Model created in COMSOL Multiphysics 6.4

Superheated Steam Drying of a Wood Particle

Introduction

Drying of porous media is a crucial process in industries such as food and paper manufacturing. Superheated steam drying (SSD) offers several advantages over other drying methods. For sensitive products like food, SSD helps minimize substance degradation, browning, and oxidation. Additionally, the SSD process can reduce energy consumption by up to 50% and shorten drying time by up to 80% compared to hot-air drying. Superheated steam dryers are typically more compact and require less investment than hot-air dryers. At temperatures above 120°C, SSD also inactivates microorganisms and ensures product hygiene. Despite the high operating temperatures, the degradation rate of product compounds remains relatively low due to the short retention time.

Higher drying rates can be achieved with SSD due to the superior heat transfer properties of superheated steam. It has a higher thermal conductivity and heat capacity than hot air, and it does not resist the diffusion of evaporated moisture in its own vapor. The material to be dried is introduced in the superheated steam flow, where moisture evaporates through convective heating. This heat transfer process is highly effective, as the high heat capacity and thermal conductivity of superheated steam, combined with its low viscosity, facilitate rapid penetration into the material. Consequently, this drying method is particularly effective for porous materials and results in a shorter retention time.

Modeling such processes requires considering multiple physical effects, including fluid flow, heat transfer, and mass transport with evaporation. These effects are strongly coupled, and predefined interfaces in COMSOL Multiphysics can be used to model these phenomena in a hygroscopic porous medium.

This tutorial demonstrates how to model the superheated steam drying process of a spherical wood particle exposed to laminar flow of superheated steam. The evolution of the moisture content on a dry basis within the wood particle is analyzed for different inlet steam temperatures under nonequilibrium conditions. Model parameters are based on those in Ref. 1, where SSD was modeled using an effective diffusivity formulation.

Model Definition

The model solves the coupled heat and mass transfer problem in a domain with a spherical porous wood particle, exposed in laminar flow of a superheated steam. Since the geometry and boundary conditions are symmetrical, only one quarter of the geometry is modeled. Figure 1 depicts the model geometry.

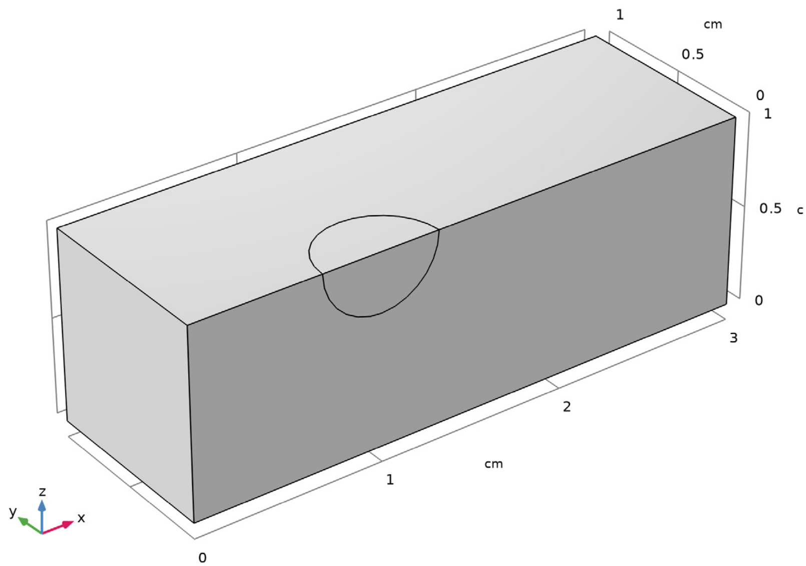

Figure 1: The model geometry.

The computational domain comprises the spherical wood particle, which diameter is equal to 6.2 mm, and a steam flow around the particle. The length of flow domain is 3 cm, height and width are equal to 1 cm.

HEAT AND MOISTURE TRANSPORT

The thermodynamic properties of superheated water vapor are described automatically in the Moist Air feature of the Heat Transfer interface. As the input term for water vapor, the relative humidity ϕ_w from the moisture transport equation is used in the Heat Transfer and Fluid Flow interfaces. To get the properties of the pure vapor we can define the inlet and initial relative humidity values as p_a / p_{sat}, where p_a is an absolute pressure, and p_{sat} is the vapor saturation pressure at the inlet temperature.

FLUID FLOW

The Laminar Flow interface solves for compressible Navier–Stokes equations to compute the velocity and pressure fields of the free flow and Brinkman equations to calculate the flow field and pressure distribution of vapor in the porous medium. It is assumed that there is no liquid water in the free flow domain. This means that all the moisture leaves the porous medium under vapor state.

