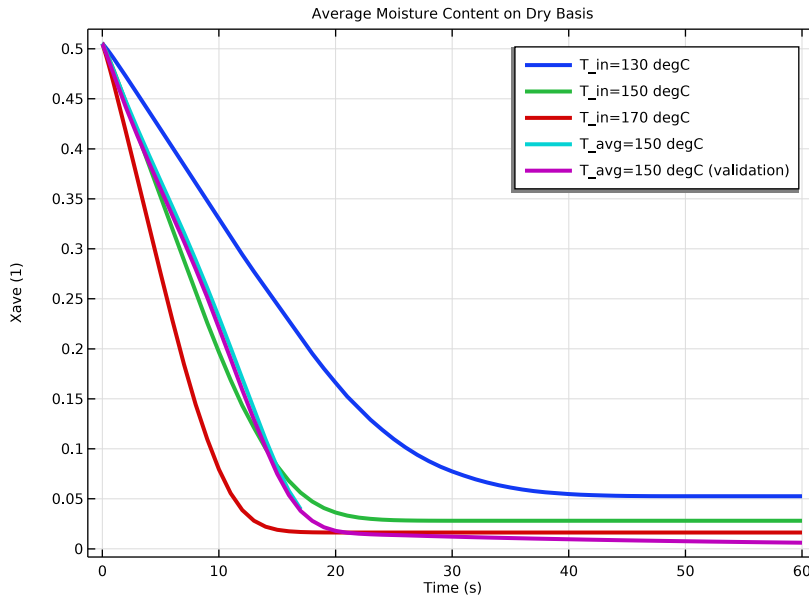



Figure 2: The moisture content for three constant temperatures together with the time-varying temperature with and without accounting for temperature variations in the flow.

Application Library path: Heat_Transfer_Module/Phase_Change/
superheated_steam_drying_optimization

Modeling Instructions

This example starts from an existing model from the Heat Transfer Module Application Library.

APPLICATION LIBRARIES

- 1 From the **File** menu, choose **Application Libraries**.
- 2 In the **Application Libraries** window, select **Heat Transfer Module > Phase Change > superheated_steam_drying** in the tree.
- 3 Click  **Open**.

GLOBAL DEFINITIONS



Parameters I

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

Name	Expression	Value	Description
T_avg	150[degC]	423.15 K	Average temperature
tmax	60[min]	3600 s	Final time
Tmin	130[degC]	403.15 K	Minimum inlet temperature
Tmax	170[degC]	443.15 K	Maximum inlet temperature

DEFINITIONS (COMPI)

Control Function I (cfuncI)

- 1 In the **Model Builder** window, expand the **Component I (compI)** node.
- 2 Right-click **Component I (compI)** > **Definitions** and choose **Control Variables** > **Control Function**.
- 3 In the **Settings** window for **Control Function**, locate the **Input** section.
- 4 From the **Extrapolation** list, choose **Linear**, because the tolerance of the bisection associated with the stop condition might cause the argument to be marginally outside the bounds.
- 5 Locate the **Output** section. In the f_{\min} text field, type Tmin.
- 6 In the f_{\max} text field, type Tmax.
- 7 In the c_0 text field, type $0.5 \cdot (T_{\max} + T_{\min})$.
- 8 Locate the **Control Variable Discretization** section. From the **Control type** list, choose **Piecewise Bernstein polynomial**.
- 9 Locate the **Units** section. Click  **Select Input Quantity**.
- 10 In the **Physical Quantity** dialog, select **General** > **Dimensionless (1)** in the tree.
- 11 Click **OK**.
- 12 In the **Settings** window for **Control Function**, locate the **Units** section.
- 13 Click  **Select Output Quantity**.
- 14 In the **Physical Quantity** dialog, select **General** > **Temperature (K)** in the tree.
- 15 Click **OK**.

SHARED PROPERTIES

Ambient Properties I (ampri)

- 1 In the **Model Builder** window, expand the **Component I (comp1) > Definitions > Shared Properties** node, then click **Ambient Properties I (ampri)**.
- 2 In the **Settings** window for **Ambient Properties**, locate the **Ambient Conditions** section.
- 3 In the T_{amb} text field, type `cfunc1(t/tmax)`.
- 4 In the ϕ_{amb} text field, type `mt.pA/mt.fpsat(cfunc1(t/tmax))`.
Using `cfunc1(t/tmax)` instead of `cfunc1(t)` ensures that the entire range of the **Control Function** is utilized.

LAMINAR FLOW (SPF)

- 1 In the **Model Builder** window, under **Component I (comp1)** click **Laminar Flow (spf)**.
- 2 In the **Settings** window for **Laminar Flow**, locate the **Physical Model** section.
- 3 From the **Compressibility** list, choose **Incompressible flow**.

