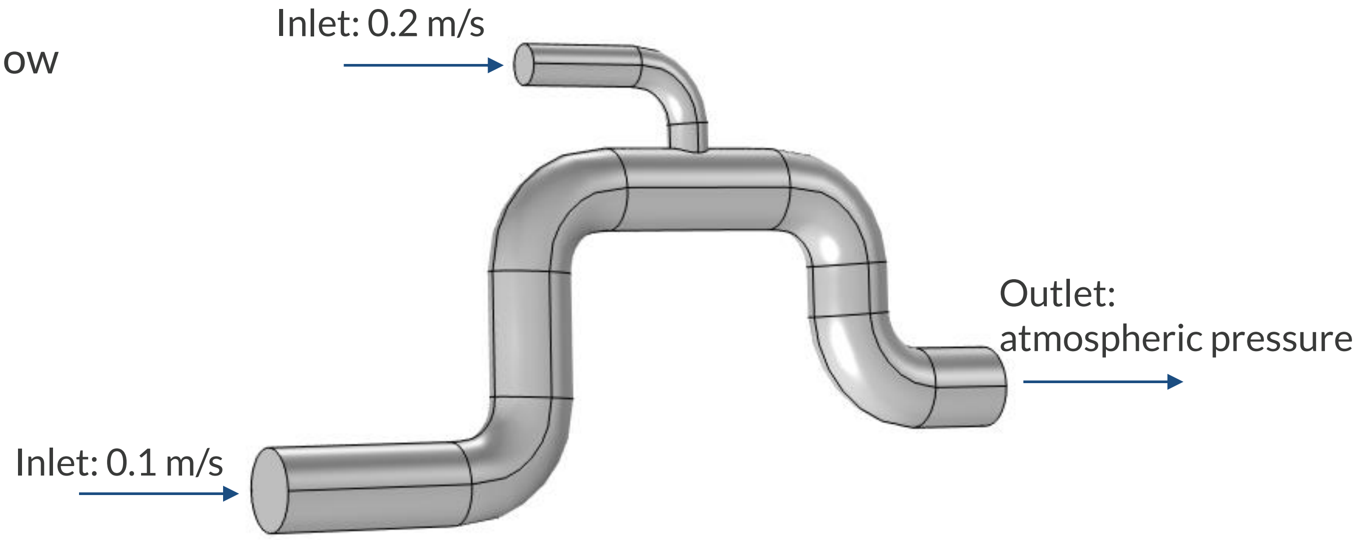
CFD and Heat tranfser

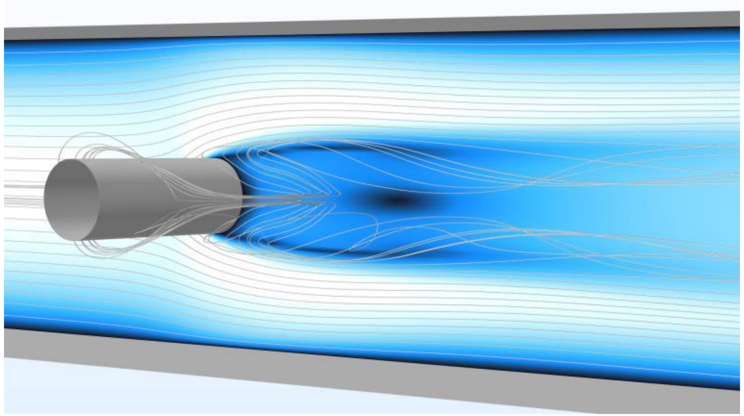
Flow in tubes, turbulent and laminar

- Material: Water
- First step: Flow
- Second step Flow and Heat



Contents of This Presentation

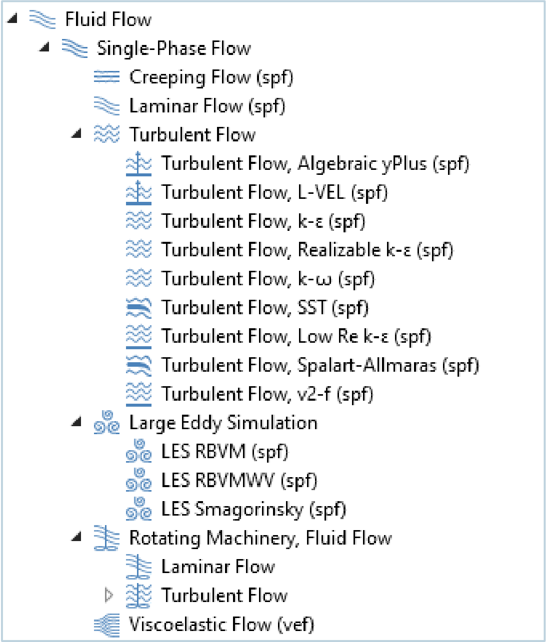
- Laminar and turbulent flow models for:
  - Single-phase flow
  - Multiphase flow
  - Non-isothermal flow and conjugate heat transfer
  - High Mach number flow
  - Reacting Flow
  - Thin-film and porous media flow
- General and multiphysics capabilities
- Tutorials and benchmarks
- Details of the CFD module



Instantaneous streamlines and velocity magnitude for periodic 3D flow around a cylinder in a channel.

Single-Phase Flow

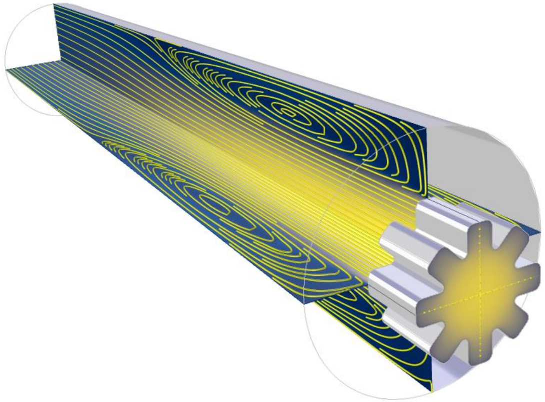
- Creeping flow also called Stokes flow
- Laminar flow
  - Newtonian and non-Newtonian flow
- Turbulent flow
  - 2 algebraic models
  - 7 transport-equation models
- Large eddy simulation (LES)
  - 3 variational multi-scale models
- Rotating machinery
  - Laminar and turbulent flow
- Viscoelastic flow



The Single-Phase Flow user interfaces as displayed in the Physics list in the CFD Module.

Single-Phase Flow: General Functionality

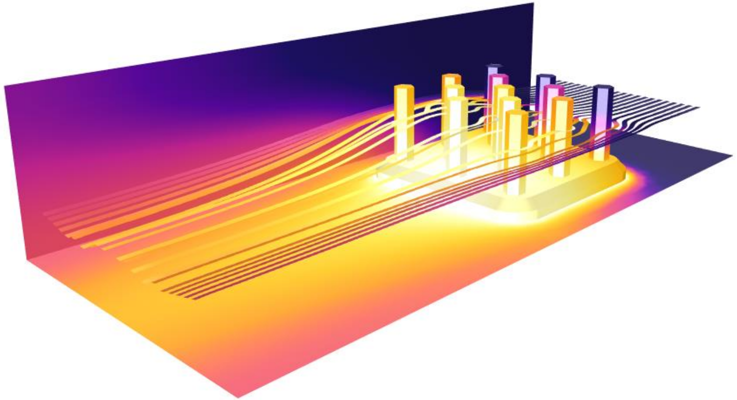
- Swirl flow
  - Includes the out-of-plane velocity component for axisymmetric flows
- Enable porous media domains
  - Model porous media flow or coupled free and porous media flow
- Gravity and reduced-pressure option
- Special purpose boundary conditions
  - Fully developed laminar and turbulent inflow and outflow
  - Wall conditions on internal shells for simulating thin immersed structures
  - Screen conditions for simulating thin perforated plates and wire gauzes



Fully developed turbulent flow condition at a star-shaped inlet.

Algebraic Turbulence Models

- Turbulent viscosity evaluated from the Reynolds number based on local speed and wall distance
  - Algebraic yPlus
  - L-VEL
- Advantages:
  - Robust
  - Computationally inexpensive
- Disadvantage:
  - Less accurate



Surface temperature and streamlines in a benchmark for electronic cooling.

Transport Equations for Turbulence: Two Equation Models

k-ε models

- The standard k-ε model with realizability constraints
- The realizable k-ε model

k-ω model

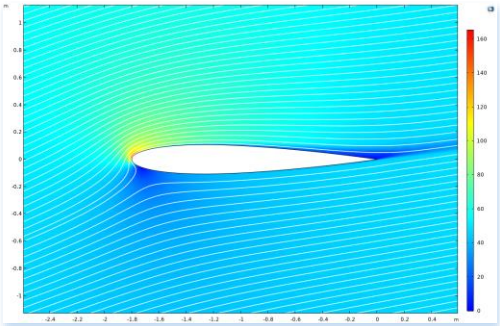
- The revised Wilcox k-ω model (1998) with realizability constraints

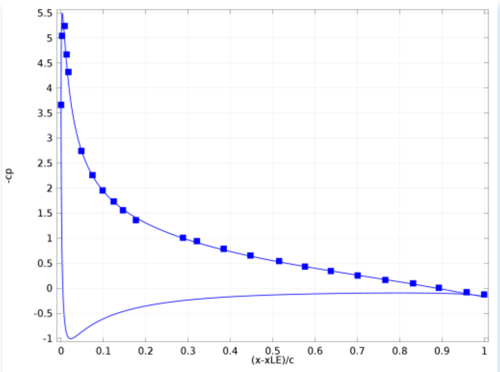
SST model

- Combines the k-ε model in the free stream with the k-ω model close to walls

Low Re k-ε model

- The AKN k-ε model





Benchmark model of a NACA0012 airfoil using the SST turbulence model.

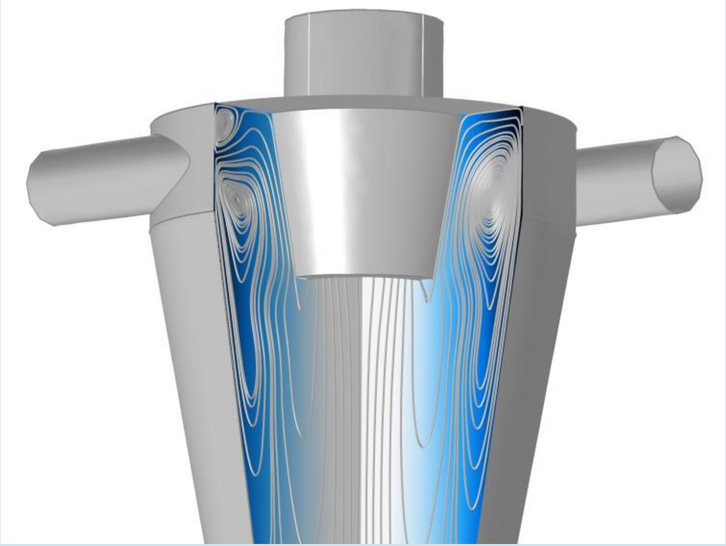
Transport Equation Turbulence Models

Spalart-Allmaras

- One-equation model with rotational correction, developed for
aerodynamic applications

v^2-f model

- An extension of the k-ε model which accounts for turbulence anisotropy by solving for the wall-normal turbulence velocity fluctuations



Flow in a hydrocylone. A typical application where v^2-f gives superior results over two-equation models such as k-ε or SST.

Wall Treatment

Wall functions for smooth and rough walls

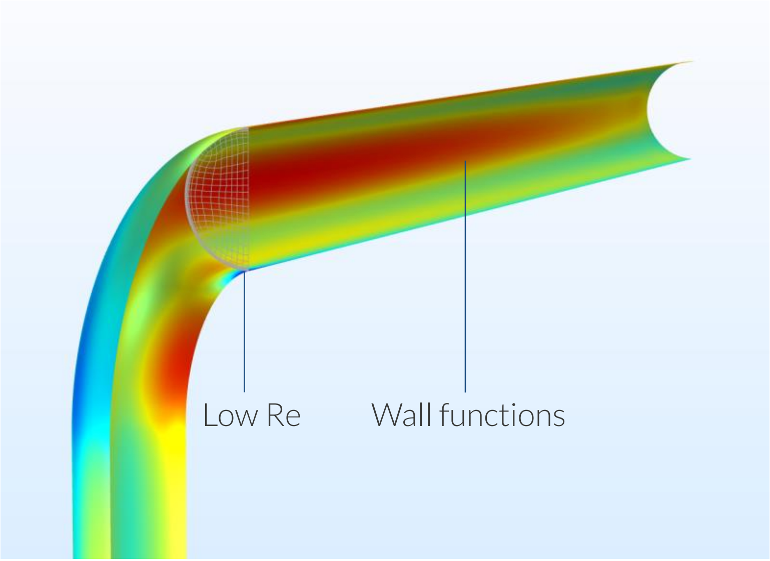
- Robust, applicable for coarse meshes, but limited accuracy
- Supported by k-ε, Realizable k-ε and k-ω

Low-Reynolds-number treatment

- Resolves the flow all the way down to walls, accurate
- Supported by all turbulence models except k-ε and realizable k-ε

Automatic wall treatment

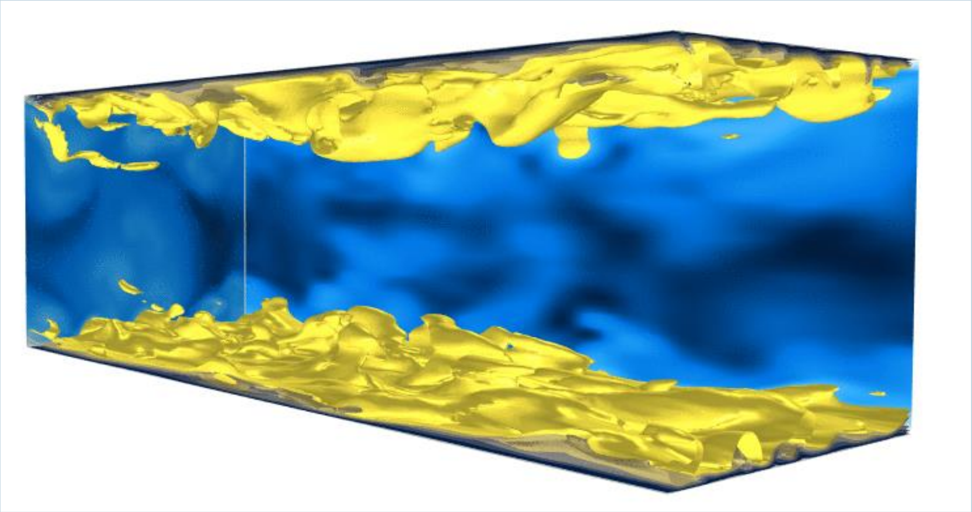
- Switches between low-Re treatment and wall functions, accuracy according to local mesh resolution
- Inherits the robustness provided by wall functions
- Default for all turbulence models except k-ε and realizable k-ε



Flow in a pipe elbow simulated with the k-ω model.

Large Eddy Simulation

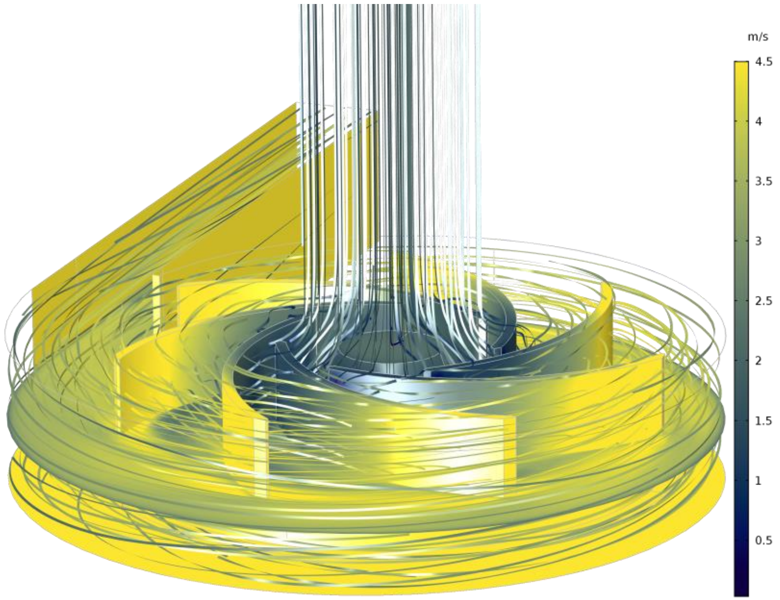
- The larger three-dimensional, unsteady eddies are resolved, whereas the effect of the smaller eddies is modeled
- Simulations must be three-dimensional and time dependent
- Computationally demanding
- The three current interfaces are based on variational multiscale methods
- Nonisothermal LES



LES of turbulent channel flow at $Re_T = 395$

Rotating Machinery

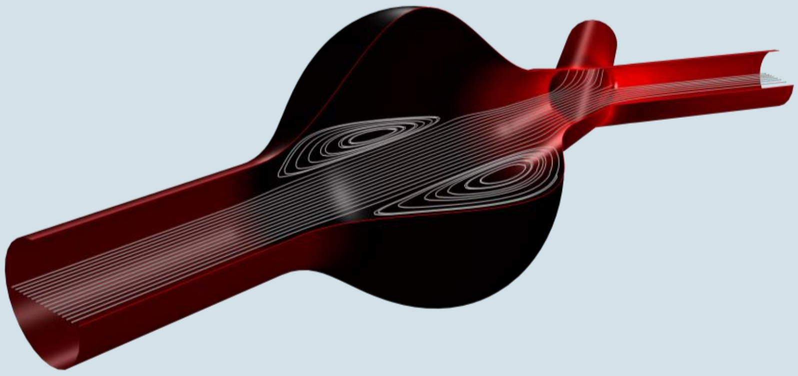
- Laminar and turbulent
- Sliding mesh
  - Accurate time-dependent simulations
- Frozen rotor
  - Fast, stationary approximations
  - Can provide starting conditions for a sliding mesh simulation
  - Stationary free surface post-processing feature
- Interior wall conditions
  - Simulate infinitely thin blades and baffles



Velocity field in a centrifugal pump.

