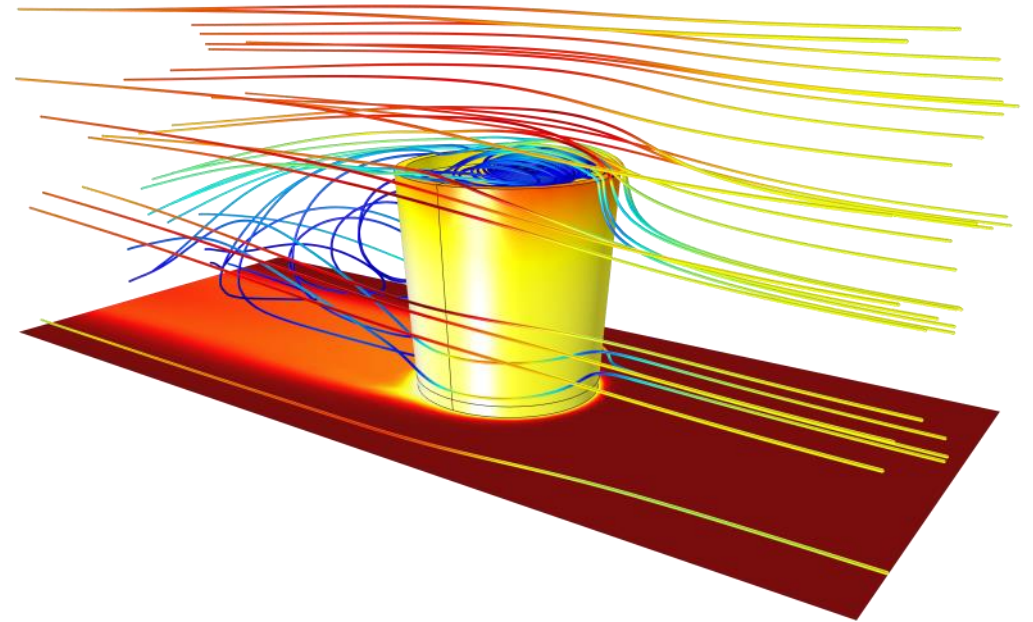


Modeling Moisture Transport, Evaporation and Condensation

Nicolas Huc

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

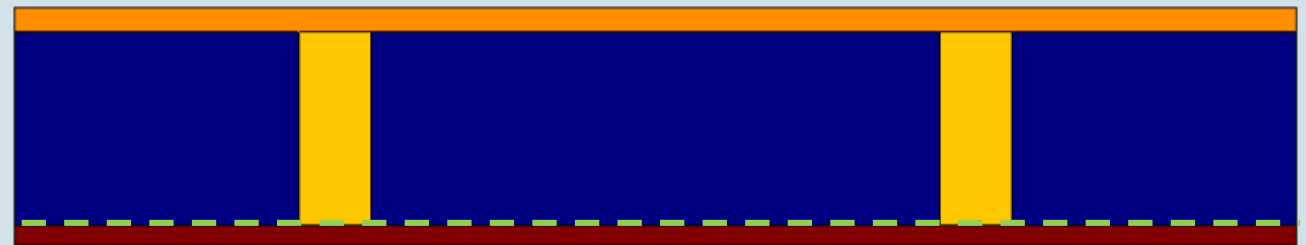
Detection of Condensation

- 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

- $T = 273.15 \text{ K}$
- $\phi = 80\%$



Interior

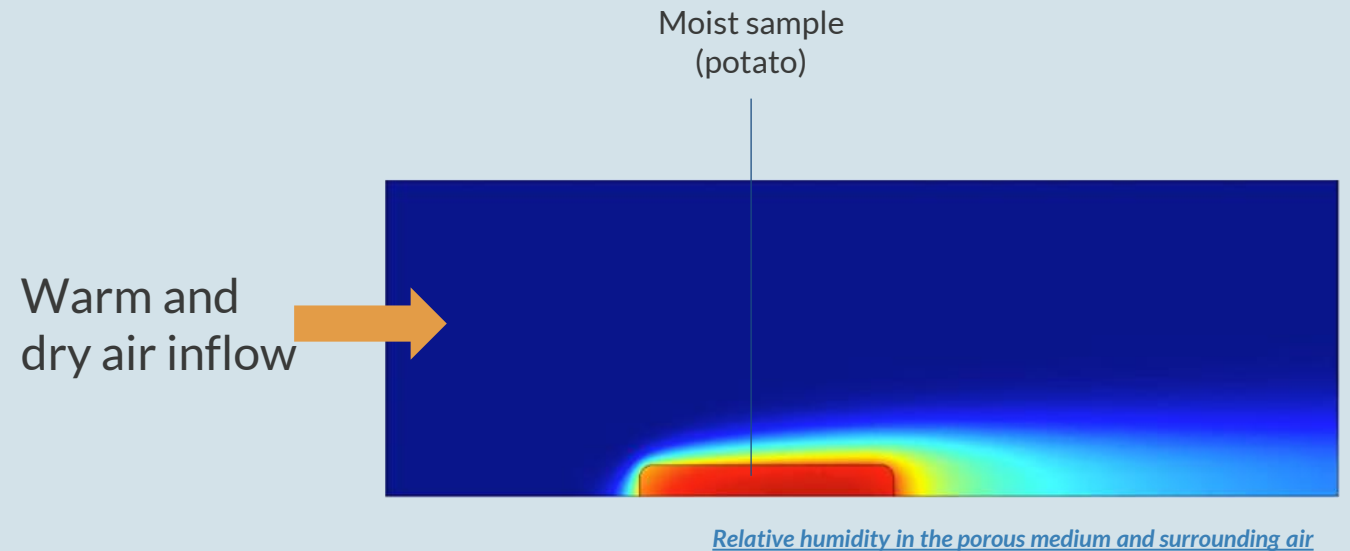
- $T = 292.15 \text{ K}$
- $\phi = 50\%$

- Vapor barrier
- Wood
- Cellulose
- Wooden panel (OSB)
- Plaster

Control of Phase Change

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

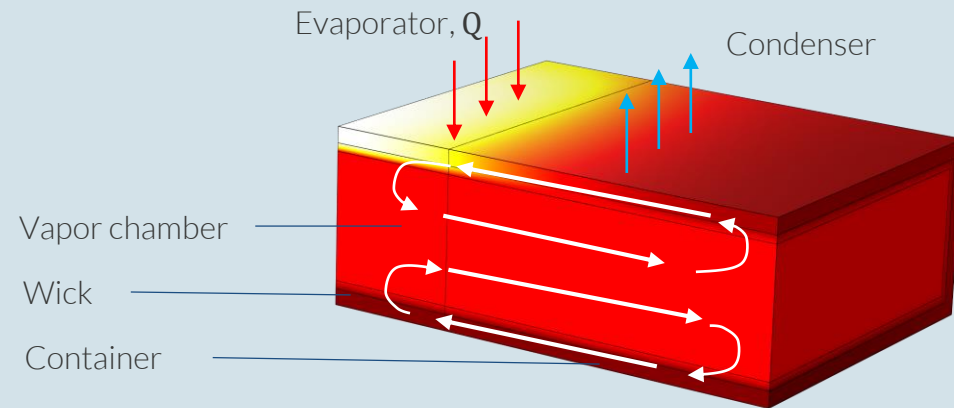
Evaporation in Porous Media



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

Moisture Transport Description

Relative Humidity

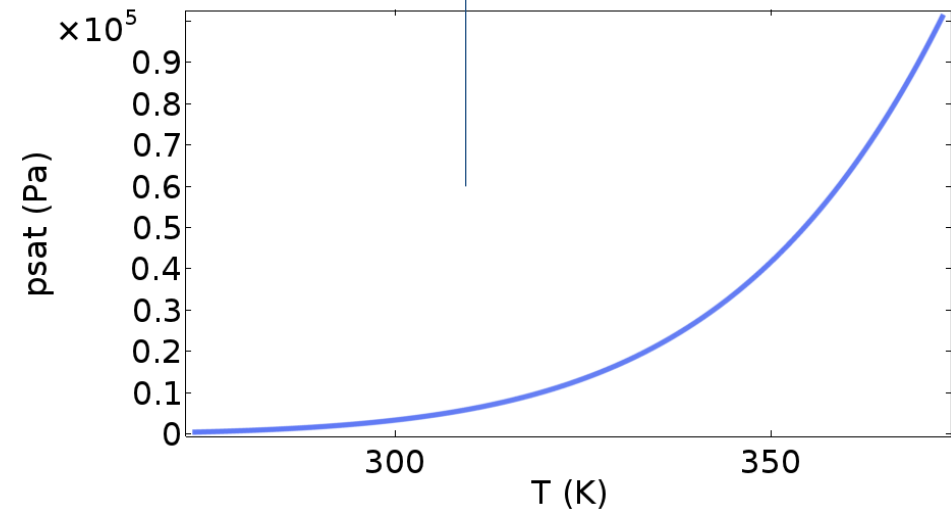
- The saturation $p_{sat}(T)$, increases with temperature

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

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

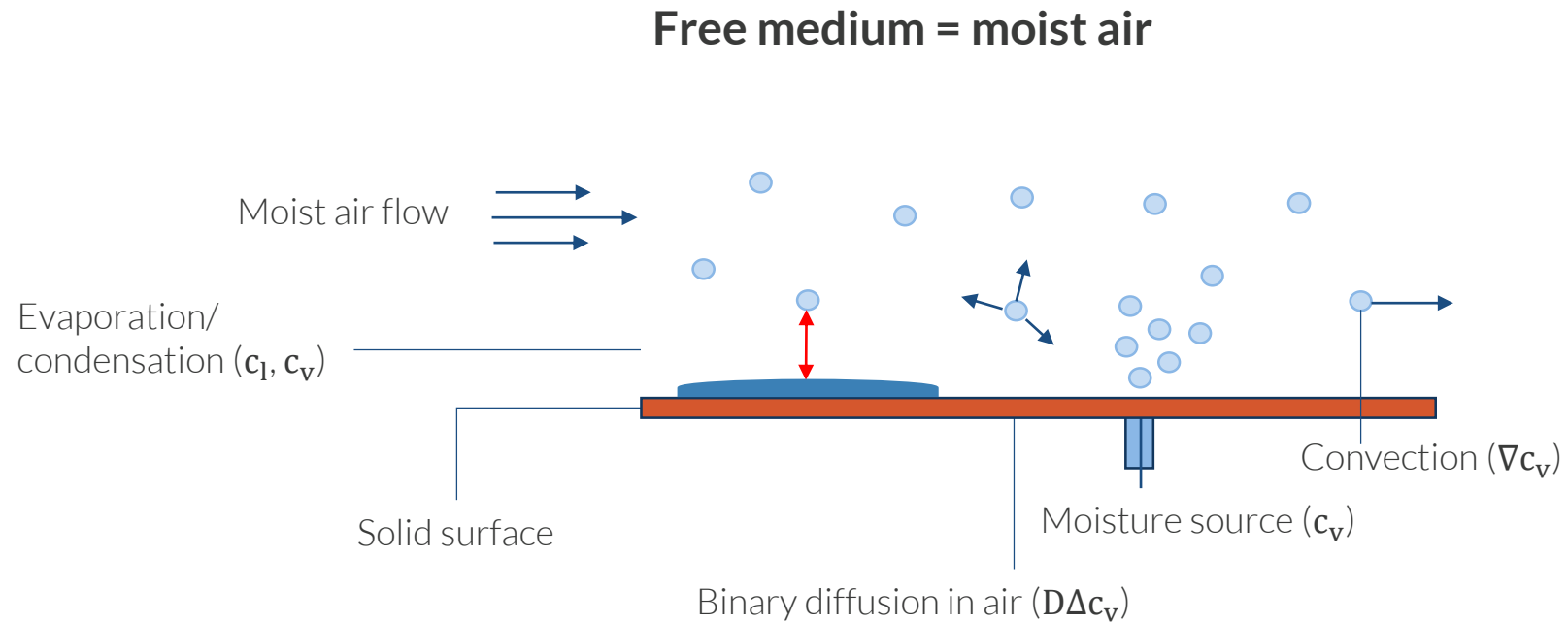
$$\varphi = \frac{p_v}{p_{sat}}$$

Supersaturation: $\varphi > 1$



Saturation curve for water, $\varphi=1$

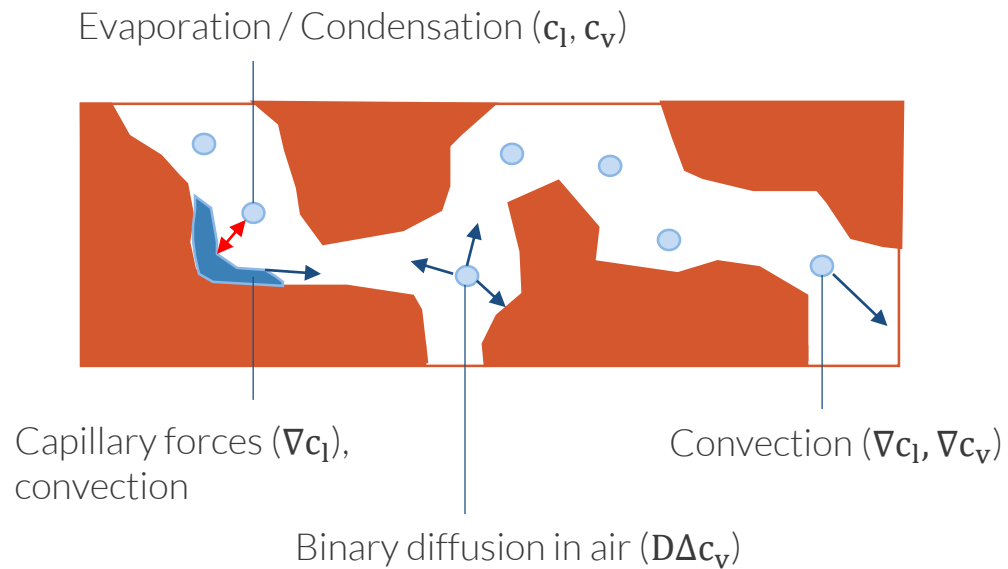
Moisture Transport: Moist Air



○ Water vapor (c_v) ◐ Liquid water (c_l)

