Spotlight On…

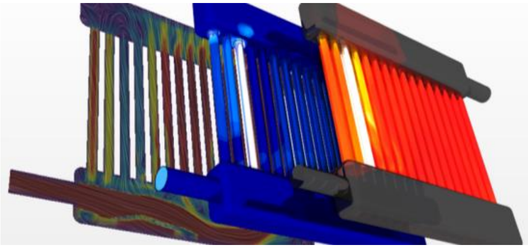
Simcenter STAR-CCM+ Hybrid Multiphase Modeling

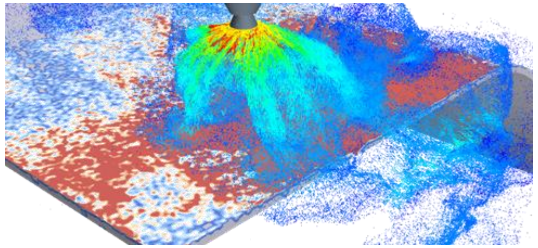
Realize Innovation.

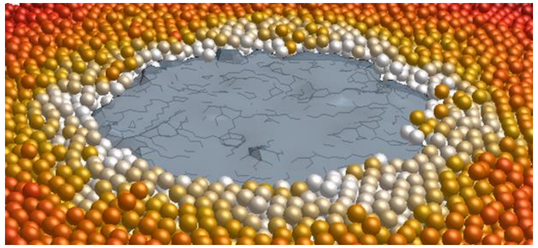
Overview: Multiphase

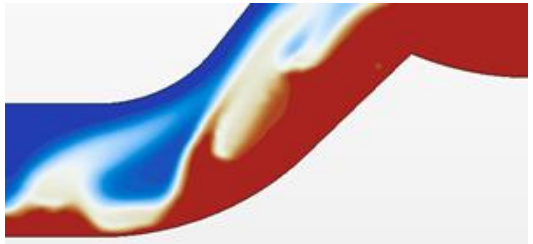
Hybrid Multiphase Flow Applications

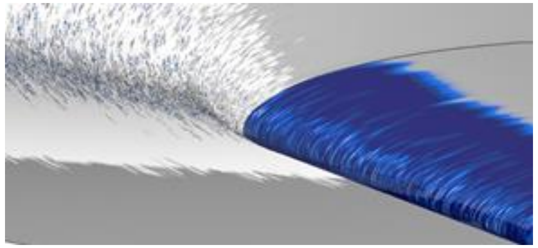
SIEMENS
Ingenuity for life


Evaporators/Condensers

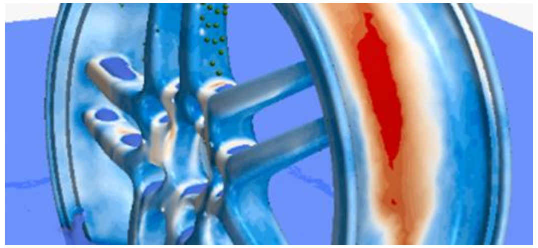

Spray Painting

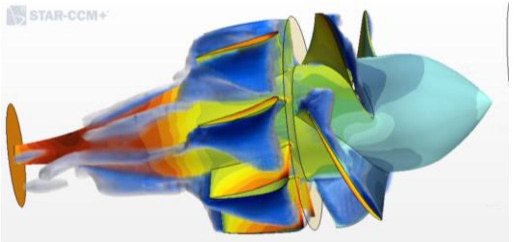

Additive Manufacturing


Nuclear Applications

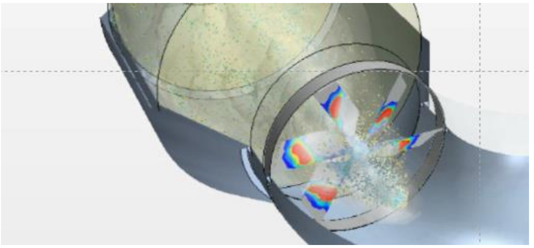

Aircraft Icing

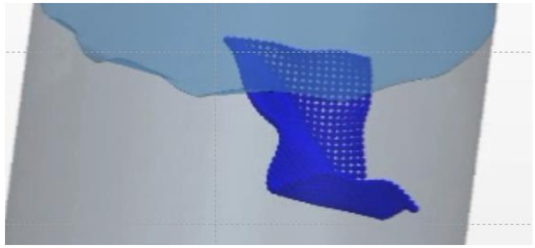

Vehicle Water Management

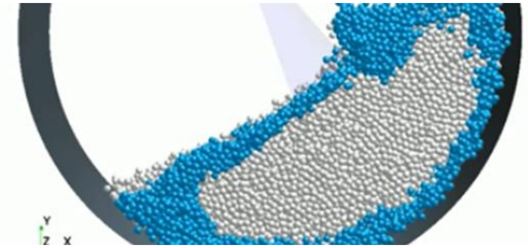

Coating/Dipping

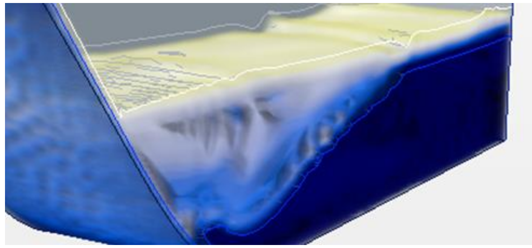


Multiphase Pumps


Aftertreatment


Washing Machines/Dishwashers


Coating


Spillways and Water Treatment

Discover Better Designs, *Faster!*

SIEMENS
Ingenuity for life

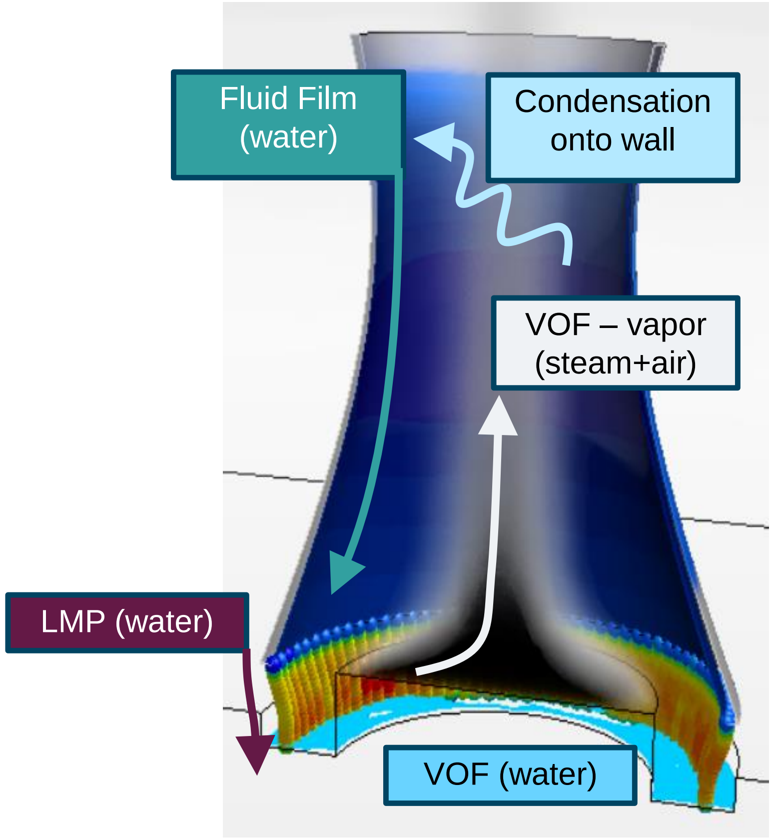
Maximize water recovery for a cooling tower

Intelligent design exploration to maximize water recovery:

- Vary radius of inlet, gap at base of tower
- Constrain tower height and steam flow rate

Requires hybrid multiphase approach

- Allows solution in timeframe needed for design exploration
- VOF vapor phase used for steam and air
- Water for VOF vapor phase condenses on the wall to form Fluid Film
- The Fluid Film runs down the wall under gravity
- On reaching the lower edge of the tower, it drips off as LMP droplets
- Droplets fall into a pool of VOF where the water phase is recovered



Discover Better Designs, *Faster!*

SIEMENS
Ingenuity for life

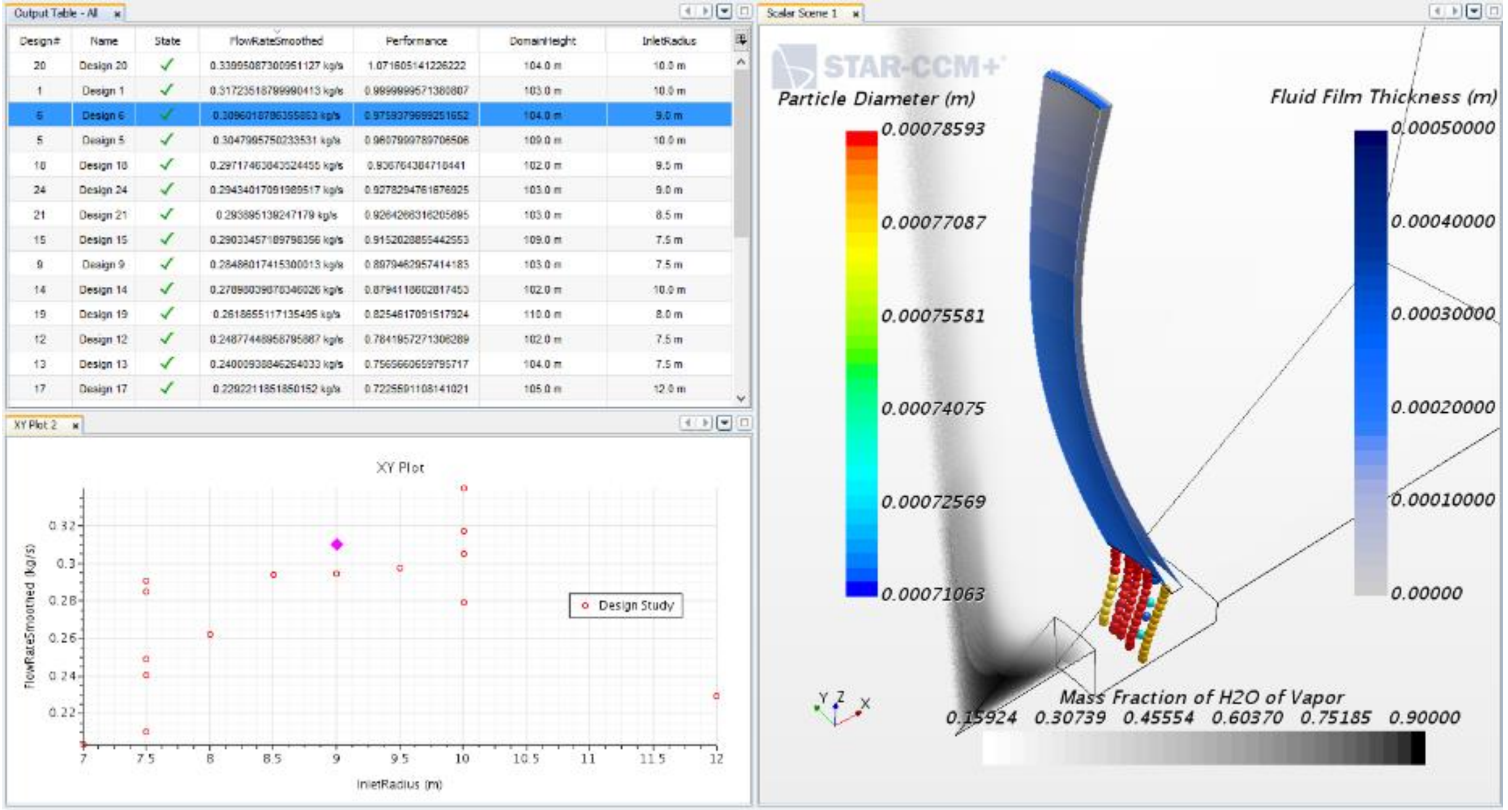
Maximize water recovery for a cooling tower

Design manager used to assess many different design configurations:

- Industry leading hybrid-adaptive search algorithm
- Examine plots and scenes for any design

Results :

- The water recovery was found to be greatest with the inlet having radii in the range 9-10m
- At larger radii the recovered water tended to hit the inlet rather than the pool



