Correlation of Experimental Data with Autodesk® Simulation Moldflow® Insight Transient Cooling Results

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Learning Objectives

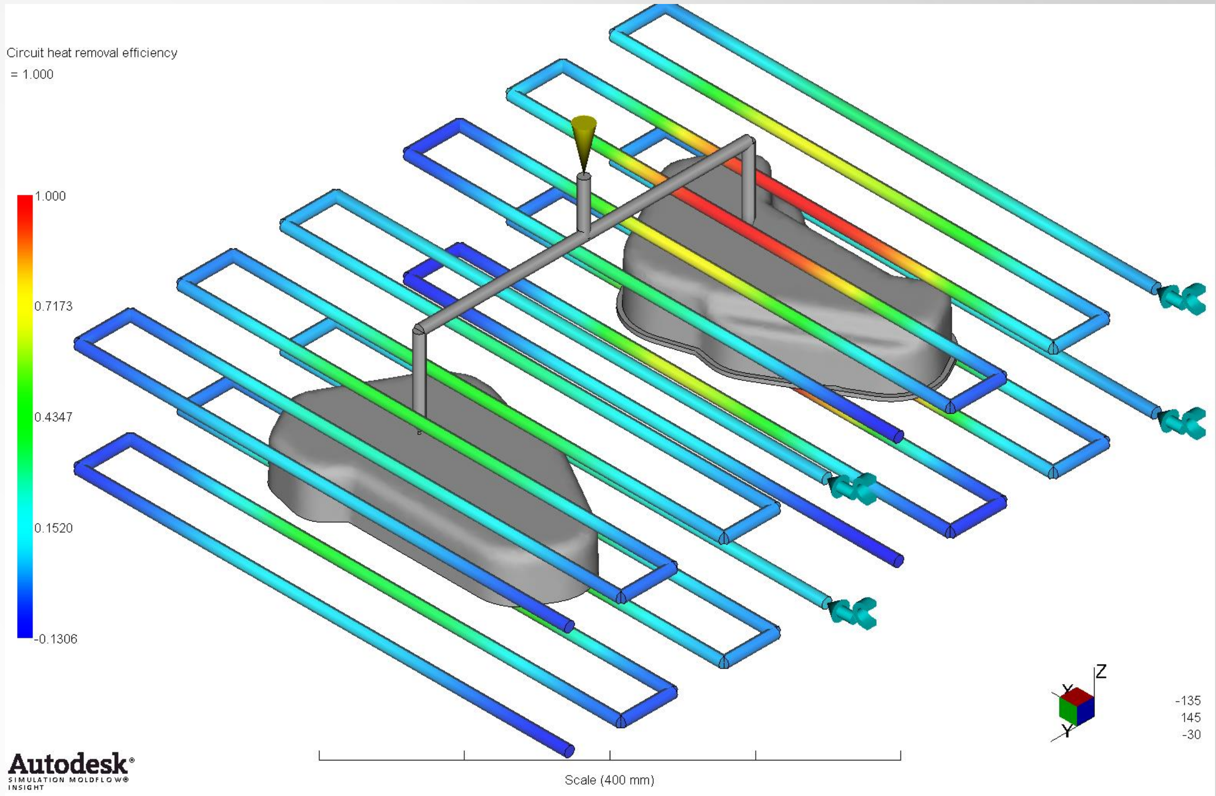
At the end of this class, you will be able to:

- List the variables that may affect the accuracy of the simulation results in the cooling analysis of Autodesk® Simulation Moldflow® Insight
- Identify improvements that can be performed to a model in order to increase its accuracy
- Describe the benefits of the transient cooling analysis
- Distinguish the differences between cycle average thermal solution and transient cooling solution

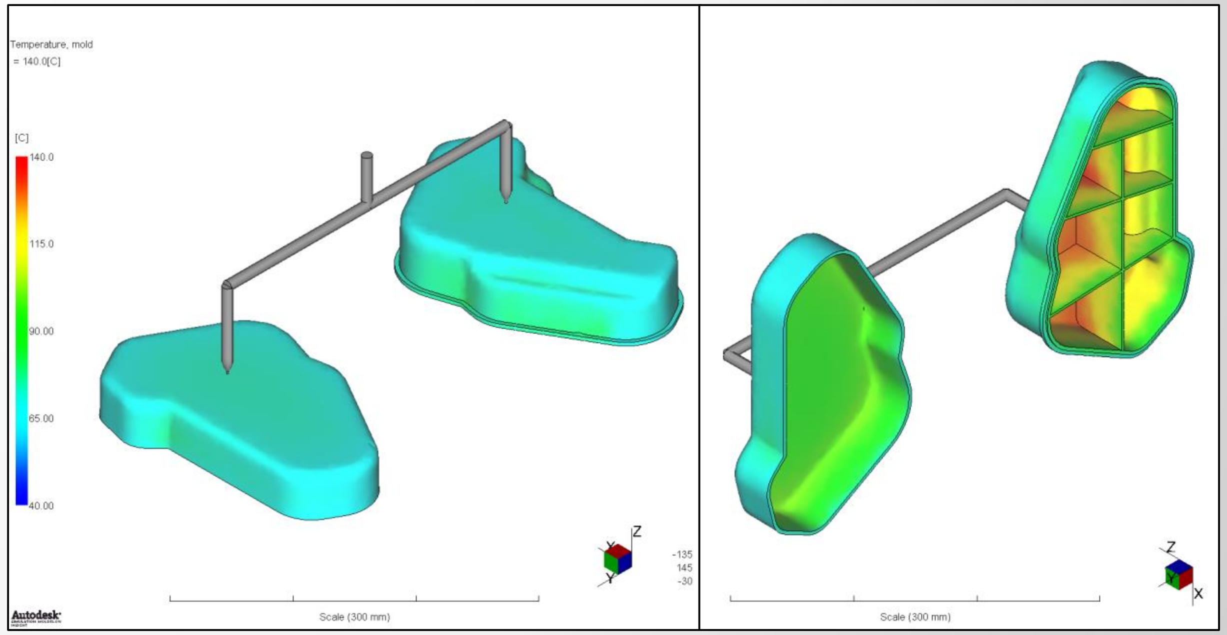
Introduction

- Why cooling analysis?
  - Identify hot spots
  - Identify and reduce defects
  - Efficient design of cooling system
  - Reduce machining operations

