

Condensation Risk in a Wood-Frame Wall

Introduction

This tutorial shows how to model heat and moisture transport in a wood-frame wall to evaluate the risk of condensation inside the wall. Different design and modeling approaches are compared under stationary outdoor conditions. In addition, the effect of the diurnal variation of outdoor humidity on the humidity distribution in the wall is computed.

Model Definition

The model is the 2D representation of a portion of a wood-frame wall placed between different outdoor and indoor conditions. The risk of condensation in the wall is evaluated through the coupled computation of heat and moisture transport. Values of relative humidity close to unity indicate a risk of condensation.

Figure 1 shows the model geometry.



Figure 1: Model geometry.

The wall is made of the following components:

- Two wood studs made in pine
- Three isolation boards made in cellulose
- A bracing made of a wooden panel
- An interior siding made of a gypsum

In addition, a vapor barrier made of plastic coated paper may be placed between the gypsum interior siding and the isolation boards.

Convective heat and moisture flux conditions are applied on the top and bottom boundaries to model the outdoor and indoor air flows surrounding the wall. The outdoor and indoor heat transfer coefficients are set as $h_{ext}=25 \text{ W/(m\cdot K)}$ and $h_{int}=8 \text{ W/(m\cdot K)}$. The outdoor and indoor moisture transfer coefficients are set to $\beta_{ext} = 25 \cdot 10^{-8} \text{ s/m}$ and $\beta_{int} = 8 \cdot 10^{-8} \text{ s/m}$, according to the heat and mass transfer boundary layers analogy.

The side boundaries are supposed to be totally isolated regarding heat and moisture.

DYNAMIC MODELING OF HEAT AND MOISTURE TRANSPORT

In this approach, both the transport of liquid moisture by capillary forces and the transport of vapor by diffusion are computed, and the latent heat effect due to vapor diffusion is modeled. In addition, heat and moisture storage is considered, and moisture-dependent thermal properties are used. The corresponding equations, defined in the Norm EN 15026, are solved by default by the Moisture Transport in Building Materials and Heat Transfer in Building Materials interfaces:

$$\begin{split} (\rho C_p)_{\rm eff} &\frac{\partial T}{\partial t} - \nabla \cdot (k_{\rm eff} \nabla T + L_{\rm v} \delta_{\rm p} \nabla (\phi p_{\rm sat})) = Q \\ & \xi \frac{\partial \phi}{\partial t} - \nabla \cdot (\xi D_{\rm w} \nabla \phi + \delta_{\rm p} \nabla (\phi p_{\rm sat})) = G \end{split}$$

Here

- $(\rho C_p)_{\text{eff}}$ (SI unit: J/(m³·K)) is the effective volumetric heat capacity at constant pressure
- T (SI unit: K) is the temperature
- k_{eff} (SI unit: W/(m·K)) is the effective thermal conductivity
- $L_{\rm v}$ (SI unit: J/kg) is the latent heat of evaporation
- $\delta_{\rm p}$ (SI unit: s) is the vapor permeability
- ϕ (dimensionless) is the relative humidity
- p_{sat} (SI unit: Pa) is the vapor saturation pressure
- Q (SI unit: W/m³·s) is the heat source
- ξ (SI unit: kg/m³) is the moisture storage capacity
- $D_{\rm w}$ (SI unit: m²/s) is the moisture diffusivity
- G (SI unit: kg/m³·s) is the moisture source

See Ref. 1 for details about the norm EN 15026.

STATIC MODELING OF HEAT AND MOISTURE TRANSPORT

By ignoring heat and moisture storage, latent heat effect, and capillary transport of liquid moisture, the following equations are obtained for heat and moisture transport:

$$-\nabla \cdot (k_{\text{eff}} \nabla T) = Q$$
$$-\nabla \cdot (\delta_{\text{p}} \nabla (\phi p_{\text{sat}})) = G$$

These equations are known as the Glaser method. They can be solved in the Moisture Transport in Building Materials interface by setting the moisture diffusivity to 0, and in the Heat Transfer in Building Materials interface by setting the vapor permeability to 0.

The advantage of this second approach is that you need to provide less hygroscopic material properties. In particular, the moisture diffusivity used for the expression of the liquid transport flux is not required. However, for high values of relative humidity, the simplifications mentioned above may result in an overestimation of the relative humidity and in consequence of the risk of condensation.

MODELING OF THE VAPOR BARRIER

Upside and downside moisture fluxes defined by $\beta(\phi_d - \phi_u)$ and $\beta(\phi_u - \phi_d)$ are applied at the interface between the interior siding and the isolation to model the vapor barrier. The moisture transfer coefficient β is defined as

$$\beta = \frac{\delta p_{\text{sat}}}{\mu d_{\text{s}}}$$

where δ is the vapor permeability of still air (SI unit: s), p_{sat} is the saturation pressure of water vapor (SI unit: Pa), μ is the vapor resistance factor (dimensionless), and d_s is the vapor barrier thickness (SI unit: m).

DIURNAL VARIATIONS OF OUTDOOR CONDITIONS

The effect of time-dependent outdoor conditions on condensation risk is studied by using typical weather data from ASHRAE database. Average temperature and relative humidity ambient conditions in Dublin from the 15^{th} to the 17^{th} of April are used for the definition of the convective flux conditions on the exterior side of the wall. The simulation is run over two days with the temperature and relative humidity conditions shown in the graph of Figure 2.



Figure 2: Ambient data for temperature and relative humidity used on the exterior side of the wall.

TEMPERATURE AND MOISTURE DISTRIBUTIONS WITHOUT VAPOR BARRIER

The temperature and moisture distributions due to the different outdoor and indoor conditions are shown in Figure 3 and Figure 4. The highest values of relative humidity are obtained close to the bracing.



Figure 3: Temperature distribution, stationary study without vapor barrier.