Moisture Transport: Porous Media

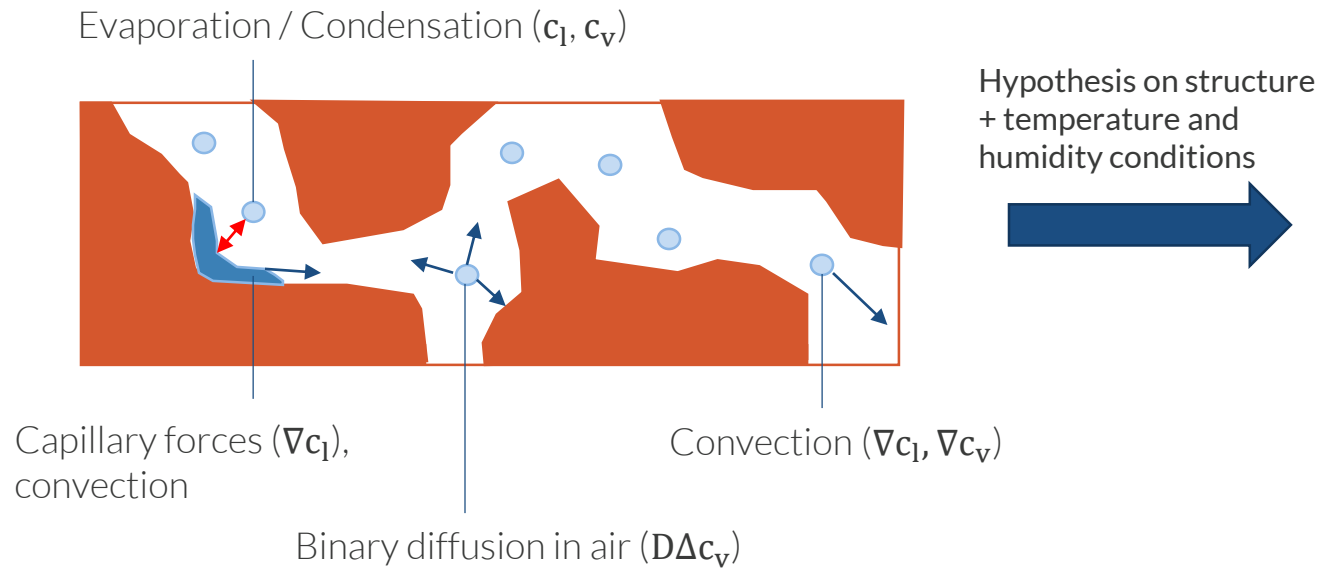
Porous medium



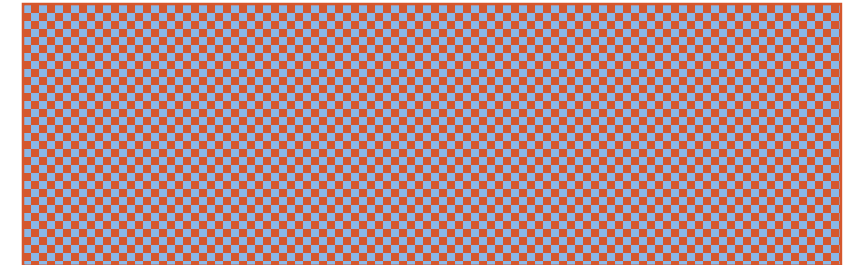
○ Water vapor (c_v)  Liquid water (c_l)

Moisture Transport: Building Material

Porous medium



Building material

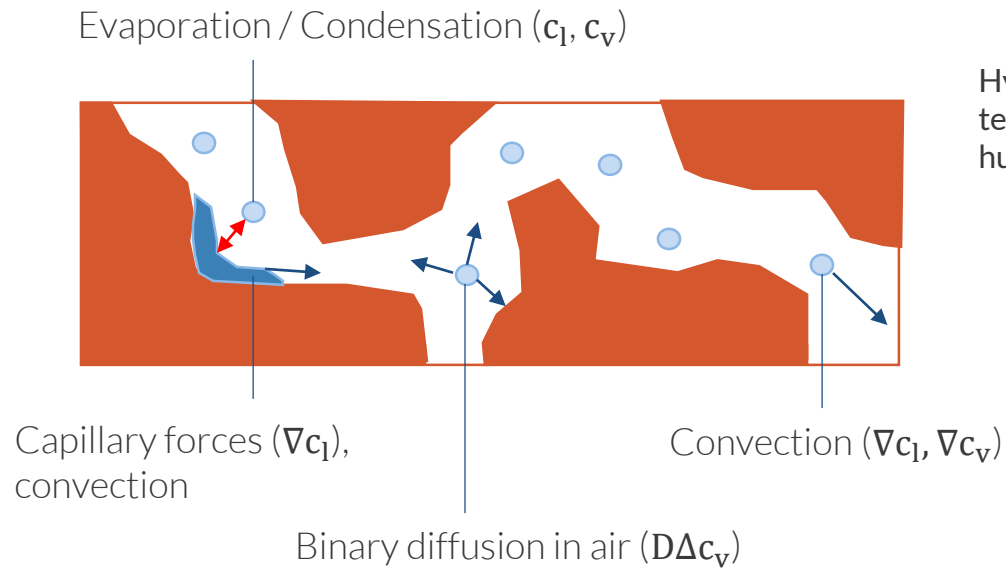


- Assumes equilibrium between the vapor and liquid phases, $w_c = w_c(\varphi)$
- Capillary forces
- Vapor diffusion

○ Water vapor (c_v) ● Liquid water (c_l)