HEAT TRANSFER IN MOIST AIR (HT)


- 1 In the **Model Builder** window, under **Component I (comp1)** click **Heat Transfer in Moist Air (ht)**.
- 2 In the **Settings** window for **Heat Transfer in Moist Air**, locate the **Physical Model** section.
- 3 In the T_{ref} text field, type `T_avg`.


STUDY 1: INITIAL CONTROL

- 1 In the **Model Builder** window, click **Study 1**.
- 2 In the **Settings** window for **Study**, type `Study 1: Initial Control` in the **Label** text field.

Lets neglect the effect of the temperatures variations on the flow by using a stationary flow in the analysis for the heat transfer and moisture transport.


ADD STUDY

- 1 In the **Home** toolbar, click  **Windows** and choose **Add Study**.
- 2 Go to the **Add Study** window.
- 3 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies > Stationary**.
- 4 Click the **Add Study** button in the window toolbar.
- 5 In the **Select Study** tree, select **Empty Study**.

- 6 Click the **Add Study** button in the window toolbar twice.
- 7 In the **Home** toolbar, click  **Add Study** to close the **Add Study** window.

STUDY 2

Step 1: Stationary

- 1 In the **Settings** window for **Stationary**, locate the **Physics and Variables Selection** section.
- 2 In the **Solve for** column of the table, under **Component 1 (comp1)**, clear the checkboxes for **Heat Transfer in Moist Air (ht)** and **Moisture Transport in Free and Porous Media (mt)**.
- 3 In the **Solve for** column of the table, under **Component 1 (comp1) > Multiphysics**, clear the checkboxes for **Moisture Flow 1 (mfl)**, **Heat and Moisture 1 (ham1)**, and **Nonisothermal Flow 1 (nitfl)**.
- 4 In the **Solve for** column of the table, under **Component 1 (comp1) > Definitions**, clear the checkbox for **Control Variables**.
- 5 In the **Model Builder** window, click **Study 2**.
- 6 In the **Settings** window for **Study**, type Study 2: Stationary Flow in the **Label** text field.
- 7 Locate the **Study Settings** section. Clear the **Generate default plots** checkbox.
- 8 In the **Study** toolbar, click  **Compute**.

STUDY 1: INITIAL CONTROL


Step 1: Time Dependent

- 1 In the **Model Builder** window, expand the **Study 1: Initial Control** node.
- 2 Right-click **Study 1: Initial Control > Step 1: Time Dependent** and choose **Copy**.



STUDY 3

In the **Model Builder** window, right-click **Study 3** and choose **Paste 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 (comp1)**, clear the checkbox for **Laminar Flow (spf)**.
- 3 Click to expand the **Values of Dependent Variables** section. Find the **Values of variables not solved for** subsection. From the **Settings** list, choose **User controlled**.
- 4 From the **Method** list, choose **Solution**.

- 5 From the **Study** list, choose **Study 2: Stationary Flow, Stationary**.
- 6 Locate the **Study Extensions** section. In the table, click to select the cell at row number 1 and column number 2.
- 7 Click  **Delete**.
- 8 Clear the **Auxiliary sweep** checkbox.

General Optimization

- 1 In the **Study** toolbar, click  **Optimization** and choose **General Optimization**.
- 2 In the **Settings** window for **General Optimization**, locate the **Optimization Solver** section.
- 3 From the **Method** list, choose **MMA**.
- 4 In the **Maximum number of model evaluations** text field, type 50.
- 5 Click to expand the **Solver Settings** section. Find the **Objective settings** subsection. From the **Objective scaling** list, choose **Initial solution based**.
- 6 Click **Add Expression** in the upper-right corner of the **Objective Function** section. From the menu, choose **Global definitions > Parameters > tmax - Final time - s**.
- 7 Locate the **Objective Function** section. Select the **Condition-based final time** checkbox.
- 8 In the **Stop expression** text field, type tmax - t.
- 9 Locate the **Control Variables and Parameters** section. Click  **Add**.
- 10 In the table, enter the following settings:

Parameter	Initial value	Scale	Lower bound	Upper bound	Unit
tmax (Final time)	60[min]	60[min]	10[min]	60[min]	s

- 11 Click **Add Expression** in the upper-right corner of the **Constraints** section. From the menu, choose **Component I (comp1) > Definitions > Control Function I > comp1.cfunc1.avg - Control function average - K**.
- 12 Click **Add Expression** in the upper-right corner of the **Constraints** section. From the menu, choose **Component I (comp1) > Definitions > Nonlocal couplings > comp1.aveop1(expr) - Average I**.