Design#	Name	State	FlowRateSmoothed	Performance	DomainHeight	InletRadius
20	Design 20	✓	0.33995087300951127 kg/s	1.071605141226222	104.0 m	10.0 m
1	Design 1	✓	0.3172351879990413 kg/s	0.9999999571380807	103.0 m	10.0 m
6	Design 6	✓	0.3096018786355853 kg/s	0.9759379699251652	104.0 m	9.0 m
5	Design 5	✓	0.3047995750233531 kg/s	0.9807999789706506	109.0 m	10.0 m
18	Design 18	✓	0.29717463843524455 kg/s	0.936764384718441	102.0 m	9.5 m
24	Design 24	✓	0.29434017091989517 kg/s	0.9278294761876925	103.0 m	9.0 m
21	Design 21	✓	0.283895138247179 kg/s	0.9264266316205895	103.0 m	8.5 m
15	Design 15	✓	0.29033457189798356 kg/s	0.9152028855442553	109.0 m	7.5 m
9	Design 9	✓	0.28488017415300013 kg/s	0.8979462957414183	103.0 m	7.5 m
14	Design 14	✓	0.27098039878346026 kg/s	0.8794118602817453	102.0 m	10.0 m
19	Design 19	✓	0.2618655117135495 kg/s	0.8254817091517924	110.0 m	8.0 m
12	Design 12	✓	0.24877448958795887 kg/s	0.7841957271306289	102.0 m	7.5 m
13	Design 13	✓	0.24000938846264033 kg/s	0.7565660659795717	104.0 m	7.5 m
17	Design 17	✓	0.2292211851850152 kg/s	0.7225591108141021	105.0 m	12.0 m

Key Requirements

SIEMENS
Ingenuity for life

Parametric Models

Flexible and Robust Meshing

Multiphysics

Speed and Performance

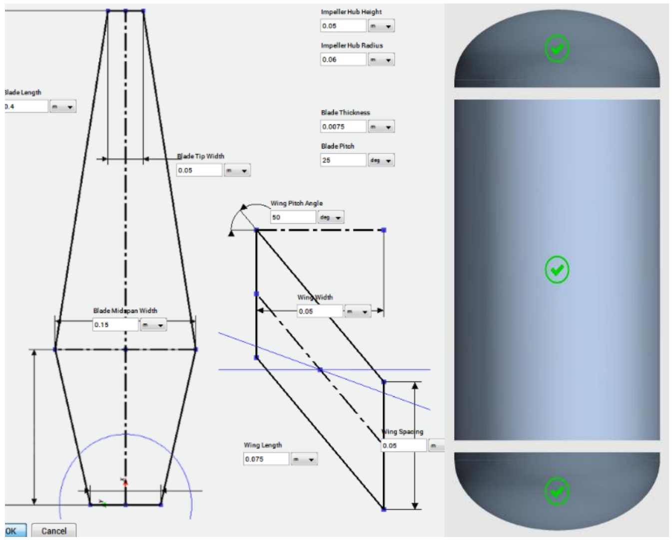
Powerful Data Analysis

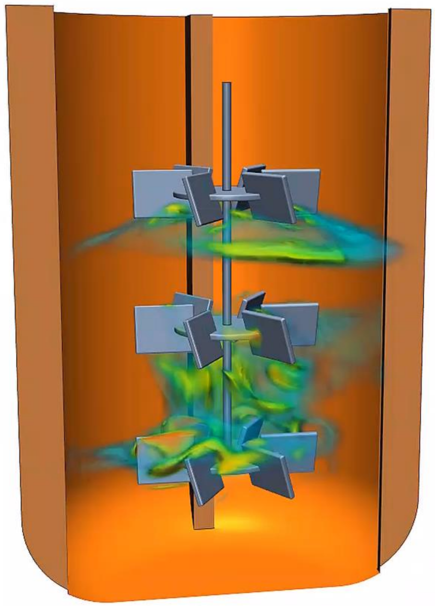
Workflow Automation

Intelligent Design Exploration

Simcenter STAR-CCM+

- Built-in parametric 3D CAD tool
- Bi-directional connectivity to CAD/PLM tools





Key Requirements

Parametric Models

Flexible and Robust Meshing

Multiphysics

Speed and Performance

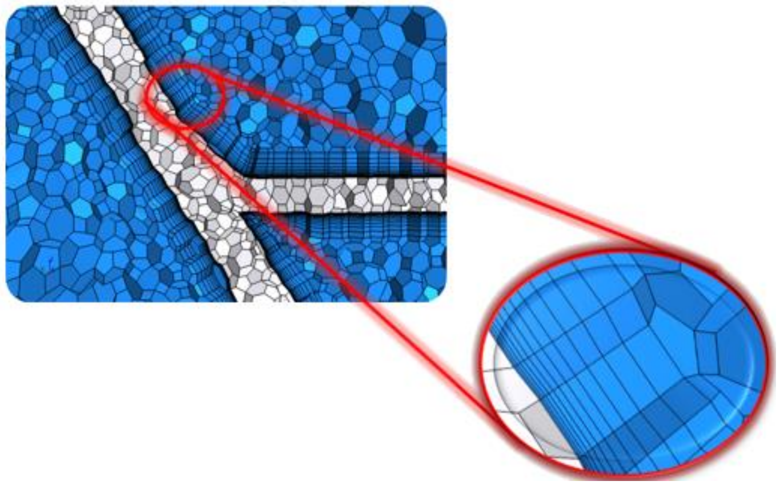
Powerful Data Analysis

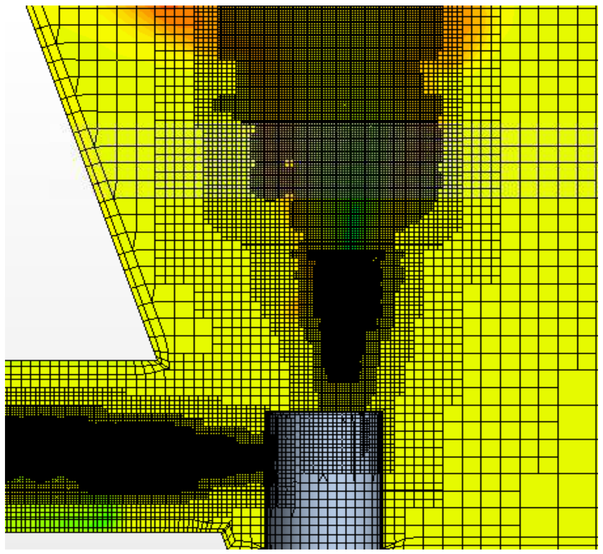
Workflow Automation

Intelligent Design Exploration

Simcenter STAR-CCM+

- Fully automated process
- Solution-based mesh refinement using tables
- Conformal prism layer meshes for accurate CHT



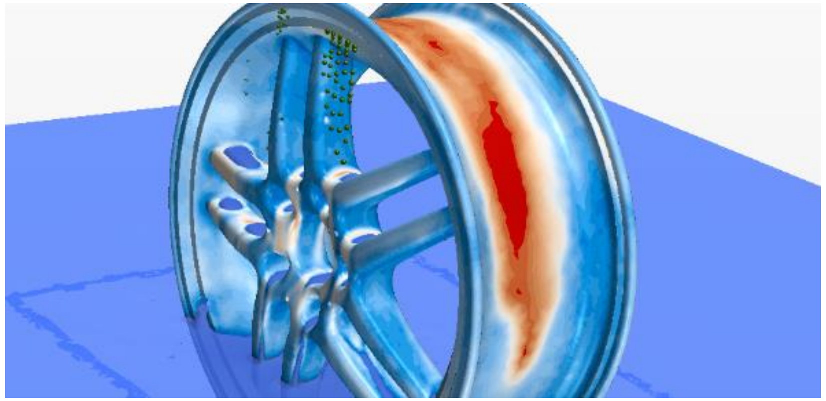


Key Requirements

- Parametric Models
- Flexible and Robust Meshing
- **Multiphysics**
- Speed and Performance
- Powerful Data Analysis
- Workflow Automation
- Intelligent Design Exploration

Simcenter STAR-CCM+

- Comprehensive suite of multiphase and phase interaction models
- Predict and understand real-world behavior:
  - Multi-regime, multi-scale, multiphase flows
- Efficient hybrid modelling to allow even the most complex problems to be solved efficiently whilst retaining details

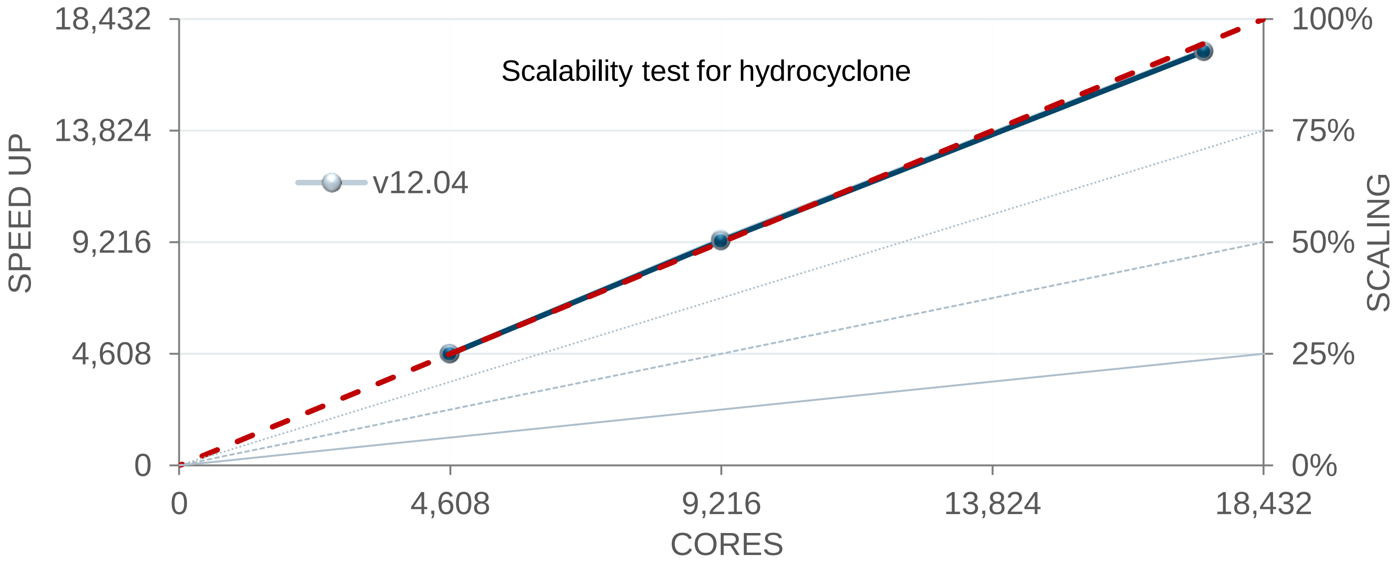


Key Requirements

- Parametric Models
- Flexible and Robust Meshing
- Multiphysics
- **Speed and Performance**
- Powerful Data Analysis
- Workflow Automation
- Intelligent Design Exploration

Simcenter STAR-CCM+

- Wide range of methods to balance compute time and accuracy
- Fast solvers with excellent scalability

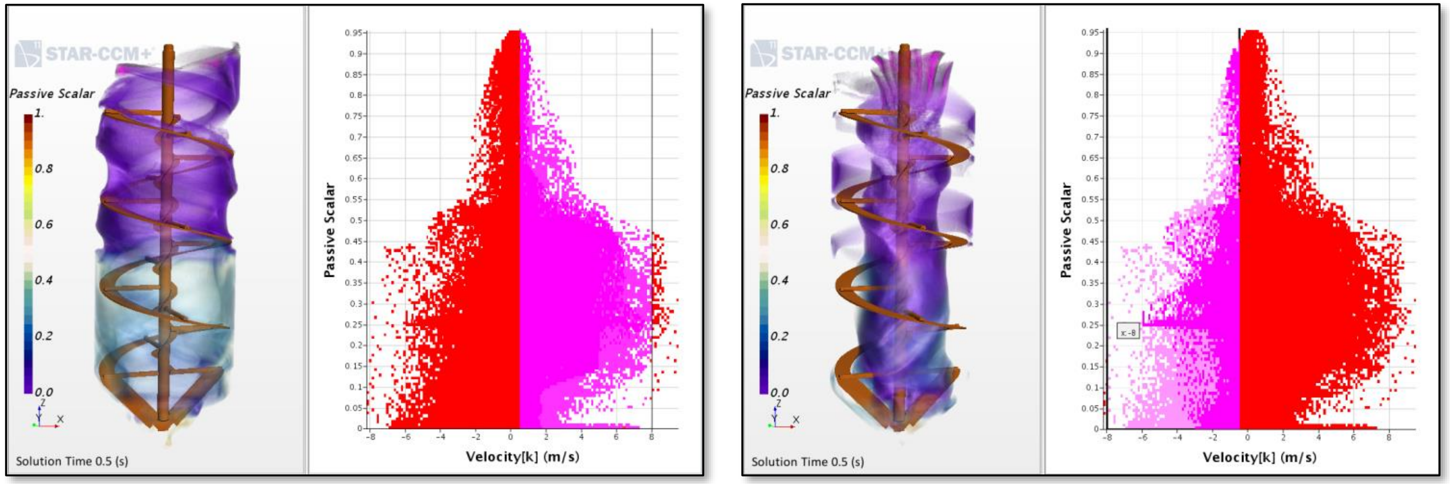


Key Requirements

- Parametric Models
- Flexible and Robust Meshing
- Multiphysics
- Speed and Performance
- **Powerful Data Analysis**
- Workflow Automation
- Intelligent Design Exploration