Non-Newtonian Fluids

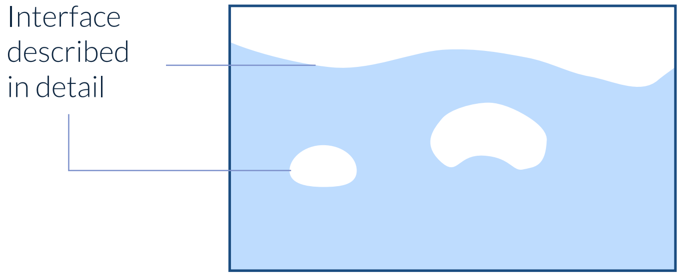
- Inelastic non-Newtonian:
  - Power law
  - Carreau
  - Bingham-Papanastasiou
  - Herchel-Bukley-Papanastasiou
  - Casson-Papanastasiou
- Viscoelastic:
  - Oldroyd-B
  - Giesekus
  - FENE-P

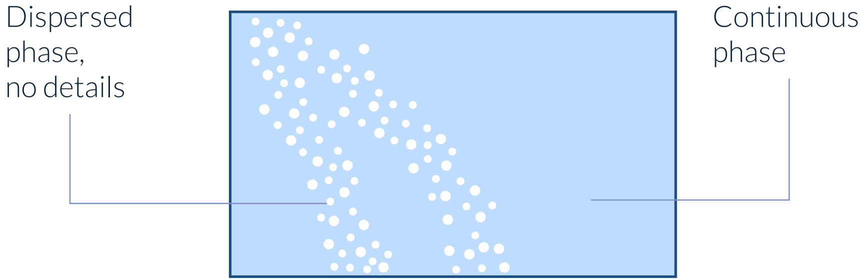


Viscoeleastic flow: Blood flow in an abdominal aeortic aneurysm. The colormap displays the total wall stress. A brighter red color indicates a larger stress.

Multiphase Flow

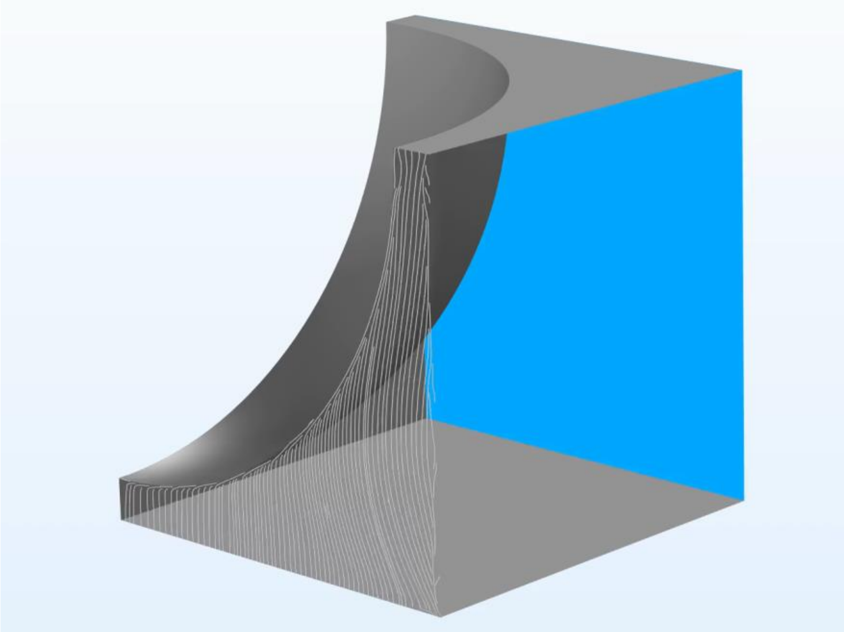
- Separated flows
  - Two-phase flow, level set
  - Two-phase flow, phase field
  - Three-phase flow, phase field
- Dispersed flows
  - Incompressible and compressible
  - Bubbly flow
  - Mixture model
  - Euler-Euler model
  - Phase transport (couple to single- or multiphase flow)
  - Bubbles, droplets, or particles much smaller than the model domain





Multiphase Flow – Dispersed Flows

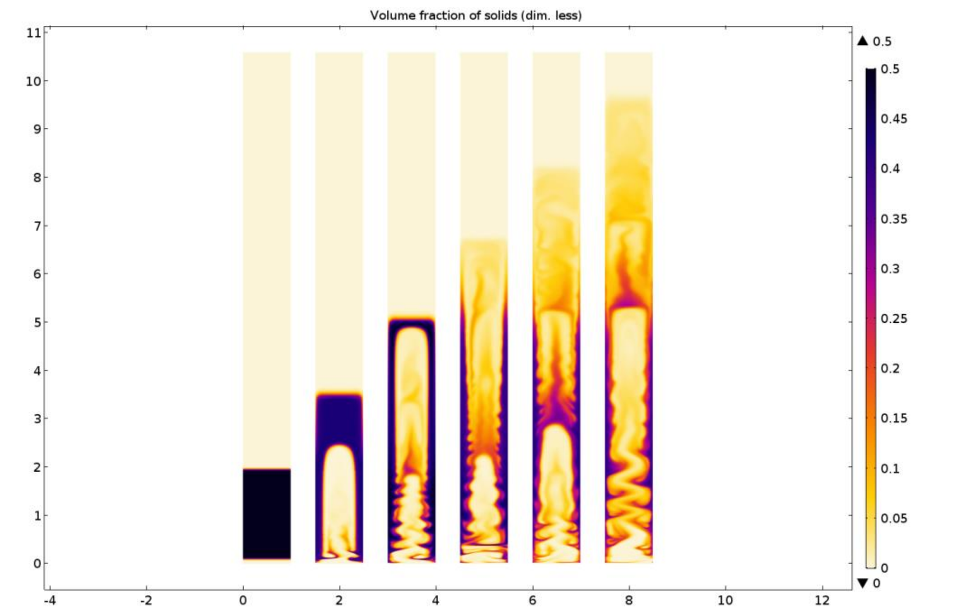
- Bubbly Flow & Mixture Model
  - Relative motion (slip) assumes that the particle relaxation time is small compared to the time scale of the mean flow
  - Bubble-induced turbulence
  - Mass transfer between phases
  - Spherical and non-spherical particles
  - Compatible with all RANS turbulence models
  - Phase transport mixture model for arbitrary number of phases



Enhanced sedimentation of dispersed particles below a curved boundary. Simulated with the Mixture Model, k-ε interface.

Multiphase Flow – Dispersed Flows

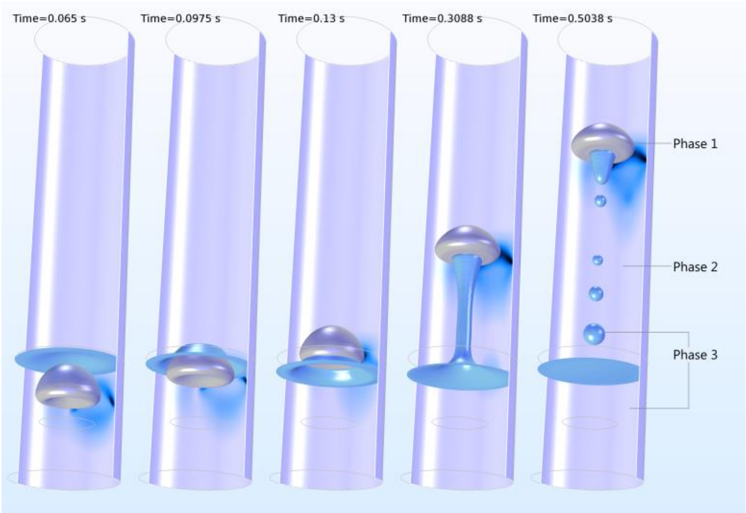
- Euler-Euler Flow
  - General two-phase flow
  - No restriction on particle relaxation time
  - Spherical and non-spherical particles
  - Mixture or phase-specific k-e turbulence model



Euler-Euler multiphase floe model of a fluidized bed.

Multiphase Flow - Separated Flows

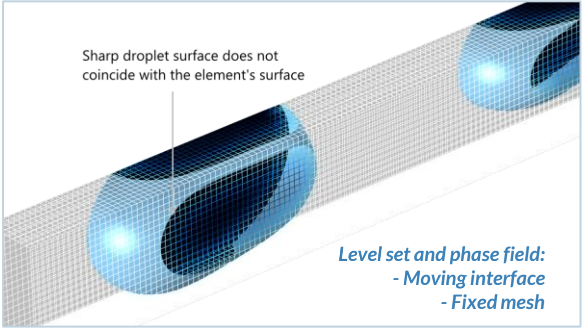
- Tracks the exact surface location using the level-set or phase-field models, or by using a moving-mesh interface
- Accurate modeling of surface-tension effects
- Includes a surface-tension coefficient library
- Compatible with all RANS turbulence models



Three-phase flow using the phase-field method.

Separated Flows

- Three complimentary methods:
  - Level set: fixed mesh
  - Phase field: fixed mesh
  - Moving mesh



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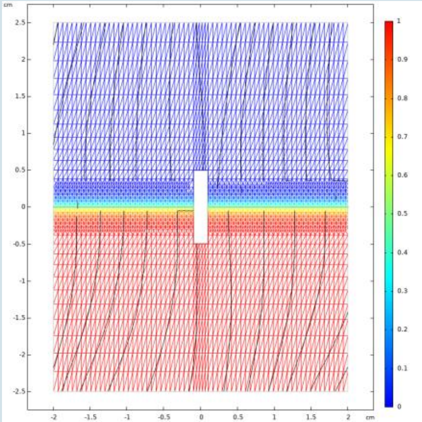
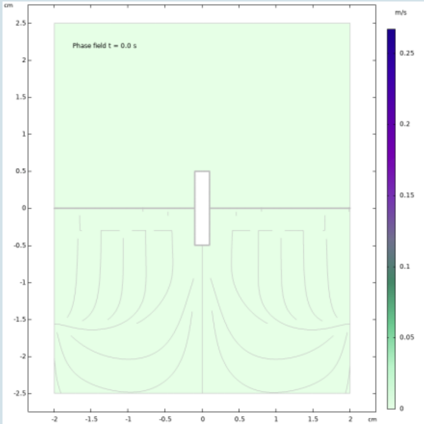
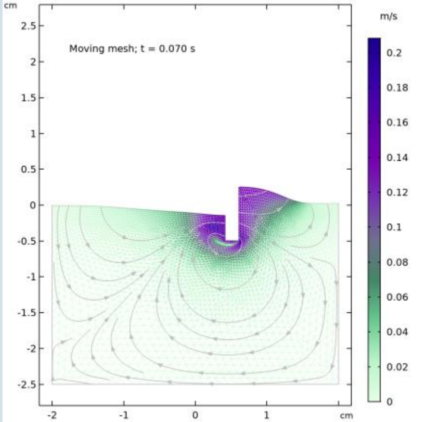
Adaptive mesh with phase field and level set. Note: The rectangle moves with moving mesh.

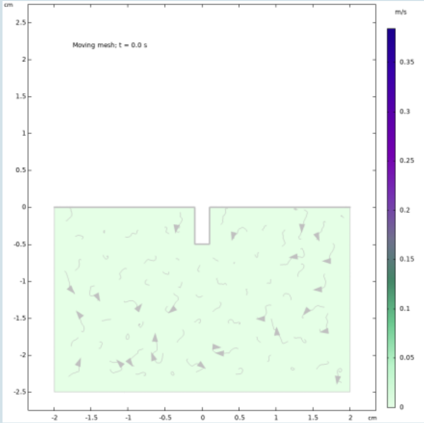


The phase boundary is modeled with phase field. Almost identical results with level set.





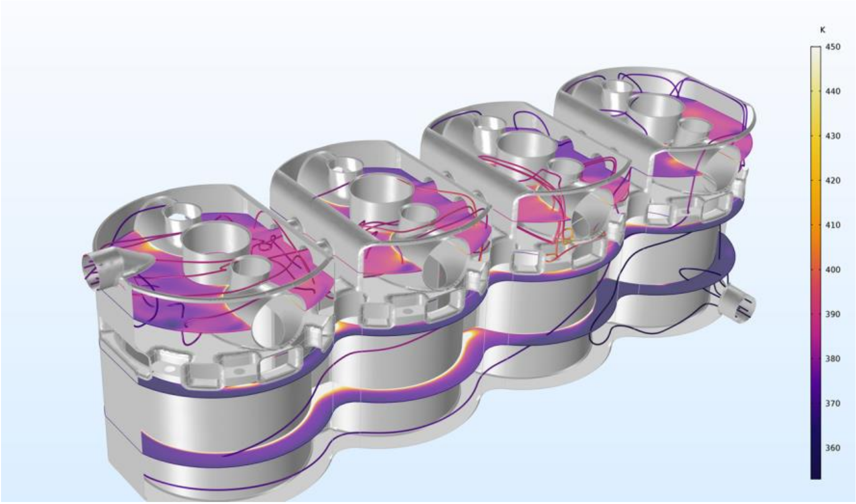
Moving mesh: Elements coincide with interface.



Moving mesh: Both the rectangle and the phase boundary move with moving mesh.

Non-Isothermal Flow and Conjugate Heat Transfer

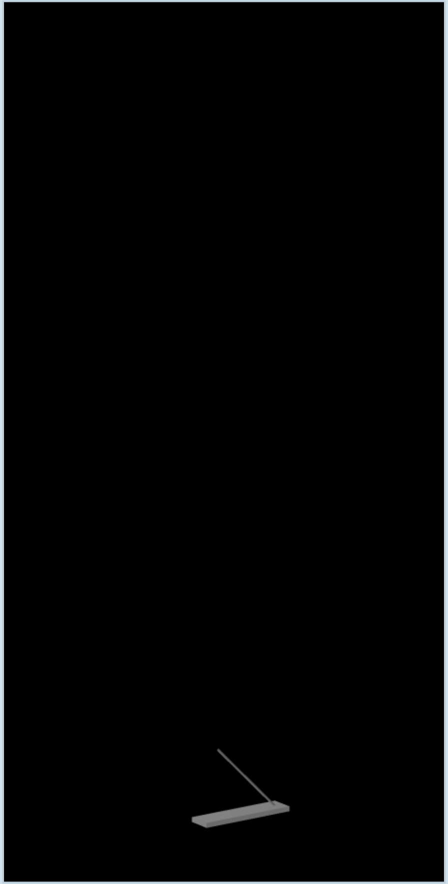
- Heat transfer in fluids and solids
- Laminar and turbulent flow
- Bouyancy-induced turbulence
- Compressible, weakly compressible, or Boussinesq approximation
- Dispersed multiphase flow using the mixture model, laminar and turbulent



Conjugate heat transfer in the cooling of an engine block.

