Application of CFD for Analyzing Quenching and Quench System Design

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Purpose

Quenching - one of last (and more dramatic) steps in heat treat process

Poor quench?

- Distortion
- Part to part variation
- Uneven properties within

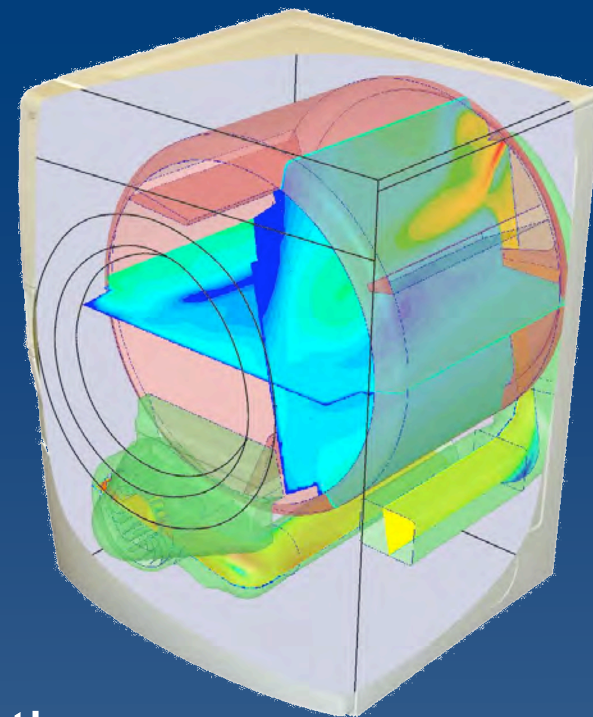
Advanced quenchants can help

CFD can be used to analyze and optimize quench processes

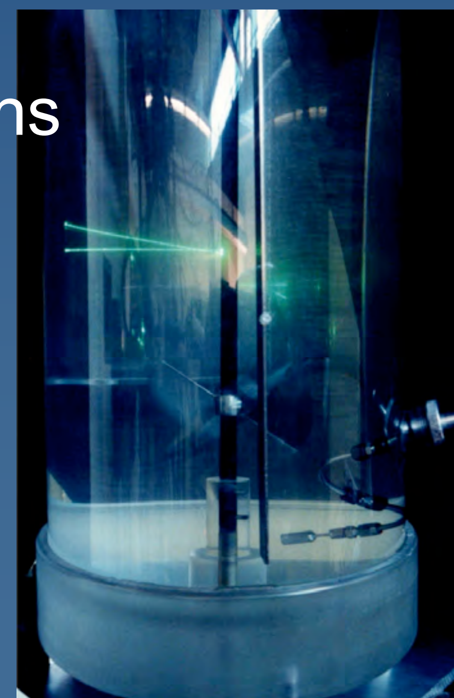
Outline

- Overview of CFD
- Modeling choices and guidelines
- Quenching fluid flow challenges
- Examples of quench simulation results
- A non-metals example

Why Use CFD?



- Complements testing activities
- More data than testing
- Provides insight into process
- Allows for “what-if” studies
- Less expensive than cut-and-try iterations
- Provides confidence in making modifications



What can CFD do (easily)?

- Predict velocity patterns
- Predict relative heat transfer rates
- Assess the effects of operational or physical changes

What can it *not* do (easily)?

- Assess maintenance issues
- Boiling heat transfer
- Absolute heat transfer rates
- Transition flows, separation
- Transient phenomena (e.g., loading)

Overview of CFD

- Fluid flow governed by Navier-Stokes equations
- Cannot be solved in their full form
  - ➢ Drop less important terms
  - ➢ Divide domain into smaller volumes (cells)
  - ➢ Make linear approximation between cells
  - ➢ Use turbulence model for sub-grid fluid motion
  - ➢ Use ‘wall treatment’ for steep gradients near surfaces

$$\frac{\partial(\varrho u)}{\partial x} + \frac{\partial(\varrho v)}{\partial y} + \frac{\partial(\varrho w)}{\partial z} = 0$$

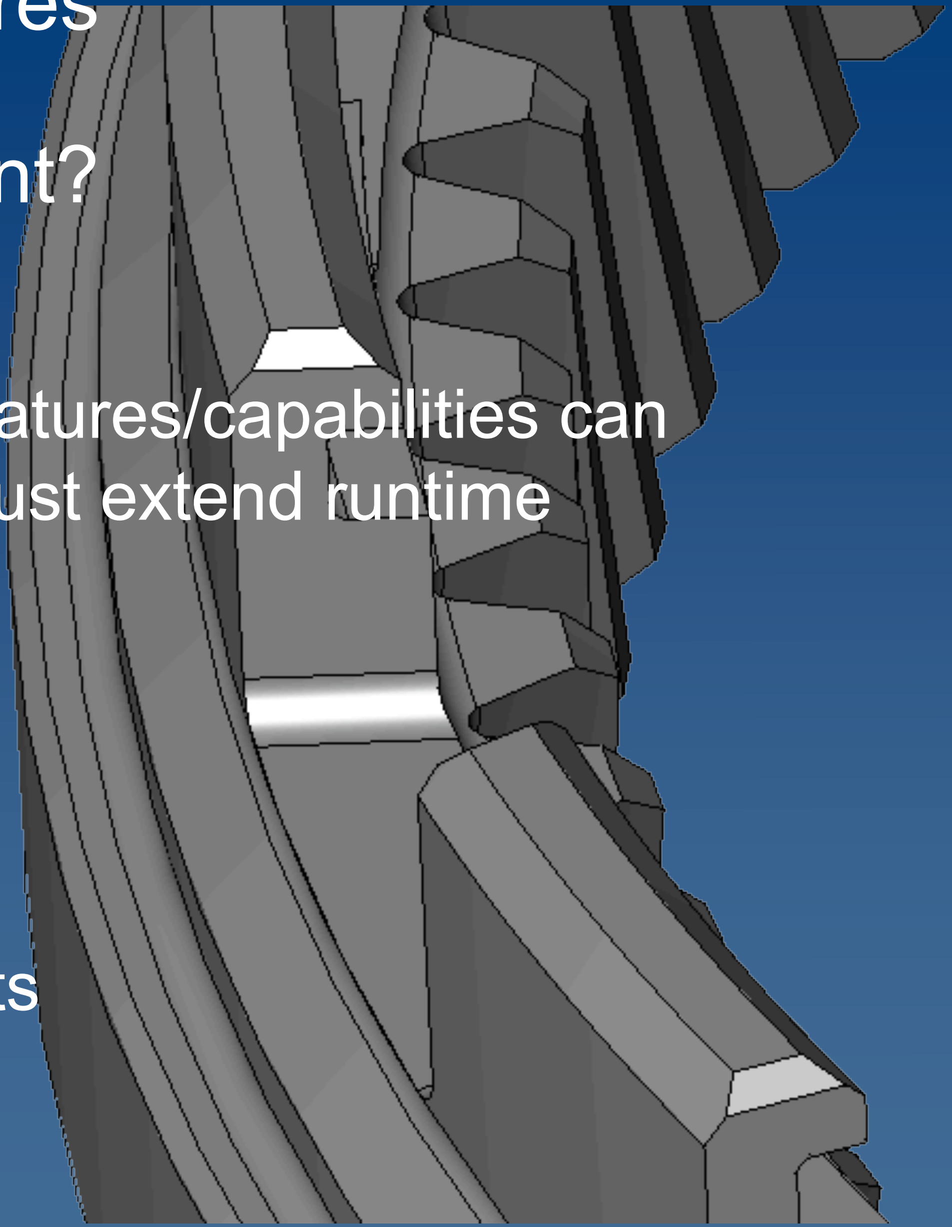
$$\left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z}\right) = -\frac{\partial p}{\partial x} + \varrho\, g_x\, \beta\, \theta + \mu \left[\Lambda^2 u + \frac{1}{3} \frac{\partial}{\partial x} \operatorname{div} w\right]$$

Turbulence Models

Several different methods of modeling sub-grid scale motion (turbulence) are available

- k-ε model (several variations) [2 eqns.]
- k-ω model (several variations) [2 eqns.]
- Reynolds Stress models [7 eqns.]
- Large Eddy Simulation (fine mesh, transient)
- Direct Numerical Simulation (no model, very fine mesh, transient)

Choice of Model Features
or
What is Really Important?



Adding additional model features/capabilities can enhance model results or just extend runtime

- Free surface flow
- Impeller driven flow
- Support structures
- Small features and offsets
- Boiling

Gridding (1 of 4)

Computational domain is subdivided and approximated by a (large) number of computational cells. Typical building blocks are:

Hexahedron (hex) - best quality, if not skewed

Tetrahedron (tet) - lower quality, but good for irregular domains

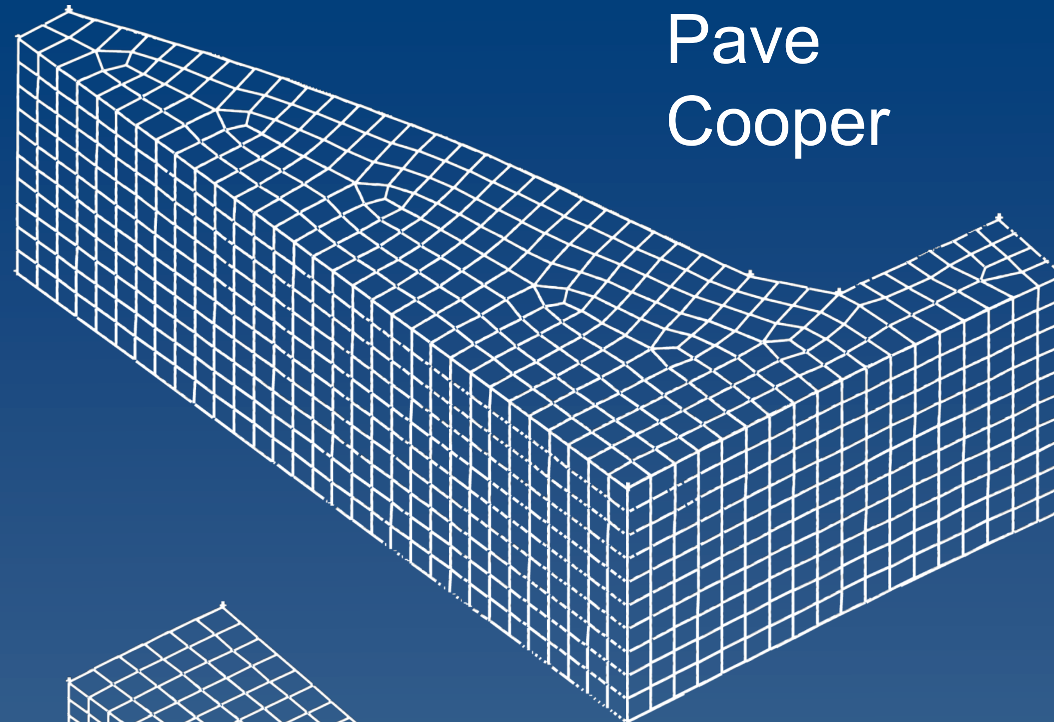
Prism - better than tet, if flow aligned with long direction

Pyramid - usually used to transition from hex to tet

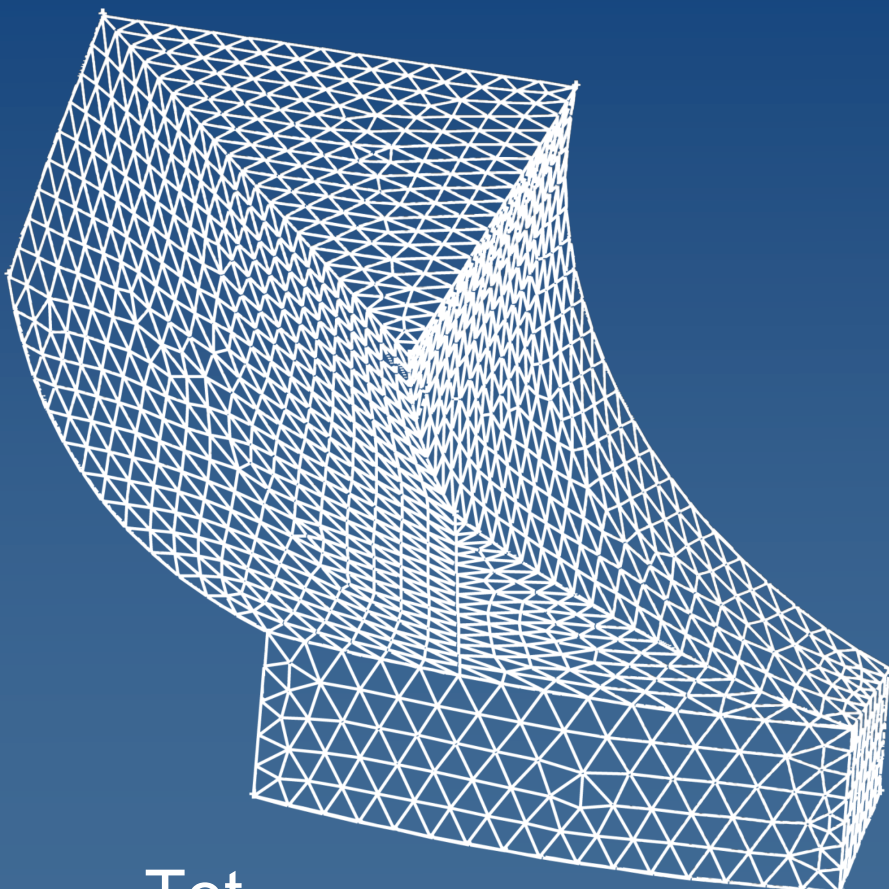
Polyhedron (poly) - good quality, good for irregular geometries

Gridding (2 of 4)