Simcenter STAR-CCM+

- Powerful, integrated post processing and visualization
- Tools to understand complex interdependencies



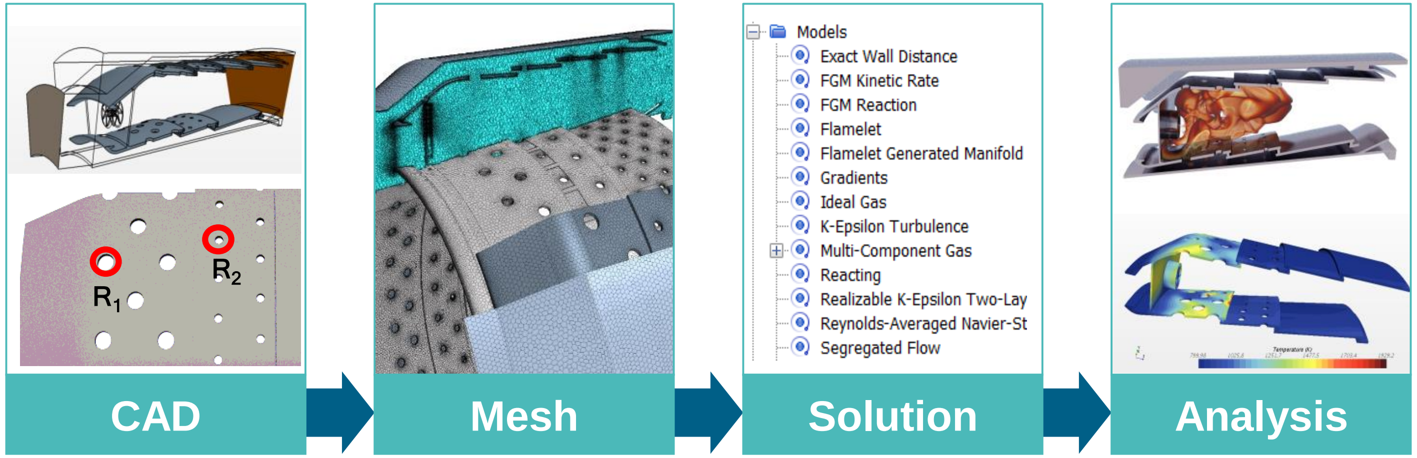
Key Requirements

SIEMENS
Ingenuity for life

- Parametric Models
- Flexible and Robust Meshing
- Multiphysics
- Speed and Performance
- Powerful Data Analysis
- **Workflow Automation**
- Intelligent Design Exploration

Simcenter STAR-CCM+

- End-to-end pipelined workflow in one environment
- Workflow easily repeated with a few clicks enabling design space exploration

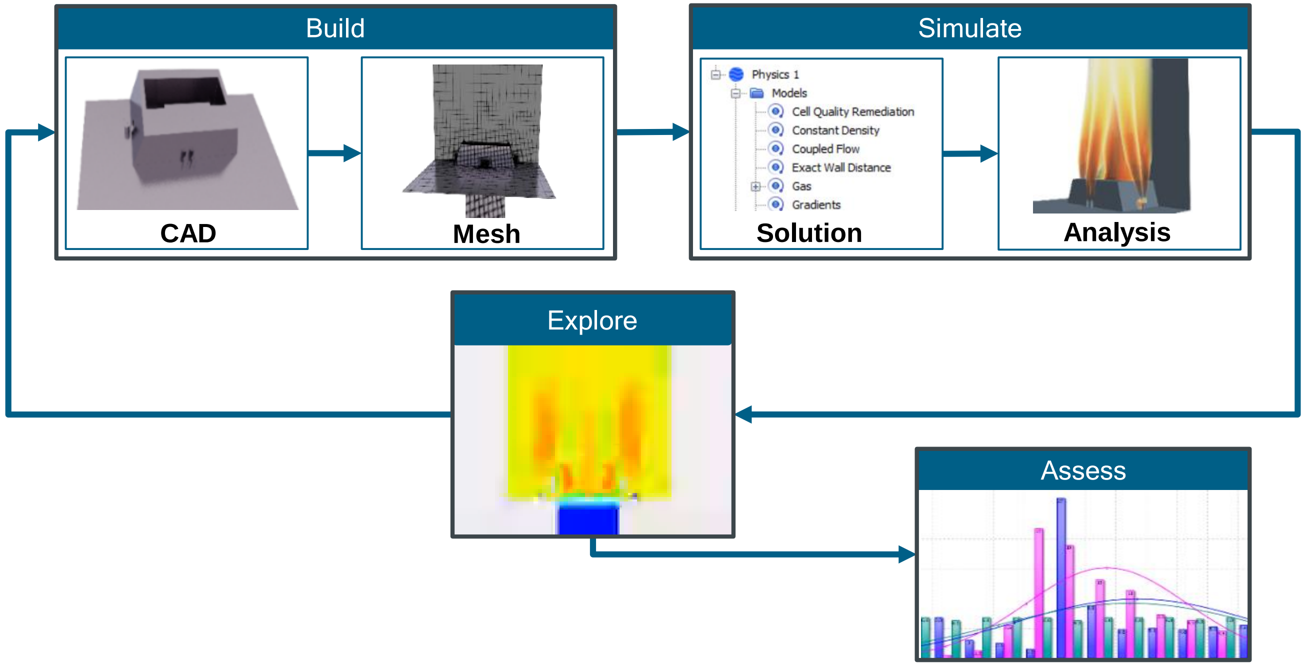


Key Requirements

- Parametric Models
- Flexible and Robust Meshing
- Multiphysics
- Speed and Performance
- Powerful Data Analysis
- Workflow Automation
- **Intelligent Design Exploration**

Simcenter STAR-CCM+

- Fully integrated in Simcenter STAR-CCM+
- Leverages HEEDS design optimization technology



Multiphase Modeling in Simcenter STAR-CCM+

- Parametric Models
- Flexible and Robust Meshing
- Multiphysics
- Speed and Performance
- Powerful Data Analysis
- Workflow Automation
- Intelligent Design Exploration

Spotlight on Hybrid Multiphase

- Comprehensive suite of multiphase models
  - Eulerian Multiphase (EMP)
  - Mixture Multiphase (MMP)
  - Volume Of Fluid (VOF)
  - Dispersed Multiphase (DMP)
  - Fluid Film (Film)
  - Lagrangian Multiphase (LMP)
  - Discrete Element Method (DEM)
- Hybrid Modeling and Phase Interaction Models

Modeling Multiphase Flow in Simcenter STAR-CCM+

SIEMENS
Ingenuity for life

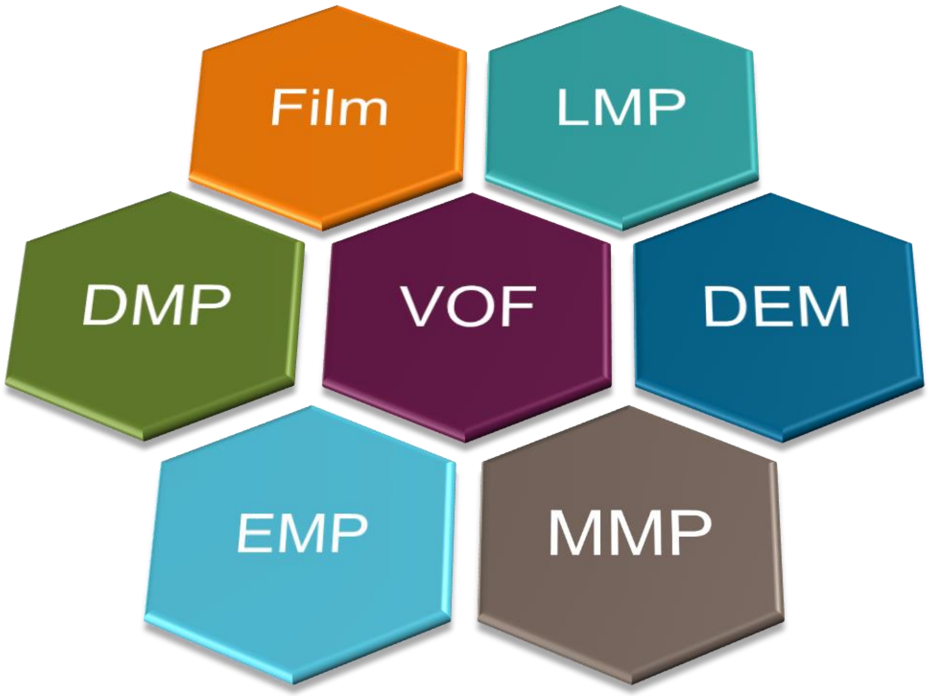
Comprehensive suite of multiphase models

Covering all flow regimes

- Wide range of models
- Use the most appropriate model for each regime
  - Dispersed, stratified, mixed, slug, discrete etc.

Hybrid modeling strategy

- Models can be used together in a single simulation
- Use each model for its appropriate regime
- Minimize computational cost through effective use of models
- Allowed by mass transfer mechanisms such as impingement, evaporation or reactions

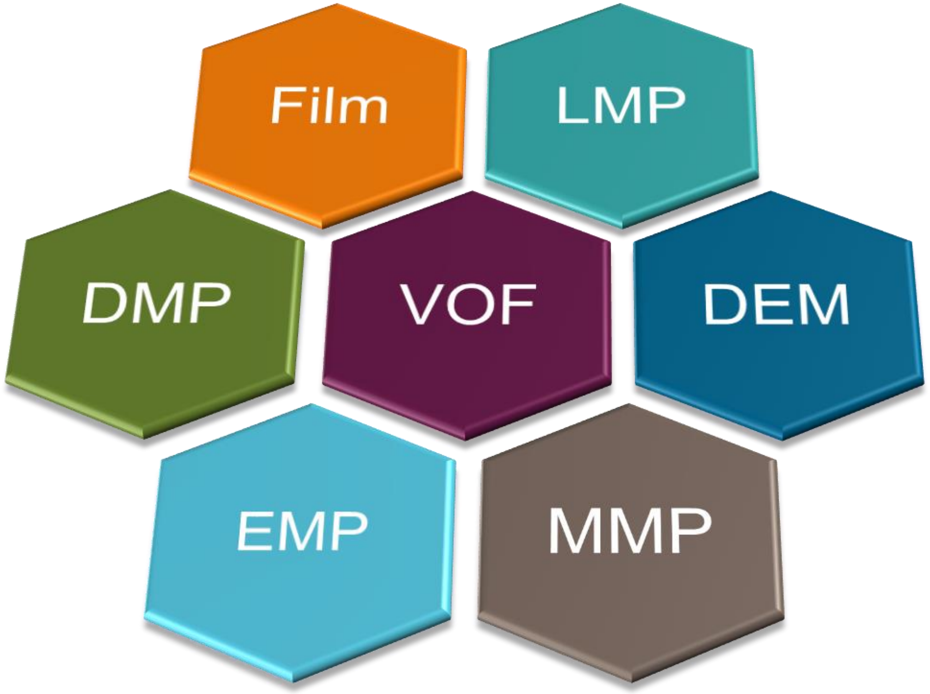


Modeling Multiphase Flow in Simcenter STAR-CCM+

Comprehensive suite of multiphase models

There are seven multiphase models in Simcenter STAR-CCM+

- Eulerian Multiphase (EMP)
- Mixture Multiphase (MMP)
- Volume Of Fluid (VOF)
- Dispersed Multiphase (DMP)
- Fluid Film (Film)
- Lagrangian Multiphase (LMP)
- Discrete Element Method (DEM)