Non-Isothermal Flow and Conjugate Heat Transfer

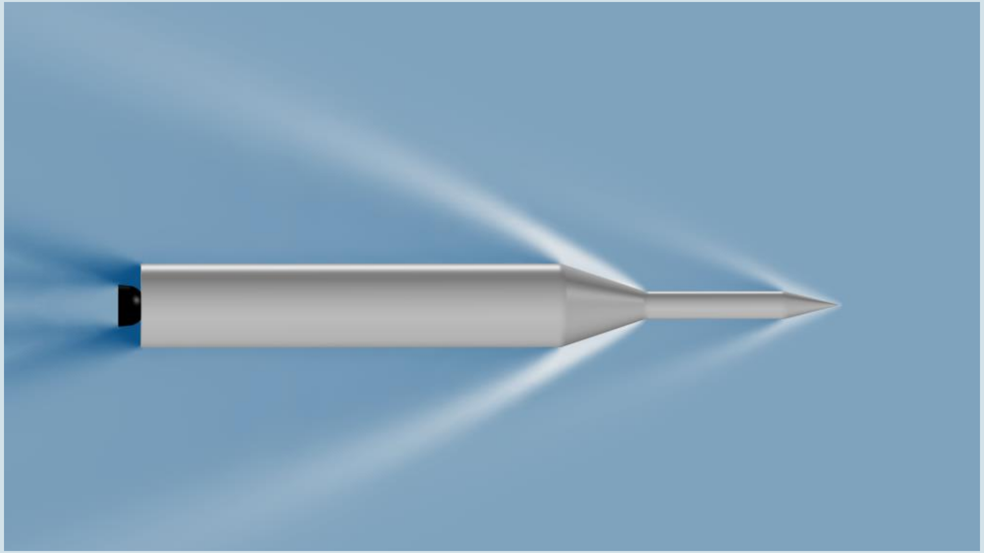
- Correlations for heat transfer coefficients
- Heat transfer in porous media
- Thermal wall functions when using the k-ε, Realizable k-ε or k-ω turbulence models
- Turbulent Prandtl number models:
  - Kays-Crawford and extended Kays-Crawford
- Nonisothermal LES



LES nonisothermal flow

High Mach Number Flow

- Laminar and turbulent flow
- k-ε turbulence model
- Spalart-Allmaras model
- Fully compressible flow for all Mach numbers
- Viscosity and conductivity can be determined from Sutherland's law
- Compressible Euler equations for transient, isentropic flow

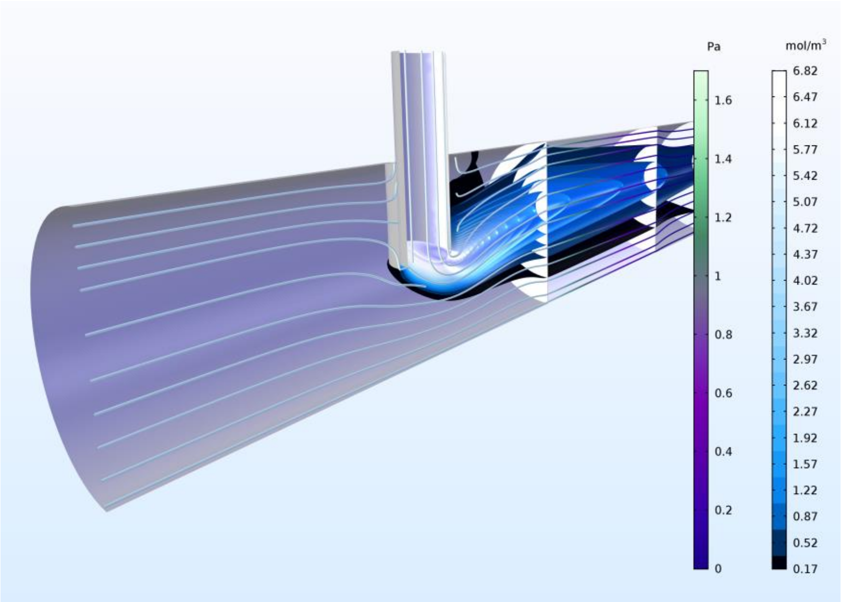


Density variations around a rocket at supersonic speed. Light color indicates high density.

Reacting Flow

Multi-component transport and flow in diluted and concentrated solutions

- Fickian and mixture-averaged diffusion
- Migration of charged species in electric fields
- Mass transport in free and porous media flow
- Turbulent mixing and reactions
- Stefan velocities on boundaries with reactions
- Concentration-dependent density and viscosity in flow description

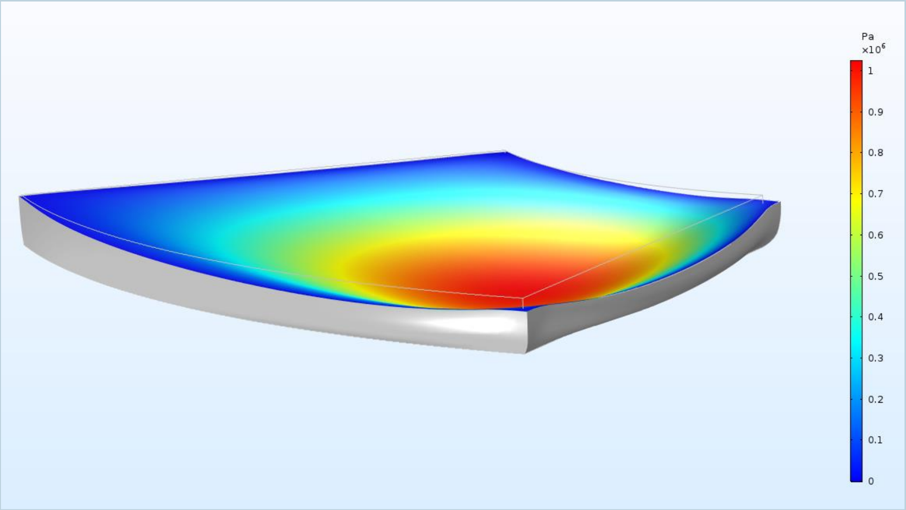


Reacting flow in a tubular reactor.

Thin-Film Flow

Reynolds' equations

- For lubrication and flow in narrow channels and cracks (3D shells)
- Supports gaseous cavitation



Surface pressure in the liquid lubricating film and structural deformation in a tilted pad bearing.

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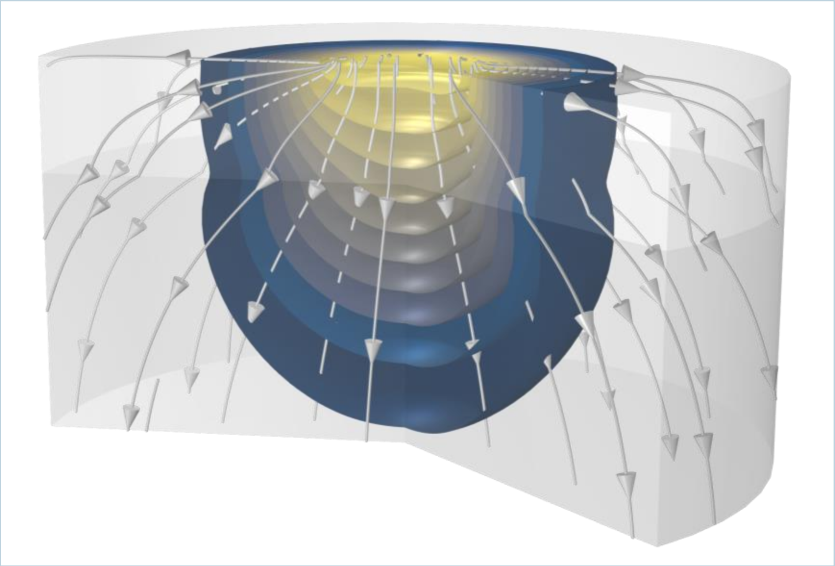
Porous Media Flow

- Laminar or turbulent free flow coupled to porous media flow including Forchheimer drag (high interstitial velocities)
- Darcy's law and Brinkman's equations, isotropic or anisotropic permeability
- Two-phase flow, Darcy's law with capillary pressure models
- Multiphase flow with an arbitrary number of phases using phase transport



Flow field and concentration distribution in unsaturated soil layers.

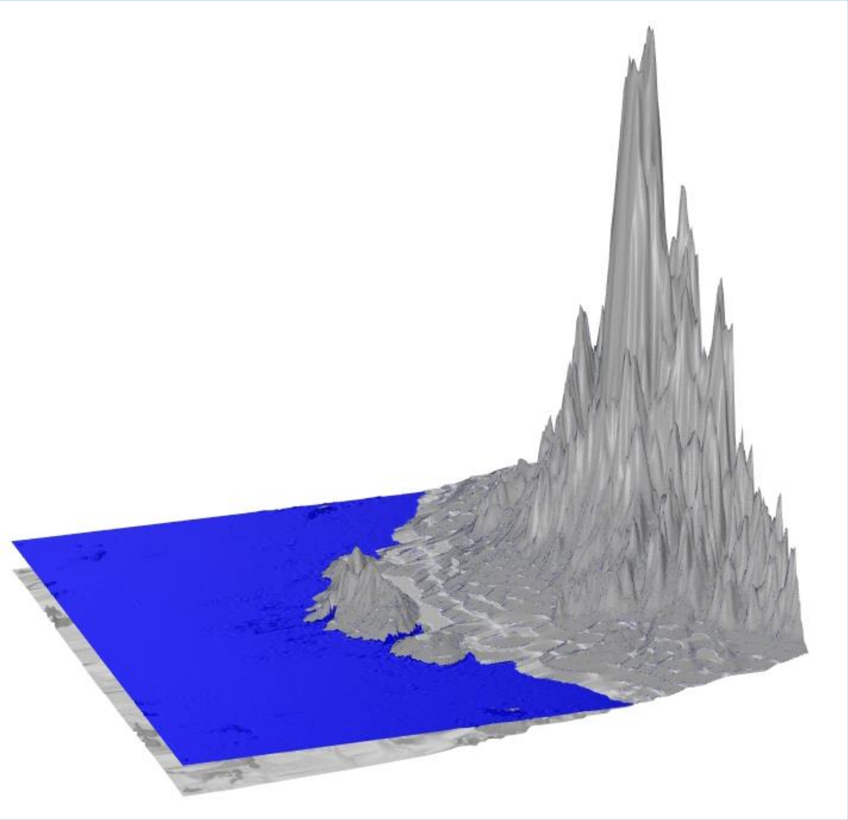
Shallow Water Equations Interface

- Solves for water depth and momentum on surfaces (2D) or curves (1D)

$$\frac{\partial h}{\partial t} + \nabla \cdot (\boldsymbol{u}h) = 0$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -g\nabla(h + h_B) + \boldsymbol{F}$$

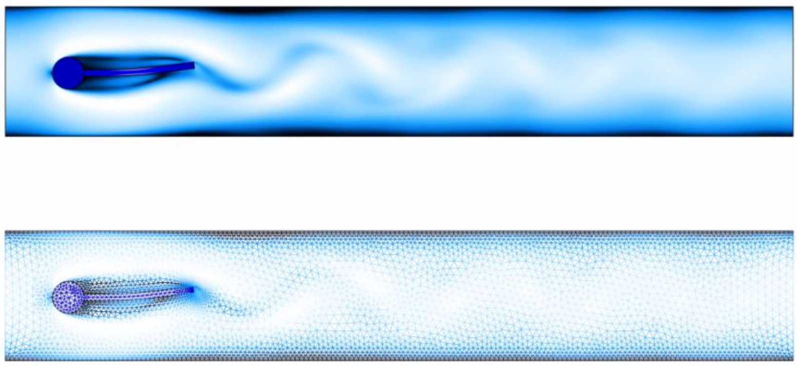
- A digital elevation map (DEM) can be used to specify the bottom topology



Wave impact simulated with the Shallow Water Equations interface using a DEM for the bottom topography

Supporting Multiphysics Capabilities

- Conjugate heat transfer including surface-to-surface radiation
  - Radiosity method and participating media
  - With Heat Transfer Module
- Reaction Engineering
  - Material balances and detailed kinetics from chemical equations
  - With Chemical Reaction Engineering Module
- Particle Tracing
  - Lagrange-Euler two-phase flow
  - Charged particles: Flow and electric fields
  - With Particle Tracing Module
- Fluid-structure interaction (FSI)
  - With Structural Mechanics or MEMS Module



Benchmark model for fluid-structure interactions.

Supporting Multiphysics Capabilities

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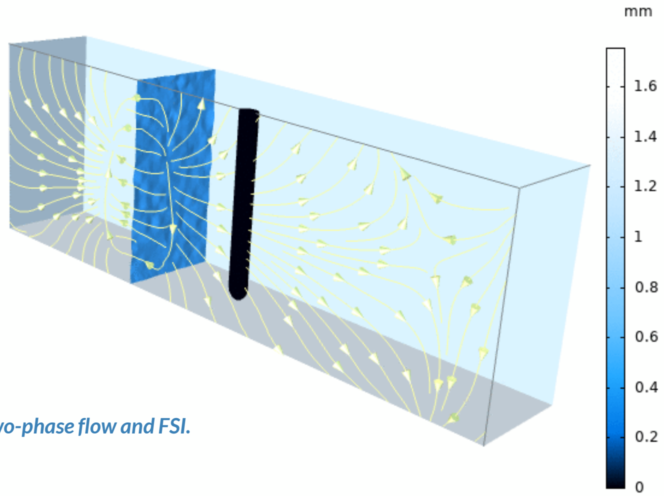
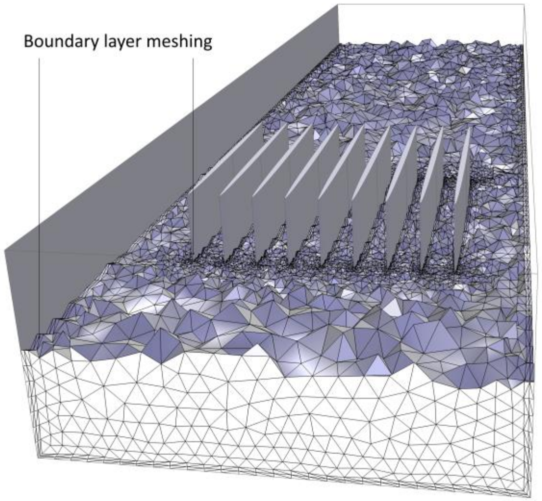


Two-phase flow and FSI.

General Capabilities in the CFD Module

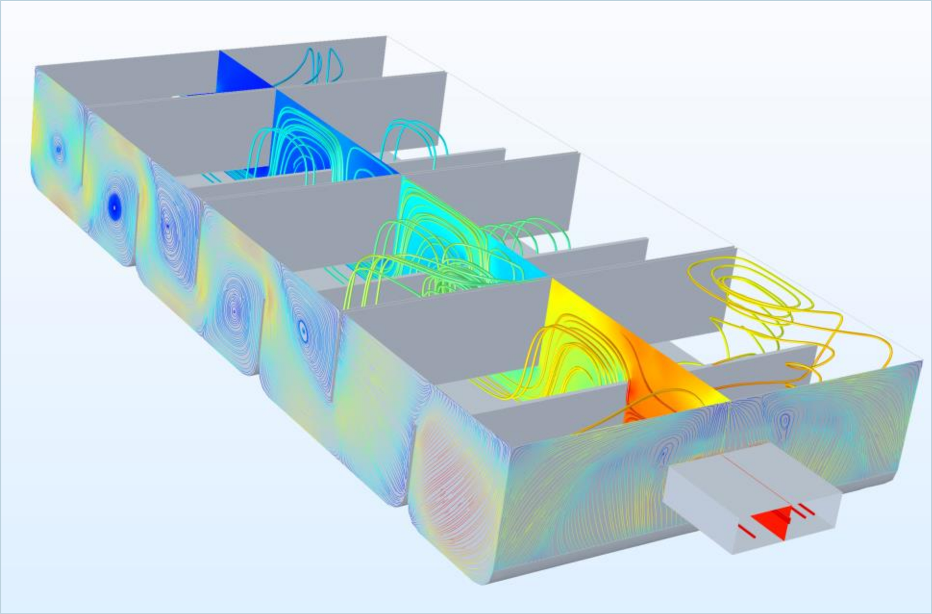
- Robustness, performance, and accuracy
- Solvers
  - Automatic solver suggestions
  - Algebraic and Geometric multigrid
  - Pseudo time-stepping
  - Cluster computing
- State of the art FEM for CFD
  - Stabilization techniques
  - Discontinuous Galerkin for sliding meshes
- Meshing
  - Physics-controlled mesh
  - Boundary layer mesh
  - Mesh control entities for advanced meshing



Automatic boundary layer meshing.

CFD Applications: Water Treatment

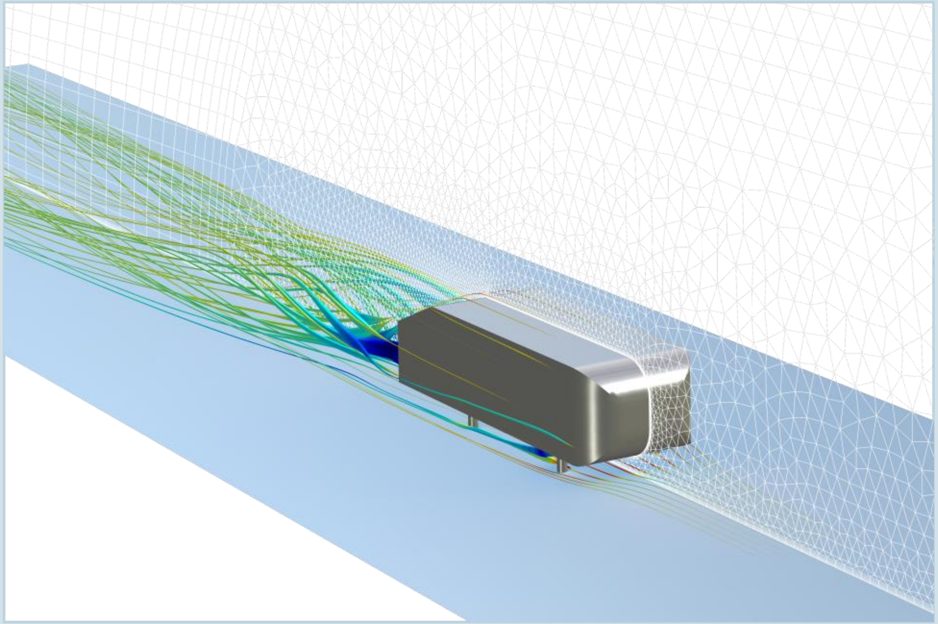
- Water treatment basin design
- Turbulent flow
- Transport of a reacting species



Flow field and concentration in a water treatment basin.