Figure 4: Relative humidity distribution, stationary study without vapor barrier.

EFFECT OF VAPOR BARRIER ON HEAT AND MOISTURE DISTRIBUTION

The graph of Figure 5 shows that the addition of a vapor barrier between the interior siding and the isolation reduces the risk of condensation at the interface between the wooden frame/isolation and the bracing.



Figure 5: Effect of vapor barrier on relative humidity distribution across the wall, in the wooden frame and in the isolation.

The effect on temperature distribution is shown in Figure 6.



Figure 6: Effect of vapor barrier on temperature distribution across the wall, in the wooden frame and in the isolation.

COMPARISON OF THE MODELING APPROACHES

The Glaser method overestimates the relative humidity and hence the risk of condensation by not taking into account the liquid transport which becomes significant when the



relative humidity is high, close to the bracing. The effect on temperature and moisture distribution is shown in Figure 7 and Figure 8.

Figure 7: Comparison of the modeling approaches for the temperature distribution across the wall, in the wooden frame and in the isolation.



Figure 8: Comparison of the modeling approaches for the relative humidity distribution across the wall, in the wooden frame and in the isolation.

Reference

1. EN 15026, Hygrothermal performance of building components and building elements - Assessment of moisture transfer by numerical simulation, CEN, 2007.

Application Library path: Heat_Transfer_Module/ Buildings_and_Constructions/wood_frame_wall

Modeling Instructions

From the File menu, choose New.

NEW

In the New window, click 🔗 Model Wizard.

MODEL WIZARD

- I In the Model Wizard window, click **2D**.
- 2 In the Select Physics tree, select Heat Transfer>Heat and Moisture Transport> Building Materials.
- 3 Click Add.
- 4 Click 🔿 Study.
- 5 In the Select Study tree, select General Studies>Stationary.
- 6 Click **M** Done.

ROOT

First define the geometry of the wall, composed of wood studs and isolation boards, completed at the top and bottom by a bracing and an interior siding.

GLOBAL DEFINITIONS

Parameters 1

- I In the Model Builder window, under Global Definitions click Parameters I.
- 2 In the Settings window for Parameters, locate the Parameters section.
- 3 Click 📂 Load from File.
- 4 Browse to the model's Application Libraries folder and double-click the file wood_frame_wall_parameters.txt.

GEOMETRY I

Rectangle 1 (r1)

- I 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 L.
- 4 In the **Height** text field, type t_il + t_i + t_b.
- 5 Click 틤 Build Selected.
- 6 Click to expand the Layers section. In the table, enter the following settings:

Layer name	Thickness (m)
Layer 1	t_il
Layer 2	t_i

7 Click 🟢 Build All Objects.

Rectangle 2 (r2)

- I 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 d_wf.
- 4 In the **Height** text field, type t_i.
- 5 Locate the Position section. In the x text field, type L/4-d_wf/2.
- 6 In the y text field, type t_i1.
- 7 Click 🟢 Build All Objects.

Copy I (copyI)

- I In the Geometry toolbar, click 💭 Transforms and choose Copy.
- 2 Select the object r2 only.
- 3 In the Settings window for Copy, locate the Displacement section.
- 4 In the x text field, type L/2.
- 5 Click 🟢 Build All Objects.

DEFINITIONS

Ambient Properties 1 (ampr1)

- I 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_ext.
- 4 In the ϕ_{amb} text field, type phi_ext.

Now, set the physics interfaces for the modeling of heat and moisture transport with the method described in Dynamic modeling of Heat and Moisture Transport.

HEAT TRANSFER IN BUILDING MATERIALS (HT)

Building Material I

- I In the Model Builder window, under Component I (comp1)> Heat Transfer in Building Materials (ht) click Building Material I.
- **2** In the **Settings** window for **Building Material**, locate the **Building Material Properties** section.
- 3 From the Specify list, choose Vapor resistance factor.

Heat Flux 1

- I In the Physics toolbar, click Boundaries and choose Heat Flux.
- 2 Select Boundary 7 only.
- 3 In the Settings window for Heat Flux, locate the Heat Flux section.
- 4 From the Flux type list, choose Convective heat flux.
- **5** In the *h* text field, type h_ext.
- 6 From the T_{ext} list, choose Ambient temperature (amprl).

Heat Flux 2

- I In the Physics toolbar, click Boundaries and choose Heat Flux.
- **2** Select Boundary 2 only.
- 3 In the Settings window for Heat Flux, locate the Heat Flux section.
- 4 From the Flux type list, choose Convective heat flux.
- **5** In the *h* text field, type h_int.
- 6 In the T_{ext} text field, type T_int.

Initial Values 1

- I In the Model Builder window, click Initial Values I.
- 2 In the Settings window for Initial Values, locate the Initial Values section.
- **3** In the *T* text field, type T_int.

MOISTURE TRANSPORT IN BUILDING MATERIALS (MT)

Building Material I

I In the Model Builder window, under Component I (compl)>

Moisture Transport in Building Materials (mt) click Building Material I.

- 2 In the Settings window for Building Material, locate the Building Material section.
- **3** From the Specify list, choose Vapor resistance factor.

Moisture Flux 1

- I In the Physics toolbar, click Boundaries and choose Moisture Flux.
- 2 Select Boundary 7 only.
- 3 In the Settings window for Moisture Flux, locate the Moisture Flux section.
- 4 From the Flux type list, choose Convective moisture flux, pressures difference.
- **5** In the β_p text field, type beta_ext.
- 6 From the T_{ext} list, choose Ambient temperature (amprl).

7 From the $\phi_{w,ext}$ list, choose Ambient relative humidity (amprl).

Moisture Flux 2

- I In the Physics toolbar, click Boundaries and choose Moisture Flux.
- 2 Select Boundary 2 only.
- 3 In the Settings window for Moisture Flux, locate the Moisture Flux section.
- 4 From the Flux type list, choose Convective moisture flux, pressures difference.
- **5** In the β_p text field, type beta_int.
- **6** In the *T*_{ext} text field, type T_int.
- 7 In the $\phi_{w,ext}$ text field, type phi_int.