http://www.xcentricmold.com/



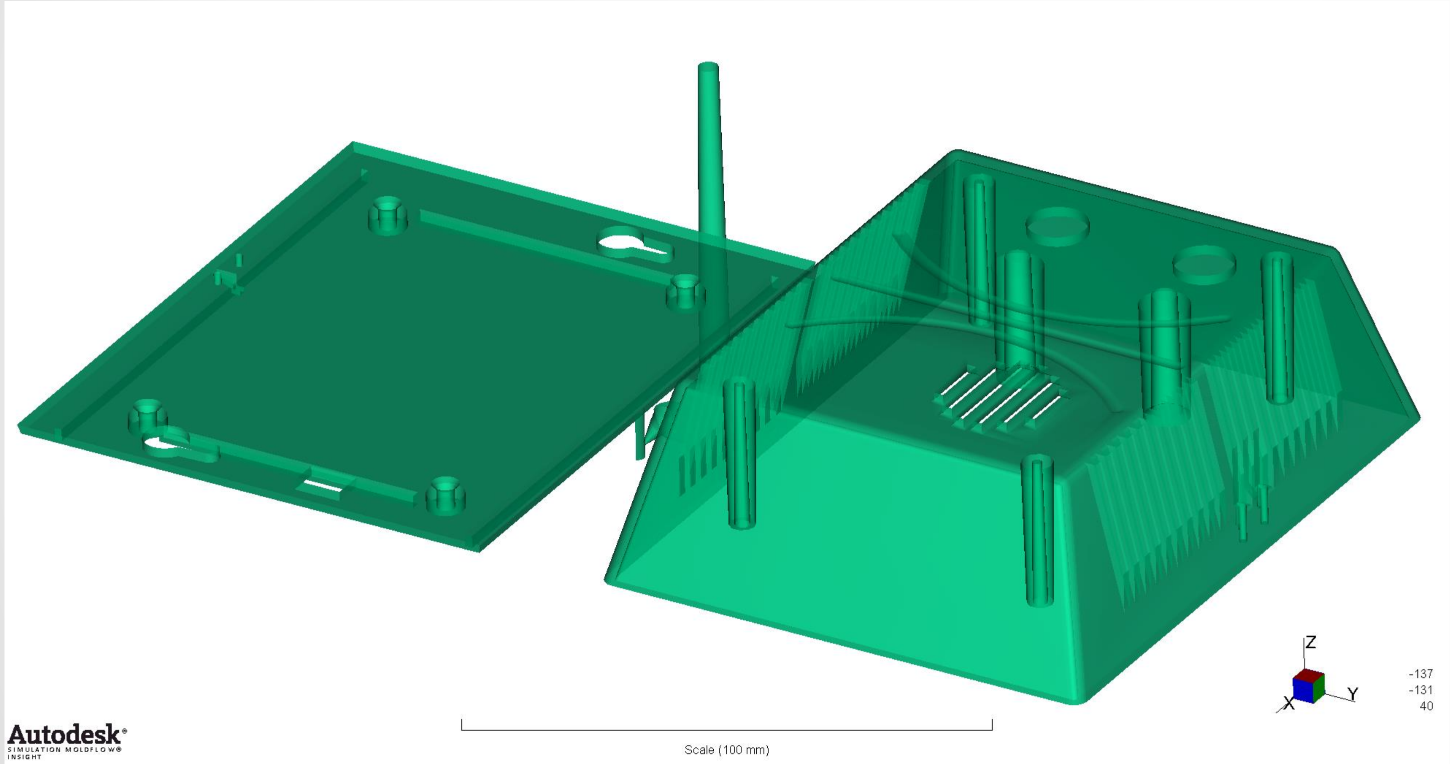
Circuit Heat Removal Efficiency

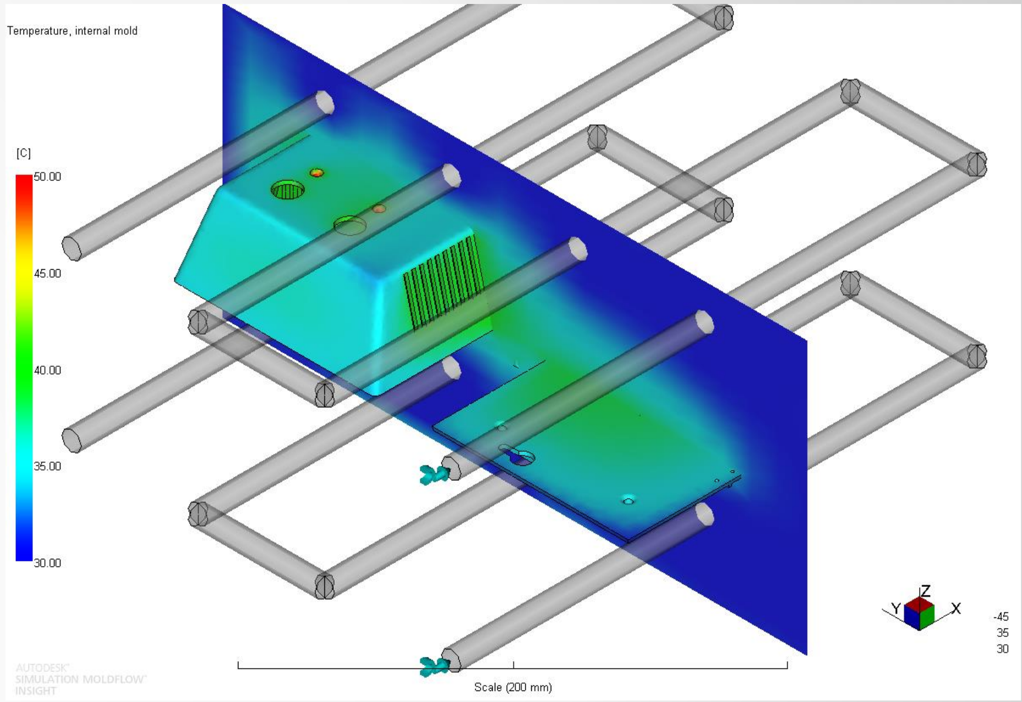


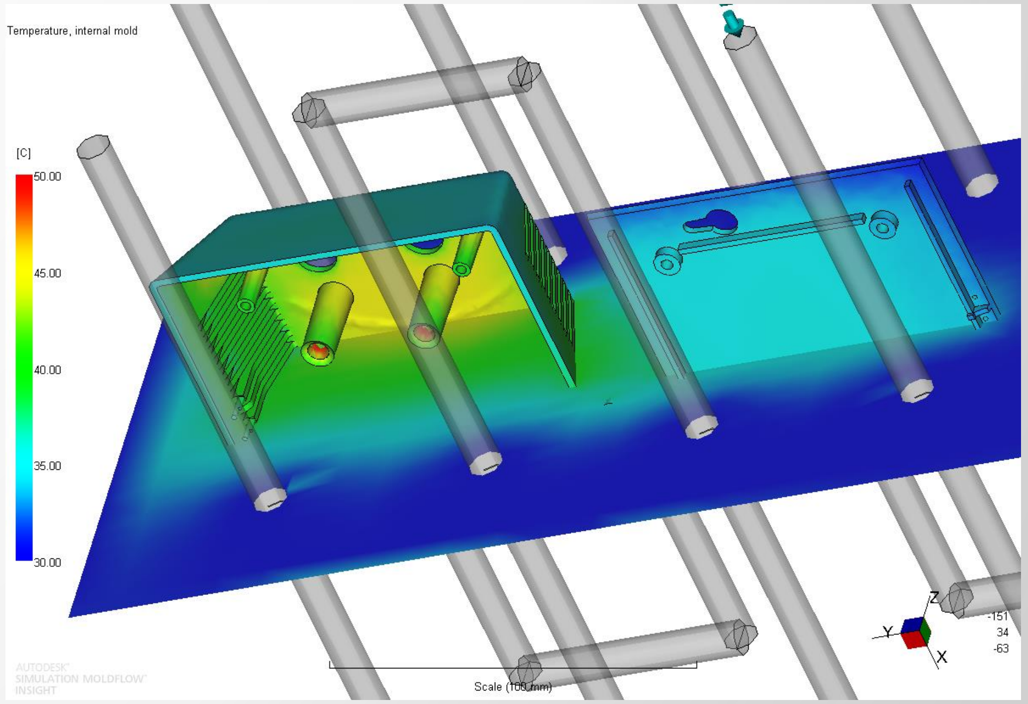
Mold Temperature

Introduction

- Hot spots due to inefficient cooling



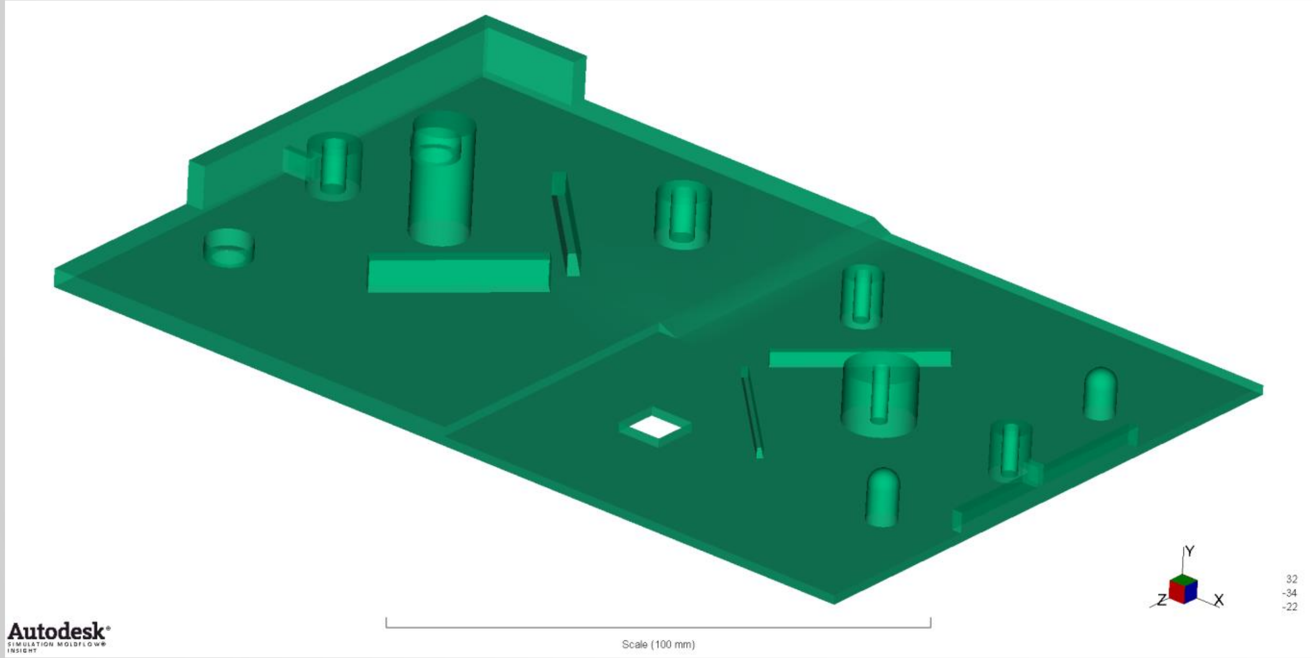


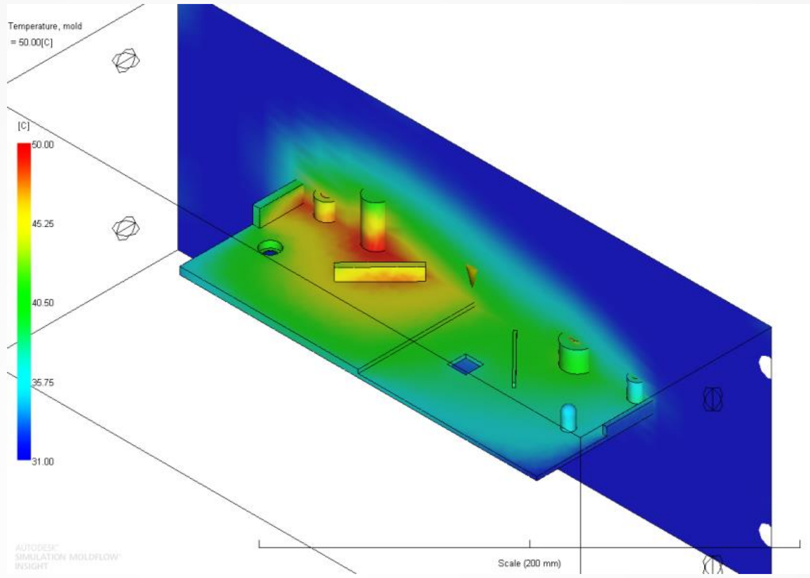


Mold Temperature

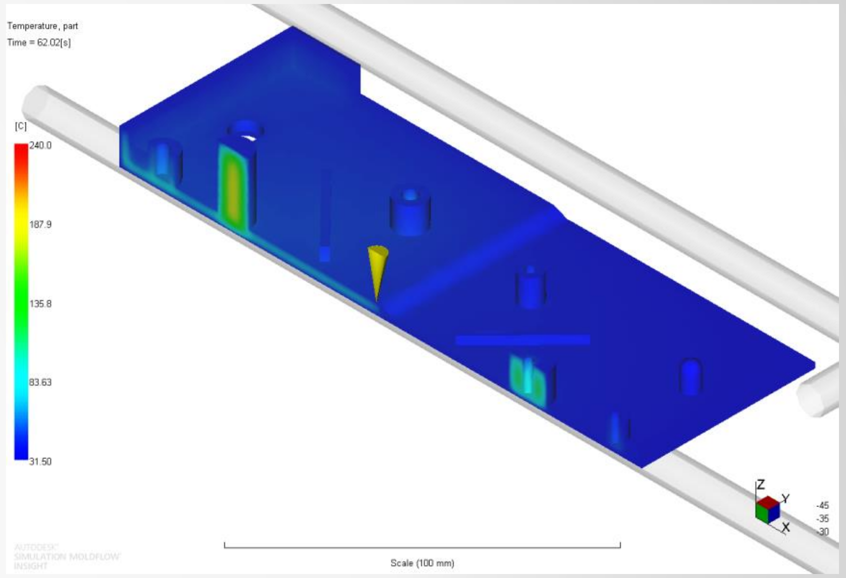
Introduction

- Sink marks and warpage due to uneven part cooling

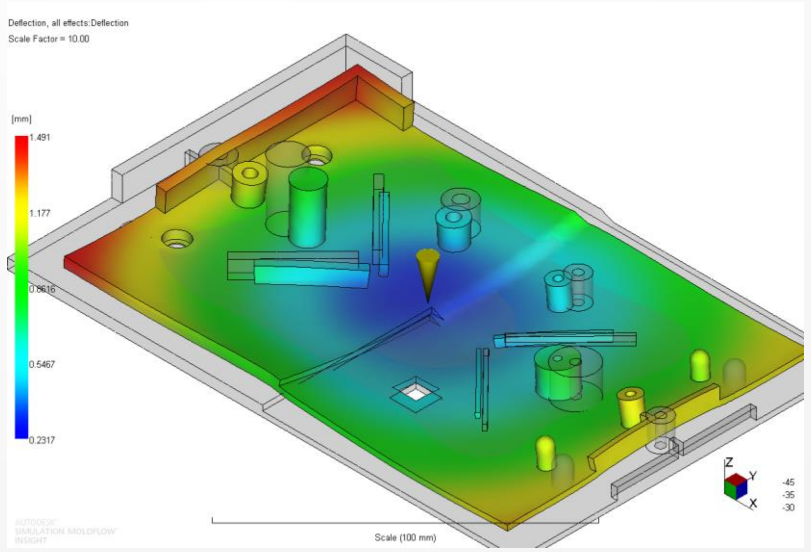




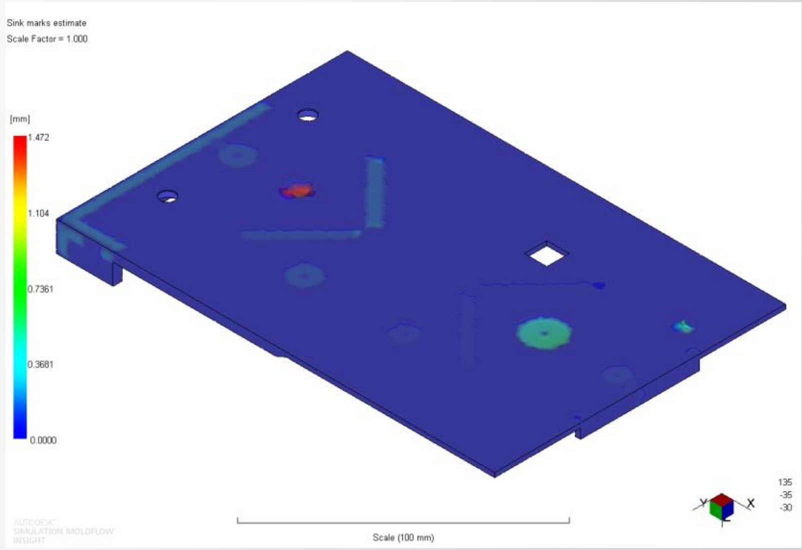
Mold Temperature



Part Temperature



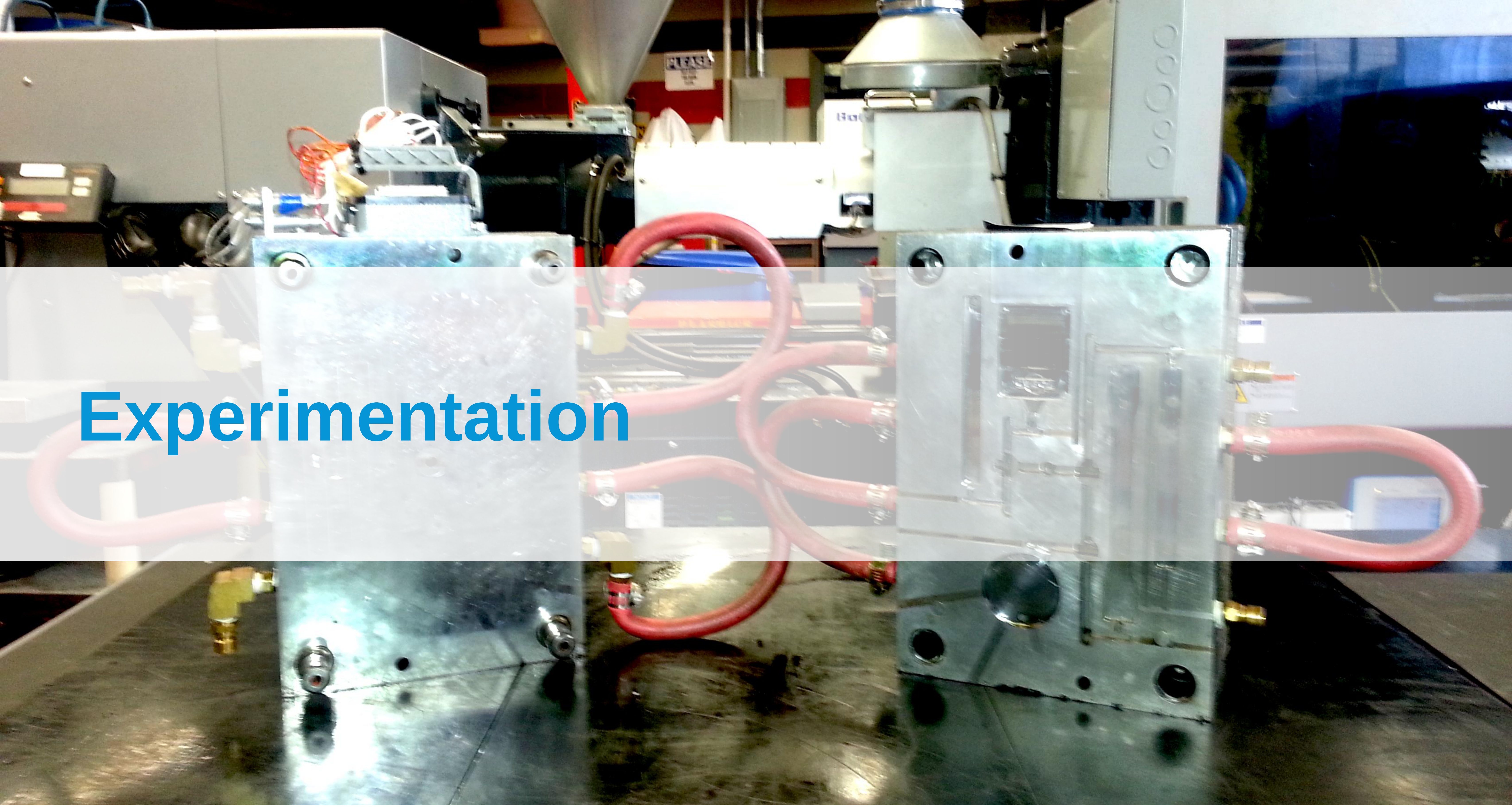
Warpage



Sink marks

Outline

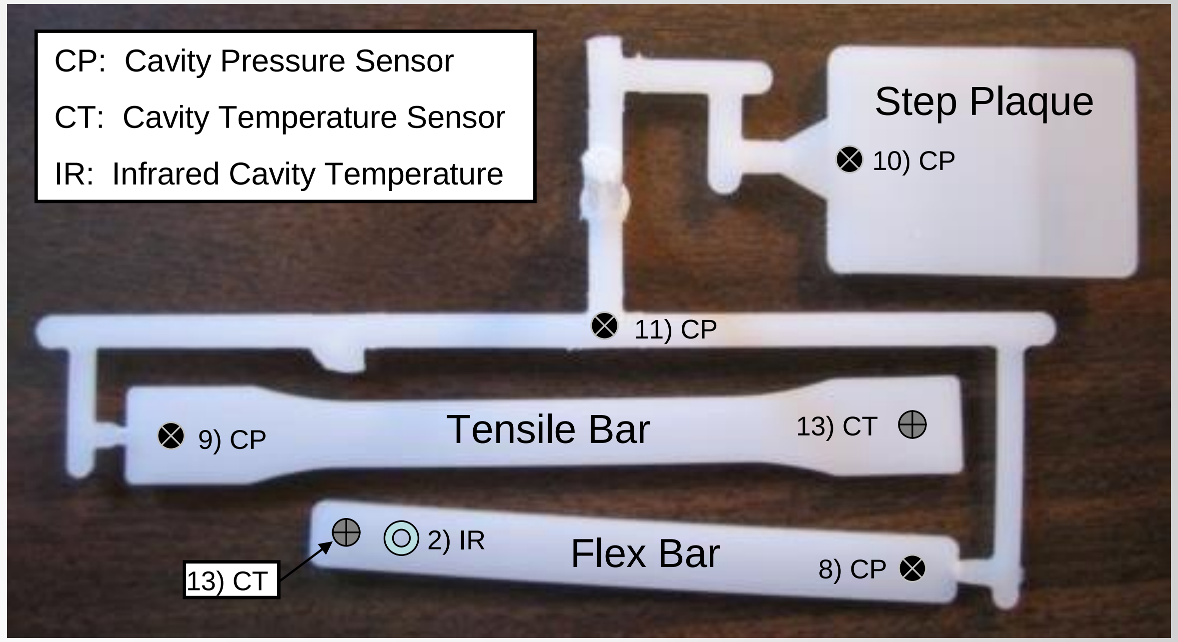
- Experimentation
- Review of Cooling Theory
- BEM Cooling Analysis
- FEM Cooling Analysis
  - Mold Temperature Options
  - Solvers
- Factors that Affect the Analysis
  - Mold Properties
  - Resin Properties
  - Interface Properties
- Simulation vs. Experimental Results
- Summary and Conclusions

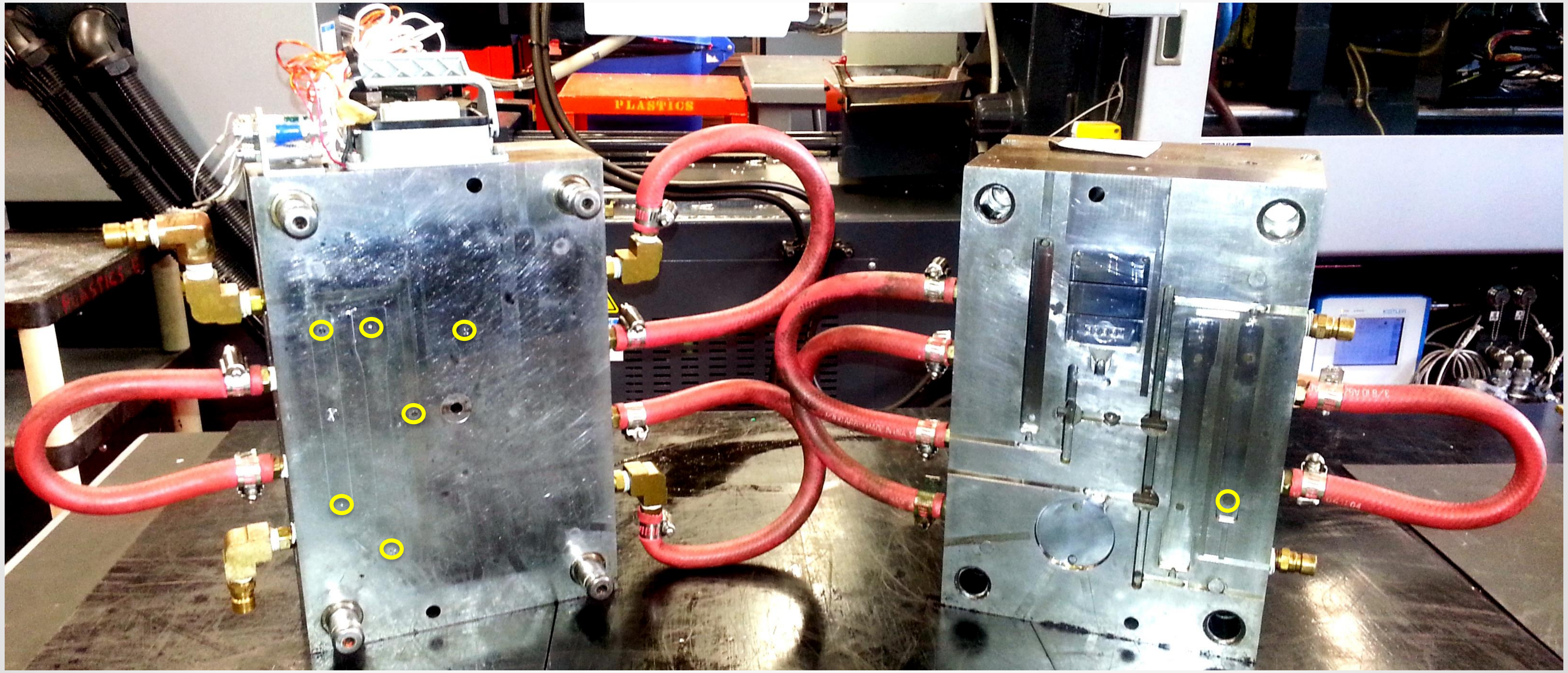


Experimentation

Experimentation

- ASTM test specimens mold



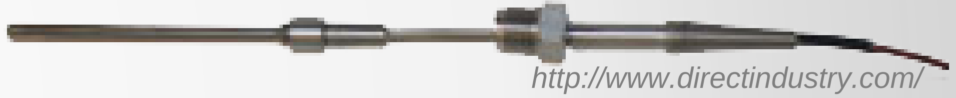


Experimentation

- Cavity Sensors
  - 2 Priamus® 4011A type N temperature sensors
  - 4 Priamus® cavity pressure transducers
  - IR OMEGA® OS1562 temperature sensors
- Cooling Lines
  - 2 Type J shielded temperature sensors
- Data Acquisition Systems
  - RJG eDART®
    - Machine signals
    - Cooling lines thermocouples
  - Priamus ® eDAQ 8102A
    - Cavity pressure and temperature sensors


http://www.priamus.com/

Type-N thermocouple


http://www.directindustry.com/

Type-J thermocouple

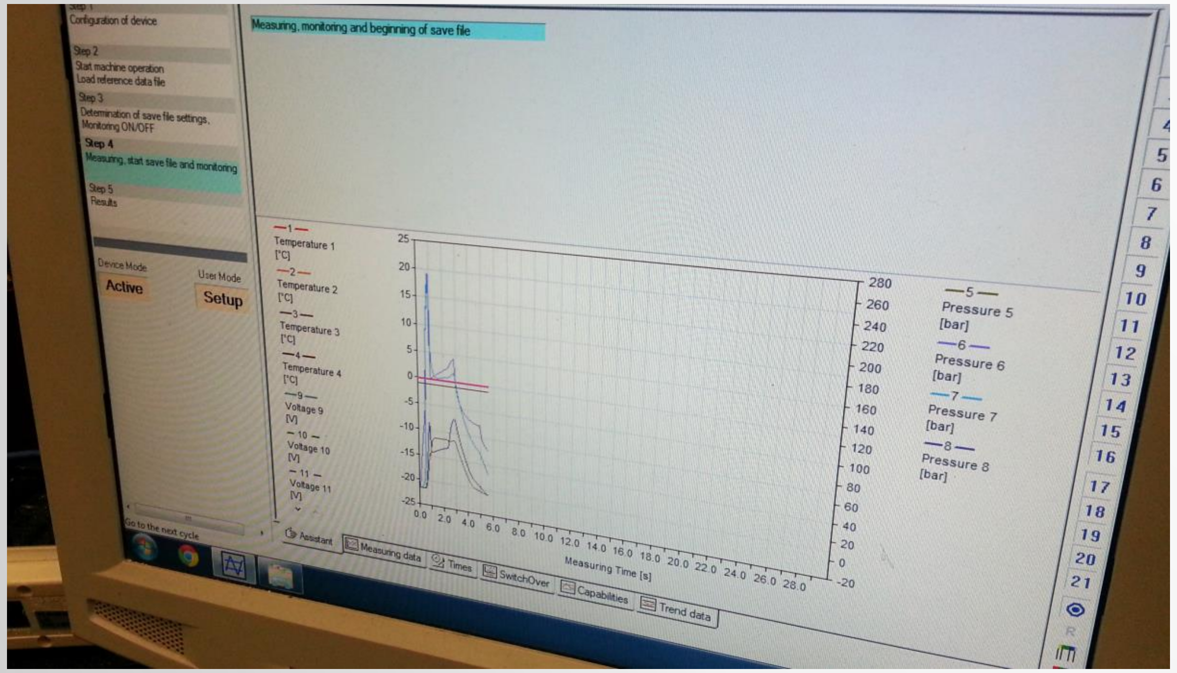
Experimentation

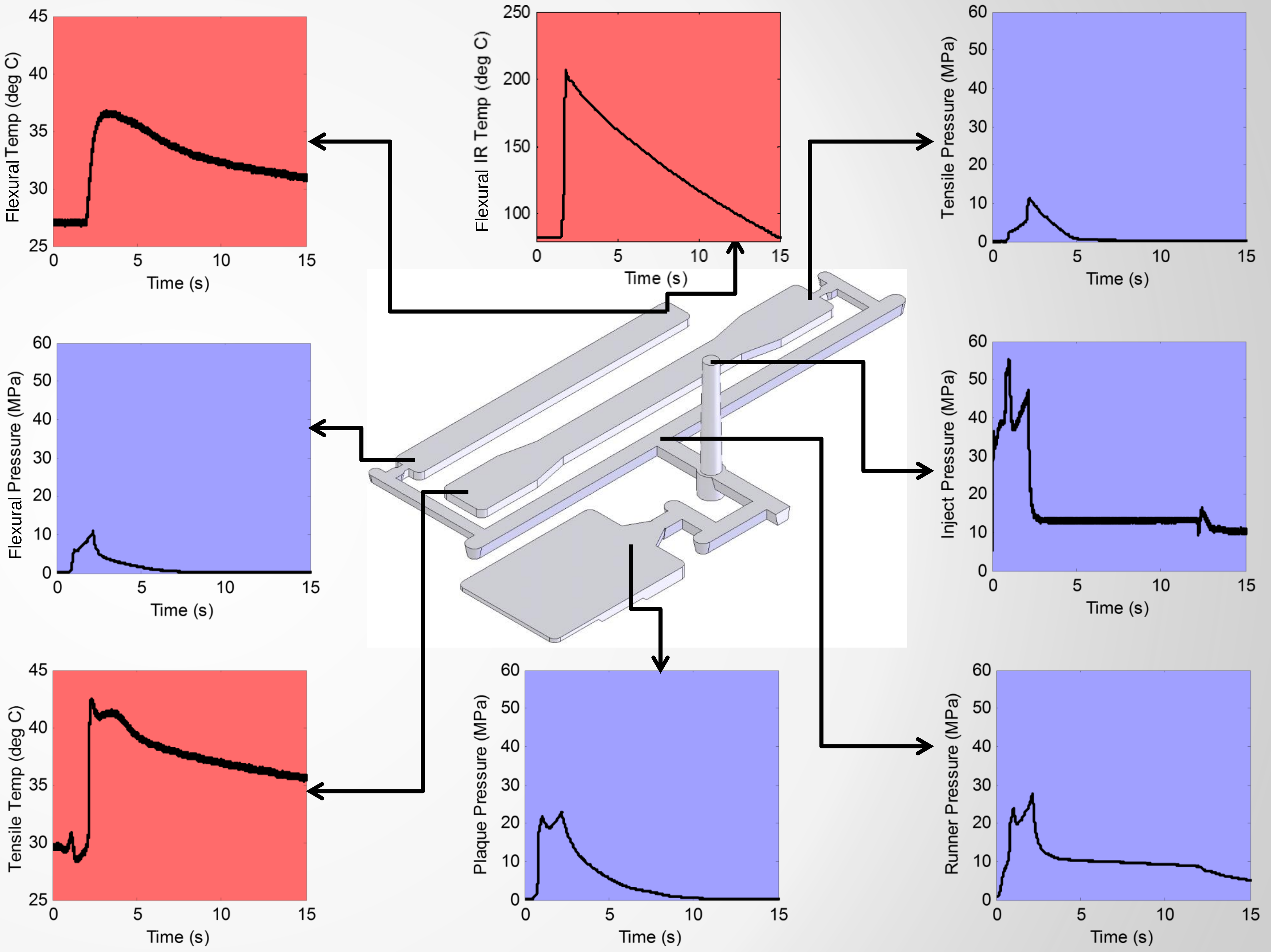
- Electric Injection Molding Machine
  - Ferromatic Milacron Elektra 50 ton
  - Braskem CP201HC Polypropylene

http://www.machinestock.com/

Data acquisition

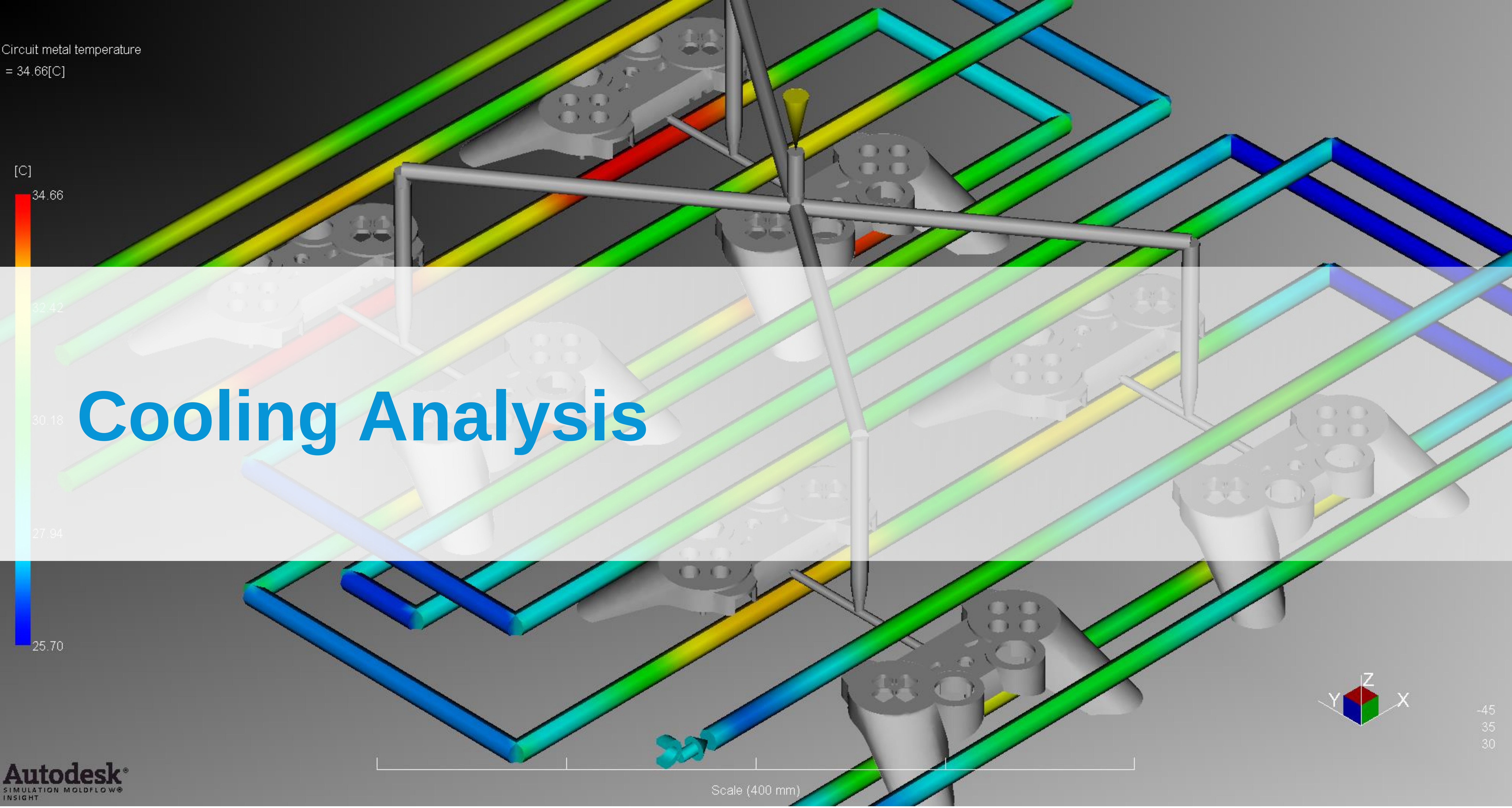
- The correlation study will focus on the flexural bar data
- Data acquired for the other cavities will be used for validation of the simulations