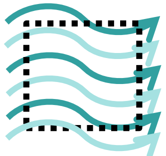


Modeling Multiphase Flow in Simcenter STAR-CCM+

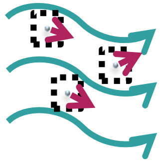
SIEMENS
Ingenuity for life

Comprehensive suite of multiphase models

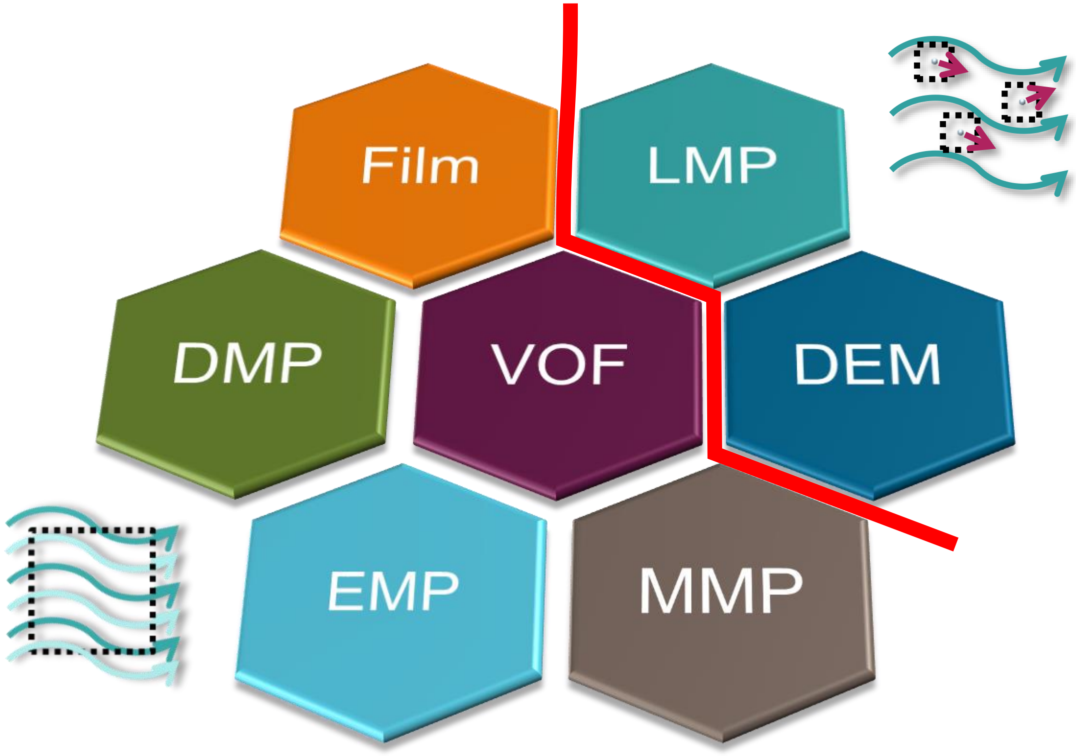
These models can be split into two families

Eulerian Models 

- The observer considers the particles, bubbles, or droplets to be a continuum passing through a fixed volume

Lagrangian Models 

- The observer tracks parcels of particles as they move through space & time

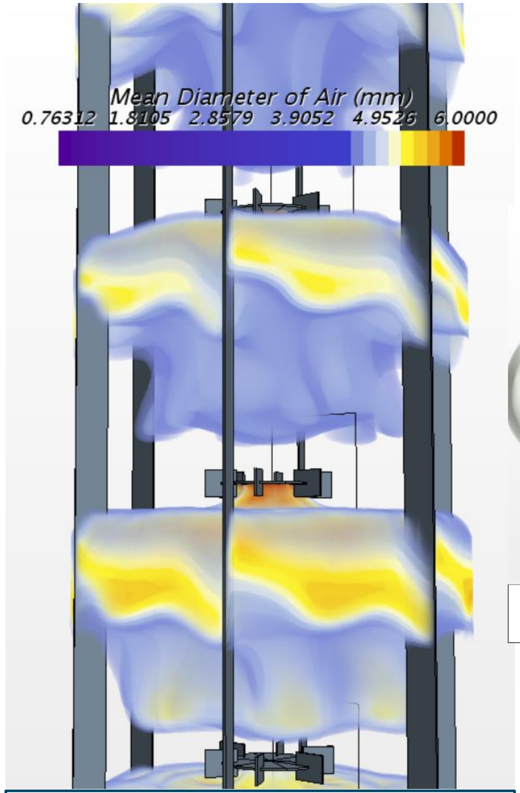


Modeling Multiphase Flow in Simcenter STAR-CCM+

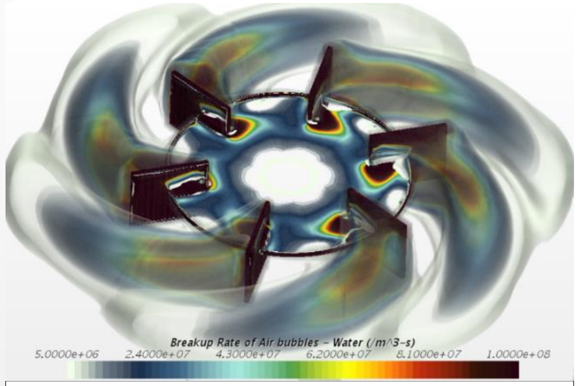
SIEMENS
Ingenuity for life

Eulerian Multiphase (EMP) Model

- Used for modeling miscible fluids mixed on length scales smaller than we wish to resolve
- The most 'complete' multiphase model
  - Solves a set of transport equations for each phase
- Can model phase change and crystal growth
- Models for tracking the population of size distribution of bubbles or droplets
- Use Cases:
  - Bubble Columns
  - Mixing Vessels
  - Settling Tanks
  - Fluidized Beds



Mixing Tank – Location of Large Bubbles

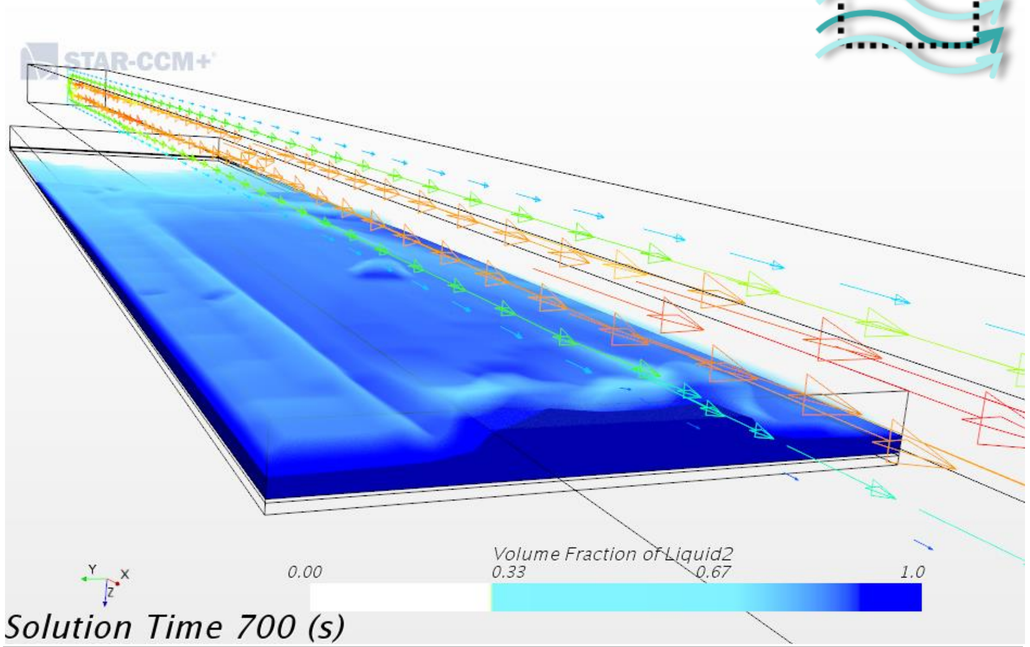


Breakup Rate of Bubbles

Modeling Multiphase Flow in Simcenter STAR-CCM+

Mixture Multiphase (MMP) Model

- Used for similar applications to EMP
  - Phases are assumed to be miscible
- Lightweight model compared to EMP
  - Only solves one set of transport equations
  - Solves for volume fraction
  - Allows slip between phases
    - Relative motion accounted through drag laws
- Can model phase change
  - Wall boiling
- Use Cases:
  - Fuel Cells
  - Nuclear: Steam Generators
  - Boilers



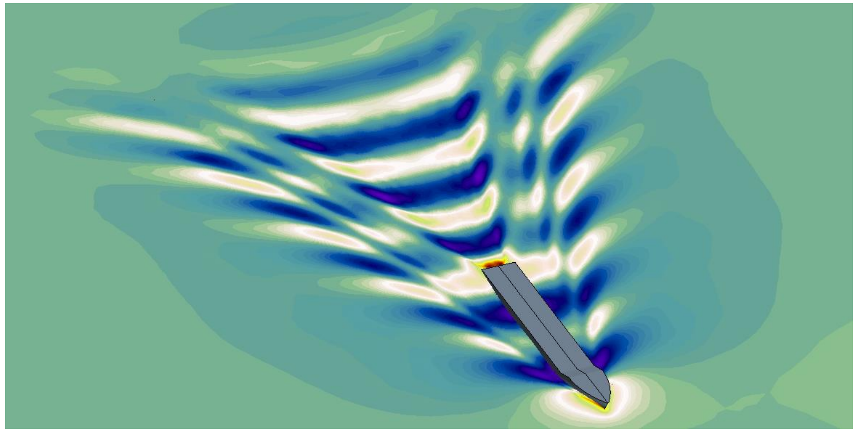
Water Formation in a PEM Fuel Cell

Modeling Multiphase Flow in Simcenter STAR-CCM+

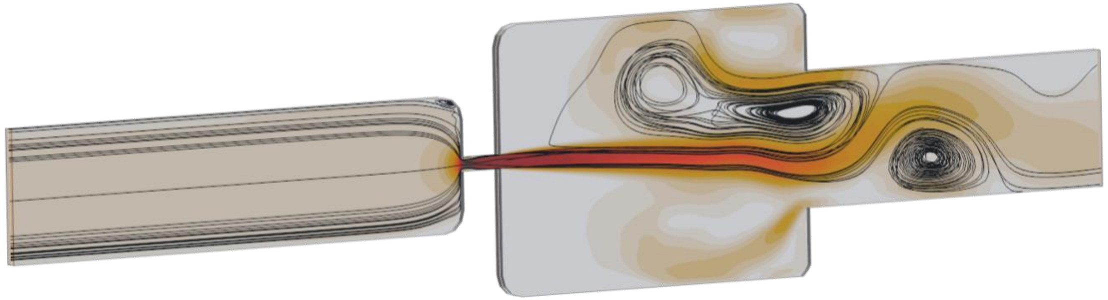
SIEMENS
Ingenuity for life

Volume Of Fluid (VOF) Model

- Used to track the motion of free surfaces
  - For immiscible fluids with a sharp interface
- Can model phase change
  - Boiling/evaporation/condensation/cavitation
  - Solidification/melting
- Can include the effects of surface tension
- Predefined VOF waves for marine simulations
- Use Cases:
  - Marine Hydrodynamics and Seakeeping
  - Fuel Tank Sloshing
  - Oil and Gas Flow Assurance
  - IC Engine Cooling