Initial Values 1

- I In the Model Builder window, click Initial Values I.
- 2 In the Settings window for Initial Values, locate the Initial Values section.
- **3** In the $\phi_{w,0}$ text field, type phi_int.

Thin Moisture Barrier I

- I In the Physics toolbar, click Boundaries and choose Thin Moisture Barrier.
- **2** Select Boundaries 4, 9, 12, 15, and 18 only.

Pick materials from the library for the wood studs (pine), the isolation (cellulose), the interior siding (gypsum), and the vapor barrier (plastic coated paper). In addition, define a new material for the bracing.

ADD MATERIAL

- I In the Home toolbar, click 🙀 Add Material to open the Add Material window.
- 2 Go to the Add Material window.
- 3 In the tree, select Building>Wood (pine).
- 4 Click Add to Component in the window toolbar.
- 5 In the tree, select Building>Cellulose board.
- 6 Click Add to Component in the window toolbar.
- 7 In the tree, select Building>Gypsum board.
- 8 Click Add to Component in the window toolbar.
- 9 In the tree, select Building>Plastic coated paper.
- **IO** Click **Add to Component** in the window toolbar.

II In the Home toolbar, click 🙀 Add Material to close the Add Material window.

MATERIALS

Wood (pine) (mat1)

- I In the Model Builder window, under Component I (compl)>Materials click Wood (pine) (matl).
- **2** Select Domains 4 and 6 only.

Cellulose board (mat2)

- I In the Model Builder window, click Cellulose board (mat2).
- **2** Select Domains 2, 5, and 7 only.

Gypsum board (mat3)

- I In the Model Builder window, click Gypsum board (mat3).
- 2 Select Domain 1 only.

Plastic coated paper (mat4)

- I In the Model Builder window, click Plastic coated paper (mat4).
- 2 In the Settings window for Material, locate the Geometric Entity Selection section.
- **3** From the **Geometric entity level** list, choose **Boundary**.
- 4 Select Boundaries 4, 9, 12, 15, and 18 only.

Wooden panel (OSB)

- I In the Model Builder window, right-click Materials and choose Blank Material.
- 2 In the Settings window for Material, type Wooden panel (OSB) in the Label text field.
- **3** Select Domain 3 only.
- k_eff
- I In the Model Builder window, expand the Component I (compl)>Materials> Wooden panel (OSB) (mat5) node.
- 2 Right-click Component I (compl)>Materials>Wooden panel (OSB) (mat5)>Basic (def) and choose Functions>Interpolation.
- 3 In the Settings window for Interpolation, type k_eff in the Label text field.
- 4 Locate the **Definition** section. In the **Function name** text field, type k_eff.
- **5** In the table, enter the following settings:

t	f(t)	
0	0.11	

t	f(t)
0.97	0.14
1	0.6

- 6 Locate the Interpolation and Extrapolation section. From the Interpolation list, choose Piecewise cubic.
- 7 From the Extrapolation list, choose Linear.
- 8 Locate the Units section. In the Argument table, enter the following settings:

Argument	Unit
t	1

9 In the Function table, enter the following settings:

Function	Unit
k_eff	W/(m*K)

Interpolation: Dw

- I In the Home toolbar, click f(X) Functions and choose Global>Interpolation.
- **2** In the **Settings** window for **Interpolation**, type **Interpolation**: Dw in the **Label** text field.
- 3 Locate the Definition section. In the Function name text field, type Dw.
- **4** In the table, enter the following settings:

t	f(t)	
0	2.93e-12	
0.97	2.93e-12	
1	6.52e-10	

- **5** Locate the **Interpolation and Extrapolation** section. From the **Interpolation** list, choose **Piecewise cubic**.
- 6 From the Extrapolation list, choose Linear.
- 7 Locate the Units section. In the Argument table, enter the following settings:

Argument	Unit
t	1

8 In the **Function** table, enter the following settings:

Function	Unit
Dw	m^2/s

Analytic: wc

- I In the Home toolbar, click f(X) Functions and choose Global>Analytic.
- 2 In the Settings window for Analytic, type Analytic: wc in the Label text field.
- **3** In the **Function name** text field, type wc.
- 4 Locate the Definition section. In the Expression text field, type 202.68*x^2 24.813*
 x + 6.1962.
- **5** Locate the **Units** section. In the table, enter the following settings:

Argument	Unit
x	1

6 In the Function text field, type kg/m^3.

Wooden panel (OSB) (mat5)

- In the Model Builder window, under Component I (compl)>Materials click
 Wooden panel (OSB) (mat5).
- 2 In the Settings window for Material, locate the Material Contents 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(mt .phi)	W/(m·K)	Basic
Density	rho	646	kg/m³	Basic
Heat capacity at constant pressure	Ср	1500	J/(kg·K)	Basic
Diffusion coefficient	D_iso ; Dii = D_iso, Dij = 0	Dw(mt.ph i)	m²/s	Basic
Water content	w_c	wc(mt.ph i)	kg/m³	Basic
Vapor resistance factor	mu_vrf	162	1	Basic

4 In the Model Builder window, collapse the Wooden panel (OSB) (mat5) node.

Refine the mesh to improve the discretization of the bracing and interior siding.

MESH I

- I In the Model Builder window, under Component I (compl) click Mesh I.
- 2 In the Settings window for Mesh, locate the Physics-Controlled Mesh section.
- 3 From the Element size list, choose Extremely fine.

Set the study to ignore the vapor barrier as a first step, and compute.

STUDY I (STATIONARY, WITHOUT VAPOR BARRIER)

- I In the Model Builder window, click Study I.
- 2 In the Settings window for Study, type Study 1 (Stationary, without vapor barrier) in the Label text field.

