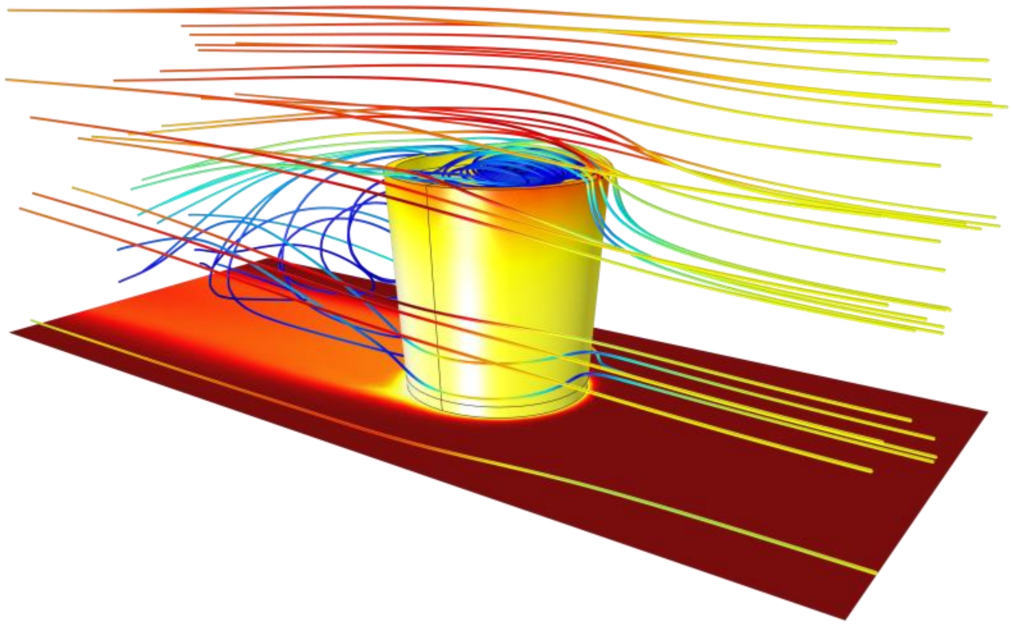
Modeling Moisture Transport, Evaporation and Condensation

Nicolas Huc

COMSOL

Agenda

- Role of Moisture Transport, Applications
- Moisture Transport Description
- Moisture Transport features in COMSOL Multiphysics
  - Moist Air
  - Building Material
  - Hygroscopic porous media
  - Heat And Moisture
- Modeling Strategies
  - Condensation Detection
  - Control of Phase Change
  - Thermal Management



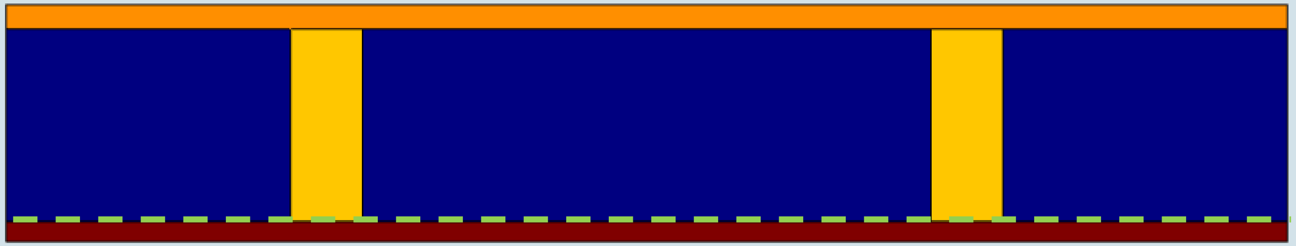
Simulation of conjugate heat transfer with phase change in water in a beaker

Detection of Condensation

- Damage of electronic devices
- Oxidation of metals, delamination
- Alteration of isolation properties of building materials
- Mold formation

Condensation Risk in a Wood-Frame Wall

Exterior
- $T = 273.15\ K$
- $\phi = 80\%$



Interior
- $T = 292.15\ K$
- $\phi = 50\%$

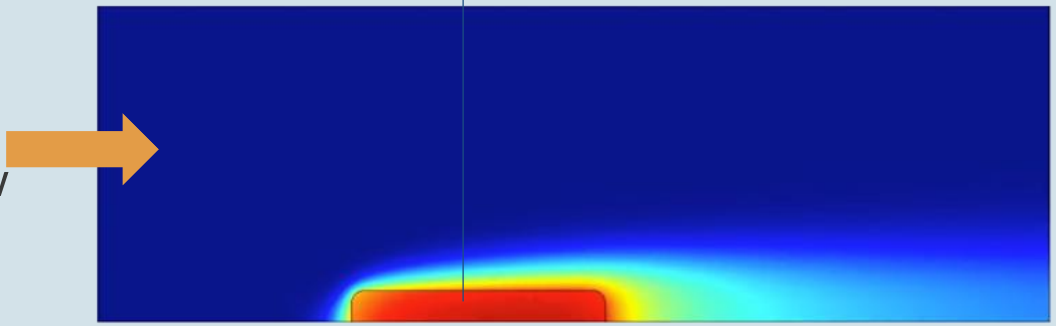
Vapor barrier
Wood
Cellulose
Wooden panel (OSB)
Plaster

comsol.com/model/condensation-risk-in-a-wood-frame-wall-43871

Control of Phase Change

- Material processing
- Food drying, cooking
- Drying of initial construction moisture

Evaporation in Porous Media

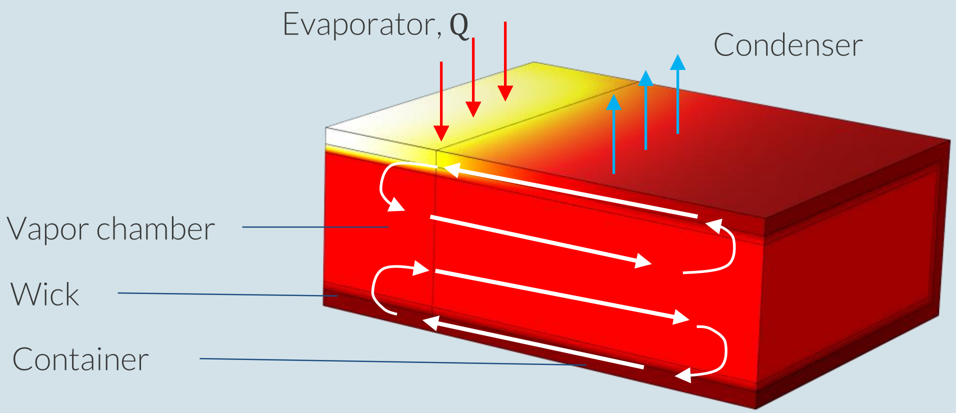


Relative humidity in the porous medium and surrounding air

Thermal Management

- Latent heat of evaporation
- Evaporative cooling walls
- Heat pipes

Evaporation and condensation in a flat heat pipe



Temperature distribution in a heat pipe

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Moisture Transport Description

Relative Humidity

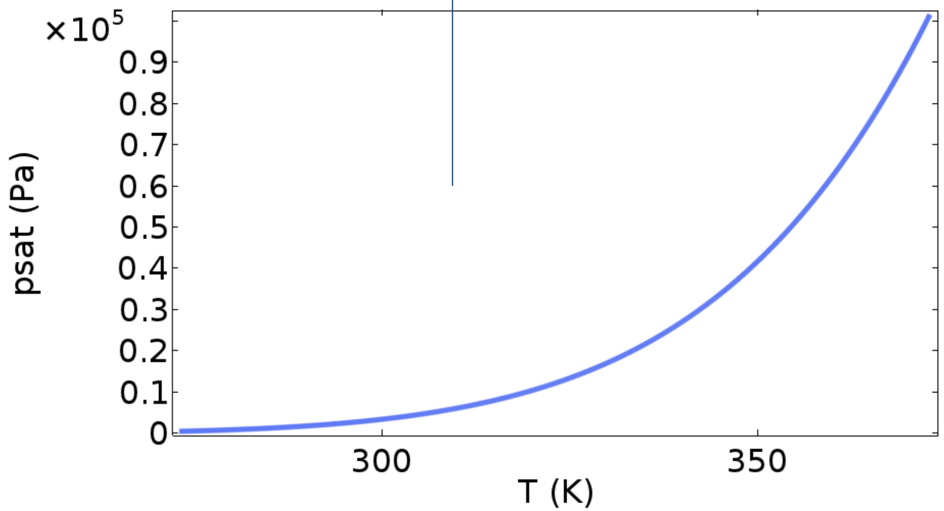
- The saturation $p_{sat}(T)$, increases with temperature

$$p_{sat}(T) = 610.7[\mathrm{Pa}] \cdot 10^{7.5\frac{T - 273.15[\mathrm{K}]}{T - 35.85[\mathrm{K}]}}$$

- The relative humidity is the ratio between the partial pressure of vapor and the saturation pressure

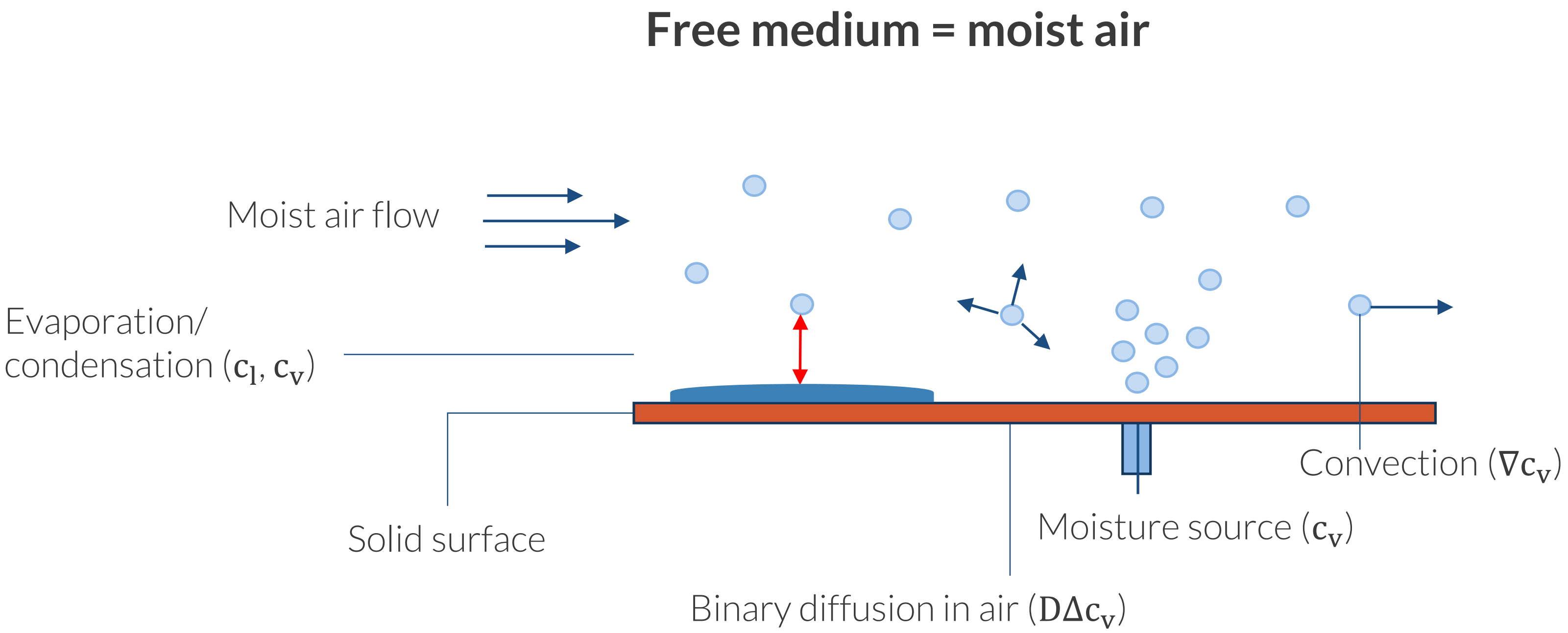
$$\varphi = \frac{p_v}{p_{sat}}$$

Supersaturation: $\phi > 1$



Saturation curve for water, φ=1

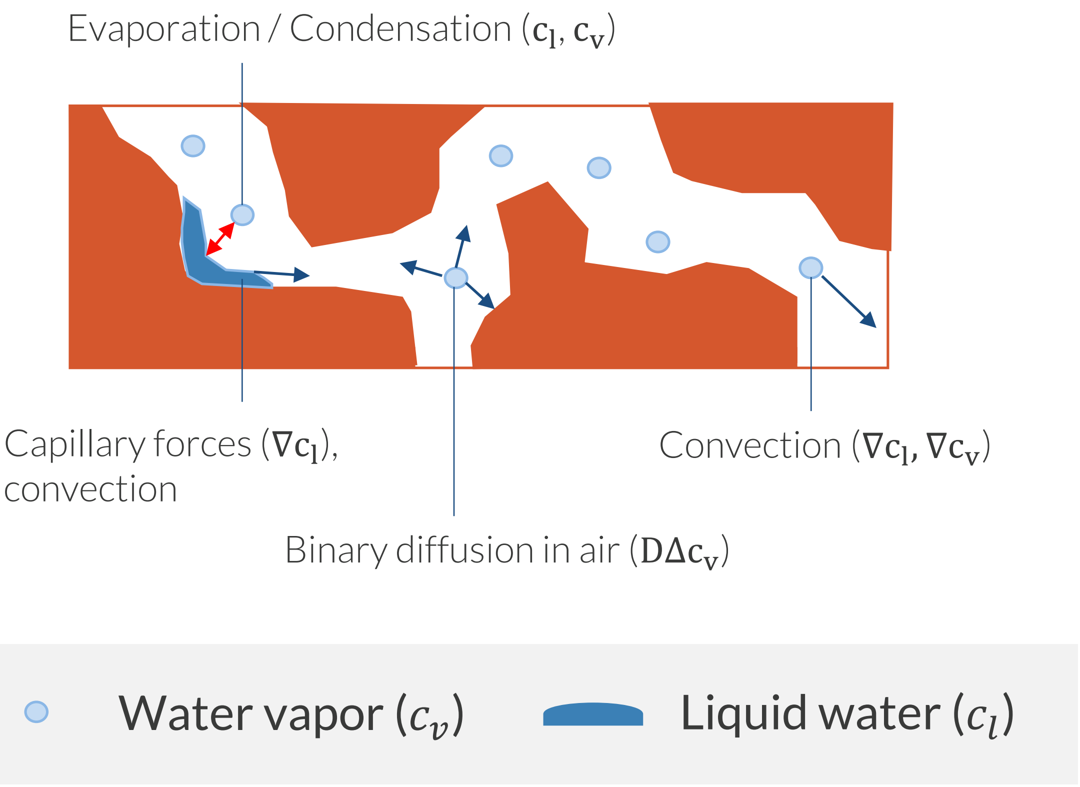
Moisture Transport: Moist Air



Water vapor (c_v) Liquid water (c_l)