Kelvin waves around vessel



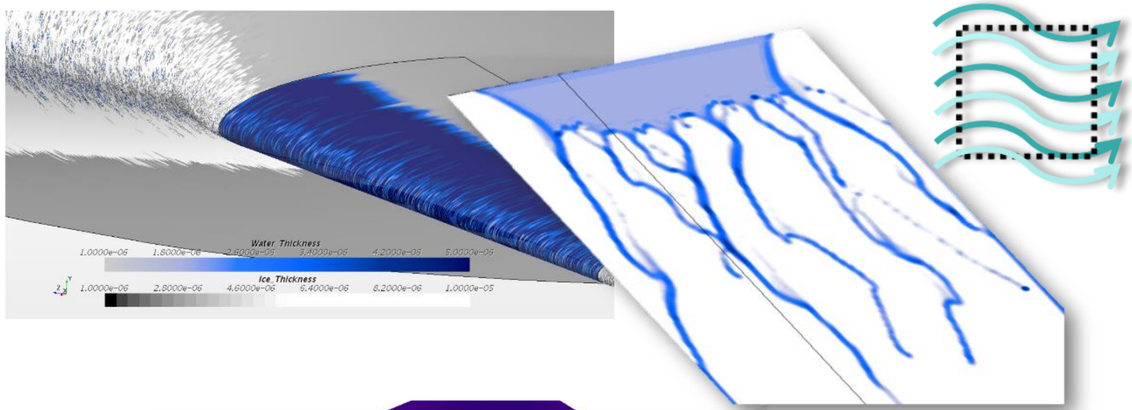
Cavitating throttle

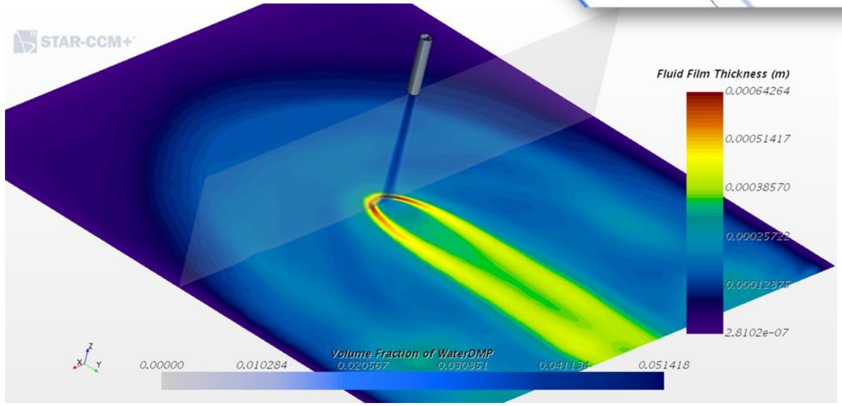
Modeling Multiphase Flow in Simcenter STAR-CCM+

SIEMENS
Ingenuity for life

Fluid Film Model

- Used for modeling a thin layer of fluid on surfaces
  - Thickness stored on the surface rather than resolved
- Can capture rivulets and surface tension effects
- Can model phase change
  - Evaporation and condensation
  - Melting and solidification
- Multiple application areas:
  - Vehicle Rainwater Management
  - Selective Catalytic Reduction (SCR)
  - Fuel Sprays
  - Spray Coating / Deposition
  - Aircraft Ice Protection



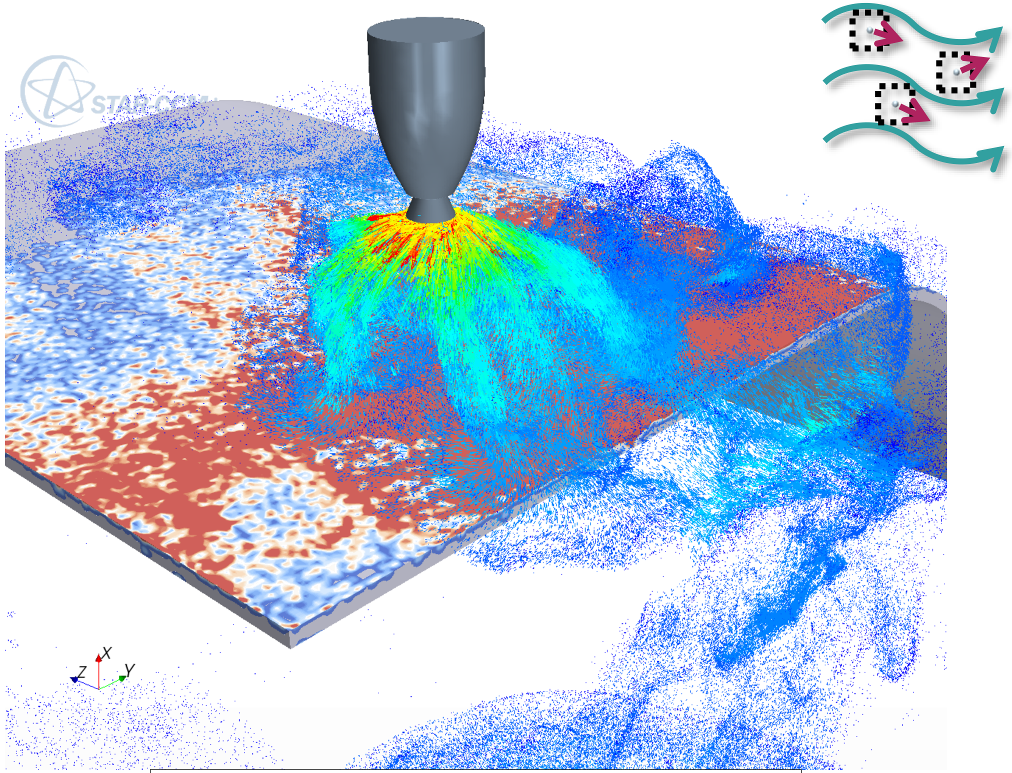


Modeling Multiphase Flow in Simcenter STAR-CCM+

SIEMENS
Ingenuity for life

Lagrangian Multiphase (LMP) Model

- Solves the path of discrete droplets or particles
  - Large numbers of droplets tracked by grouping into parcels
  - Can be one way or two way coupled with the flow
- Suitable for dilute dispersed phases
  - Low volume fraction and little particle-particle collision
- Models for:
  - Droplet splashing and rebound at walls
  - Primary atomization and secondary breakup
  - Evaporation, condensation and reactions
- Use Cases
  - Vehicle Water Management
  - Selective Catalytic Reduction (SCR)
  - Spray Coating
  - Erosion
  - Liquid Fuel Combustion



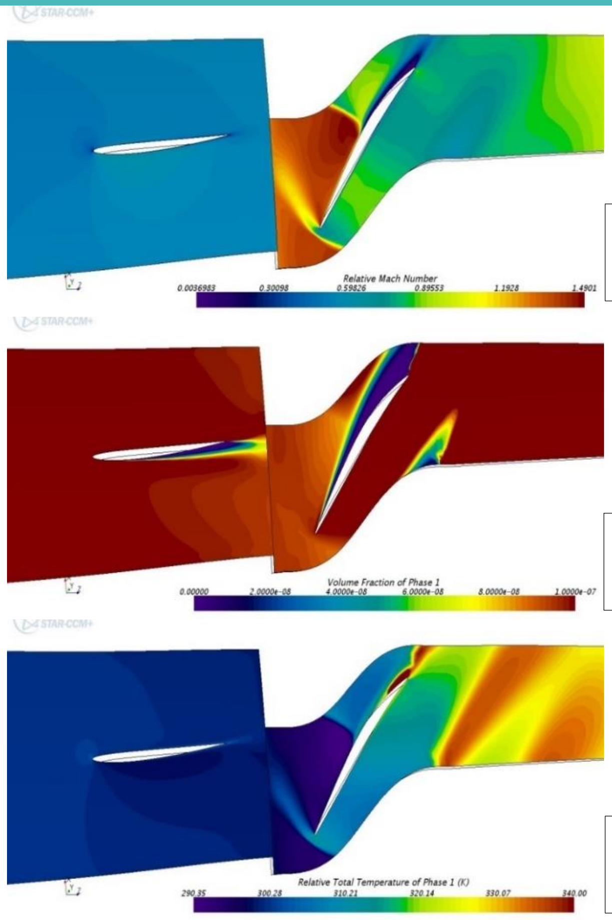
Spray painting with Lagrangian Multiphase

Modeling Multiphase Flow in Simcenter STAR-CCM+

SIEMENS
Ingenuity for life

Dispersed Multiphase (DMP) Model

- Used for dilute Eulerian dispersed phases
  - Analogous to Lagrangian Multiphase
  - Volume fraction too low to affect continuous phase
  - E.g. rain or sand in air
- Continuous phase solved by another model
  - E.g. single phase model
- Can be used as post-processing step, or be two-way coupled with the flow
- Use Cases:
  - Vehicle Water Management
  - Aircraft Icing
  - Sand Ingestion



Relative Mach Number

DMP Volume Fraction

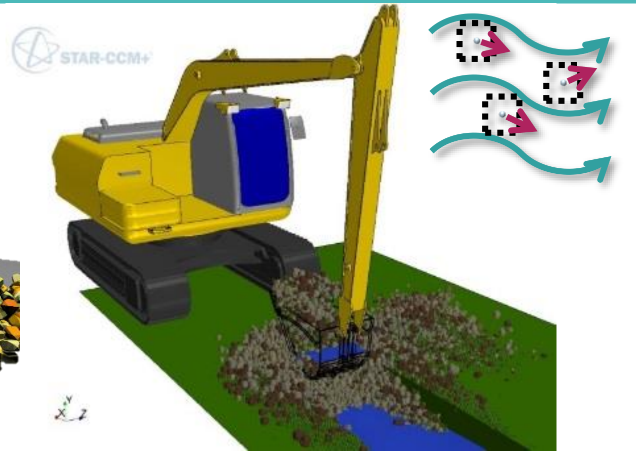
DMP Relative Temperature

Modeling Multiphase Flow in Simcenter STAR-CCM+

SIEMENS
Ingenuity for life

Discrete Element Method (DEM)

- Model non-spherical particles such as aggregates
  - Where bulk particle behavior important
  - Where particles are densely packed (in contact)
- Particles may break and deform
- Can be coupled with the flow in a single package
- Use Cases:
  - Fluidized beds
  - Rock mechanics
  - Conveying aggregates
  - Tablet coating
  - Plugging fissures in oil wells
  - Crop harvesting and lawn mowing



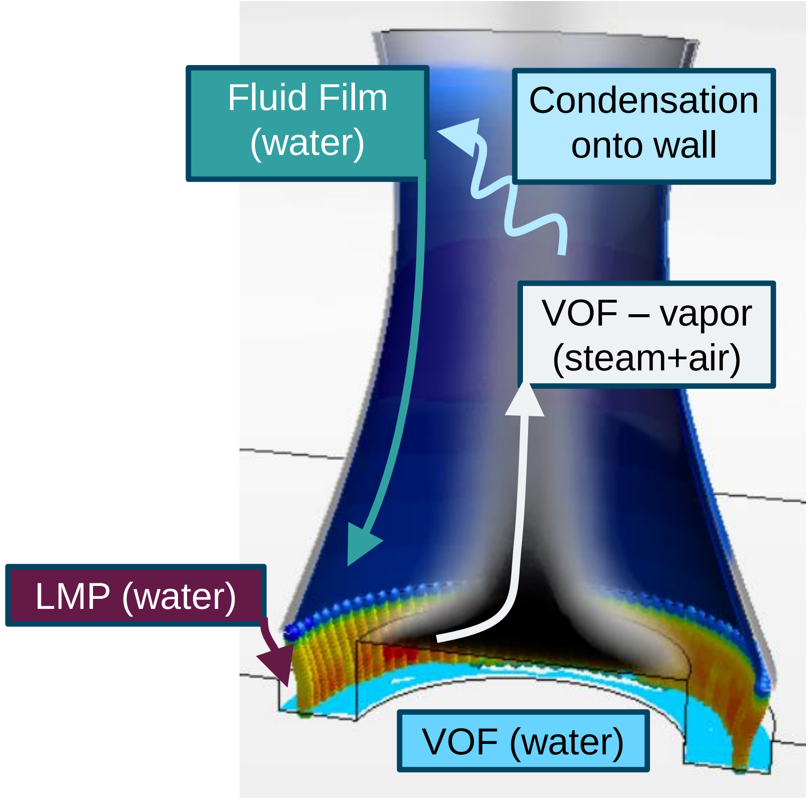
Excavation of rocks using DEM

Modeling Multiphase Flow in Simcenter STAR-CCM+

SIEMENS
Ingenuity for life

Hybrid Modeling and Phase Interaction Models

- Simcenter STAR-CCM+ has a wide range of multiphase models
  - Covering every flow regime
- Real world flows, however, cover more than one regime
  - Need to be able to use more than one model together
  - This is hybrid multiphase modeling
    - Allows us to efficiently model complex applications
- Remember again our cooling tower example
  - Uses three multiphase models
    - VOF, Fluid Film and LMP
- In the following sections, the hybrid multiphase modeling capabilities and benefits of Simcenter STAR-CCM+ are presented



Summary

SIEMENS
Ingenuity for life

- Predict and understand real-world behavior of multiphase flows
- Explore many design variants early in development

Parametric Models

Flexible and Robust Meshing

Multiphysics

Speed and Performance

Powerful Data Analysis

Workflow Automation

Intelligent Design Exploration

Simcenter STAR-CCM+

- Comprehensive suite of multiphase models
- Covering all multiphase regimes in real world problems
- Computationally efficient hybrid approaches

Hybrid Multiphase Modeling in Simcenter STAR-CCM+

Why So Many Models?