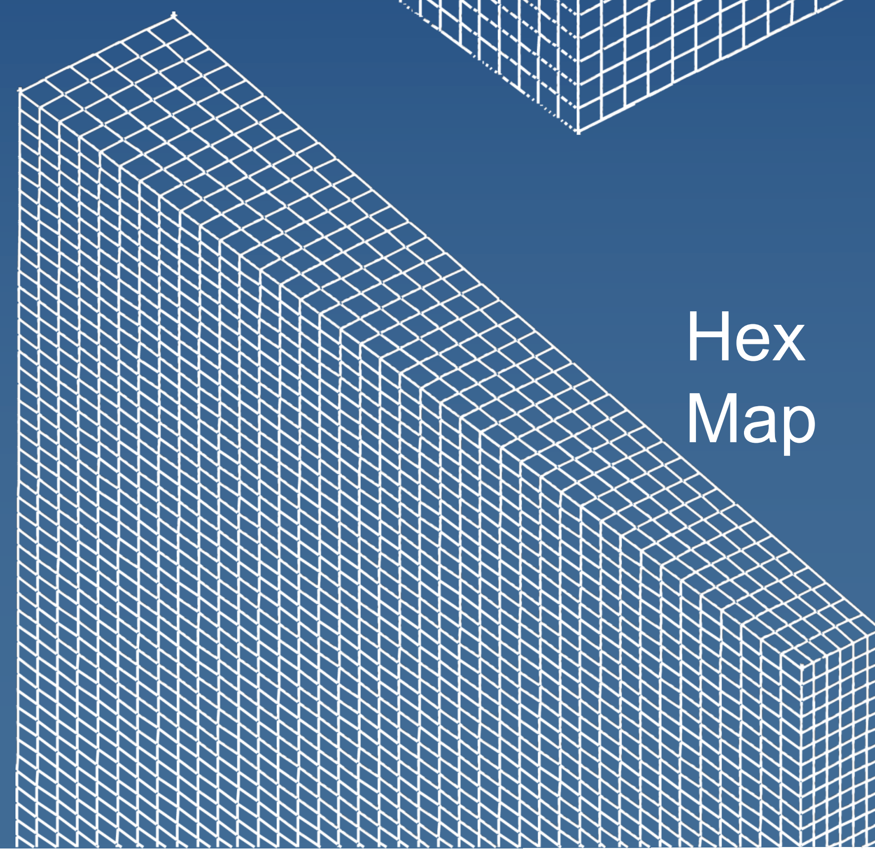
Example grid volumes



Pave
Cooper



Tet
Unstructured

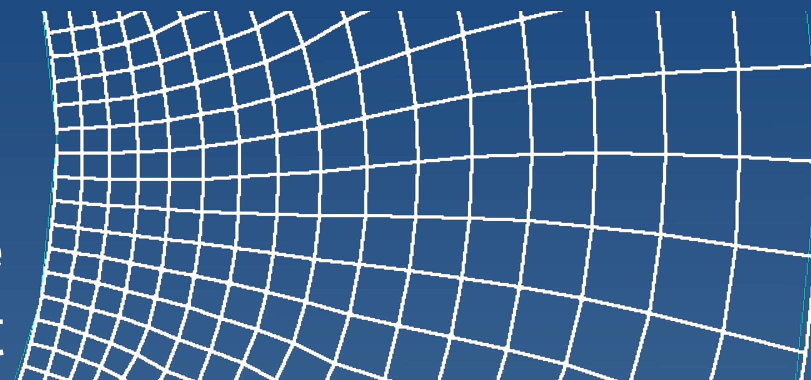


Hex
Map

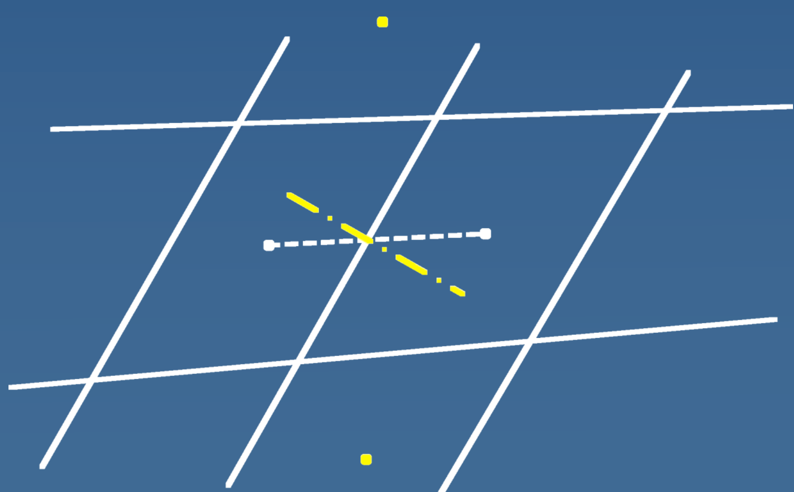
Gridding (3 of 4)

Poor grid quality can skew results and hamper or prevent convergence

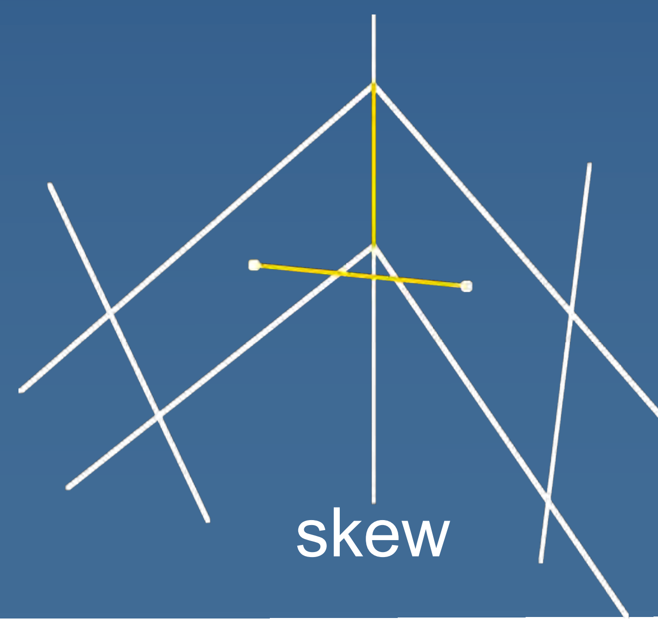
cell aspect ratio



cell size gradient



non-orthongal

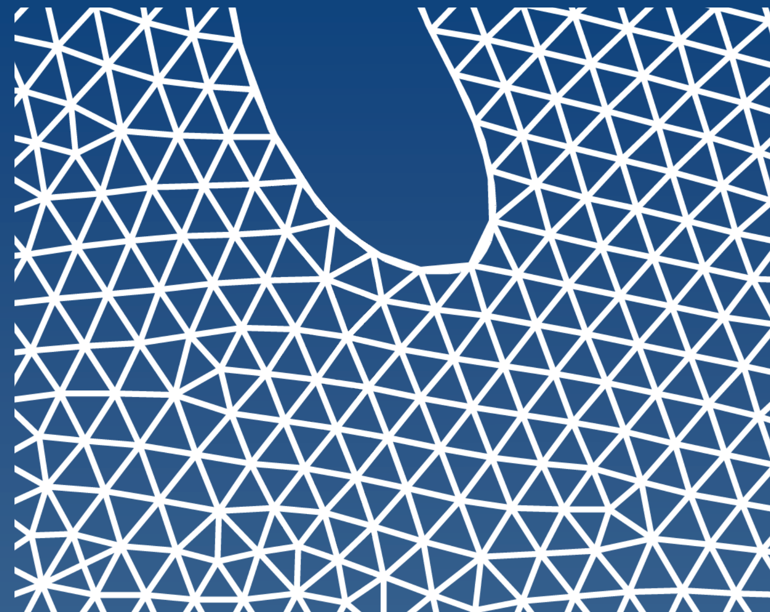


skew

Gridding (4 of 4)

Special care needed near hard boundaries

Quad
Pave



Tri
Pave

Quad Pave
w/Boundary
Layer

6-10 cells
minimum
needed for
any flow
passage

Typical CFD Quench Study Goals

Easy

- Good flow distribution
- Treat all parts about the same
- Determine which of several options is better

Harder

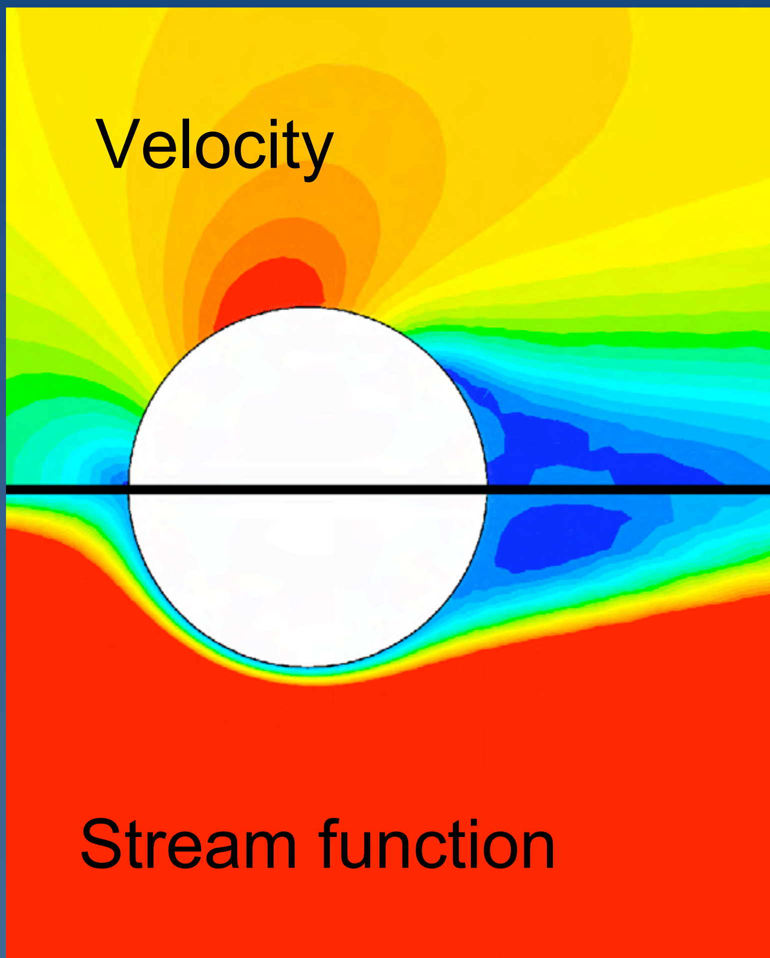
- Provide uniform flow/heat transfer around part

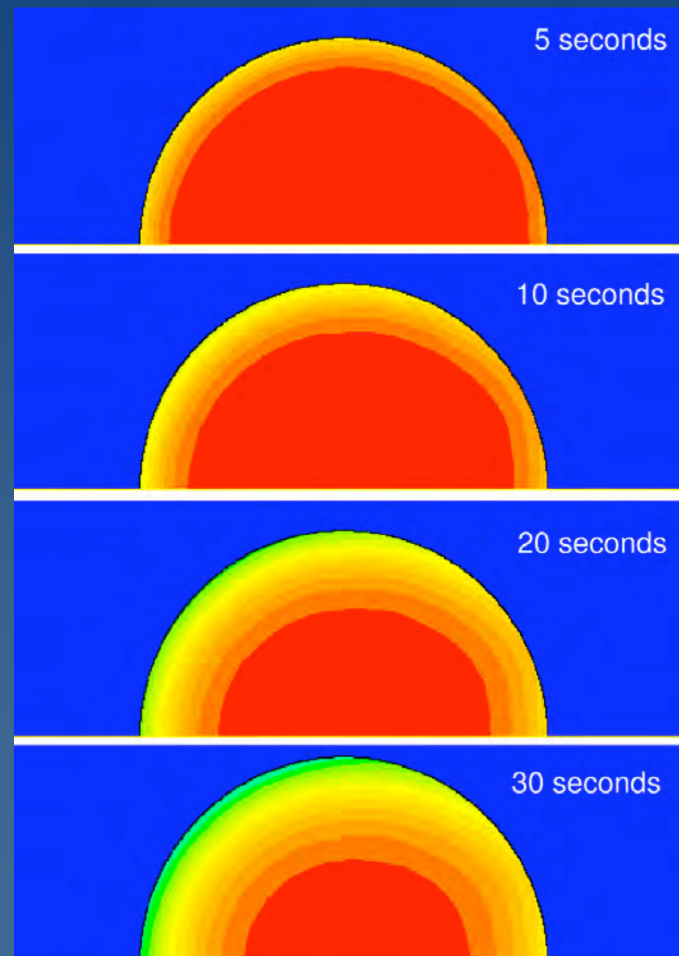
Very hard

- Predict absolute levels of heat flux rates

Quenching Challenges

Heat transfer is reduced on back side of parts





Gas quenching of a bar in cross-flow

Quenching Challenges

Racking and Fixturing Obstructs Flow

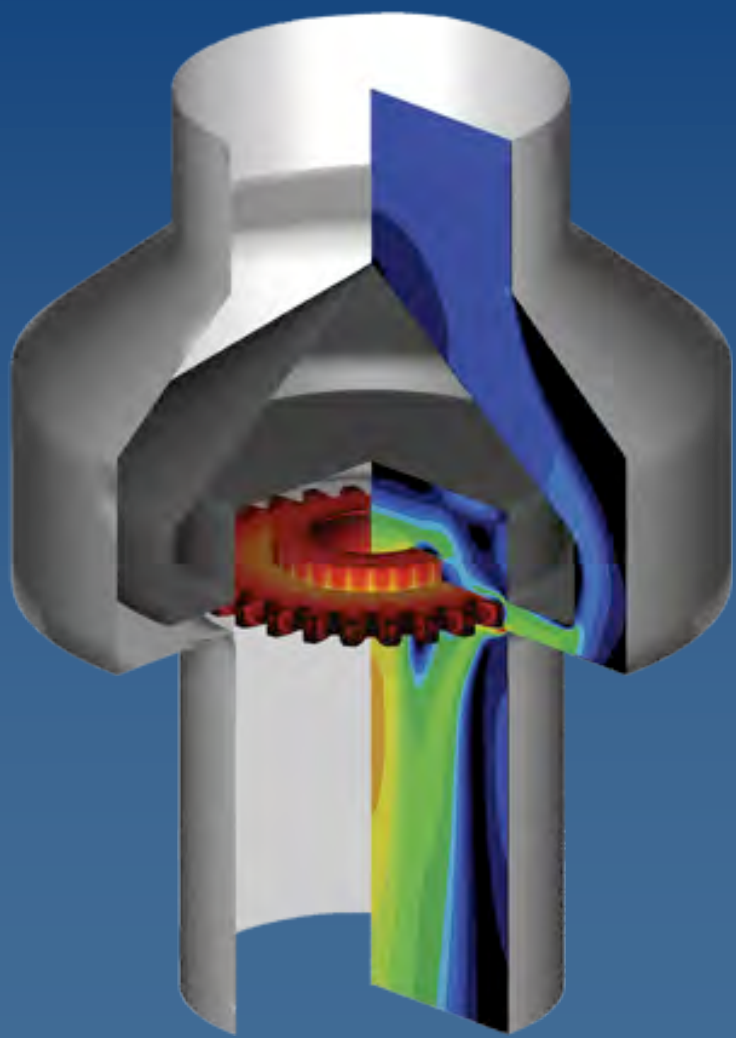
Parts exposed to incoming flow will have higher heat transfer rates

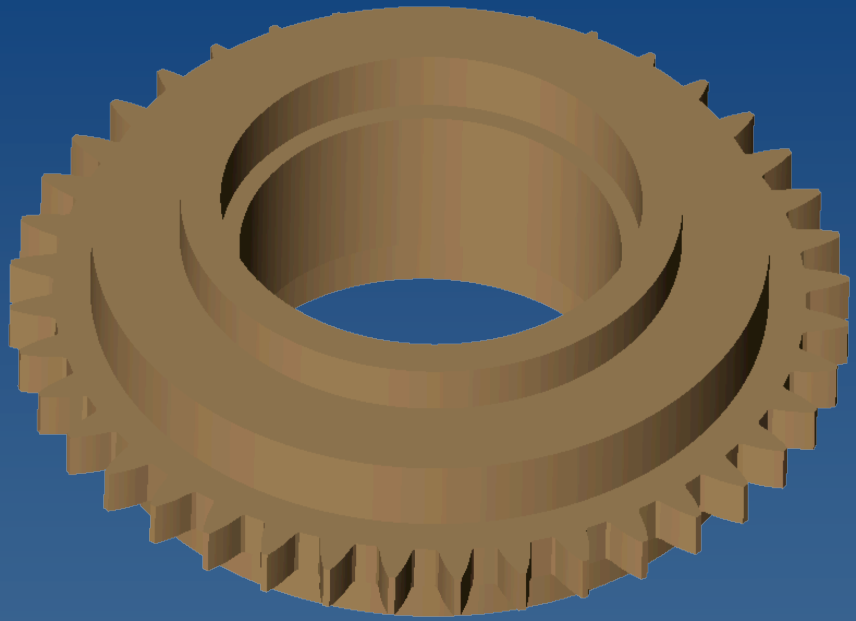
Case Studies:

- Intensive Quenching of Single Gear
- Quench Tank with Draft Tubes
- A Non-Metals Example

Case Study - Intensive Quenching

Geometry/Quench Fixture





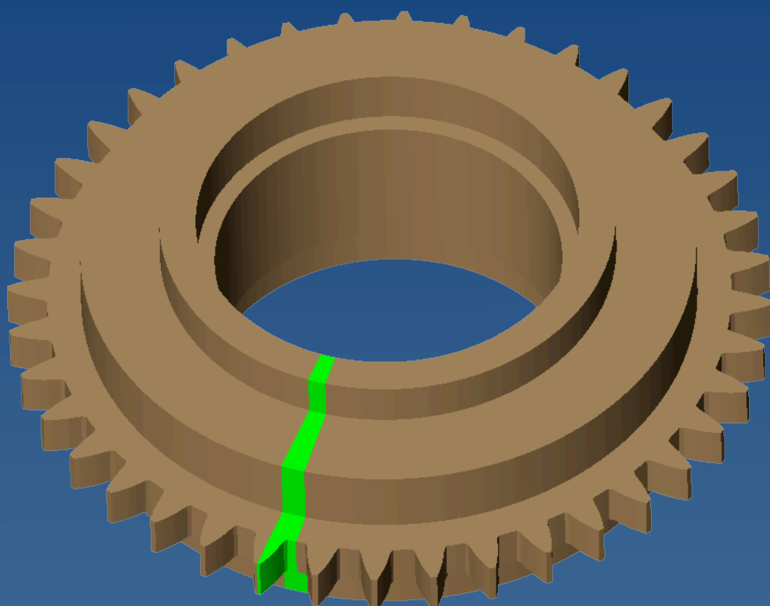
4” diameter spur gear

40 teeth

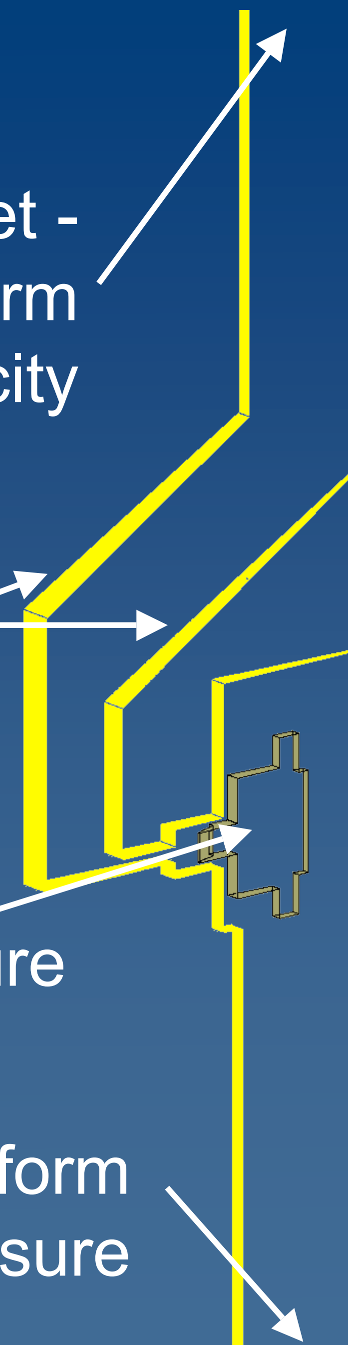
Quenched in plain water at 330 GPM

Case Study - Intensive Quenching

Domain/Boundary Conditions



Symmetry reduces domain to 4.5° wedge



Case Study - Intensive Quenching

Grid Details

Subdivide domain to allow for meshing with high quality cells

Gold - hexmap

395,638 cells

max skewness - 0.025

Green - quadpave & tripave cooper

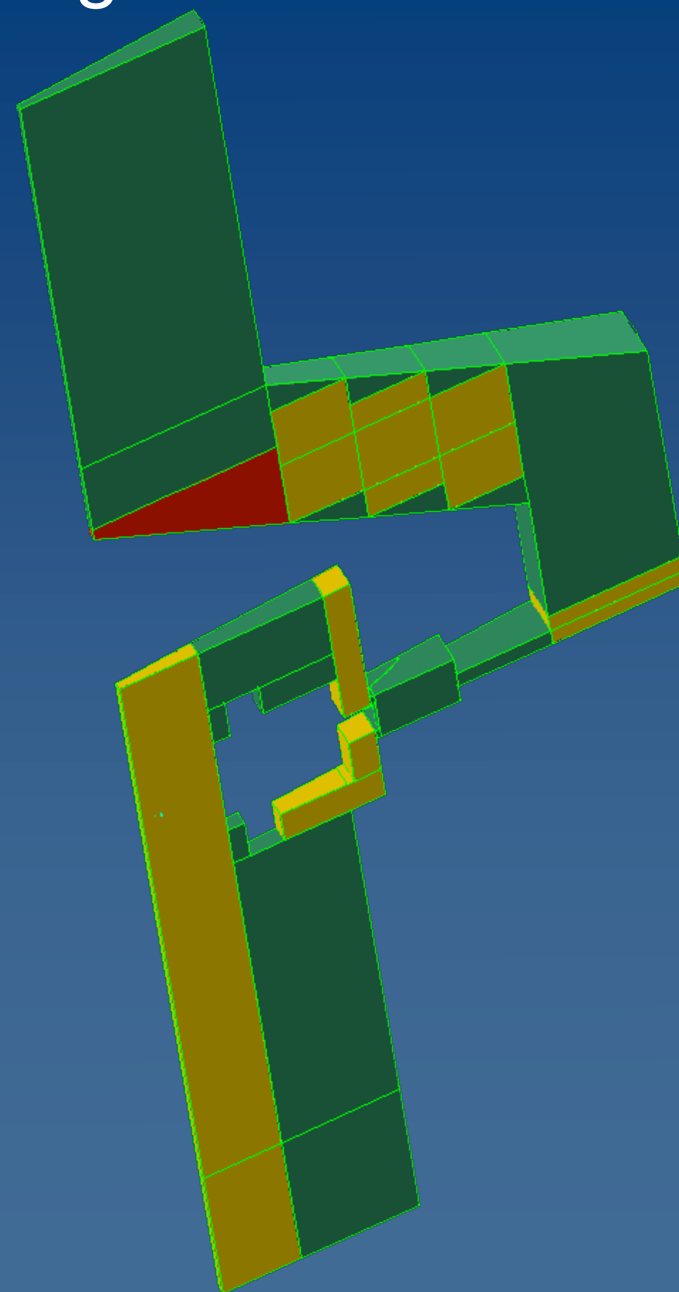
1,047,121 cells

max skewness - 0.77

Red - tet unstructured

123,567 cells

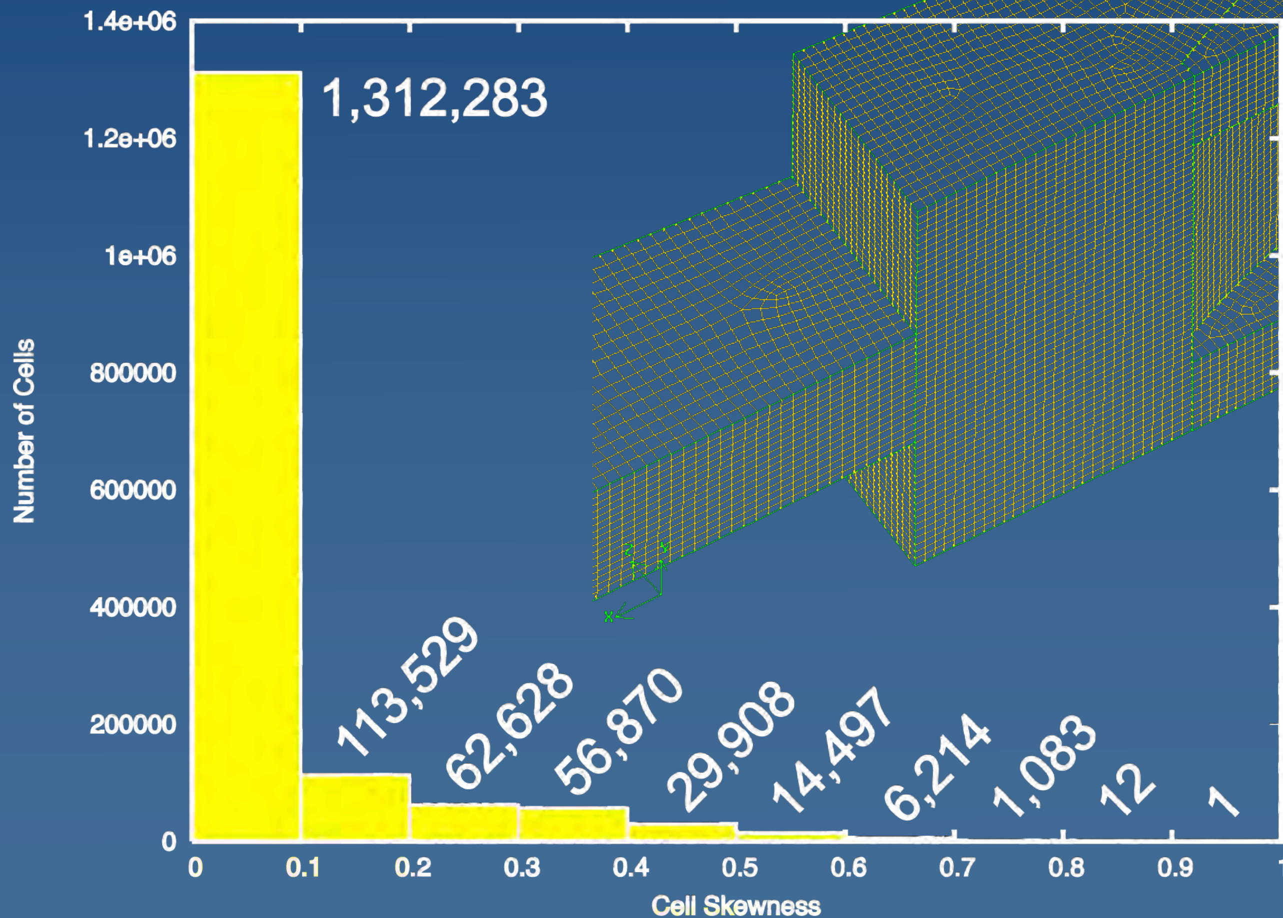
max skewness - 0.90

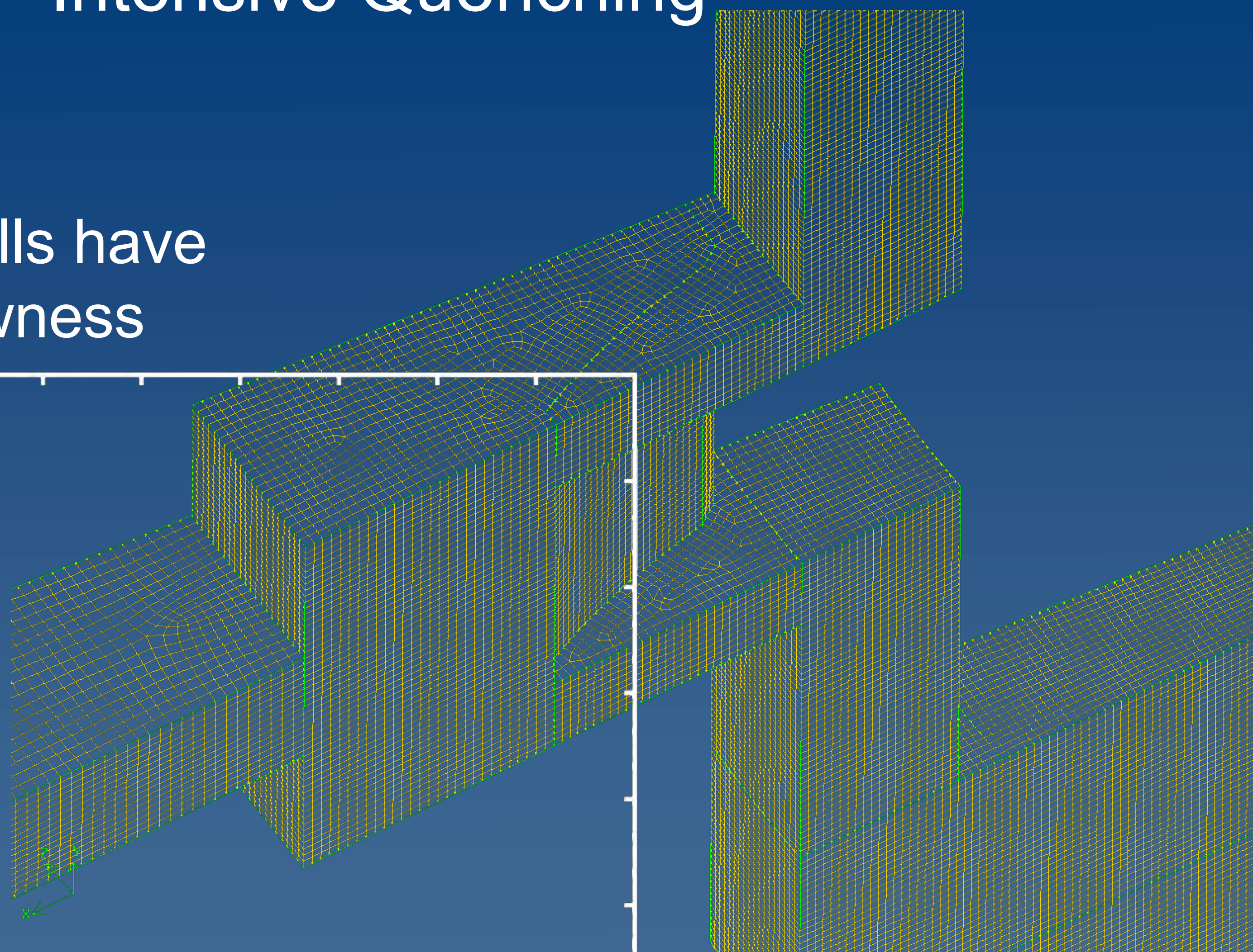