Moisture Transport: Hygroscopic Porous Media

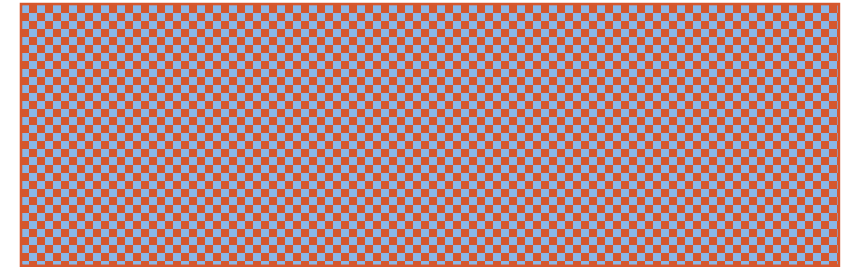
Porous medium



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

Heat and Moisture Flow in Air

Governing equations

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

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

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

Relative
humidity

Governing equations

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

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

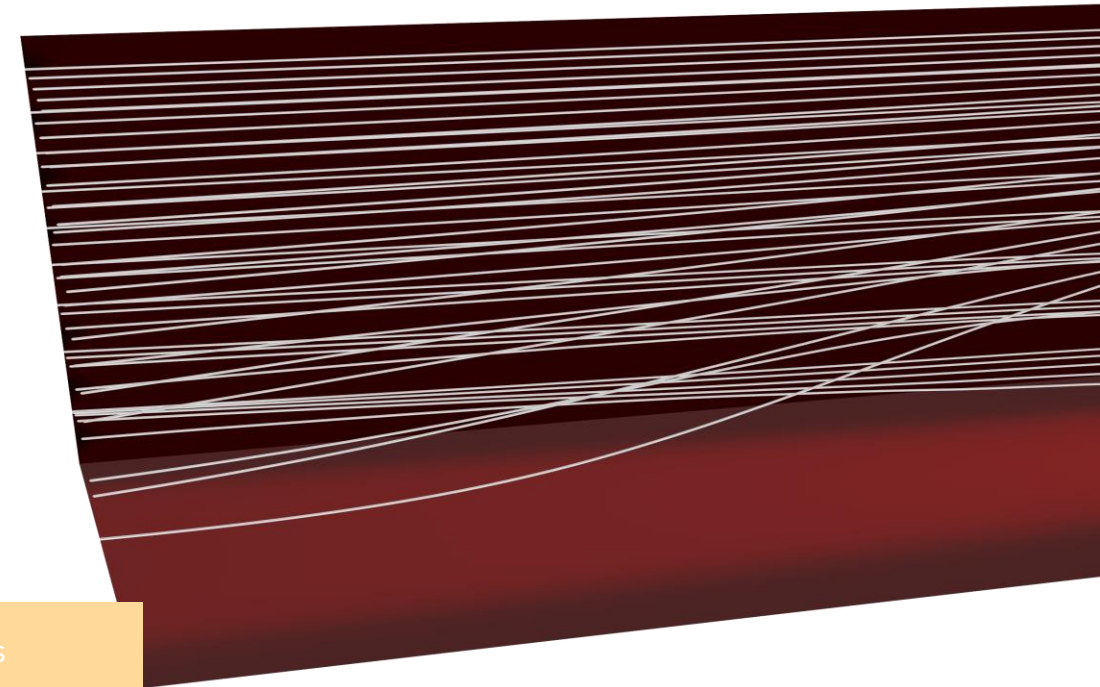
Velocity,
pressure

Temperature

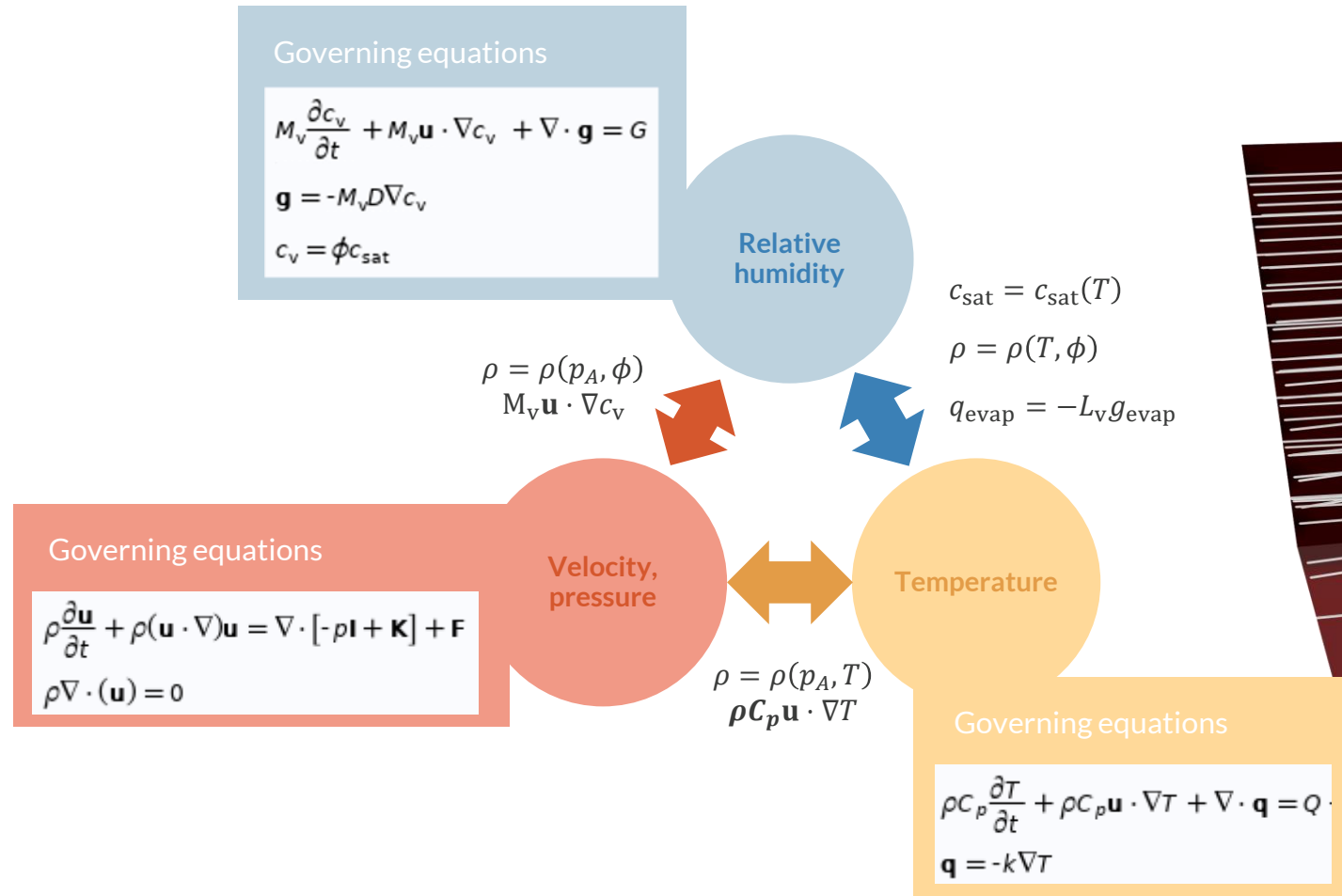
Governing equations

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

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



Heat and Moisture Flow in Air



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

The screenshot shows the 'Settings' window for a 'Moist Air' material in COMSOL. The window is titled 'Settings' and 'Moist Air'. It contains several sections for defining material properties:

- Label:** Moist Air 1
- Domain Selection:** (Expanded)
- Override and Contribution:** (Expanded)
- Equation:** (Expanded)
- Model Input:** (Expanded)
 - Absolute pressure:** P_A is set to 'User defined' with a value of 1[atm].
 - Velocity:** \mathbf{u} is set to 'User defined' with x and y components both set to 0.
 - Temperature:** T is set to 'Temperature (ham1)'.
- Moist Air Properties:** (Expanded)
 - Diffusion coefficient:** D is set to 2.6e-5[m^2/s].

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

The screenshot shows the 'Settings' dialog for a 'Building Material' in COMSOL. The 'Label' is 'Building Material 1'. The 'Domain Selection' is expanded. Under 'Model Input', the 'Absolute pressure' is set to 'User defined' with a value of '1[atm]' and units 'Pa'. The 'Relative humidity' is set to 'Relative humidity (mt)' with units ' ϕ_w '. The 'Temperature' is set to 'Temperature (ham1)' with units 'T'. Under the 'Building Material' section, 'Moisture diffusivity' is set to 'From material' with units ' D_w '. 'Moisture storage function' is set to 'From material' with units ' $w(\phi_w)$ '. 'Specify' is set to 'Vapor resistance factor' with units ' μ '. 'From material' is also set for the parameter below it.

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

Settings
Hygroscopic Porous Medium

▸ Domain Selection

▸ Override and Contribution

▸ Equation

▸ Model Input

▼ Porous Matrix Properties

Porosity:
 ϵ_p From material

Permeability:
 κ From material

Moisture storage function:
 $w(\phi_w)$ From material

▼ Moist Air Properties

Diffusion coefficient:
 D 2.6e-5[m^2/s] m^2/s

$$D_{\text{eff}} = \frac{(1 - s_l)\epsilon_p D}{\tau}$$

Effective diffusivity model:
 Millington and Quirk model

$$\tau = [(1 - s_l)\epsilon_p]^{-7/3} \epsilon_p^2$$

Velocity field:
 u_g User defined

0	x	m/s
0	y	

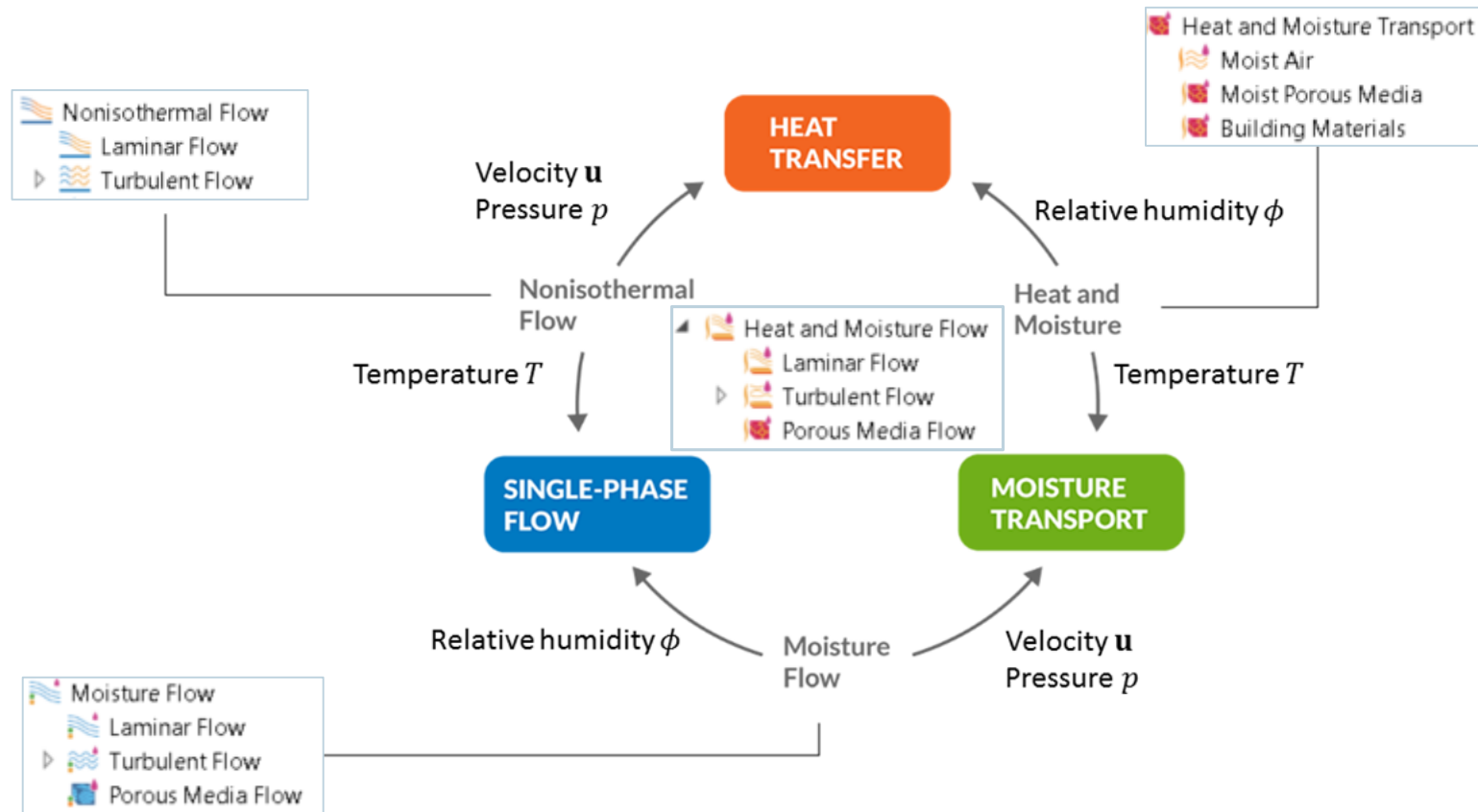
▼ Liquid Water Properties

Relative liquid water permeability:
 κ_{rl} 1

Capillary model:
 Kelvin's law

$$g_{lc} = \rho_l \frac{\kappa_{rl} \kappa}{\mu_l} \nabla p_c, \quad p_c = -\frac{RT \rho_l}{M_v} \ln(\phi_w)$$

Heat and Moisture Transport: Physics and Multiphysics Interfaces



Condensation Detection

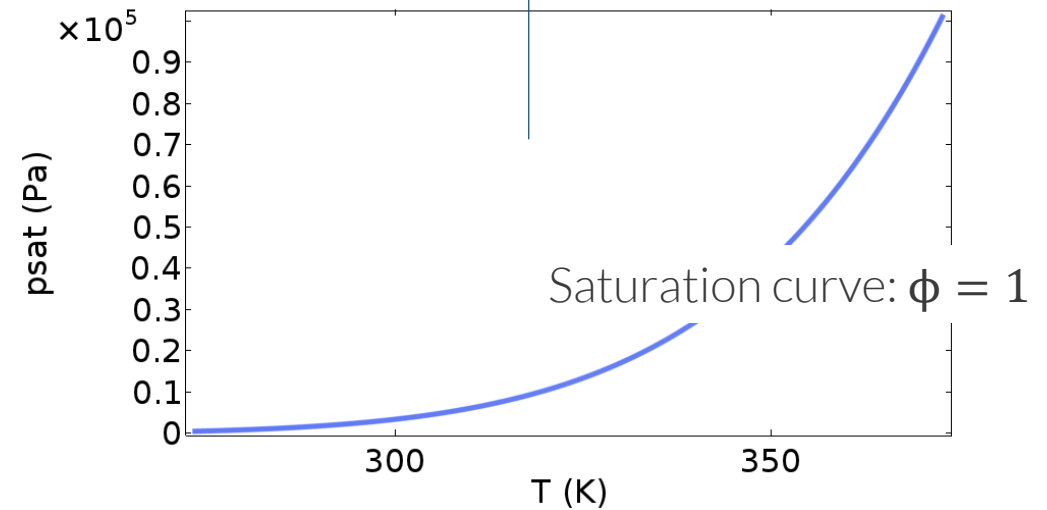
Detection of Condensation

Saturation pressure $p_{sat}(T)$

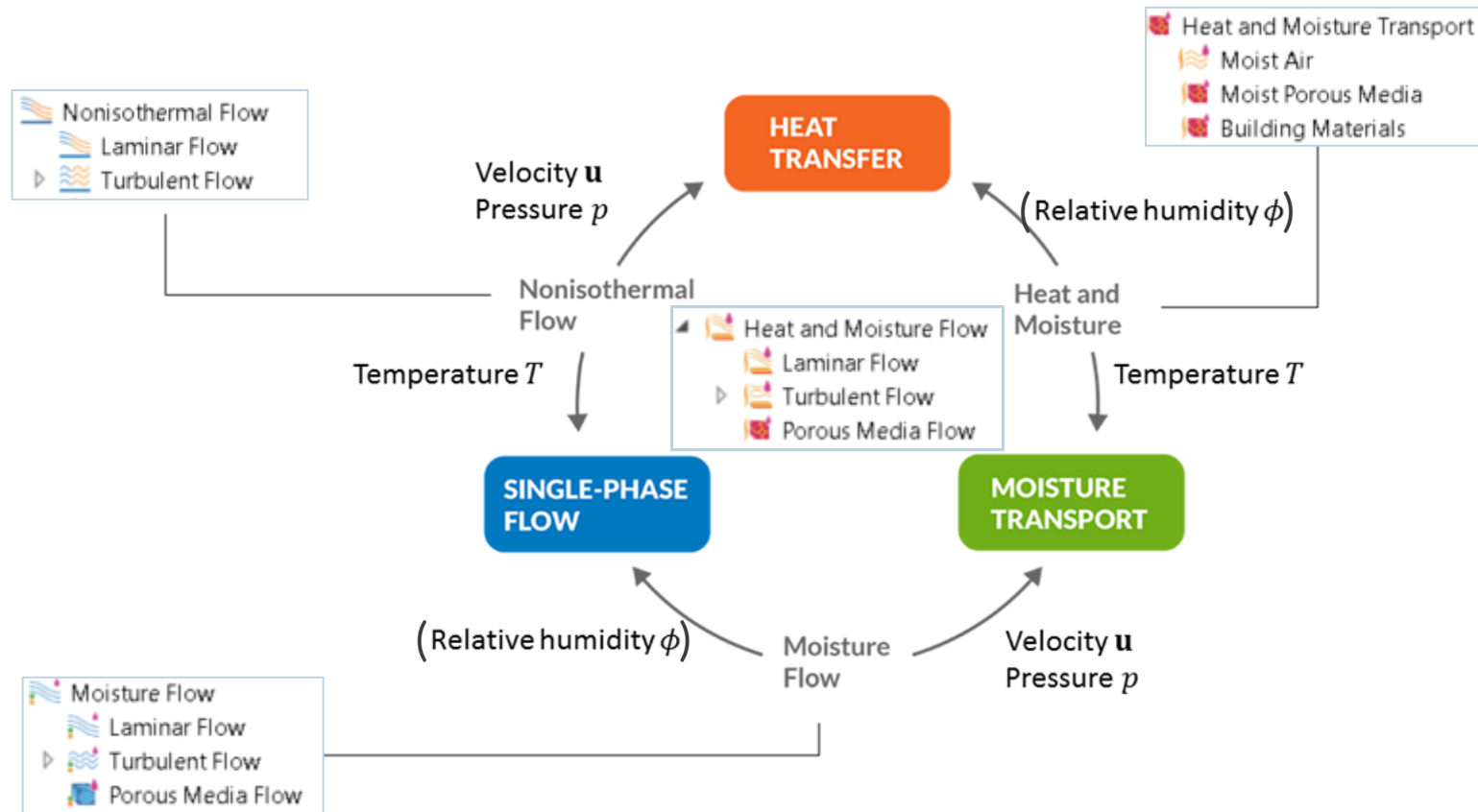
Supersaturation: $\phi > 1$
= risk of condensation