With an additional liquid phase in porous medium capillary effects also arise, and the liquid flow is driven by a pressure gradient and the capillary pressure $p_c = p_g - p_l$. In this model, the capillary effects are treated by an additional capillary flux term in the transport equation, defined from the capillary pressure gradient by a Darcy's law:

$$\mathbf{g}_{lc} = \rho_l \frac{\kappa_{rl}\kappa}{\mu_l} \nabla p_c ,$$

where κ is total permeability of the porous medium, and μ_l is viscosity of the liquid phase. The capillary pressure p_c and relative liquid water permeability κ_{rl} are calculated from the van Genuchten model, that is available in the Liquid Water subfeature of Moisture Transport interface.

The liquid-phase velocity is small compared to the vapor velocity. Liquid transport is driven by the gas-phase pressure gradient ∇p_g, and its velocity $\mathbf{u}_l$ is computed with the use of Darcy's law according to

$$\mathbf{u}_l = -\frac{\kappa_{rl}\kappa}{\mu_l} \nabla p_g .$$

Finally, due to the dimensions of the porous medium, the gravity effects on transport are neglected in both phases.

HEAT TRANSFER

Inside the porous domain, convection of both liquid and gaseous phases contributes to the heat convective term. It is possible to account for the liquid water and vapor phases, by using the liquid saturation calculated by the moisture transport equation.

Averaged heat capacity $(\rho C_p)_{eff}$ is defined by taking into account the properties of the porous matrix (ρ_s, $C_{p,s}$), vapor (ρ_g, $C_{p,g}$), and liquid water (ρ_l, $C_{p,l}$):

$$(\rho C_p)_{eff} = \varepsilon_p (s_g \rho_g C_{p,g} + s_l \rho_l C_{p,l}) + \theta_s \rho_s C_{p,s} .$$

For effective thermal conductivity of porous medium k_{eff} the user-defined value is used, that was obtained from experiments (Ref. 1).

The combined convection term in the porous media takes the form

$$(\rho_g C_{p,g} \mathbf{u}_g + \rho_l C_{p,l} \mathbf{u}_l) \cdot \nabla T .$$

The capillary flux of enthalpy due to the presence of the liquid water in the pores is included in the following heat source term:

$$Q = -C_{p,\mathrm{l}}\mathbf{g}_{\mathrm{lc}} \cdot \nabla T.$$

The heat of evaporation is inserted as a source term in the heat transfer equation:

$$Q_{\mathrm{evap}} = -L_{\mathrm{v}} G_{\mathrm{evap}},$$

where L_{v} (J/mol) is the latent heat of evaporation.

Surface-to-ambient radiation can take significant role under the high steam temperatures. To take it into account, the radiative heat flux is defined on the upside surface of the wood particle:

$$q_{\mathrm{r,\,amb}} = \varepsilon\sigma(T_{\mathrm{amb}}^4 - T^4),$$

where ε is the surface emissivity, σ is the Stefan–Boltzmann constant, and T_{amb} is the ambient superheated steam temperature.

MOISTURE TRANSPORT IN FREE AND POROUS MEDIUM

Superheated steam drying process implies that equilibrium between liquid and vapor phases cannot be assumed. In this case the liquid saturation and vapor mass fraction are not related, and the water conservation equations for the liquid phase and vapor phase must be solved separately, that is, the nonequilibrium formulation has to be used. See the *Heat Transfer Module User's Guide* for the governing equations.

Unlike the equilibrium assumption, the evaporation source is taken into account for the mass conservation equations. The moisture source due to evaporation is calculated as a deviation from the equilibrium state:

$$G_{\mathrm{evap}} = K_{\mathrm{evap}}\frac{M_{\mathrm{v}}}{RT}(p_{\mathrm{v,\,eq}} - p_{\mathrm{v}}),$$

where K_{evap} (1/s) is the evaporation rate, $p_{\mathrm{v,eq}}$ is the equilibrium vapor pressure, p_{v} is the pressure of water vapor, and R (J/(mol·K) is the universal gas constant.

The equilibrium vapor pressure can be given as a function of water activity a_{w} and vapor saturation pressure p_{sat}:

$$p_{\mathrm{v,\,eq}} = a_{\mathrm{w}} p_{\mathrm{sat}}.$$

The saturation pressure is calculated automatically in the Moist Air feature of Heat Transfer and Moisture Transfer interfaces.

Results

After 1 hour of superheated steam drying, the average moisture content on the dry basis in the wood particle decreases from initial value of 50% to about 5%, when the steam temperature at the inlet is equal to 130°C, and to about 1%, when the inlet temperature is 170°C. We can see almost homogeneous distribution of moisture content in the wood particle at the end of the drying process (Figure 2).