SIEMENS
Ingenuity for life

- Each multiphase model is built on assumptions and is suited to a particular regime
  - Not an issue if physical problem is restricted to this regime
  - Renders model invalid for other regimes
- Multiphase model must be carefully chosen depending on flow regimes present - Using only one model requires simplification and assumption
- For example:
  - The Volume of Fluid (VOF) model assumes phases form free surfaces, artificially sharpening boundary between phases
    - Ideal for modeling flow around a marine vessel
    - Any bubbles droplets should be resolved
- Real flow problems cover multiple flow regimes and such assumptions may be unacceptable

Applicable Regimes

SIEMENS
Ingenuity for life

Stratified

- Free Surfaces
  - VOF, Fluid Film

Dispersed

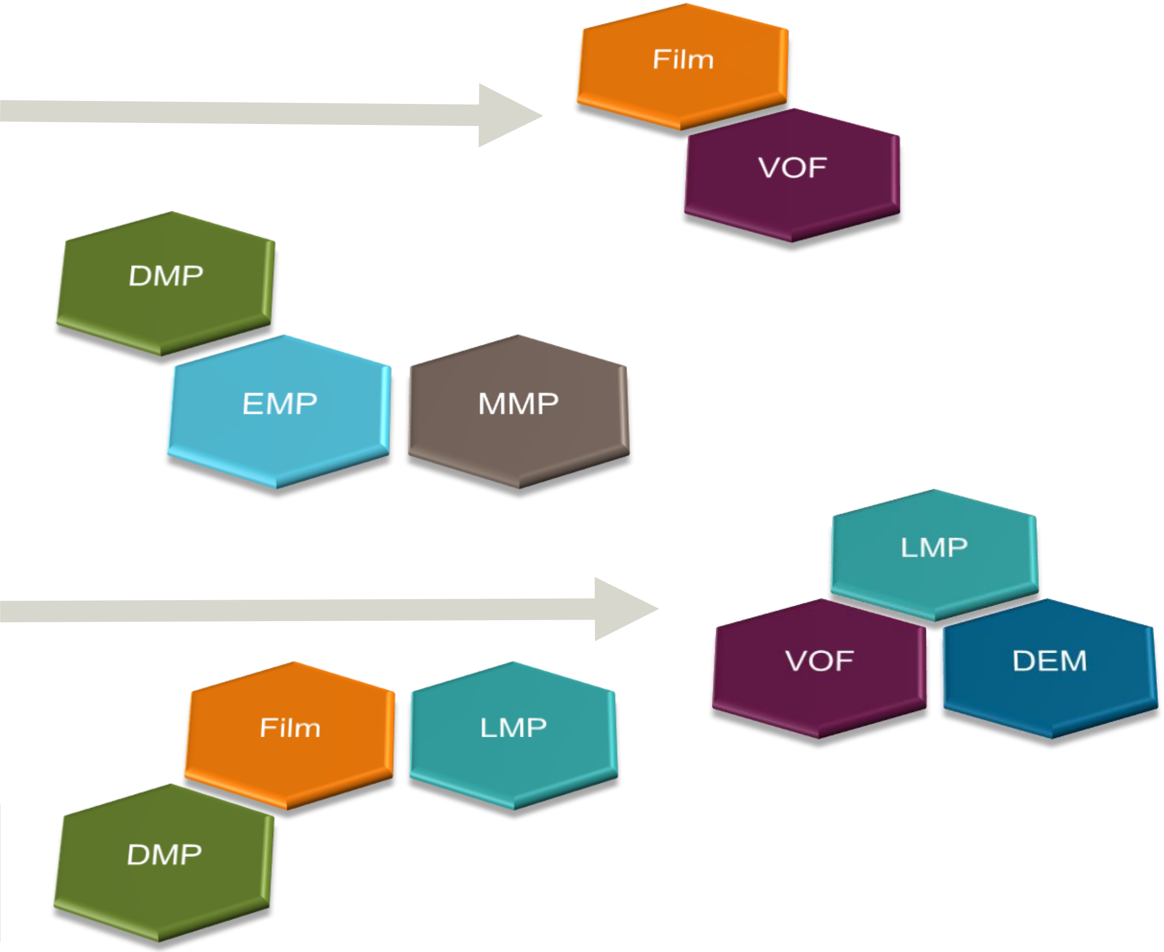
- Unresolved droplets/bubbles
  - EMP, MMP, DMP

Discrete

- Resolved particles/droplets/bubbles
  - LMP, DEM, VOF (fine mesh)

Dilute

- Low volume fraction
  - DMP, LMP, Fluid Film



Efficient Modeling of Real World Multiphase Flows

SIEMENS
Ingenuity for life

Three options for modeling multi-regime real world multiphase flows:

1. Use highest fidelity model
   - VOF can be used as a quasi-DNS multiphase model, resolving every droplet, bubble and film
   - Typically not feasible
   - Under-resolution leads to inaccuracy
2. Use several models together to cover all regimes
   - E.g. VOF for free surfaces, Fluid Film for thin films, and LMP for droplets
   - Software must provide all relevant phase interactions, appropriate mass and energy transfer models
3. Expand the applicability of a standard model (e.g. EMP) to cover multiple regimes

All of the above are possible in Simcenter STAR-CCM+

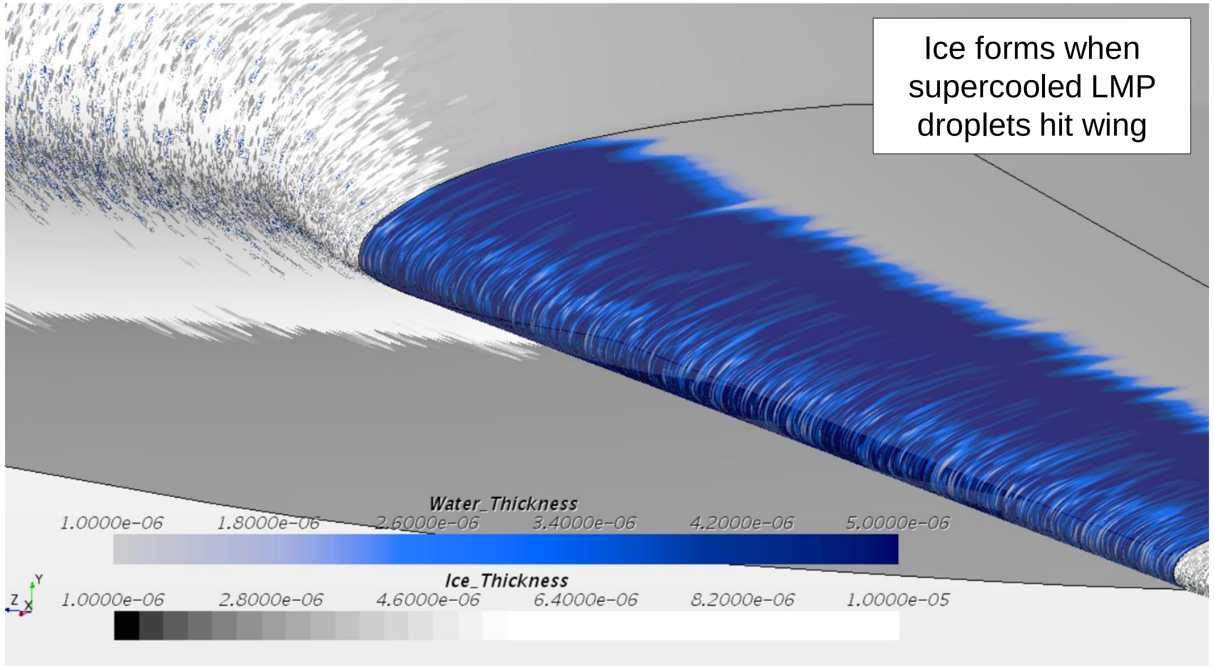
Hybrid Multiphase

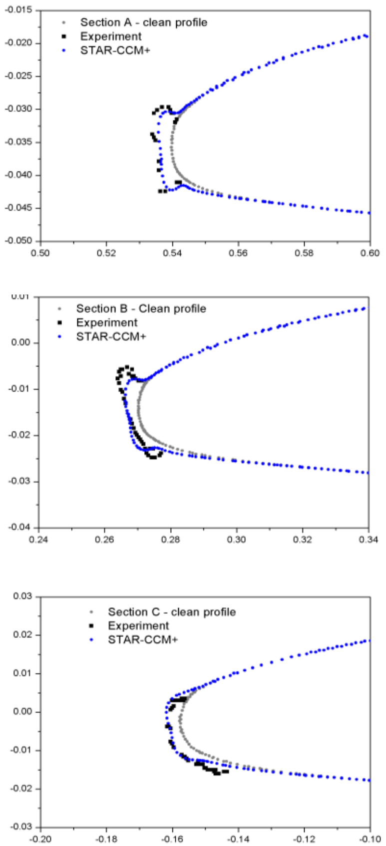
Multiple Models Working Together

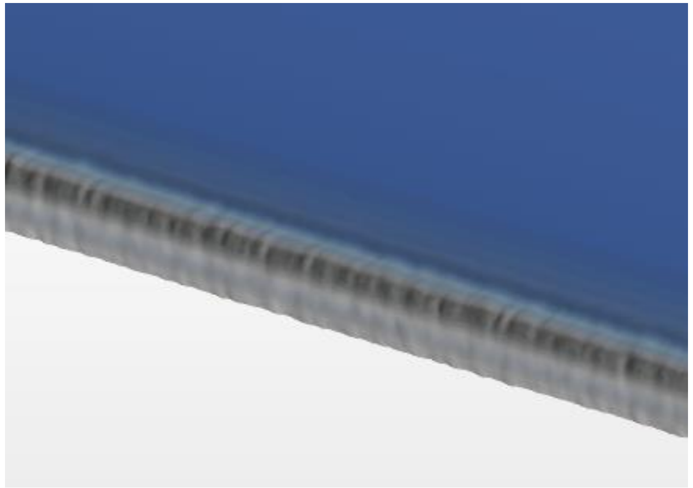
Application Example – Aircraft Icing

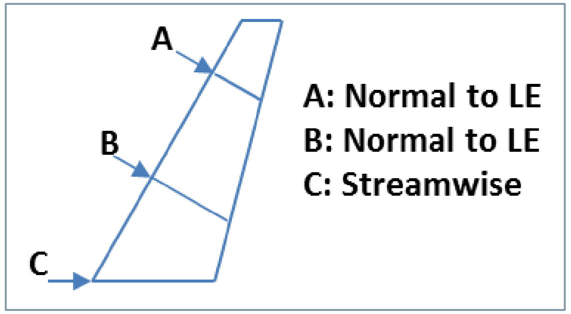
SIEMENS
Ingenuity for life

- Melting and solidification of liquid film
- Option to remove the solidified mass in the film to morph the mesh by the appropriate amount to model applications such as ice build up