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

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



Detection of Condensation



Detection of Condensation

Heat Transfer interface
+
Moist Air feature



Default results:
heat transfer

Postprocessing:
moisture content

The screenshot shows the COMSOL Multiphysics interface for a model named 'condensation_electronic_device.mph'. The 'Model Builder' tree on the left shows the 'Moist Air 1' feature selected under the 'Heat Transfer in Solids and Fluids' interface. The 'Settings' pane for 'Moist Air 1' is open, showing the 'Domain Selection' set to 'Manual' with '2' selected. The 'Equation' section is expanded to 'Thermodynamics, Moist Air', where the 'Input quantity' is set to 'Relative humidity'. The relative humidity equation is displayed as:

$$0 \leq \phi_w \leq 1, \quad c_v = c_v(T, \rho_a, x_{vap}), \quad x_{vap} = \frac{M_v}{M_a} \cdot \frac{\phi_w p_{sat}(T_{\phi_w})}{p_{\phi_w} - \phi_w p_{sat}(T_{\phi_w})}$$

The 'Relative humidity' input is set to 'Ambient relative humidity (ampr1)'. The 'Relative humidity, temperature condition' is set to 'Ambient temperature (ampr1)'. The 'Relative humidity, absolute pressure condition' is set to 'Ambient absolute pressure (ampr1)'. The 'Graphics' window shows a contour plot of 'Relative humidity (1)' on a 'Surface: Temperature (K)'. The plot shows a color gradient from yellow (0.96) to red (1.0), with a 'Hole' and an 'Electrical component' labeled. The plot axes range from -5 to 50 mm. The bottom status bar shows '1.48 GB | 2.15 GB'.

Detection of Condensation

Heat Transfer interface
+
Moist Air feature



Default results:
heat transfer

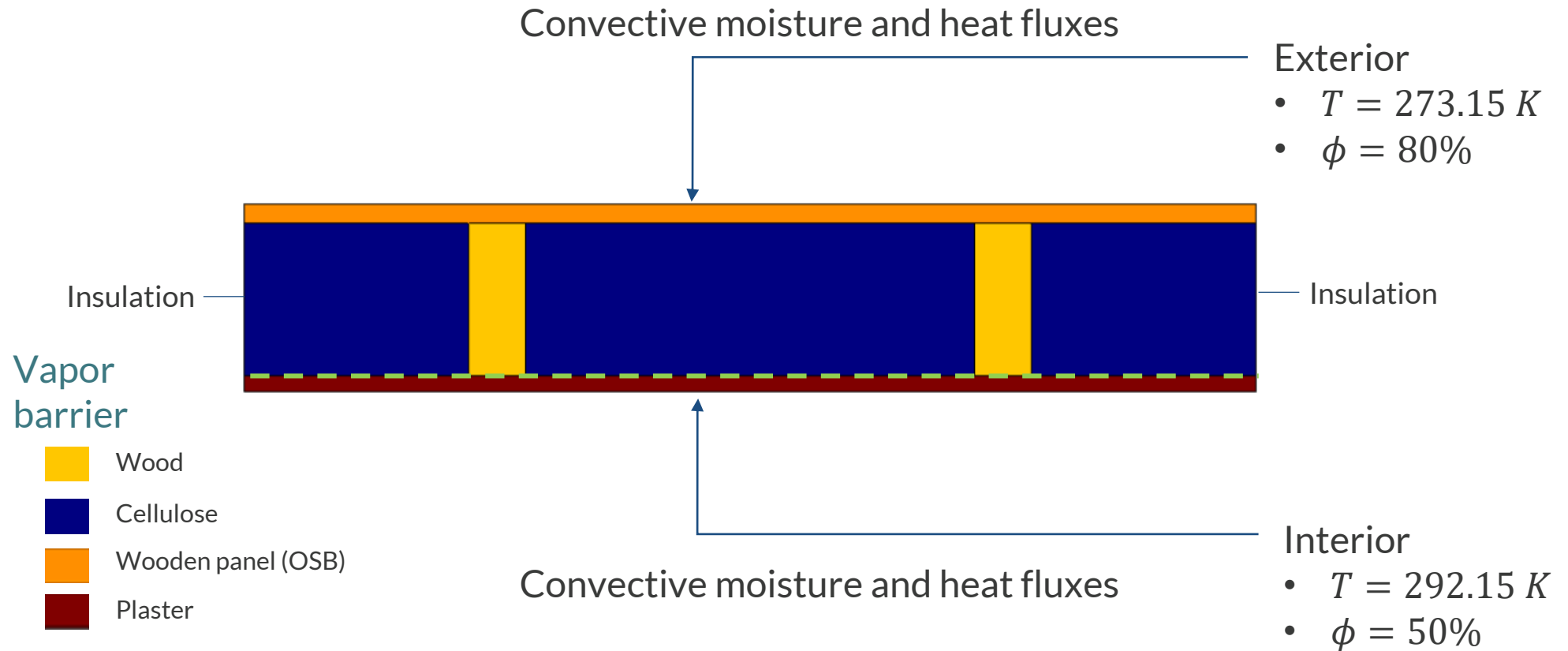
Postprocessing:
moisture content

The screenshot shows the COMSOL Multiphysics interface for a model named 'condensation_electronic_device.mph'. The 'Model Builder' tree on the left shows the 'Moist Air 1' feature selected under the 'Heat Transfer in Solids and Fluids' interface. The 'Settings' pane for 'Moist Air 1' shows the 'Domain Selection' set to 'Manual' with '2' selected. The 'Equation' section is expanded to show the 'Thermodynamics, Moist Air' section, with the 'Input quantity' set to 'Relative humidity'. The equation for relative humidity is displayed as:

$$0 \leq \phi_w \leq 1, \quad c_v = c_v(T, \rho_a, x_{vap}), \quad x_{vap} = \frac{M_v}{M_a} \cdot \frac{\phi_w p_{sat}(T_{\phi_w})}{\rho_{\phi_w} - \phi_w p_{sat}(T_{\phi_w})}$$

The 'Relative humidity' section shows the input quantity set to 'Ambient relative humidity (ampr1)'. The 'Relative humidity, temperature condition' is set to 'Ambient temperature (ampr1)'. The 'Relative humidity, absolute pressure condition' is set to 'Ambient absolute pressure (ampr1)'. The 'Saturation' plot on the right shows the 'Maximum Relative Humidity' (blue line) and the 'Saturation Indicator' (green line) over a 25-hour period. The plot shows a peak in relative humidity around 5 hours, where the saturation indicator is set to 1, indicating a 'Risk of condensation'.

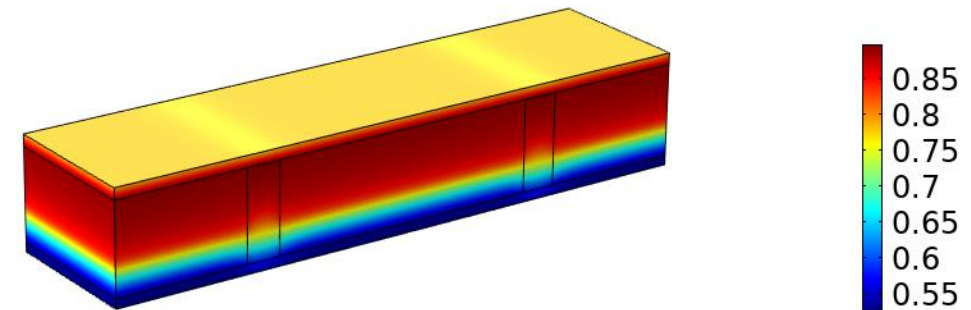
Condensation Risk in a Wood-Frame Wall



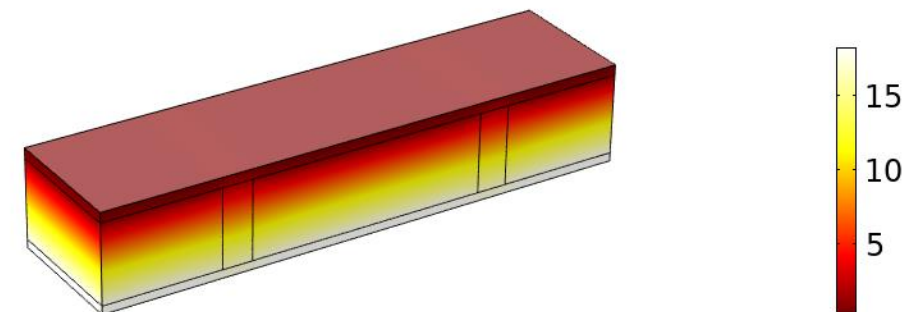
Condensation Risk in a Wood-Frame Wall

- Heat Transfer in Building Materials
 - Building Material 1
 - Initial Values 1
 - Thermal Insulation 1
 - Heat Flux 1
 - Heat Flux 2
- Moisture Transport in Building Materials
 - Building Material 1
 - Initial Values 1
 - Insulation 1
 - Moisture Flux 1
 - Moisture Flux 2
 - Thin Moisture Barrier 1
- Multiphysics
 - Heat and Moisture 1

Surface: Relative humidity (1)



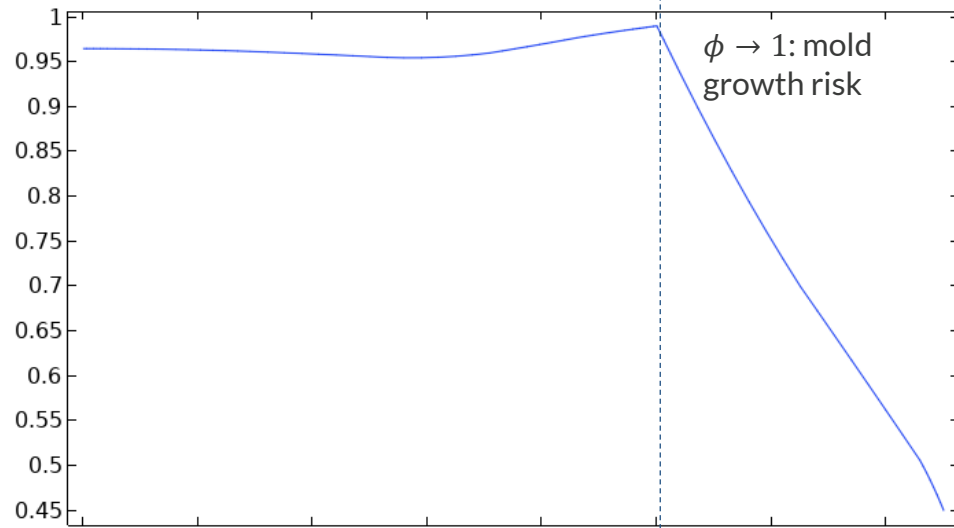
Surface: Temperature (degC)



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

Mold risk in Building Materials

- Heat and moisture in an insulated roof

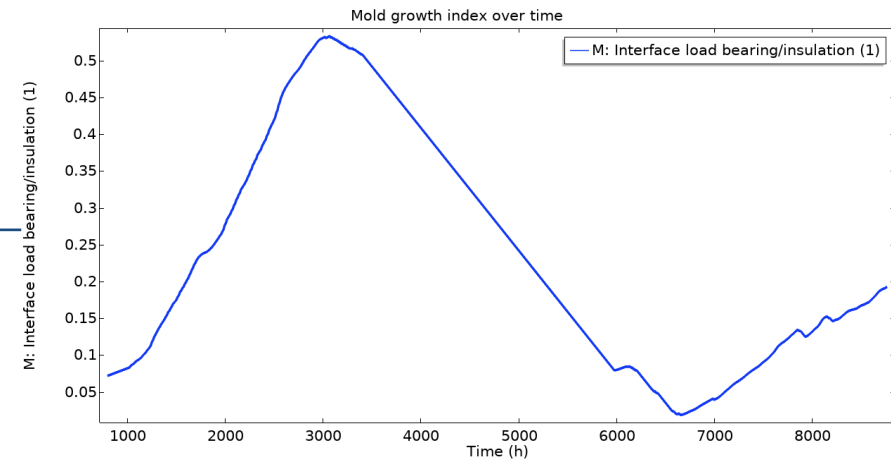


- VTT model: mold growth prediction

- 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

The screenshot displays the COMSOL Multiphysics interface for a simulation titled "condensation_electronic_device_transport_diffusion.mph".