Step 1: Stationary

- I In the Model Builder window, under Study I (Stationary, without vapor barrier) click Step I: Stationary.
- 2 In the Settings window for Stationary, locate the Physics and Variables Selection section.
- **3** Select the Modify model configuration for study step check box.
- 4 In the tree, select Component I (compl)>Moisture Transport in Building Materials (mt)> Thin Moisture Barrier I.
- 5 Click 💋 Disable.

Solution I (soll)

- I In the Study toolbar, click **The Show Default Solver**.
- 2 In the Model Builder window, expand the Solution I (soll) node.
- 3 In the Model Builder window, expand the Study I (Stationary, without vapor barrier)> Solver Configurations>Solution I (sol1)>Stationary Solver I node, then click Fully Coupled I.
- **4** In the **Settings** window for **Fully Coupled**, click to expand the **Method and Termination** section.

Due to the high dependency of material properties on relative humidity, the default solver fails to converge. A first solution consists to reduce the damping factor value. Another solution is to use a dynamic damping factor value automatically defined by the solver in each iteration. To do so, use the **Automatic highly nonlinear** method.

- 5 From the Nonlinear method list, choose Automatic highly nonlinear (Newton).
- 6 In the Study toolbar, click **=** Compute.

RESULTS

Surface

The default plots show the temperature (Figure 3) and relative humidity (Figure 4) distributions.

- I In the Model Builder window, expand the Results>Temperature (ht) node, then click Surface.
- 2 In the Settings window for Surface, locate the Expression section.
- 3 From the Unit list, choose degC.

Now, define another study and run the computation with the vapor barrier.

ADD STUDY

- I In the Study toolbar, click 2 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>Stationary.
- 4 Click Add Study in the window toolbar.
- 5 In the Study toolbar, click Add Study to close the Add Study window.

STUDY 2 (STATIONARY, WITH VAPOR BARRIER)

- I In the Model Builder window, click Study 2.
- 2 In the **Settings** window for **Study**, type Study 2 (Stationary, with vapor barrier) in the **Label** text field.
- **3** In the **Study** toolbar, click **= Compute**.

RESULTS

Temperature (ht) 1

Plot the temperature and moisture distribution to check the effect of the vapor barrier. First, define cut lines across the wall, through the wood and the cellulose.

Cut Line Wood (Solution 1)

- I In the Model Builder window, expand the Results>Datasets node.
- 2 Right-click Results>Datasets and choose Cut Line 2D.
- **3** In the **Settings** window for **Cut Line 2D**, type **Cut Line Wood** (Solution 1) in the **Label** text field.
- 4 Locate the Line Data section. In row Point I, set X to L/4.

- **5** In row **Point 2**, set **X** to L/4.
- 6 Click 💽 Plot.
- 7 In row **Point I**, set **Y** to **0.15**.
- 8 Click 💿 Plot.

Cut Line Cellulose (Solution 1)

- I Right-click Cut Line Wood (Solution I) and choose Duplicate.
- 2 In the Settings window for Cut Line 2D, type Cut Line Cellulose (Solution 1) in the Label text field.
- 3 Locate the Line Data section. In row Point 1, set X to L/2.
- 4 In row Point 2, set X to L/2.
- 5 Click 💽 Plot.

Cut Line Wood (Solution 2)

- I In the Model Builder window, right-click Cut Line Wood (Solution I) and choose Duplicate.
- 2 In the Settings window for Cut Line 2D, type Cut Line Wood (Solution 2) in the Label text field.
- 3 Locate the Data section. From the Dataset list, choose Study 2 (Stationary, with vapor barrier)/Solution 2 (sol2).
- 4 Click 💽 Plot.

Cut Line Cellulose (Solution 2)

- I In the Model Builder window, right-click Cut Line Cellulose (Solution I) and choose Duplicate.
- 2 In the **Settings** window for **Cut Line 2D**, type **Cut Line Cellulose** (Solution 2) in the **Label** text field.
- 3 Locate the Data section. From the Dataset list, choose Study 2 (Stationary, with vapor barrier)/Solution 2 (sol2).
- 4 Click 💽 Plot.

Now, follow the instructions below to reproduce the plots of Figure 5 and Figure 6.

Temperature Across the Wall (Comparison)

- I In the Results toolbar, click \sim ID Plot Group.
- 2 In the Settings window for ID Plot Group, type Temperature Across the Wall (Comparison) in the Label text field.

- 3 Locate the Data section. From the Dataset list, choose None.
- 4 Locate the **Plot Settings** section.
- 5 Select the x-axis label check box. In the associated text field, type Distance from exterior (m).

Wood (without vapor barrier)

- I Right-click Temperature Across the Wall (Comparison) and choose Line Graph.
- 2 In the Settings window for Line Graph, locate the Data section.
- 3 From the Dataset list, choose Cut Line Wood (Solution I).
- 4 Locate the y-Axis Data section. From the Unit list, choose degC.
- 5 Click to expand the Coloring and Style section. From the Color list, choose Red.
- 6 From the Width list, choose 2.
- 7 Click to expand the Legends section. Select the Show legends check box.
- 8 From the Legends list, choose Manual.
- 9 In the table, enter the following settings:

Legends

Wood (without vapor barrier)

IO In the **Label** text field, type Wood (without vapor barrier).

II In the Temperature Across the Wall (Comparison) toolbar, click 💿 Plot.