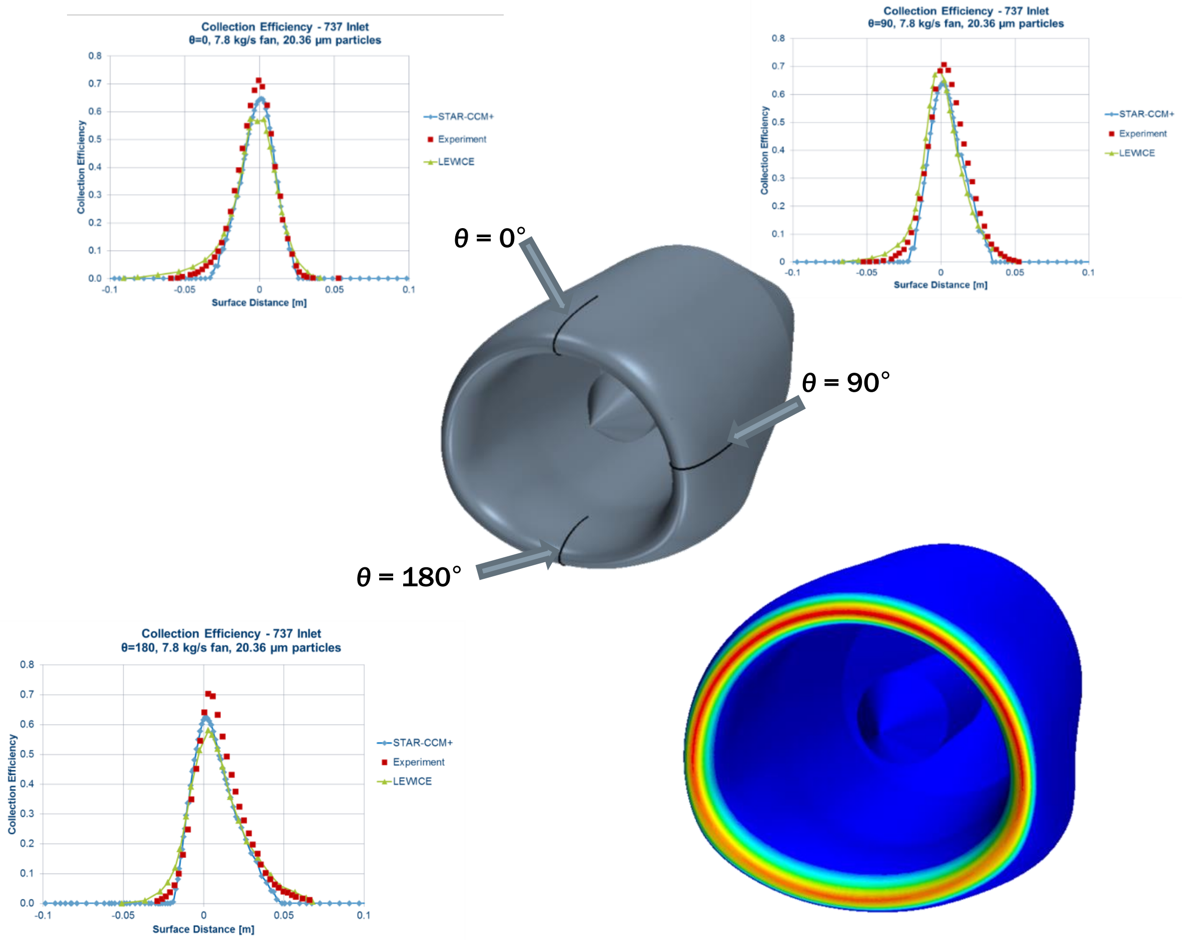


Comparison of results from Simcenter STAR-CCM+ with “Experimental Investigation of Ice Accretion Effects on a Swept Wing”, Papadakis, M., et al, DOT/FAA/AR-05/39, 2005

Application Example – Nacelle Collection Efficiency

- Used for similar use cases to LMP-Film
  - DMP is a lightweight Eulerian model
    - Suitable for low volume fractions (mists, fine sprays, small bubbles)

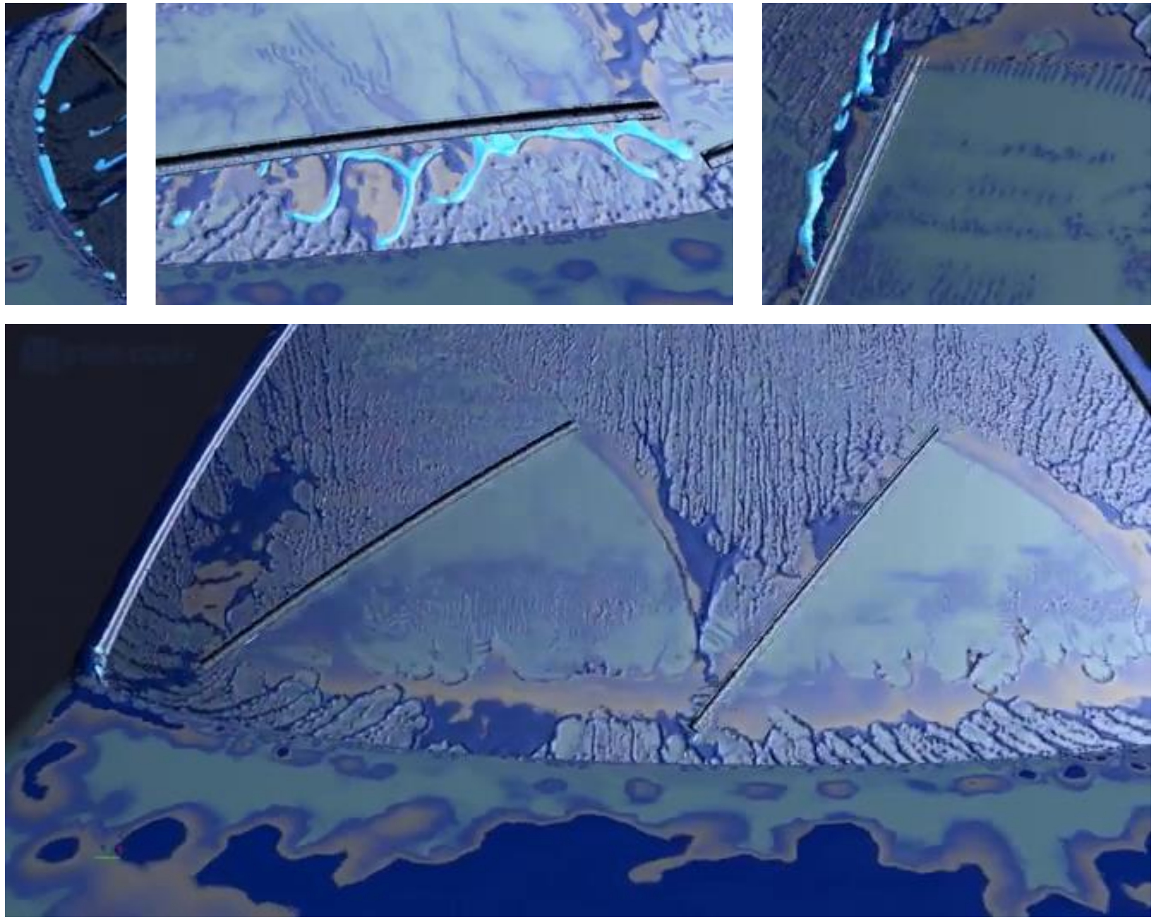
- DMP -> Film Impingement
  - Similar to LMP, DMP phases can impinge into film
  - Example shows icing collection efficiency as a result of super-cooled DMP droplets impinging on a nacelle



Collection efficiency modeling on B737 nacelle

Application Example – Vehicle Water Management

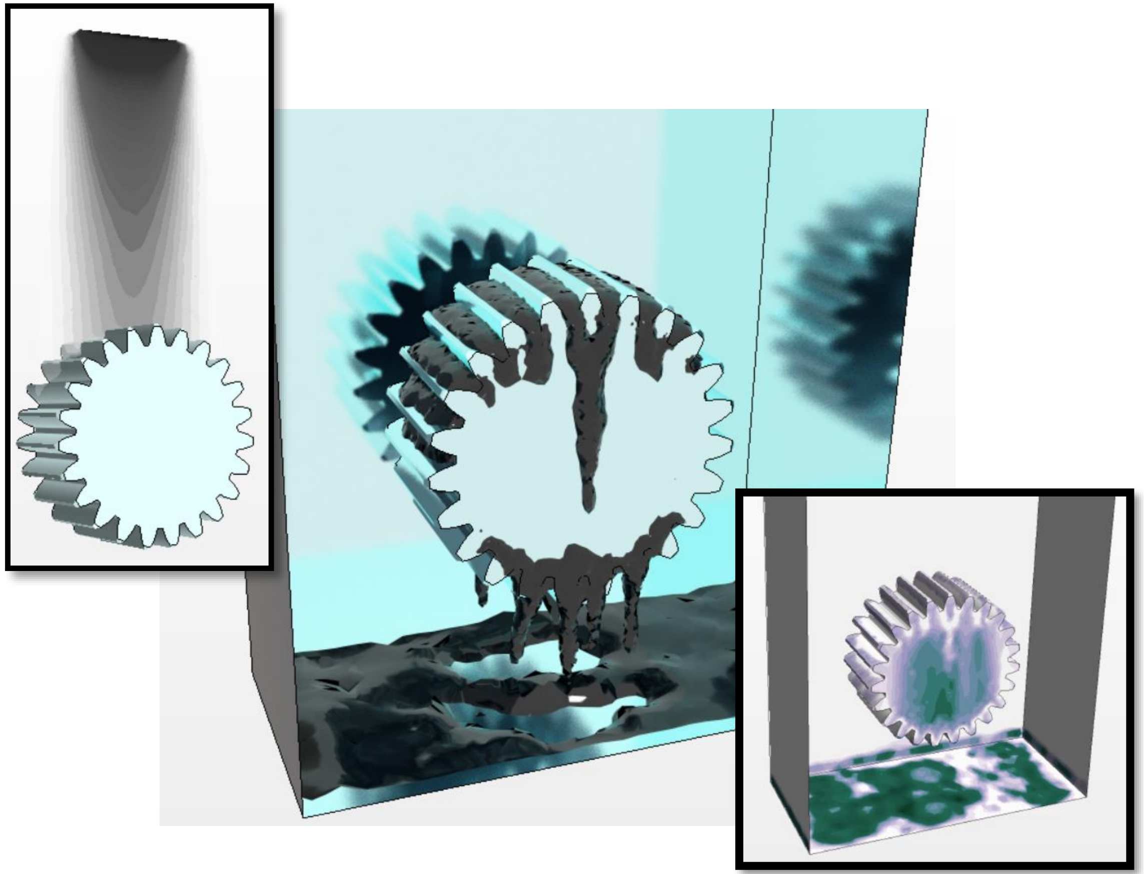
- Background
  - Regulations require visibility in key areas
  - Using hybrid VOF-film we can study interaction with aerodynamics
- Results
  - Fluid Film regions are indicated by dark blue
  - VOF regions by cyan color
- Surface tension forces passed between models
  - Ensures consistent behavior in transition regions
- Flow features in thicker regions of fluid can only be captured by VOF
  - Hybrid approach provides cost effect way to do this



Rainwater management using hybrid VOF-Film

Application Example - Gear Box

- Reduced computational expense for hybrid multiphase simulations
  - Removes the need for LMP for dilute dispersed phases
  - Removes stochastic effects due to discrete impingements
- Example shows DMP spray forming a Fluid Film on a rotating gear
  - When the film becomes thick it transitions to VOF
- Use Cases
  - Vehicle Water Management/Soiling
  - Modeling Air Bubbles in Steel