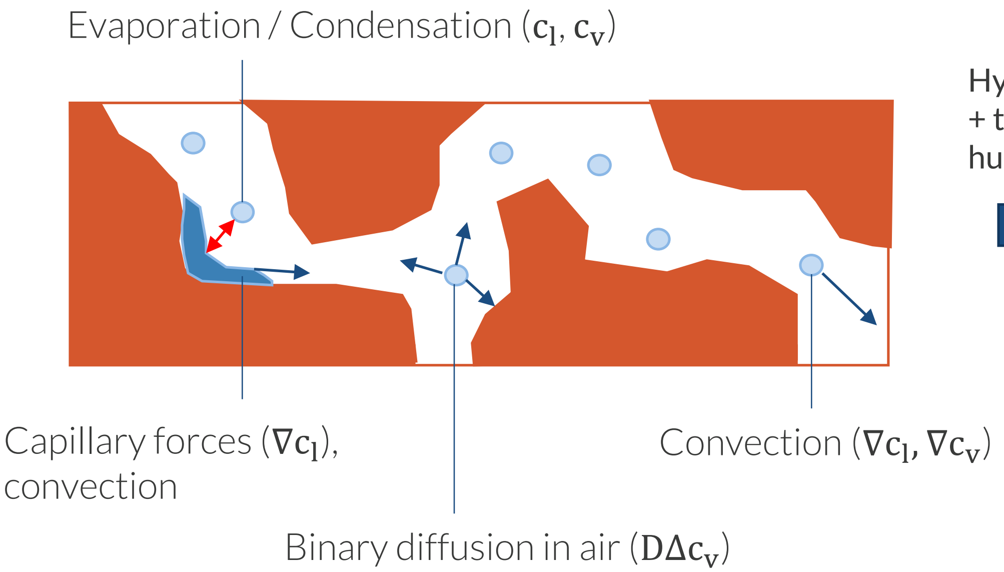
Moisture Transport: Porous Media

Porous medium



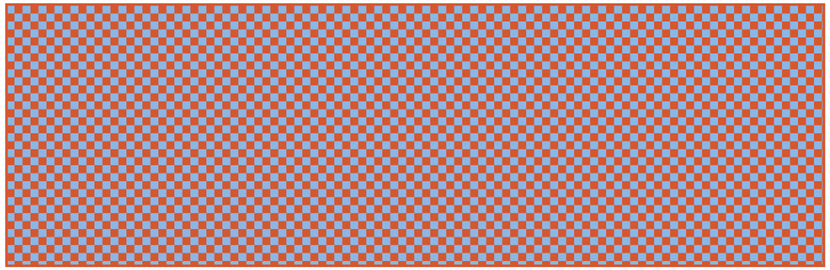
Moisture Transport: Building Material

Porous medium



Hypothesis on structure + temperature and humidity conditions

Building material

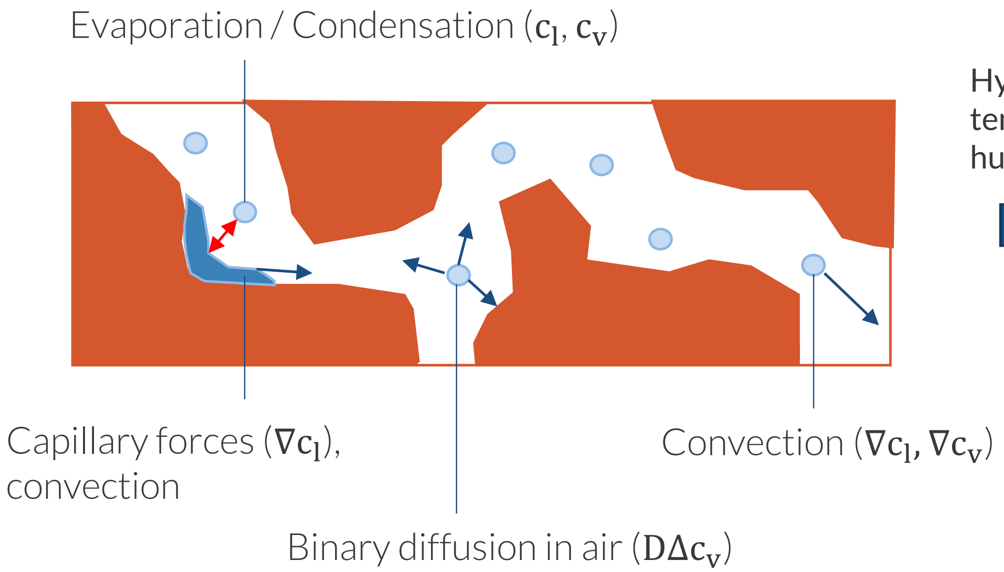


- Assumes equilibrium between the vapor and liquid phases, $w_c = w_c(\varphi)$
- Capillary forces
- Vapor diffusion

Water vapor (c_v) Liquid water (c_l)

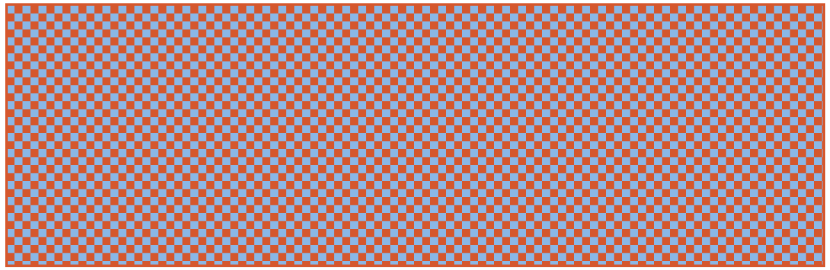
Moisture Transport: Hygroscopic Porous Media

Porous medium



Hypothesis on structure + temperature and humidity conditions

Hygroscopic Porous Media



- Assumes equilibrium between the vapor and liquid phases, $w_c = w_c(\varphi)$
- Liquid water convection and capillary flow
- Vapor diffusion and convection
- Gravity forces

Water vapor (c_v) Liquid water (c_l)

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Heat and Moisture Flow in Air

Governing equations

$$M_v \frac{\partial c_v}{\partial t} + M_v \mathbf{u} \cdot \nabla c_v + \nabla \cdot \mathbf{g} = G$$

$$\mathbf{g} = -M_v D \nabla c_v$$

$$c_v = \phi c_{sat}$$

Relative humidity

Governing equations

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot [-p\mathbf{I} + \mathbf{K}] + \mathbf{F}$$

$$\rho \nabla \cdot (\mathbf{u}) = 0$$

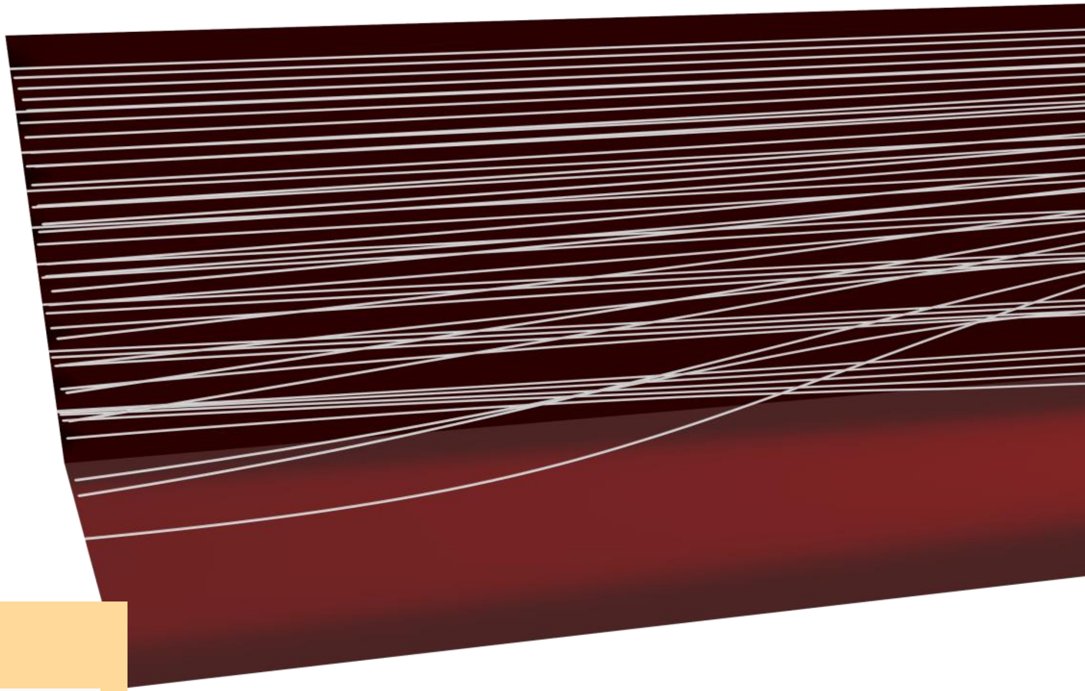
Velocity, pressure

Temperature

Governing equations

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q$$

$$\mathbf{q} = -k \nabla T$$



Heat and Moisture Flow in Air

Governing equations

$$M_v \frac{\partial c_v}{\partial t} + M_v \mathbf{u}\cdot\nabla c_v + \nabla\cdot\mathbf{g} = G$$

$$\mathbf{g} = -M_v D \nabla c_v$$

$$c_v = \phi c_{sat}$$

Relative humidity

$$c_{sat} = c_{sat}(T)$$

$$\rho = \rho(T, \phi)$$

$$q_{evap} = -L_v g_{evap}$$

$$\rho = \rho(p_A, \phi)$$

$$M_v \mathbf{u}\cdot\nabla c_v$$

Governing equations

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u}\cdot\nabla)\mathbf{u} = \nabla\cdot[-p\mathbf{I} + \mathbf{K}] + \mathbf{F}$$

$$\rho\nabla\cdot(\mathbf{u}) = 0$$

Velocity, pressure

Temperature

$$\rho = \rho(p_A, T)$$

$$\boldsymbol{\rho C_p}\mathbf{u}\cdot\nabla T$$

Governing equations

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u}\cdot\nabla T + \nabla\cdot\mathbf{q} = Q$$

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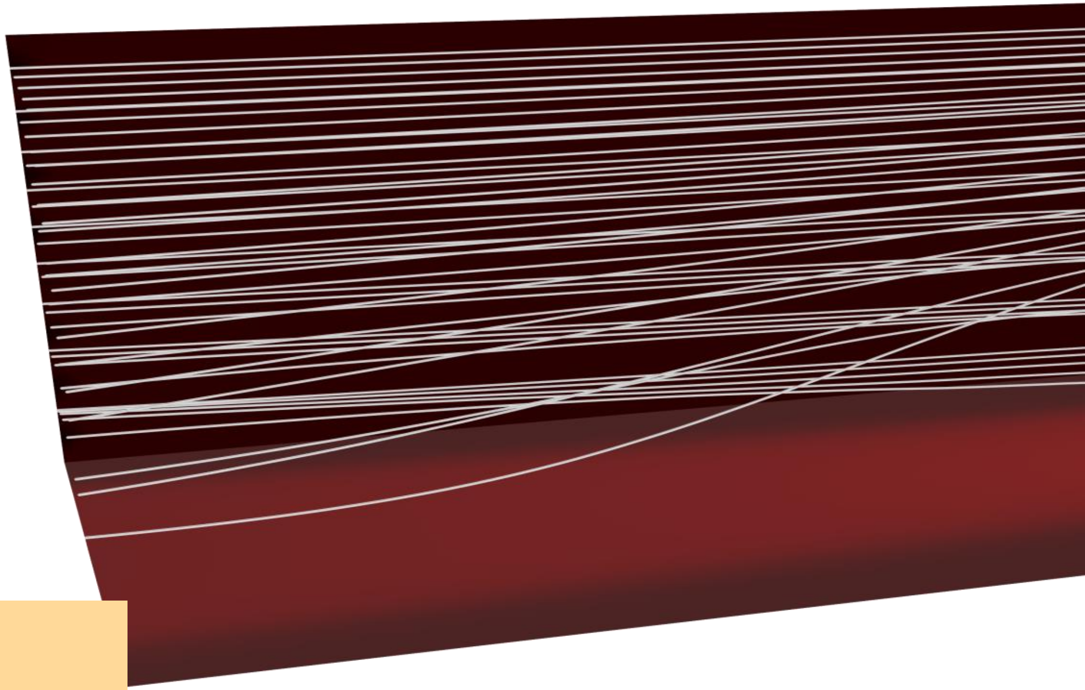
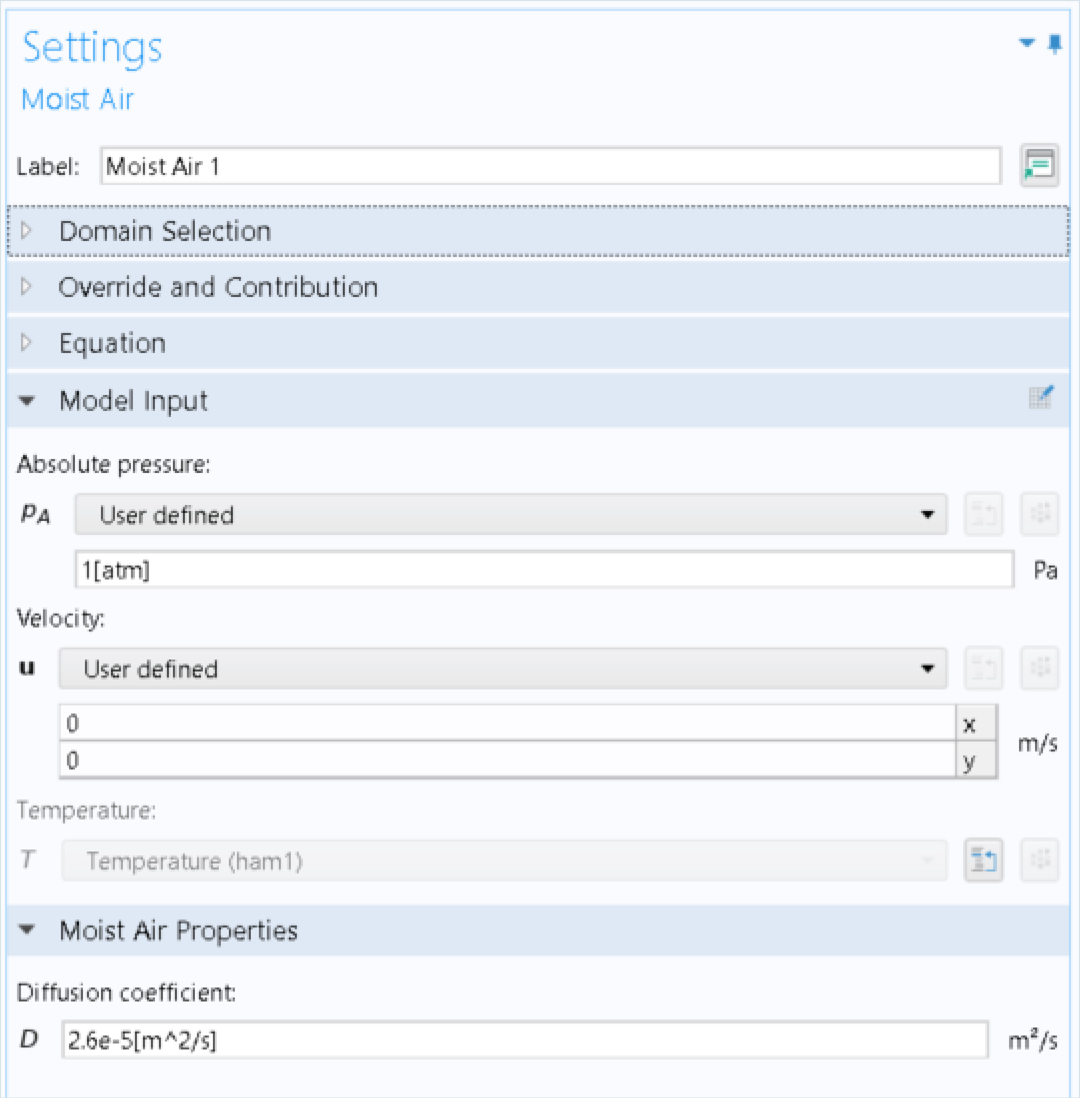