Model Builder: Shows the hierarchy of the model. Under "Component 1", "Moisture Transport in Air" is selected, with "Moist Surface 1" highlighted. The "Results" section lists various output variables, including "Relative Humidity" and "Liquid water concentration over time".

Settings: The "Moist Surface" settings are shown. The equation is set to "Study 2, Time Dependent". The governing equations are:

$$-\mathbf{n} \cdot \mathbf{g}_w = d_z g_{\text{evap}}$$

$$g_{\text{evap}} = \begin{cases} M_v K (c_{\text{sat}} - c_v) & \text{if } c_v > c_{\text{sat}} \text{ or } c_l > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$M_v \frac{\partial c_l}{\partial t} = -d_z g_{\text{evap}}, \quad c_l(0) = c_{l,\text{init}}$$

The "Moist Surface Settings" include an "Evaporation rate factor" $K = 1$ m/s and an "Initial liquid water concentration on moist surface" $c_{l,\text{init}} = 0$ mol/m².

Graphics: A 2D plot shows the "Surface: Relative humidity (1)" at "Time=4 h". The plot displays a color map of relative humidity (ranging from 0.96 to 1.0) and a vector field of velocity. The color scale indicates that condensation (RH = 1) is occurring in the upper right region of the domain.

Moisture Transport interface
+
Moist Surface



Default results:
heat & moisture transport

Detection of Condensation

The screenshot shows the COMSOL Multiphysics interface for a simulation titled "condensation_electronic_device_transport_diffusion.mph".

Model Builder: Shows the hierarchy of the model. Under "Component 1", the "Moist Surface 1" boundary is selected. The "Results" section lists various data series, including "Liquid water concentration over time".

Settings - Moist Surface:

- Label: Moist Surface 1
- Equation: $-\mathbf{n} \cdot \mathbf{g}_w = d_z g_{\text{evap}}$
- Equation for g_{evap} :
$$g_{\text{evap}} = \begin{cases} M_v K (c_{\text{sat}} - c_v) & \text{if } c_v > c_{\text{sat}} \text{ or } c_l > 0 \\ 0 & \text{otherwise} \end{cases}$$
- Equation for $M_v \frac{\partial c_l}{\partial t}$: $M_v \frac{\partial c_l}{\partial t} = -d_z g_{\text{evap}}, \quad c_l(0) = c_{l,\text{init}}$
- Moist Surface Settings:
 - Evaporation rate factor: $K = 1$ m/s
 - Initial liquid water concentration on moist surface: $c_{l,\text{init}} = 0$ mol/m²

Graphics:

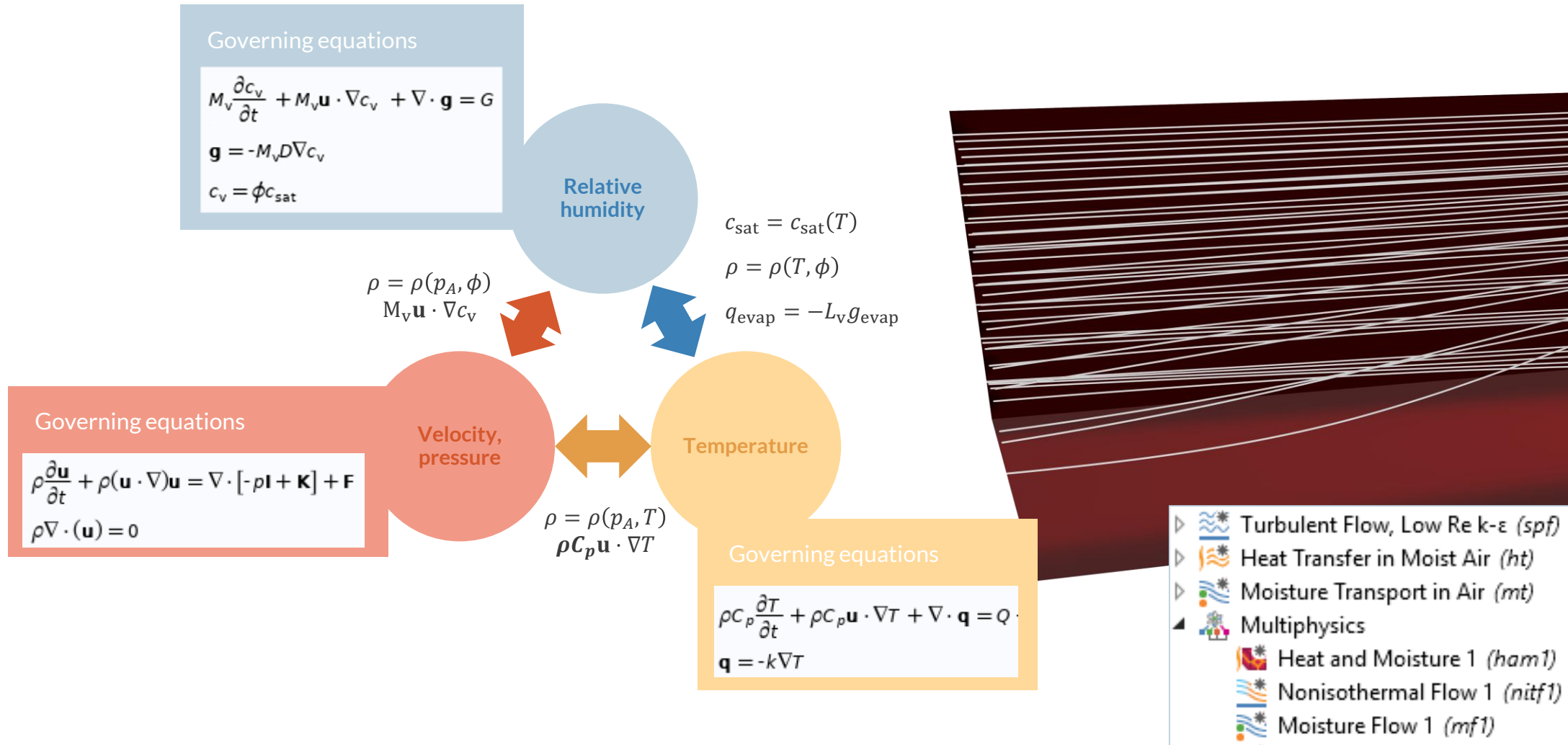
- Moist Surface:** A 2D plot showing a rectangular region with dimensions 50 mm by 50 mm.
- Water Concentration:** A point graph titled "Point Graph: Liquid water concentration on moist surface (mol/m²)". The y-axis is "Liquid water concentration on moist surface (mol/m²)" ranging from 0 to 1.1. The x-axis is "Time (h)" ranging from 0 to 20. The graph shows a sharp peak of approximately 1.05 mol/m² occurring at about 5.5 hours.

Moisture Transport interface + Moist Surface



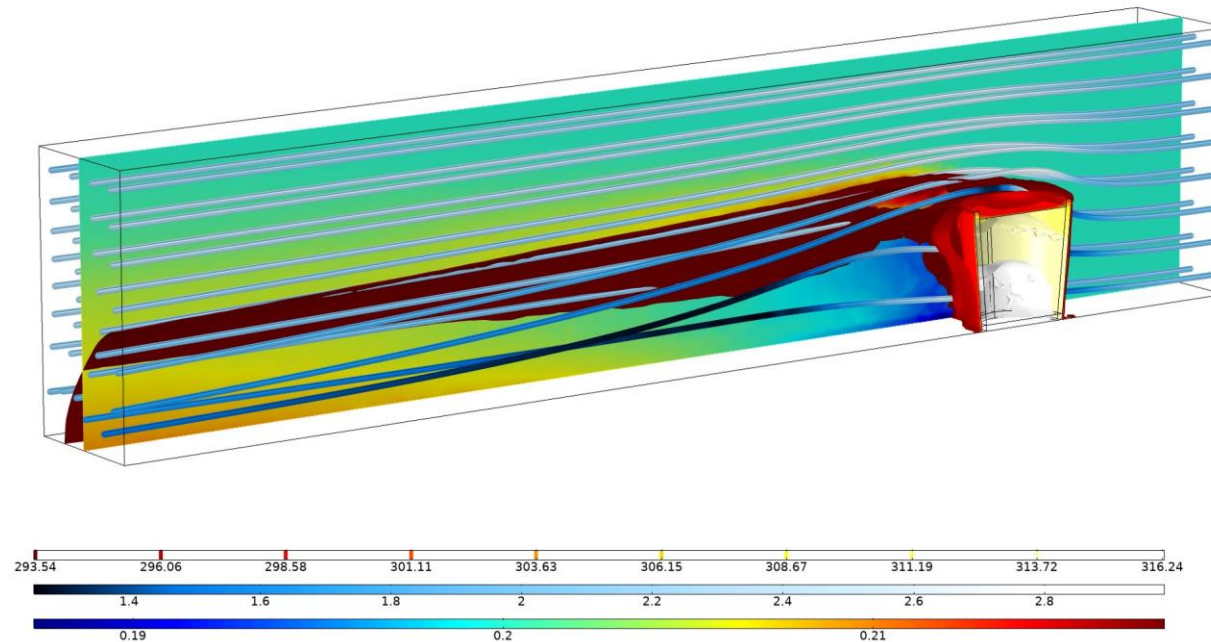
Default results: heat & moisture transport

Heat and Moisture Flow in Air



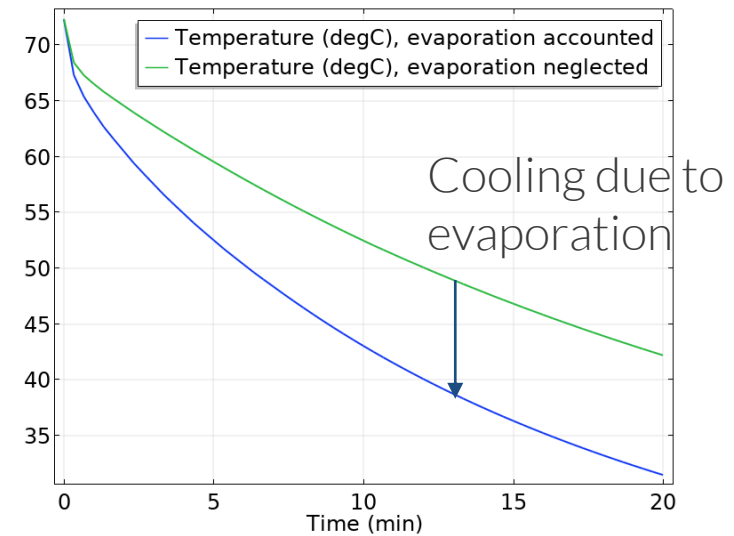
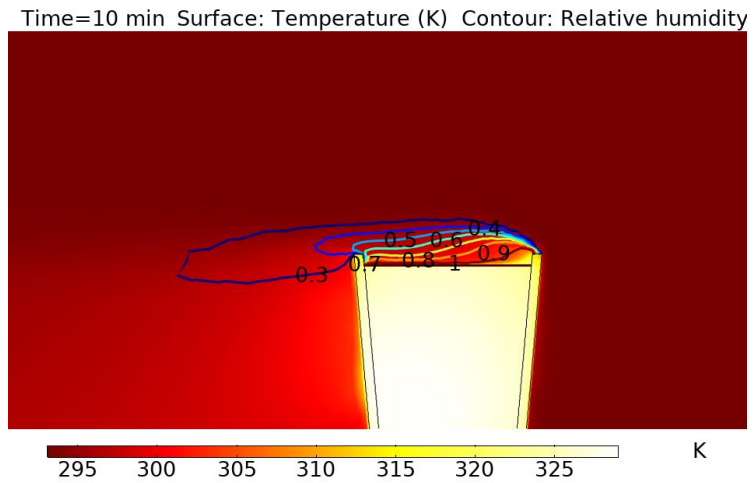
Evaporative Cooling