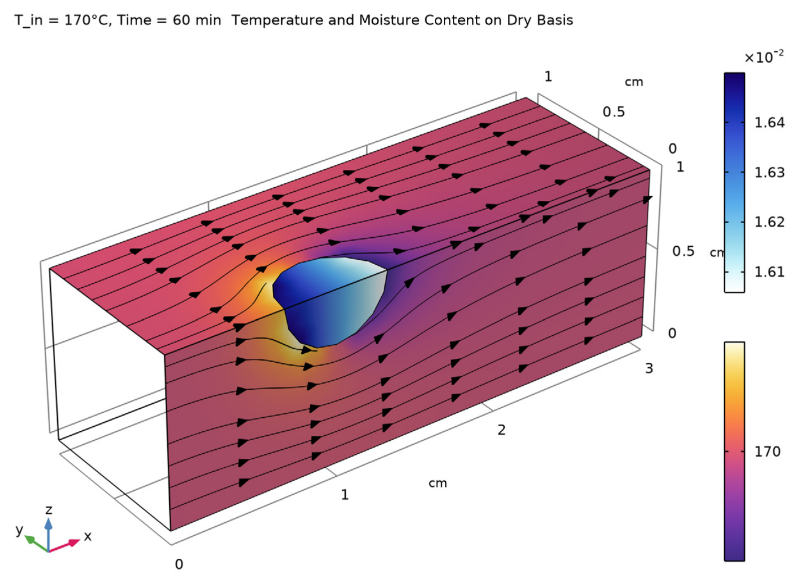

Figure 2: Temperature in the free flow and moisture content in the wood particle after 1 hour of the drying process for inlet steam temperature of 170°C.

As we can see on the Figure 3, the drying process gets faster for increasing values of the inlet temperature.

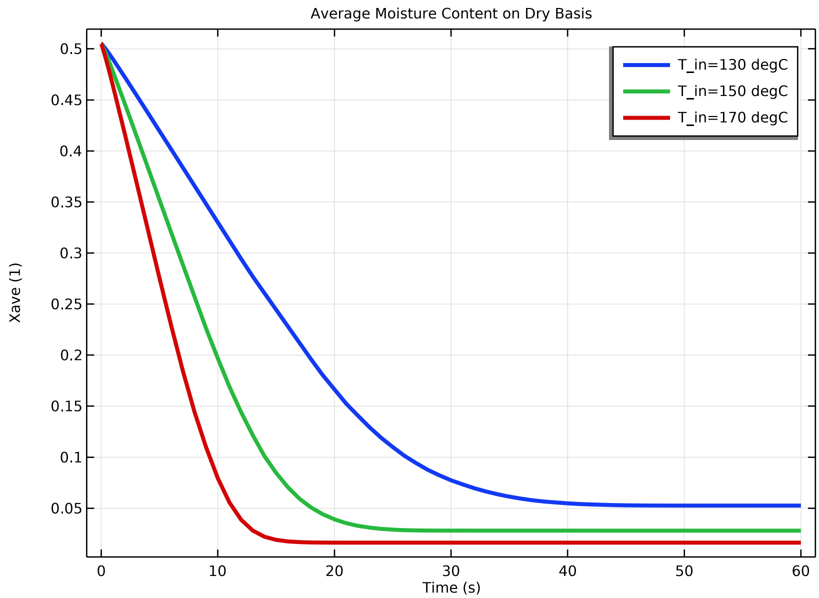

Figure 3: Average moisture content on dry basis in the wood particle for different values of the inlet temperature.

The nonequilibrium formulation allows us to set inlet temperature much higher then the saturation value, and model different regimes of superheated steam drying.

The Figure 4 shows the average temperature of the wood particle during the drying process.