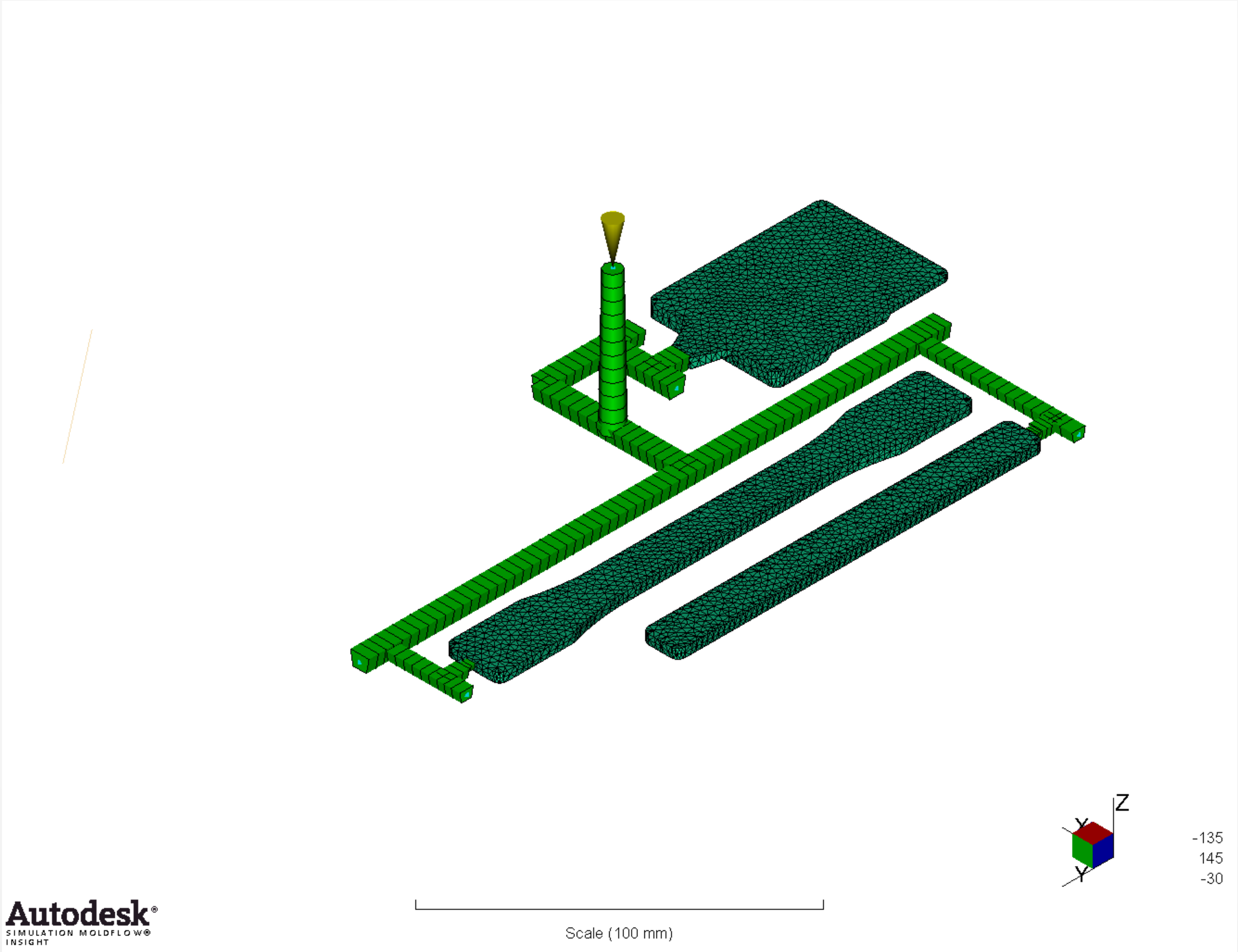
Guthrie Gordon, UMass Lowell

Cooling Analysis



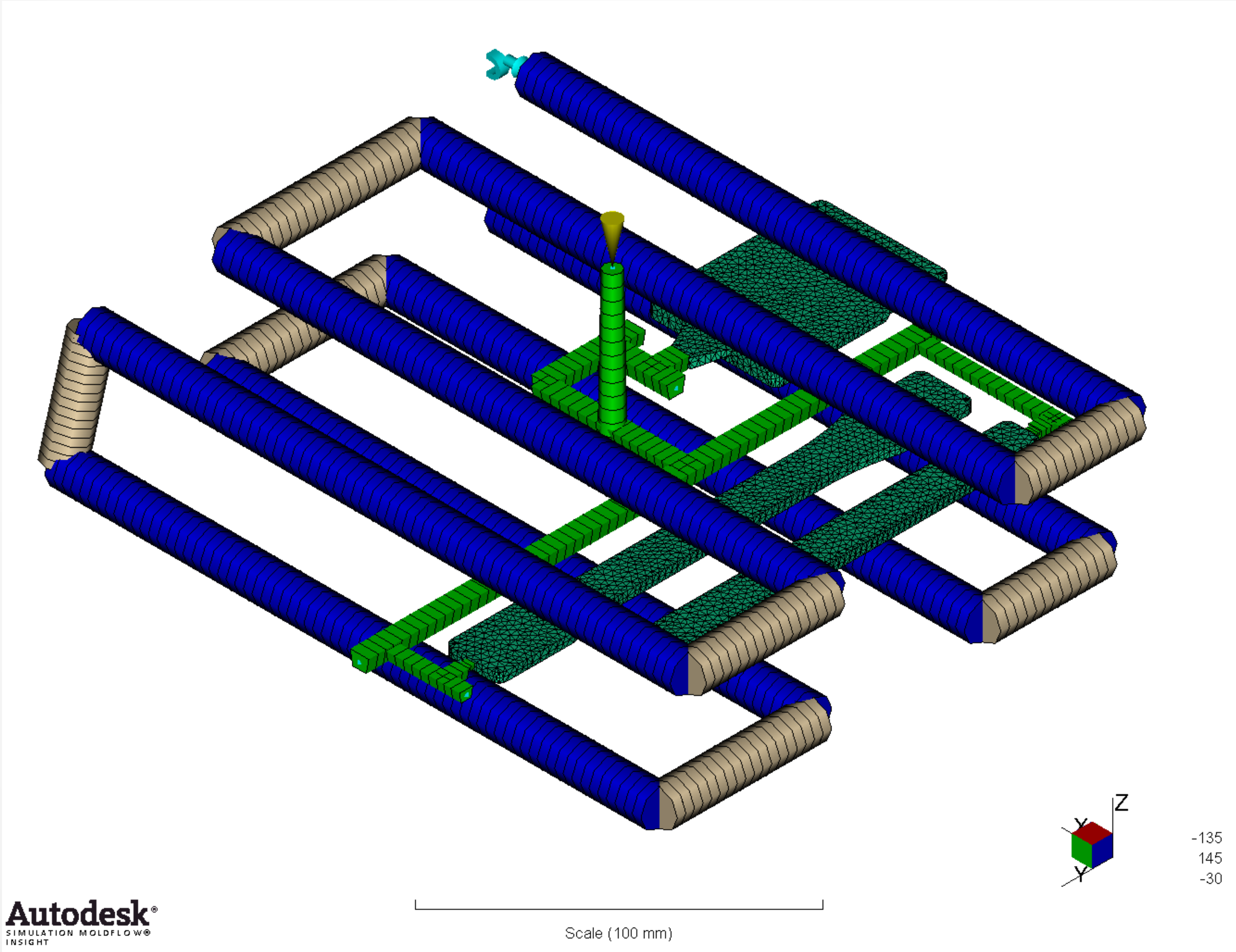
Model Setup

- Import and mesh parts with 3D elements
- Model runners as beam elements



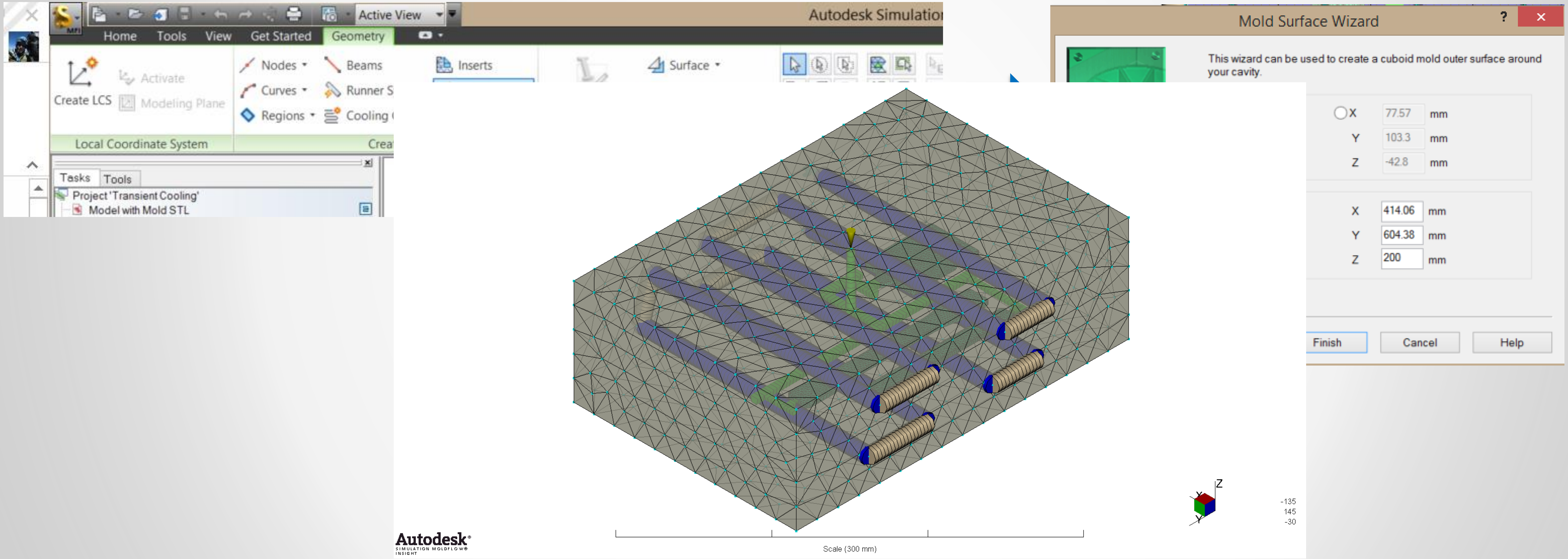
Model Setup

- Model cooling system with beam elements



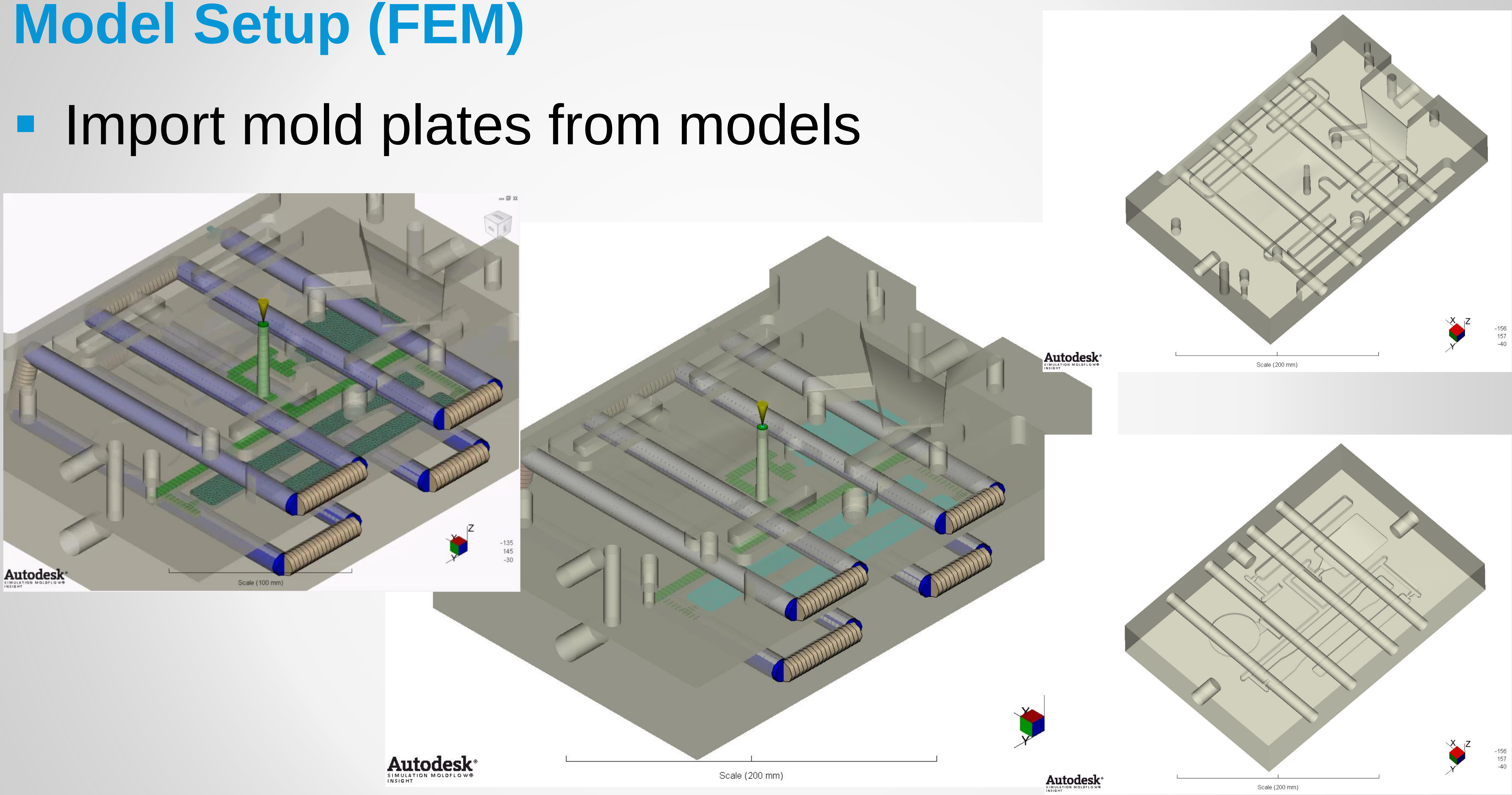
Model Setup (BEM)

- Create mold surface mesh



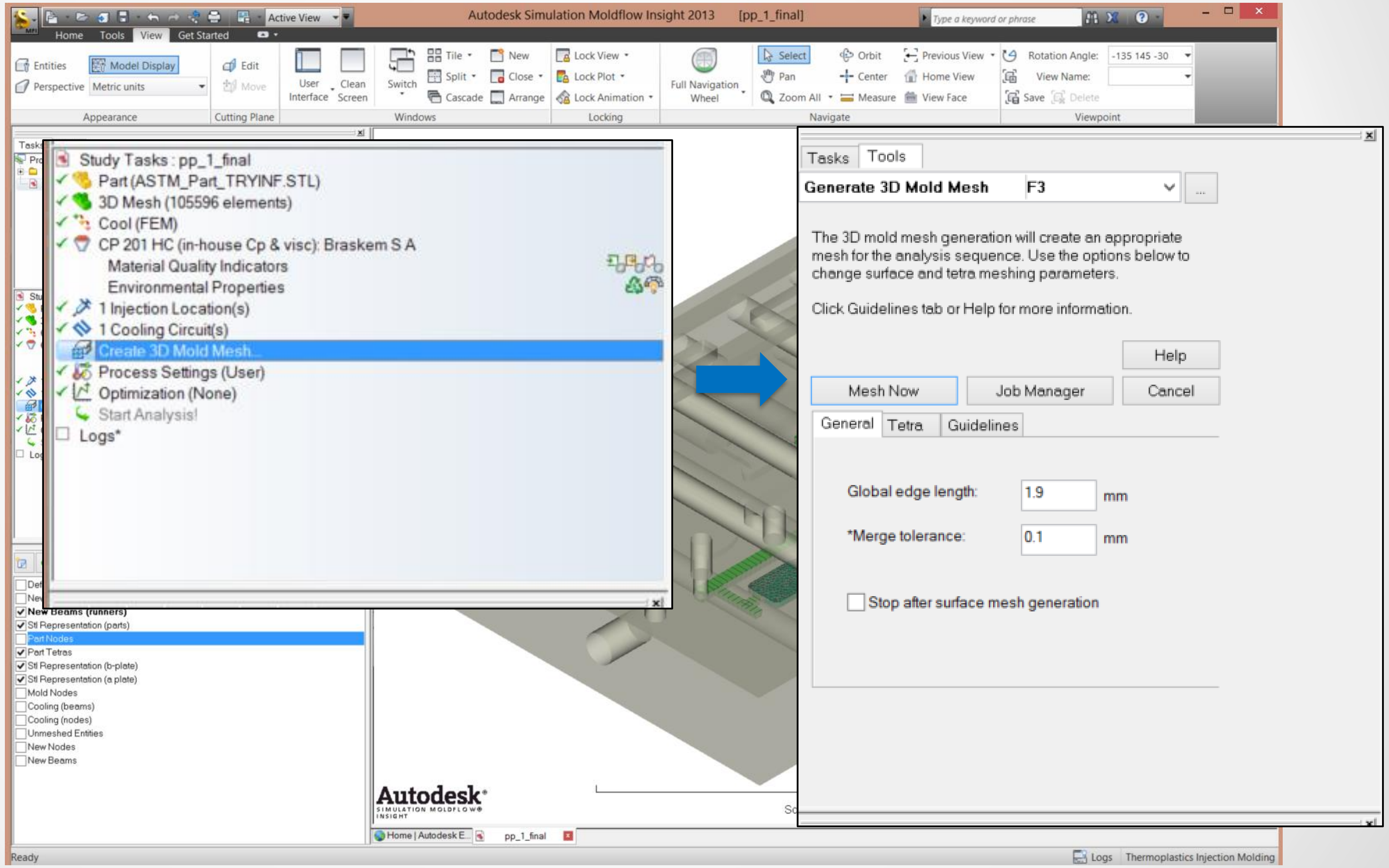
Model Setup (FEM)

- Import mold plates from models



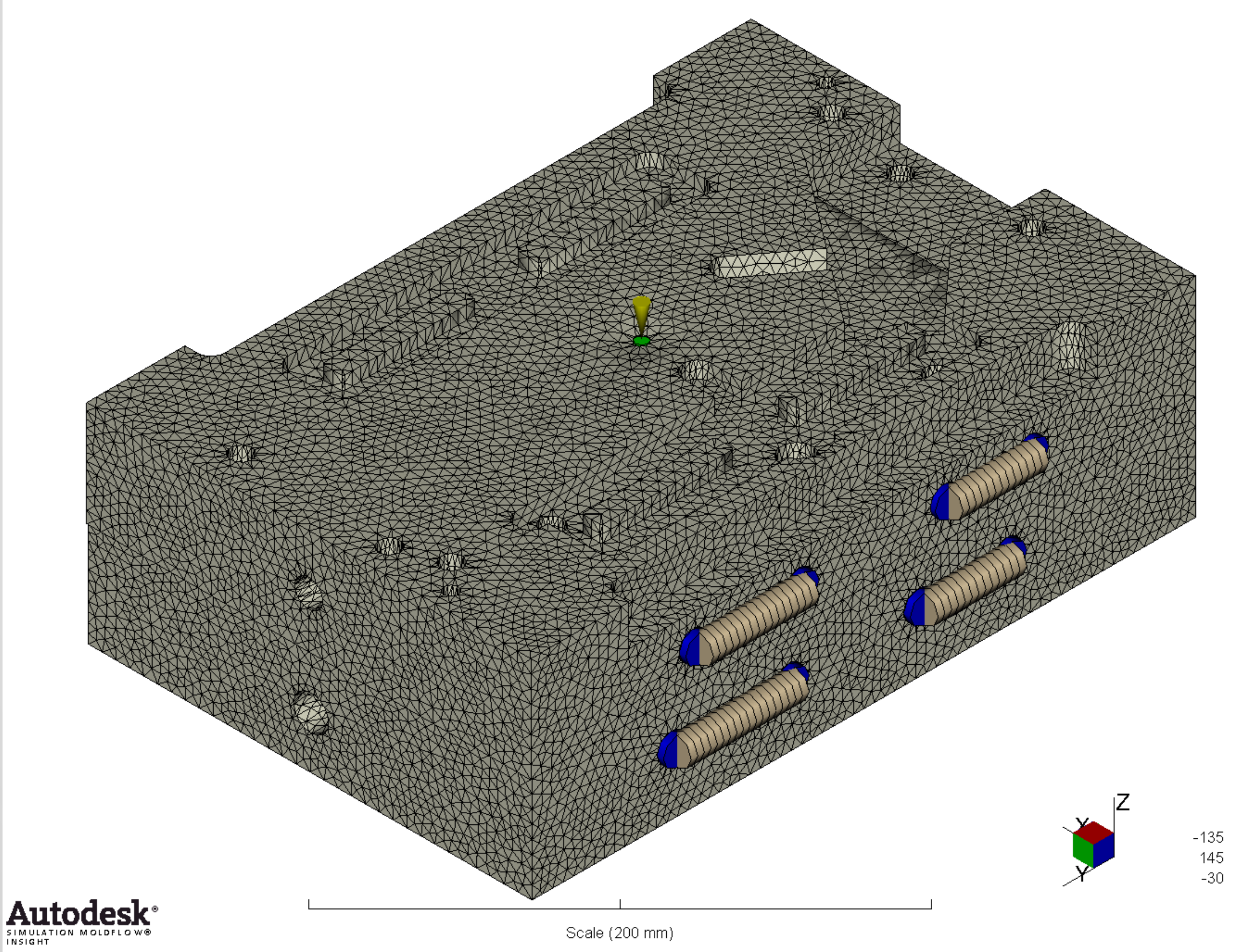
Model Setup (FEM)

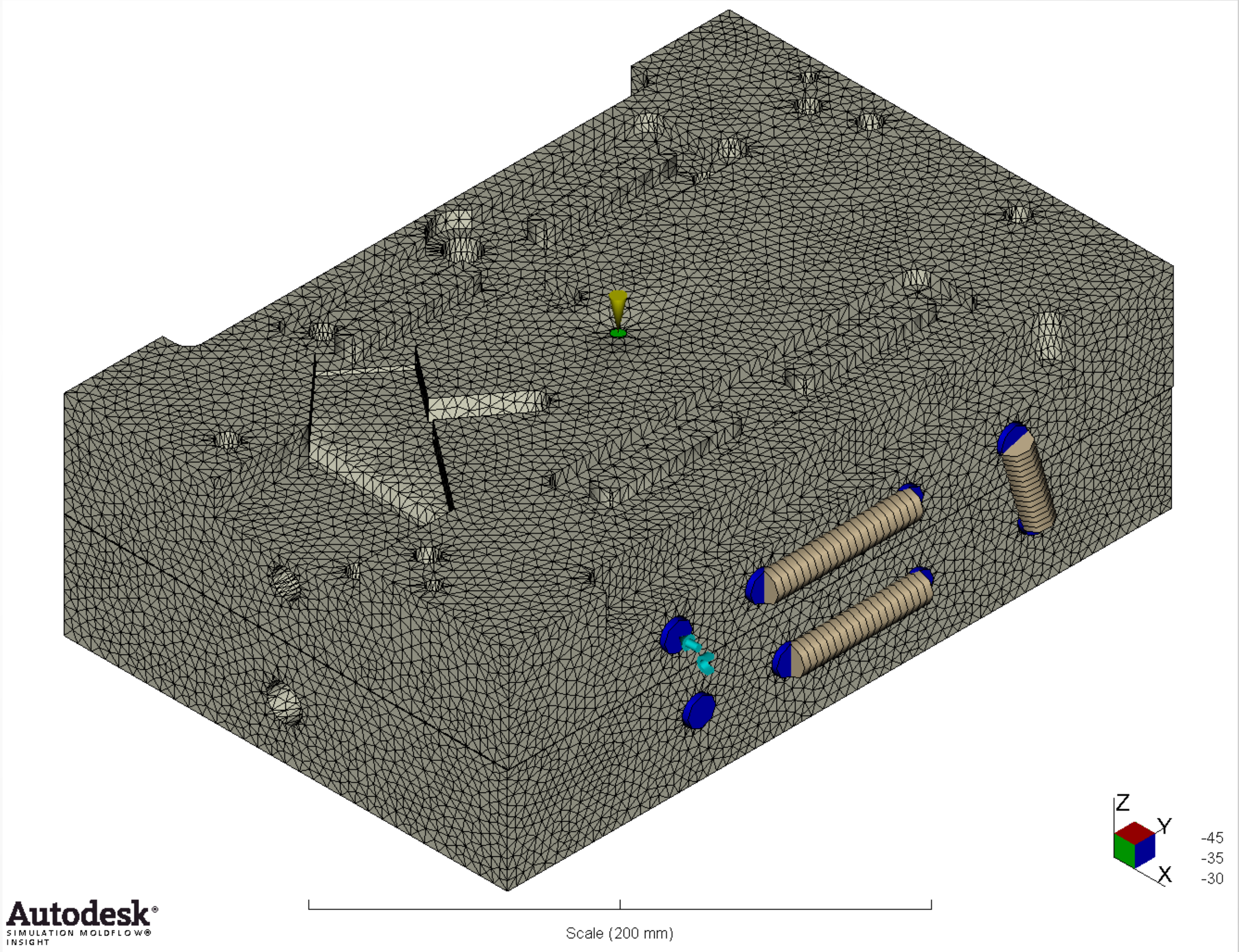
- Create mold mesh



Model Setup (FEM)

- Create mold mesh





What is BEM and FEM?