Moisture Transport Features

in COMSOL Multiphysics®

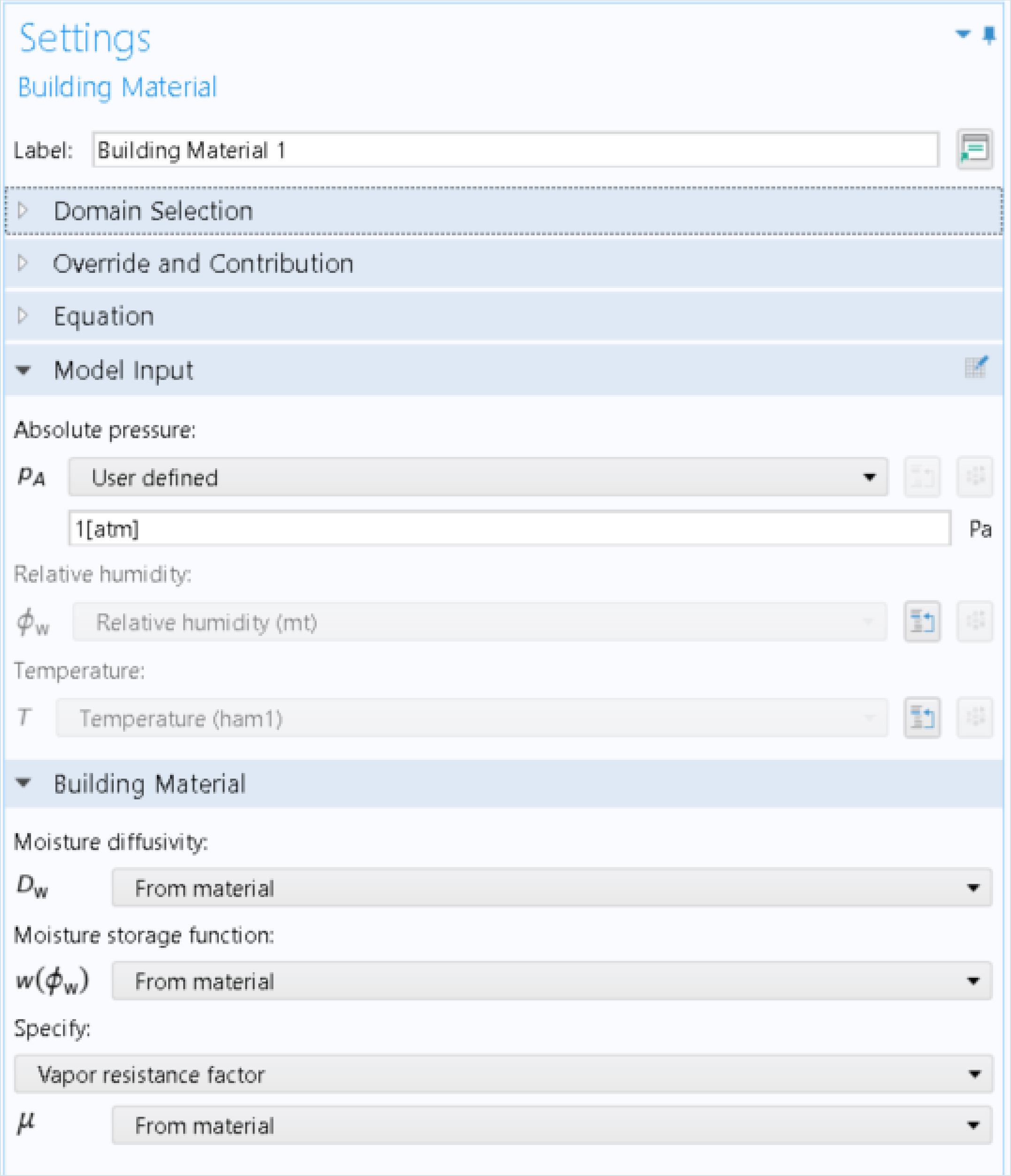
Moist Air

- Required inputs:
  - Pressure
  - Velocity
  - Temperature
  - Diffusion coefficient
- No phase change in the bulk
- Laminar or turbulent flow
- Condensation and evaporation on surrounding walls
  - Moist surface
  - Wet surface



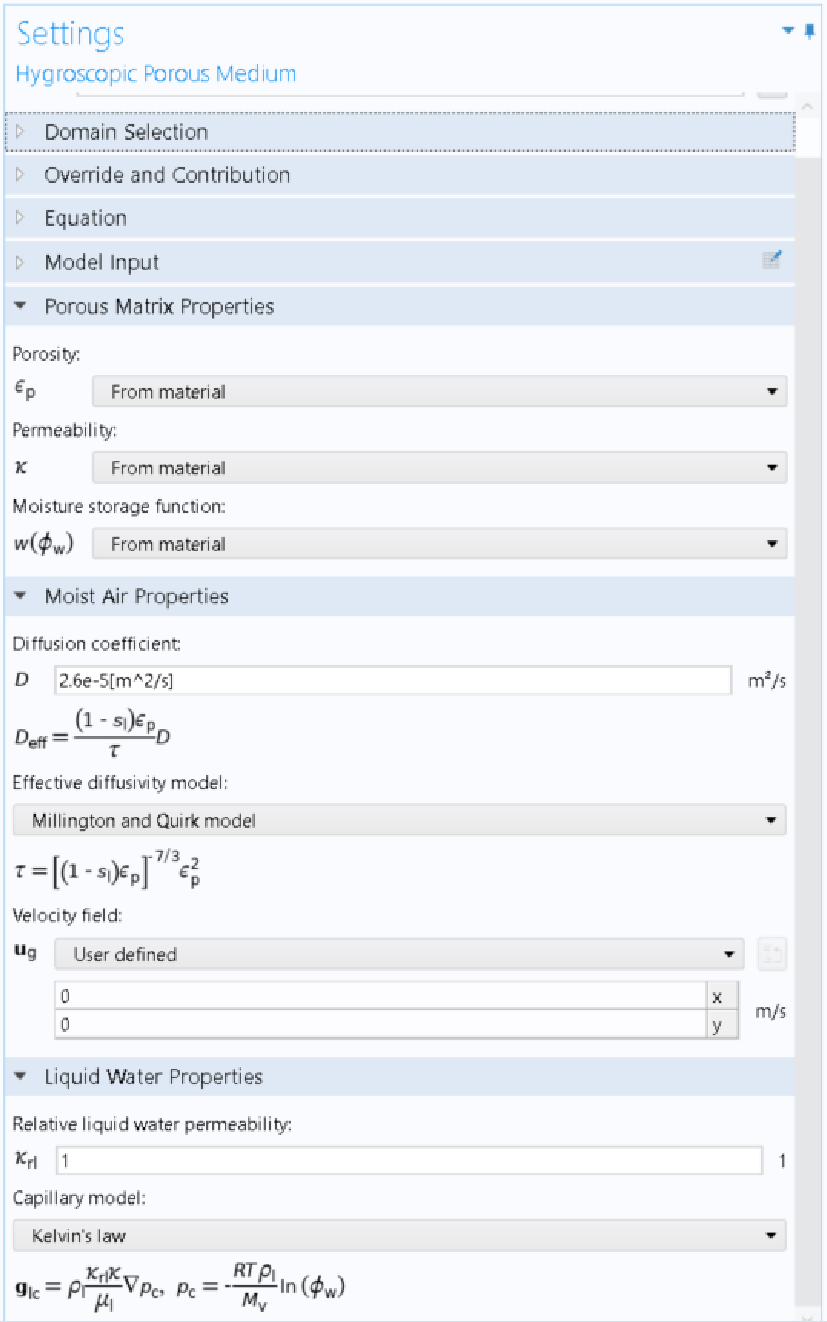
Building Material

- Required inputs:
  - Pressure
  - Temperature
  - Moisture diffusivity $D_w(\phi)$
  - Moisture storage function $w(\phi)$ (sorption isotherm)
  - Vapor permeability δ_p or vapor resistance factor μ
- Equilibrium between the vapor and liquid phases, Laminar or turbulent flow
- Convection and gravity are neglected
- Equations from EN15026:2007



Hygroscopic Porous Medium

- Required inputs:
  - Pressure
  - Temperature
  - Porosity, permeability
  - Moisture storage function
  - Diffusion coefficient, diffusivity model
  - Vapor velocity
  - Relative liquid water permeability
  - Capillary model
- Vapor diffusion and convection
- Liquid water convection and capillary flow
- Gravity forces



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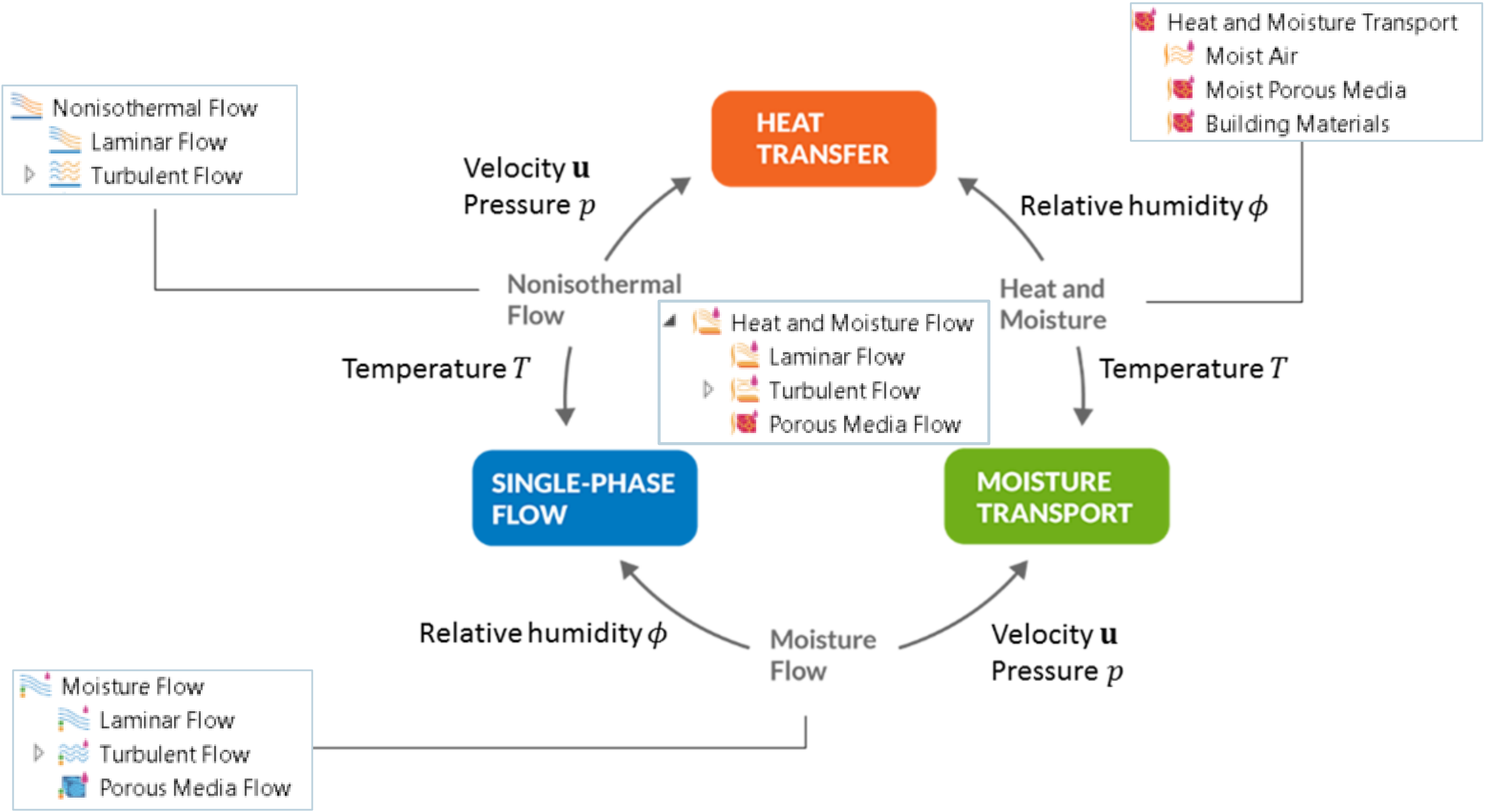
Heat and Moisture Transport: Physics and Multiphysics Interfaces



Condensation Detection

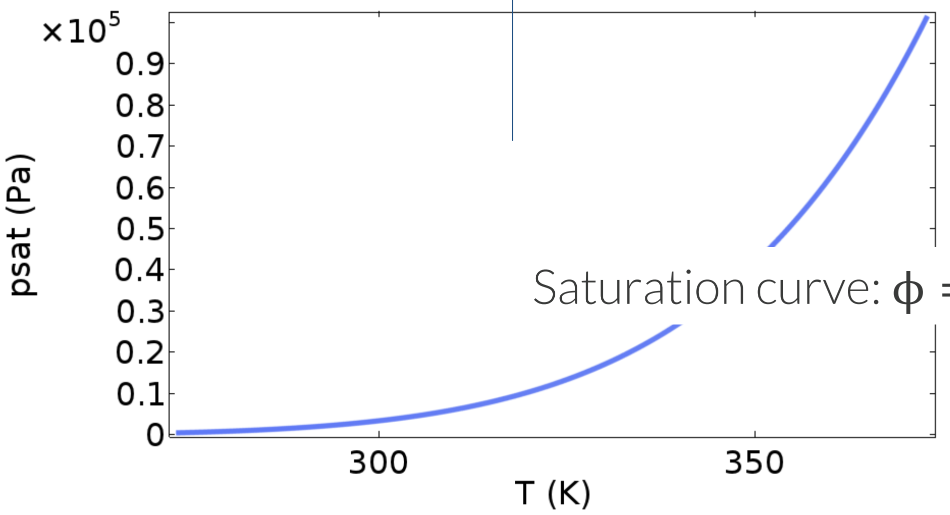
Detection of Condensation

Saturation pressure $p_{sat}(T)$

$$p_{sat}(T) = 610.7[\mathrm{Pa}] \cdot 10^{7.5\frac{T-273.15[\mathrm{K}]}{T-35.85[\mathrm{K}]}}$$