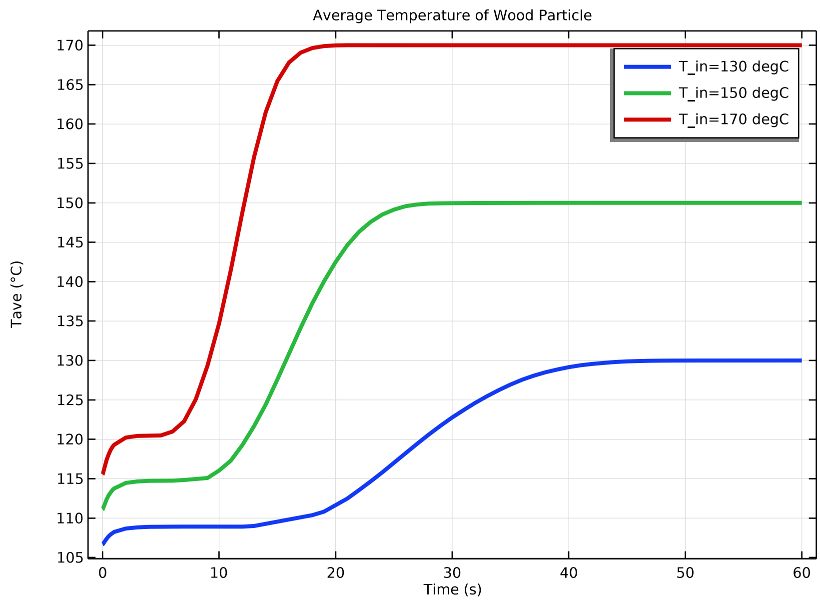

Figure 4: Average temperature of the wood particle for different values of the inlet temperature.

Reference

1. K.H. Le, N. Hampel, A. Kharaghani, A. Bück, and E. Tsotsas, "Superheated steam drying of single wood particles: A characteristic drying curve model deduced from continuum model simulations and assessed by experiments," *Drying Technology*, vol. 36, no. 15, pp. 1866–1881, 2018.

Application Library path: `Heat_Transfer_Module/Phase_Change/superheated_steam_drying`

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 **3D**.

2 In the **Select Physics** tree, select **Heat Transfer** > **Heat and Moisture Transport** > **Heat and Moisture Flow** > **Laminar Flow**.

3 Click **Add**.

4 In the **Added physics interfaces** tree, select **Moisture Transport in Air (mt)**.

5 Click **Remove**.

6 In the **Select Physics** tree, select **Chemical Species Transport** > **Moisture Transport** > **Moisture Transport in Free and Porous Media (mt)**.

7 Click **Add**.

8 Click **Study**.

9 In the **Select Study** tree, select **General Studies** > **Time Dependent**.

10 Click **Done**.

Start with specifying the model parameters.

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
dp	6.2[mm]	0.0062 m	Wood particle diameter
L	3[cm]	0.03 m	Length of drying chamber
H	1[cm]	0.01 m	Height of drying chamber
U_in	0.02[m/s]	0.02 m/s	Inlet velocity
T_in	130[degC]	403.15 K	Inlet temperature
K0	1[1/s]	1 1/s	Evaporation source rate
por	0.65	0.65	Porosity
sl0	0.6	0.6	Initial liquid water saturation

Name	Expression	Value	Description
kappa	1e-12[m^2]	1E-12 m²	Permeability
Cp_b	770[J/(kg*K)]	770 J/(kg·K)	Dry bulk heat capacity of wood particle
rho_b	740[kg/m^3]	740 kg/m³	Dry bulk density of wood particle
k_eff	0.14[W/(m*K)]	0.14 W/(m·K)	Effective thermal conductivity

Now, define the geometry.

GEOMETRY 1

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

2 In the **Settings** window for **Geometry**, locate the **Units** section.

3 From the **Length unit** list, choose **cm**.

Block 1 (blk1)

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

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

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

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

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

6 Click **Build Selected**.

Sphere 1 (sph1)

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

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

3 In the **Radius** text field, type `dp/2`.

4 Locate the **Position** section. In the **x** text field, type `L/3`.

5 In the **z** text field, type `H`.

6 Click **Build Selected**.

Partition Objects 1 (par1)

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Partition Objects**.

2 Select the object **sph1** only.

3 In the **Settings** window for **Partition Objects**, locate the **Partition Objects** section.

4 Click to select the **Activate Selection** toggle button for **Tool objects**.

5 Select the object **blk1** only.

6 Select the **Keep tool objects** checkbox.

7 Click **Build Selected**.

Delete Entities 1 (del1)

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

2 In the **Settings** window for **Delete Entities**, locate the **Entities or Objects to Delete** section.

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

4 On the object **par1**, select Domain 1 only.

5 Click **Build Selected**.

Form Union (fin)

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

DEFINITIONS

Define the variable for the moisture content on dry basis.

Variables 1

1 In the **Model Builder** window, under **Component 1 (comp1)** 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
Xdry	mt.wc/rho_b		Moisture content on dry basis

Define the water activity as a function of the moisture content on dry basis. The advantage of using functions is that they can be plotted immediately.

Water activity

1 In the **Definitions** toolbar, click **Analytic**.

2 In the **Settings** window for **Analytic**, type `Water activity` in the **Label** text field.

3 In the **Function name** text field, type `wa`.

4 Locate the **Definition** section. In the **Expression** text field, type `if(X>0.256,1,X/0.256*(2-X/0.256))`.

5 In the **Arguments** text field, type `X`.

6 Locate the **Units** section. In the **Function** text field, type `1`.

7 In the table, enter the following settings:

Argument	Unit
X	1

Now, define the selections to simplify the model setup.