Cellulose (without vapor barrier)

- I Right-click Wood (without vapor barrier) and choose Duplicate.
- 2 In the **Settings** window for **Line Graph**, type Cellulose (without vapor barrier) in the **Label** text field.
- 3 Locate the Data section. From the Dataset list, choose Cut Line Cellulose (Solution 1).
- 4 Locate the Coloring and Style section. From the Color list, choose Blue.
- **5** Locate the **Legends** section. In the table, enter the following settings:

Legends

Cellulose (without vapor barrier)

6 In the Temperature Across the Wall (Comparison) toolbar, click 💽 Plot.

Wood (with vapor barrier)

- I In the Model Builder window, right-click Wood (without vapor barrier) and choose Duplicate.
- 2 In the Settings window for Line Graph, type Wood (with vapor barrier) in the Label text field.
- 3 Locate the Data section. From the Dataset list, choose Cut Line Wood (Solution 2) .
- **4** Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dashed**.
- 5 Locate the Legends section. In the table, enter the following settings:

Legends

Wood (with vapor barrier)

6 In the Temperature Across the Wall (Comparison) toolbar, click 💽 Plot.

Cellulose (with vapor barrier)

- I In the Model Builder window, right-click Cellulose (without vapor barrier) and choose Duplicate.
- 2 In the Settings window for Line Graph, type Cellulose (with vapor barrier) in the Label text field.
- 3 Locate the Data section. From the Dataset list, choose Cut Line Cellulose (Solution 2).
- **4** Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dashed**.
- **5** Locate the **Legends** section. In the table, enter the following settings:

Legenus

Cellulose (with vapor barrier)

6 In the Temperature Across the Wall (Comparison) toolbar, click 💽 Plot.

Temperature Across the Wall (Comparison)

- I In the Model Builder window, click Temperature Across the Wall (Comparison).
- 2 In the Settings window for ID Plot Group, locate the Legend section.
- **3** From the **Position** list, choose **Lower right**.

Wood (without vapor barrier)

- I In the Model Builder window, click Wood (without vapor barrier).
- 2 In the Settings window for Line Graph, click to expand the Title section.

3 From the **Title type** list, choose **None**.

Cellulose (without vapor barrier)

- I In the Model Builder window, click Cellulose (without vapor barrier).
- 2 In the Settings window for Line Graph, locate the Title section.
- 3 From the Title type list, choose None.

Wood (with vapor barrier)

- I In the Model Builder window, click Wood (with vapor barrier).
- 2 In the Settings window for Line Graph, locate the Title section.
- **3** From the **Title type** list, choose **None**.

Cellulose (with vapor barrier)

- I In the Model Builder window, click Cellulose (with vapor barrier).
- 2 In the Settings window for Line Graph, locate the Title section.
- **3** From the **Title type** list, choose **None**.

Temperature Across the Wall (Comparison)

- I In the Model Builder window, click Temperature Across the Wall (Comparison).
- 2 In the Settings window for ID Plot Group, click to expand the Title section.
- 3 From the Title type list, choose Manual.
- 4 In the **Title** text area, type Temperature across the wall.
- 5 In the Temperature Across the Wall (Comparison) toolbar, click 💿 Plot.

Relative Humidity Across the Wall (Comparison)

- I Right-click Temperature Across the Wall (Comparison) and choose Duplicate.
- 2 In the Model Builder window, click Temperature Across the Wall (Comparison) I.
- **3** In the **Settings** window for **ID Plot Group**, type Relative Humidity Across the Wall (Comparison) in the **Label** text field.

Wood (without vapor barrier)

- I In the Model Builder window, click Wood (without vapor barrier).
- 2 In the Settings window for Line Graph, locate the y-Axis Data section.
- 3 In the **Expression** text field, type mt.phi.

Cellulose (without vapor barrier)

- I In the Model Builder window, click Cellulose (without vapor barrier).
- 2 In the Settings window for Line Graph, locate the y-Axis Data section.

3 In the Expression text field, type mt.phi.

Wood (with vapor barrier)

- I In the Model Builder window, click Wood (with vapor barrier).
- 2 In the Settings window for Line Graph, locate the y-Axis Data section.
- 3 In the Expression text field, type mt.phi.

Cellulose (with vapor barrier)

- I In the Model Builder window, click Cellulose (with vapor barrier).
- 2 In the Settings window for Line Graph, locate the y-Axis Data section.
- 3 In the **Expression** text field, type mt.phi.
- 4 In the Relative Humidity Across the Wall (Comparison) toolbar, click 💽 Plot.

Relative Humidity Across the Wall (Comparison)

- I In the Model Builder window, click Relative Humidity Across the Wall (Comparison).
- 2 In the Settings window for ID Plot Group, locate the Legend section.
- 3 From the Position list, choose Lower left.
- 4 Locate the Title section. In the Title text area, type Relative humidity across the wall.
- 5 In the Relative Humidity Across the Wall (Comparison) toolbar, click 🗿 Plot.

Next, define new interfaces and a new study for the modeling of heat and moisture transport with the method described in Static modeling of Heat and Moisture Transport.

ADD PHYSICS

- I 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 Heat Transfer>Heat and Moisture Transport>Building Materials.
- 4 Click Add to Component I in the window toolbar.

Disable the multiphysics coupling node to be able to set the vapor permeability to 0 in the **Heat Transfer in Building Materials** interface. By doing this the latent heat effect is ignored in the heat transfer equation.

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

MULTIPHYSICS

Heat and Moisture 2 (ham2)

In the Model Builder window, under Component 1 (comp1)>Multiphysics right-click Heat and Moisture 2 (ham2) and choose Disable.

Now, define the physics features.

HEAT TRANSFER IN BUILDING MATERIALS 2 (HT2)

Building Material I

- I In the Model Builder window, under Component I (compl)> Heat Transfer in Building Materials 2 (ht2) click Building Material I.
- 2 In the Settings window for Building Material, locate the Model Inputs section.
- **3** From the ϕ_w list, choose **Relative humidity (mt2/bml)**.
- 4 Locate the Building Material Properties section. From the δ_p list, choose User defined. In the associated text field, type 0.