Classical Benchmarks

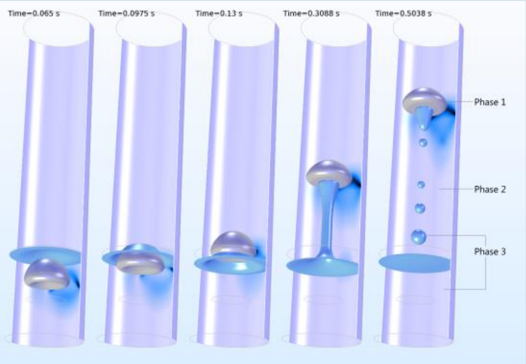
- Laminar flow
  - Blasius Boundary Layer
- Turbulent flow
  - Ahmed Body
  - NACA0012 Airfoil
  - Turbulent Backstep
- High Mach-number flow
  - Sajben Diffuser



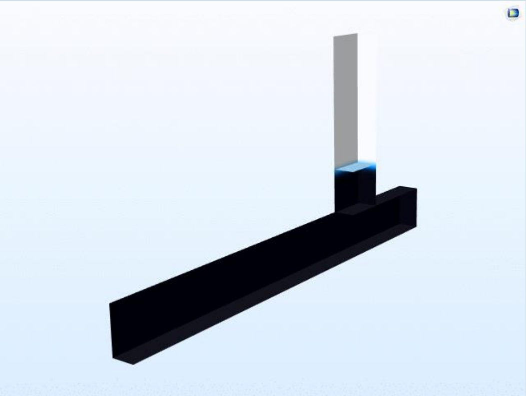
Flow around an Ahmed body.

Benchmarks

- Laminar flow
  - Inclined Screen
- Non-isothermal flow
  - Displacement Ventilation
  - Fluid Damper
  - Round-Jet Burner
- Turbulent flow
  - Pipe Elbow
- High Mach-number flow
  - Expansion Fan
- Multiphase flow
  - Airlift Loop Reactor
  - Dense suspension
  - Droplet breakup
  - Three-Phase Bubble
- Thin-film flow
  - Elastohydrodynamic interaction
  - 1D Plane Slider Bearing
  - 1D Step Bearing



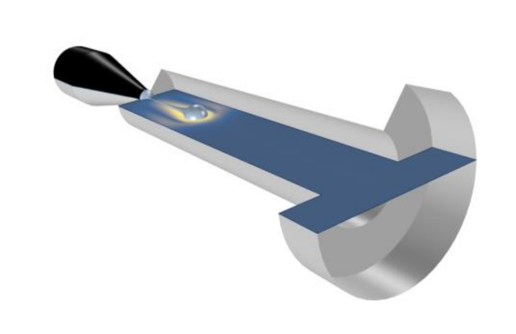
Three-phase flow tutorial



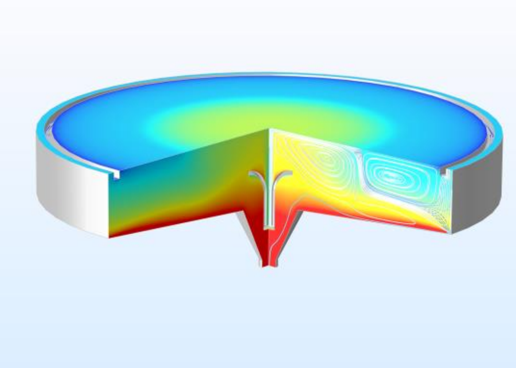
Droplet breakup benchmark.

Industrial Application Tutorials

- Multiphase flow
  - Fluidized Bed
  - Inkjet Nozzle
  - Sedimentation Clarifier
- Single-phase flow
  - Baffled Stirred Mixer
  - Flow in a Hydrocyclone
  - Water Purification Reactor
- Non-isothermal flow
  - Heat Sink
- High Mach-number flow
  - Supersonic Air-to-Air Ejector
- Thin-film flow
  - Journal Bearing
  - Tilted Pad Thrust Bearing



Inkjet droplet in a micro nozzle modeled with the phase field method for two-phase flow.



Contaminant removal in a secondary clarifier for wastewater treatment.

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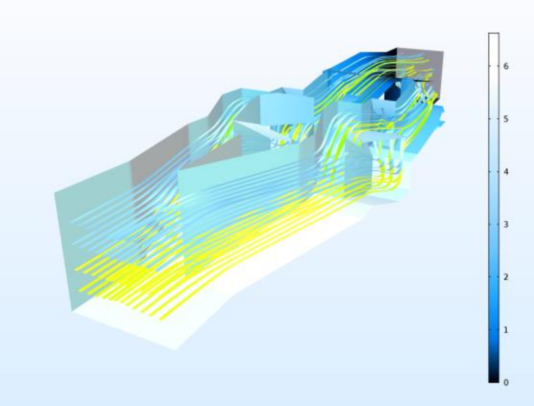
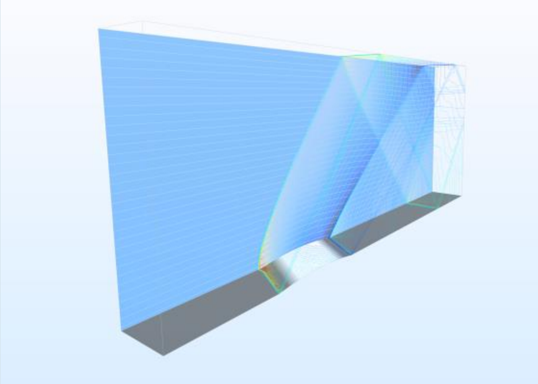
Physics Phenomena Tutorials

- Multiphase flow
  - Capillary Filling
  - Low Permeable Lens
  - Phase Separation
  - Rising Bubble
- Single-phase flow
  - Flow over a Backstep
  - Non-Newtonian Flow
  - Oldroyd-B Viscoelastic Fluid
  - Rotating Disk
  - Turbulent Mixing
- High Mach-number flow
  - 3D Euler Bump
- Particle tracing
  - Micromixer
  - Thermophoresis

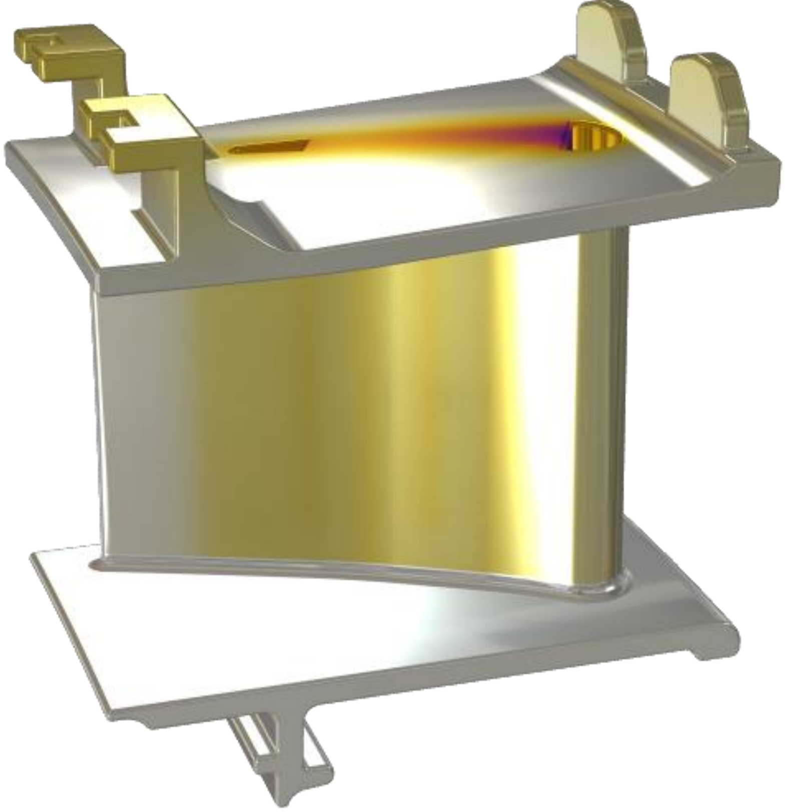


Micro mixing



3D Euler bump.

Heat Transfer Module



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  - Mixer Module
- Polymer Flow Module
- Microfluidics Module
- Porous Media Flow Module
- Subsurface Flow Module
- Pipe Flow Module
- Molecular Flow Module
- Metal Processing Module
- Heat Transfer Module

STRUCTURAL & ACOUSTICS

- Structural Mechanics Module
  - Nonlinear Structural Materials Module
  - Composite Materials Module
  - Geomechanics Module
  - Fatigue Module
  - Rotordynamics Module
- Multibody Dynamics Module
- MEMS Module
- Acoustics Module

CHEMICAL

- Chemical Reaction Engineering Module
- Battery Design Module
- Fuel Cell & Electrolyzer Module
- Electrodeposition Module
- Corrosion Module
- Electrochemistry Module

MULTIPURPOSE

- Optimization Module
- Material Library
- Particle Tracing Module
- Liquid & Gas Properties Module

INTERFACING

- LiveLink™ *for* MATLAB®
- LiveLink™ *for* Simulink®
- LiveLink™ *for* Excel®
- CAD Import Module
- Design Module
- ECAD Import Module
- LiveLink™ *for* SOLIDWORKS®
- LiveLink™ *for* Inventor®
- LiveLink™ *for* AutoCAD®
- LiveLink™ *for* Revit®
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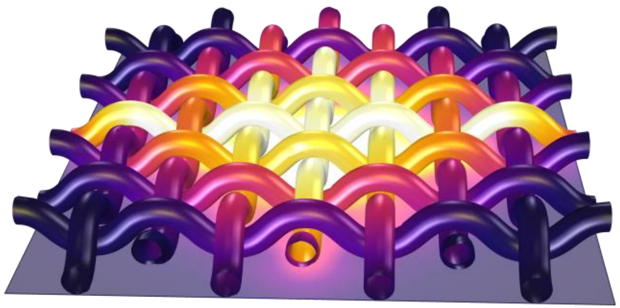
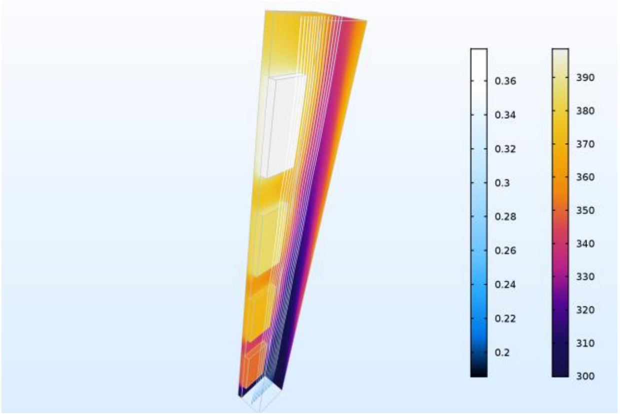
Heat Transfer Mechanisms

Heat Transfer Mechanisms

- Conduction:
  - Fourier's law
  - Isotropic, anisotropic, linear, and nonlinear thermal conductivity
- Convection:
  - Natural and forced convection
  - Laminar, or turbulent flow
- Radiation:
  - Surface-to-surface
  - Participating media



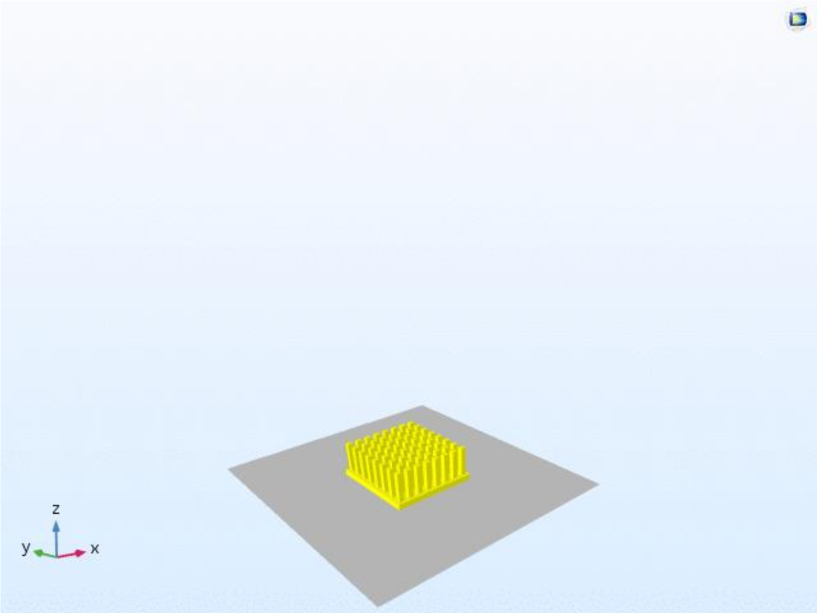
Conduction in a fiber structure.



Convection in air coupled to conduction in a solid materials.

Studies for Heat Transfer

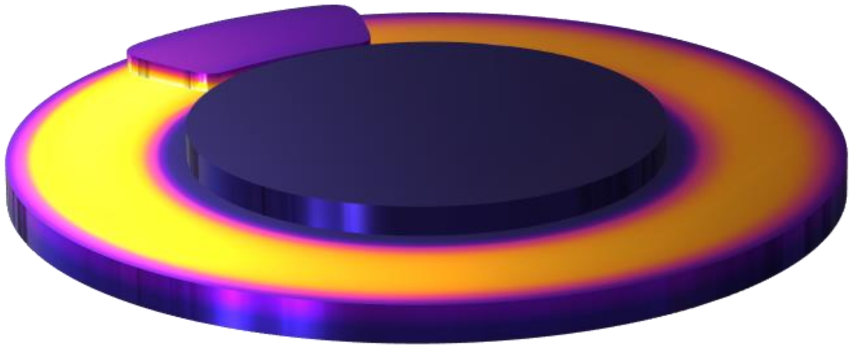
- Heat Transfer studies
  - Stationary
  - Time dependent
  - Thermal Perturbation, Frequency Domain or Eigenfrequency
- Multiphysics studies
  - One way and two way coupled studies for nonisothermal flow
  - Frozen rotor for rotating machinery
- Solvers
  - Automatic solver suggestion
  - Fully coupled or segregated solvers
  - Multigrid, domain decomposition
  - Pseudo time-stepping



Time dependent study of a heat sink with flow drive by natural convection.

Heat Transfer in Solids

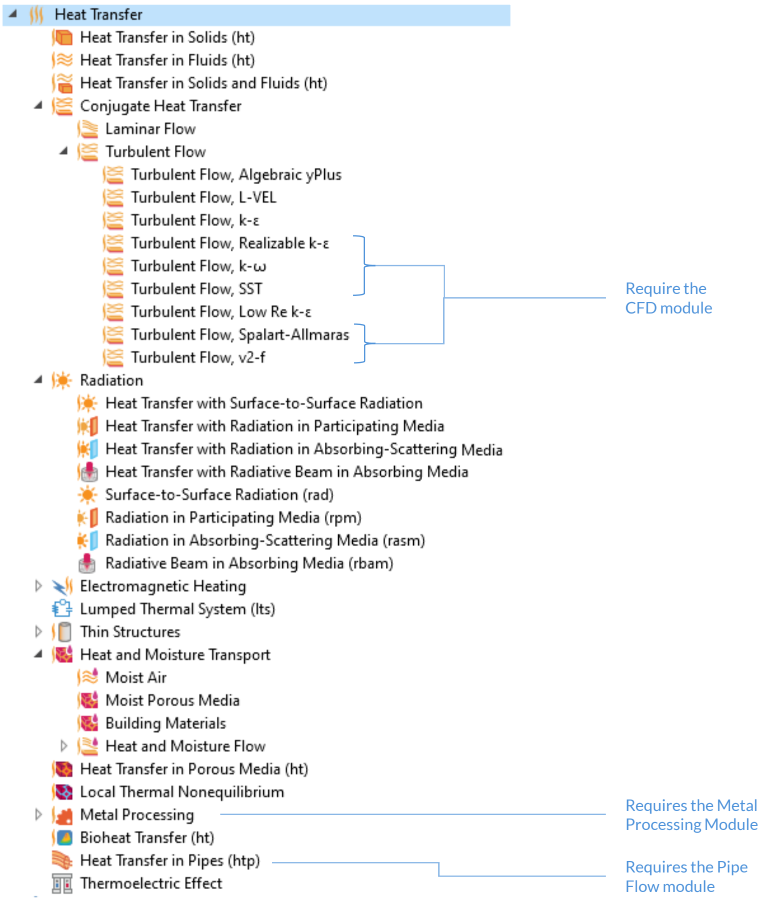
- Isotropic, anisotropic, linear, and nonlinear thermal conductivity
- Heat transfer by translation
- Heat sources:
  - User-defined, space or time dependent
  - From other physics interfaces
- Predefined multiphysics couplings for
  - Thermal expansion
  - Thermoelastic damping
  - Electromagnetic heating
  - ...



Temperature of a disc brake of a car in brake-and-release sequence.