- ▲ Turbulent Flow, Low Re k-ε
 - ▢ Fluid Properties 1
 - ▢ Initial Values 1
 - ▢ Wall 1
 - ▢ Inlet 1
 - ▢ Open Boundary 1
 - ▢ Symmetry 1
- ▲ Heat Transfer in Moist Air
 - ▢ Moist Air 1
 - ▢ Initial Values 1
 - ▢ Thermal Insulation 1
 - ▲ Fluid 1
 - ▢ Convectively Enhanced Conductivity 1
 - ▢ Solid 1
 - ▢ Inflow 1
 - ▢ Open Boundary 1
 - ▢ Symmetry 1
 - ▢ Initial Values 2
- ▲ Moisture Transport in Air
 - ▢ Moist Air 1
 - ▢ Initial Values 1
 - ▢ Insulation 1
 - ▢ Inflow 1
 - ▢ Open Boundary 1
 - ▢ Symmetry 1
 - ▢ Wet Surface 1
- ▲ Multiphysics
 - ▢ Heat and Moisture 1
 - ▢ Nonisothermal Flow 1
 - ▢ Moisture Flow 1
 - ▢ Heat and Moisture 2



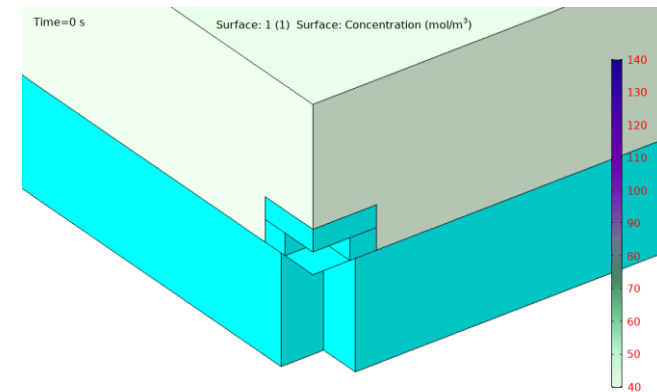
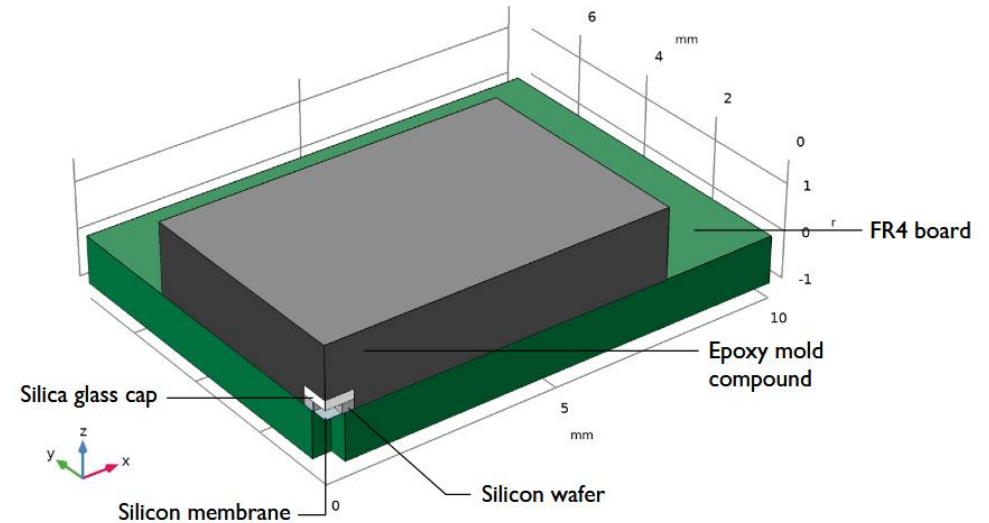
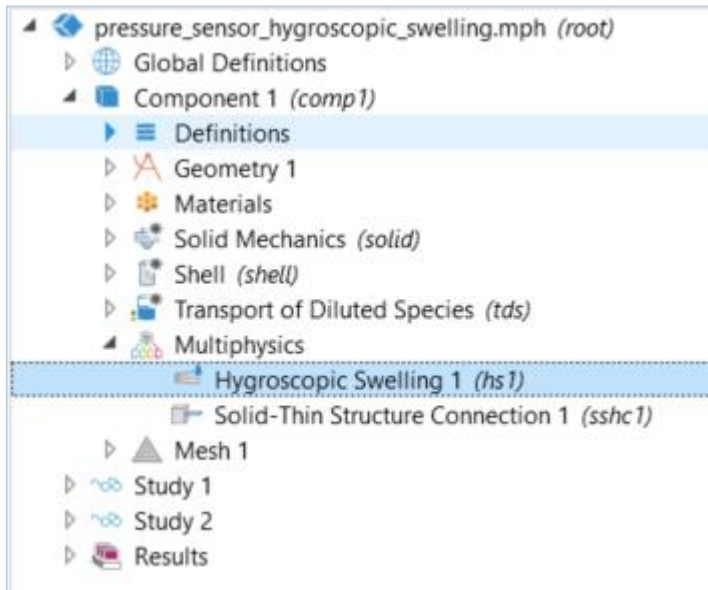
Heat and moisture in the Evaporative Cooling model

Evaporative Cooling






Hygroscopic Swelling in a MEMS Pressure Sensor

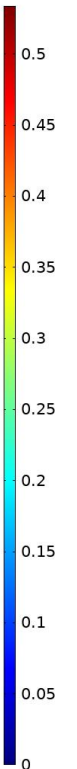
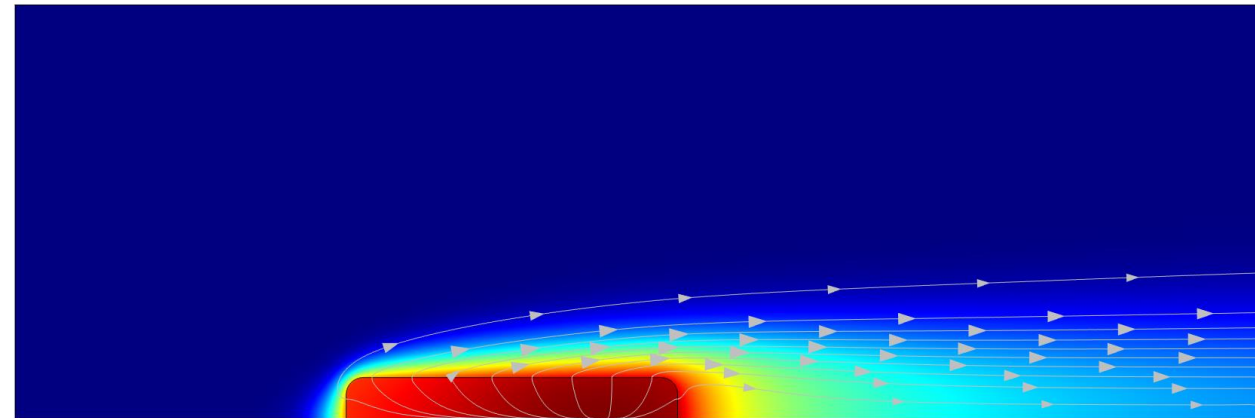
- Structural Mechanics
- Moisture diffusion
- Hygroscopic swelling



Hygroscopic swelling in a MEMS pressure sensor

Heat and Moisture Transport in Porous Media

- ▲  Laminar Flow (*spf*)
 - ▢ Fluid Properties 1
 - ▢ Initial Values 1
 - ▢ Wall 1
 - ▢ Fluid and Matrix Properties 1
 - ▢ Inlet 1
 - ▢ Outlet 1
- ▲  Moisture Transport in Air (*mt*)
 - ▢ Moist Air 1
 - ▢ Initial Values 1
 - ▢ Insulation 1
 - ▢ Hygroscopic Porous Medium 1
 - ▢ Initial Values 2
 - ▢ Inflow 1
 - ▢ Outflow 1
- ▲  Heat Transfer in Moist Air (*ht*)
 - ▢ Moist Air 1
 - ▢ Initial Values 1
 - ▢ Thermal Insulation 1
 - ▢ Moist Porous Medium 1
 - ▢ Inflow 1
 - ▢ Outflow 1