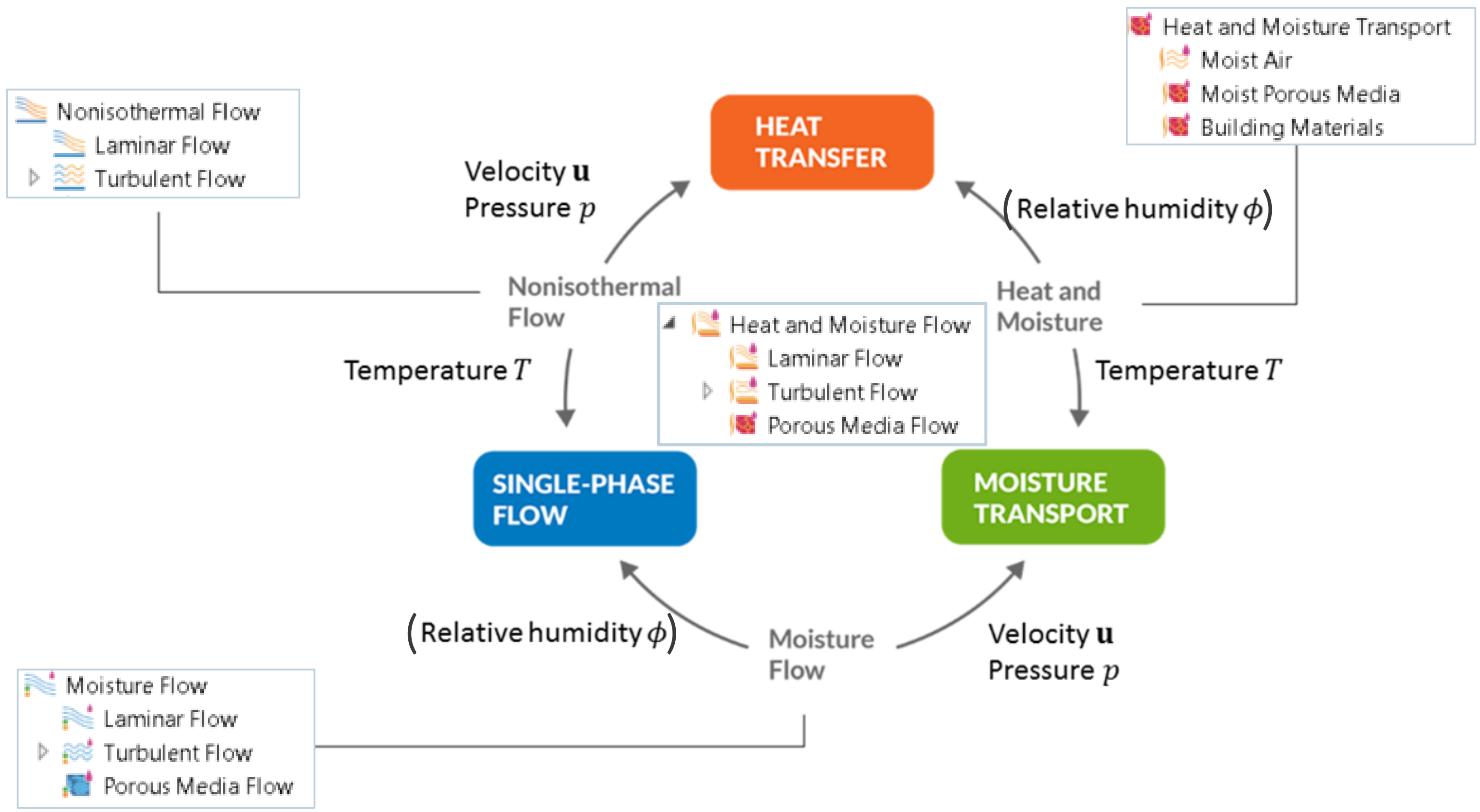
$$\phi = \frac{p_v}{p_{sat}}$$

Supersaturation: $\phi > 1$
= risk of condensation



Saturation curve: $\phi = 1$

Detection of Condensation



Detection of Condensation

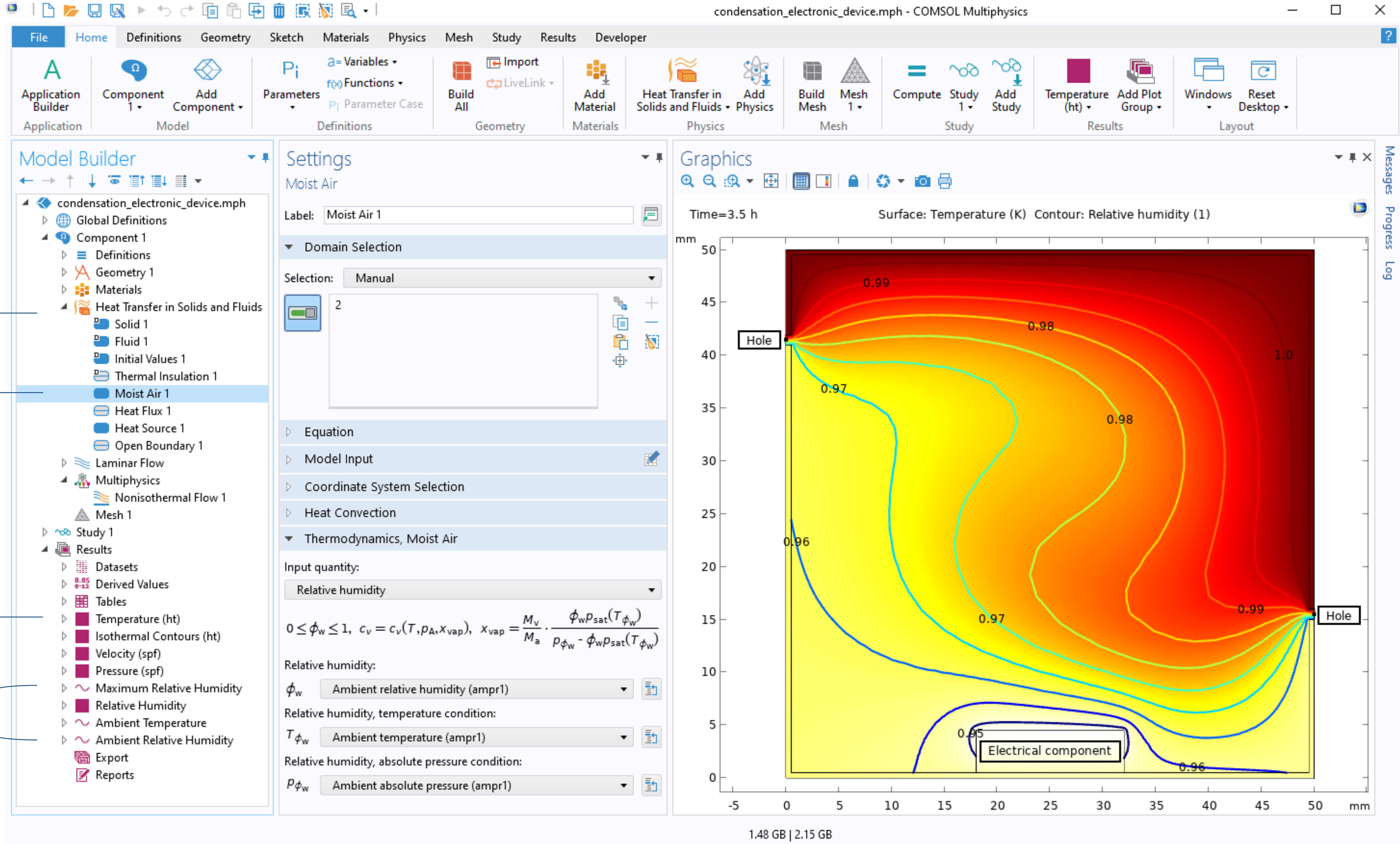
Heat Transfer interface

+

Moist Air feature

Default results: heat transfer

Postprocessing: moisture content



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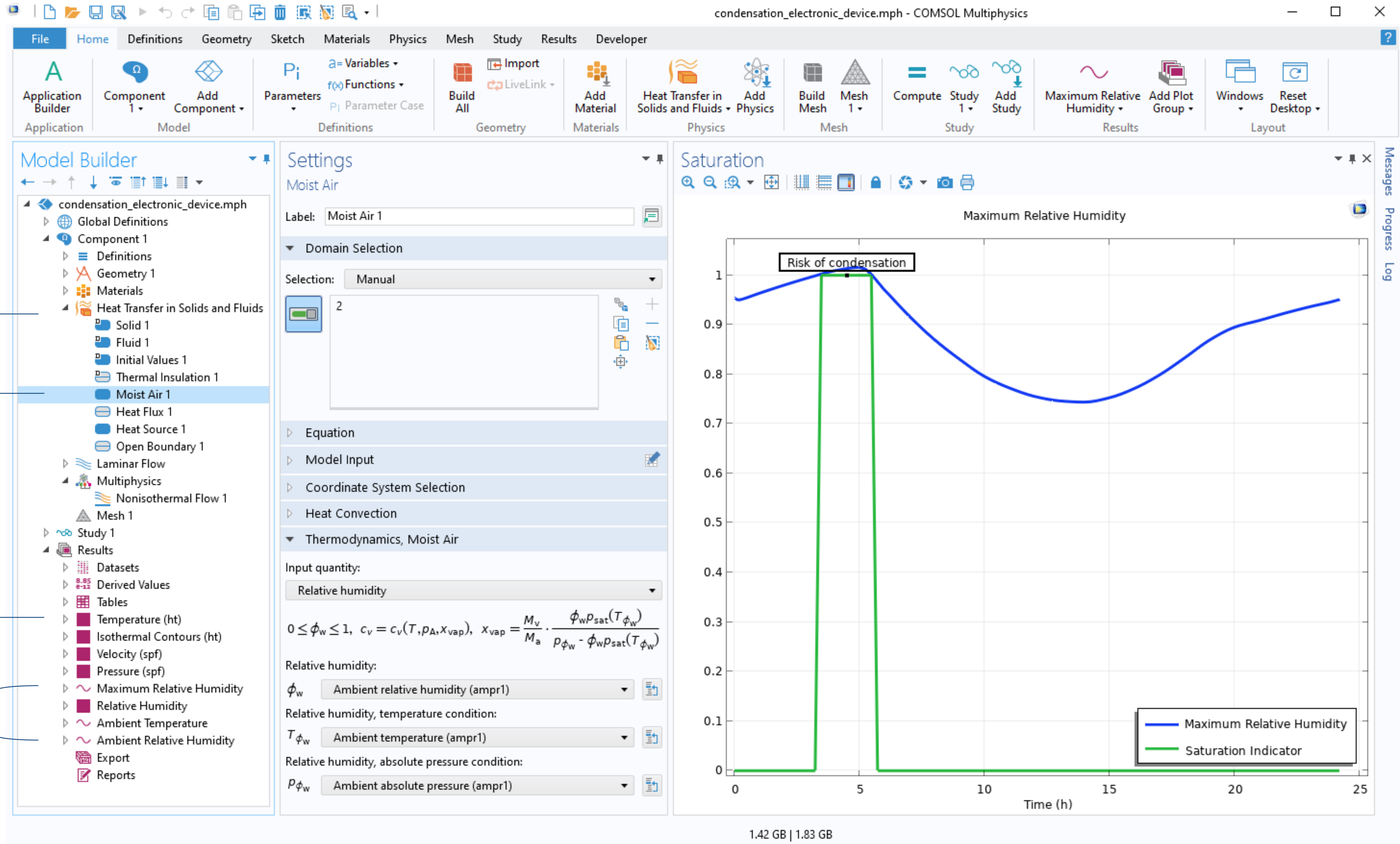
Detection of Condensation

Heat Transfer interface

+

Moist Air feature



Default results:
heat transfer

Postprocessing:
moisture content

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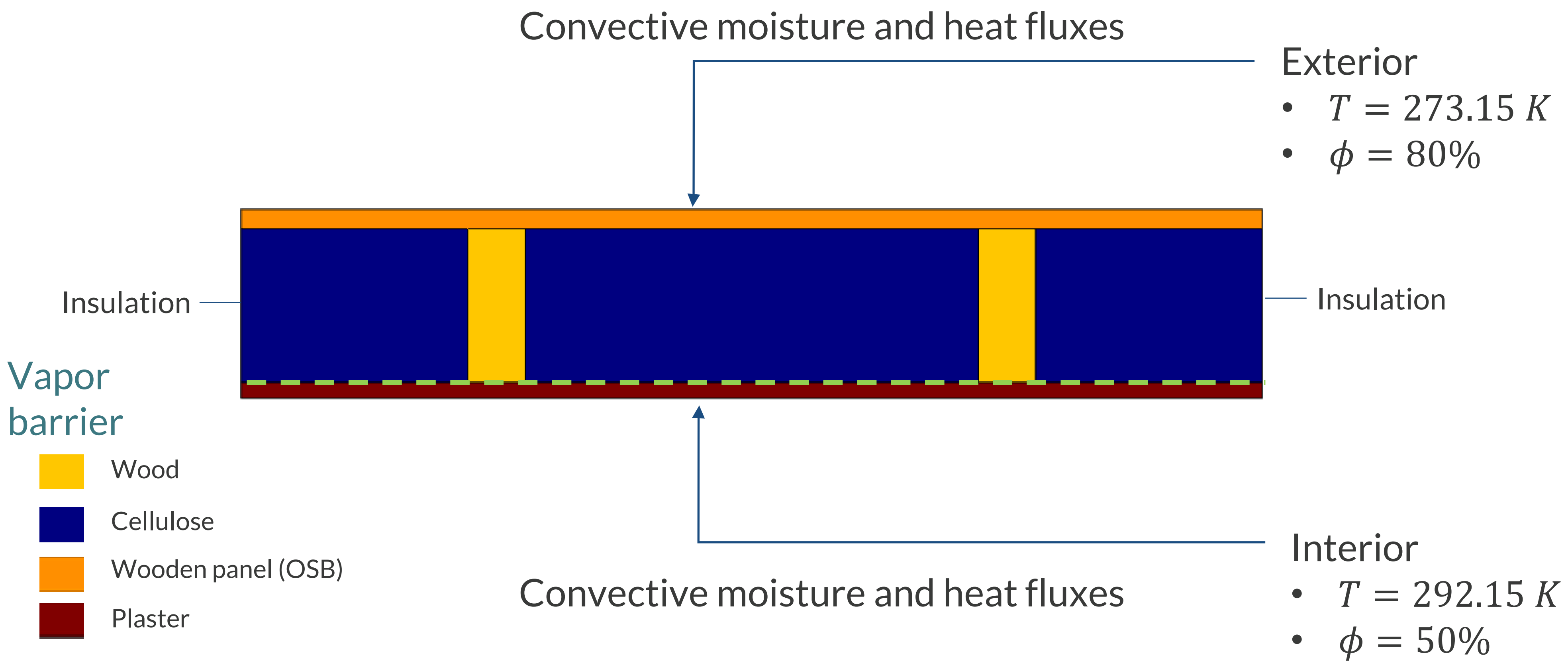
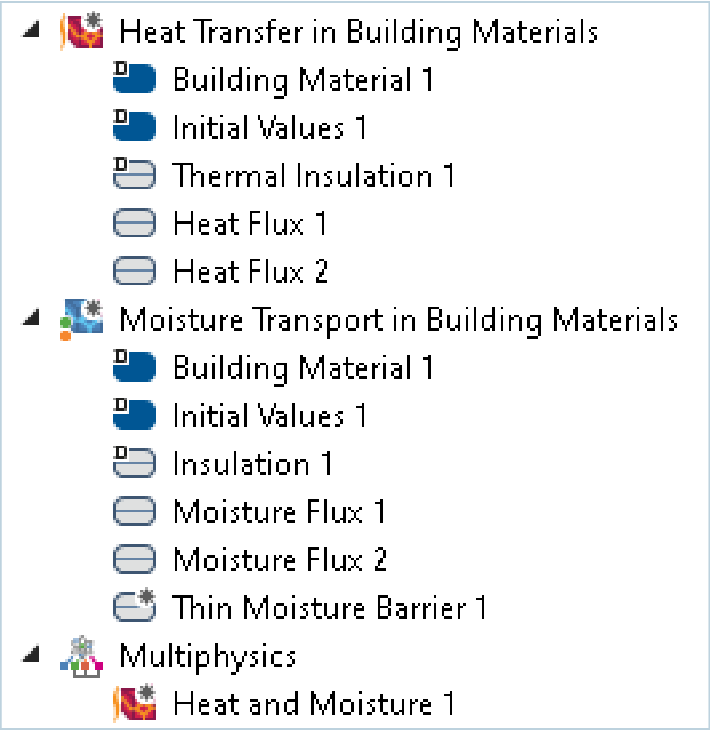
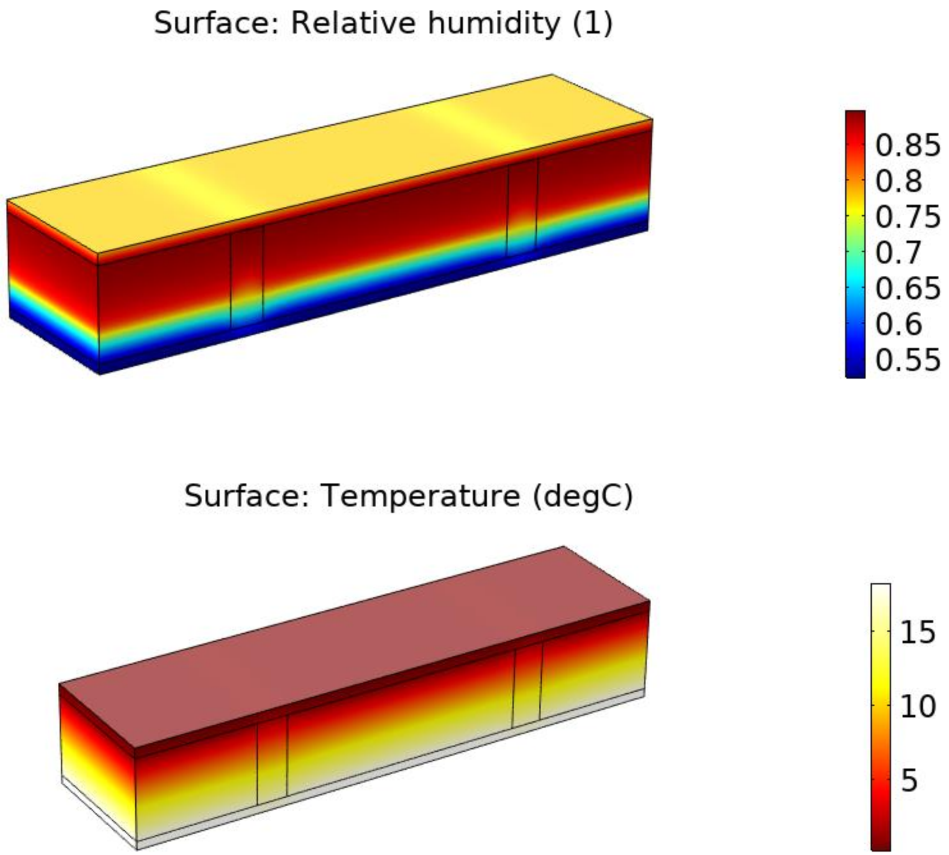
Condensation Risk in a Wood-Frame Wall