Heat Transfer in Fluids

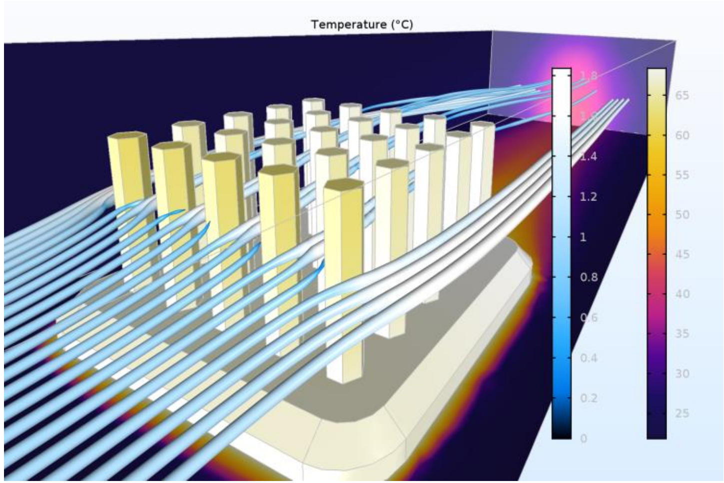
- Laminar and turbulent flow:
  - Viscous dissipation
  - Pressure work
- Fluid-solid interface:
  - Temperature continuity or
  - Boundary layer approximation
- Heat transfer specific boundary conditions:
  - Inflow , outflow, open boundary
  - Screen, fan
  - …



The Heat Transfer interfaces list in COMSOL Multiphysics.

Heat Transfer in Fluids

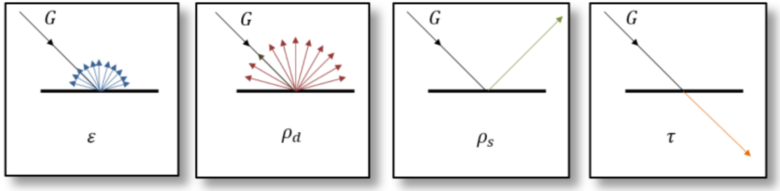
- Conjugate heat transfer
  - Natural convection (free convection) induced by gravity forces
  - Forced convection
- Library:
  - Heat transfer coefficients (Nu)
  - Equivalent thermal conductivity
- Marangoni effect with a predefined library of surface tension coefficient



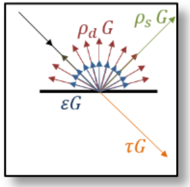
Conjugate heat transfer in and around a heat sink.

Surface-to-Surface Radiation

- Calculation of view factors with shadowing effects
- Temperature, wavelength and directional dependent surface properties
- Diffuse and mixed diffuse-specular surface, semitransparent layers
- External radiation sources
  - User defined
  - From the sun (automatic position computation)
- Supports plane and sector symmetry



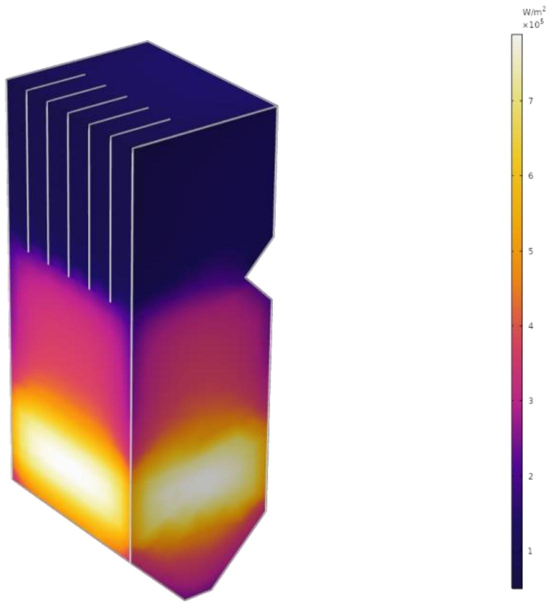
Absorption/Emission, Diffuse reflection, Specular reflection and Transmission of incident radiation



Combined absorption, emission, diffusion and transmission on a semitransparent surface

Radiation in Participating Media

- Emission/absorption in participating media
- Ray scattering
  - Isotropic
  - Linear anisotropic
  - Nonlinear Anisotropic Scattering
  - Henyey Greenstein
- Modeling methods
  - Rosseland approximation
  - P1 approximation
  - Discrete Ordinate Method
- Wavelength dependent properties

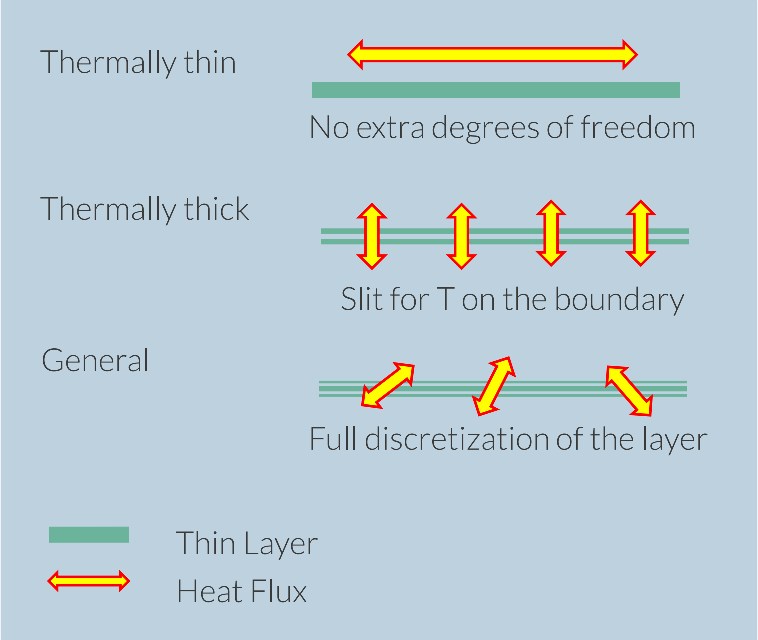


Radiative heat transfer in a utility boiler with internal obstacles.

Heat Transfer in Thin Structures and Specific Media

Heat Transfer in Thin Structures

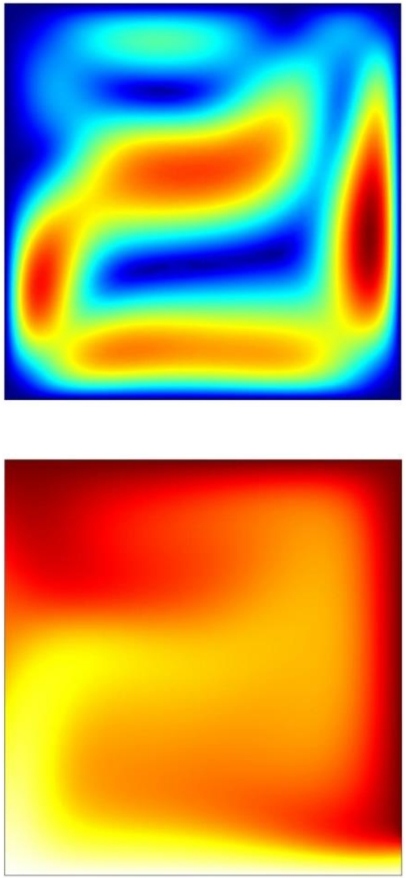
- Heat transfer in thin layers
  - Thermally thin
  - Thermally thick
  - General
- Heat transfer in films
- Heat transfer in fractures
- Dedicated material types
  - Single layer material
  - Multilayer material
  - Layered material stack
- Specialized data sets, 3D postprocessing



Thin Layer types.

Heat Transfer in Porous Media

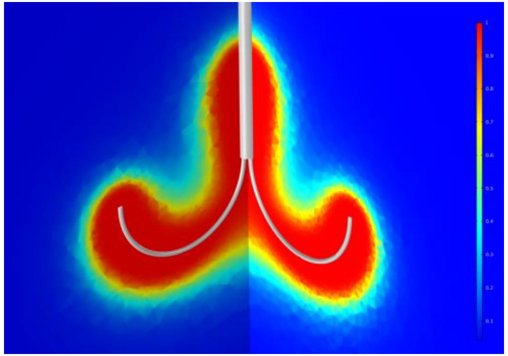
- Coupling between fluid and solid matrix
- Local thermal non-equilibrium
- Geothermal heating
- Immobile fluids
- Thermal dispersion due to tortuous paths in porous media
- Volume averaging of material properties

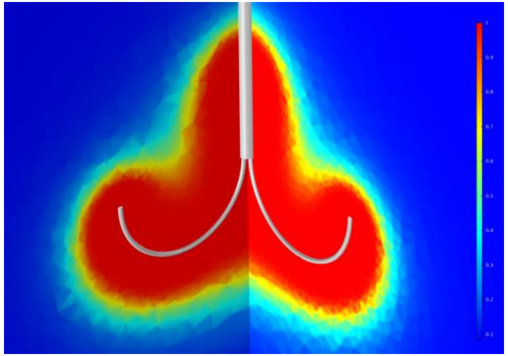


Velocity field (top) and temperature (bottom) profile due to buoyancy in porous media.

Heat Transfer in Biological Tissues

- Heat transfer in living tissue
  - Tissue and blood properties
  - Blood perfusion rate
  - Arterial blood temperature
  - Metabolic heat rate
- Bioheat source
- Damage in living tissues
  - Temperature threshold model
  - Energy absorption model
  - Cryogenic damage
- External heat sources (RF, DC current)





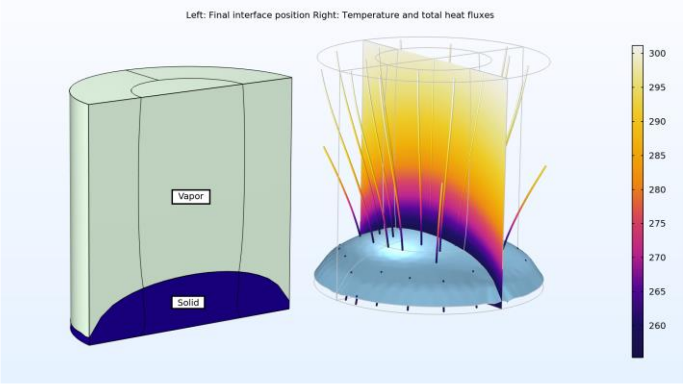
Tissue necrosis area during tumor ablation process at 2.5 min (top) and 5 min (bottom).

Phase Change

Phase Change and Material Transition

- Phase change material using apparent heat capacity formulation:
  - Phase change temperature
  - Latent heat
  - Material properties for each phase
  - Material properties smoothing during phase change
- Phase Change Interface combined with Deformed Geometry feature:
  - Phase change temperature
  - Latent heat
  - One geometrical domain per phase

- Irreversible transformations in solids:
  - Temperature threshold, Arrhenius kinetics, and user-defined transformation models
  - Enthalpy change
  - Material properties for each state



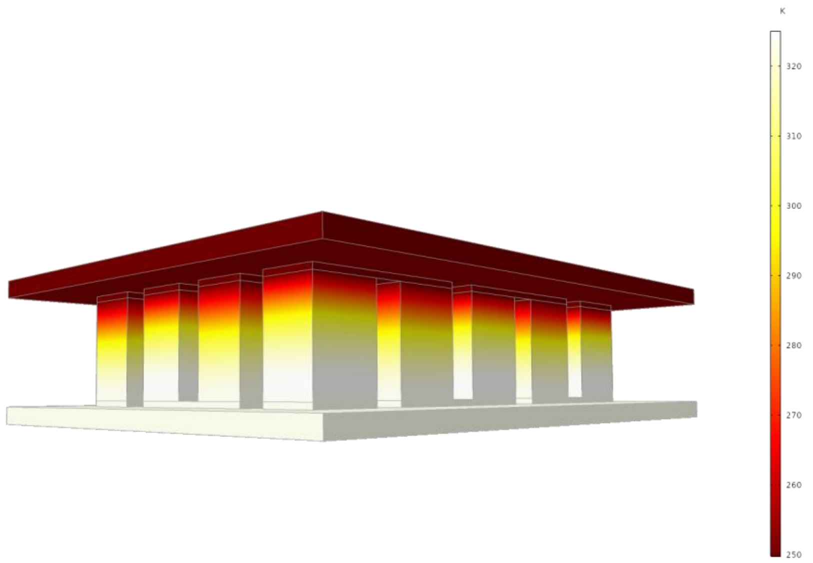
Gas and solid phases (left), and phase change interface, temperature, and total heat flux streamlines (right).

Multiphysics and Heat Transfer

COMSOL

Electromagnetic Heating and Thermoelectric Effects

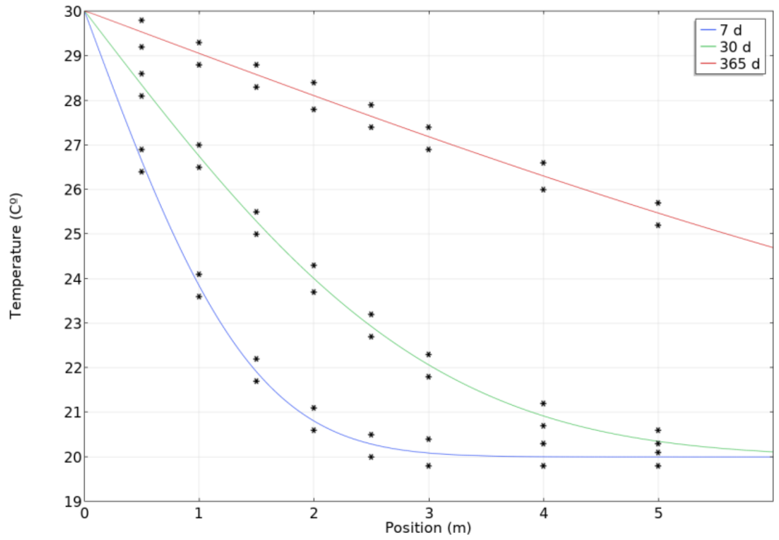
- Electromagnetic heating:
  - Joule heating
  - Induction heating (with AC/DC module)
  - Microwave heating (with RF module)
- Thermoelectric effects:
  - Peltier,
  - Seebeck, and
  - Thomson effects



Temperature drop demonstrating Peltier effect in a single-stage thermoelectric cooler.

Heat and Moisture Transport

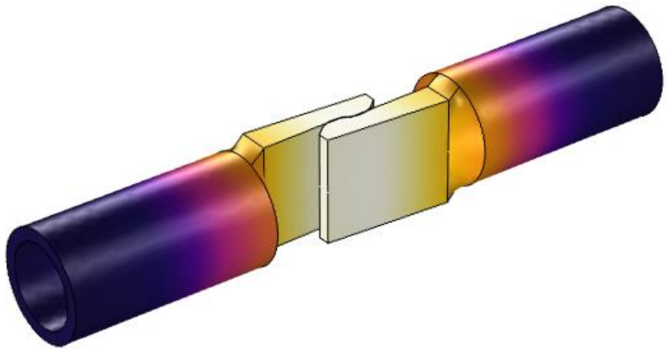
- Predefined multiphysics couplings for moisture transport, flow, and heat transfer
- Building Material model follows ISO 15026 specifications
- Moisture transport in air and in hygroscopic media
- Heat and Moisture Flow interface with support for laminar and turbulent flows
- Wet surface and Moist surface conditions to account for evaporation and condensation
- Thermal properties are dependent of the moisture content, accounts for latent heat of evaporation



Comparison of COMSOL Multiphysics temperature profile (solid lines) with ISO 15026 reference range (*).

Thermal Contact

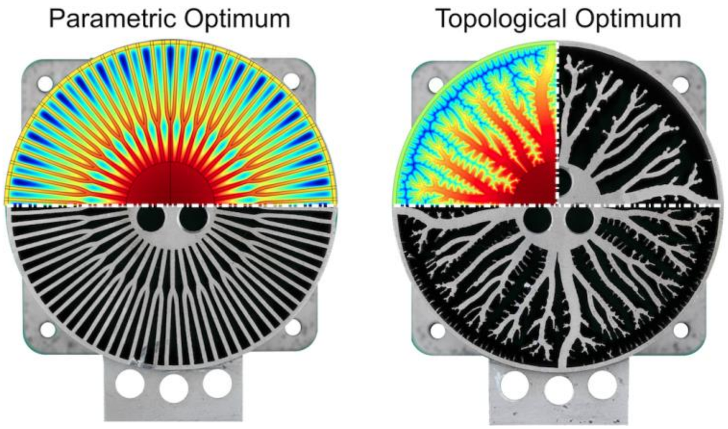
- Predefined models for:
  - Equivalent Thin Resistive Layer
  - Pressure dependent thermal conductance (constriction conductance)
  - Conductance through the fluid (gap conductance)
  - Surface-to-surface radiation contribution (radiative conductance)
- Coupling with structural mechanics contact and electrical contact
- Friction heat source with partition coefficient definition



Temperature in two contacting parts of a switch inducted by Joule heating. Electrical current and the heat flow from one part to the other through the contact surface. Thermal and electrical apparent resistances are coupled to the mechanical contact pressure.