- Conduction Equation
  - Heat transfer through mold steel

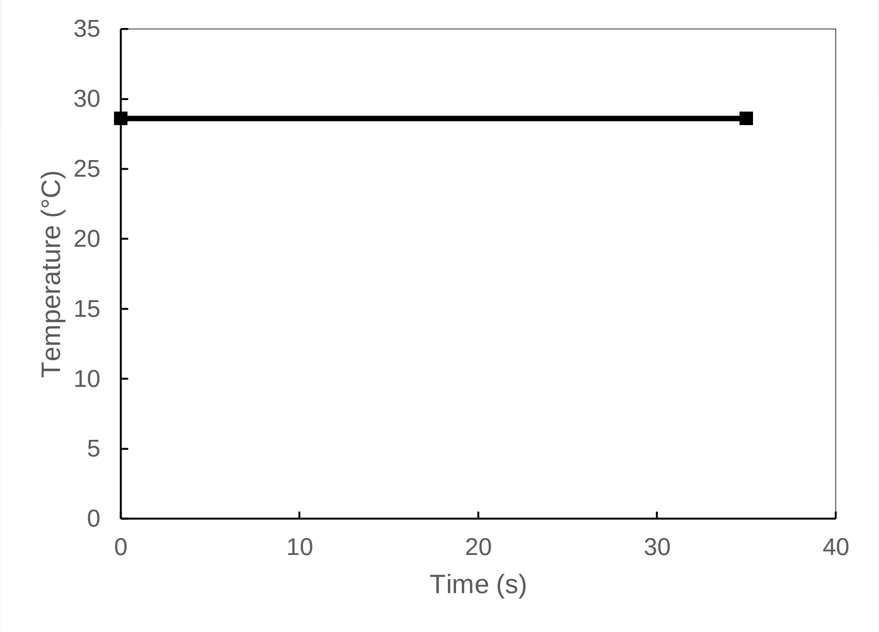
$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) \xrightarrow[\textit{for steel}]{\textit{constant k}} \underbrace{\frac{\partial T}{\partial t}}_{\text{Transient Term}} = \alpha \nabla^2 T$$

- Boundary Conditions:
  - Heat flux from the melt
  - Heat flux to the cooling channels

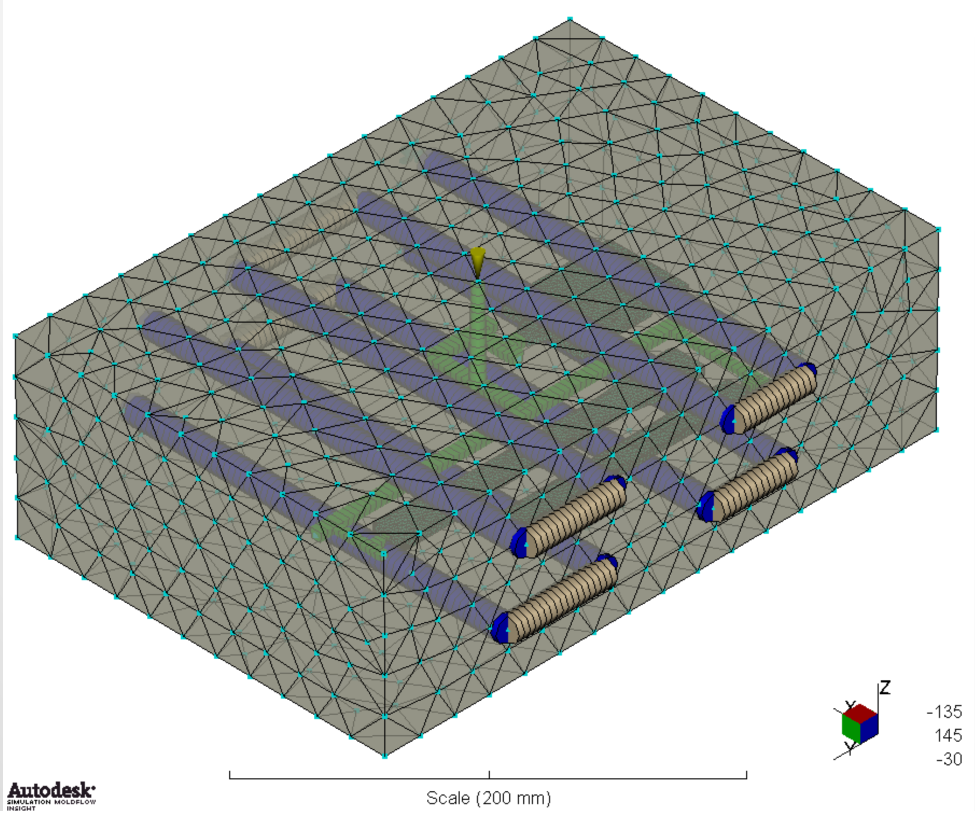
BEM Cooling Analysis

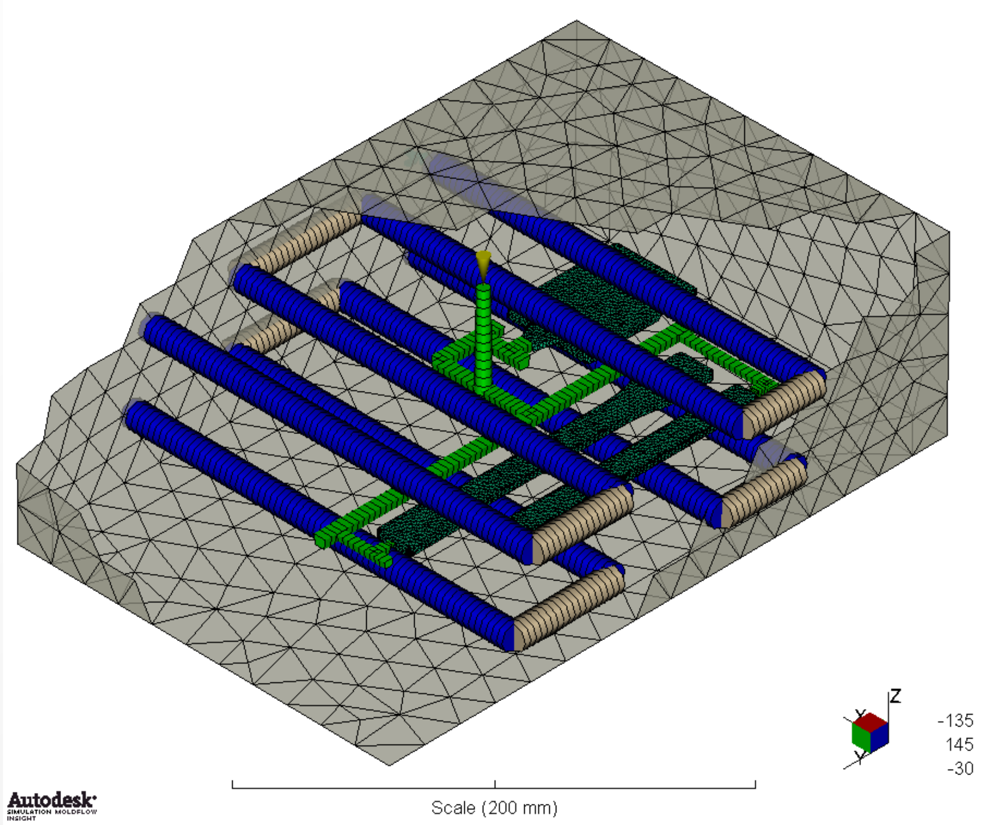
- Boundary Element Method
  - Steady-state solution