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: $Q_{in} = 100W$

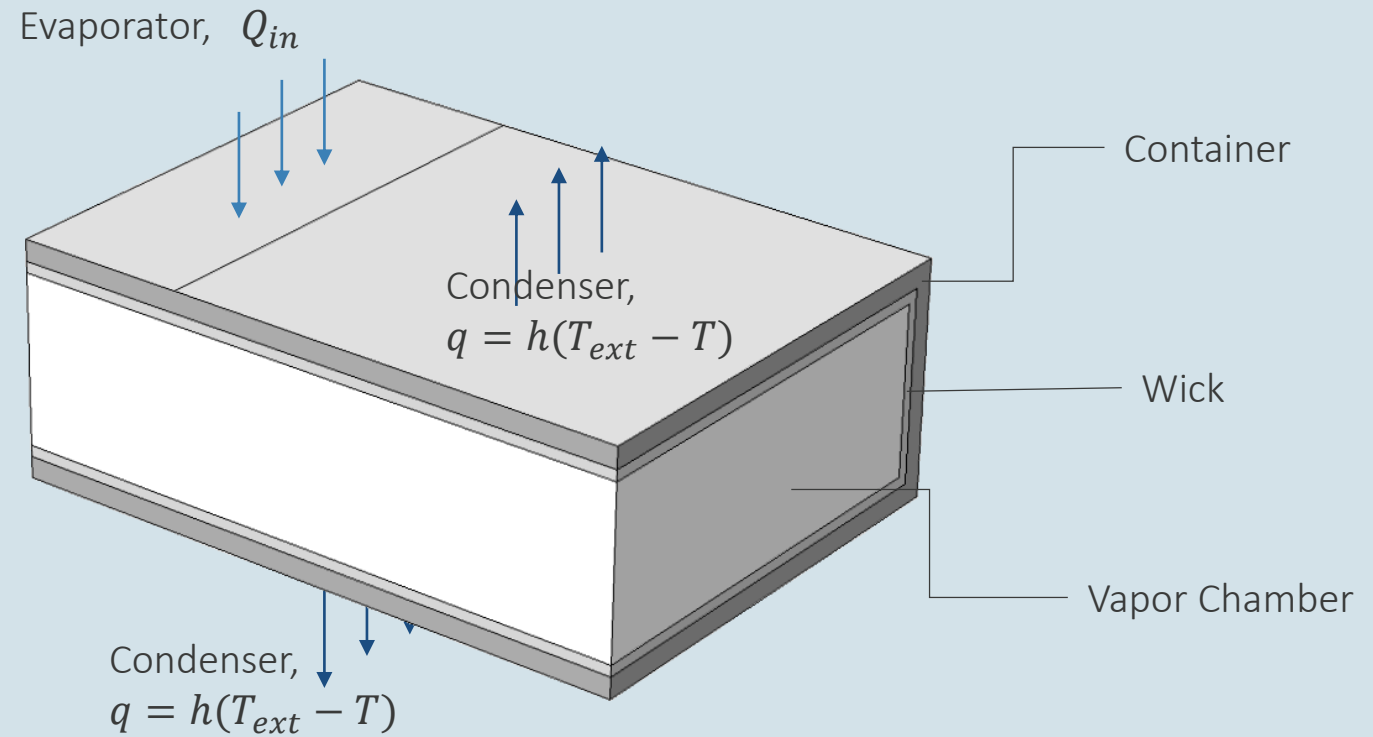
- Heat transfer coefficient

$$h = 1100 \frac{W}{m^2K}$$

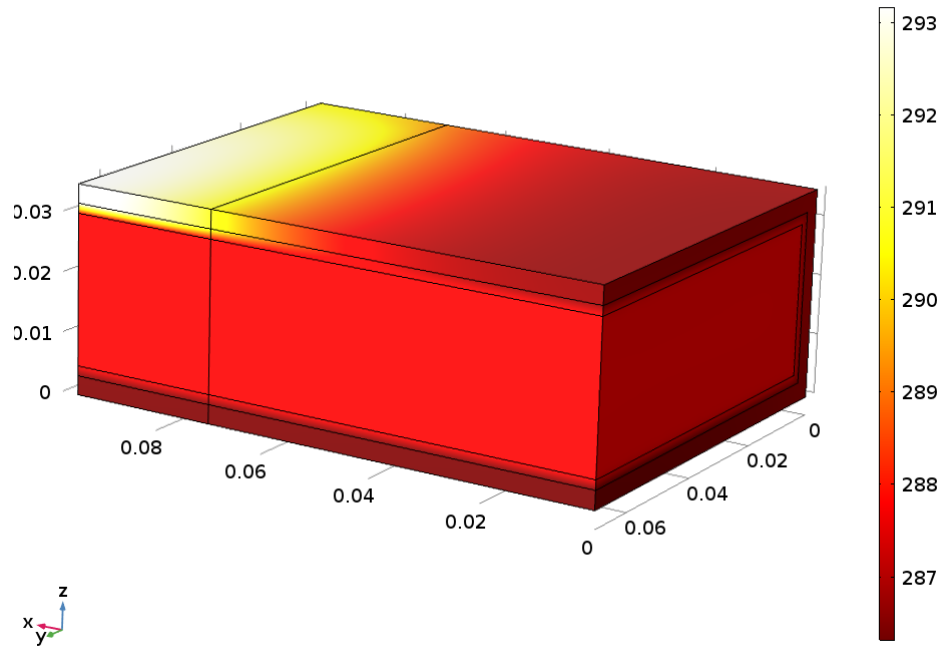
- External temperature

$$T_{ext} = 285K$$

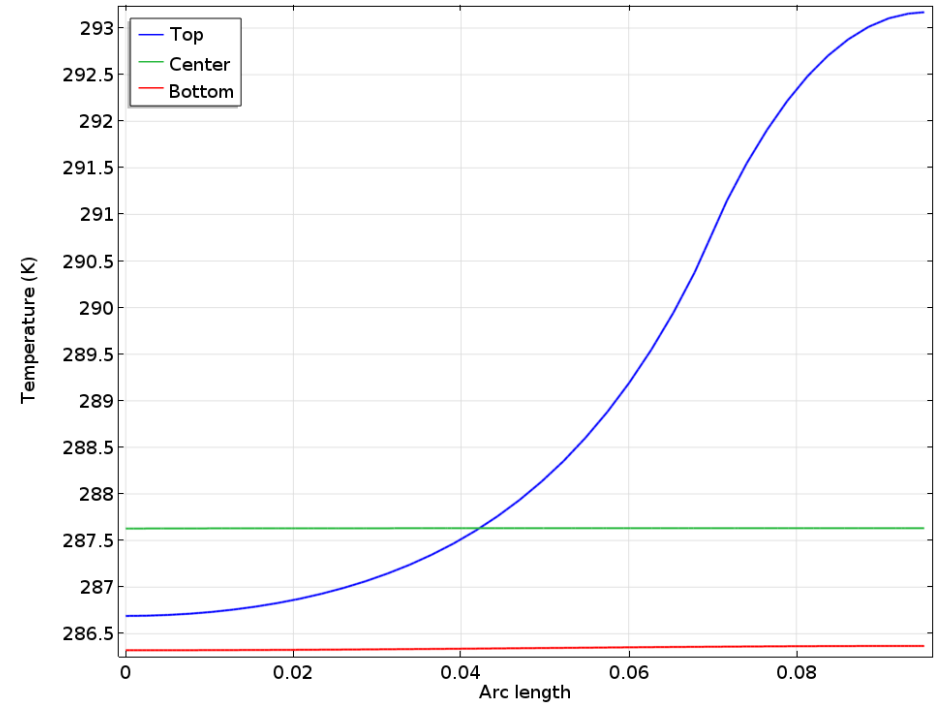
- Only $\frac{1}{4}$ of the chamber is modeled due to symmetry



Flat Heat Pipe

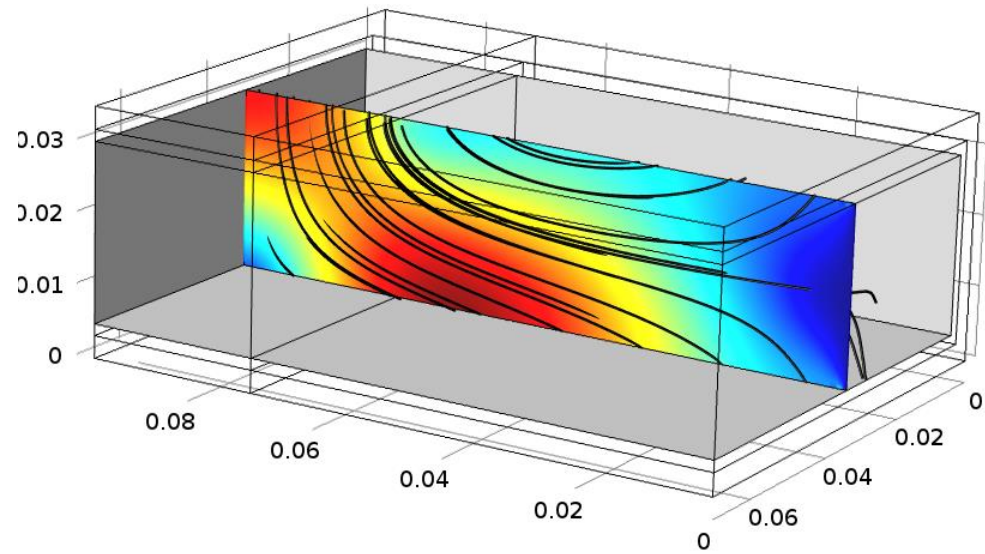


Temperature distribution in heat pipe

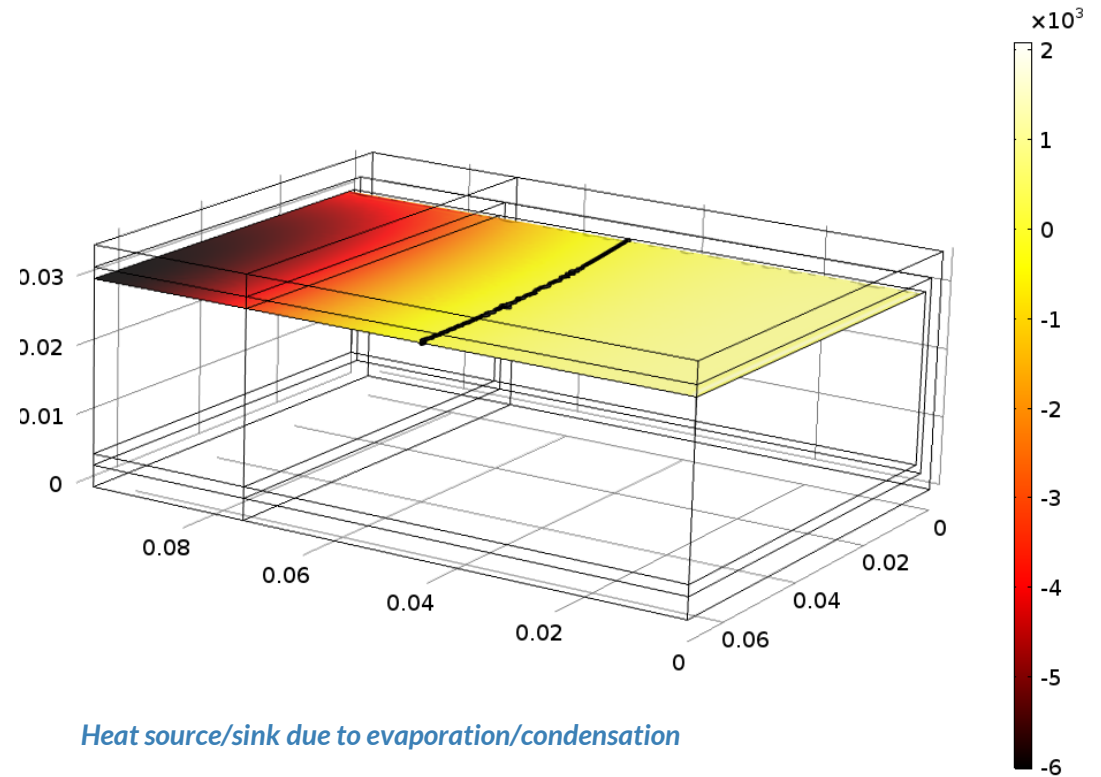
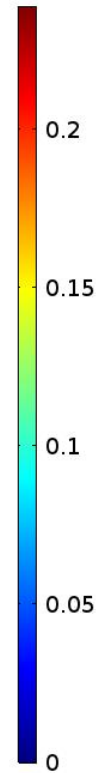


Temperature profiles at top, center and bottom of heat pipe

Flat Heat Pipe



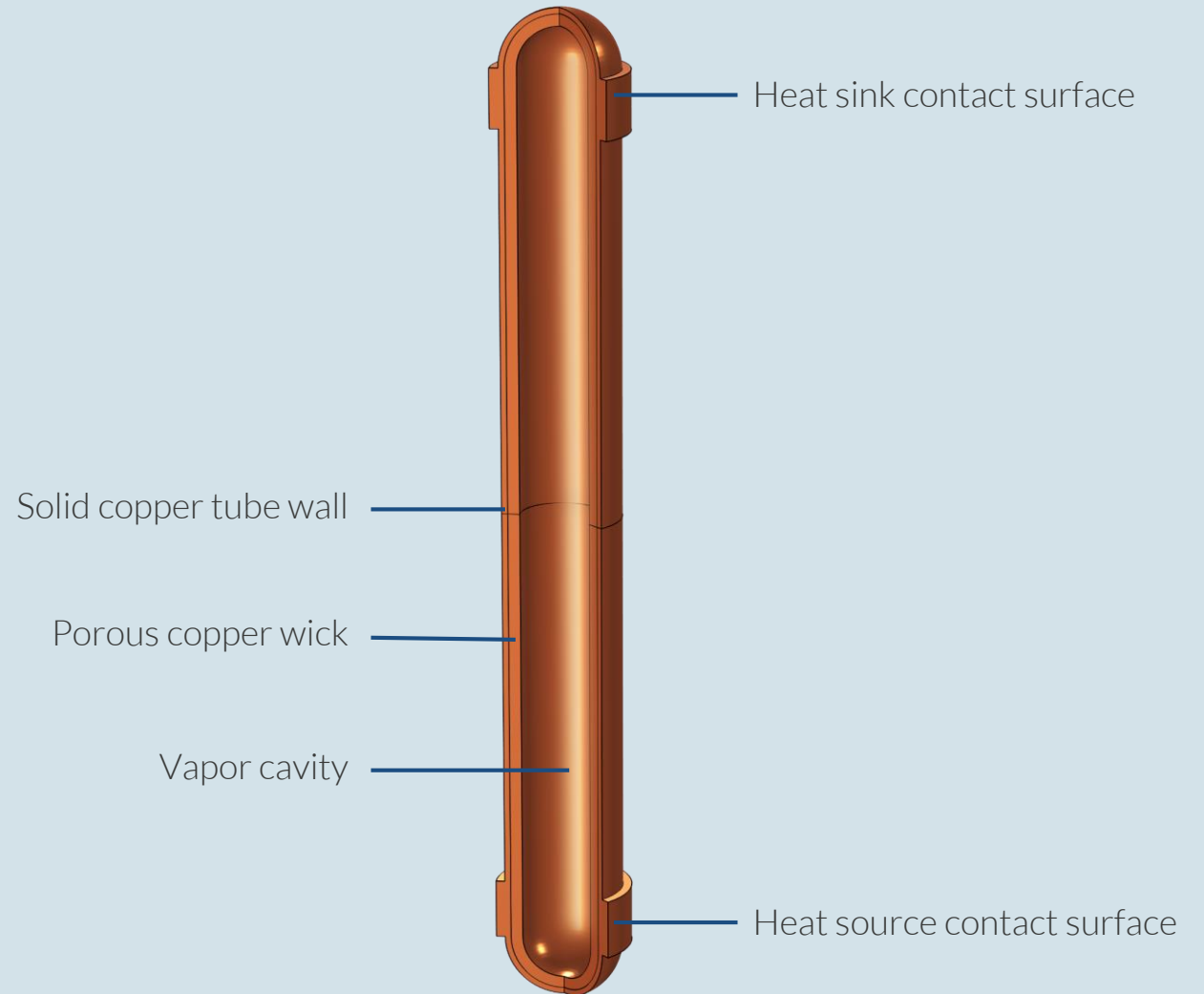
Velocity field in vapor chamber



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 through a porous wick
- Liquid and vapor properties generated using the thermochemistry database.