Heat Transfer with Shape and Topology Optimization

- With Optimization Module
- Common scenario:
  - Maximize cooling or heating at given operating conditions and with certain geometry constraints
- Depending on 3D printing or conventional manufacturing:
  - Topology optimization
  - Shape optimization



Heat sink designs generated by parametric (left) and topology (right) optimization. Image courtesy Fritz Lange, Fraunhofer Institute.

Material, Weather Data, and Geometry Part Libraries

Material Libraries

- Building
  - Cellular concrete
  - Wood (pine)
  - Gypsum board
  - Glass wool board
  - Cellulose board
  - Glass wool batt
  - Cellulose batt
  - Cellulose (loose)
  - Lime silica brick
  - Plastic coated paper
  - Expanded polystyrene board (EPS)
  - Extruded polystyrene board (XPS)

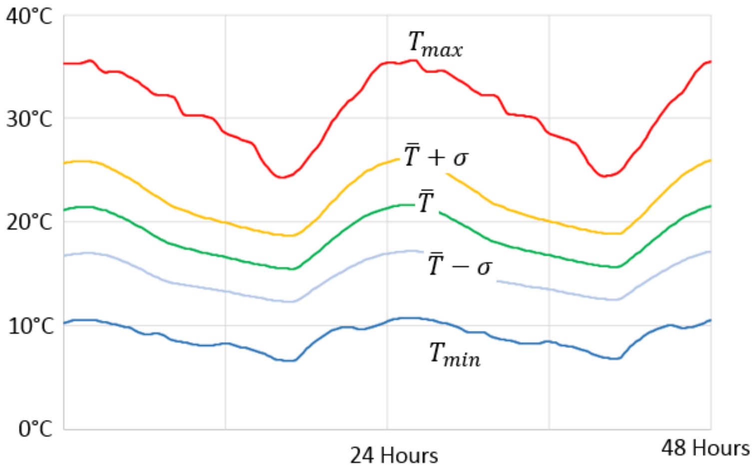
- Bioheat
  - Bone
  - Fat
  - Liver (human)
  - Liver (porcine)
  - Lung
  - Muscle
  - Myocardium (human)
  - Myocardium (porcine)
  - Prostate
  - Renal cortex
  - Renal medulla
  - Skin
  - Spleen

- Liquids and Gases
  - Gases
    - Air
    - Nitrogen
    - Oxygen
    - Carbon dioxide
    - Hydrogen
    - Helium
    - Steam
    - Propane
    - Ethanol vapor
    - Diethyl ether vapor
    - Freon12 vapor
    - SiF4
  - Liquids
    - Engine oil
    - Ethanol
    - Diethyl ether
    - Ethylene glycol
    - Gasoline
    - Glycerol
    - Heptane
    - Mercury
    - Toluene
    - Transformer oil
    - Water
    - R-134A (C2H2F4)
    - R-22 (CHClF2)

Screenshots from the Heat Transfer Module's Material Library.

Meteorological Data

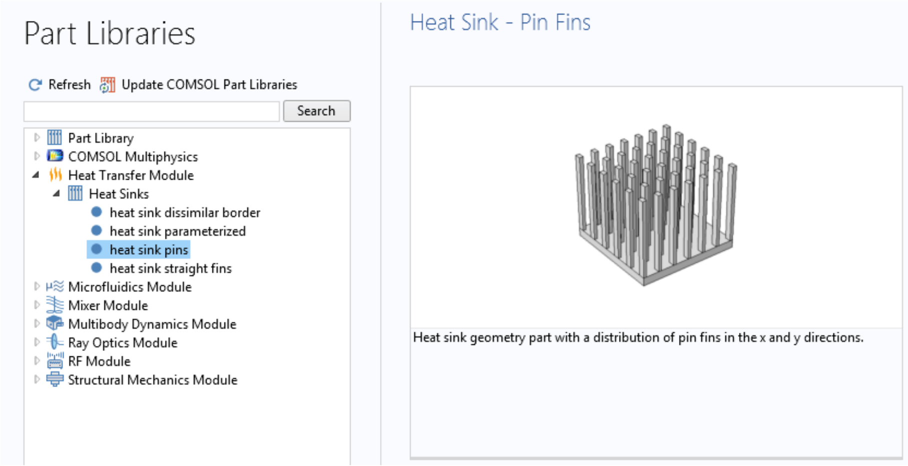
- Historical data for about 8000 weather stations all other the world (Weather Data Viewer 5.0, ASHRAE 2013 and 6.0, ASHRAE 2017)
- Temperature, dew point, air pressure, wind speed, and direct and diffuse solar irradiation as a function of calendar day and time
- Integrated in heat transfer interfaces and features



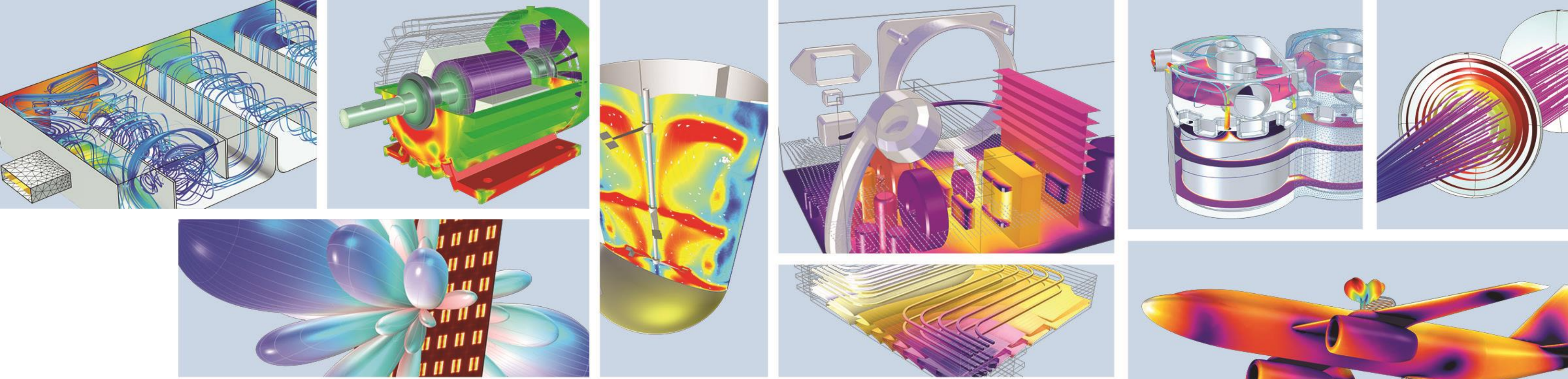
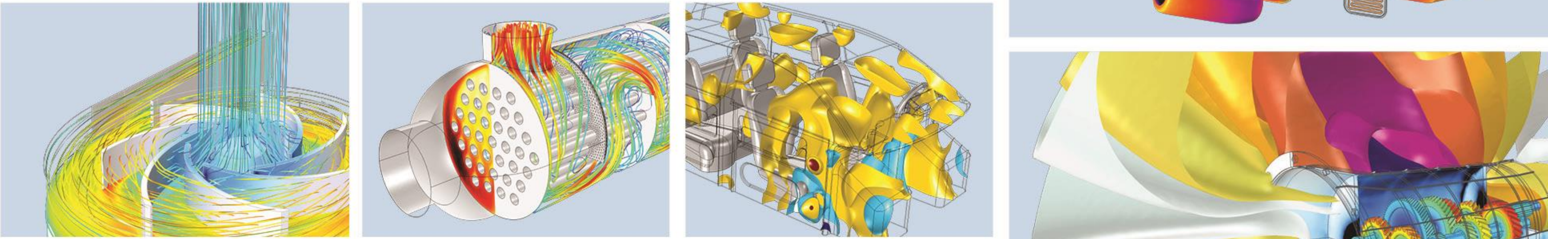
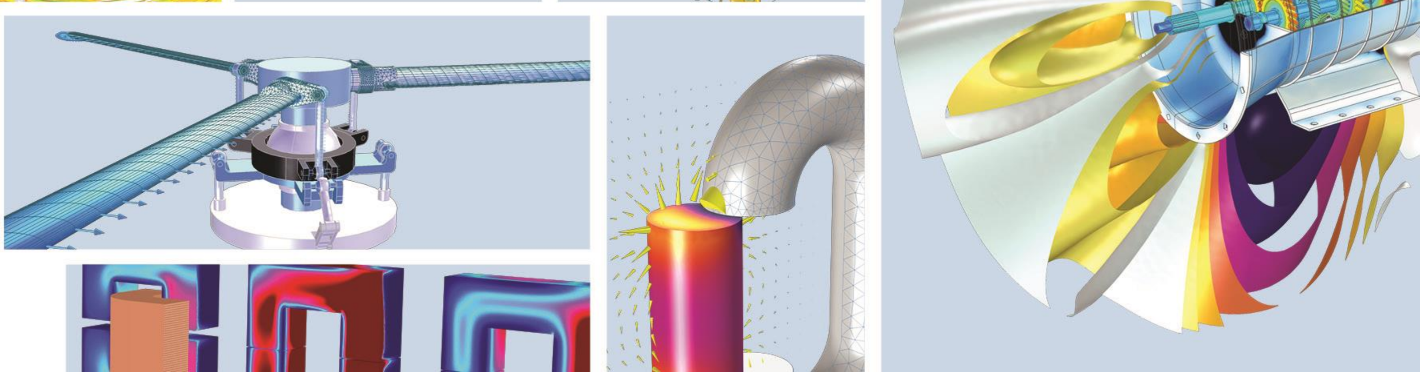
Temperature variation during two days.

Geometry Parts for Heat Sinks

- Contains geometry parts for different types of heat sinks:



The heat sink part library.

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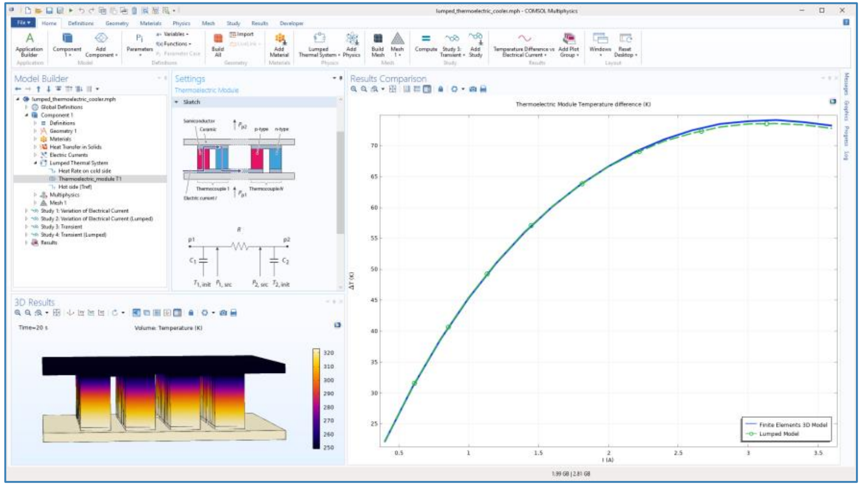
Extra Slides

Lumped Thermal Systems

- Discrete thermal systems
- External terminal feature connects a lumped thermal system to a finite element model in any dimension

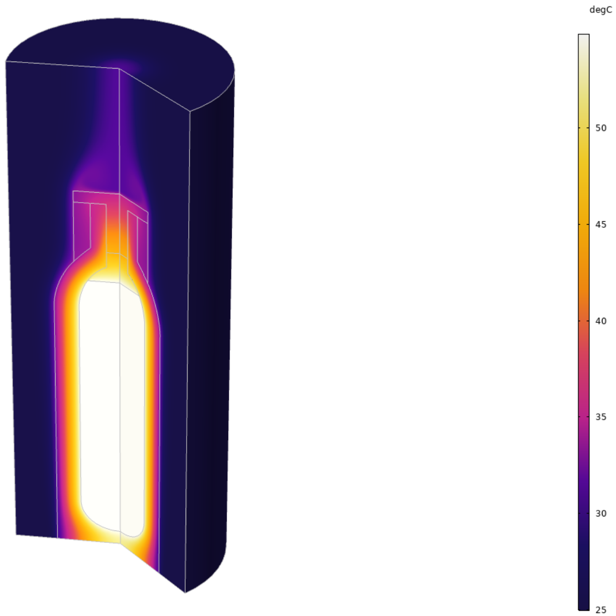
One-node Device	Two-node Device
Temperature	Conductive Thermal Resistor
Thermal Mass	Thermal Capacitor
Heat Rate	Heat Rate Source
External Terminal	Convective Thermal Resistor
Radiative Heat Rate	Radiative Thermal Resistor
	Thermoelectric Module
	Heat Pipe



Comparison between a FEM model for TEC and the corresponding lumped thermal system.

Isothermal Domains

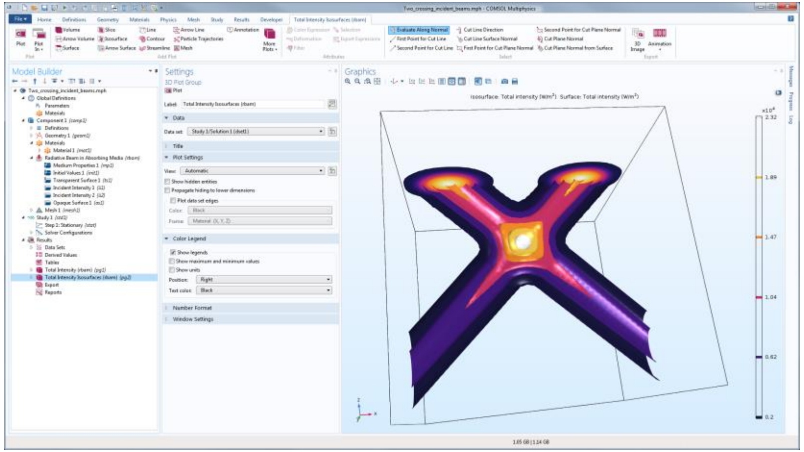
- Lumped model to represent isothermal regions
- Fully compatible with other heat transfer features
- Predefined interface conditions
  - Thermal insulation
  - Ventilation
  - Convective heat flux
  - Thermal contact



Coffee temperature change in a version of vacuum flask model with isothermal domain for coffee. Other domains are handle using classical FEM features.

Radiation in non-emitting media

- Absorbing-scattering media
  - The medium does not emit radiation
  - Otherwise, similar to radiation in participating media
  - Light Diffusion Equation
- Radiative beam in absorbing media
  - Based on Beer-Lambert law
  - Absorbing media properties
  - Support for multiple incident beams (does not account for interference)
  - Each beam as a specific propagation directions



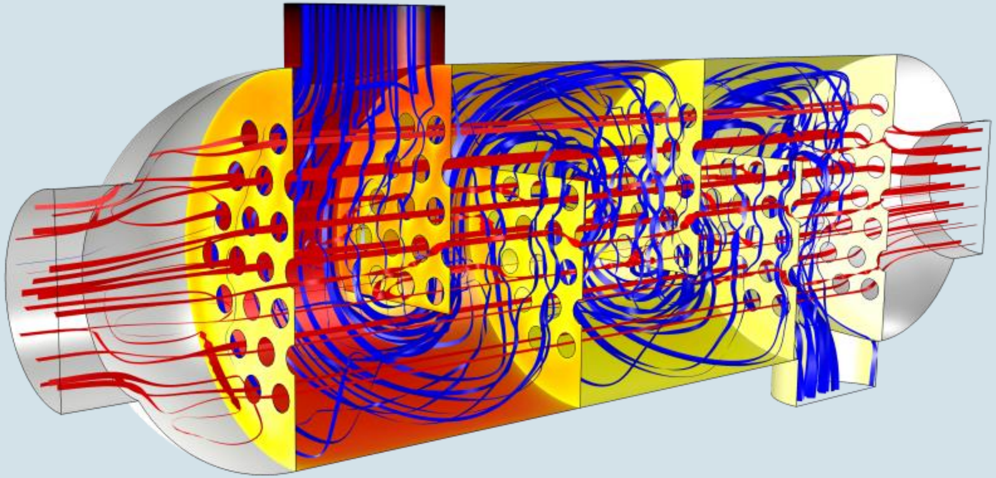
Radiative beam tutorial.