$$\cancelto{0}{\frac{\partial T}{\partial t}} = \alpha \nabla^2 T$$

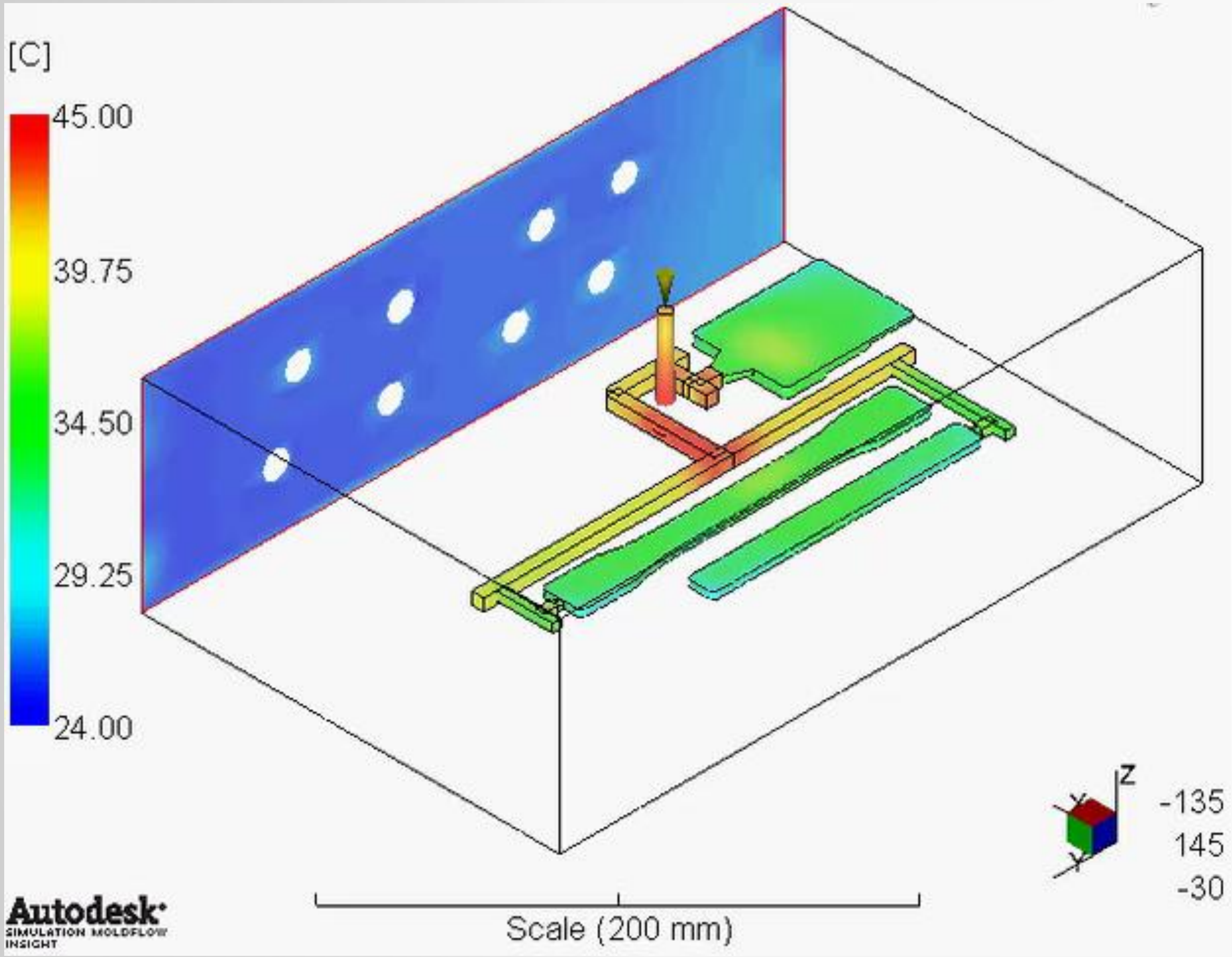


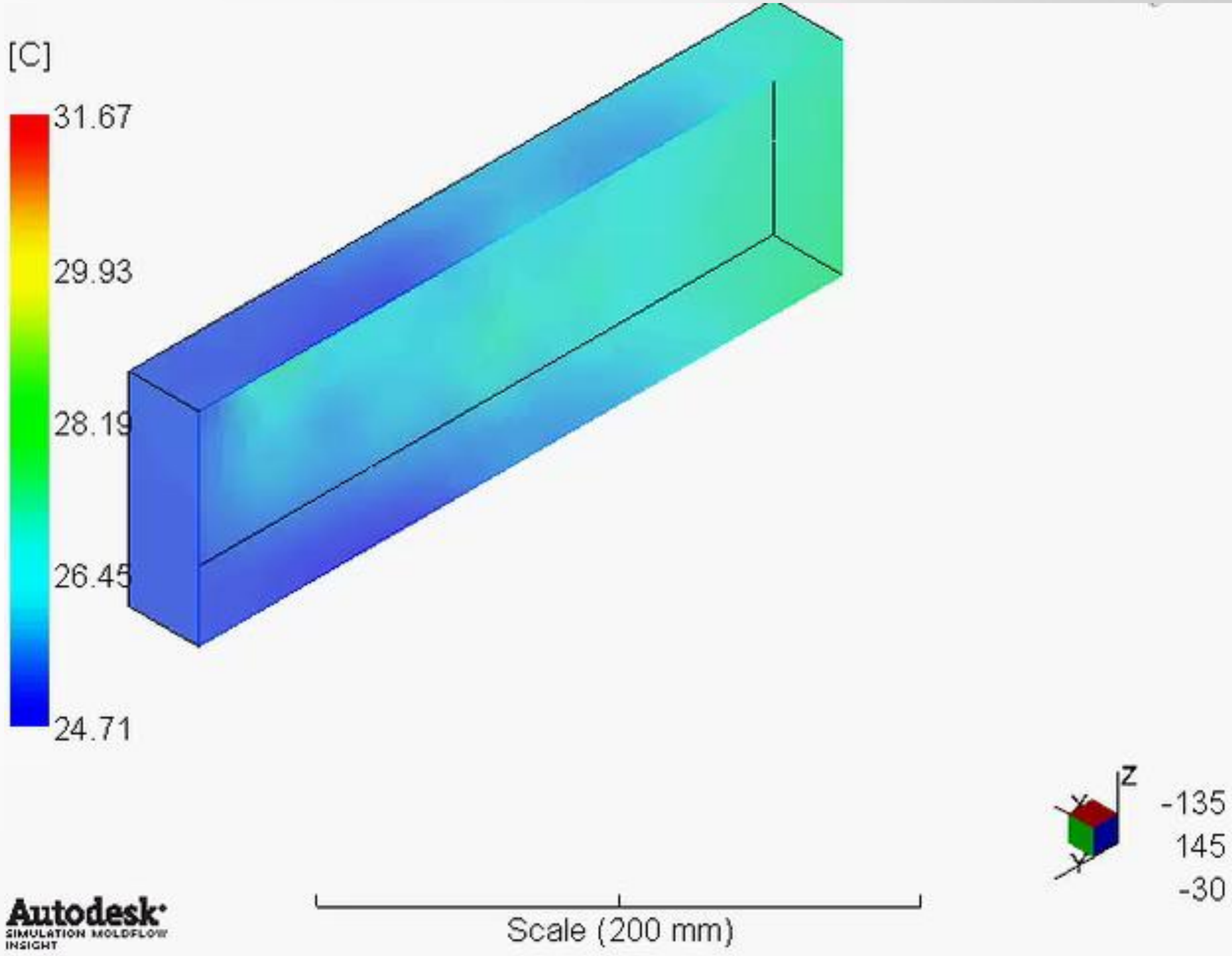
  - Surface mesh of the mold boundary





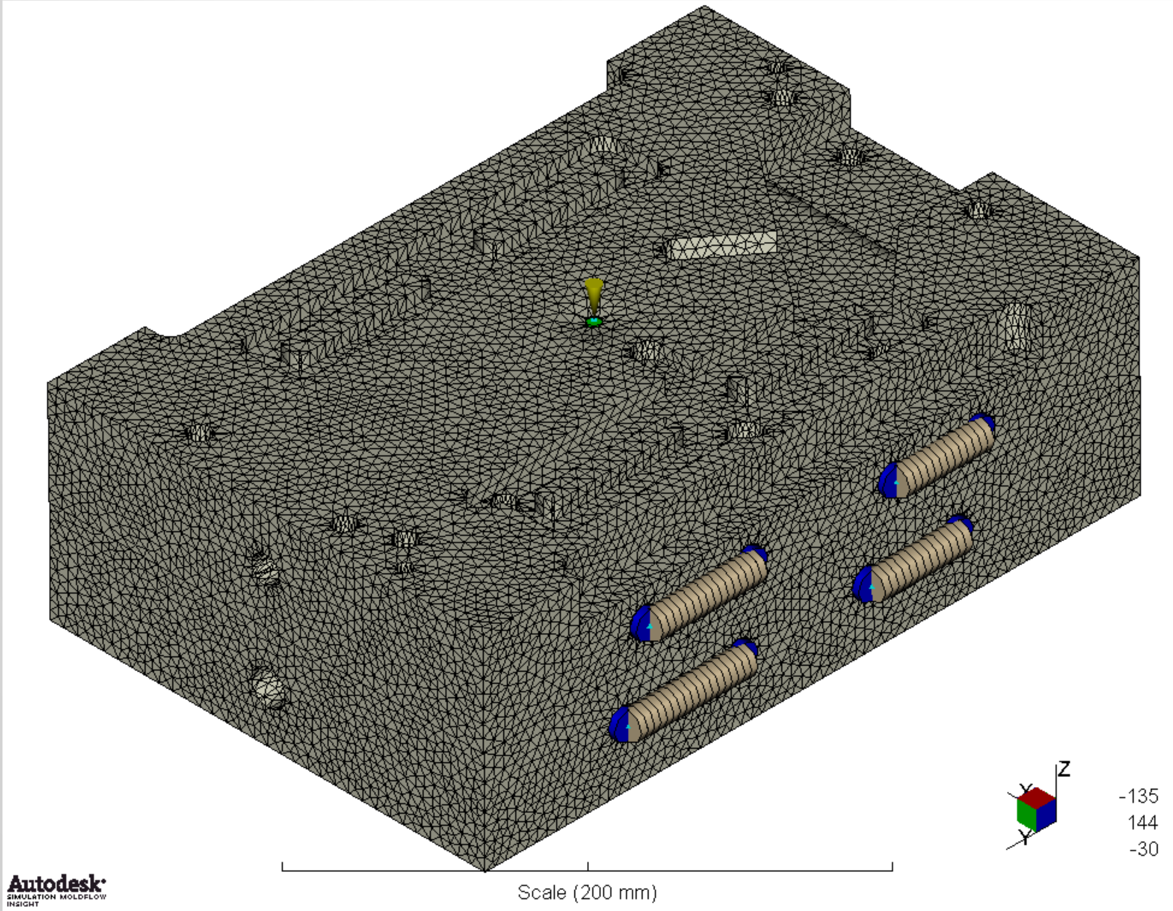
BEM Cooling Analysis

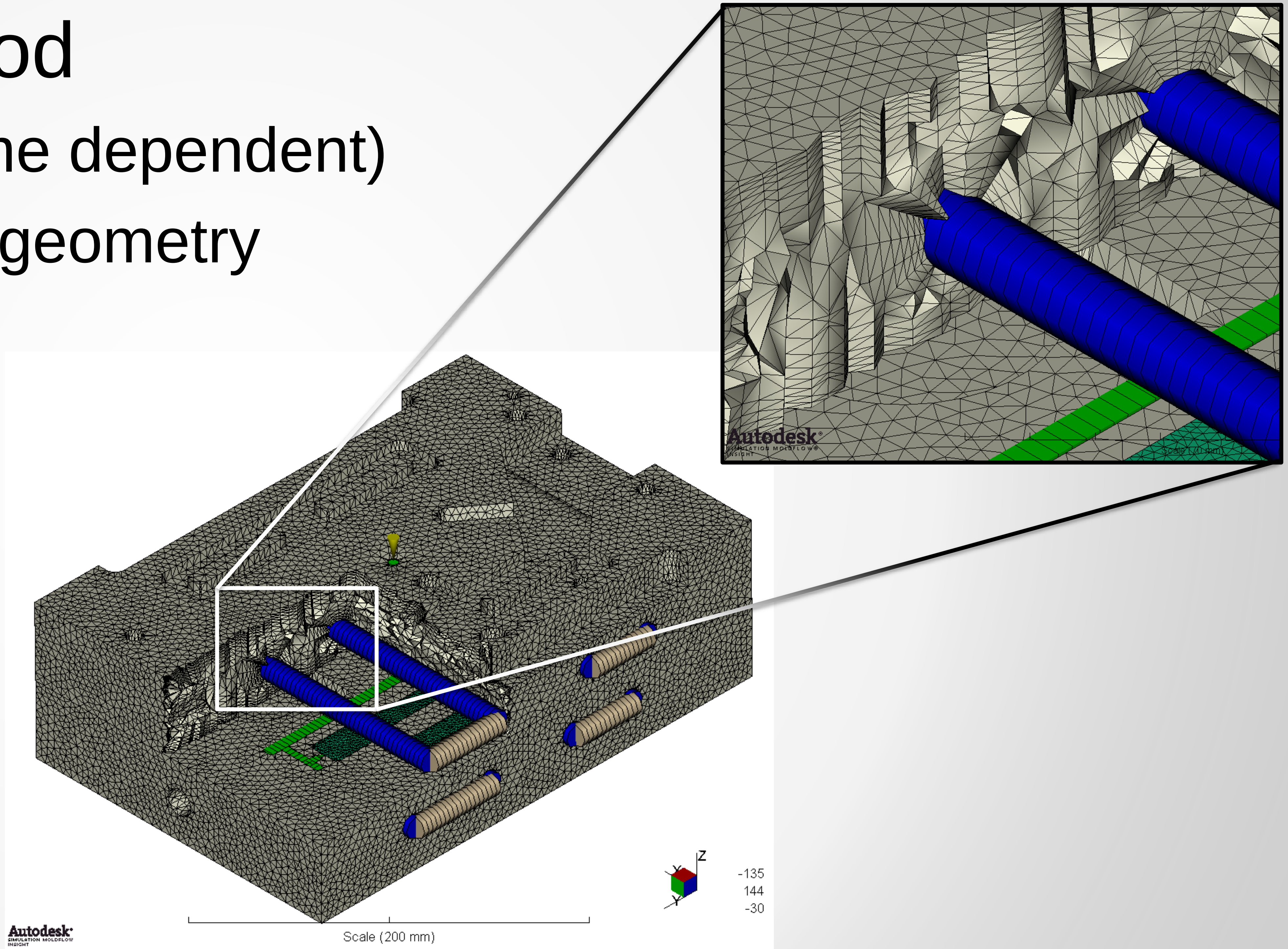




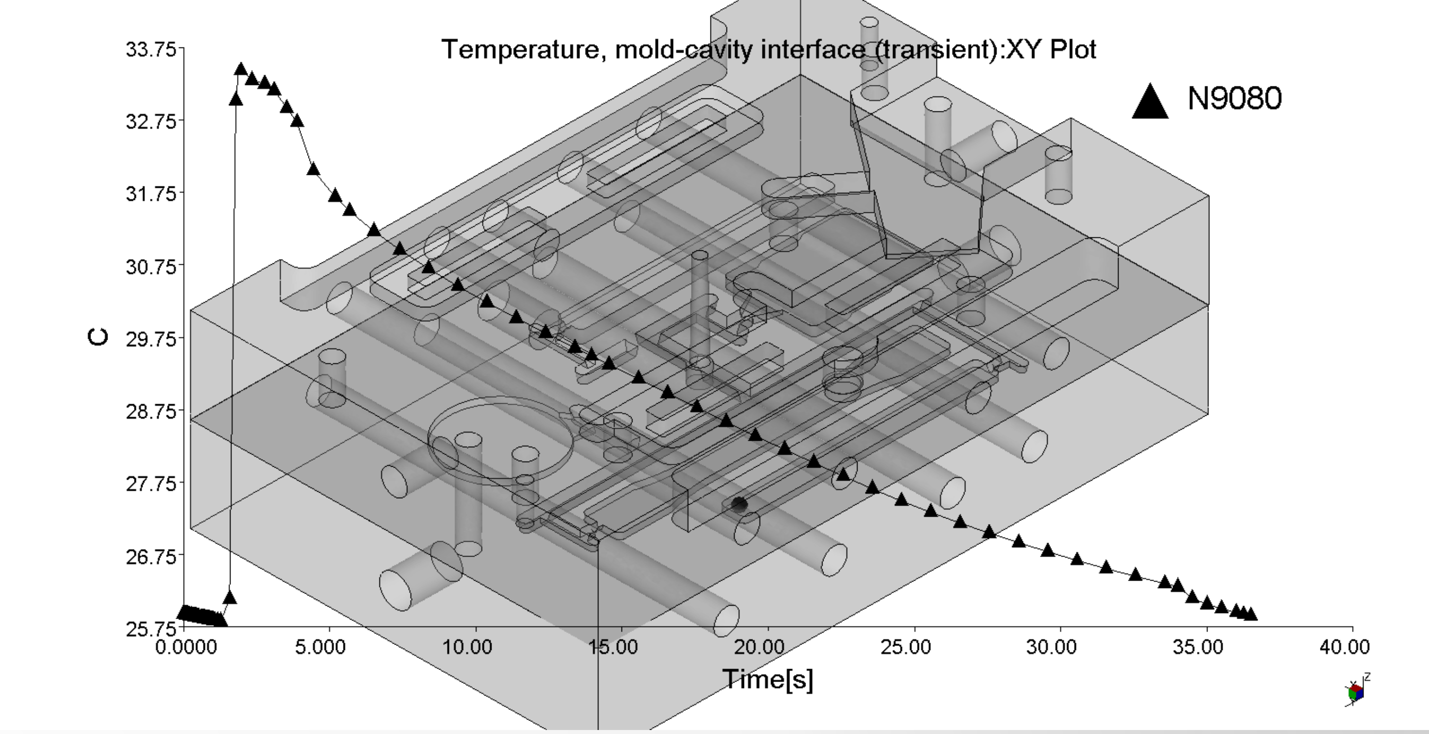
FEM Cooling Analysis

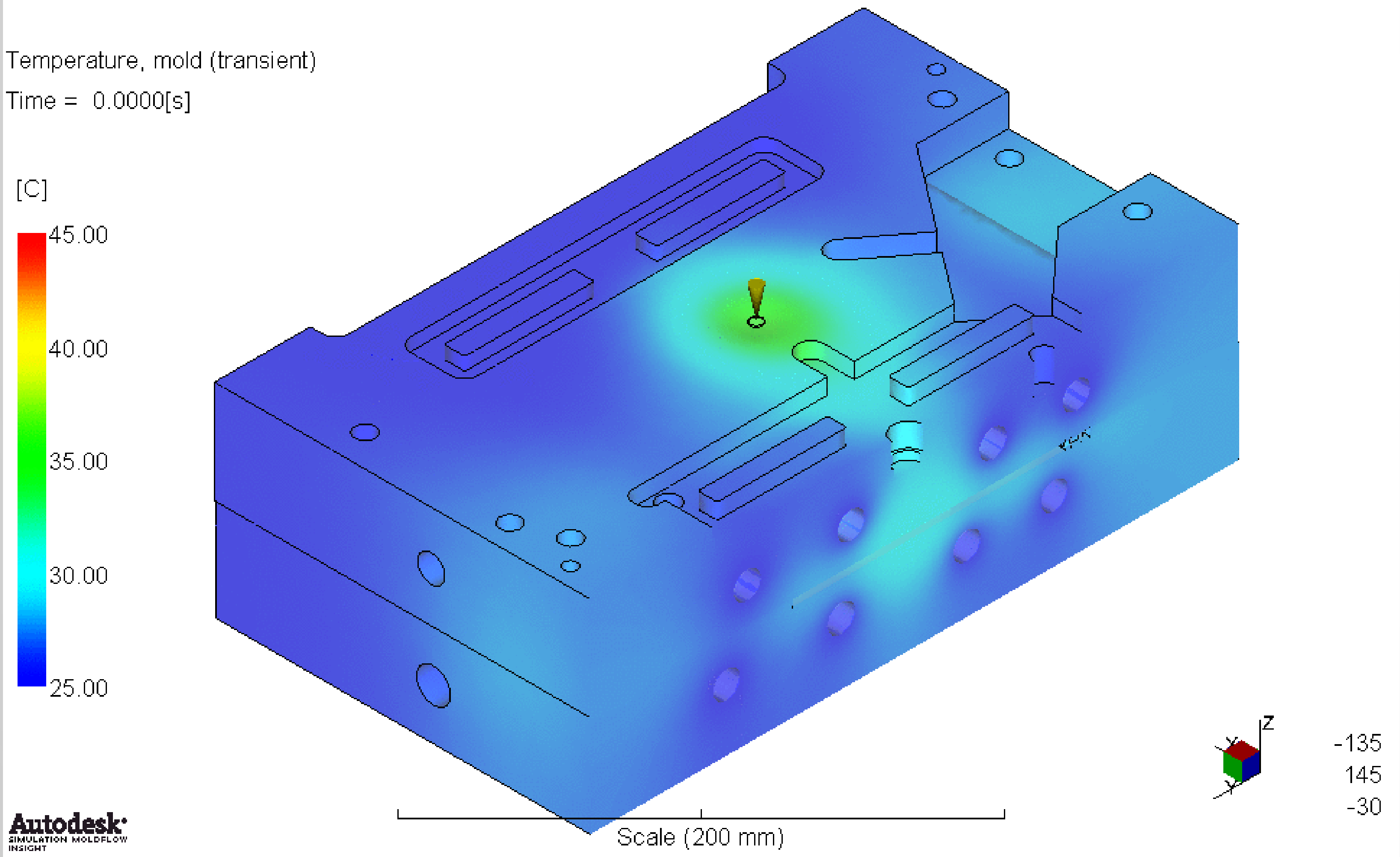
- Finite Element Method
  - Transient solution (time dependent)
  - 3D mesh of the mold geometry

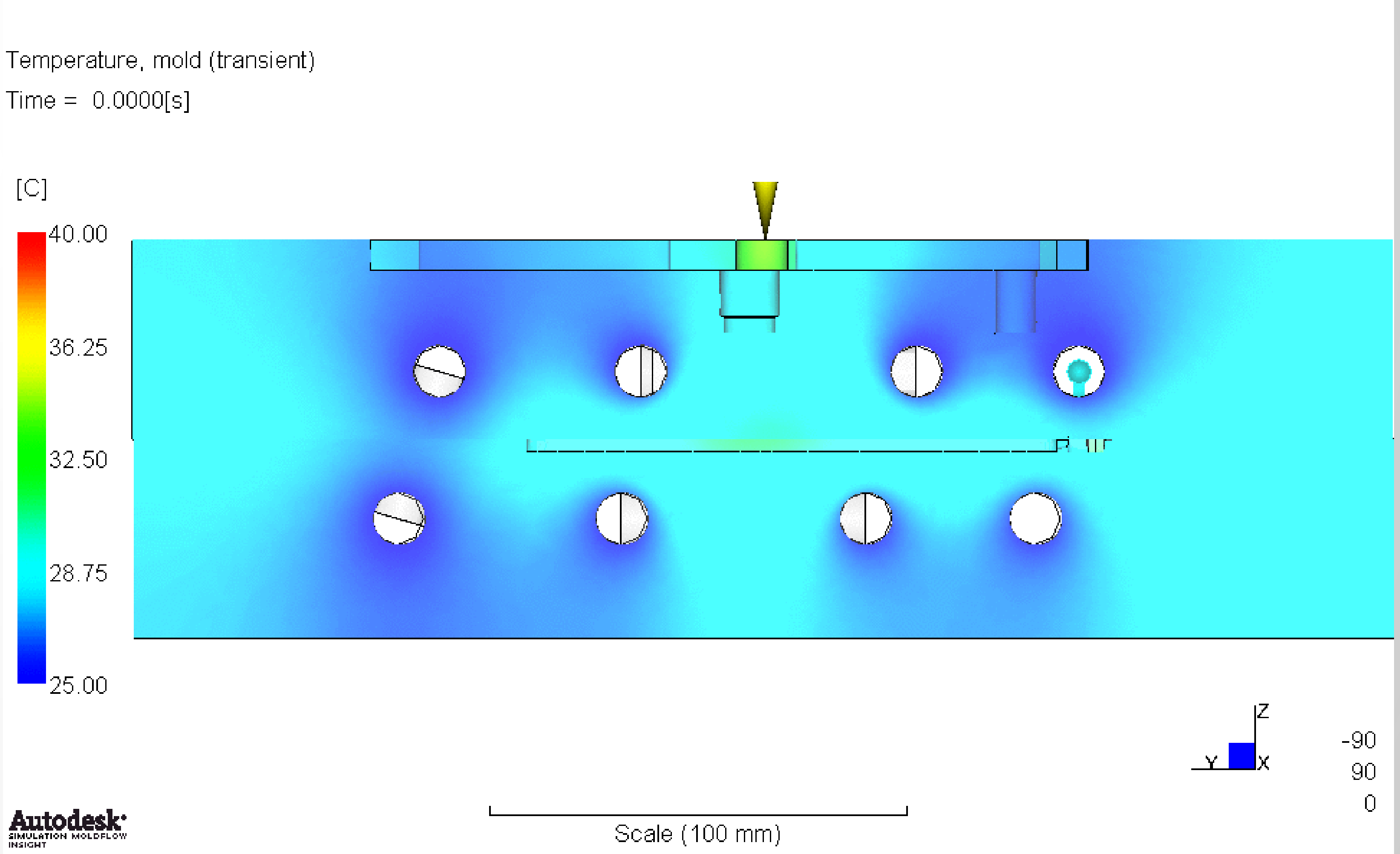




FEM Cooling Analysis







When to use FEM or BEM?

- FEM provides a time-dependent thermal solution of the mold
  - Heat transfer during the cycle
  - Heat accumulation between cycles

- FEM can determine time to reach a thermally stable cycle
  - Provides information about heat transfer rates in the mold

- BEM provides an average temperature useful to identify hot spots in the mold.

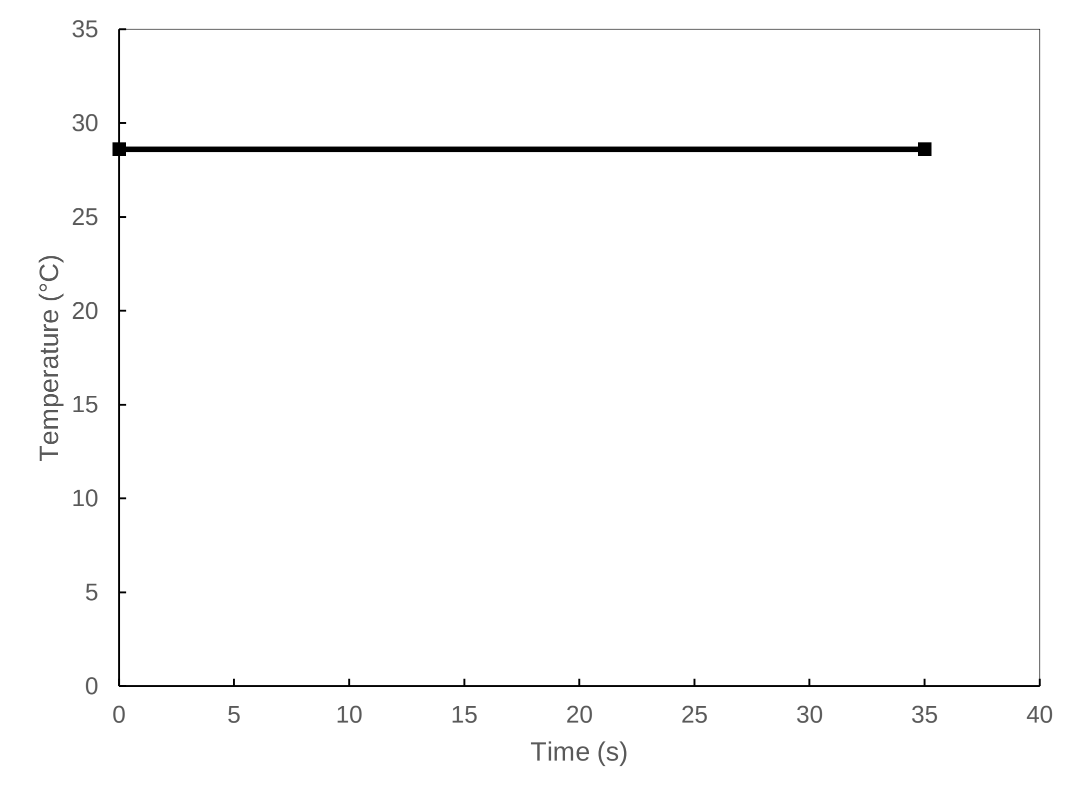
- BEM requires less computation time than FEM

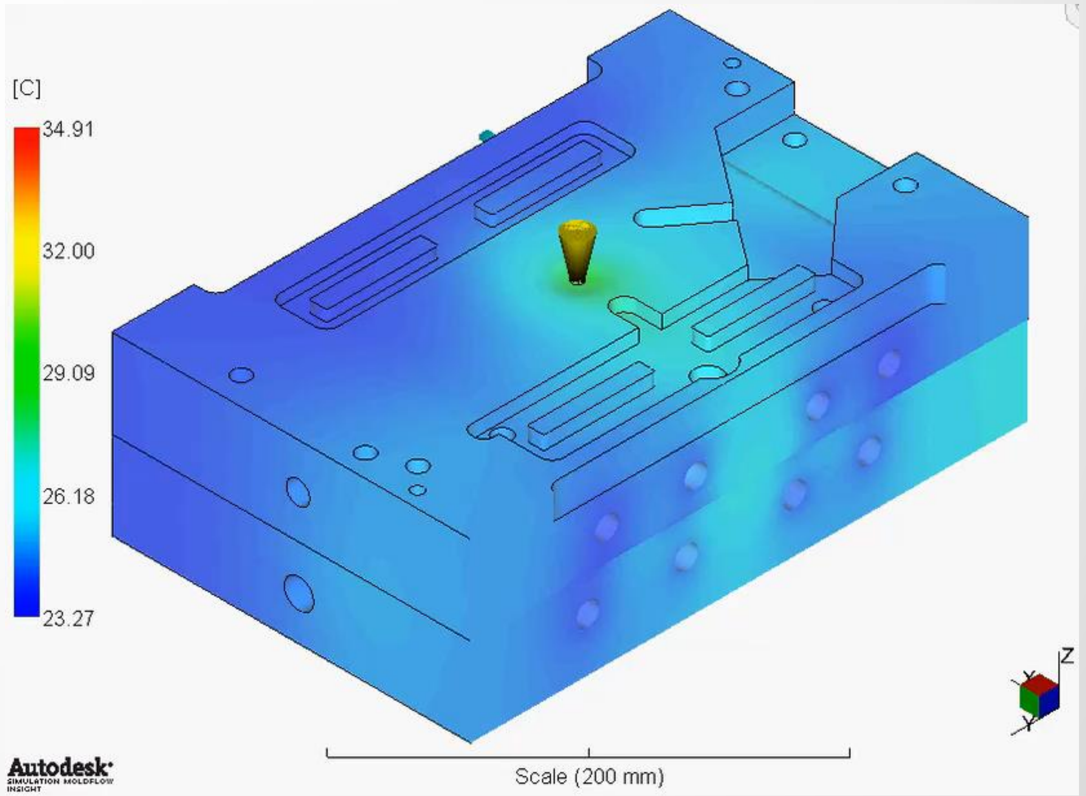
Mold Temperature Options

- There are 3 temperature options for the transient (FEM) cooling analysis:
  - Average within cycle
  - Transient within cycle
  - Transient from production start-up

Mold Temperature Options

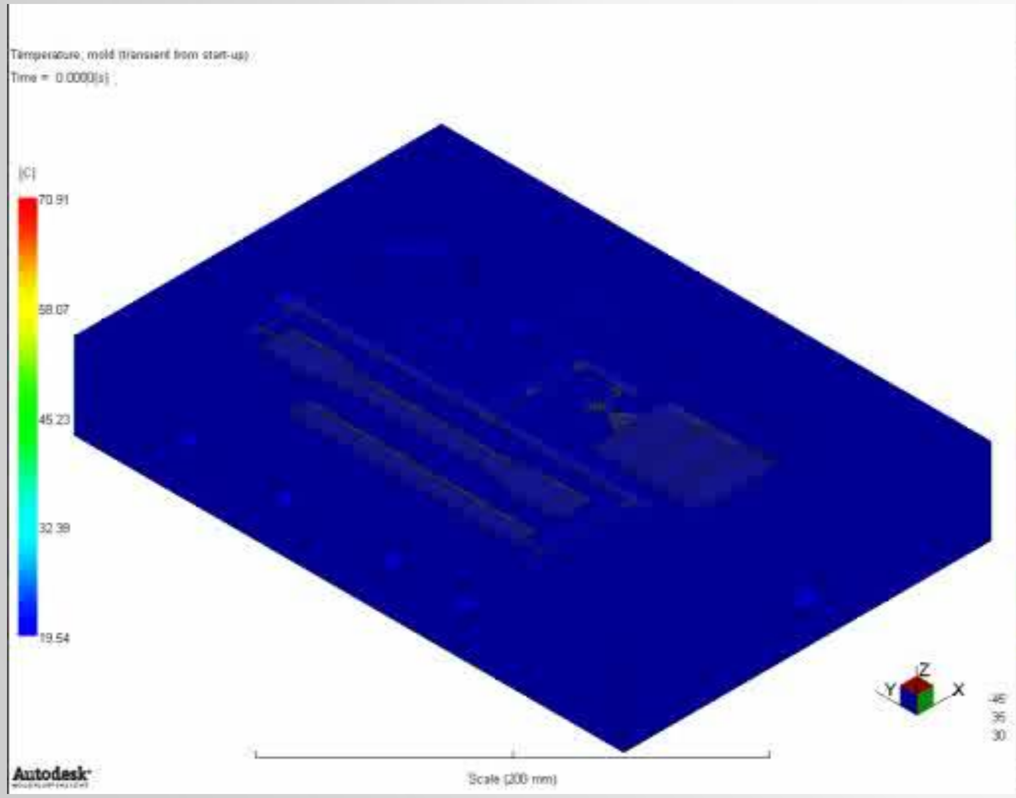
- Average within cycle
  - Similar to BEM solution
  - Average temperature throughout cycle for each location