Symmetry Boundaries

1 In the **Definitions** toolbar, click **Explicit**.

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

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

4 Select Boundaries 2, 4, 7, and 8 only.

5 In the **Label** text field, type `Symmetry Boundaries`.

Inlet Boundary

1 In the **Definitions** toolbar, click **Explicit**.

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

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

4 Select Boundary 1 only.

5 In the **Label** text field, type `Inlet Boundary`.

Outlet Boundary

1 In the **Definitions** toolbar, click **Explicit**.

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

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

4 Select Boundary 10 only.

5 In the **Label** text field, type `Outlet Boundary`.

Porous Medium

1 In the **Definitions** toolbar, click **Explicit**.

2 Select Domain 2 only.

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

Define an average operator in the porous domain, in order to evaluate the average moisture content evolution.

Average 1 (aveop1)

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Average**.

2 In the **Settings** window for **Average**, locate the **Source Selection** section.

3 From the **Selection** list, choose **Porous Medium**.

Define the ambient conditions that will be used later in the domain and boundary conditions.

Ambient Properties 1 (ampr1)

1 In the **Physics** toolbar, click **Shared Properties** and choose **Ambient Properties**.

2 In the **Settings** window for **Ambient Properties**, locate the **Ambient Conditions** section.

3 In the T_{amb} text field, type `T_in`.

4 In the ϕ_{amb} text field, type `mt.pA/mt.fpsat(T_in)`.

MATERIALS

Add porous material to the materials node, but do not define their properties at this point. After setting up the physics interface, COMSOL Multiphysics automatically detects which material properties are needed.

Wood particle

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **More Materials** > **Porous Material**.

2 In the **Settings** window for **Porous Material**, type `Wood particle` in the **Label** text field.

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

4 Click to expand the **Appearance** section. From the **Material type** list, choose **Wood**.

Now, define the domain and boundary conditions for each interface. Start with the **Laminar Flow** interface, by setting the physical model parameters, initial and boundary conditions, and by adding a **Porous Medium** domain condition.

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 **Compressible flow (Ma<0.3)**.

4 Select the **Enable porous media domains** checkbox.

Initial Values 1

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Laminar Flow (spf)** click **Initial Values 1**.

2 In the **Settings** window for **Initial Values**, locate the **Initial Values** section.

3 Specify the **u** vector as

U_in	x

Wall 1

1 In the **Model Builder** window, click **Wall 1**.

2 In the **Settings** window for **Wall**, locate the **Boundary Condition** section.

3 From the **Wall condition** list, choose **Slip**.

Inlet 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Inlet**.

2 In the **Settings** window for **Inlet**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Inlet Boundary**.

4 Locate the **Velocity** section. In the U_0 text field, type U_in.

Outlet 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Outlet**.

2 In the **Settings** window for **Outlet**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Outlet Boundary**.

Symmetry 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Symmetry**.

2 In the **Settings** window for **Symmetry**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Symmetry Boundaries**.

Porous Medium 1

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

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

3 From the **Selection** list, choose **Porous Medium**.

HEAT TRANSFER IN MOIST AIR (HT)

Use the ambient temperature defined previously as input for **Initial Values**.

Initial Values 1

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Heat Transfer in Moist Air (ht)** click **Initial Values 1**.

2 In the **Settings** window for **Initial Values**, locate the **Initial Values** section.

3 From the T list, choose **Ambient temperature (ampr1)**.

Add another **Initial Values** node to define the initial temperature of the wood particle equal to 100°C.

Initial Values 2

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

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

3 From the **Selection** list, choose **Porous Medium**.

4 Locate the **Initial Values** section. In the T text field, type `100[degC]`.

Inflow 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Inflow**.

2 In the **Settings** window for **Inflow**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Inlet Boundary**.

4 Locate the **Upstream Properties** section. From the T_{ustr} list, choose **Ambient temperature (ampr1)**.

Outflow 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Outflow**.

2 In the **Settings** window for **Outflow**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Outlet Boundary**.

Surface-to-Ambient Radiation 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Surface-to-Ambient Radiation**.

2 Select Boundaries 6 and 9 only.

3 In the **Settings** window for **Surface-to-Ambient Radiation**, locate the **Surface-to-Ambient Radiation** section.

4 From the ε list, choose **User defined**. In the associated text field, type `0.9`.

5 From the T_{amb} list, choose **Ambient temperature (ampr1)**.

Symmetry 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Symmetry**.