Condensation Risk in a Wood-Frame Wall

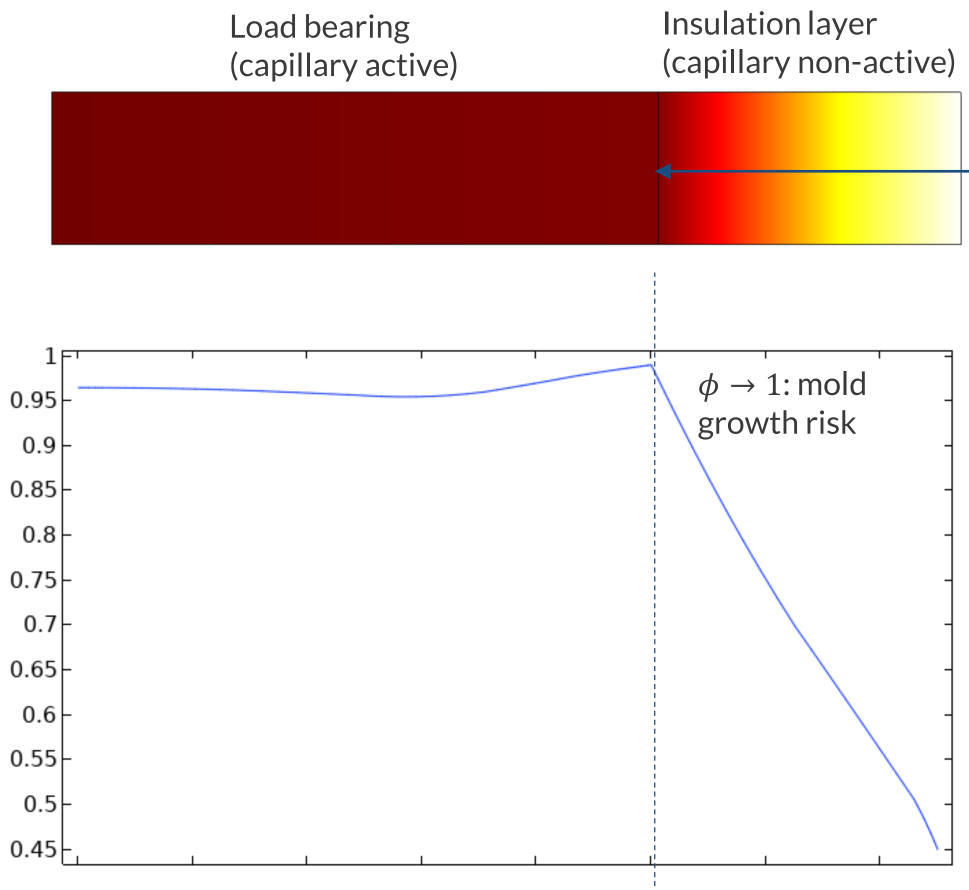




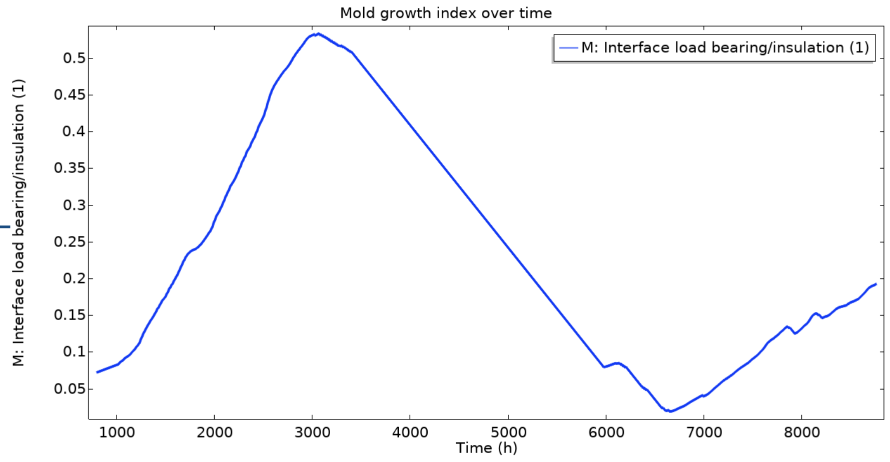
Relative humidity (up) and temperature (down) in a wood-frame wall

Mold risk in Building Materials

- Heat and moisture in an insulated roof



- VTT model: mold growth prediction
  - Mold index M, from 0 (no growth) to 6 (nearly 100% of mold on surface)
  - $\frac{dM(t)}{dt} = f(T, \phi)$
  - $f(T, \phi)$ given for several sensitivity classes



Control of Phase Change

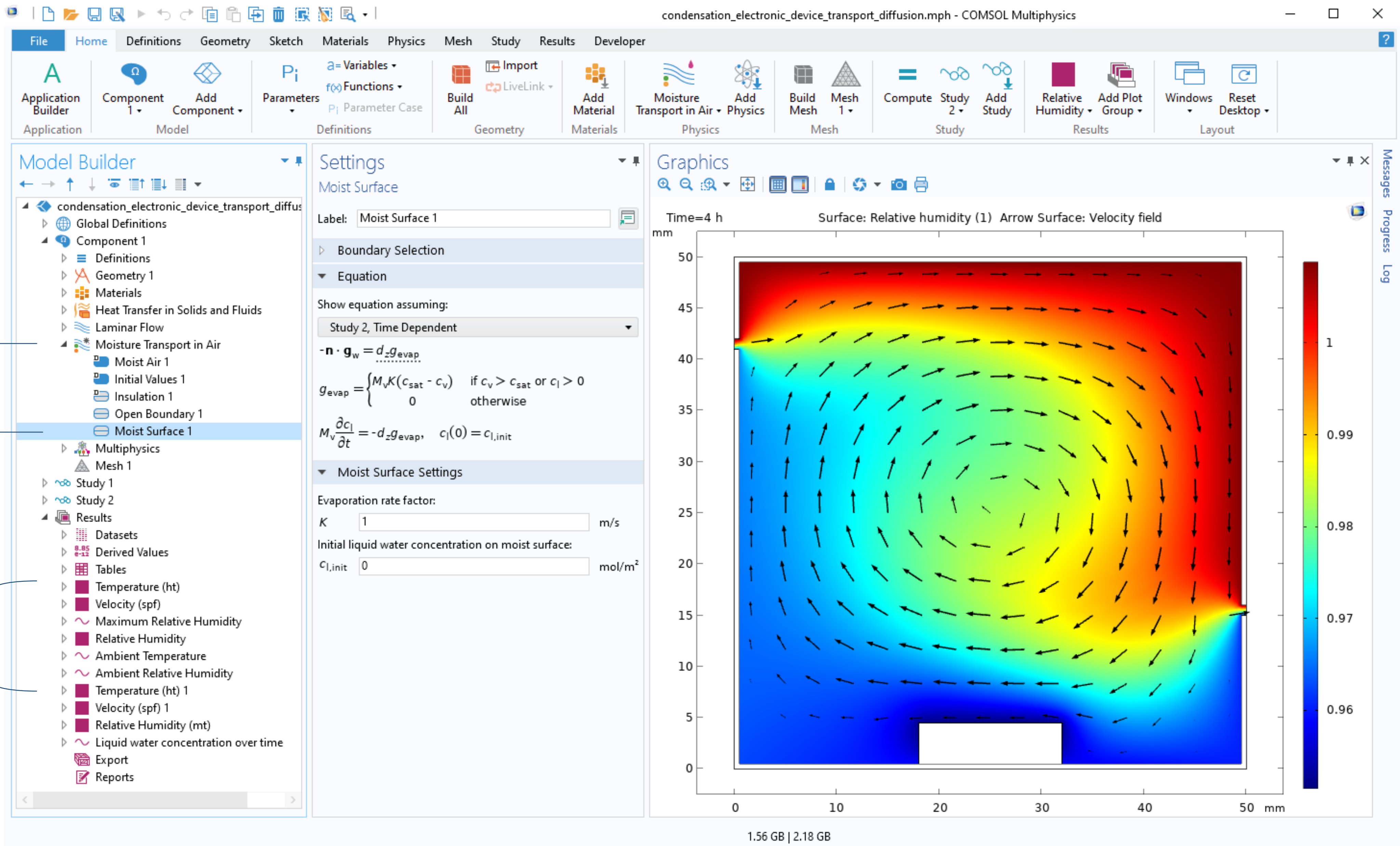
Detection of Condensation

Moisture Transport interface

+

Moist Surface

Default results:
heat & moisture transport



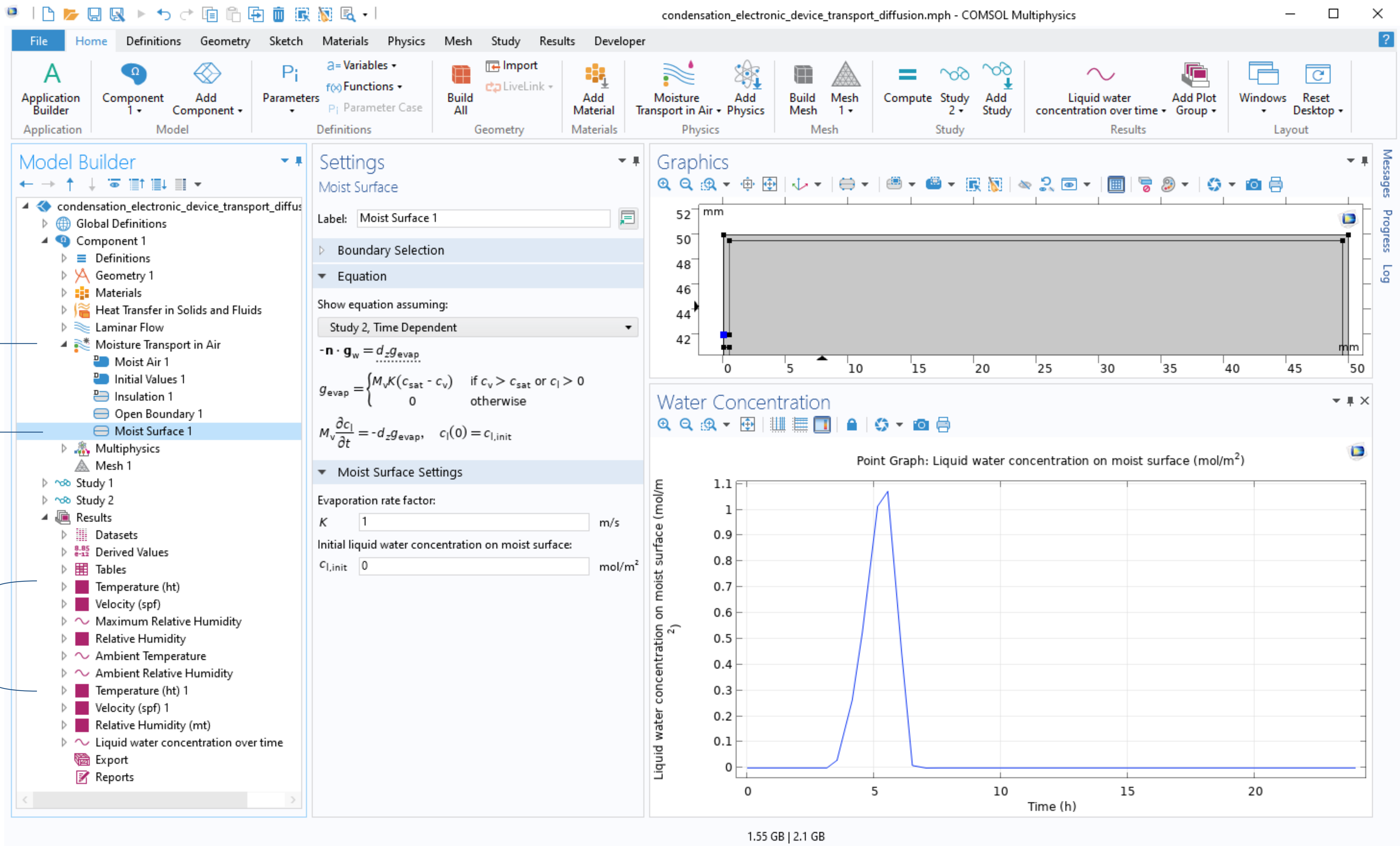
Detection of Condensation

Moisture Transport interface

+

Moist Surface

Default results: heat & moisture transport



Heat and Moisture Flow in Air

Relative humidity

Governing equations

$$M_v \frac{\partial c_v}{\partial t} + M_v \mathbf{u} \cdot \nabla c_v + \nabla \cdot \mathbf{g} = G$$

$$\mathbf{g} = -M_v D \nabla c_v$$

$$c_v = \phi c_{sat}$$

Velocity, pressure

Governing equations

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot [-p\mathbf{I} + \mathbf{K}] + \mathbf{F}$$

$$\rho \nabla \cdot (\mathbf{u}) = 0$$

Temperature

Governing equations

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q$$

$$\mathbf{q} = -k \nabla T$$

Relative humidity ↔ Velocity, pressure:

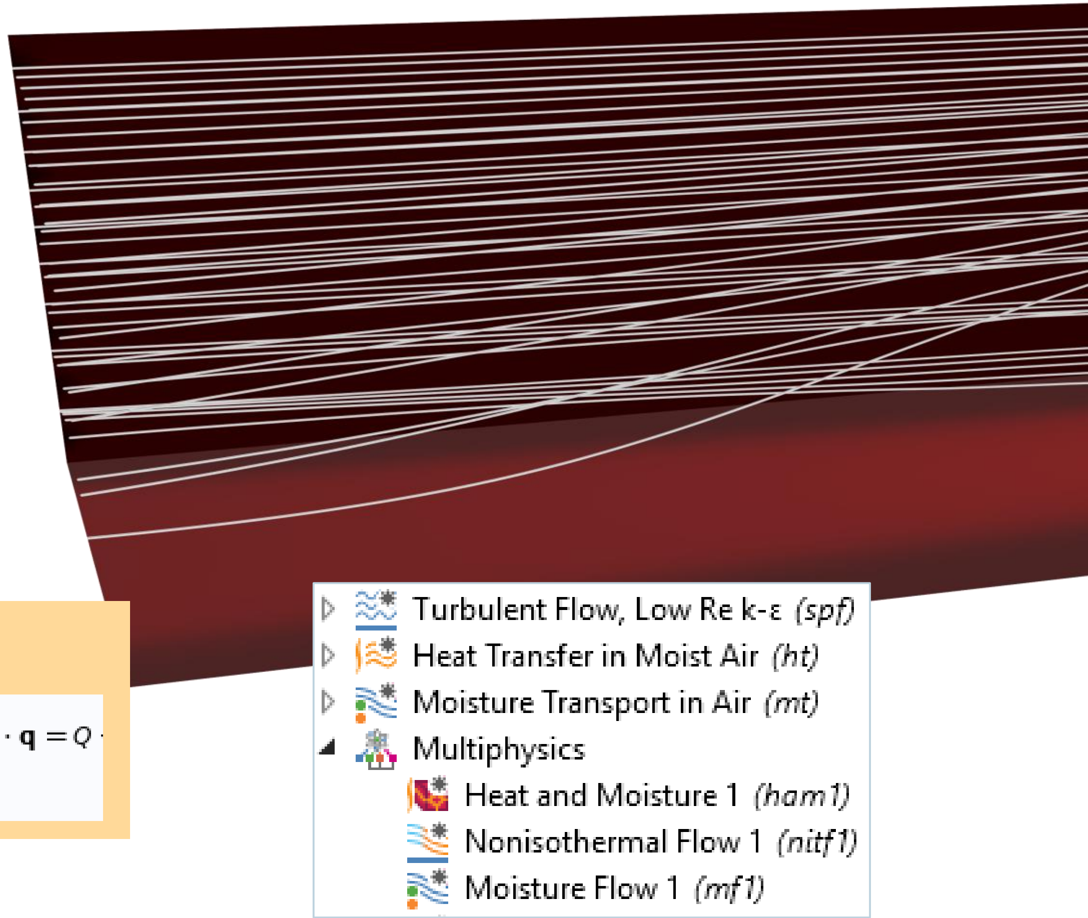
$$\rho = \rho(p_A, \phi)$$
$$M_v \mathbf{u} \cdot \nabla c_v$$