Case Study - Intensive Quenching

Grid Details

Majority of cells have very low skewness





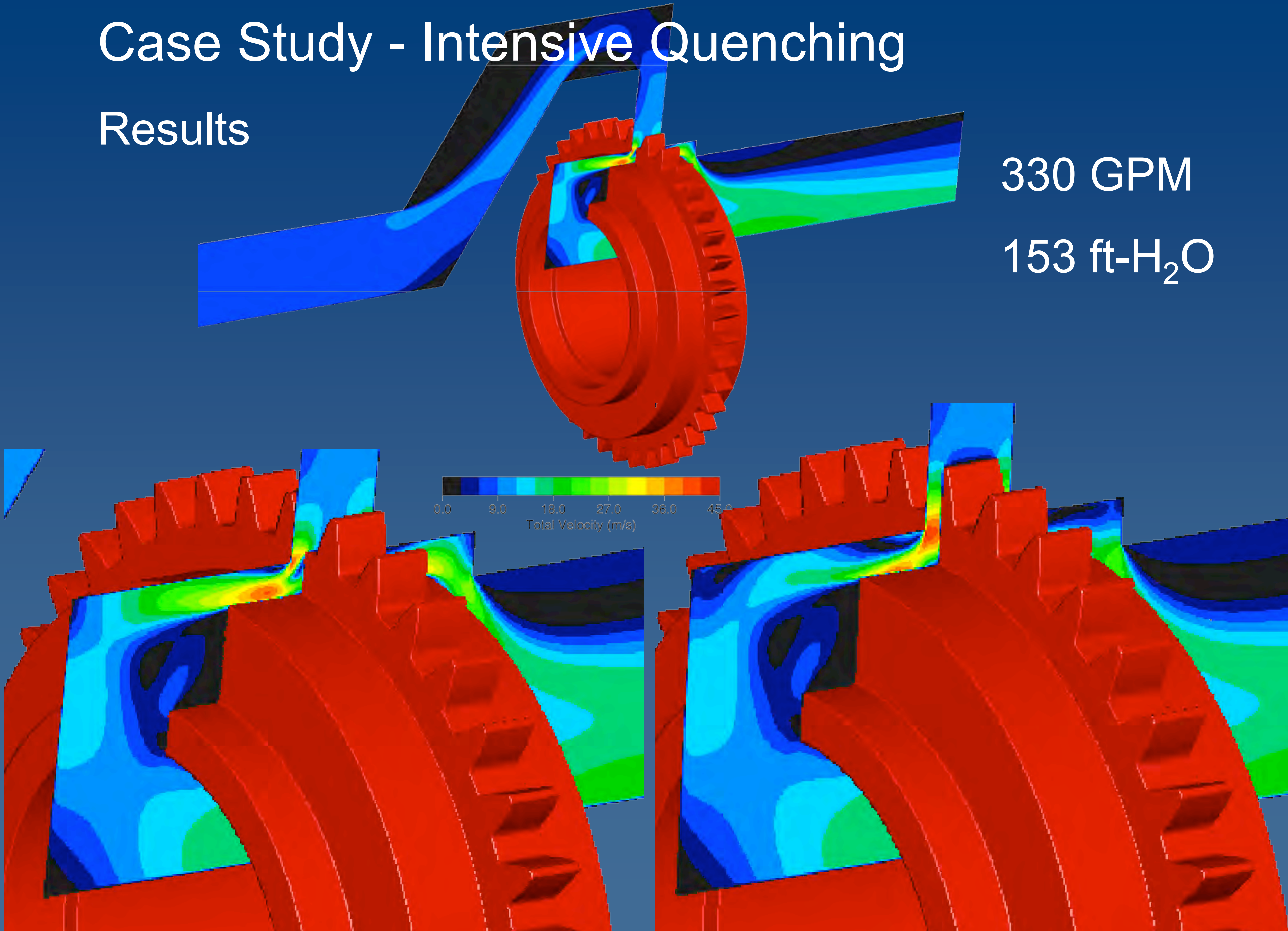
Cell size near gear = 0.2 mm

Case Study - Intensive Quenching

Results

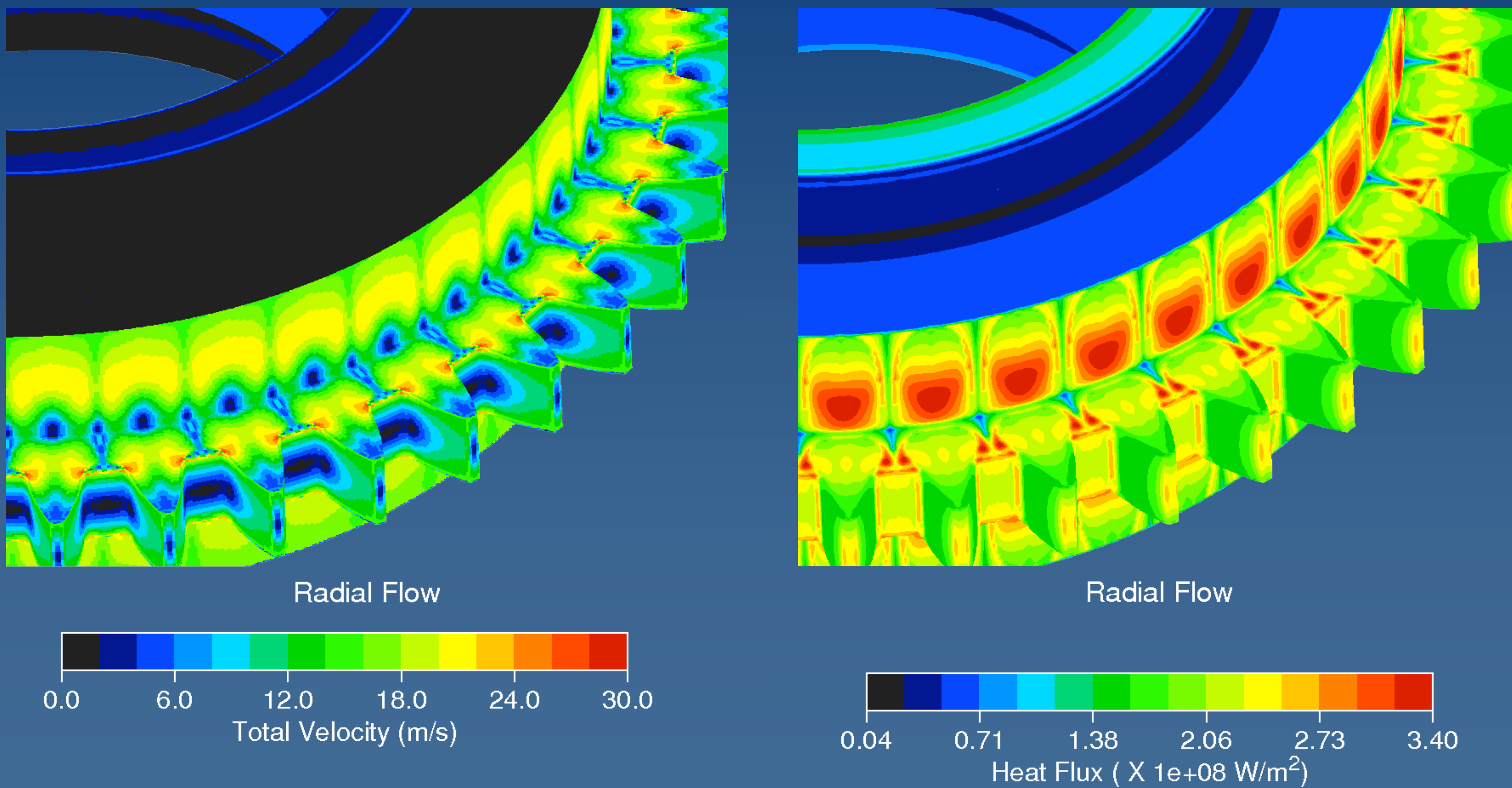
330 GPM

153 ft-H_2O



Case Study - Intensive Quenching

Results



Case Study - Quench Tank

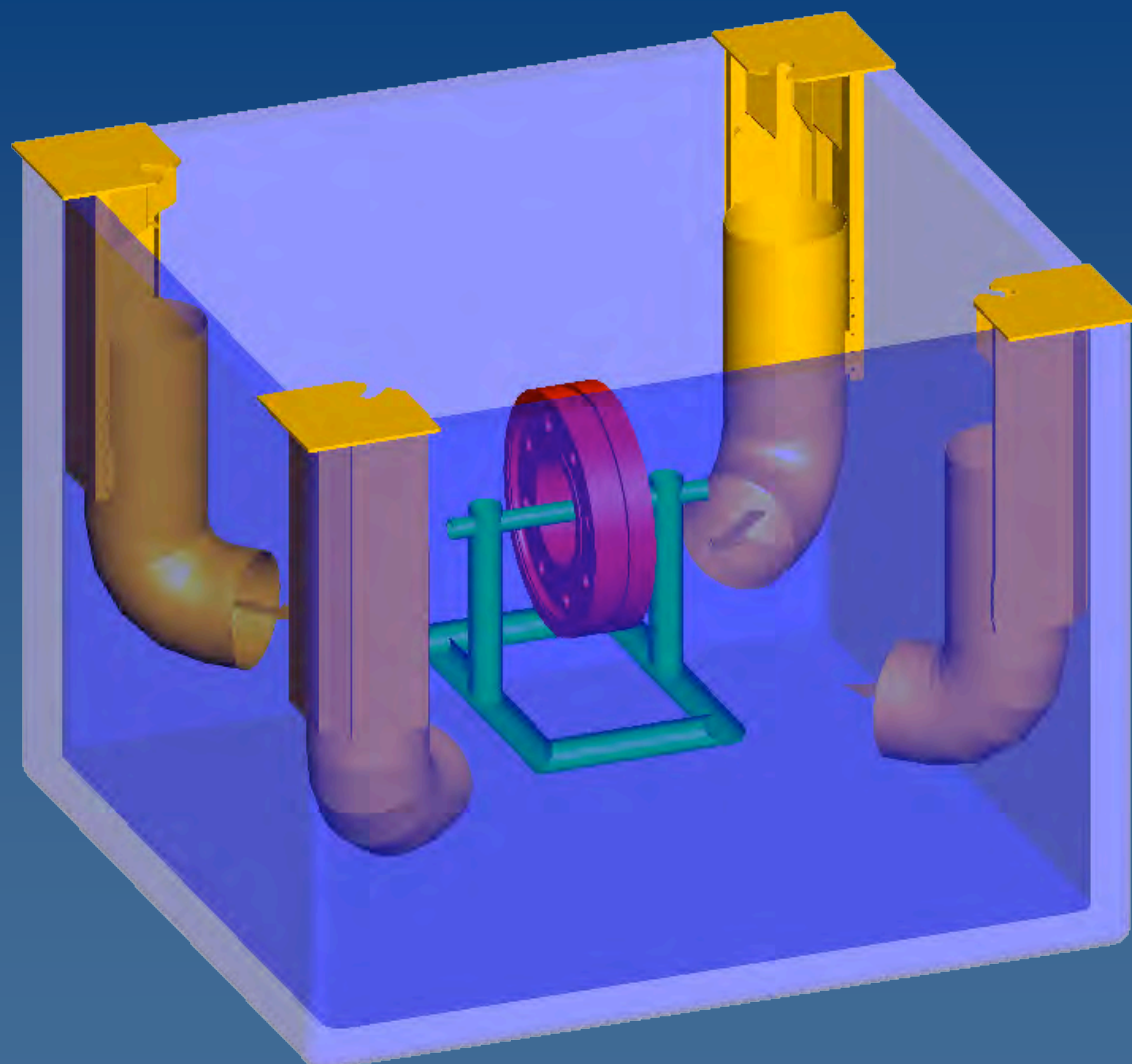
Large gear quench tank

~30,000 gallons

4 Draft tubes with propeller fans

20,000 GPM each

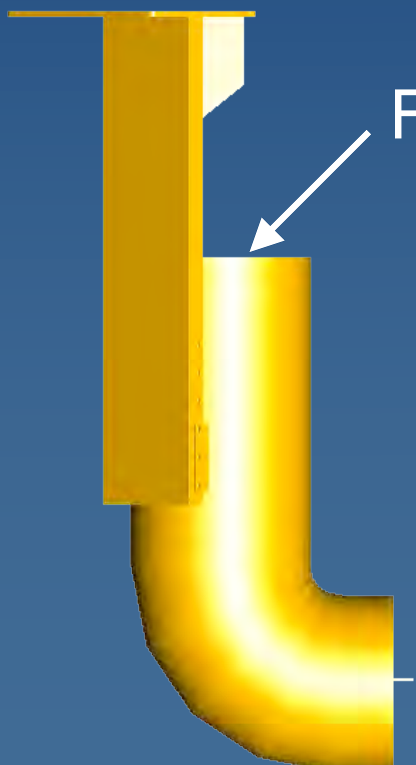
Oil or water/polymer quench



Case Study - Quench Tank

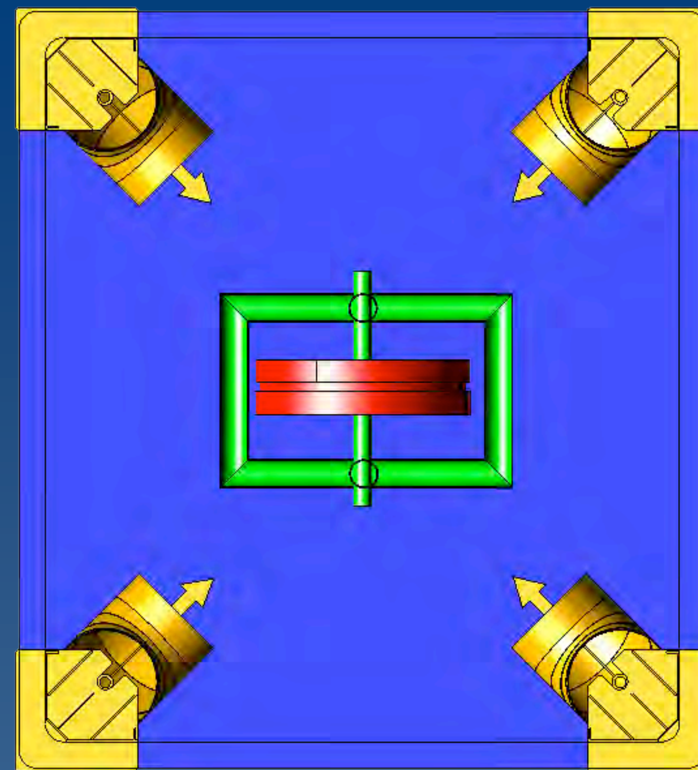
Domain/Boundary Conditions

Liquid surface treated as symmetry boundary



Flow inlet/exit

Sharp bend in draft tube may lead to angled/ non-uniform flow. Draft tubes included.



