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 the Heat Transfer Module Application Library. 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.

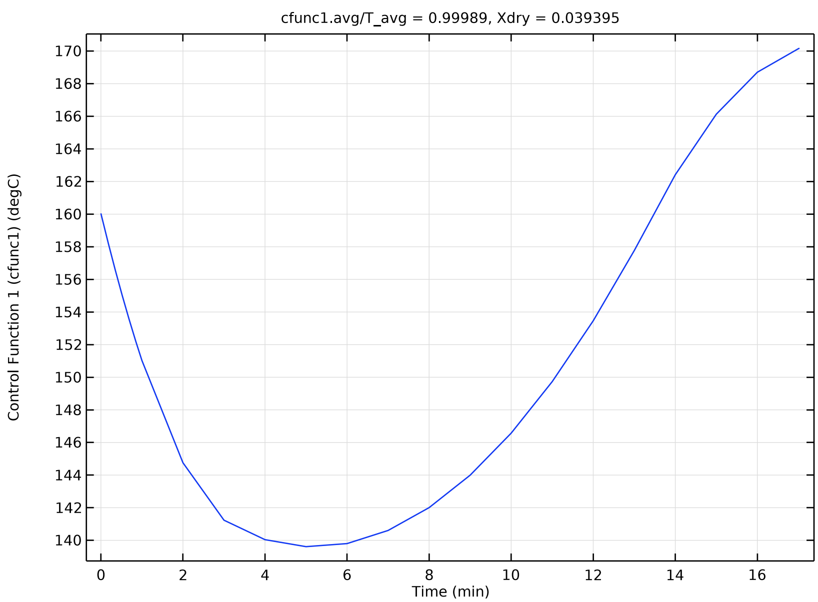


*Figure 1: The optimal temperature control is nontrivial in the sense that it has a minimum.*

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..

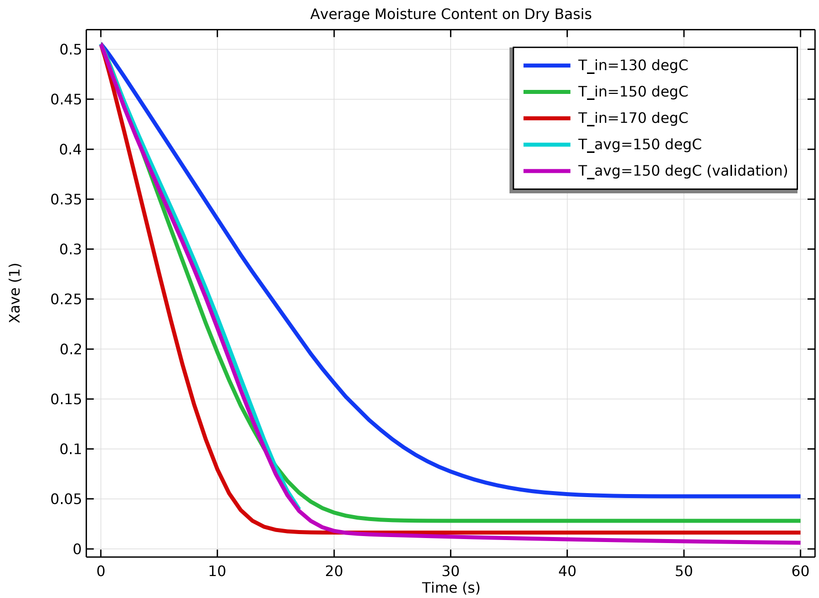


*Figure 2: The moisture content for three constant temperatures together with the time-varying temperature with and without accounting for temperature variations in the flow.*

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**Application Library path:** `Optimization_Module/Optimal_Control/superheated_steam_drying_optimization`

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## *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 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 |
|---|---|---|---|
| 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 (COMP1)

### *Control Function 1 (cfunc1)*

1. In the **Model Builder** window, expand the **Component 1 (comp1)** node.
2. Right-click **Component 1 (comp1)** > **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*(Tmax+Tmin)`.
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 1 (ampr1)*

1 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Definitions** > **Shared Properties** node, then click **Ambient Properties 1 (ampr1)**.

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 $\phi_{amb}$ 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 1 (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 1 (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 (mf1)**, **Heat and Moisture 1 (ham1)**, and **Nonisothermal Flow 1 (nitf1)**.

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 1 (comp1) > Definitions > Control Function 1 > 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 1 (comp1) > Definitions > Nonlocal couplings > comp1.aveop1(expr) - Average 1**.

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

| Expression | Lower bound | Upper bound | Evaluate for |
|---|---|---|---|
| `(comp1.cfunc1.avg-Tmin)/(T_avg-Tmin)` | | 1 | Time Dependent |
| `comp1.aveop1(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 **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 **1D Plot Group**.

**2** In the **Settings** window for **1D 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 `cfunc1.avg/T_avg = eval(cfunc1.avg/T_avg), Xdry = eval(aveop1(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.