Application Library

This presentation includes features from different modules. To get the content of the Heat Transfer module refer to https://www.comsol.com/products/specifications/heat-transfer/

Shell and Tube Heat Exchanger

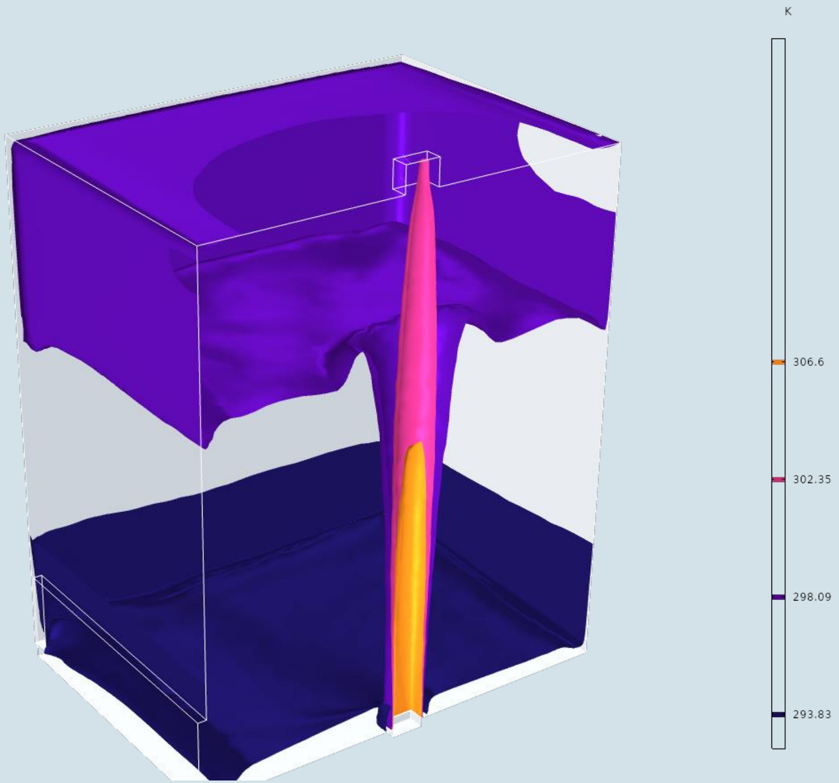
- Two separated fluids at different temperatures flow through the heat exchanger:
  - One through the tubes (tube side, red streamlines)
  - The other through the shell around the tubes (shell side, blue streamlines).



Temperature profile and the streamlines in a shell and tube heat exchanger.

Ventilation

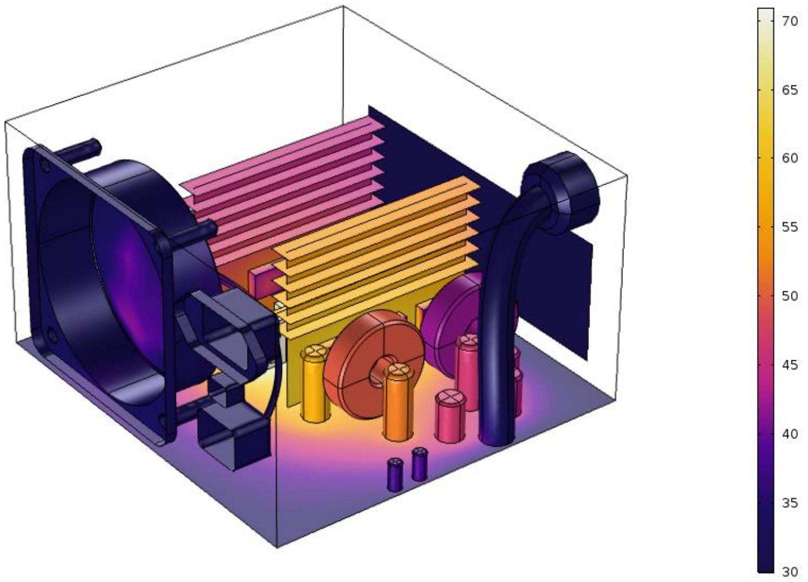
- The model investigates the performance of a displacement ventilation system.
- The flow is modeled using the *Nonisothermal Turbulent Flow, k-ω Model* interface.



Isothermal surfaces as a results of forced and free convection.

Electronic Cooling

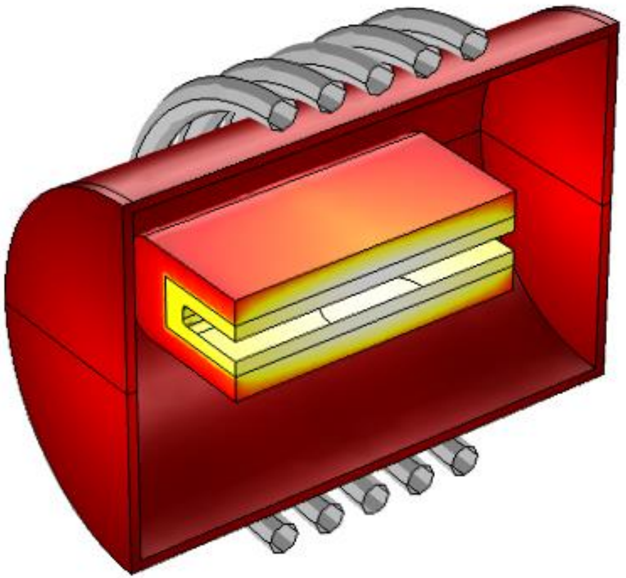
- Air cooling of a power supply unit (PSU) with multiple electronics components acting as heat sources.
- Heat transferand fluid flow are fully coupled.
- Forced convection dominates.



A fan drives the forced convection across the PSU.

Furnace Reactor

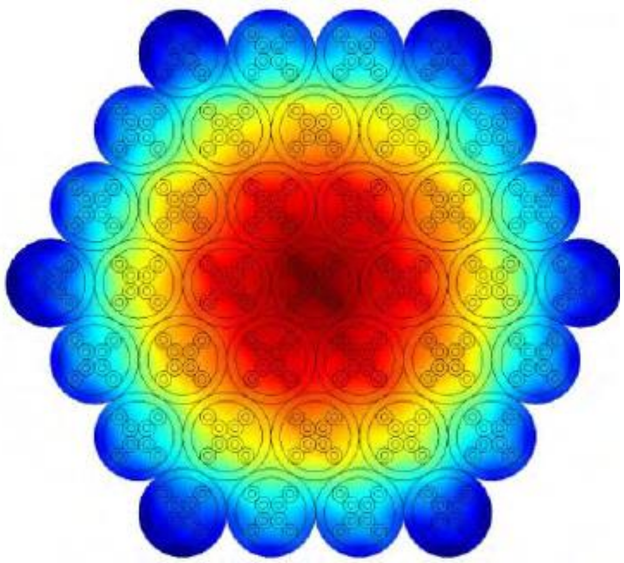
- Heating of a graphite susceptor, using an 8 kW RF signal at 20 kHz.
- The temperature distribution over the wafer is computed, as well as the temperature on the outer Quartz tube.
- At these high temperature (~2000 ^{o}C) the heat flux is dominated by radiation.
- The design of the chamber is crucial to reach a uniform temperature, efficient heating, and control of high temperature regions.



Temperature distribution in an RF-heated reactor.

Heat Losses in Wires

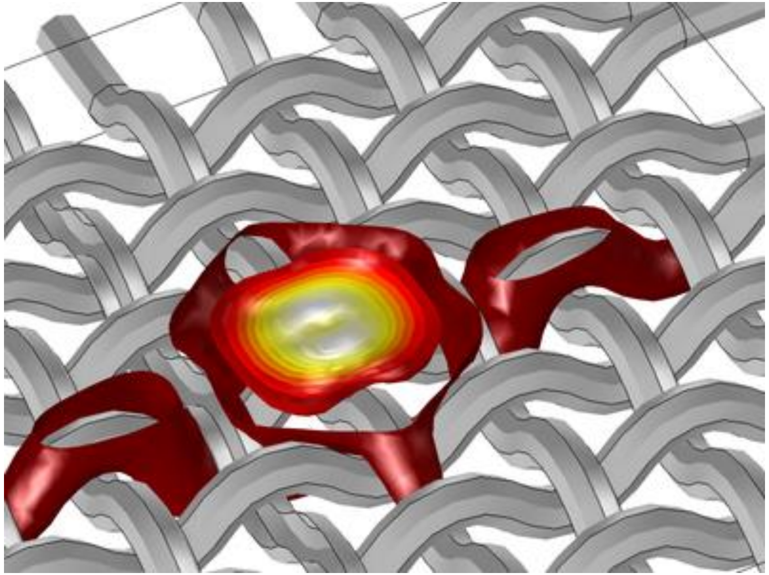
- Temperature in a cable with power over ethernet (PoE and PoE+) technology.
- Joule heating effect:
  - Takes into consideration several configurations of cable bundles in order to optimize temperature distribution.



Finite Element Analysis of Cables Heating Due to PoE/PoE+
S. Francois[1], and P. Namy[2]
1 Nexans Research Center, Lyon cedex, 2 SIMTEC, Grenoble, France
Presented at COMSOL Conference 2010 Paris.

Anisotropic Heat Transfer Through Woven Carbon Fibers

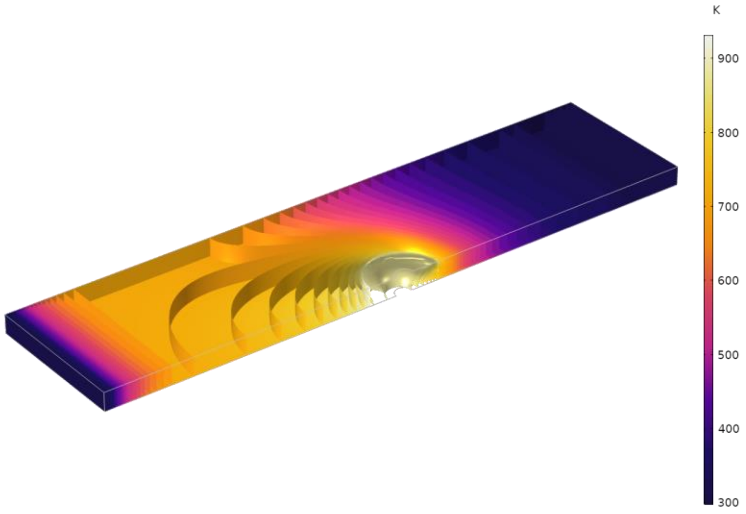
- Carbon-fiber-reinforced polymers contain woven carbon fibers:
  - Thermal conductivity along the fiber is much higher than perpendicular to it.
- Curvilinear coordinates interface:
  - Define the thermal conductivity along and perpendicular to the fibers.
- Infinite elements:
  - Avoid setting boundary conditions too close to the heat source.



Isotherms around a surface heat source in a fiber structure.

Friction Stir Welding

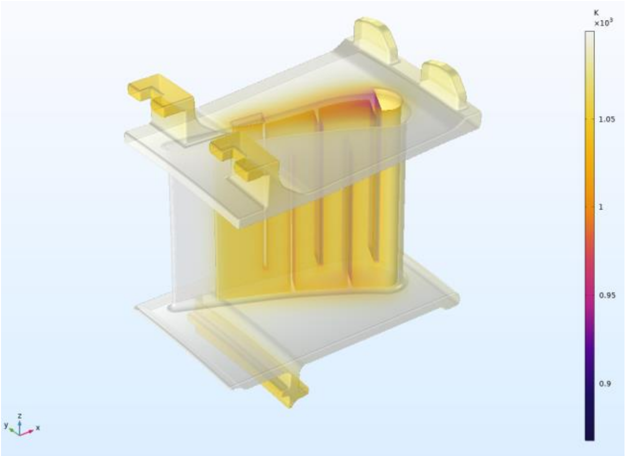
- Two plates are joined by heat generated by friction with a rotating tool.
- Heat is transferred by conduction from the tool into the plates.
- The movement of the tool is taken into account by adding a translation term.
- The plate surfaces are cooled through free convection and radiation.

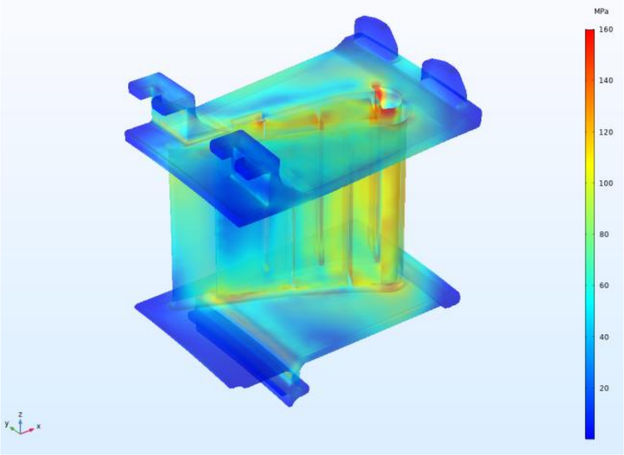


Isotherms calculated in the friction stir welding tutorial.

Thermal Stress

- Structural stresses and strains resulting from temperature gradients and thermal expansion in a stator blade.
- Heat transfer one-way coupled to solid mechanics.
- This plot shows the von Mises stress and the deformed shape of the blade.

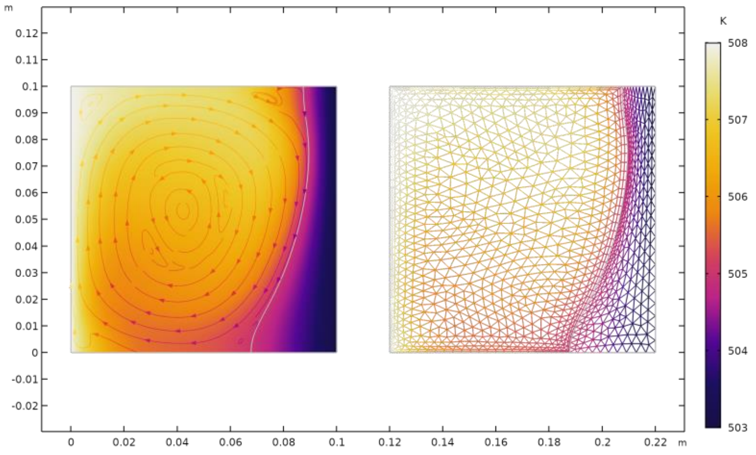




Temperature profile (top) and von Mises stresses (bottom).

Phase Change - Tin melting Front

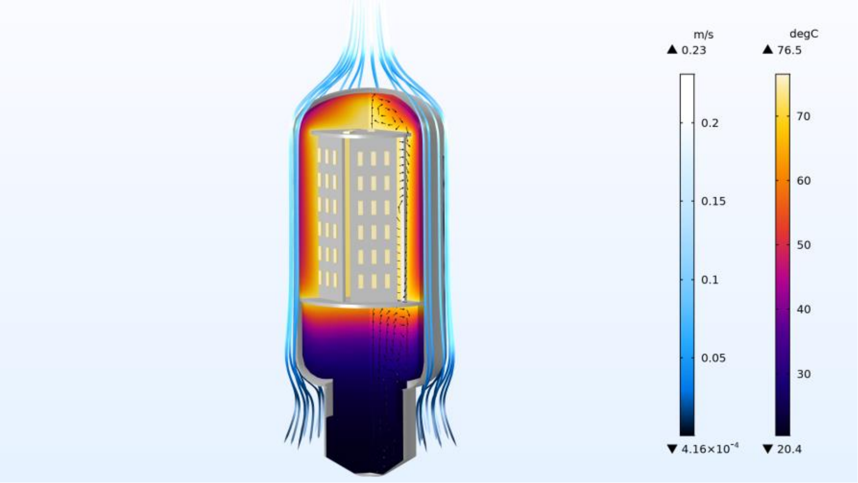
- Phase transition in a cavity containing both solid and liquid tin:
  - Temperature difference between left and right boundaries.
- Fluid and solid parts are solved in separate domains sharing a moving melting front.
- The position of the front is calculated according to the energy balance.
- Natural convection occurs in the melt.



Temperature and flow fields (left). Moving mesh (right).

Light Bulb

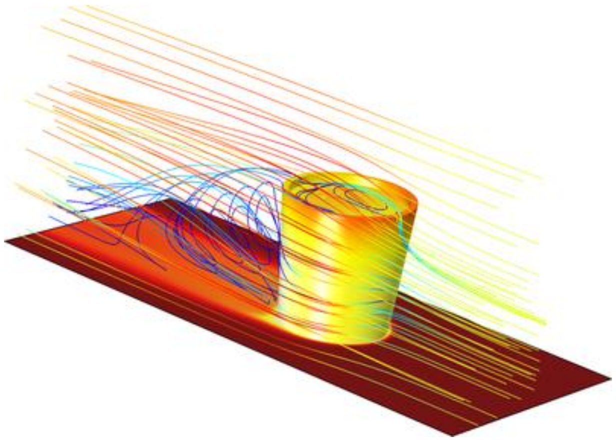
- Natural convection of air around a LED bulb
- Couples heat transport (conduction, radiation, and advection) to momentum transport (nonisothermal flow).
- Density variations due to temperature variation drive the flow.

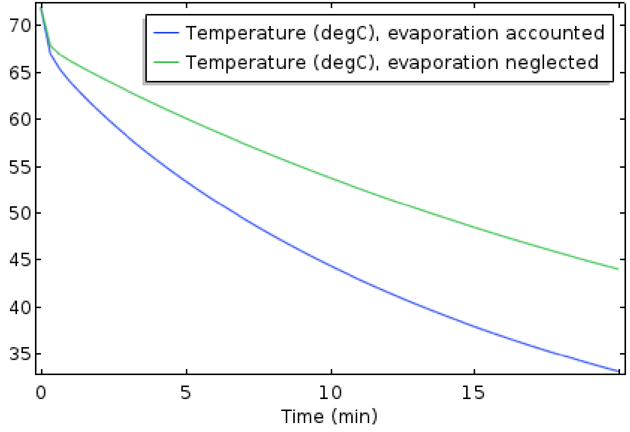


Temperature distribution (surface plot) and velocity (arrows and streamlines) in an LED bulb.