2 In the **Settings** window for **Symmetry**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Symmetry Boundaries**.

Moist Porous Medium 1

1 In the **Physics** toolbar, click **Domains** and choose **Moist Porous Medium**.

2 In the **Settings** window for **Moist Porous Medium**, locate the **Domain Selection** section.

3 From the **Selection** list, choose **Porous Medium**.

Select the *Equivalent thermal conductivity* option to specify the user-defined effective thermal conductivity of porous medium.

4 Locate the **Porous Medium Model Settings** section. From the **Effective thermal conductivity** list, choose **Equivalent thermal conductivity**.

MOISTURE TRANSPORT IN FREE AND POROUS MEDIA (MT)

Finally, set the domain, initial, and boundary conditions for the **Moisture Transport in Free and Porous Medium** interface. Switch to *Concentrated Species* option to model steam flow.

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Moisture Transport in Free and Porous Media (mt)**.

2 In the **Settings** window for **Moisture Transport in Free and Porous Media**, locate the **Physical Model** section.

3 From the **Mixture type for moist air** list, choose **Concentrated species**.

Hygroscopic Porous Medium 1

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Moisture Transport in Free and Porous Media (mt)** click **Hygroscopic Porous Medium 1**.

2 Select Domain 2 only.

Specify water activity function and evaporation rate.

3 In the **Settings** window for **Hygroscopic Porous Medium**, locate the **Moisture Transport Properties** section.

4 In the a_w text field, type `wa(Xdry)`.

5 In the K_{evap} text field, type `K0`.

Liquid Water 1

1 In the **Model Builder** window, click **Liquid Water 1**.

2 In the **Settings** window for **Liquid Water**, locate the **Liquid Water Properties** section.

3 From the **Capillary model** list, choose **Pressure**.

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 $s_{1,0}$ text field, type `sl0`.

Symmetry 1

1. In the **Physics** toolbar, click **Boundaries** and choose **Symmetry**.
2. In the **Settings** window for **Symmetry**, locate the **Boundary Selection** section.
3. From the **Selection** list, choose **Symmetry Boundaries**.

Initial Values 1

1. In the **Model Builder** window, under **Component 1 (comp1)** > **Moisture Transport in Free and Porous Media (mt)** > **Hygroscopic Porous Medium 1** > **Moist Air 1** click **Initial Values 1**.
2. In the **Settings** window for **Initial Values**, locate the **Initial Values** section.
3. In the $\phi_{w,0}$ text field, type 1.

Symmetry 1

1. In the **Physics** toolbar, click **Boundaries** and choose **Symmetry**.
2. In the **Settings** window for **Symmetry**, locate the **Boundary Selection** section.
3. From the **Selection** list, choose **Symmetry Boundaries**.

Use the ambient temperature and humidity defined previously as input for **Initial Values** and **Inflow**.

Initial Values 1

1. In the **Model Builder** window, under **Component 1 (comp1)** > **Moisture Transport in Free and Porous Media (mt)** click **Initial Values 1**.
2. In the **Settings** window for **Initial Values**, locate the **Initial Values** section.
3. From the $\phi_{w,0}$ list, choose **Ambient relative humidity (ampr1)**.

Inflow 1

1. In the **Physics** toolbar, click **Boundaries** and choose **Inflow**.
2. In the **Settings** window for **Inflow**, locate the **Boundary Selection** section.
3. From the **Selection** list, choose **Inlet Boundary**.
4. Locate the **Upstream Properties** section. From the T_{ustr} list, choose **Ambient temperature (ampr1)**.
5. From the $\phi_{w,ustr}$ list, choose **Ambient relative humidity (ampr1)**.

Outflow 1

1. In the **Physics** toolbar, click **Boundaries** and choose **Outflow**.
2. In the **Settings** window for **Outflow**, locate the **Boundary Selection** section.
3. From the **Selection** list, choose **Outlet Boundary**.

Symmetry 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Symmetry**.

2 In the **Settings** window for **Symmetry**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Symmetry Boundaries**.

MATERIALS

The porous material properties can now be specified.

Wood particle (pmat1)

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Materials** click **Wood particle (pmat1)**.