Entire tank simulated to allow for non-symmetric flow

Propeller fans omitted

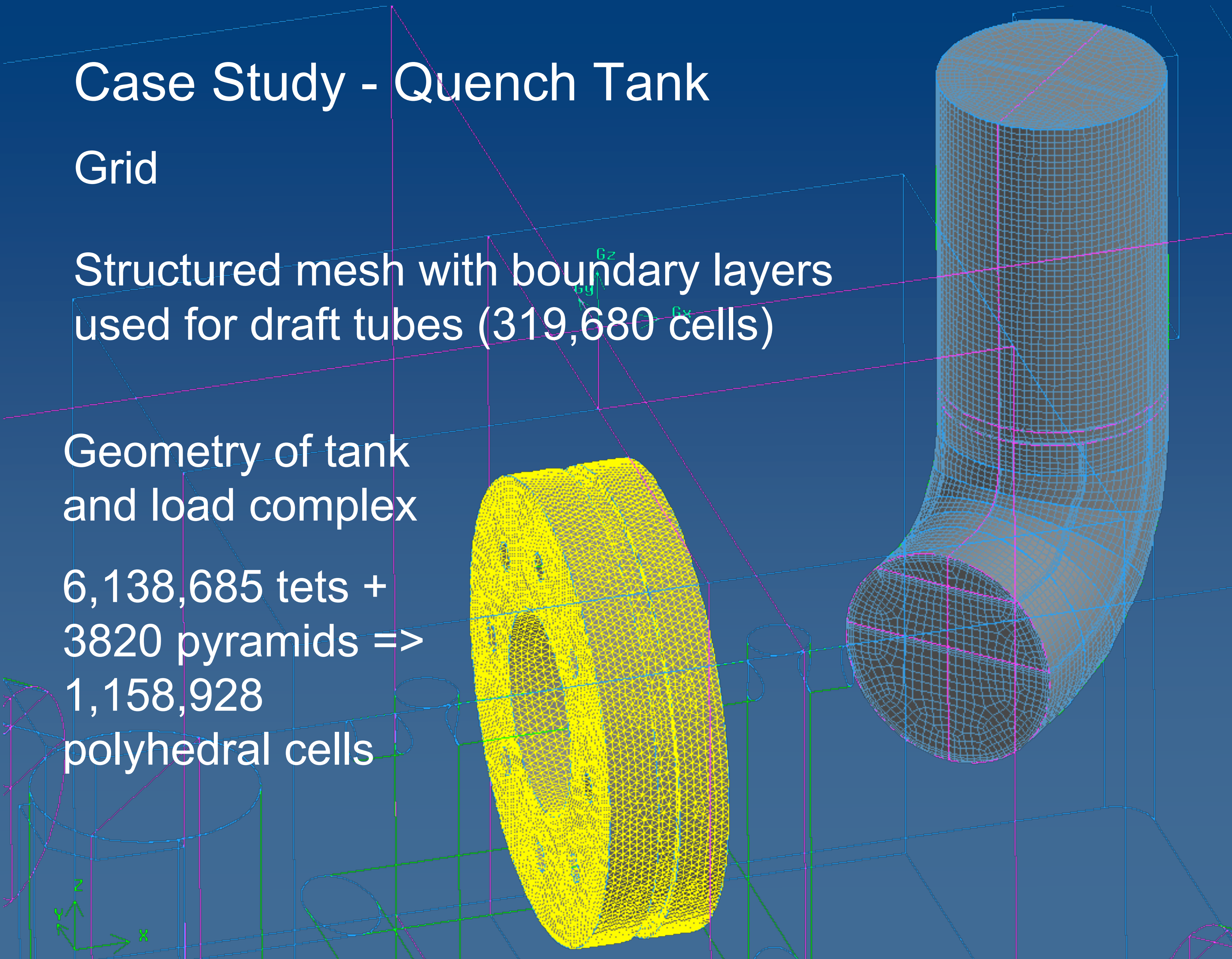
Case Study - Quench Tank

Grid

Structured mesh with boundary layers used for draft tubes (319,680 cells)

Geometry of tank and load complex

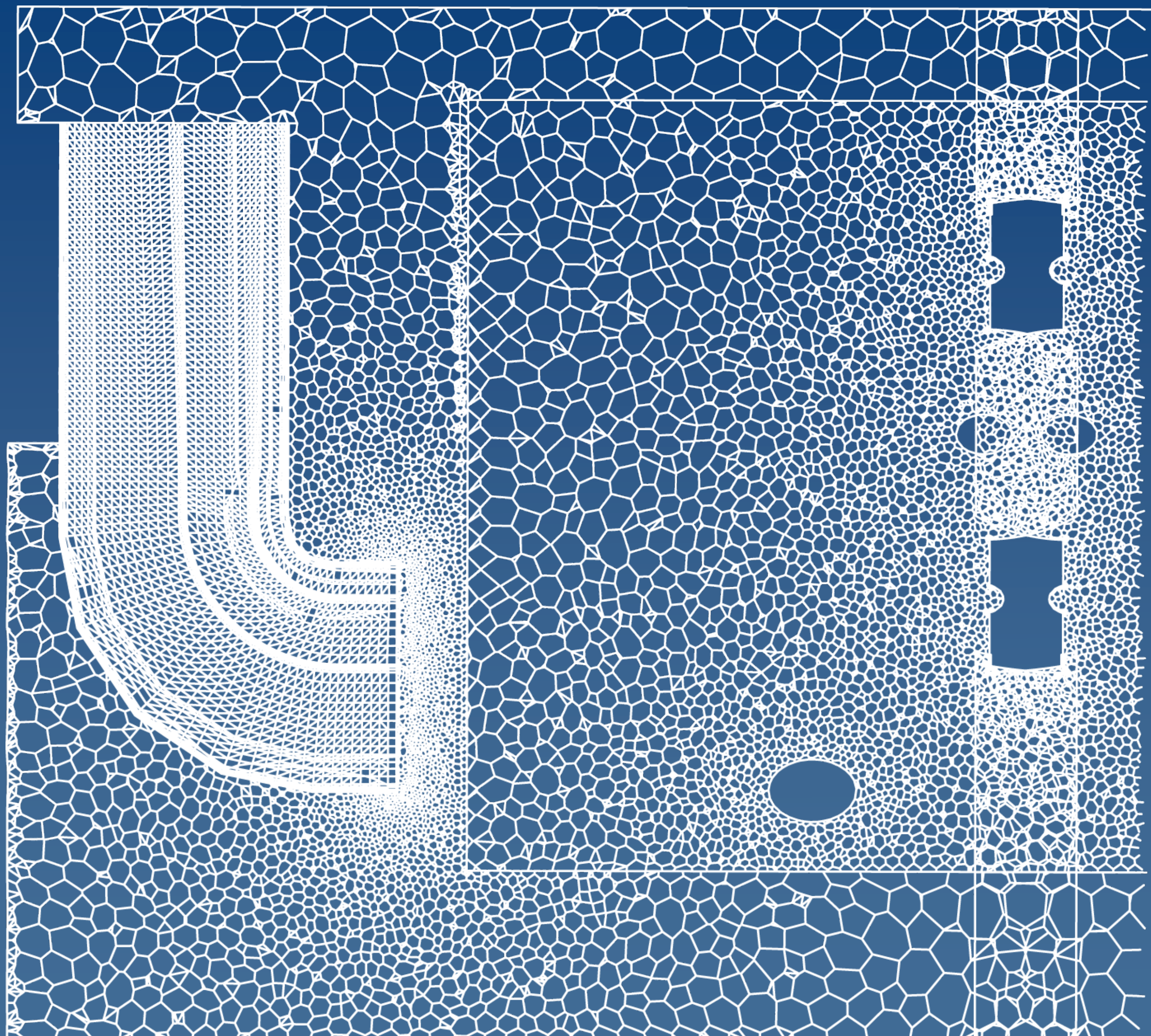
6,138,685 tets + 3820 pyramids => 1,158,928 polyhedral cells



Case Study - Quench Tank

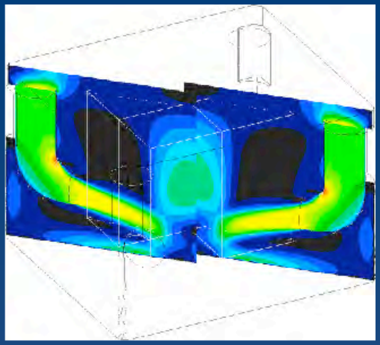
Grid

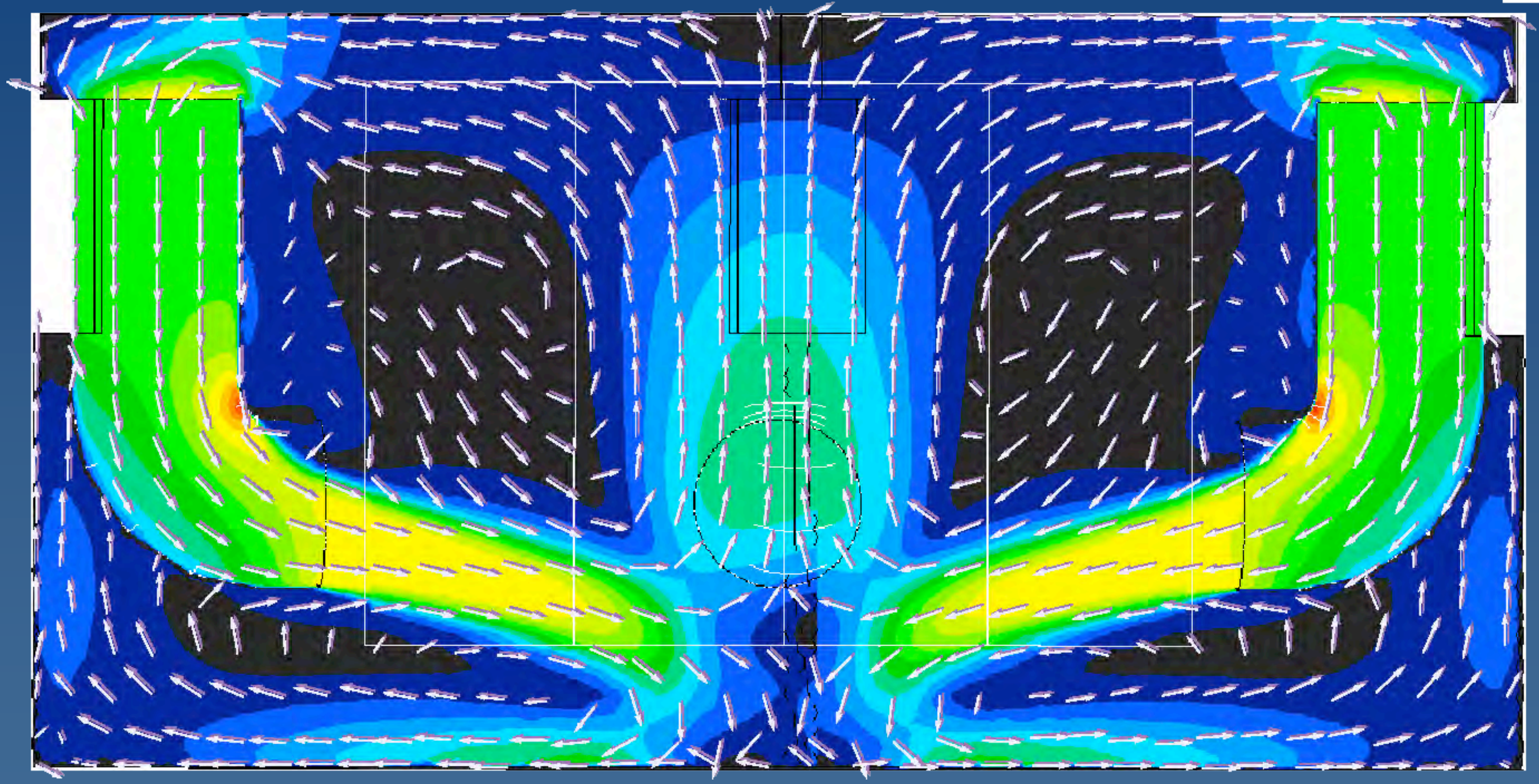
Section through model showing structured and polyhedral grid topology



Case Study - Quench Tank

Results - Base model (no load)

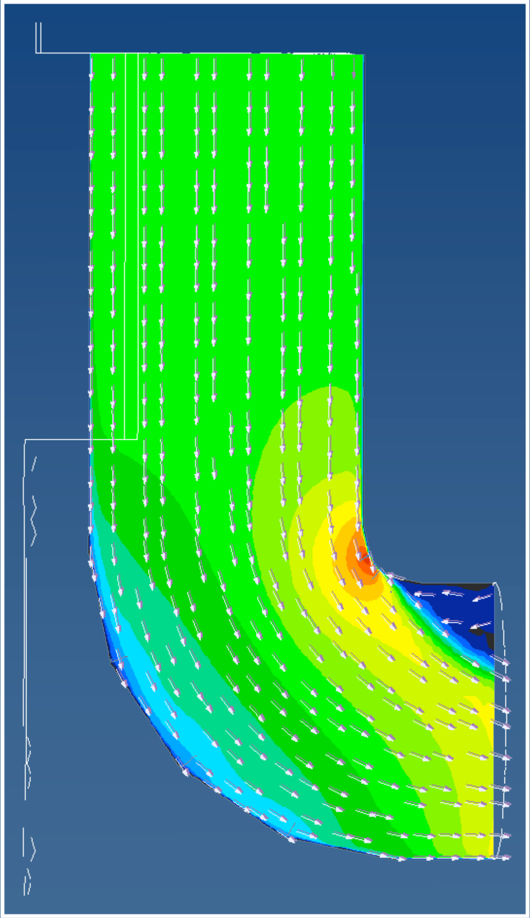




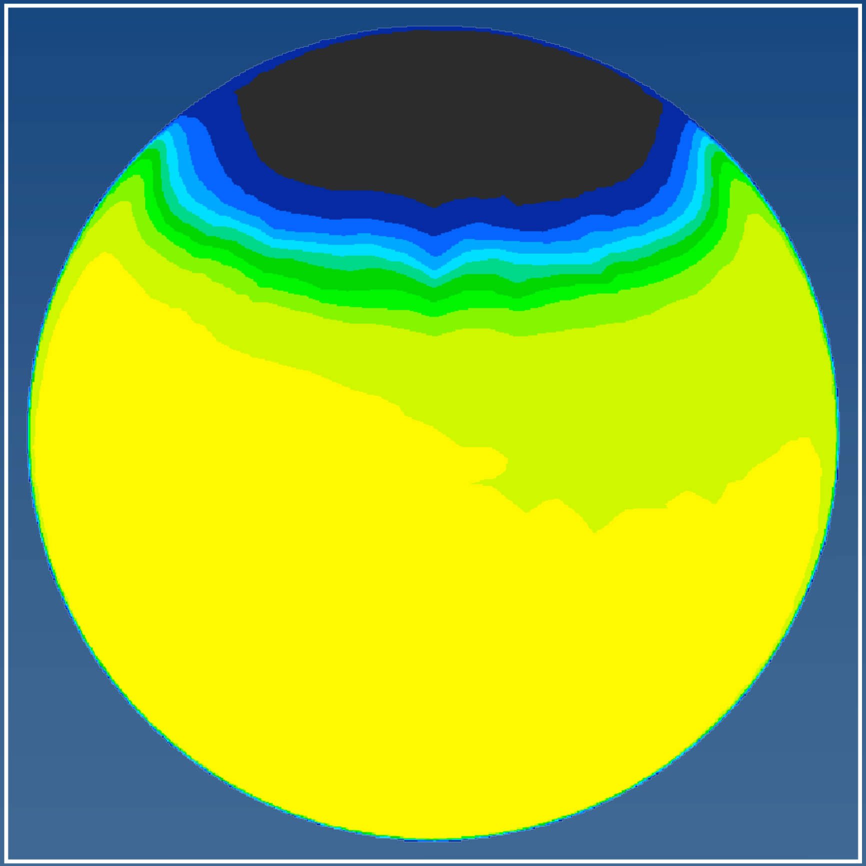
Section through draft tubes shows flow leaving at a downward angle