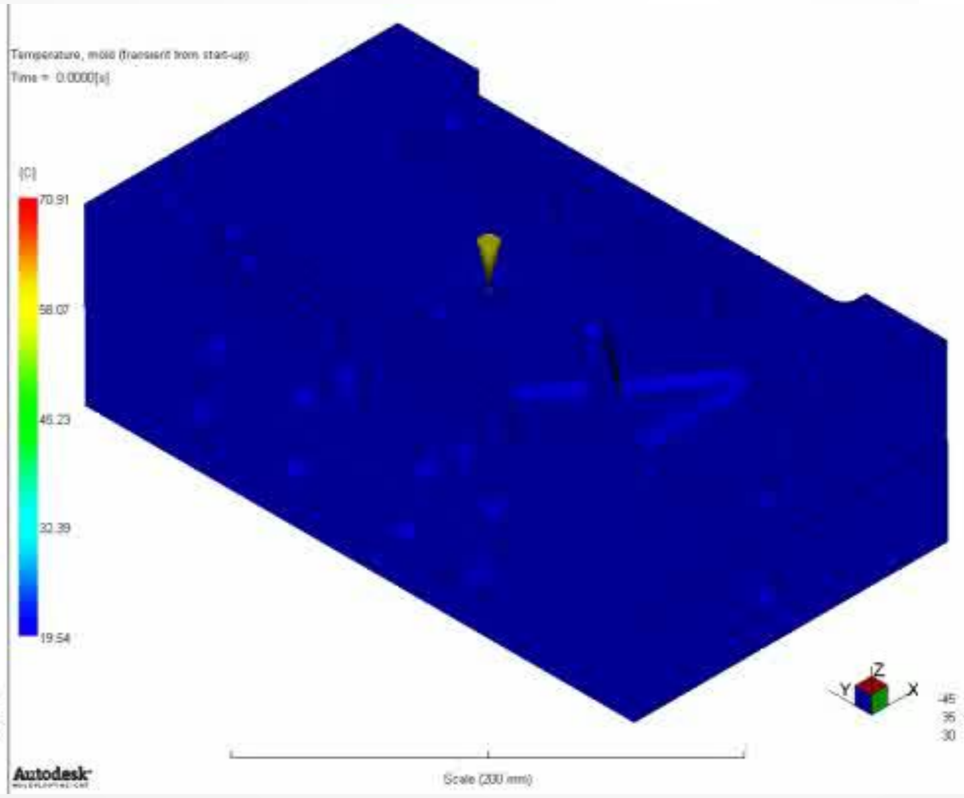


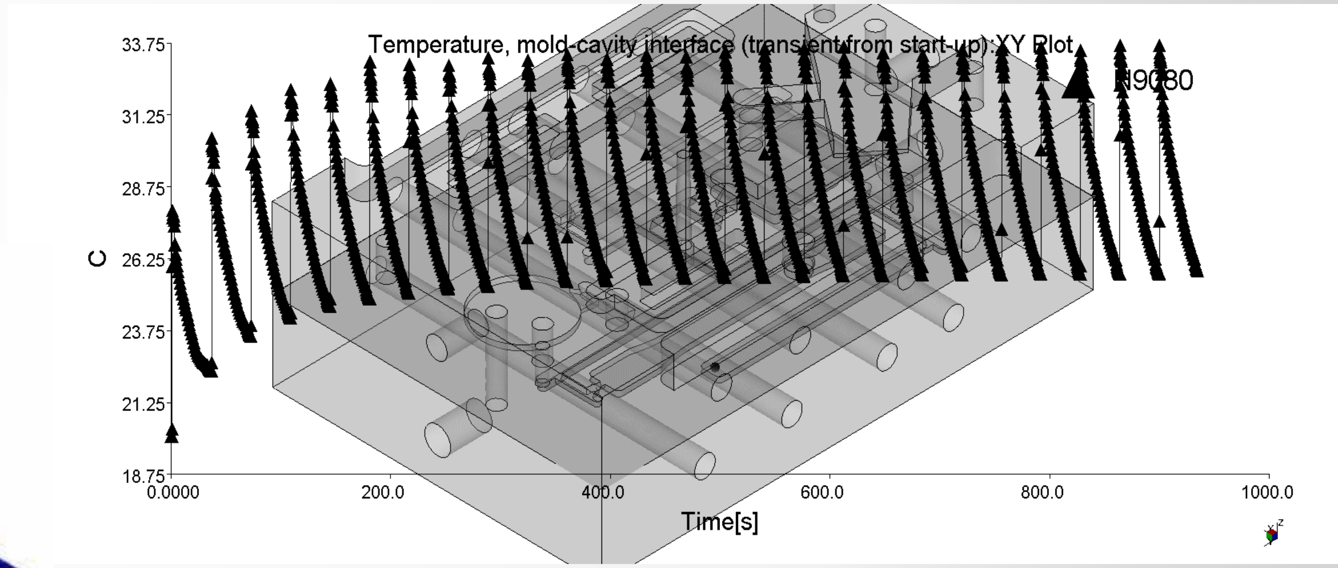


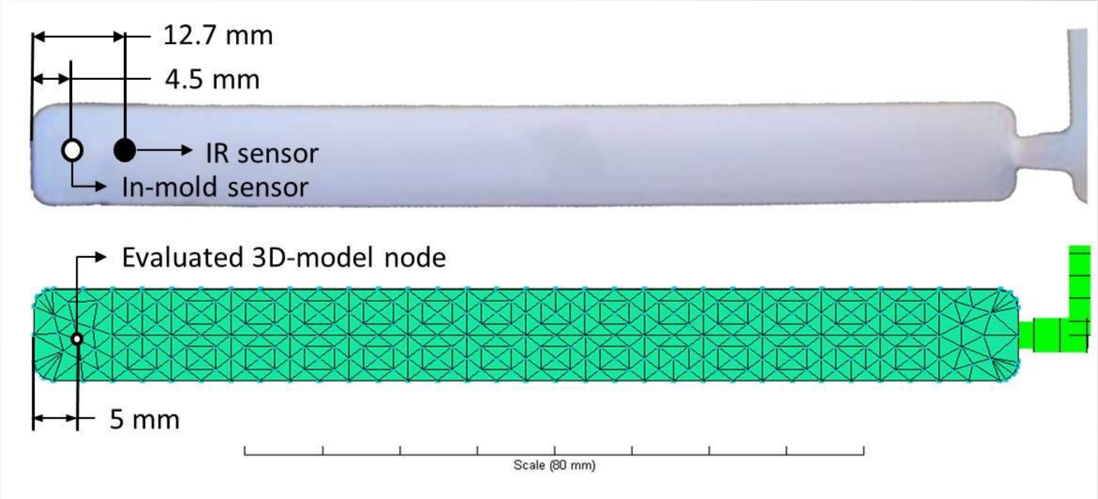
Mold Temperature Options

- Transient from production startup
  - Temperature development from startup cycle until thermal steady state is achieved.
  - Startup temperature set by user



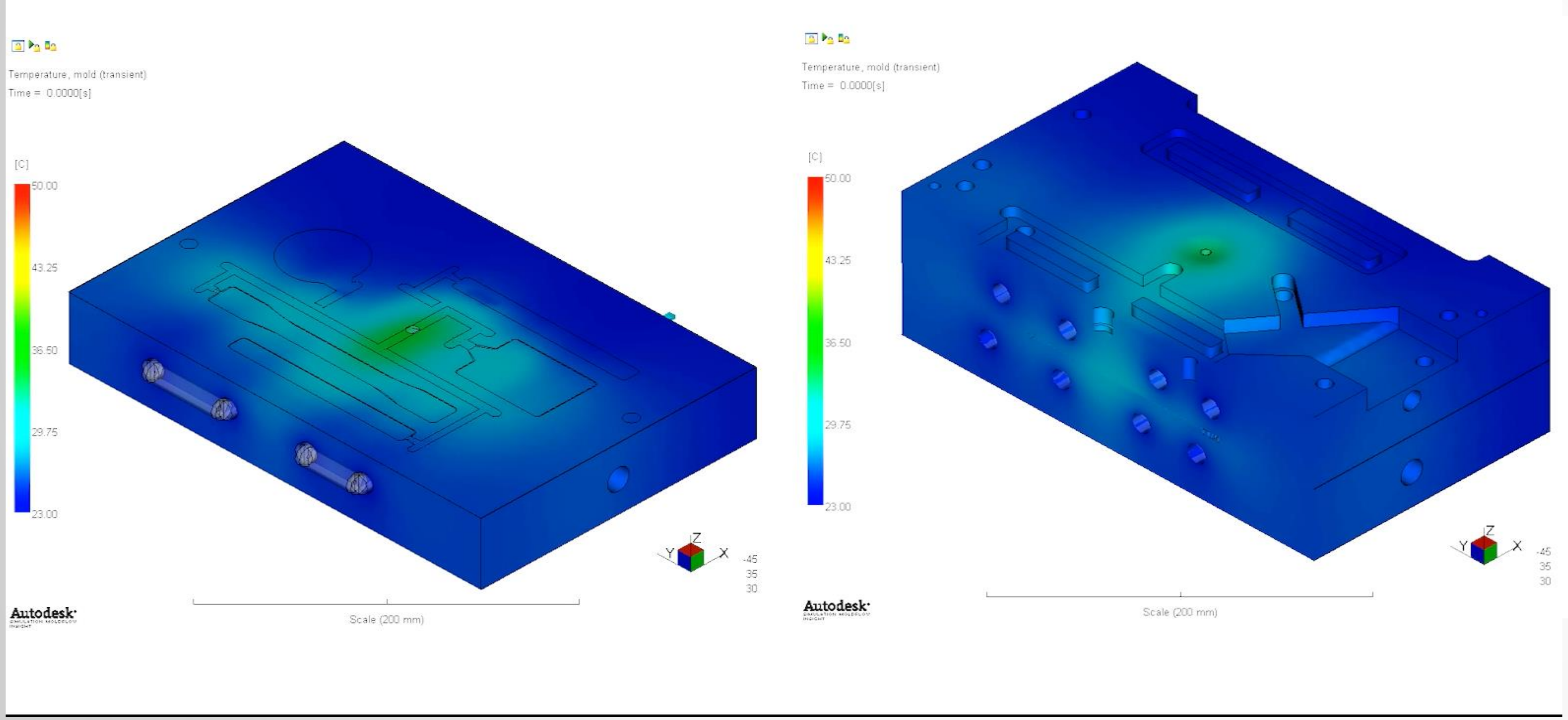


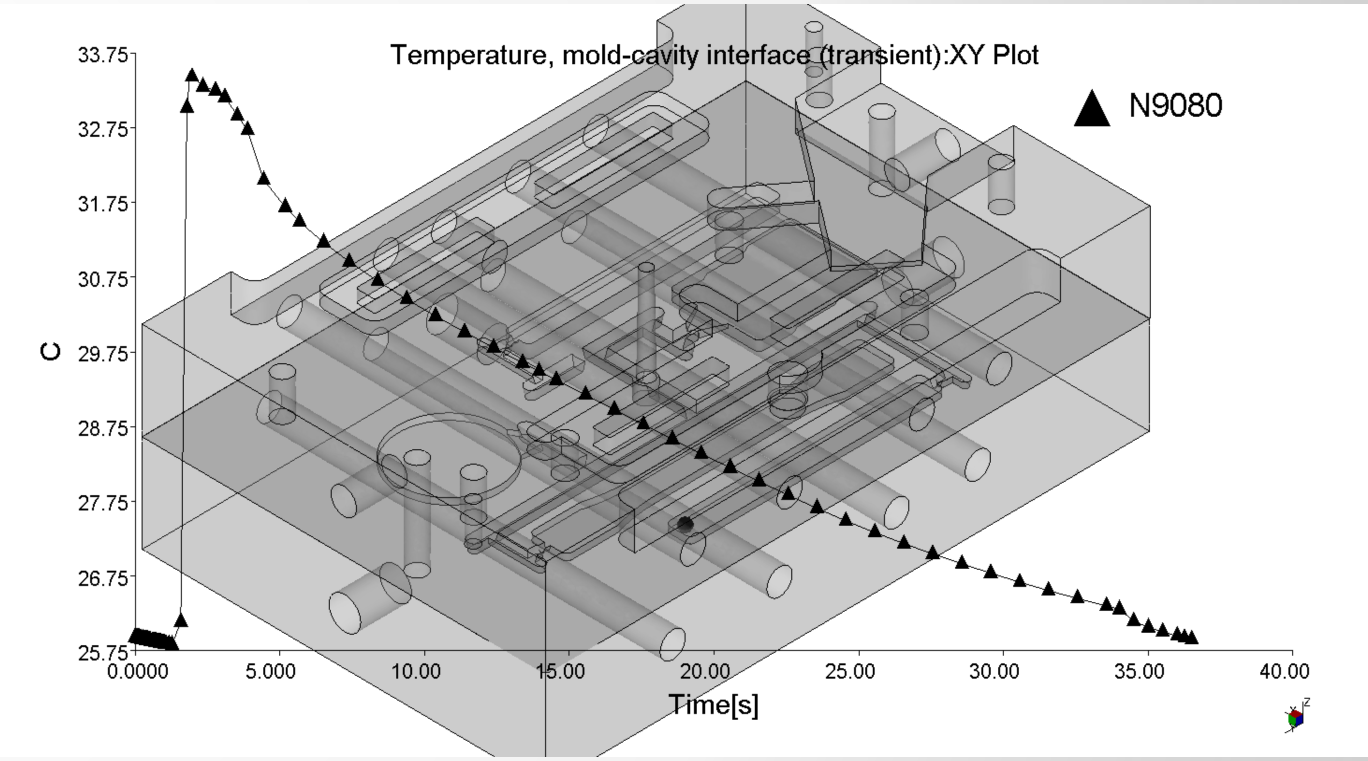




Mold Temperature Options

- Transient within cycle
  - Temperature at each time step for a stable cycle



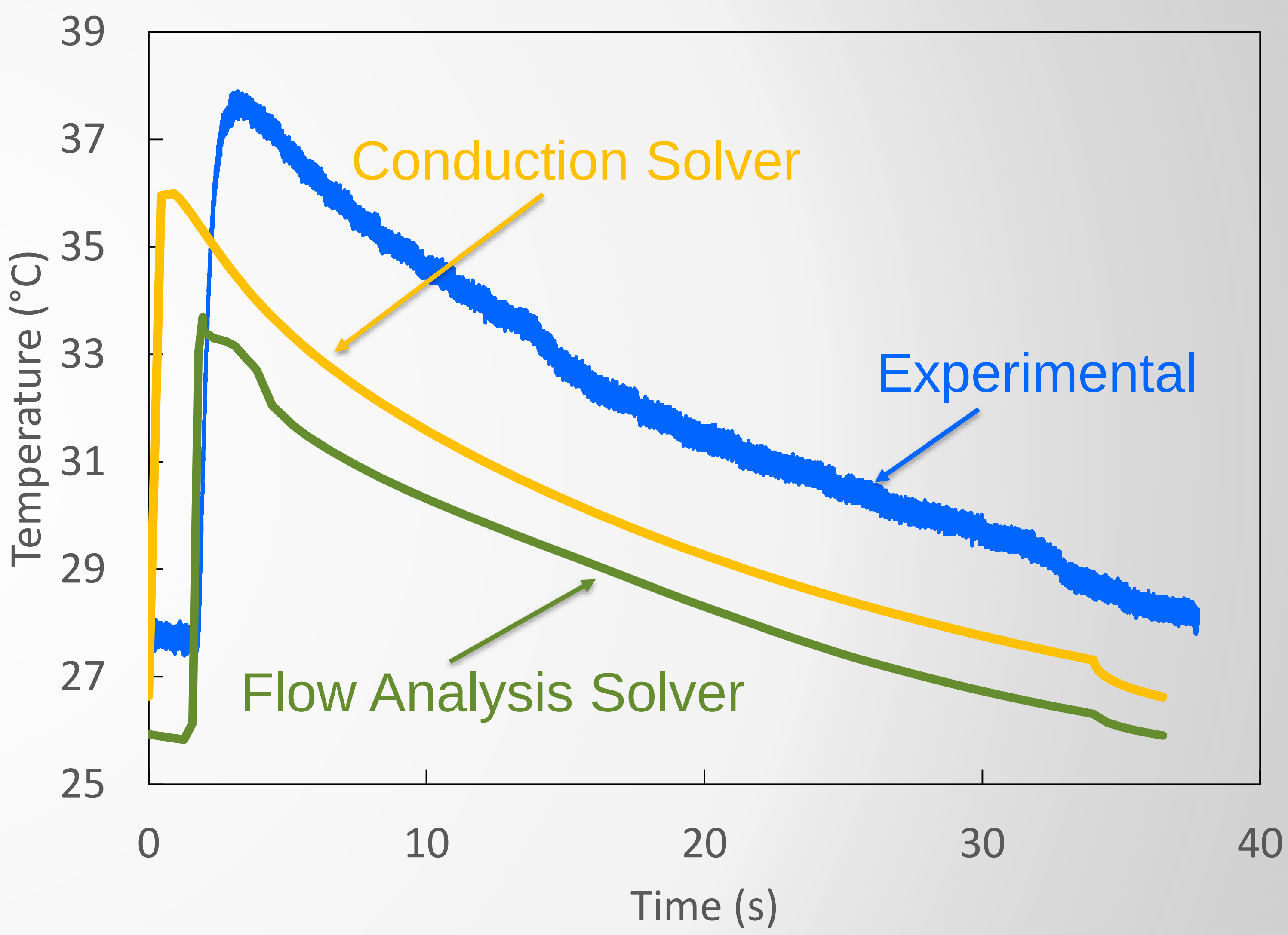


Solver options

- Two solvers are available for the FEM cooling analysis:
  - Conduction solver
    - Assumes cavity temperature equal to the nominal melt temperature
    - This temperature is achieved at the start of the analysis
    - Considers only heat conduction
  - Flow analysis on each iteration
    - Solves entire flow analysis and calculates temperature distribution using this data.
    - Uses the temperature data to perform the flow solution again.
    - The process is repeated until convergence.

Solver options

- Conduction solver had an immediate increase in the cavity-melt interface temperature
- The increase started at flow front arrival on the flow analysis solver
- Predicted temperature was higher for the conduction solution



Summary of Analysis Options

Solver	Main Characteristics	CPU time used	
		Conduction Solver	Flow Analysis Solver
Averaged within cycle	- Provides an average temperature - Equivalent to BEM results - Not time dependent	5,269 s (1.5 h) 1x	103,730 (28.8 h) 19x
Transient within cycle	- Provides a temperature at a ***stable cycle*** - Time dependent	21,272 s (5.9 h) 4x	194,070 s (53.9 h) 36x
Transient from Startup	- Provides temperature development from process startup - Stops at ***stable cycle*** (steady state) - Time dependent	114,898 s (31.9 h) 21x	842,432 s (234.0 h) 156x

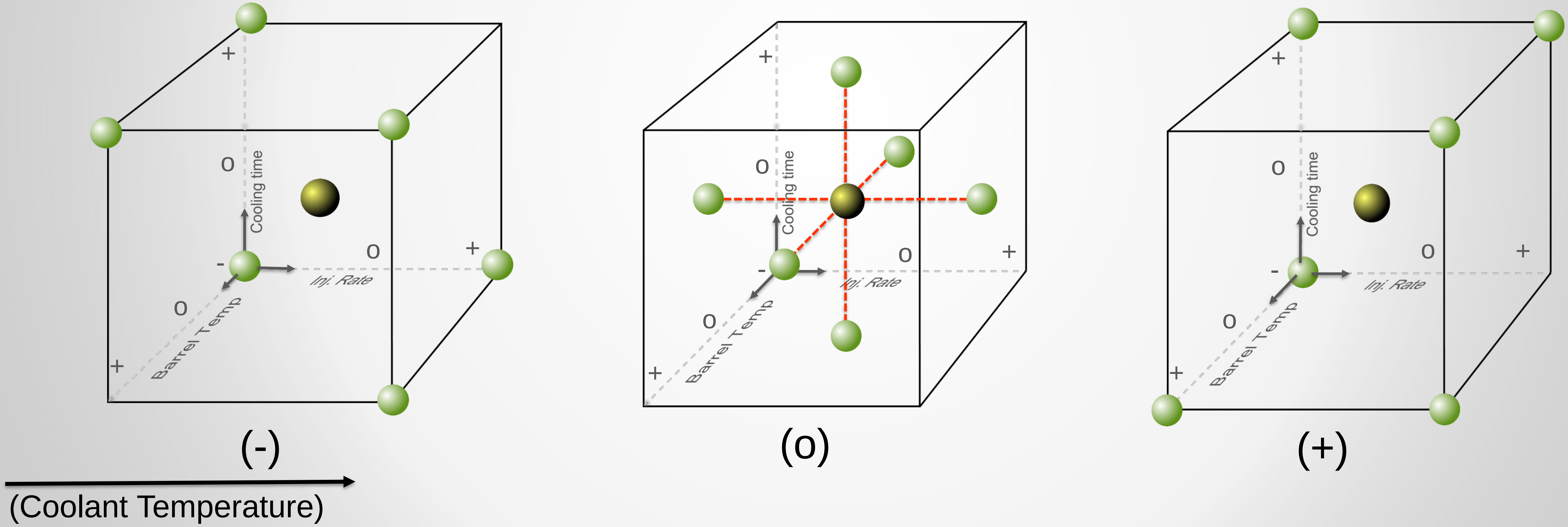
Normalized time

Experimental and Simulation Results

Design of Experiments (DOE)