Relative humidity ↔ Temperature:

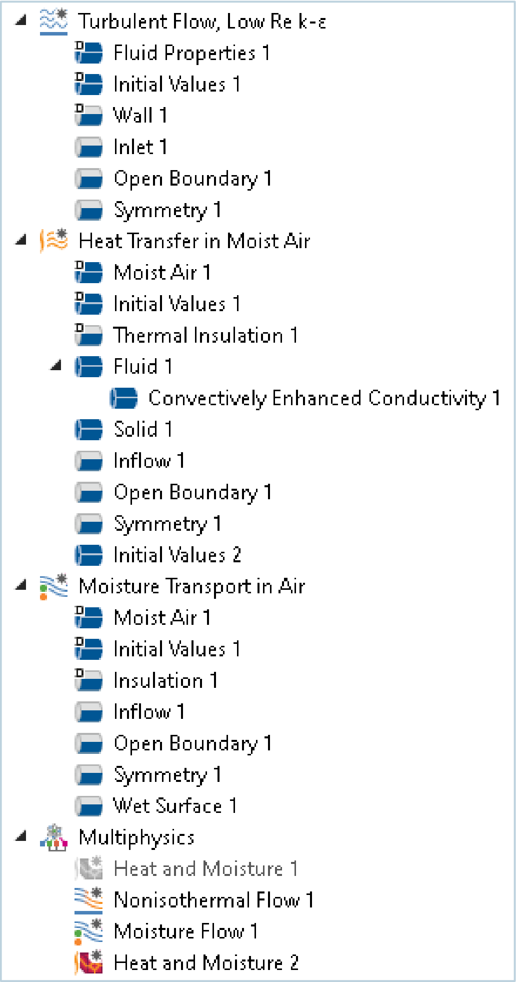
$$c_{sat} = c_{sat}(T)$$
$$\rho = \rho(T, \phi)$$
$$q_{evap} = -L_v g_{evap}$$

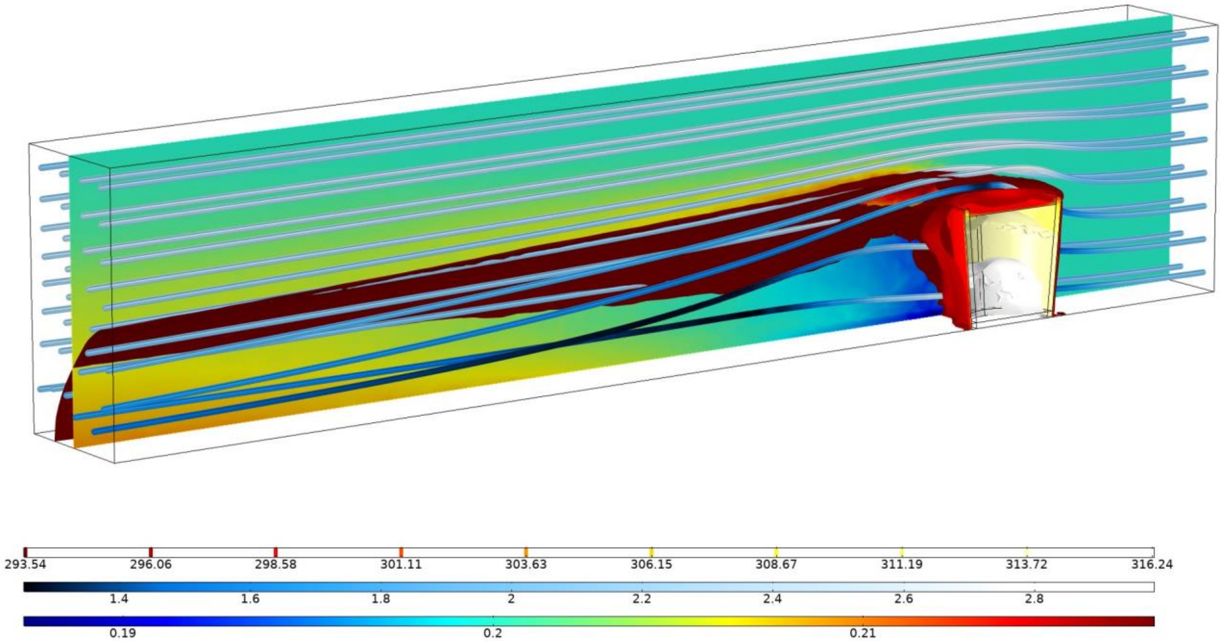
Velocity, pressure ↔ Temperature:

$$\rho = \rho(p_A, T)$$
$$\boldsymbol{\rho C_p} \mathbf{u} \cdot \nabla T$$



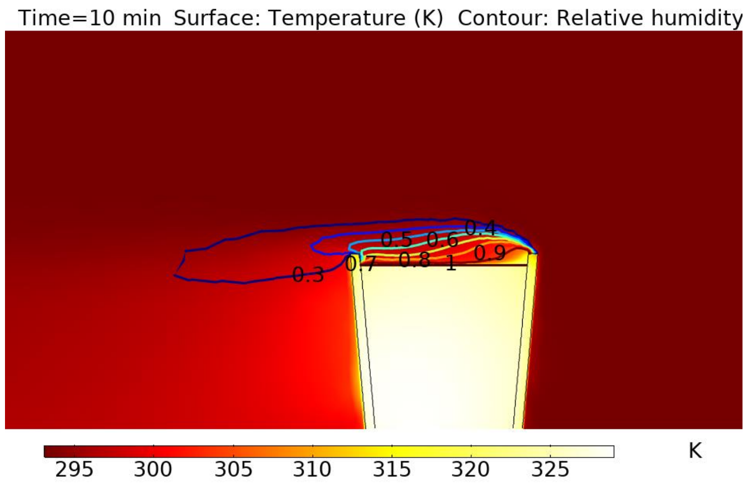
Evaporative Cooling

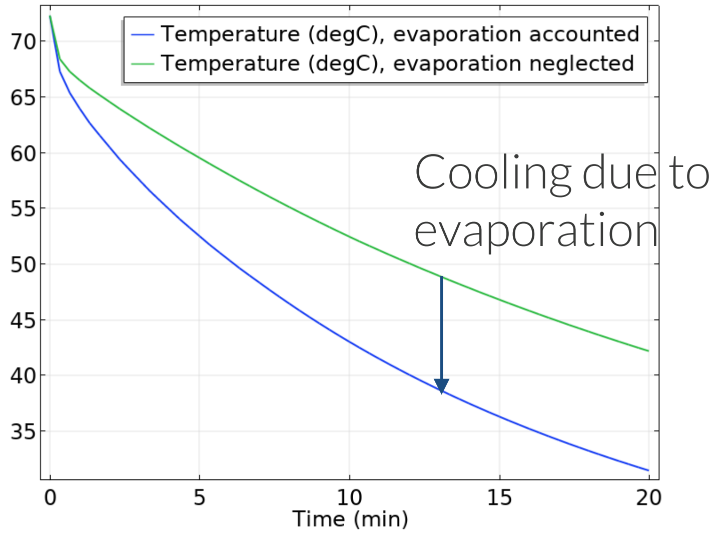




[Heat and moisture in the Evaporative Cooling model]

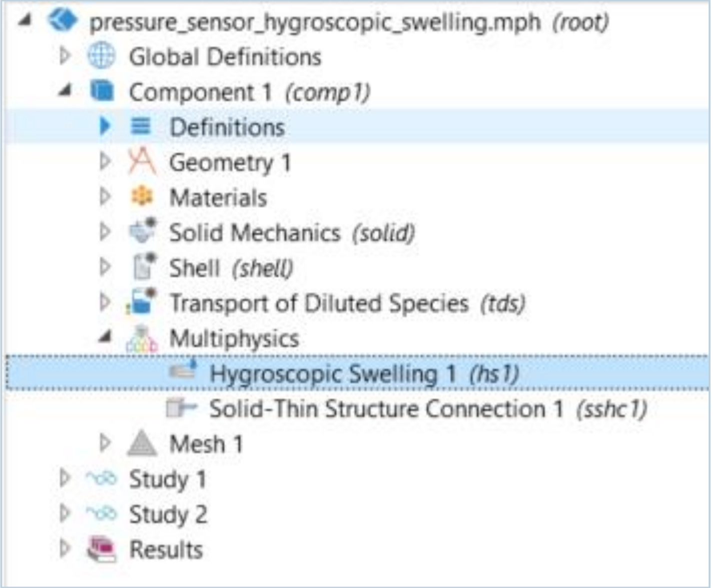
Evaporative Cooling

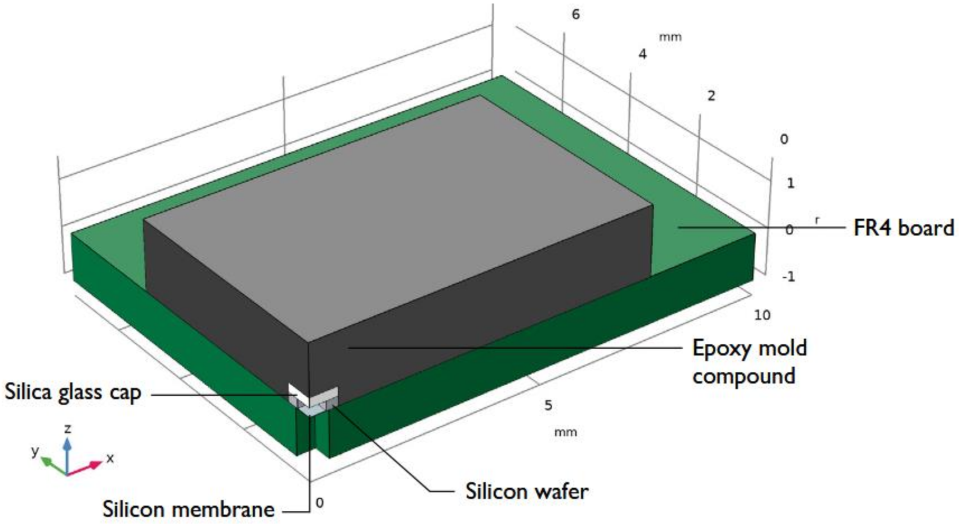


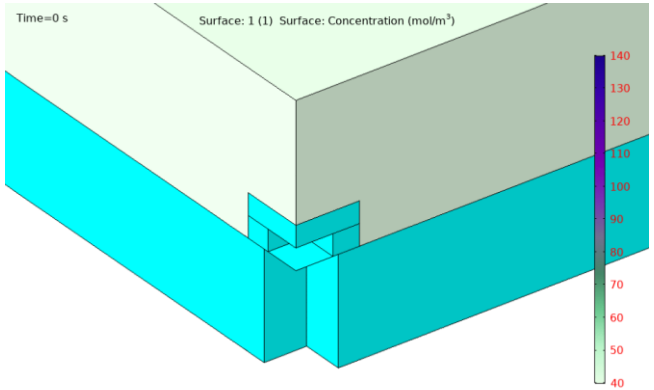


Hygroscopic Sweeling in a MEMS Pressure Sensor

- Structural Mecahnics
- Moisture diffusion
- Hygroscopic swelling







[Hygroscopic swelling in a MEMS pressure sensor]

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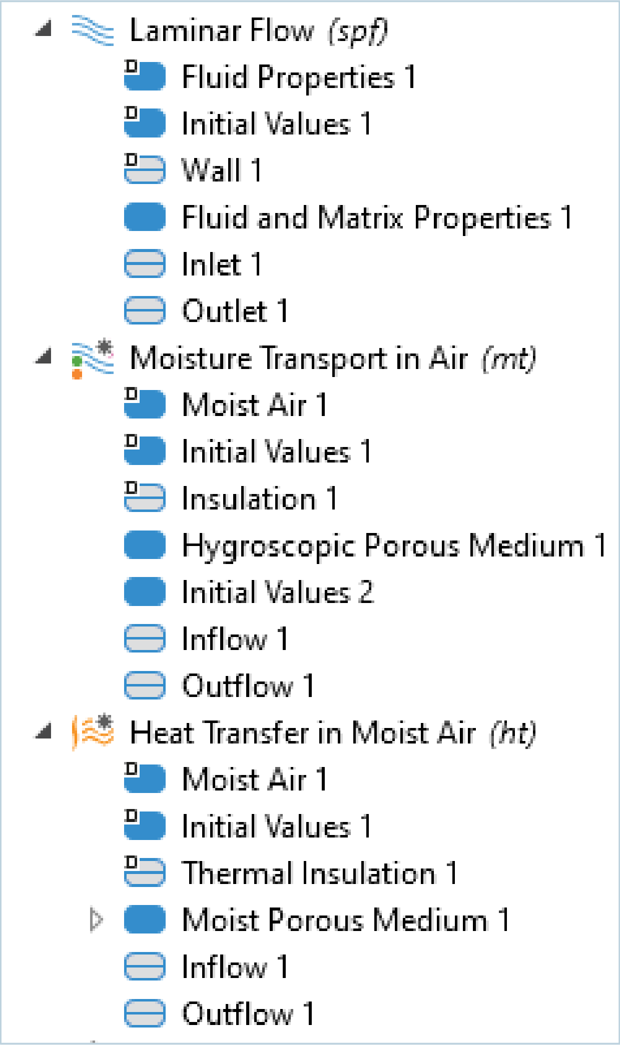
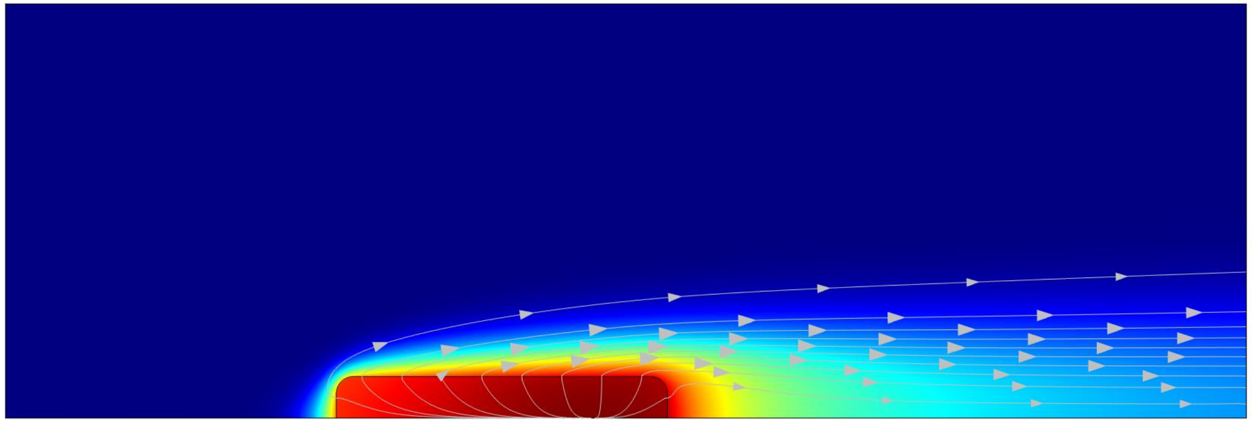
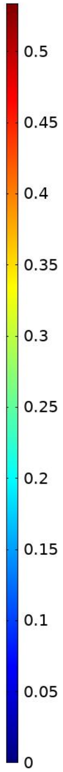
Heat and Moisture Transport in Porous Media