Heat Flux 1

- I In the Physics toolbar, click Boundaries and choose Heat Flux.
- 2 In the Settings window for Heat Flux, locate the Heat Flux section.
- 3 From the Flux type list, choose Convective heat flux.
- **4** In the *h* text field, type h_ext.
- **5** In the T_{ext} text field, type T_ext.
- 6 Select Boundary 7 only.

Heat Flux 2

- I In the Physics toolbar, click Boundaries and choose Heat Flux.
- 2 In the Settings window for Heat Flux, locate the Heat Flux section.
- 3 From the Flux type list, choose Convective heat flux.
- **4** In the *h* text field, type h_int.
- **5** In the T_{ext} text field, type T_int.
- 6 Select Boundary 2 only.

Initial Values 1

- I In the Model Builder window, click Initial Values I.
- 2 In the Settings window for Initial Values, locate the Initial Values section.
- **3** In the *T*2 text field, type T_int.

MOISTURE TRANSPORT IN BUILDING MATERIALS 2 (MT2)

Building Material I

- I In the Model Builder window, under Component I (comp1)> Moisture Transport in Building Materials 2 (mt2) click Building Material I.
- 2 In the Settings window for Building Material, locate the Model Input section.
- **3** From the *T* list, choose **Temperature (ht2)**.
- **4** In the p_A text field, type ht2.pA.

Set the moisture diffusivity to 0 to ignore the capillary transport of liquid moisture.

5 Locate the Building Material section. From the D_w list, choose User defined. From the Specify list, choose Vapor resistance factor.

Moisture Flux 1

- I In the Physics toolbar, click Boundaries and choose Moisture Flux.
- 2 In the Settings window for Moisture Flux, locate the Moisture Flux section.
- 3 From the Flux type list, choose Convective moisture flux, pressures difference.
- **4** In the β_p text field, type beta_ext.
- **5** In the T_{ext} text field, type T_ext.
- **6** In the $\phi_{w.ext}$ text field, type phi_ext.
- 7 Select Boundary 7 only.

Moisture Flux 2

- I In the Physics toolbar, click Boundaries and choose Moisture Flux.
- 2 In the Settings window for Moisture Flux, locate the Moisture Flux section.
- 3 From the Flux type list, choose Convective moisture flux, pressures difference.
- **4** In the β_p text field, type beta_int.
- **5** In the T_{ext} text field, type T_int.
- **6** In the $\phi_{w.ext}$ text field, type phi_int.
- 7 Select Boundary 2 only.

Initial Values 1

- I In the Model Builder window, click Initial Values I.
- 2 In the Settings window for Initial Values, locate the Initial Values section.
- **3** In the $\phi_{w,0}$ text field, type phi_int.

ADD STUDY

- I In the Home toolbar, click $\stackrel{\text{res}}{\longrightarrow}$ 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>Stationary.
- 4 Click Add Study in the window toolbar.
- 5 In the Home toolbar, click Add Study to close the Add Study window.

STUDY 3

Step 1: Stationary

- I In the Settings window for Stationary, locate the Physics and Variables Selection section.
- 2 In the table, clear the Solve for check boxes for Heat Transfer in Building Materials (ht) and Moisture Transport in Building Materials (mt).
- 3 In the table, clear the Solve for check box for Heat and Moisture I (ham I).
- 4 In the Model Builder window, click Study 3.
- 5 In the Settings window for Study, type Study 3 (Stationary, Glaser method) in the Label text field.
- 6 In the Home toolbar, click **=** Compute.

Next, compare the results with those obtained with the first approach (without vapor barrier). Follow the instructions below to reproduce the plots of Figure 7 and Figure 8.

RESULTS

Cut Line Wood (Solution 2) 1

In the Model Builder window, right-click Cut Line Wood (Solution 2) and choose Duplicate.

Cut Line Cellulose (Solution 2) 1

In the Model Builder window, right-click Cut Line Cellulose (Solution 2) and choose Duplicate.

Cut Line Wood (Solution 3)

- I In the Settings window for Cut Line 2D, locate the Data section.
- 2 From the Dataset list, choose Study 3 (Stationary, Glaser method)/Solution 3 (sol3).
- 3 In the Label text field, type Cut Line Wood (Solution 3) .

Cut Line Cellulose (Solution 3)

- I In the Model Builder window, click Cut Line Cellulose (Solution 2) I.
- 2 In the Settings window for Cut Line 2D, locate the Data section.

3 From the Dataset list, choose Study 3 (Stationary, Glaser method)/Solution 3 (sol3).

4 In the Label text field, type Cut Line Cellulose (Solution 3) .

Wood (with vapor barrier)

In the Model Builder window, under Results>Temperature Across the Wall (Comparison) right-click Wood (with vapor barrier) and choose Disable.

Cellulose (with vapor barrier)

In the Model Builder window, right-click Cellulose (with vapor barrier) and choose Disable.

Wood (without vapor barrier) I

In the Model Builder window, right-click Wood (without vapor barrier) and choose Duplicate.

Cellulose (without vapor barrier) |

In the Model Builder window, right-click Cellulose (without vapor barrier) and choose Duplicate.

Wood (Glaser method)

- I In the Settings window for Line Graph, type Wood (Glaser method) in the Label text field.
- 2 Locate the Data section. From the Dataset list, choose Cut Line Wood (Solution 3).
- 3 Locate the y-Axis Data section. In the Expression text field, type T2.
- **4** Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dotted**.
- **5** Locate the **Legends** section. In the table, enter the following settings:

Legends

Wood (Glaser method)

Cellulose (Glaser method)

- I In the Model Builder window, under Results>Temperature Across the Wall (Comparison) click Cellulose (without vapor barrier) 1.
- 2 In the Settings window for Line Graph, type Cellulose (Glaser method) in the Label text field.
- **3** Locate the **Data** section. From the **Dataset** list, choose **Cut Line Cellulose (Solution 3)**.
- 4 Locate the y-Axis Data section. In the Expression text field, type T2.
- **5** Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dotted**.