13 Locate the **Constraints** section. In the table, enter the following settings:, so that the

Expression	Lower bound	Upper bound	Evaluate for
$(\text{comp1}.\text{cfunc1}.\text{avg} - \text{Tmin}) / (\text{T_avg} - \text{Tmin})$		1	Time Dependent
$\text{comp1}.\text{aveop1}(\text{Xdry}) / 0.04$		1	Time Dependent

constraints are well scaled.

14 In the **Model Builder** window, click **Study 3**.


15 In the **Settings** window for **Study**, type Study 3: Optimal Control in the **Label** text field.

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

17 In the **Study** toolbar, click $t=0$ **Get Initial Value**, so that a plot can be setup for visualizing the control function while optimizing.

RESULTS

Control Function

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

2 In the **Settings** window for **ID Plot Group**, type Control Function in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 3: Optimal Control/ Solution 3 (sol3)**.

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

5 In the **Title** text area, type $\text{cfunc1}.\text{avg} / \text{T_avg} = \text{eval}(\text{cfunc1}.\text{avg} / \text{T_avg}), \text{Xdry} = \text{eval}(\text{aveop1}(\text{Xdry}))$.

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

Global 1

1 Right-click **Control Function** and choose **Global**.

2 In the **Settings** window for **Global**, click **Section toolbar** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1) > Definitions > Functions > cfunc1(s0) - Control Function 1 (cfunc1)**.

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

Expression	Unit	Description
cfunc1(t/tmax)	degC	Control Function 1 (cfunc1)

STUDY 3: OPTIMAL CONTROL

Solver Configurations

In the **Model Builder** window, expand the **Study 3: Optimal Control > Solver Configurations** node.

Solution 3 (sol3)

- 1 In the **Model Builder** window, expand the **Study 3: Optimal Control > Solver Configurations > Solution 3 (sol3)** node, then click **Optimization Solver 1**.
- 2 In the **Settings** window for **Optimization Solver**, locate the **Optimization Solver** section.
- 3 Select the **Move limits** checkbox.
- 4 Click to expand the **Advanced** section. From the **Compensate for nojac terms** list, choose **Off**.
- 5 In the **Model Builder** window, expand the **Study 3: Optimal Control > Solver Configurations > Solution 3 (sol3) > Optimization Solver 1 > Time-Dependent Solver 1** node, then click **Advanced**.
- 6 In the **Settings** window for **Advanced**, click to expand the **Assembly Settings** section.
- 7 Clear the **Reuse sparsity pattern** checkbox to get a cleaner log.

General Optimization

- 1 In the **Model Builder** window, under **Study 3: Optimal Control** click **General Optimization**.
- 2 In the **Settings** window for **General Optimization**, click to expand the **Output** section.
- 3 Select the **Plot** checkbox.
- 4 In the table, enter the following settings:

Plot group	Plot window
Control Function	Graphics

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


Use the last study to verify that neglecting the temperature variations effect on the flow is an acceptable assumption.

Step 1: Time Dependent

In the **Model Builder** window, right-click **Step 1: Time Dependent** and choose **Copy**.

STUDY 4: VALIDATION

In the **Model Builder** window, right-click **Study 4** and choose **Paste 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 (comp1)**, select the checkbox for **Laminar Flow (spf)**.
- 3 Click to expand the **Values of Dependent Variables** section. Find the **Values of variables not solved for** subsection. From the **Method** list, choose **Solution**.
- 4 From the **Study** list, choose **Study 3: Optimal Control, Time Dependent**.
- 5 Find the **Initial values of variables solved for** subsection. From the **Settings** list, choose **User controlled**.
- 6 From the **Method** list, choose **Solution**.
- 7 From the **Study** list, choose **Study 3: Optimal Control, Time Dependent**.
- 8 From the **Time (min)** list, choose **First**.
- 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** checkbox.
- 12 In the **Label** text field, type **Study 4: Validation**.
- 13 In the **Study** toolbar, click  **Compute**.

RESULTS

Global 2

- 1 In the **Model Builder** window, expand the **Average Moisture Content on Dry Basis** node.
- 2 Right-click **Results > Average Moisture Content on Dry Basis > Global 1** and choose **Duplicate**.
- 3 In the **Settings** window for **Global**, locate the **Data** section.
- 4 From the **Dataset** list, choose **Study 3: Optimal Control/Solution 3 (sol3)**.
- 5 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
aveop1(Xdry)	1	T_avg=150 degC

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

7 Select the **Description** checkbox.

Global 3


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

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

3 From the **Dataset** list, choose **Study 4: Validation/Solution 4 (sol4)**.

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

Expression	Unit	Description
aveop1(Xdry)	1	T_avg=150 degC (validation)

5 In the **Average Moisture Content on Dry Basis** toolbar, click  **Plot**.

The plot shows that the temperature variations do affect the flow, but the effect on the objective is marginal.