Case Study - Quench Tank

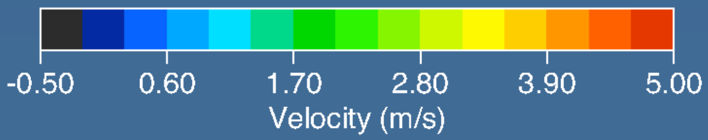
Results - Base model draft tube



Side View: Draft Tube Centerline

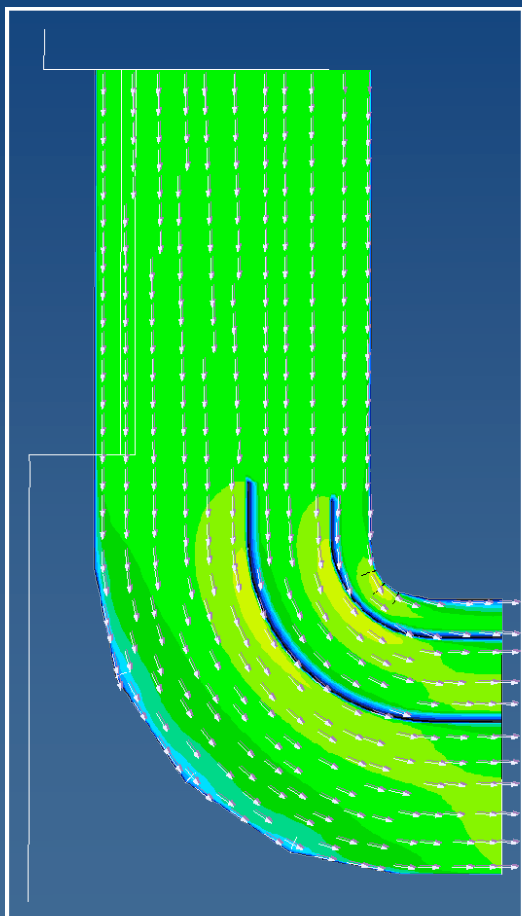


End View: Flow out of page

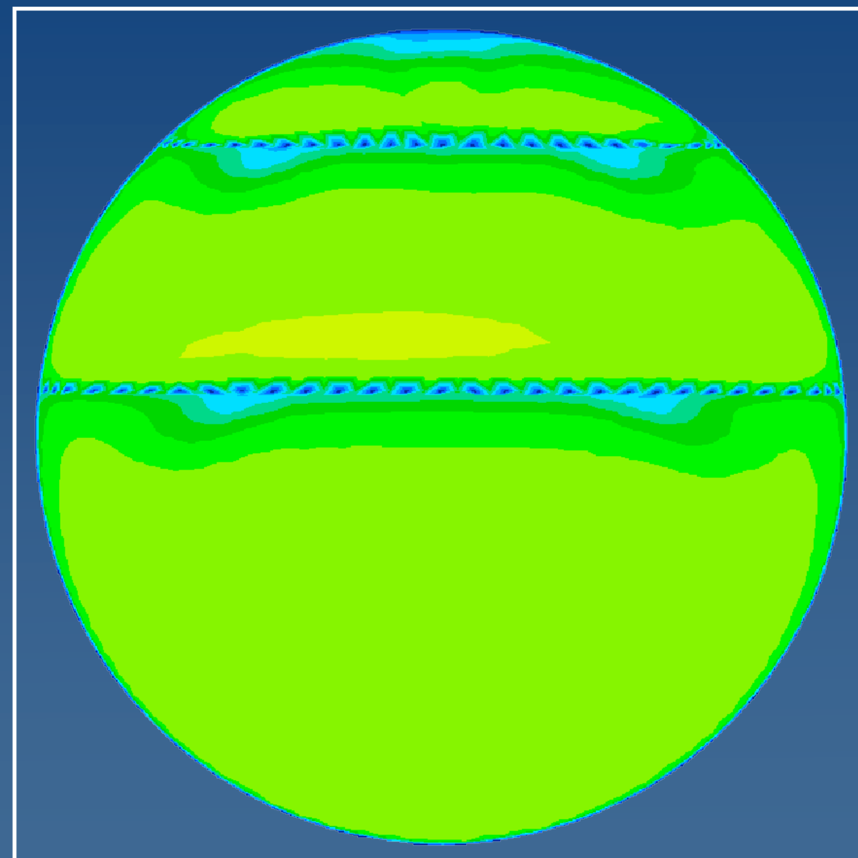


Case Study - Quench Tank

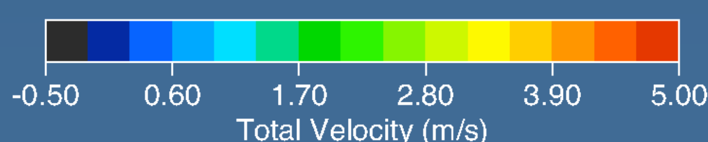
Results - effect of draft tube turning vanes



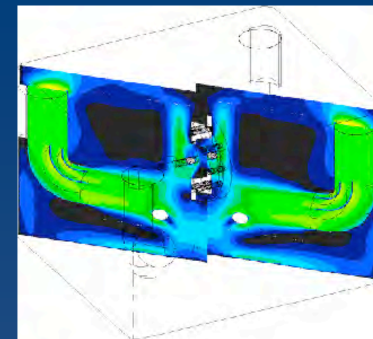
Side View: Draft Tube Centerline



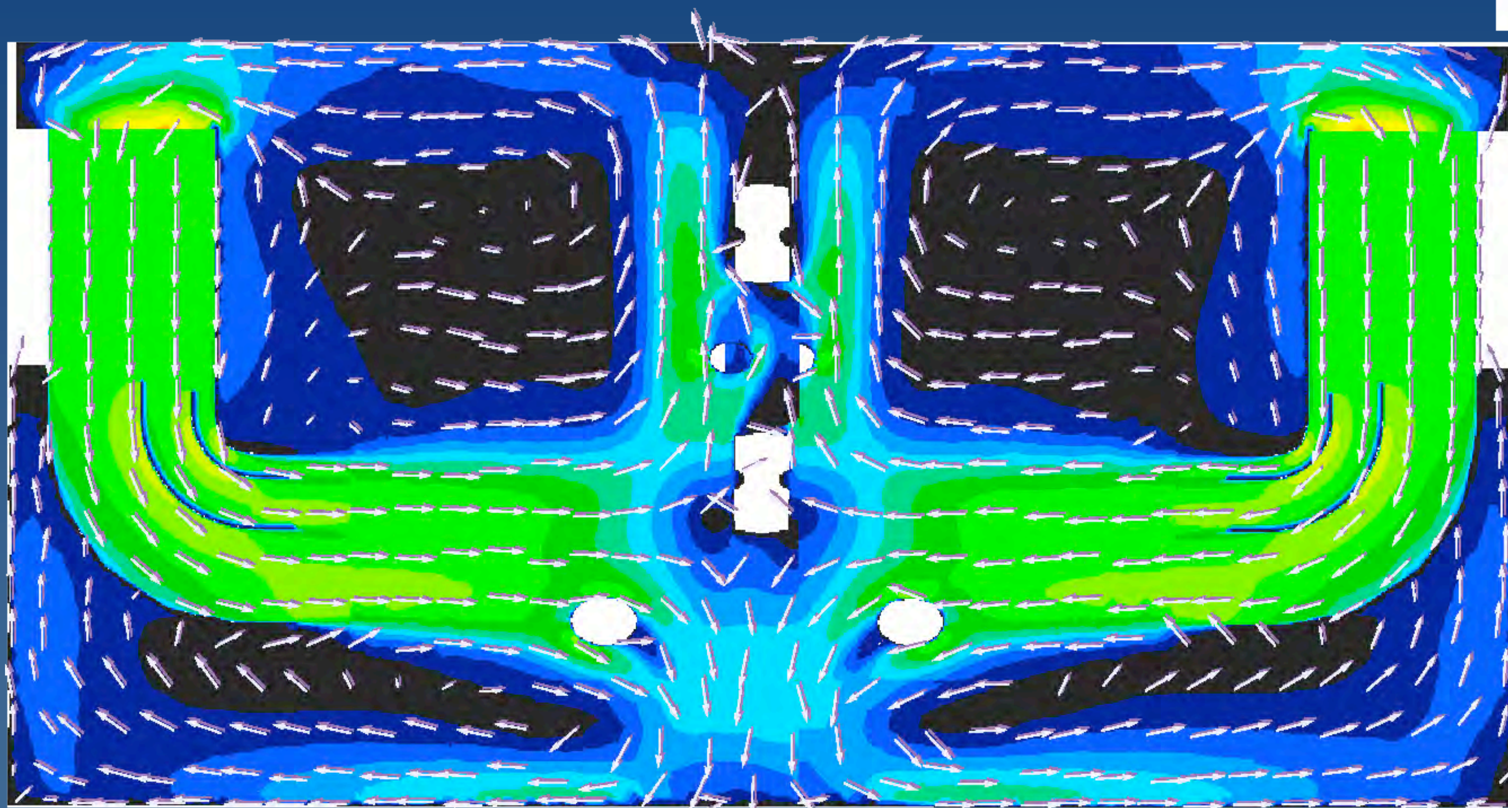
End View: Flow out of page



Case Study - Quench Tank



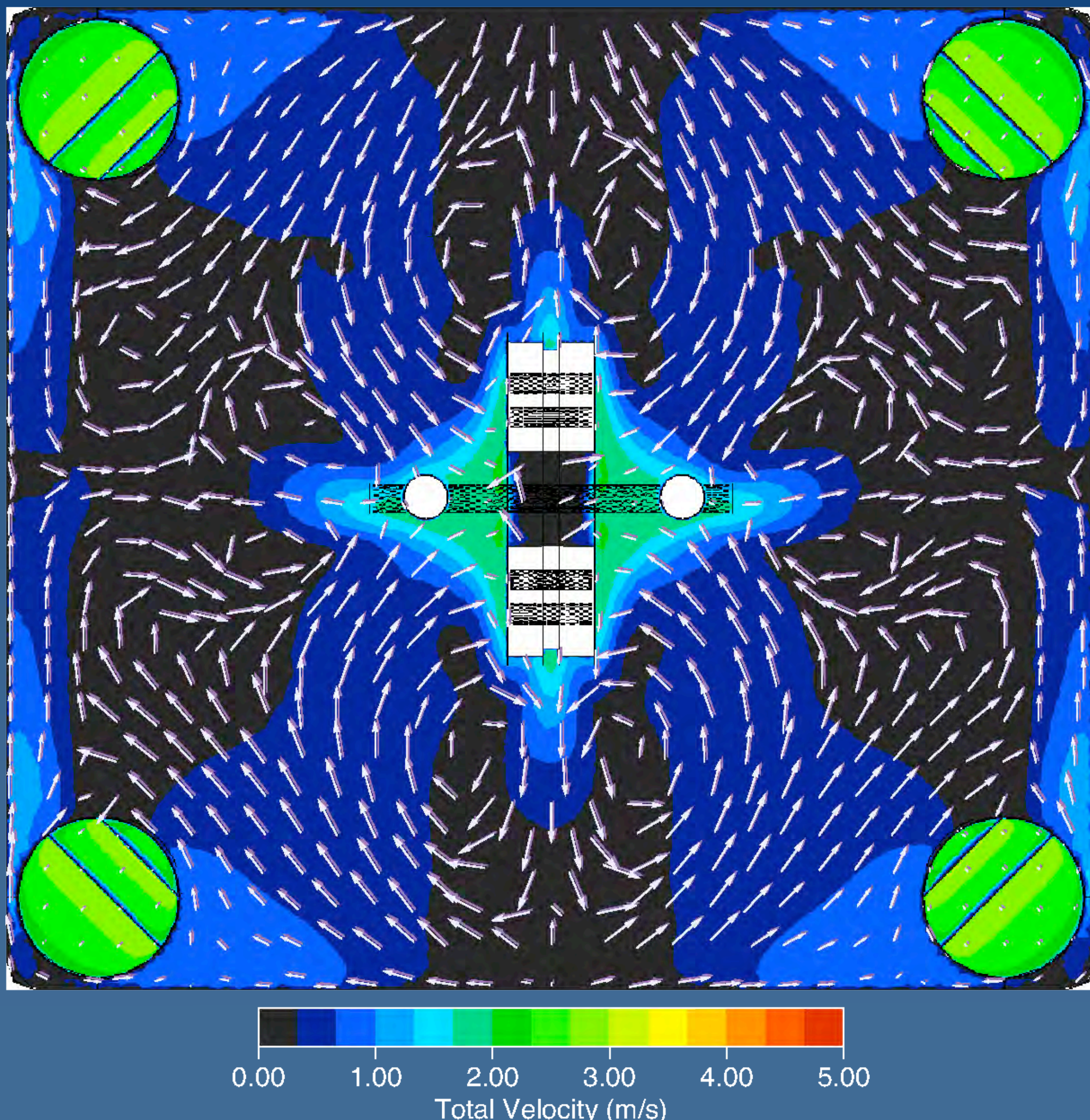
Results - Velocity field

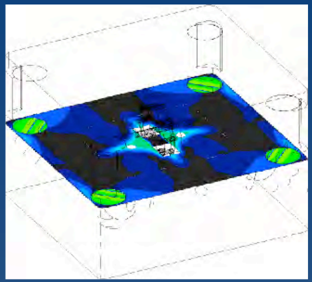


Turning vanes in elbow restore horizontal exit flow

Case Study - Quench Tank

Results - Mid-tank plane

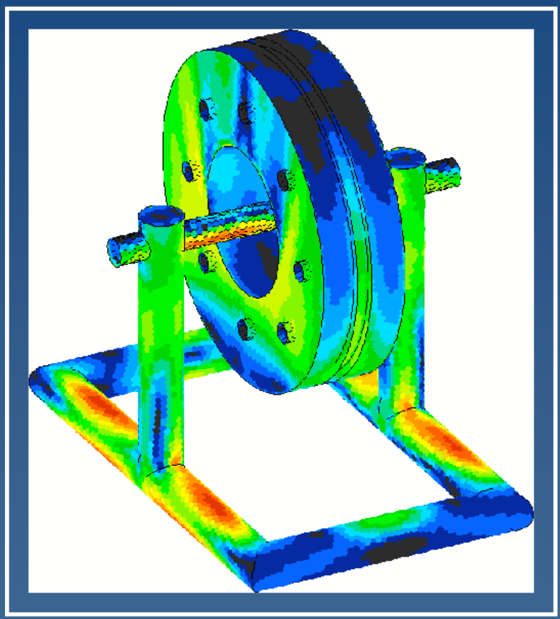




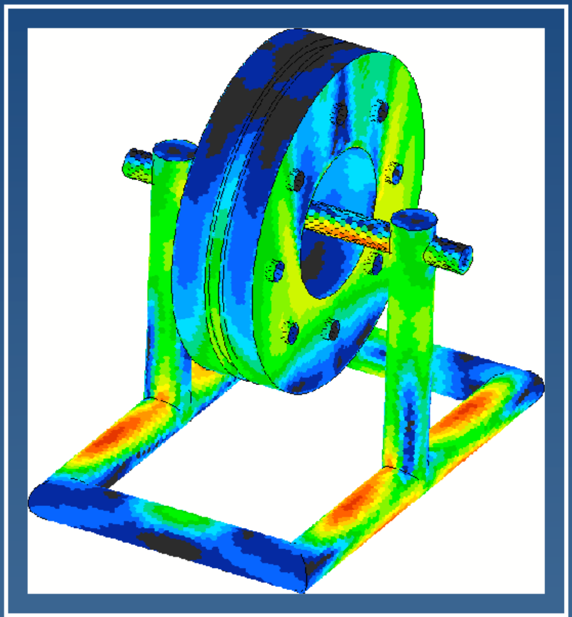
Good upward flow in center of tank along load