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

Legends		
Cellulose	(Glaser	method)

7 In the Temperature Across the Wall (Comparison) toolbar, click 💽 Plot.

Wood (with vapor barrier)

In the Model Builder window, under Results>Relative Humidity Across the Wall (Comparison) right-click Wood (with vapor barrier) and choose Disable.

Cellulose (with vapor barrier)

In the Model Builder window, right-click Cellulose (with vapor barrier) and choose Disable.

Wood (without vapor barrier) |

In the Model Builder window, right-click Wood (without vapor barrier) and choose Duplicate.

Cellulose (without vapor barrier) |

In the Model Builder window, right-click Cellulose (without vapor barrier) and choose Duplicate.

Wood (Glaser method)

- I In the Settings window for Line Graph, type Wood (Glaser method) in the Label text field.
- 2 Locate the Data section. From the Dataset list, choose Cut Line Wood (Solution 3) .
- 3 Locate the y-Axis Data section. In the Expression text field, type mt2.phi.
- **4** Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dotted**.
- 5 Locate the Legends section. In the table, enter the following settings:

Legends

Wood (Glaser method)

Cellulose (Glaser method)

I In the Model Builder window, under Results>

Relative Humidity Across the Wall (Comparison) click Cellulose (without vapor barrier) 1.

- 2 In the Settings window for Line Graph, type Cellulose (Glaser method) in the Label text field.
- 3 Locate the Data section. From the Dataset list, choose Cut Line Cellulose (Solution 3) .

- 4 Locate the y-Axis Data section. In the Expression text field, type mt2.phi.
- **5** Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dotted**.
- 6 Locate the Legends section. In the table, enter the following settings:

Legends

Cellulose (Glaser method)

7 In the Relative Humidity Across the Wall (Comparison) toolbar, click 💿 Plot.

Finally, use typical weather data for the temperature and relative humidity on exterior side, and set a new time-dependent study to check the evolution of the relative humidity in the bracing and in the isolation over two days. The weather data are available with the Heat Transfer Module license or the Subsurface Module license.

SHARED PROPERTIES

Ambient Properties 1 (ampr1)

- I In the Model Builder window, under Component I (compl)>Definitions>Shared Properties click Ambient Properties I (amprl).
- 2 In the Settings window for Ambient Properties, locate the Ambient Settings section.
- 3 From the Ambient data list, choose Meteorological data (ASHRAE 2021).
- 4 Locate the Location section. Click Set Weather Station.
- 5 In the Weather Station dialog box, select Europe>Ireland>DUBLIN AP (039690) in the tree.
- 6 Click OK.
- 7 In the Settings window for Ambient Properties, locate the Time section.
- 8 Find the **Date** subsection. In the table, enter the following settings:

Day	Month
15	04

9 Find the Local time subsection. In the table, enter the following settings:

Hour	Minute	Second
0	00	00

ADD STUDY

I In the Home toolbar, click 2 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 \sim Add Study to close the Add Study window.

STUDY 4 (TIME DEPENDENT, WITH VAPOR BARRIER)

- I In the Model Builder window, click Study 4.
- 2 In the Settings window for Study, type Study 4 (Time Dependent, with vapor barrier) in the Label text field.

Step 1: Time Dependent

- I In the Model Builder window, under Study 4 (Time Dependent, with vapor barrier) click Step I: 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 boxes for Heat Transfer in Building Materials 2 (ht2) and Moisture Transport in Building Materials 2 (mt2).
- 4 Locate the Study Settings section. From the Time unit list, choose h.
- 5 In the **Output times** text field, type range(0,1,48).

Solution 4 (sol4)

I In the Study toolbar, click **The Show Default Solver**.

Disable the consistent initialization for a better evaluation of mass balance at the beginning of the simulation.

- 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**, click to expand the **Time Stepping** section.
- **4** Find the **Algebraic variable settings** subsection. From the **Consistent initialization** list, choose **Off**.
- 5 Click **=** Compute.

Plot the ambient data used as exterior conditions as in Figure 2 by following the instructions below.

RESULTS

Ambient Data

- I In the Home toolbar, click 🚛 Add Plot Group and choose ID Plot Group.
- 2 In the Settings window for ID Plot Group, type Ambient Data in the Label text field.
- 3 Locate the Data section. From the Dataset list, choose Study 4 (Time Dependent, with vapor barrier)/Solution 4 (sol4).

Point Graph I

- I Right-click Ambient Data and choose Point Graph.
- **2** Select Point 4 only.
- 3 In the Settings window for Point Graph, locate the y-Axis Data section.
- **4** In the **Expression** text field, type ampr1.T_amb.
- 5 From the Unit list, choose degC.
- 6 Click to expand the Legends section. Select the Show legends check box.
- 7 From the Legends list, choose Manual.
- 8 In the table, enter the following settings:

Legends

Temperature

Point Graph 2

- I In the Model Builder window, right-click Ambient Data and choose Point Graph.
- **2** Select Point 4 only.
- 3 In the Settings window for Point Graph, locate the y-Axis Data section.
- **4** In the **Expression** text field, type ampr1.phi_amb.
- 5 Locate the Legends section. Select the Show legends check box.
- 6 From the Legends list, choose Manual.
- 7 In the table, enter the following settings:

Legends

Relative humidity

Ambient Data

I In the Model Builder window, click Ambient Data.

2 In the Settings window for ID Plot Group, locate the Plot Settings section.

- **3** Select the **Two y-axes** check box.
- 4 In the table, select the Plot on secondary y-axis check box for Point Graph 2.
- 5 Locate the Title section. From the Title type list, choose Manual.
- 6 In the Title text area, type Ambient data over two days.
- 7 Click the 4 Zoom Extents button in the Graphics toolbar.
- 8 In the Ambient Data toolbar, click **I** Plot.