2 In the **Settings** window for **Porous Material**, locate the **Homogenized Properties** section.

3 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Thermal conductivity	k_iso ; kii = k_iso, kij = 0	`k_eff`	W/(m·K)	Basic
Permeability	kappa_iso ; kappaii = kappa_iso, kappaij = 0	`kappa`	m²	Basic

4 Locate the **Phase-Specific Properties** section. Click **Add Required Phase Nodes**.

Solid 1 (pmat1.solid1)

1 In the **Model Builder** window, click **Solid 1 (pmat1.solid1)**.

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

3 In the θ_s text field, type `1-por`.

4 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Density	rho	`rho_b`	kg/m³	Basic
Heat capacity at constant pressure	Cp	`Cp_b`	J/(kg·K)	Basic

MESH 1

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

2 In the **Settings** window for **Mesh**, locate the **Physics-Controlled Mesh** section.

3 From the **Element size** list, choose **Coarse**.

4 Click **Build All**.

STUDY 1

The necessary time to dry the product is unknown. An initial guess of 60 minutes is made.

Step 1: Time Dependent

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

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

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

4 In the **Output times** text field, type `range(0,0.1,1)[s] range(1,10,59)[s] range(1,1,60)`.

Activate a parametric sweep to run the simulation for different inlet temperature values.

5 Click to expand the **Study Extensions** section. Select the **Auxiliary sweep** checkbox.

6 Click **Add**.

7 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
T_in (Inlet temperature)	130 150 170	degC

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

To create the plots shown in Figure 2, Figure 3, and Figure 4, reproduce the following steps.

RESULTS

Preferred Units 1

1 In the **Results** toolbar, click **Configurations** and choose **Preferred Units**.

2 In the **Settings** window for **Preferred Units**, locate the **Units** section.

3 Click **Add Physical Quantity**.

4 In the **Physical Quantity** dialog, select **General** > **Temperature (K)** in the tree.

5 Click **OK**.

6 In the **Settings** window for **Preferred Units**, locate the **Units** section.

7 In the table, enter the following settings:

Quantity	Unit	Preferred unit
Temperature	K	°C

8 Click **Apply**.

Multislice 1

1 In the **Model Builder** window, expand the **Results** > **Relative Humidity (mt)** node, then click **Multislice 1**.

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

3 Find the **x-planes** subsection. In the **Planes** text field, type 0.

4 Find the **y-planes** subsection. From the **Entry method** list, choose **Coordinates**.

5 In the **Coordinates** text field, type 0.

6 Find the **z-planes** subsection. From the **Entry method** list, choose **Coordinates**.

7 In the **Coordinates** text field, type H.

8 In the **Relative Humidity (mt)** toolbar, click **Plot**.

RESULT TEMPLATES

1 In the **Results** toolbar, click **Result Templates** to open the **Result Templates** window.

2 Go to the **Result Templates** window.

3 In the tree, select **Study 1/Solution 1 (sol1)** > **Moisture Transport in Free and Porous Media** > **Saturation (mt)**.

4 Click the **Add Result Template** button in the window toolbar.

RESULTS

Multislice 1

1 In the **Model Builder** window, expand the **Saturation (mt)** node, then click **Multislice 1**.

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

3 Find the **x-planes** subsection. In the **Planes** text field, type 0.

4 Find the **y-planes** subsection. From the **Entry method** list, choose **Coordinates**.

5 In the **Coordinates** text field, type 0.

6 Find the **z-planes** subsection. From the **Entry method** list, choose **Coordinates**.

7 In the **Coordinates** text field, type H.

8 In the **Saturation (mt)** toolbar, click **Plot**.

Temperature and Moisture Content on Dry Basis

1 In the **Results** toolbar, click **3D Plot Group**.
2 In the **Settings** window for **3D Plot Group**, type `Temperature and Moisture Content on Dry Basis` 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 `Temperature and Moisture Content on Dry Basis`.
5 In the **Parameter indicator** text field, type `T_in = eval(T_in,°C)°C, Time = eval(t,min) min`.
6 Locate the **Color Legend** section. From the **Position** list, choose **Right double**.

Surface 1

1 Right-click **Temperature and Moisture Content on Dry Basis** and choose **Surface**.
2 In the **Settings** window for **Surface**, locate the **Expression** section.
3 In the **Expression** text field, type `Xdry`.
4 Locate the **Coloring and Style** section. From the **Color table** list, choose **Kyanite**.

Selection 1

1 Right-click **Surface 1** and choose **Selection**.
2 Select Boundaries 7 and 8 only.

Surface 2

1 In the **Model Builder** window, right-click **Temperature and Moisture Content on Dry Basis** and choose **Surface**.
2 In the **Settings** window for **Surface**, locate the **Expression** section.
3 In the **Expression** text field, type `T`.
4 Locate the **Coloring and Style** section. From the **Color table** list, choose **HeatCameraLight**.

Selection 1

1 Right-click **Surface 2** and choose **Selection**.
2 Select Boundaries 2 and 4 only.

Temperature and Moisture Content on Dry Basis

In the **Model Builder** window, under **Results** click **Temperature and Moisture Content on Dry Basis**.