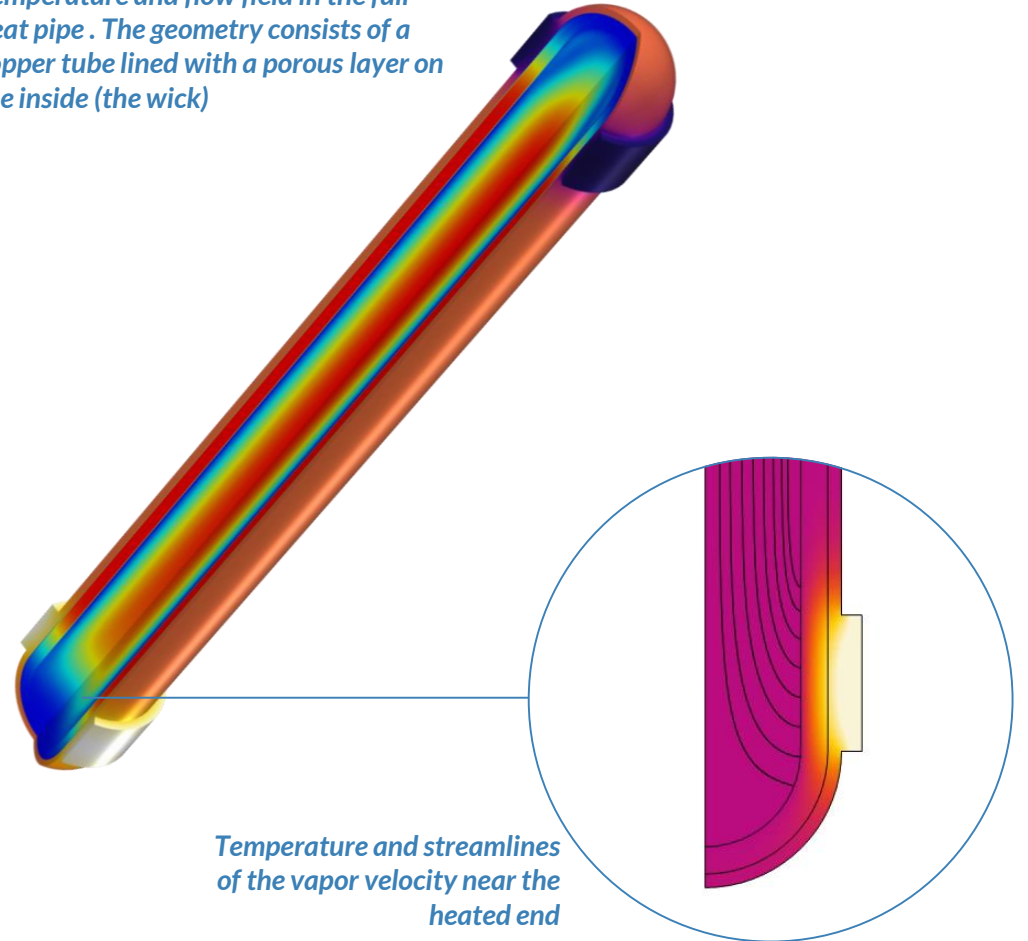
[Overview of the heat pipe model](#)

Heat Pipe With Accurate Liquid and Gas Properties

- Thermodynamics
 - Gas System 1 (pp1)
 - water
 - Vapor
 - Vapor-Liquid System 1 (pp2)
 - water
 - Heat of vaporization 1 (HeatOfVapor)
 - Ln vapor pressure 1 (LnVaporPressure)
 - Liquid

- Component 1 (comp1)
 - Definitions
 - Geometry 1
 - Materials
 - Laminar Flow (spf)
 - Fluid Properties 1
 - Initial Values 1
 - Axial Symmetry 1
 - Wall 1
 - Inlet 1
 - Brinkman Equations (br)
 - Fluid and Matrix Properties 1
 - Initial Values 1
 - Axial Symmetry 1
 - Wall 1
 - Inlet 1
 - Pressure Point Constraint 1
 - Heat Transfer in Porous Media (ht)
 - Porous Medium 1
 - Initial Values 1
 - Axial Symmetry 1
 - Thermal Insulation 1
 - Solid 1
 - Fluid 1
 - Heat Flux 1
 - Heat Flux 2
 - Boundary Heat Source 1
 - Multiphysics

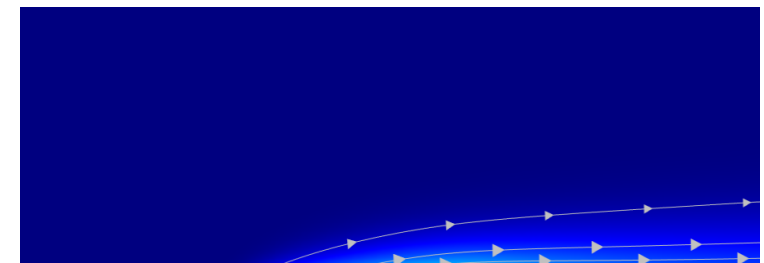
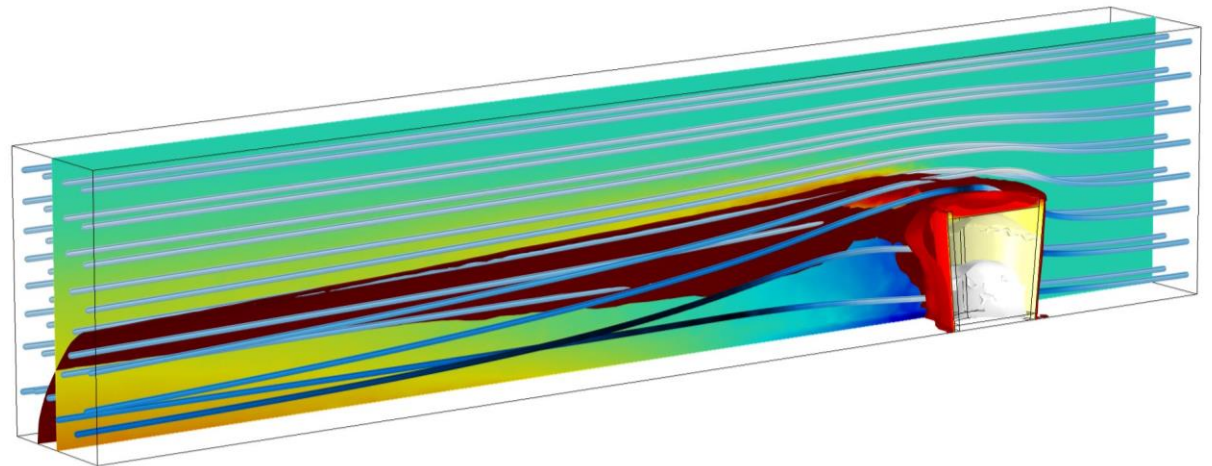
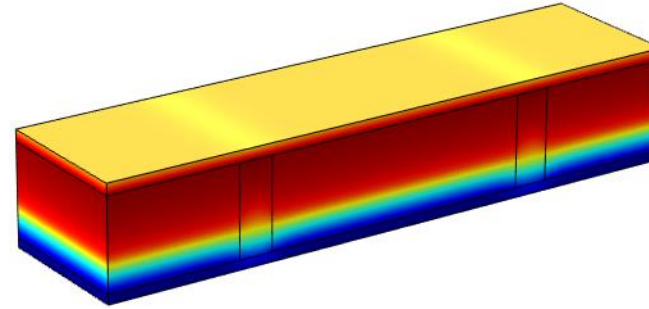
Temperature and flow field in the full heat pipe. The geometry consists of a copper tube lined with a porous layer on the inside (the wick)



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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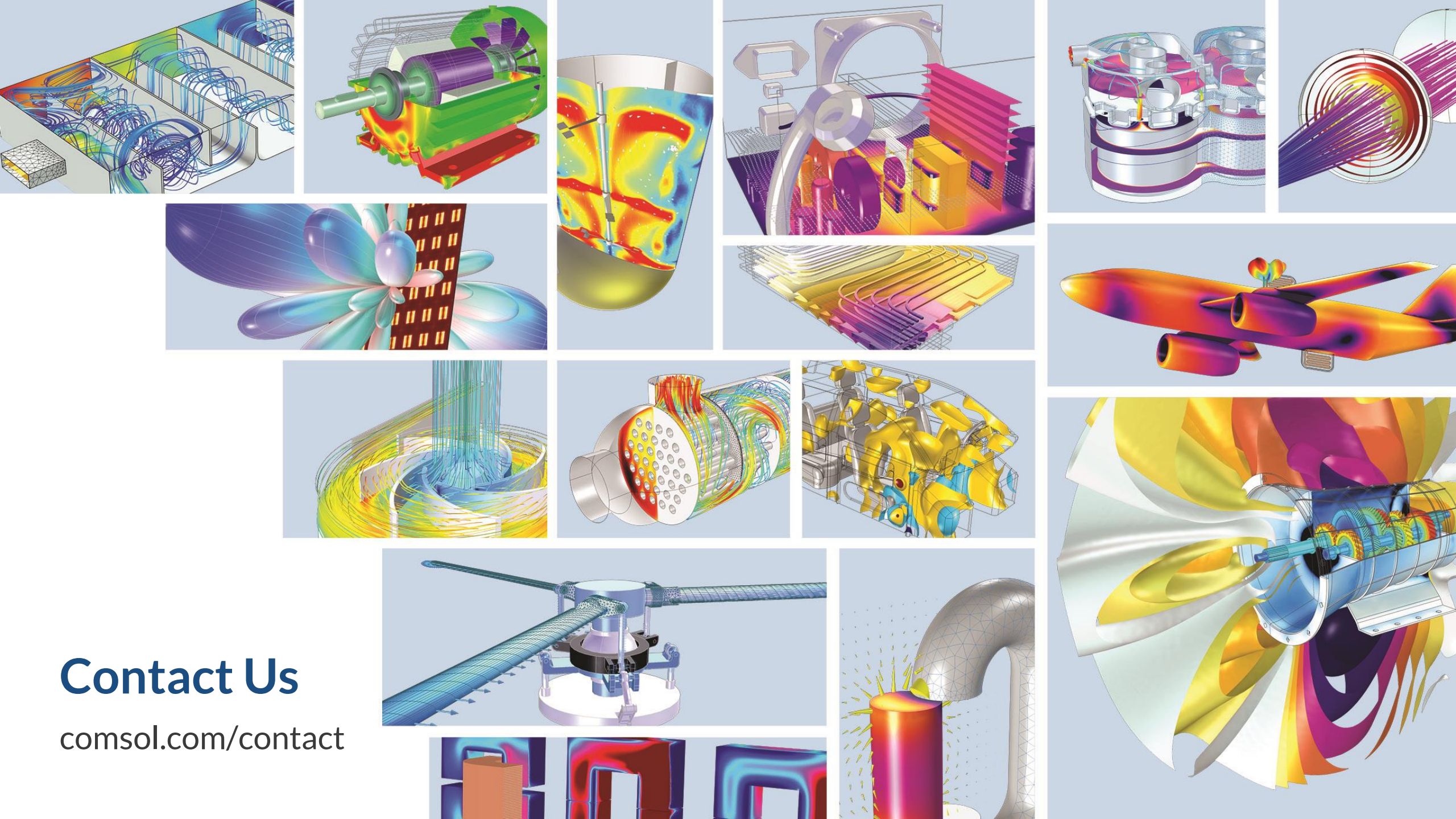
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