Define probes to plot the relative humidity in the bracing and in the isolation over time.

DEFINITIONS

Domain Point Probe: Relative humidity (bracing)

- I In the Definitions toolbar, click probes and choose Domain Point Probe.
- 2 In the Settings window for Domain Point Probe, type Domain Point Probe: Relative humidity (bracing) in the Label text field.
- **3** Locate the **Point Selection** section. In row **Coordinates**, set x to L/2.
- 4 In row **Coordinates**, set y to t_il+t_i+t_b*0.95.

Point Probe Expression 1 (ppb1)

- I In the Model Builder window, expand the Domain Point Probe: Relative humidity (bracing) node, then click Point Probe Expression I (ppbI).
- 2 In the Settings window for Point Probe Expression, locate the Expression section.
- 3 In the **Expression** text field, type mt.phi.
- **4** Click **C Update Results**.

Domain Point Probe: Relative humidity (isolation)

- I In the Model Builder window, right-click Domain Point Probe: Relative humidity (bracing) and choose Duplicate.
- 2 In the Model Builder window, click Domain Point Probe: Relative humidity (bracing) I.
- **3** In the **Settings** window for **Domain Point Probe**, type Domain Point Probe: Relative humidity (isolation) in the **Label** text field.
- 4 Locate the Point Selection section. In row Coordinates, set y to t_il+t_i*0.95.

Point Probe Expression 1 (ppb2)

- I In the Model Builder window, click Point Probe Expression I (ppb2).
- 2 In the Settings window for Point Probe Expression, click to expand the Table and Window Settings section.

- 3 From the **Output table** list, choose **New table**.
- 4 Click C Update Results.

RESULTS

Relative Humidity Over Two Days

- I In the Model Builder window, under Results click Probe Plot Group 16.
- 2 In the Settings window for ID Plot Group, type Relative Humidity Over Two Days in the Label text field.
- 3 Locate the Title section. From the Title type list, choose Manual.
- 4 In the Title text area, type Relative humidity over two days.
- 5 Locate the Plot Settings section.
- 6 Select the y-axis label check box. In the associated text field, type Relative humidity (1).

Probe Table Graph I

- I In the Model Builder window, expand the Relative Humidity Over Two Days node, then click Probe Table Graph I.
- 2 In the Settings window for Table Graph, click to expand the Legends section.
- 3 From the Legends list, choose Manual.
- **4** In the table, enter the following settings:

Legends

Point: (0.4, 0.14675)

Probe Table Graph 2

- I In the Model Builder window, click Probe Table Graph 2.
- 2 In the Settings window for Table Graph, locate the Legends section.
- 3 From the Legends list, choose Manual.
- **4** In the table, enter the following settings:

Legends

Point: (0.4, 0.1265)



5 In the Relative Humidity Over Two Days toolbar, click 💿 Plot.

Mass Balance

Follow the instructions below to check the overall mass balance over time.

- I In the Results toolbar, click (8.5) Global Evaluation.
- 2 In the Settings window for Global Evaluation, type Mass Balance in the Label text field.
- 3 Locate the Data section. From the Dataset list, choose Study 4 (Time Dependent, with vapor barrier)/Solution 4 (sol4).
- 4 Click Replace Expression in the upper-right corner of the Expressions section. From the menu, choose Component I (compl)>Moisture Transport in Building Materials> Mass balance>mt.massBalance - Mass balance - kg/s.
- 5 Click Add Expression in the upper-right corner of the Expressions section. From the menu, choose Component I (compl)>Moisture Transport in Building Materials>
 Mass balance>mt.dwcInt Total accumulated moisture rate kg/s.
- 6 Click Add Expression in the upper-right corner of the Expressions section. From the menu, choose Component I (compl)>Moisture Transport in Building Materials> Mass balance>mt.ntfluxInt - Total net moisture rate - kg/s.

- 7 Click Add Expression in the upper-right corner of the Expressions section. From the menu, choose Component I (compl)>Moisture Transport in Building Materials>
 Mass balance>mt.Glnt Total mass source kg/s.
- 8 Click **= Evaluate**.

TABLE

- I Go to the Table window.
- 2 Click Table Graph in the window toolbar.

RESULTS

Mass Balance

- I In the Model Builder window, under Results click ID Plot Group 17.
- 2 In the Settings window for ID Plot Group, type Mass Balance in the Label text field.

Table Graph I

- I In the Model Builder window, click Table Graph I.
- 2 In the Settings window for Table Graph, locate the Legends section.
- 3 Select the Show legends check box.
- 4 Locate the Coloring and Style section. From the Width list, choose 2.



Finally, to create a 3D plot of the relative humidity, follow the instructions below.

Extrusion 2D 1

- I In the **Results** toolbar, click **More Datasets** and choose **Extrusion 2D**.
- 2 In the Settings window for Extrusion 2D, locate the Data section.
- 3 From the Dataset list, choose Study 2 (Stationary, with vapor barrier)/Solution 2 (sol2).
- **4** Locate the **Extrusion** section. In the **z maximum** text field, type **0.2**.

Relative Humidity 3D

- I In the **Results** toolbar, click **I 3D Plot Group**.
- 2 In the Settings window for 3D Plot Group, type Relative Humidity 3D in the Label text field.

Relative Humidity

- I Right-click Relative Humidity 3D and choose Surface.
- 2 In the Settings window for Surface, type Relative Humidity in the Label text field.
- 3 Locate the Expression section. In the Expression text field, type mt.phi.
- 4 Locate the Coloring and Style section. Click Change Color Table.
- 5 In the Color Table dialog box, select Aurora>JupiterAuroraBorealis in the tree.
- 6 Click OK.
- 7 In the Settings window for Surface, locate the Coloring and Style section.
- 8 From the Color table transformation list, choose Reverse.
- 9 In the Relative Humidity 3D toolbar, click 🗿 Plot.