Streamline Surface 1

1 In the **Temperature and Moisture Content on Dry Basis** toolbar, click **More Plots** and choose **Streamline Surface**.

2 Select Boundaries 2 and 4 only.

3 In the **Settings** window for **Streamline Surface**, locate the **Streamline Positioning** section.

4 From the **Positioning** list, choose **Uniform density**.

5 Locate the **Coloring and Style** section. Find the **Point style** subsection. From the **Type** list, choose **Arrow**.

6 From the **Color** list, choose **Black**.

7 In the **Temperature and Moisture Content on Dry Basis** toolbar, click **Plot**.

Evaporation Rate

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

2 In the **Settings** window for **3D Plot Group**, type `Evaporation Rate` in the **Label** text field.

3 Click to expand the **Selection** section. From the **Geometric entity level** list, choose **Domain**.

4 From the **Selection** list, choose **Porous Medium**.

Surface 1

1 Right-click **Evaporation Rate** and choose **Surface**.

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

3 In the **Expression** text field, type `mt.G_evap`.

4 In the **Evaporation Rate** toolbar, click **Plot**.

Average Moisture Content on Dry Basis

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

2 In the **Settings** window for **1D Plot Group**, type `Average Moisture Content on Dry Basis` 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 `Average Moisture Content on Dry Basis`.

5 Locate the **Plot Settings** section.

6 Select the **x-axis label** checkbox. In the associated text field, type `Time (s)`.

7 Select the **y-axis label** checkbox. In the associated text field, type `Xave (1)`.

Global 1

1 Right-click **Average Moisture Content on Dry Basis** and choose **Global**.

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

3 In the table, enter the following settings:

Expression	Unit	Description
aveop1(Xdry)	1	Average 1

4 Click to expand the **Coloring and Style** section. From the **Width** list, choose **3**.

5 Click to expand the **Legends** section. Find the **Include** subsection. Clear the **Description** checkbox.

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

Average Temperature of Wood Particle

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

2 In the **Settings** window for **1D Plot Group**, type `Average Temperature of Wood Particle` in the **Label** text field.

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

4 In the **Title** text area, type `Average Temperature of Wood Particle`.

5 Locate the **Plot Settings** section.

6 Select the **x-axis label** checkbox. In the associated text field, type `Time (s)`.

7 Select the **y-axis label** checkbox. In the associated text field, type `Tave (°C)`.

Global 1

1 Right-click **Average Temperature of Wood Particle** and choose **Global**.

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

3 In the table, enter the following settings:

Expression	Unit	Description
aveop1(T)	°C	Average 1

4 Locate the **Coloring and Style** section. From the **Width** list, choose **3**.

5 Locate the **Legends** section. Find the **Include** subsection. Clear the **Description** checkbox.

6 In the **Average Temperature of Wood Particle** toolbar, click **Plot**.

Average Relative Humidity

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

2 In the **Settings** window for **1D Plot Group**, type `Average Relative Humidity` in the **Label** text field.

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

4 In the **Title** text area, type `Average Relative Humidity`.

5 Locate the **Plot Settings** section.

6 Select the **x-axis label** checkbox. In the associated text field, type `Time (s)`.

7 Select the **y-axis label** checkbox. In the associated text field, type `phi_ave (1)`.

Global 1

1 Right-click **Average Relative Humidity** and choose **Global**.

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

3 In the table, enter the following settings:

Expression	Unit	Description
aveop1(mt.phi)	1	Average 1

4 Locate the **Coloring and Style** section. From the **Width** list, choose **3**.

5 Locate the **Legends** section. Find the **Include** subsection. Clear the **Description** checkbox.

6 In the **Average Relative Humidity** toolbar, click **Plot**.

Mass Balance

1 In the **Results** toolbar, click **Evaluation Group**.

2 In the **Settings** window for **Evaluation Group**, type `Mass Balance` in the **Label** text field.

3 Locate the **Data** section. From the **Time selection** list, choose **Last**.

4 Locate the **Transformation** section. Select the **Transpose** checkbox.

Global Evaluation 1

1 Right-click **Mass Balance** and choose **Global Evaluation**.

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

3 In the table, enter the following settings:

Expression	Unit	Description
mt.massBalance	kg/s	Mass balance
mt.ma1.massBalance	kg/s	Mass balance, moist air
mt.hporous1.massBalance	kg/s	Mass balance, porous medium
mt.hporous1.lw1.massBalance	kg/s	Mass balance, porous medium, liquid water
mt.hporous1.ma1.massBalance	kg/s	Mass balance, porous medium, moist air

4 In the **Mass Balance** toolbar, click **Evaluate**.