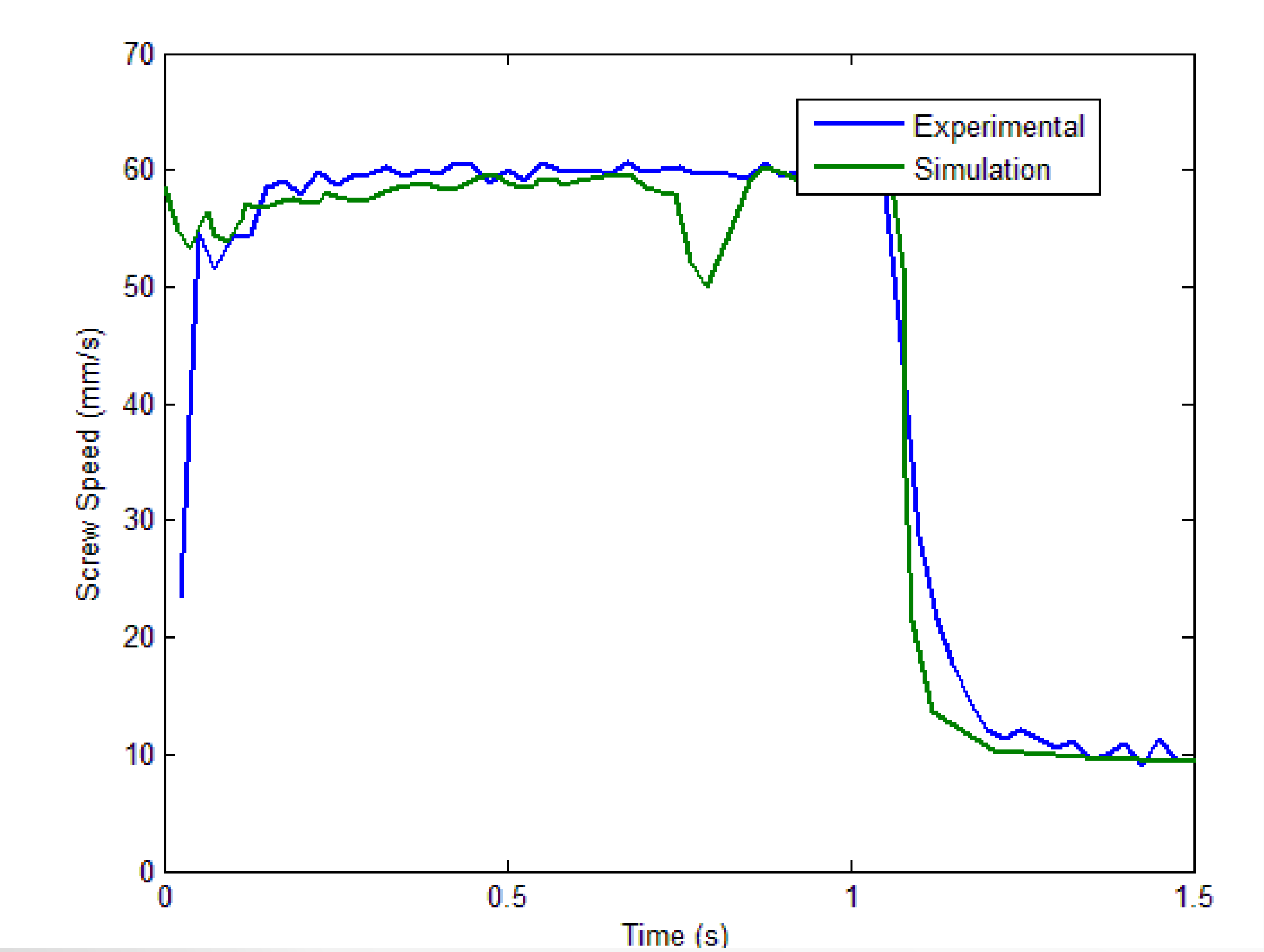
- Central composite design (21 runs)
  - Each run simulated with transient from startup using flow analysis solver

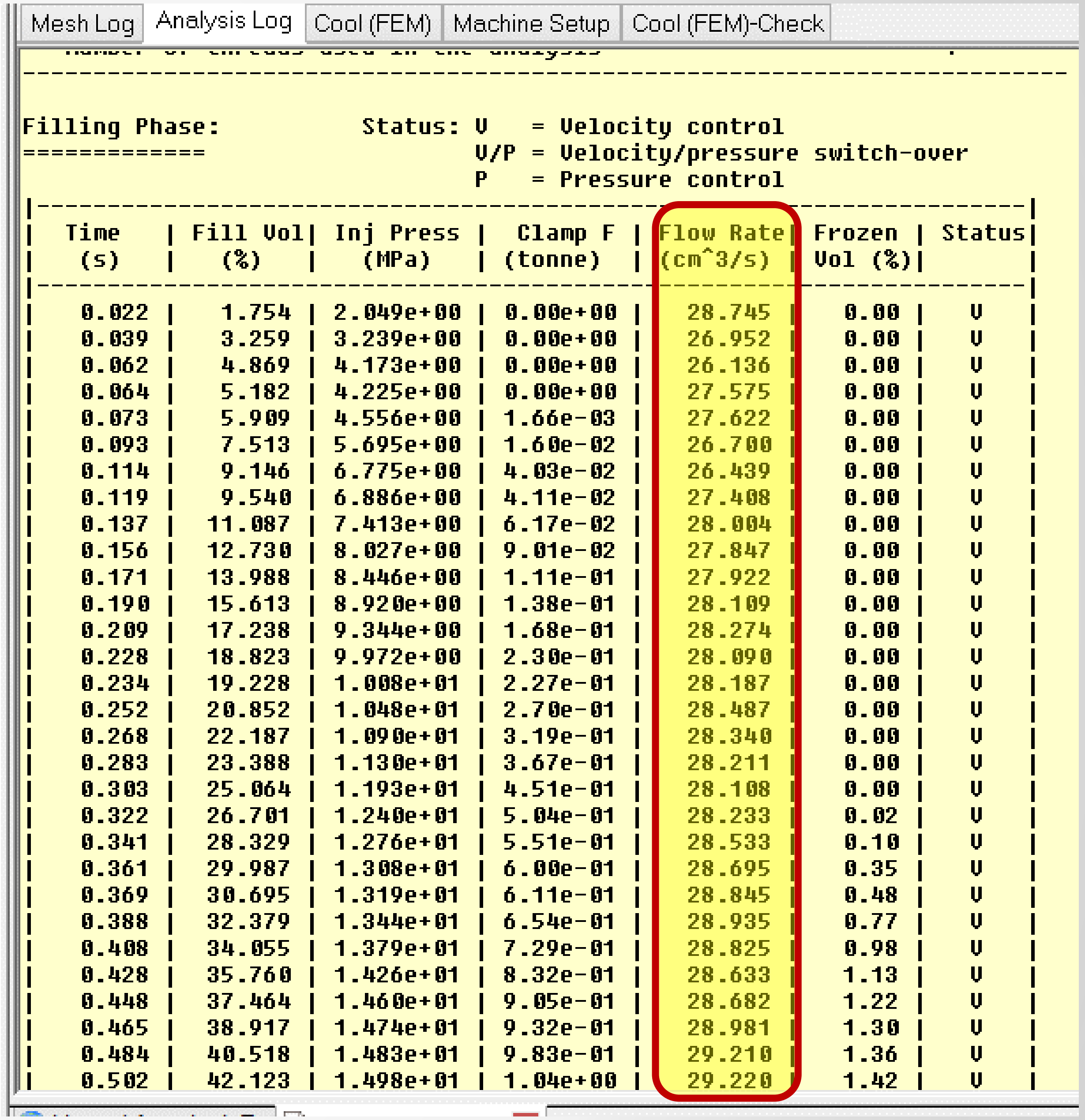
Level	Barrel Temp.	Coolant Temp.	Injection Rate	Cooling Time
-	210 °C	20 °C	60 mm/s	20 s
o	230 °C	35 °C	80 mm/s	25 s
+	250 °C	50 °C	100 mm/s	30 s



Simulation vs. Experimentation

- Injection rate





Filling Phase: Status: V = Velocity control
V/P = Velocity/pressure switch-over
P = Pressure control

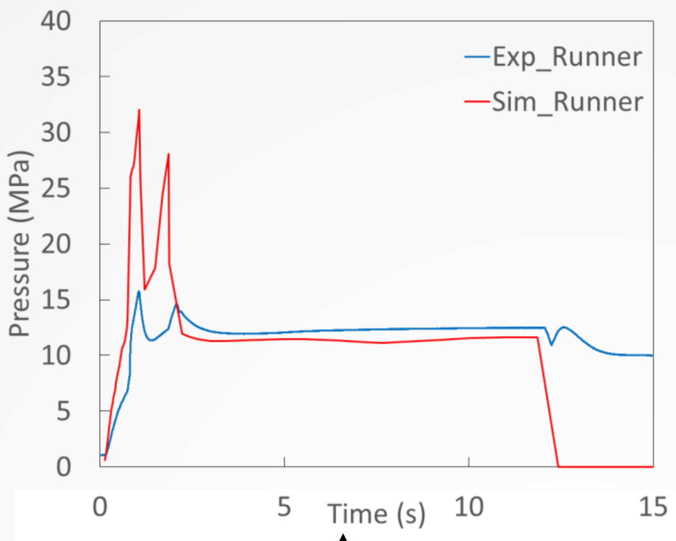
Time (s)	Fill Vol (%)	Inj Press (MPa)	Clamp F (tonne)	Flow Rate (cm^3/s)	Frozen Vol (%)	Status
0.022	1.754	2.049e+00	0.00e+00	28.745	0.00	V
0.039	3.259	3.239e+00	0.00e+00	26.952	0.00	V
0.062	4.869	4.173e+00	0.00e+00	26.136	0.00	V
0.064	5.182	4.225e+00	0.00e+00	27.575	0.00	V
0.073	5.909	4.556e+00	1.66e-03	27.622	0.00	V
0.093	7.513	5.695e+00	1.60e-02	26.700	0.00	V
0.114	9.146	6.775e+00	4.03e-02	26.439	0.00	V
0.119	9.540	6.886e+00	4.11e-02	27.408	0.00	V
0.137	11.087	7.413e+00	6.17e-02	28.004	0.00	V
0.156	12.730	8.027e+00	9.01e-02	27.847	0.00	V
0.171	13.988	8.446e+00	1.11e-01	27.922	0.00	V
0.190	15.613	8.920e+00	1.38e-01	28.109	0.00	V
0.209	17.238	9.344e+00	1.68e-01	28.274	0.00	V
0.228	18.823	9.972e+00	2.30e-01	28.090	0.00	V
0.234	19.228	1.008e+01	2.27e-01	28.187	0.00	V
0.252	20.852	1.048e+01	2.70e-01	28.487	0.00	V
0.268	22.187	1.090e+01	3.19e-01	28.340	0.00	V
0.283	23.388	1.130e+01	3.67e-01	28.211	0.00	V
0.303	25.064	1.193e+01	4.51e-01	28.108	0.00	V
0.322	26.701	1.240e+01	5.04e-01	28.233	0.02	V
0.341	28.329	1.276e+01	5.51e-01	28.533	0.10	V
0.361	29.987	1.308e+01	6.00e-01	28.695	0.35	V
0.369	30.695	1.319e+01	6.11e-01	28.845	0.48	V
0.388	32.379	1.344e+01	6.54e-01	28.935	0.77	V
0.408	34.055	1.379e+01	7.29e-01	28.825	0.98	V
0.428	35.760	1.426e+01	8.32e-01	28.633	1.13	V
0.448	37.464	1.460e+01	9.05e-01	28.682	1.22	V
0.465	38.917	1.474e+01	9.32e-01	28.981	1.30	V
0.484	40.518	1.483e+01	9.83e-01	29.210	1.36	V
0.502	42.123	1.498e+01	1.04e+00	29.220	1.42	V

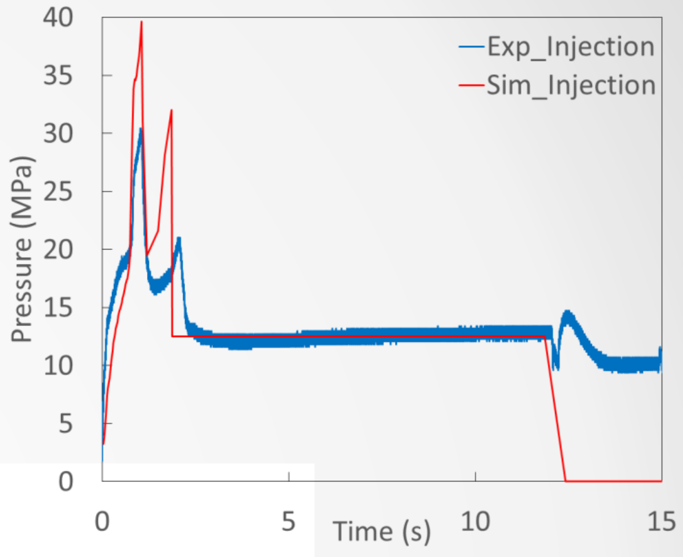
Filling data only available for cooling sequence when running flow analysis solver

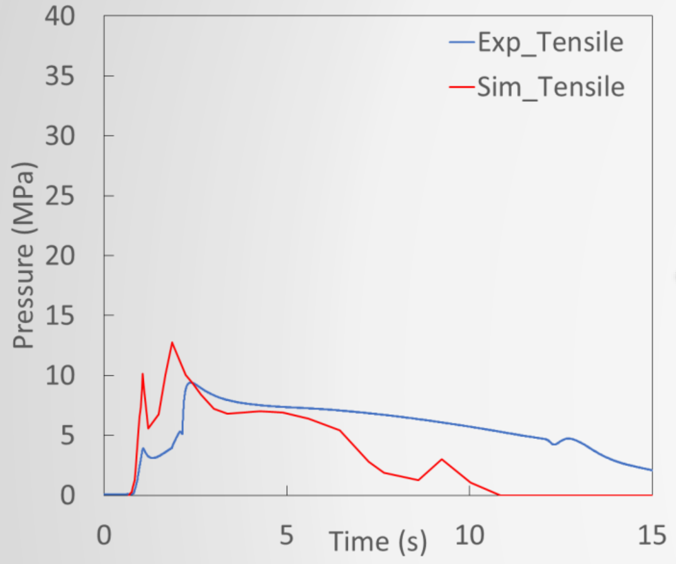
Run 1	Barrel Temp.	Coolant Temp.	Injection Rate	Cooling Time
	210 °C	20 °C	60 mm/s	20 s