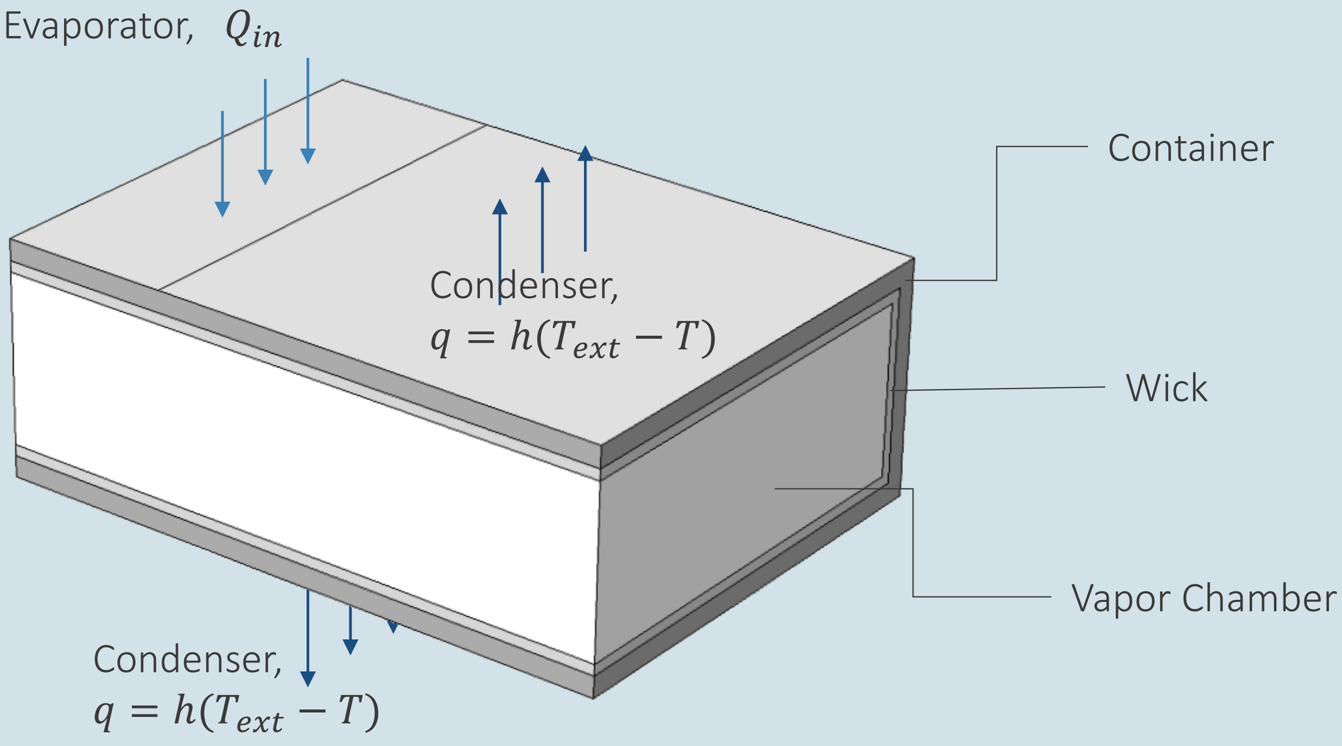


Concentration of vapor and total flux streamlines in a moist sample exposed to a dry and warm airflow. In COMSOL Multiphysics® version 5.6, the model setup is facilitated by the new features for heat and moisture transport in porous media.

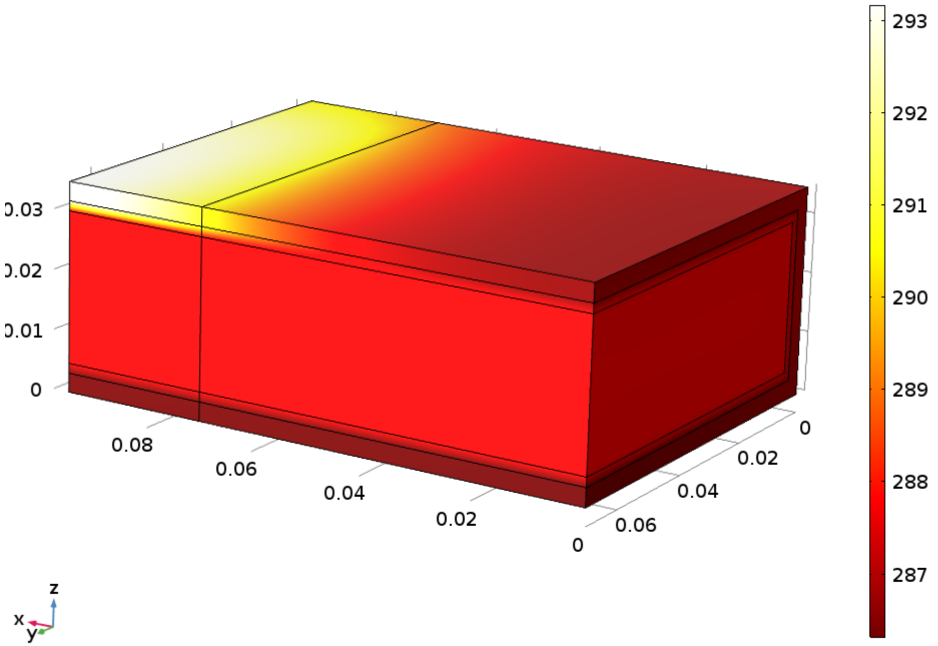
Thermal Management

Flat Heat Pipe

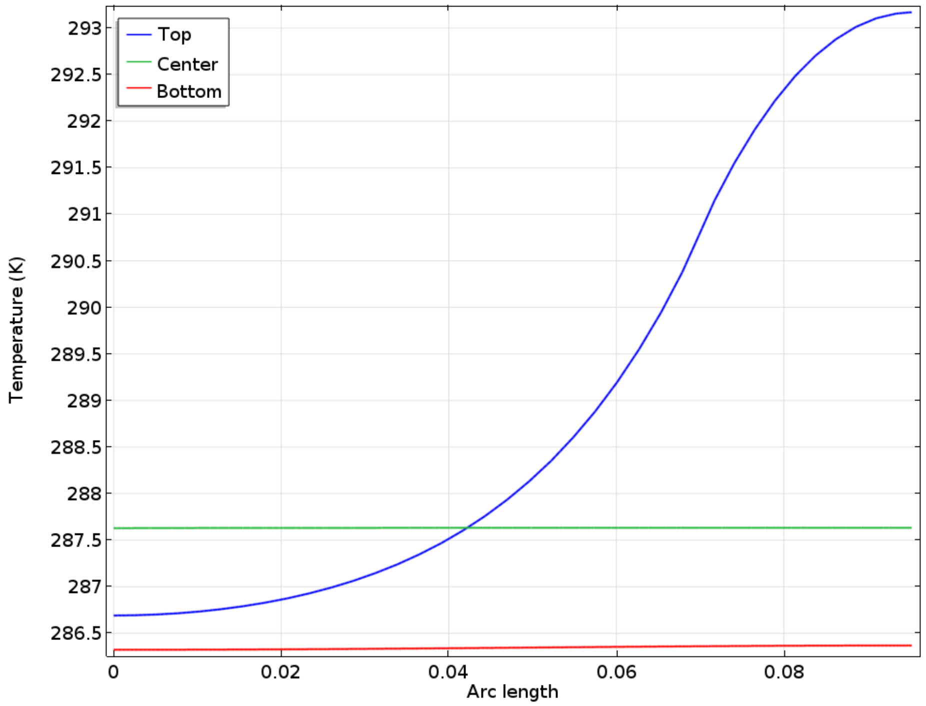
- Water-Copper Flat Heat Pipe
- Sintered Copper Powder Wick
- Heat load: $Q_{\mathrm{in}} = 100W$
- Heat transfer coefficient
  $$h = 1100 \frac{W}{m^2 K}$$
- External temperature
  $$T_{\mathrm{ext}} = 285K$$
- Only ¼ of the chamber is modeled due to symmetry



Flat Heat Pipe



Temperature distribution in heat pipe



Temperature profiles at top, center and bottom of heat pipe

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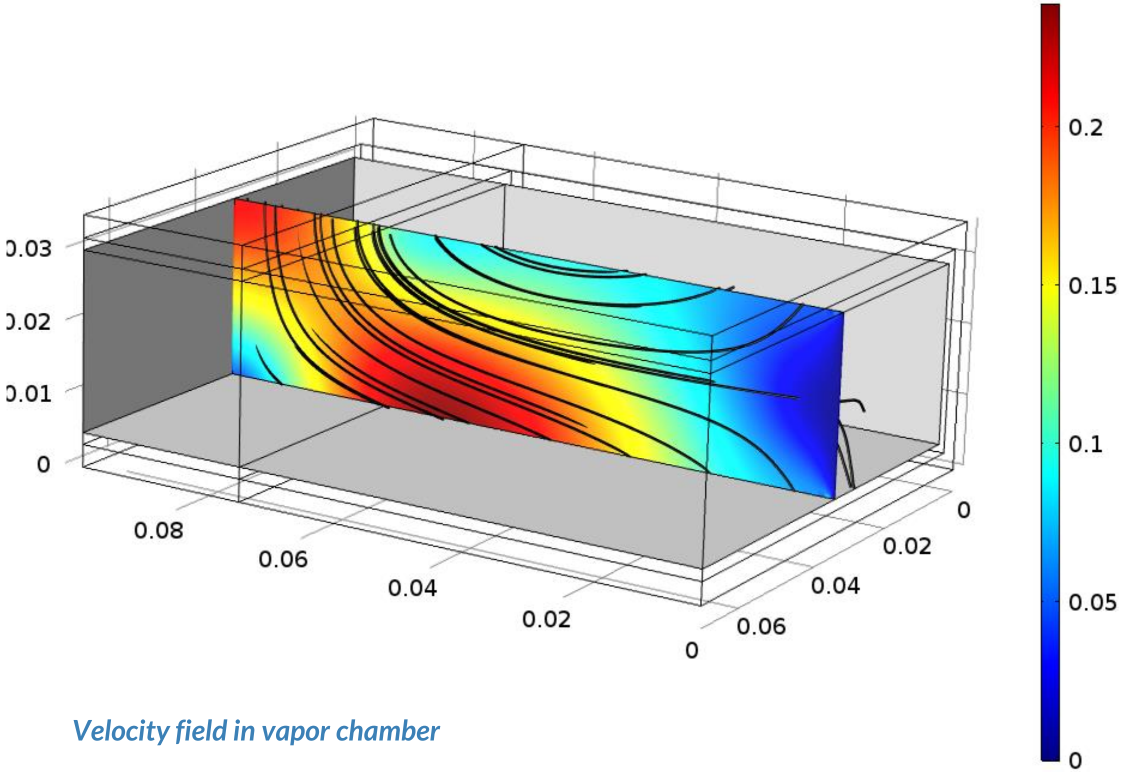
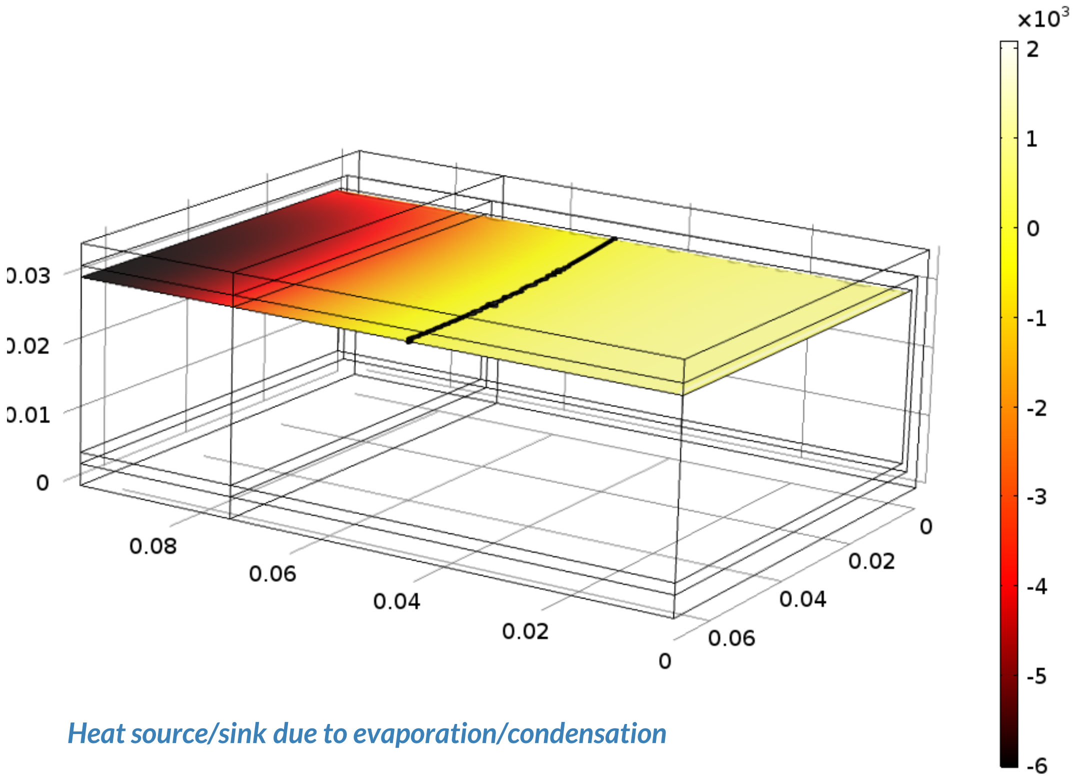
Flat Heat Pipe



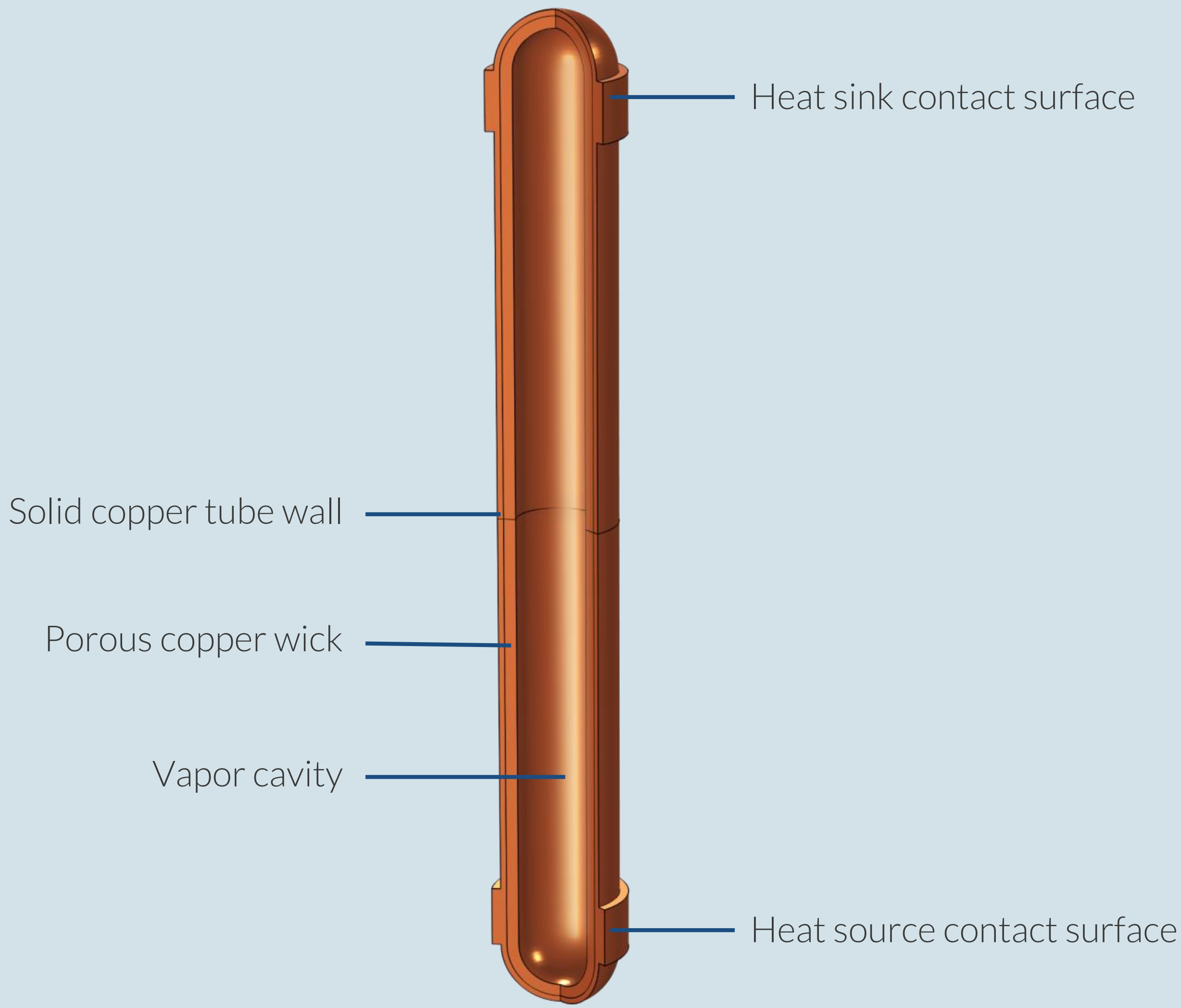
Velocity field in vapor chamber



Heat source/sink due to evaporation/condensation

Cylindrical Heat Pipe

- Water evaporates at the hot side and condenses at the cold
- Vapor driven by pressure difference
- Liquid water transported back though a porous wick
- Liquid and vapor properties generated using the thermochemistry database.