Case Study - Quench Tank

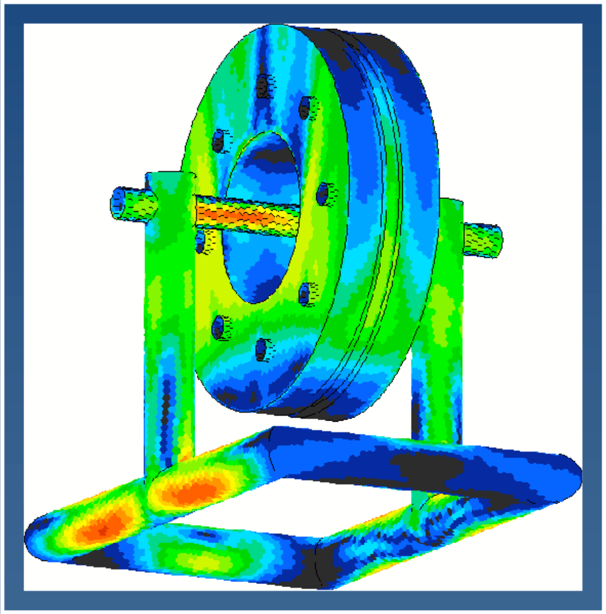
Results - Near surface velocity



Left-Top View



Right-Top View



Left-Bottom View

Case Study - Baking Cookies

System	Quench Tank	Oven
Load	Multiple parts in one or more racks	Multiple cookies on several trays
Heat transfer mode	Convection, boiling	Convection, radiation, conduction
Heat transfer fluid	Water, oil, polymer quenchant, gas	Air
Convection system	Draft tube with inlet and exit on one side of load	Fan with inlet and exit on back of oven
Direction of heat transfer	From load	To load
Goal	Uniformity	Uniformity

Case Study - Cookie Baking

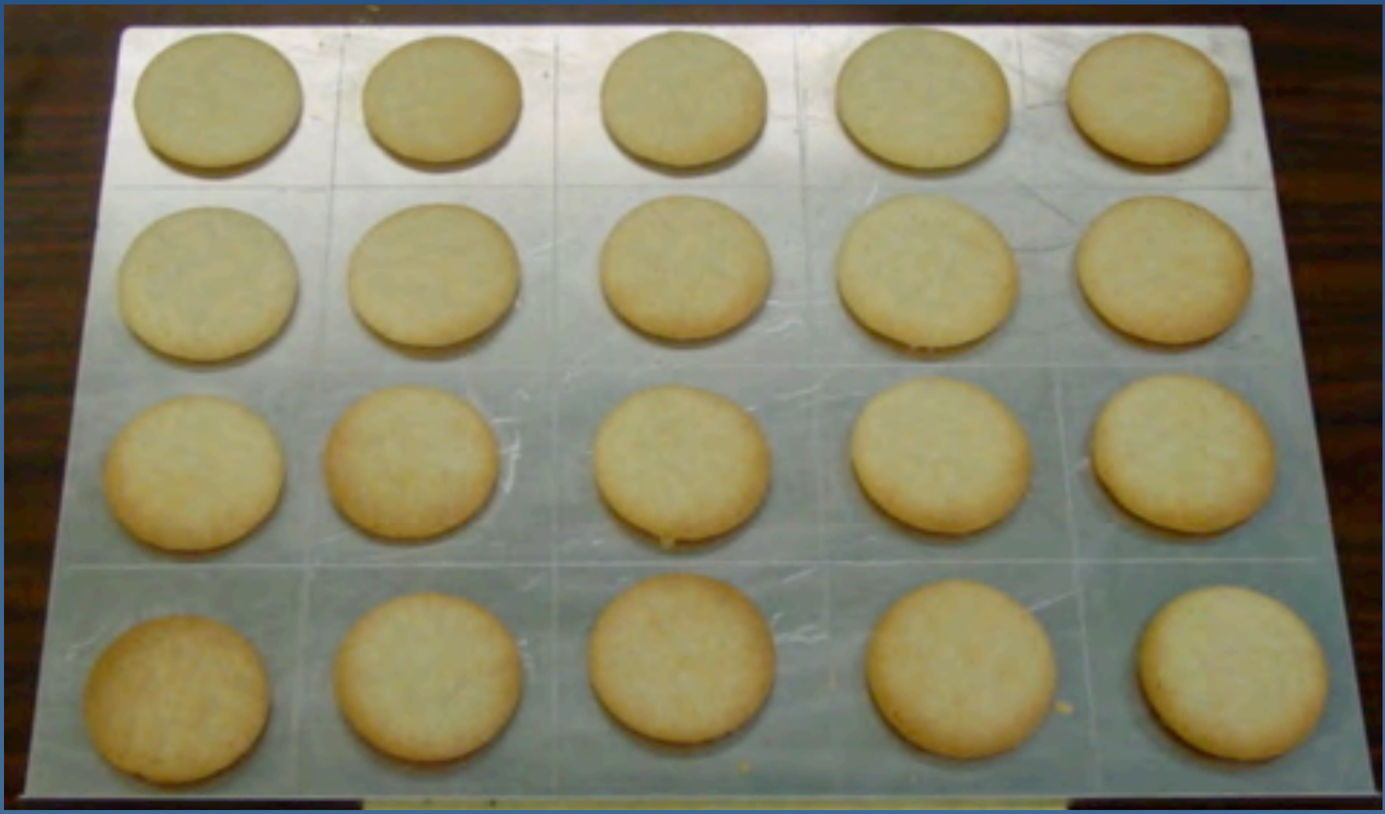
Sugar cookies as “sensors”