Impinging DMP phase, VOF phase on gear, Fluid Film phase

Hybrid Multiphase

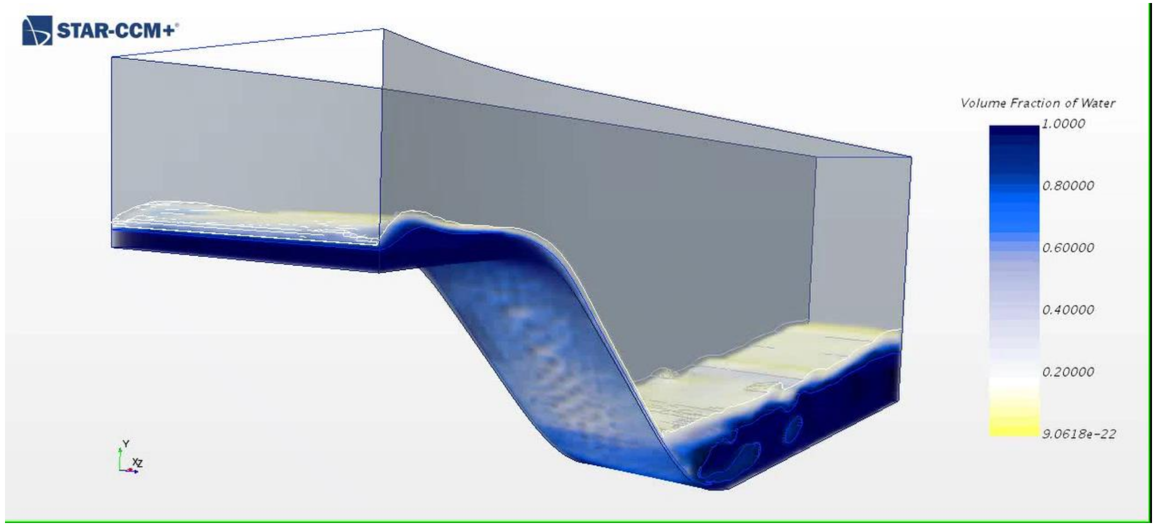
Single Model for Multiple Regimes

EMP – Multiple Flow Regime Model

SIEMENS
Ingenuity for life

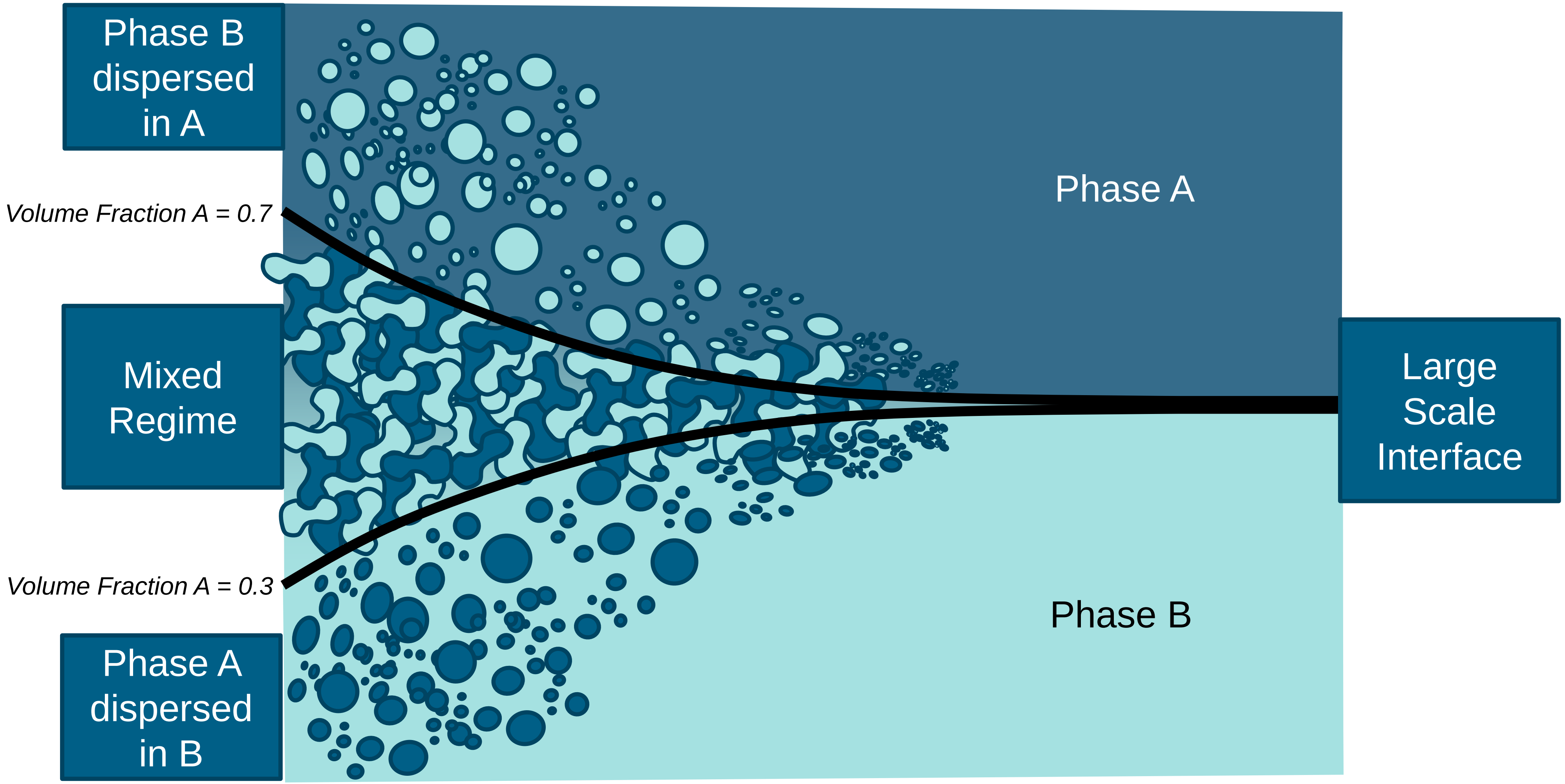
Key Information

- Combines the benefits of VOF & EMP
- Accurately simulate new applications with a computationally affordable model
  - Impractical to model small bubbles and droplets accurately with VOF as an extremely fine mesh is needed
    - Under-resolved VOF is inaccurate as there is no model to account for dispersed bubbles & droplets
  - EMP simulations do not resolve the free surfaces
- A single multiphase model captures
  - Many different co-existing flow regimes
    - Stratified flow / free surfaces
    - Dispersed sprays
    - Dispersed bubbles



Spillway model with dispersed and stratified flow

EMP – Multiple Flow Regime Model

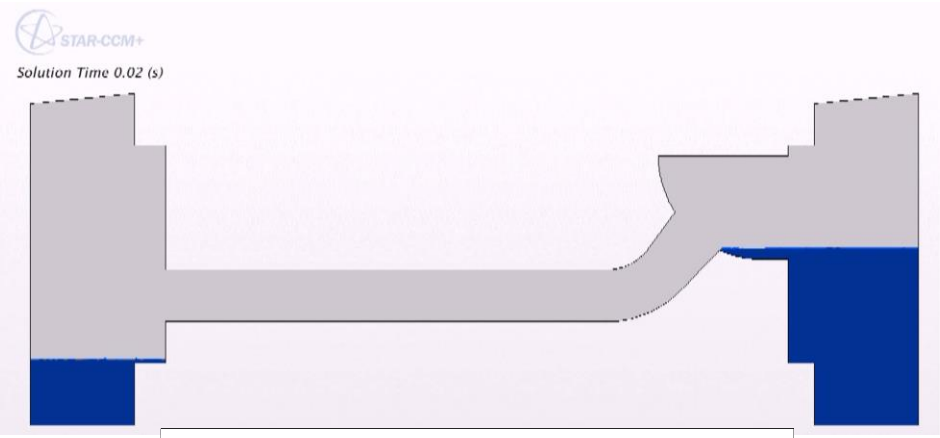


EMP – Multiple Flow Regime Model

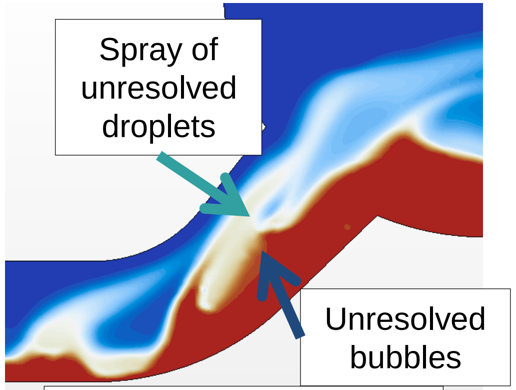
SIEMENS
Ingenuity for life

- In the interface region:
  - Gives sharp free surfaces where there is sufficient mesh similar to VOF when LSI model used
  - Uses a alternative drag model to accurately model mixed regimes where no phase dominates
- Where droplets or bubbles are too small to resolve, they are treated as dispersed phases in a continuous phase
- Bulk boiling and condensation can be modeled at the interface
- Surface tension effects can be included

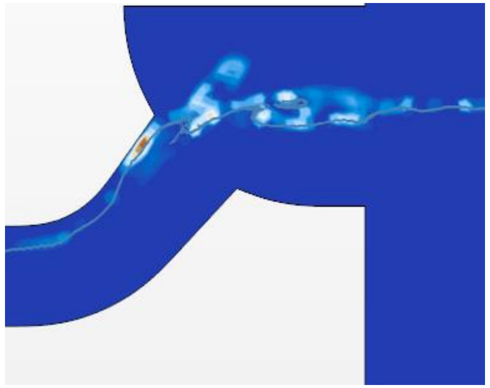
2D Model	LSI	VOF	Diff
Cells	45 340	1 600 000	**35X**



Gas-Liquid Counter-Current flow in PWR
[Deendarlianto et al., NED, 39 (2012)]



Volume Fraction of Water

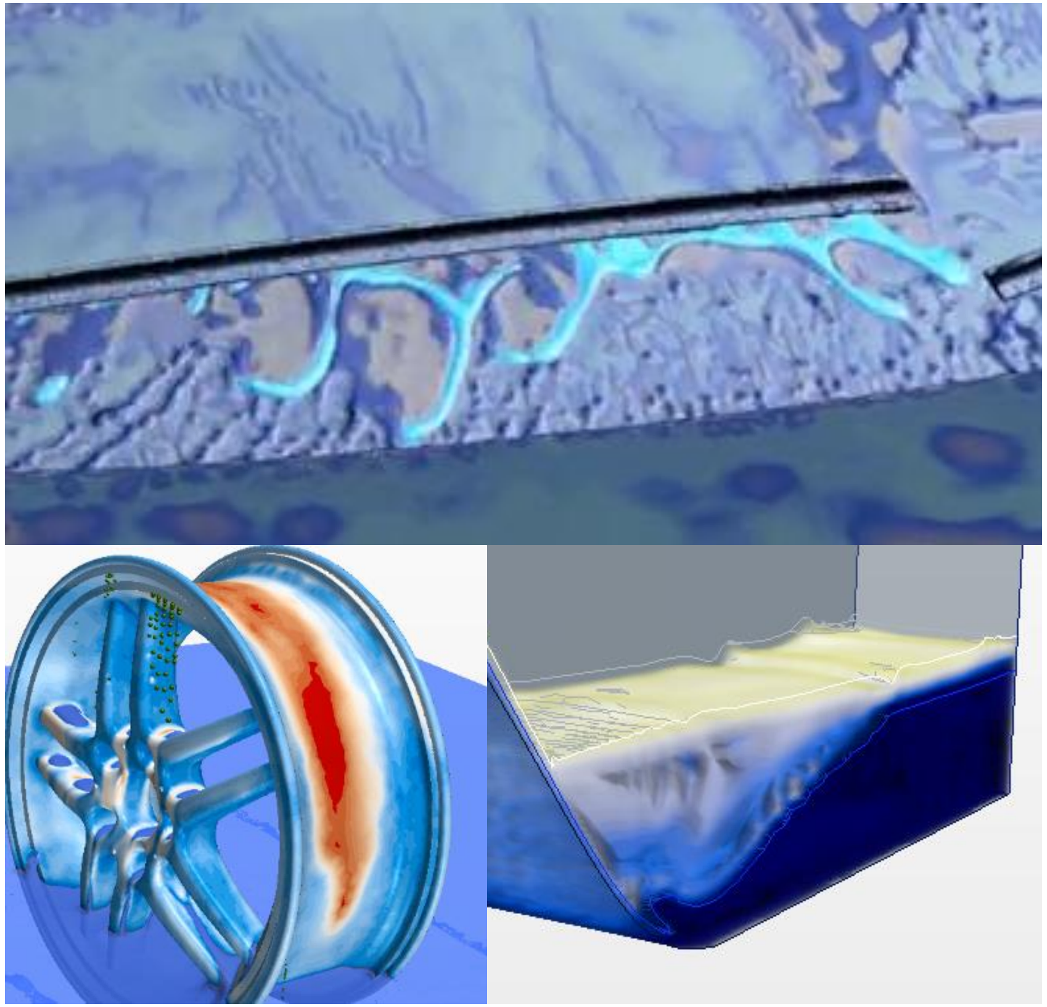


Interface Condensation

Summary

Summary

- Real world multiphase flows are complex with multiple regimes
  - Stratified, dispersed, discrete, films, ……
- Traditional multiphase models typically assume a single regime
  - Leads to inaccuracies when assumptions are violated
- Simcenter STAR-CCM+ provides hybrid multiphase modeling techniques for these real world flows
  - Many models working together through phase interactions
  - A single model to cover multiple regimes in EMP-LSI
- **These methods are being continuously developed**



Hybrid Multiphase Compatibility

SIEMENS
Ingenuity for life

	EMP						
VOF	EMP-Multiple Flow Regime Model EMP and VOF are incompatible, but above model is equivalent	VOF					
MMP			MMP				
DMP				DMP			
LMP					LMP		
DEM						DEM	
Fluid Film							Fluid Film

Spotlight On…

Simcenter STAR-CCM+
Hybrid Multiphase Modeling

Realize Innovation.

SIEMENS
Ingenuity for life