Latent Heat of Evaporation

- Evaporative cooling.
- Heat transfer, transport of water vapor, and fluid flow.
- Predefined features:
  - Term for the evaporative heat source.
  - Moist air feature to accurately describe the material properties.

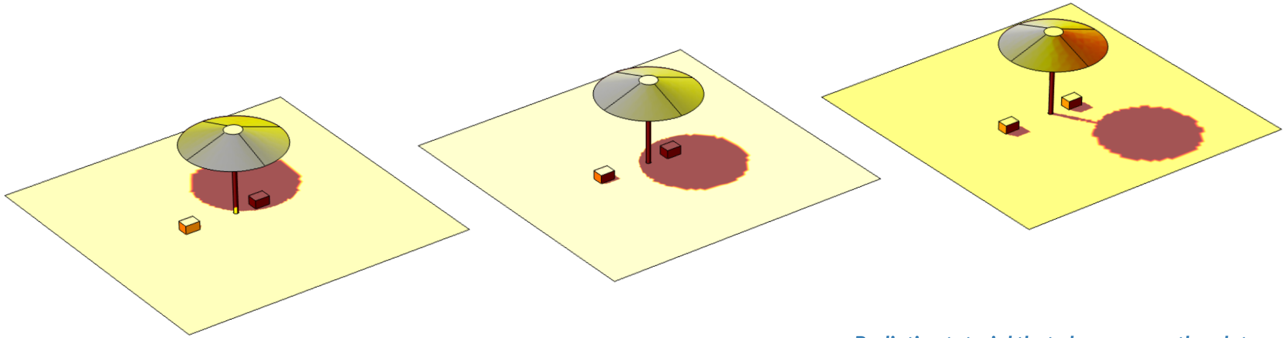




Fluid flow and temperature variation with and without evaporation at the liquid surface.

Solar and Ambient Radiation

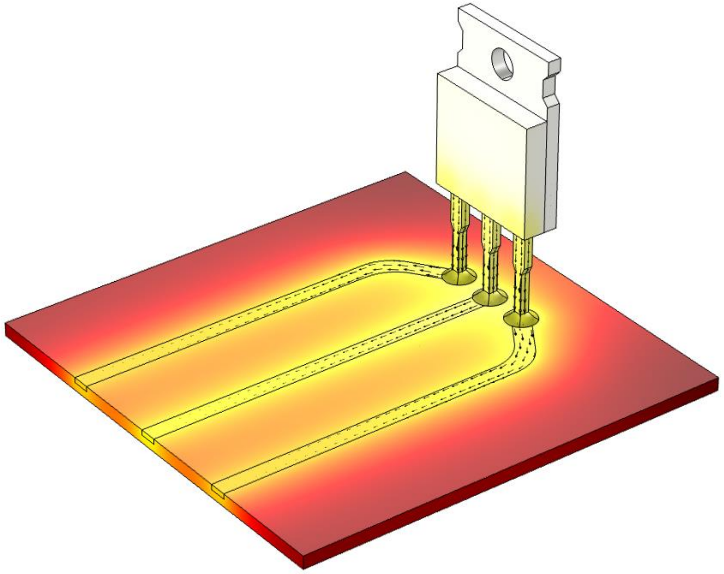
- External radiative heat source feature with solar position option.
- The sun's position and shadow effects are automatically updated.
- The wavelength dependency of surface emissivity is considered.



Radiation tutorial that also uses weather data.

Power Transistor

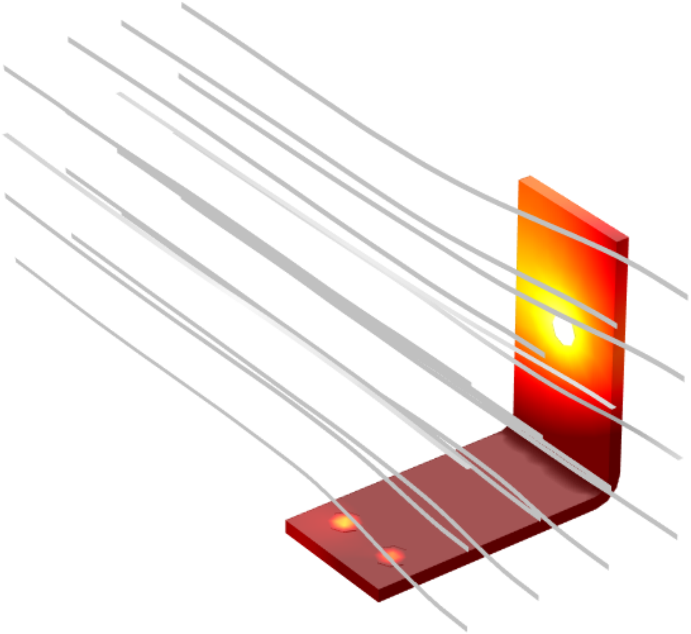
- Power transistor and the copper pathways connected to the transistor.
- The simulation estimates the operating temperature of the transistor.
- Determines if cooling is required.



Heat transfer and heat generation has to be accounted for in most power electronics applications.

Fluid Flow with Joule Heating

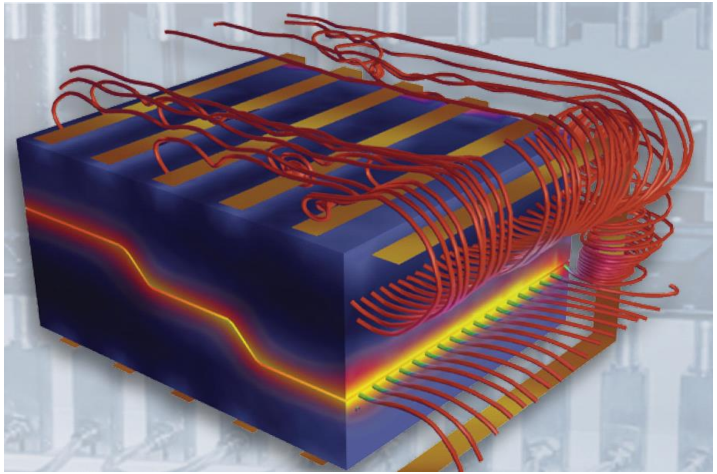
- Joule heating in a busbar cooled by an air flow.
- Couples heat transfer, electric currents and fluid flow.



Temperature and flow field in the busbar tutorial.

Induction Heating

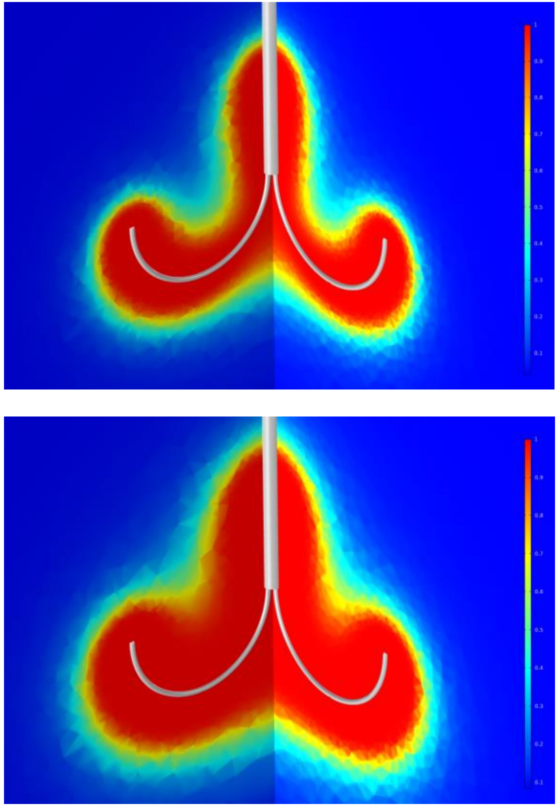
- Electromagnetic induction molding apparatus and composite material.
- Couples induction with heat transfer.



Model and pictures courtesy of José Feigenblum,
RocTool, Le Bourget Du Lac, France.

Tumor Ablation

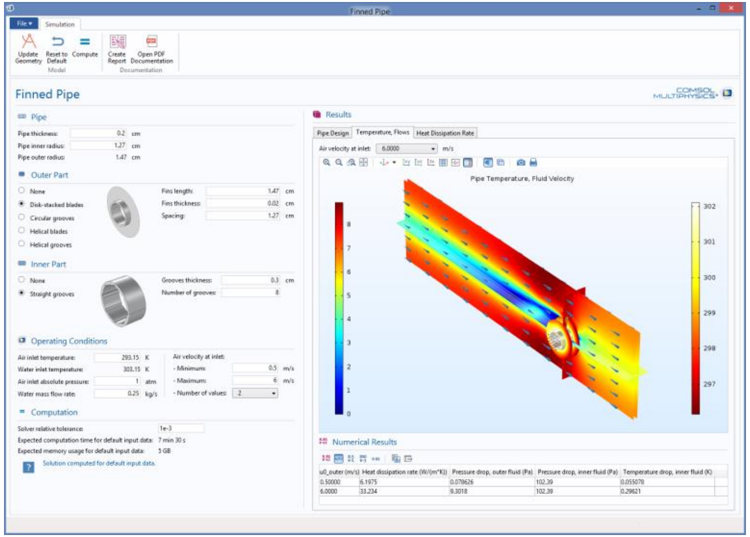
- Heating with a four-arm electric probe:
  - Joule heating.
- Bioheat Transfer interface coupled to the Electric Currents interface:
  - Transient analysis.
- Damage integral is used to predict the tissue necrosis.

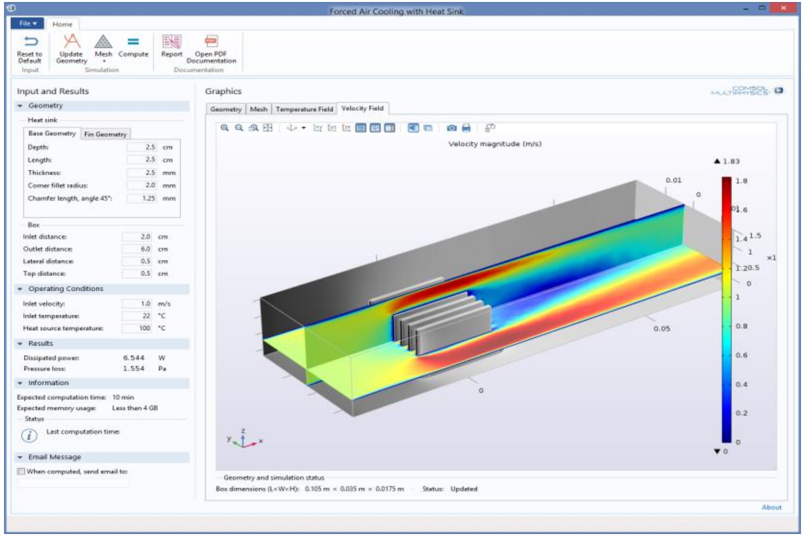


Tissue necrosis area during tumor ablation process at 2.5 min (top) and 5 min (bottom).

Simulation Application Tutorials

Simulation Application Tutorials for Heat Transfer

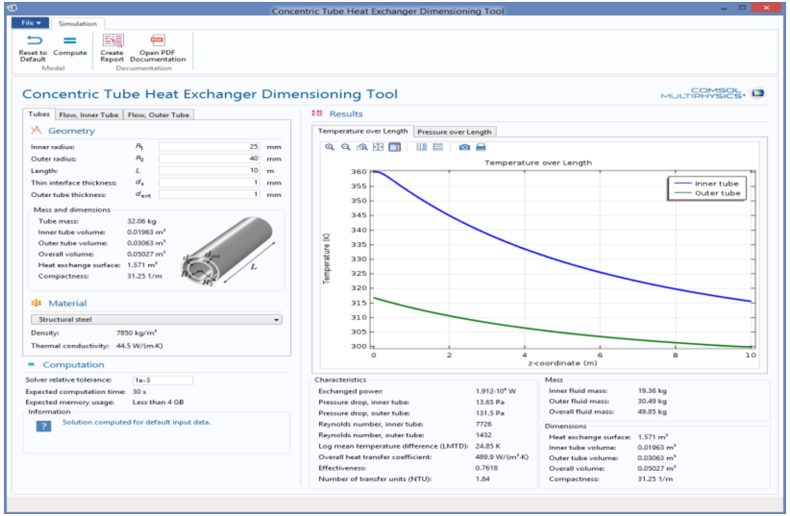




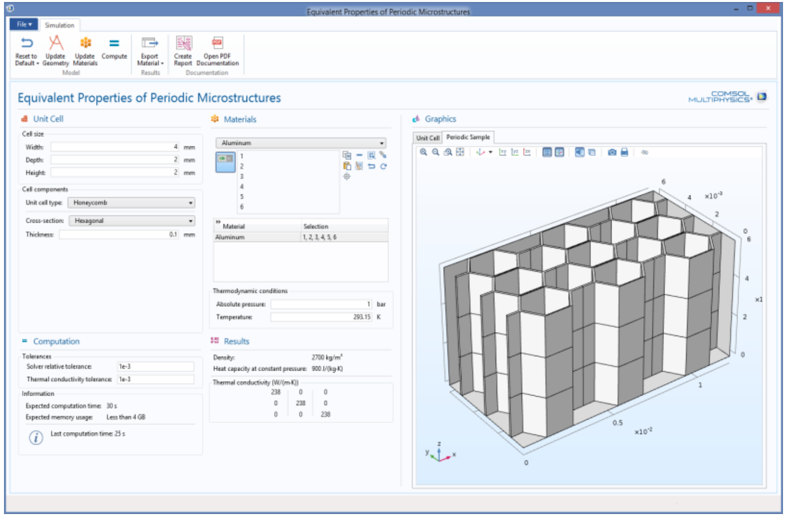
Application interface for the thermal performance of a finned pipe for cooling applications. Various geometric configurations are available.

Application interface for the modeling of heat sinks. The dimensions, shape, and the number of fins can be varied. The output gives the cooling power and the average pressure drop over the length of the system.

Simulation Application Tutorials for Heat Transfer

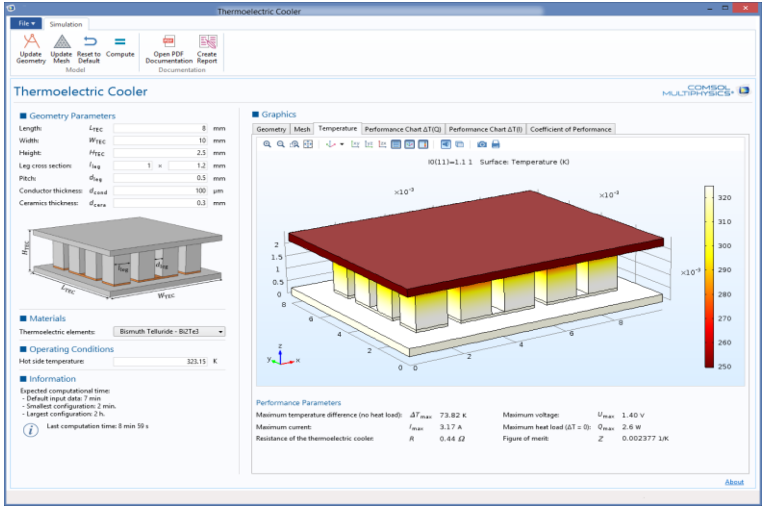


Simulation application for a heat exchanger. The tube structure, fluid properties, and boundary conditions are parameters that can be set in the user inetraface.

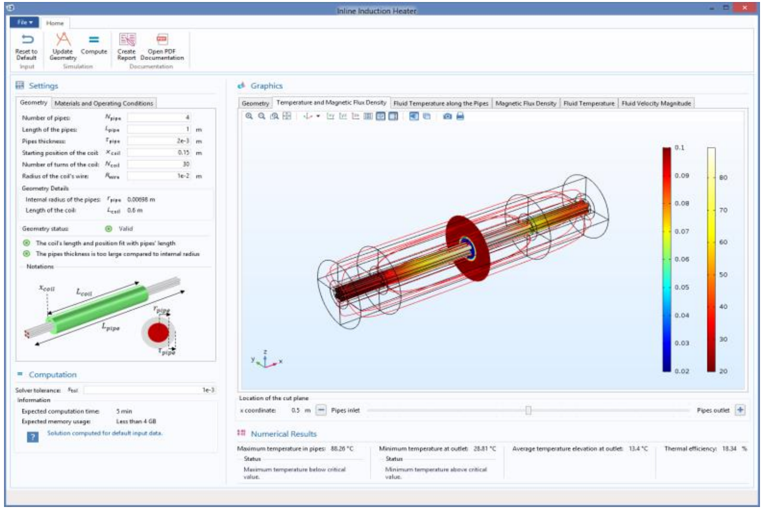


Simulation application for the estimation of equivalent thermal properties of a material with a periodic structure. Various shapes are available for the unit cell.

Simulation Application Tutorials for Heat Transfer



Simulation application for a single-stage thermoelectric cooler. The application calculates the performance depending on dimensions, geometrical configuration, materials, and operating conditions.



Simulation application for estimating magnetic induction for the heating of a liquid flowing in ferritic stainless steel pipes. A circular electromagnetic coil is wound around the pipes..