Precise preparation

Normal oven pre-heat

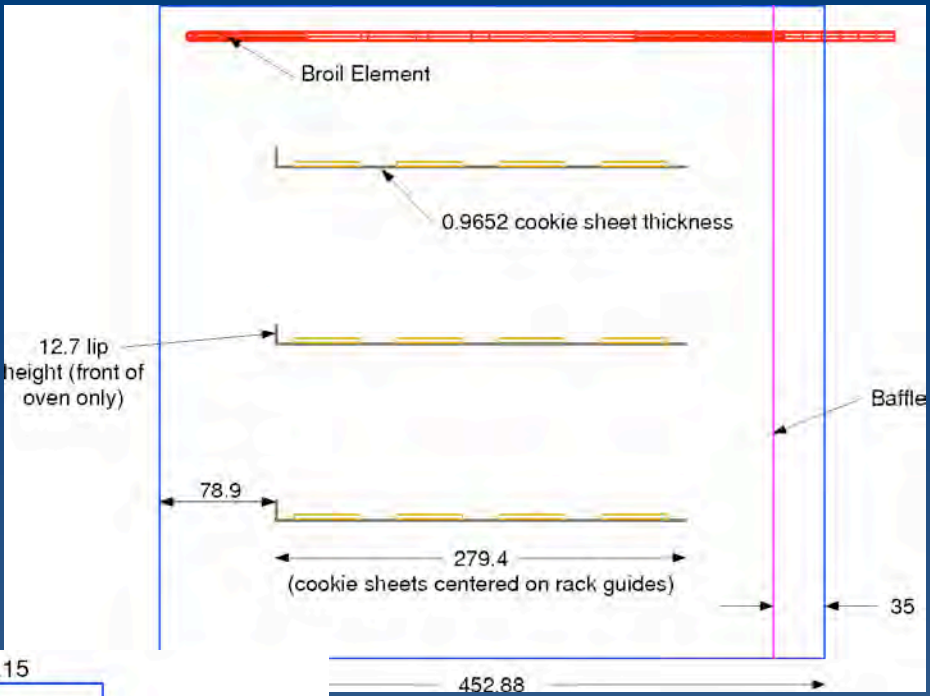
Bake 3 trays simultaneously

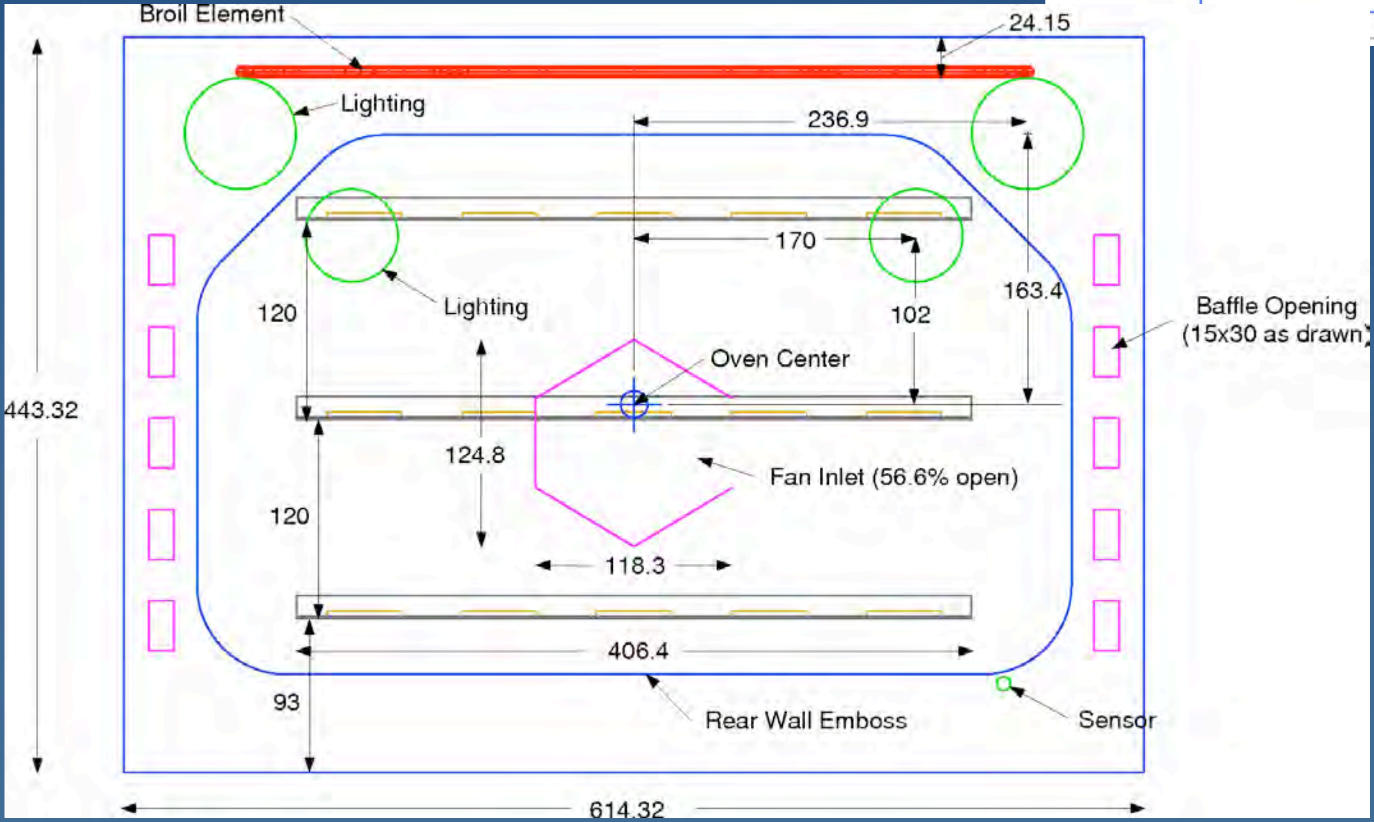
Evaluate for color uniformity



Case Study - Cookie Baking

Electric convection oven



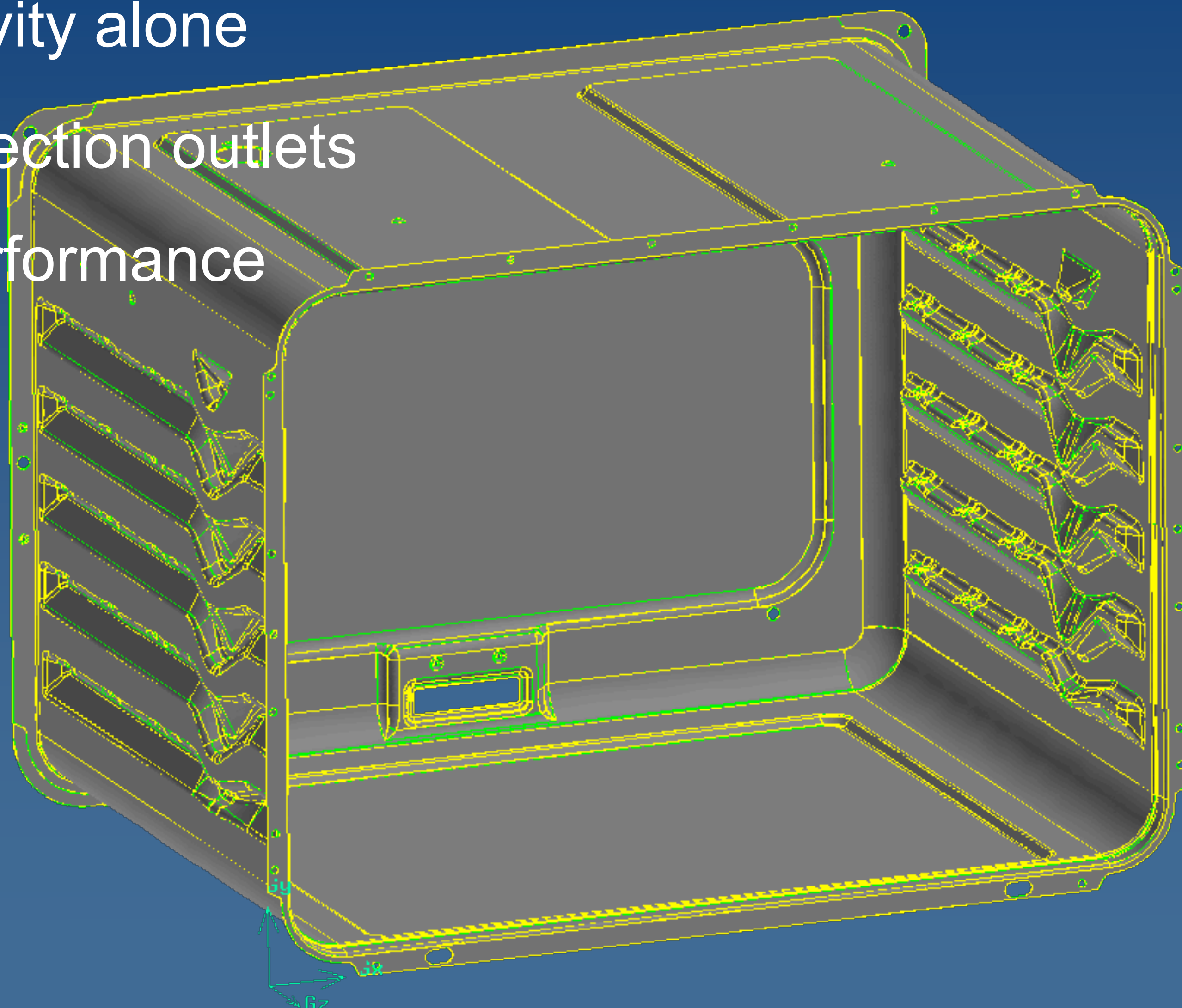


Case Study - Cookie Baking
Divide and Conquer

Consider oven cavity alone

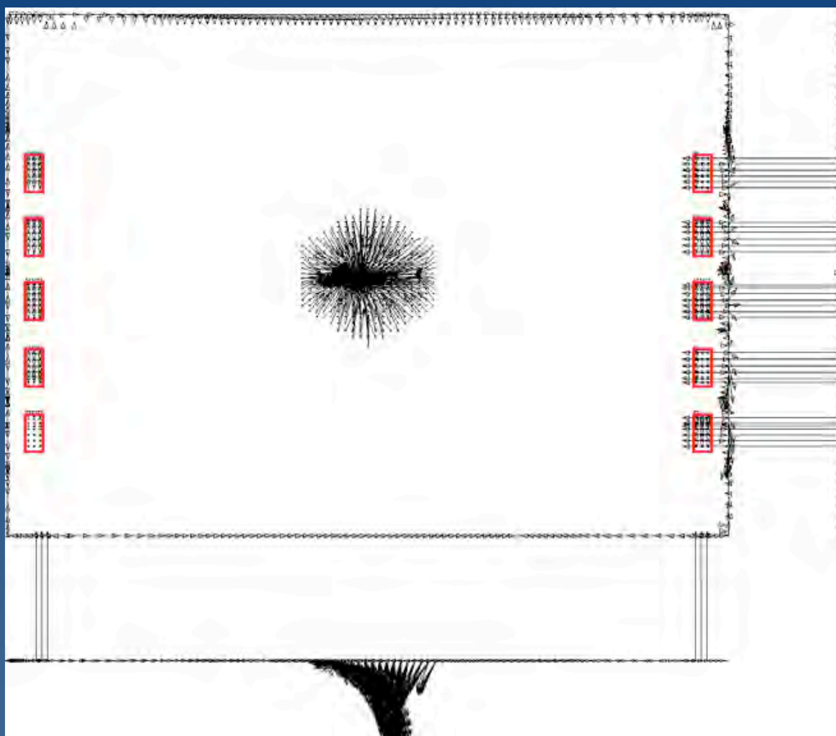
Control over convection outlets

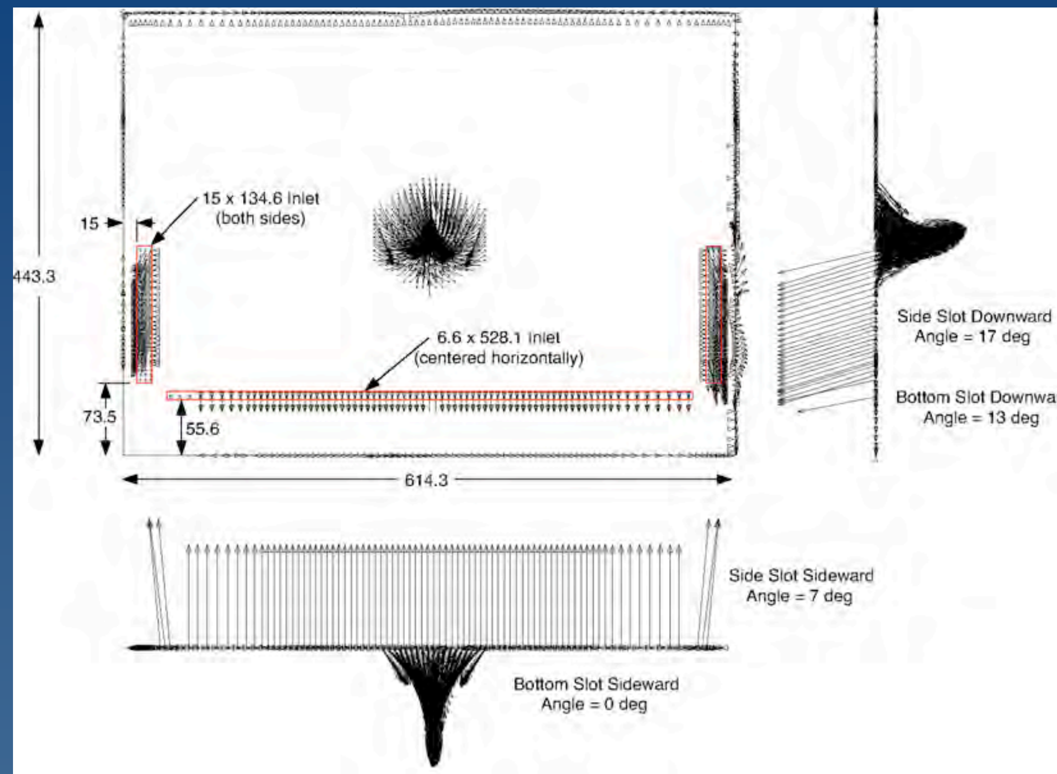
Adjust for best performance



Design fan system to deliver required flow

Case Study - Cookie Baking
Baffle Designs

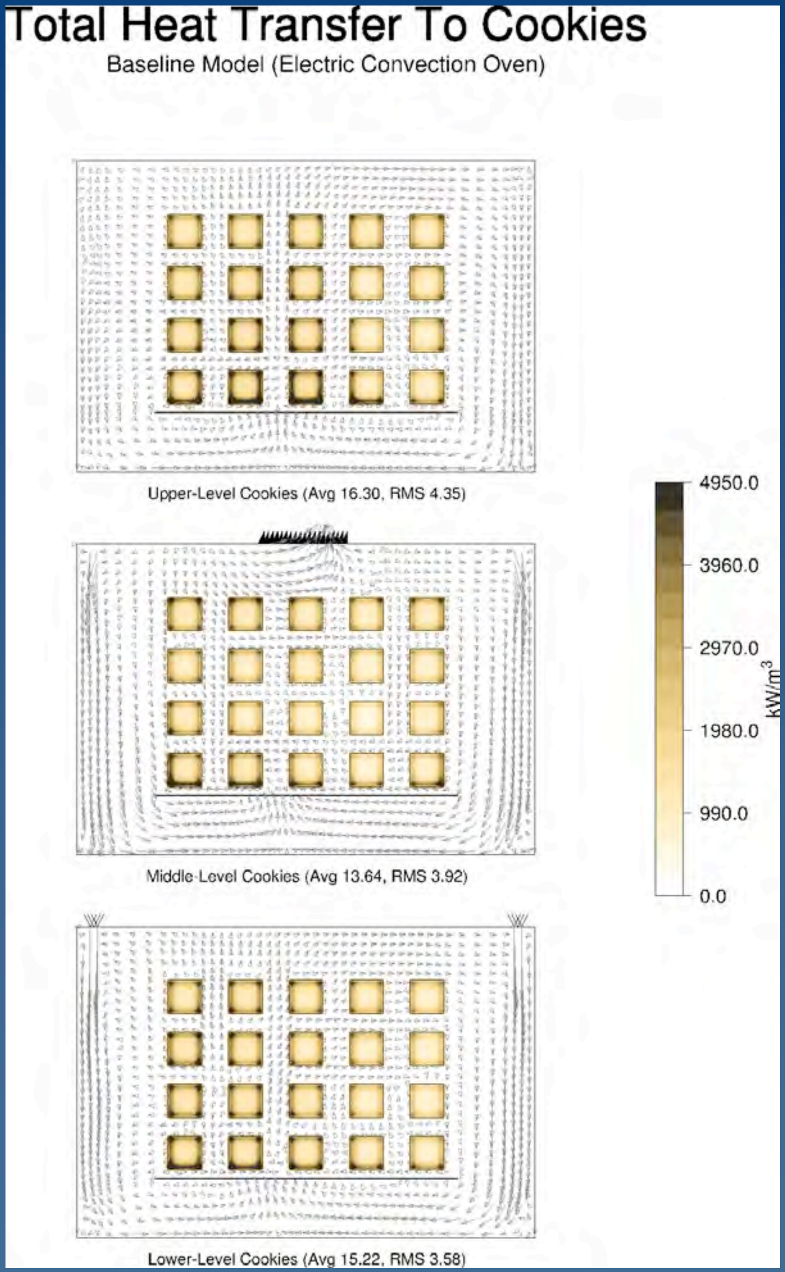




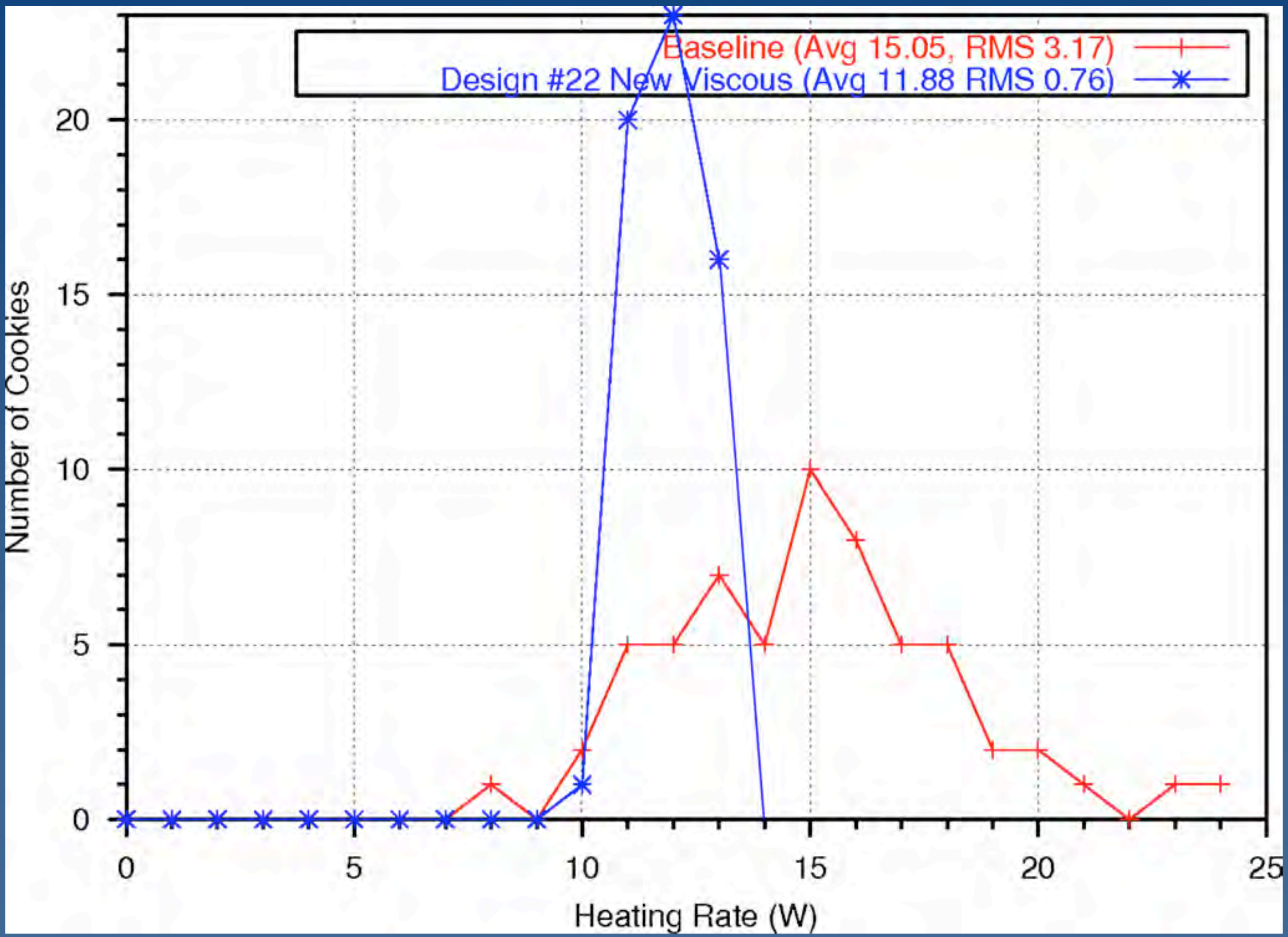
Original Design - 5 slots each side blowing straight in to cavity

Final Design - short side slots and bottom slot with specific angles and velocities

Case Study - Cookie Baking

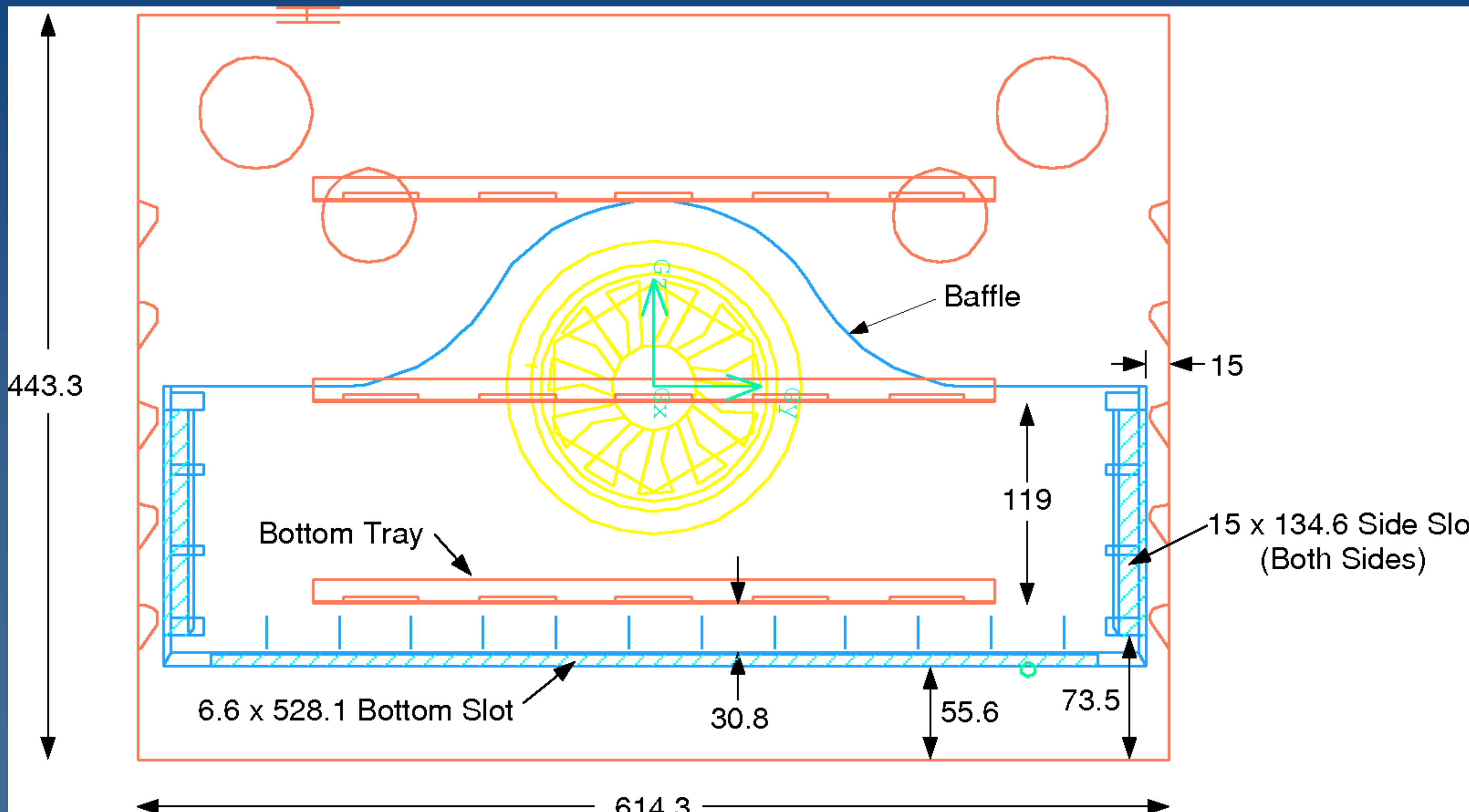


Case Study - Cookie Baking
Heat Transfer Uniformity



Final design provides significant improvement in heat transfer uniformity

Case Study - Cookie Baking Implementation



Case Study - Cookie Baking Post-Mortem

- Oven built as designed
- Good uniformity within each tray
- Variation between trays
- Suspected reason:
  - Bake and broil elements used for pre-heat
- Small adjustment provided good overall uniformity

Summary

Quenching - critical part of heat treating process

Uniformity difficult due to:

- Part geometry
- Loading patterns

CFD - an additional tool for evaluating quench system design

- Proper technique required
- Weigh results against existing knowledge/evidence

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