[Overview of the heat pipe model]

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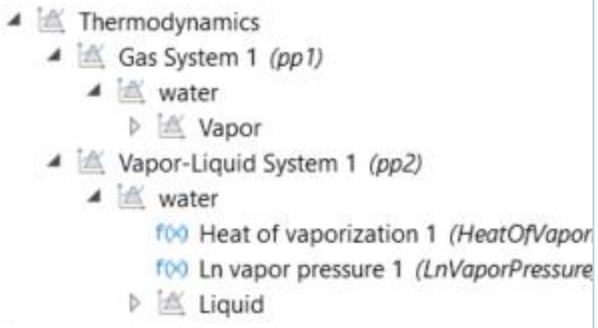
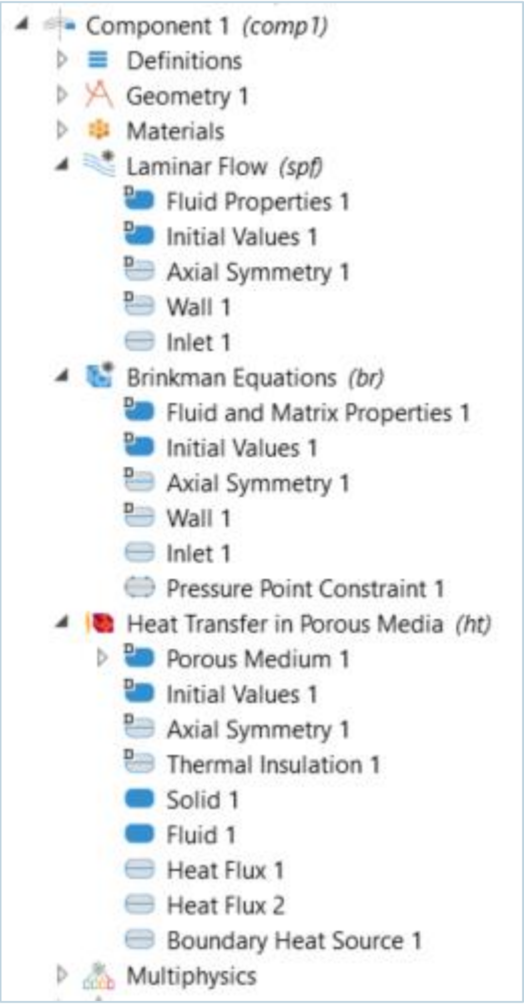
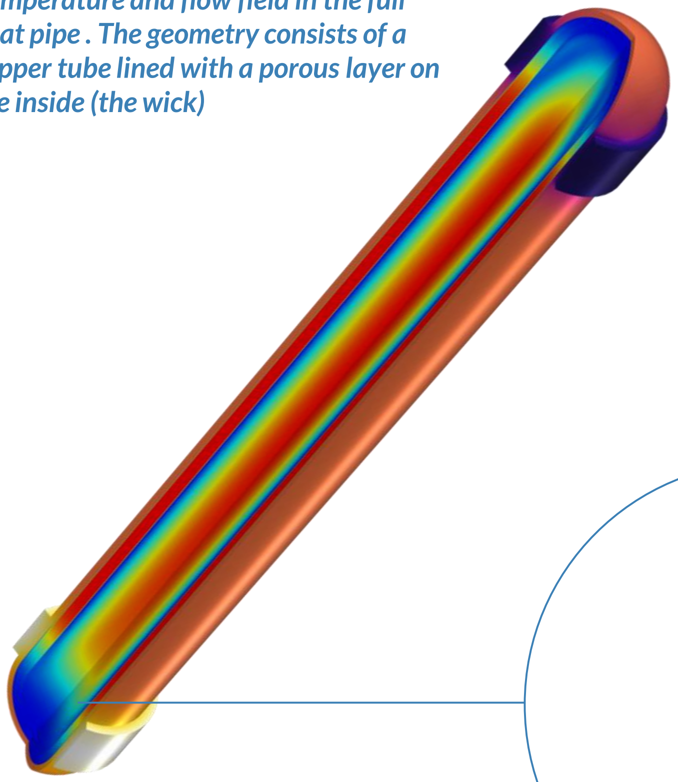
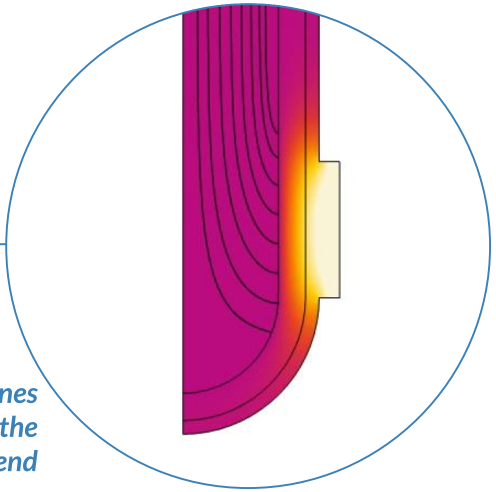
Heat Pipe With Accurate Liquid and Gas Properties





Temperature and flow field in the full heat pipe . The geometry consists of a copper tube lined with a porous layer on the inside (the wick)

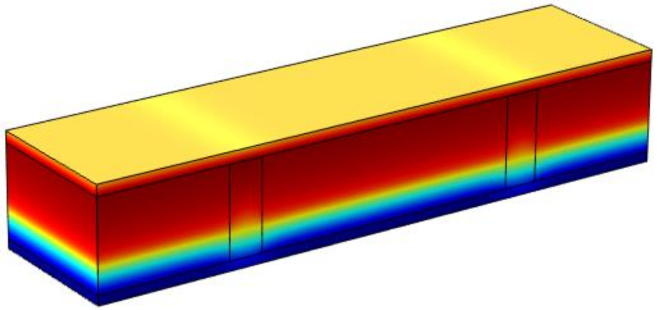


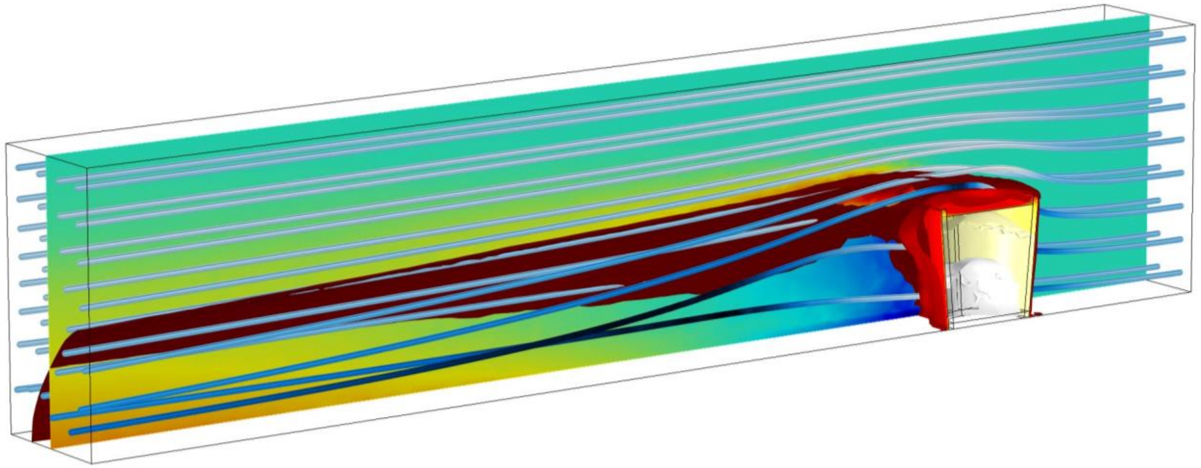


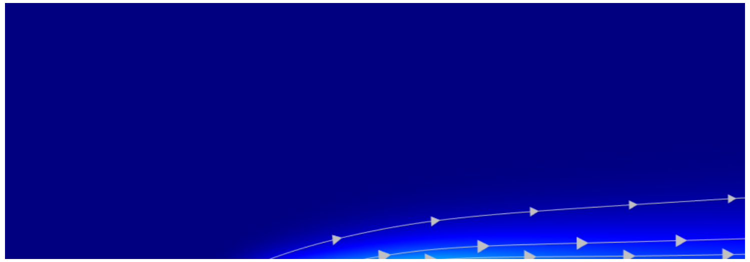
Temperature and streamlines of the vapor velocity near the heated end

Wrapping Up

- Moisture Transport Description
  - Moisture Transport
  - Condensation and evaporation
  - Heat and Moisture
- COMSOL Multiphysics features
  - Moist Air
  - Building Material
  - Hygroscopic porous media
  - Heat And Moisture
- Modeling Strategies
  - Condensation detection
  - Phase Change control
  - Thermal management







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- LiveLink™ *for* Solid Edge®
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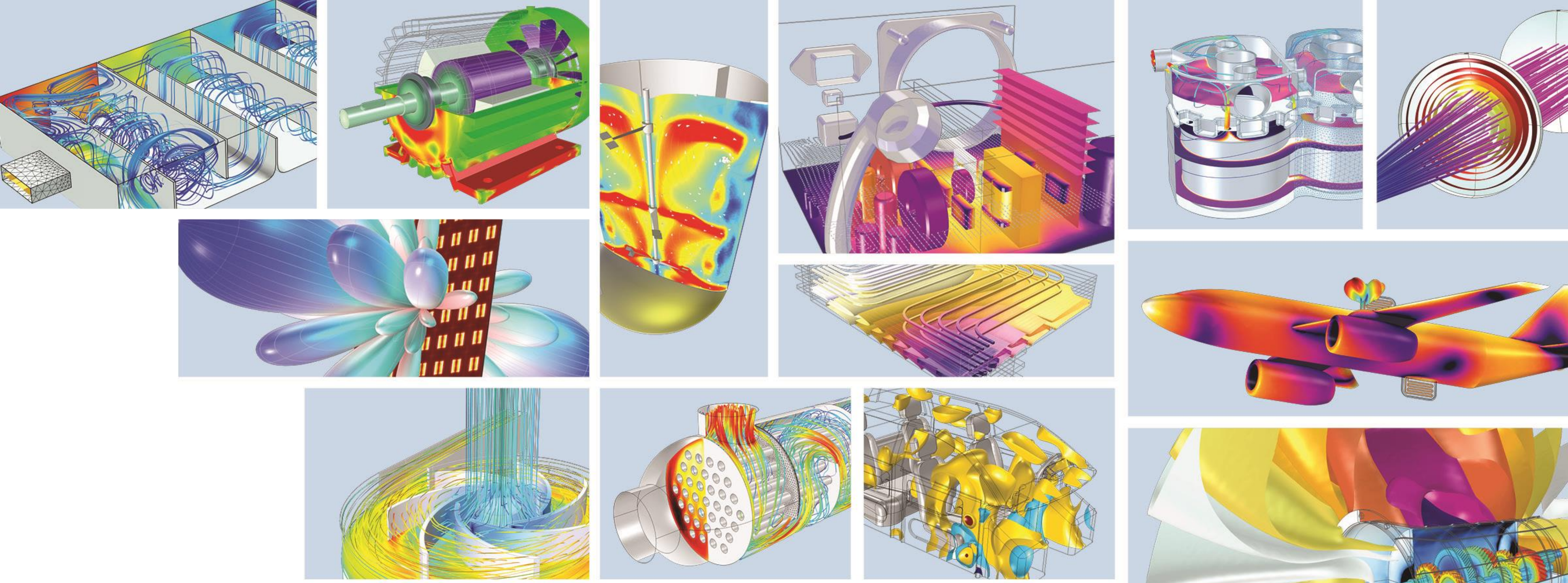

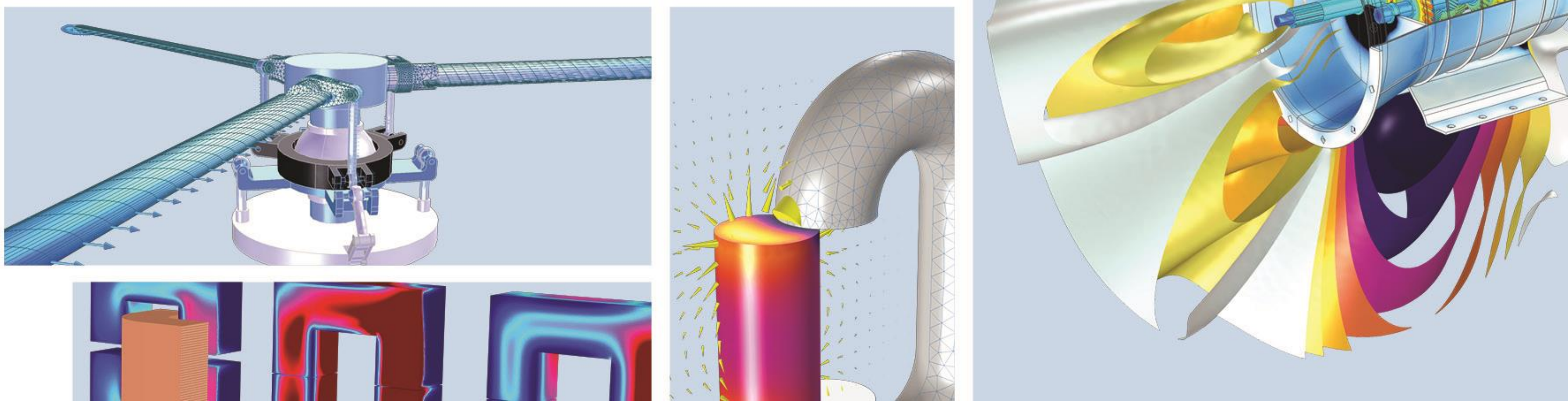

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