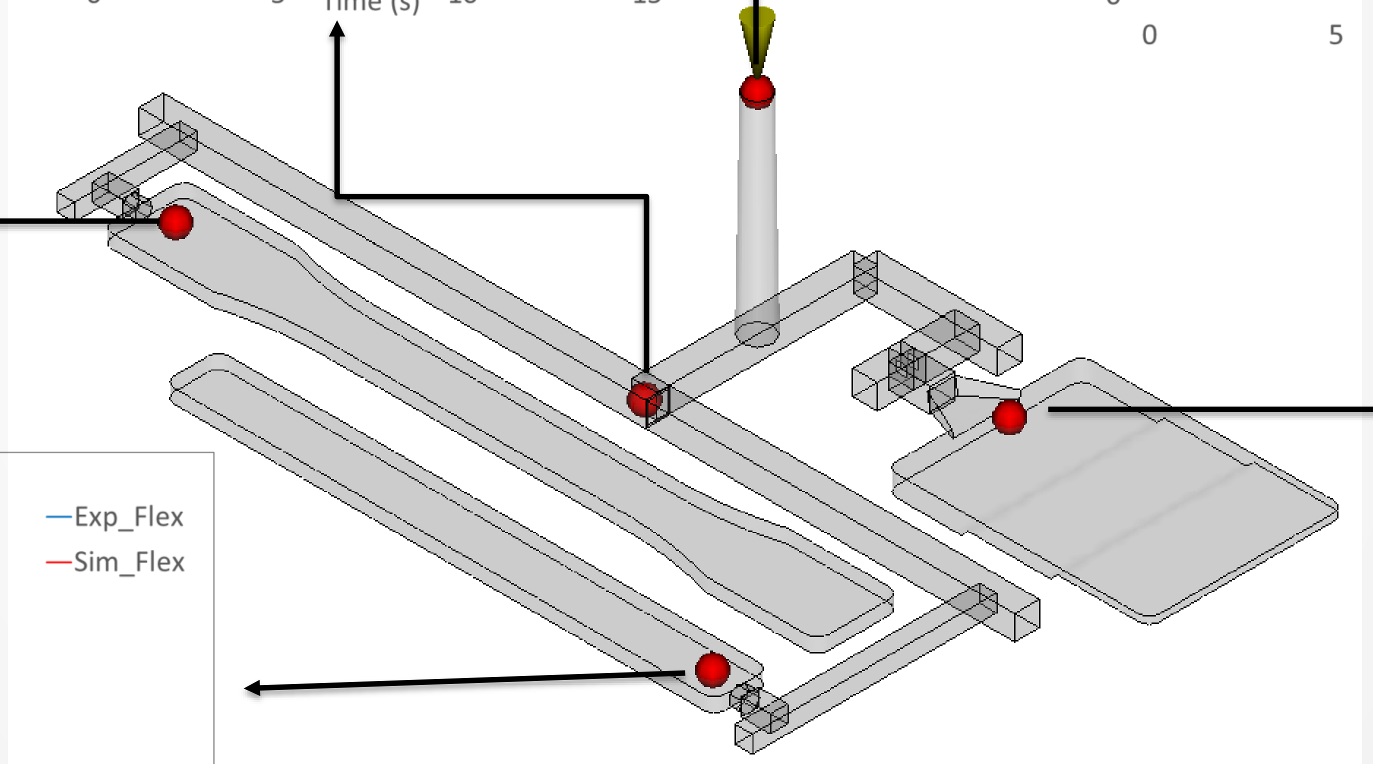
Simulation vs. Experimentation

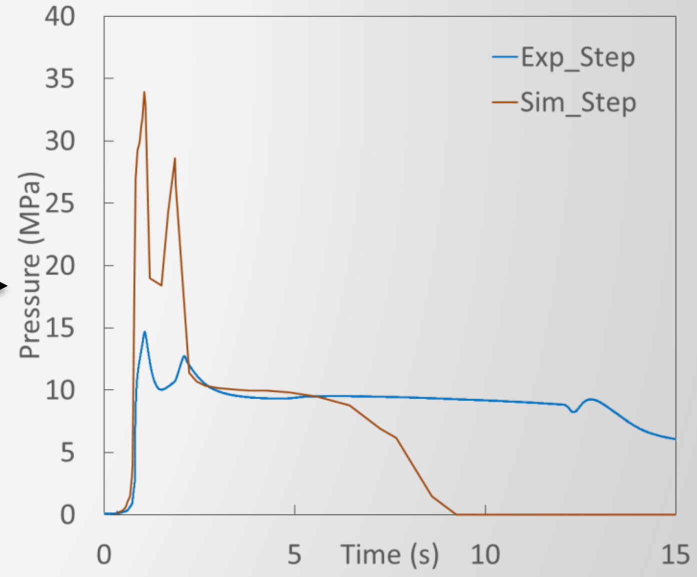
- Pressure

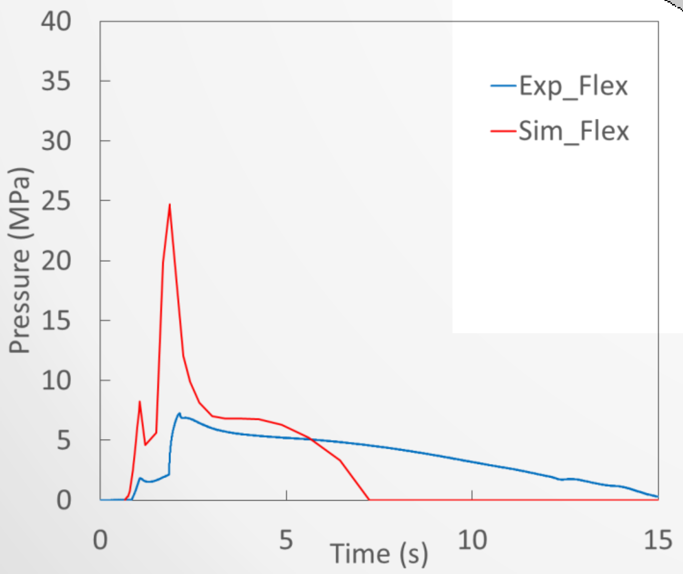








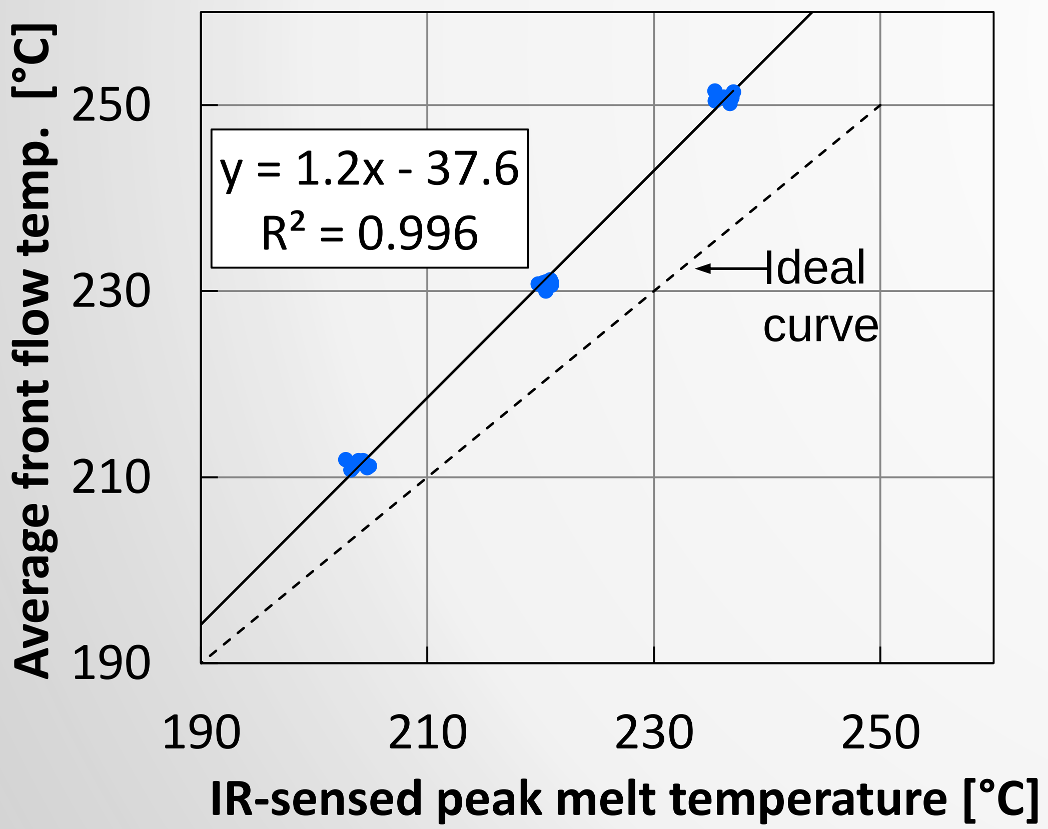


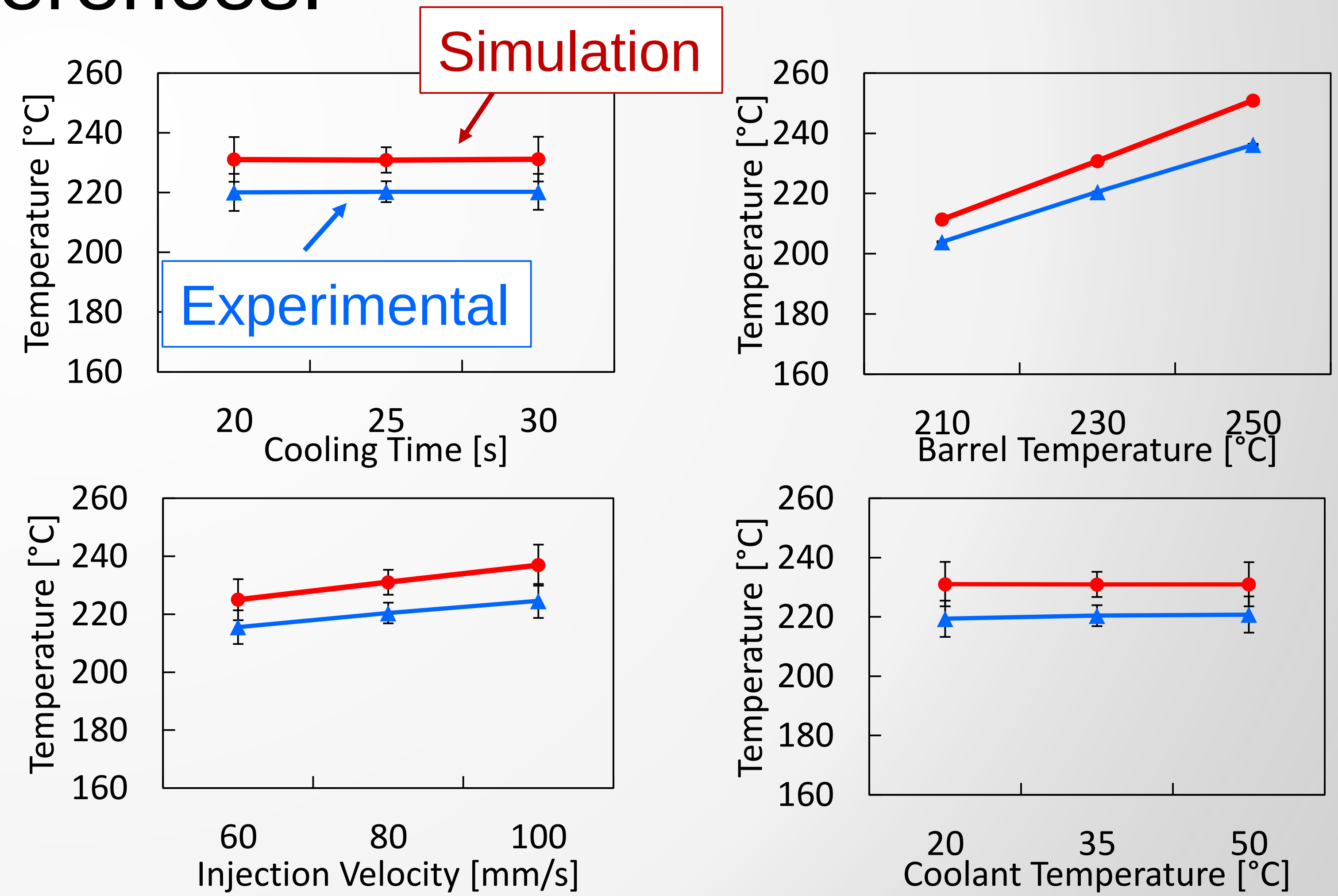


Run 1	Barrel Temp.	Coolant Temp.	Injection Rate	Cooling Time
	210 °C	20 °C	60 mm/s	20 s

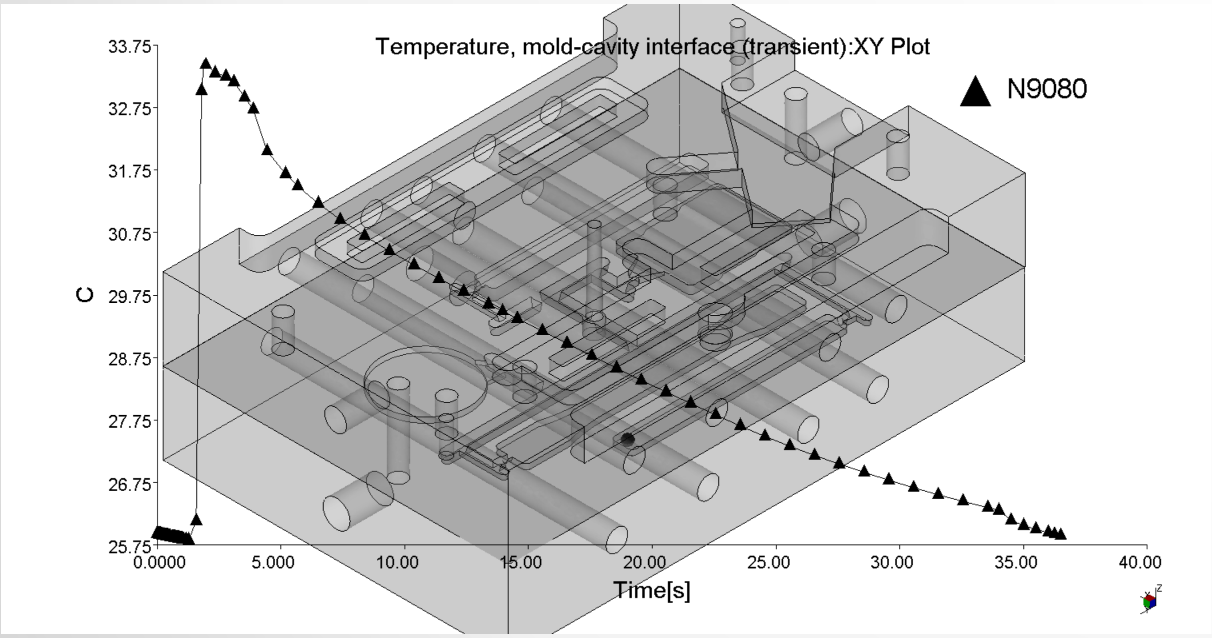
Simulation vs. Experimentation

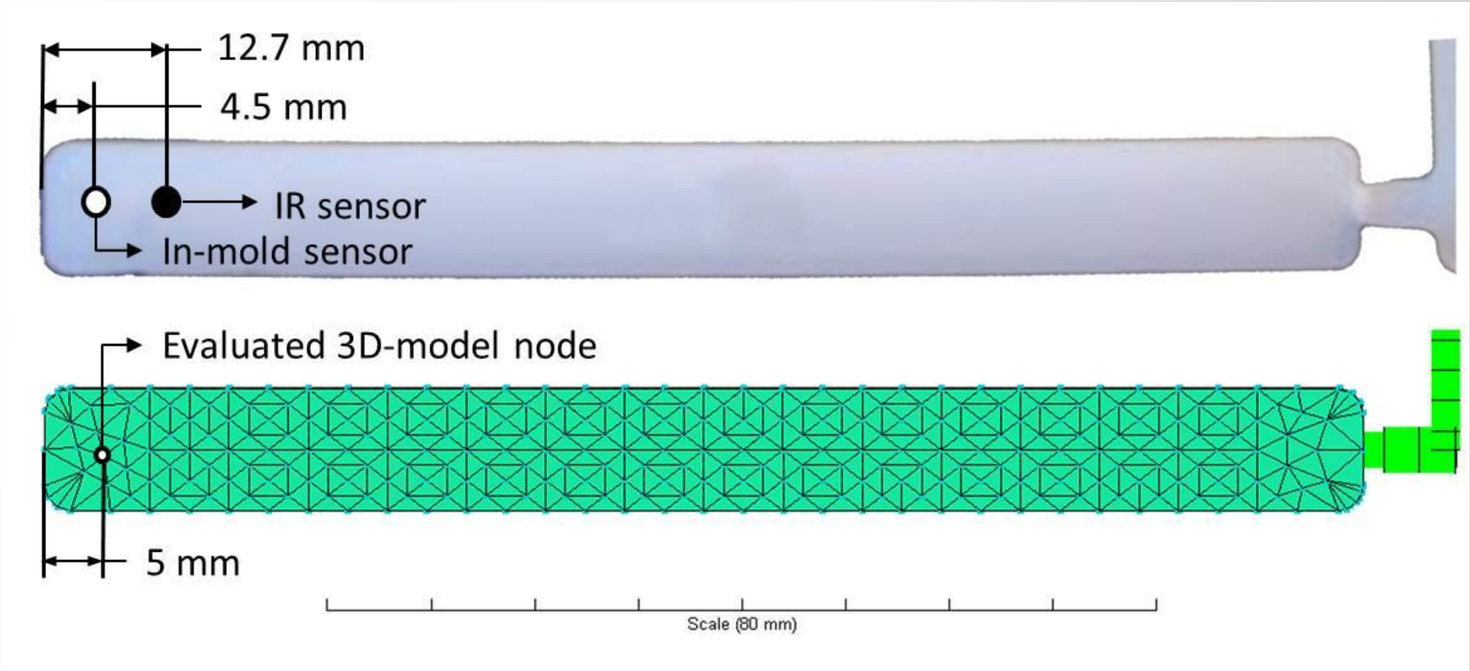
- Melt Temperature
  - Flow front temperature correlates to the IR sensed temperature
  - IR temperature was estimated assuming emissivity of 0.99. This may be the cause of the differences.





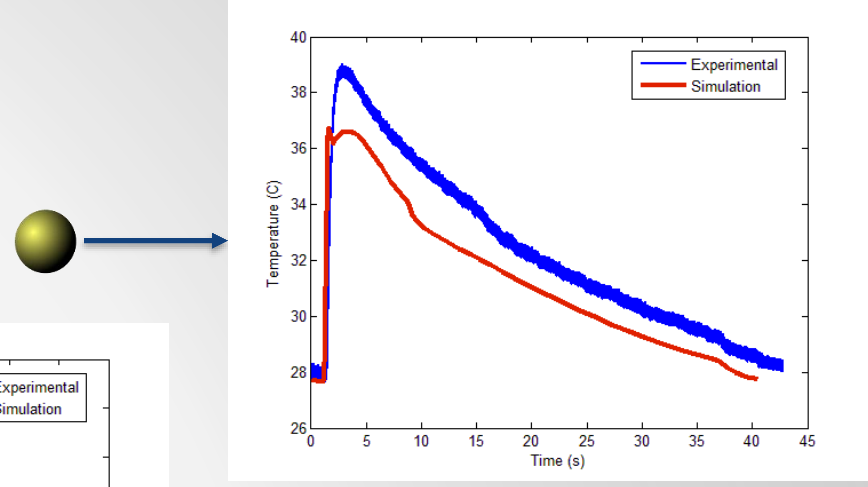
Melt-Cavity Interface Temperature

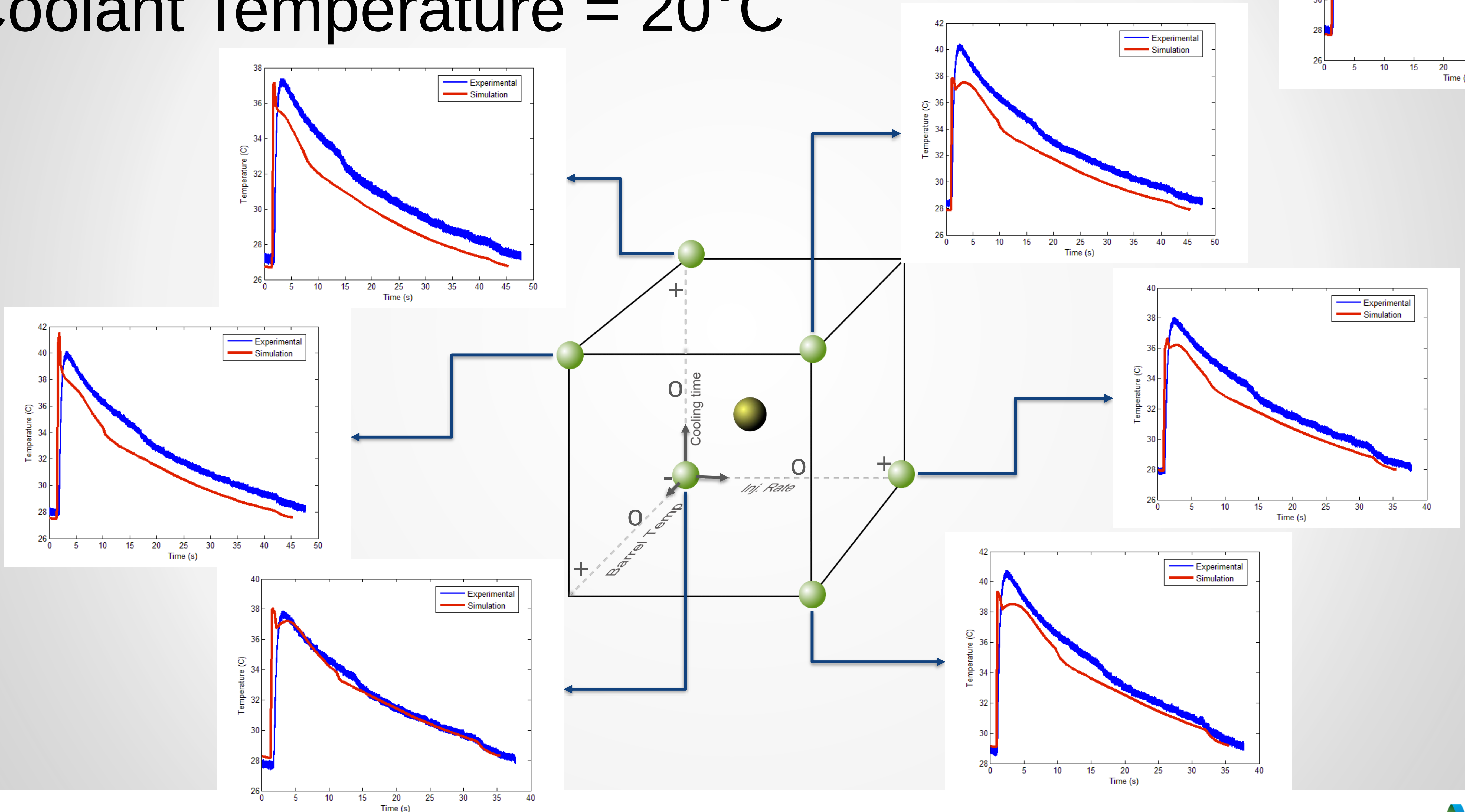




Simulation vs. Experimentation

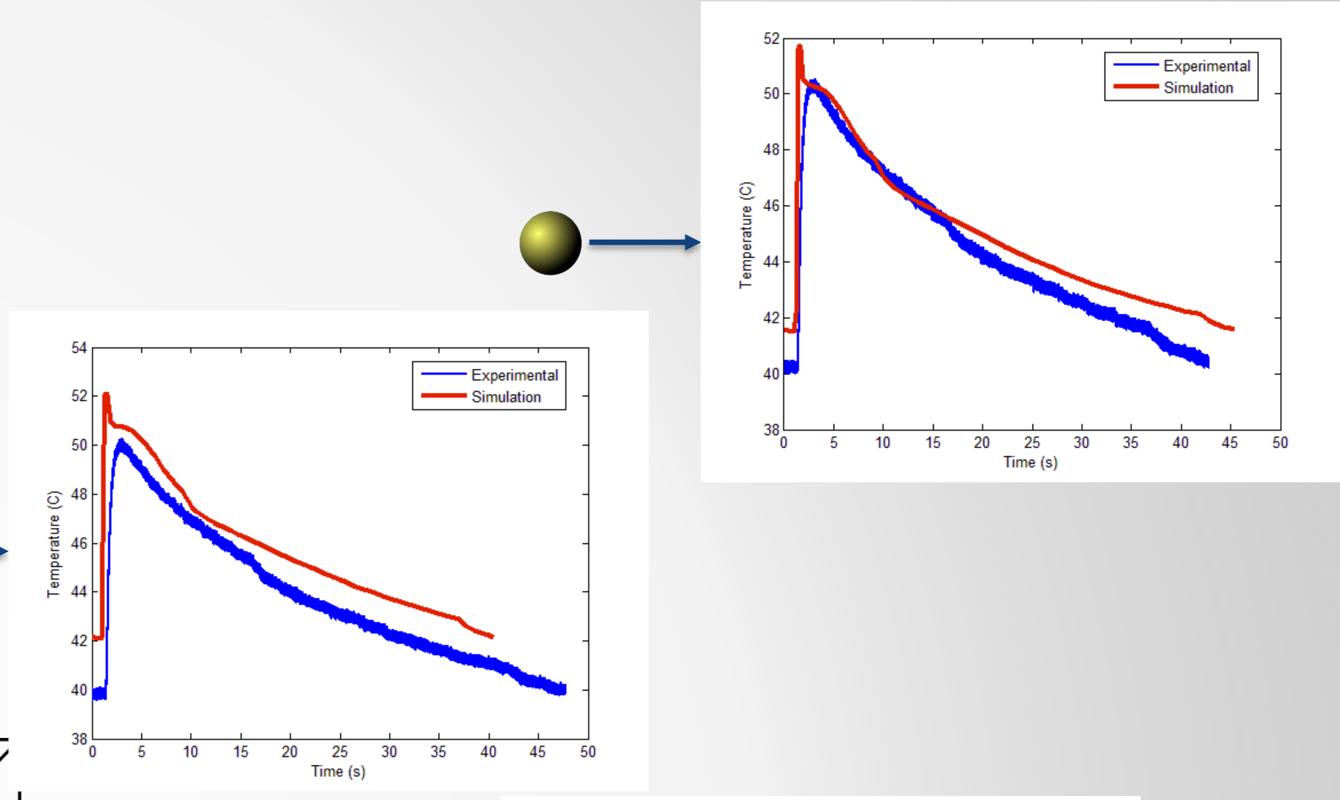
- Coolant Temperature = 20°C

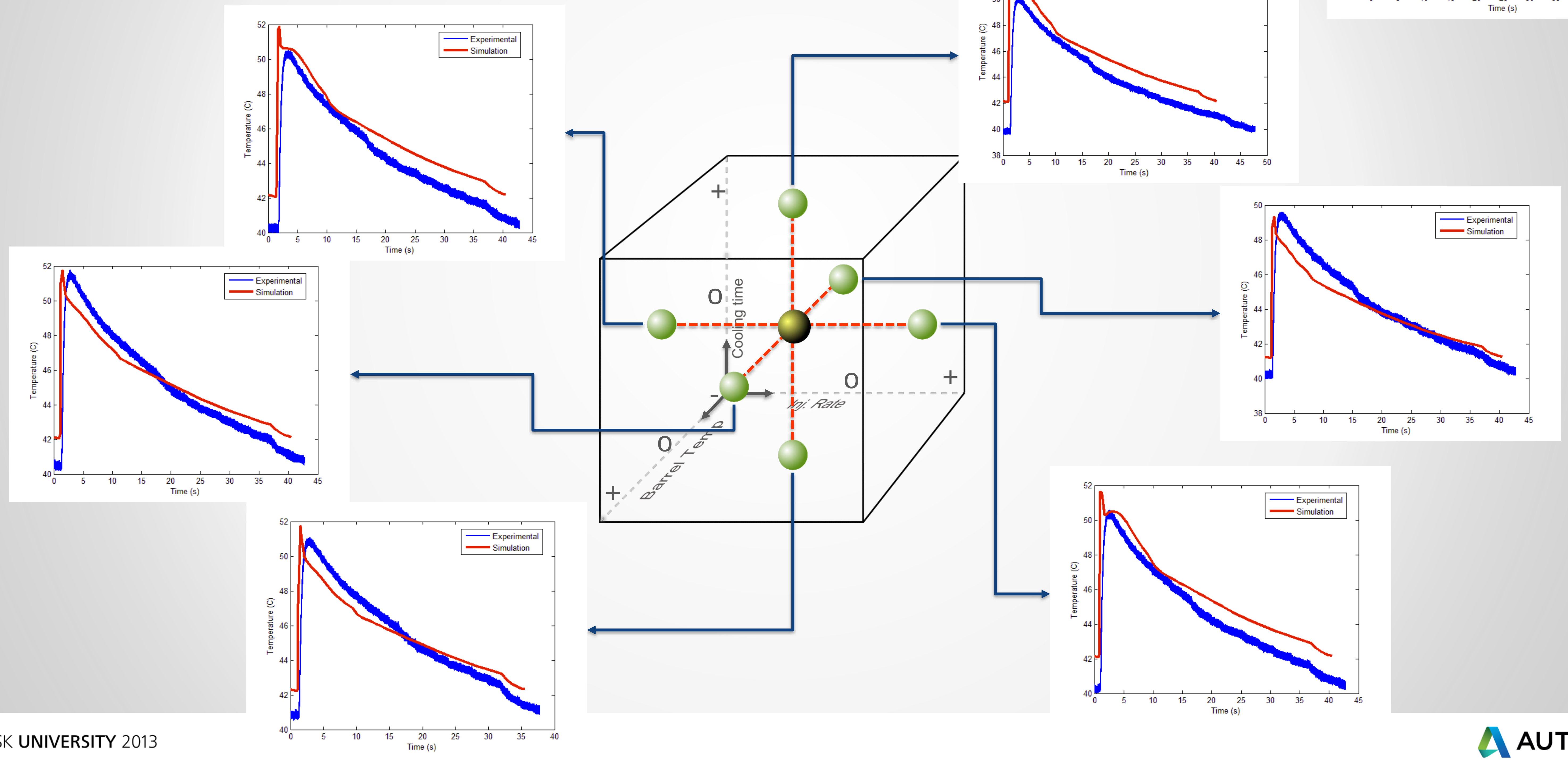




Simulation vs. Experimentation

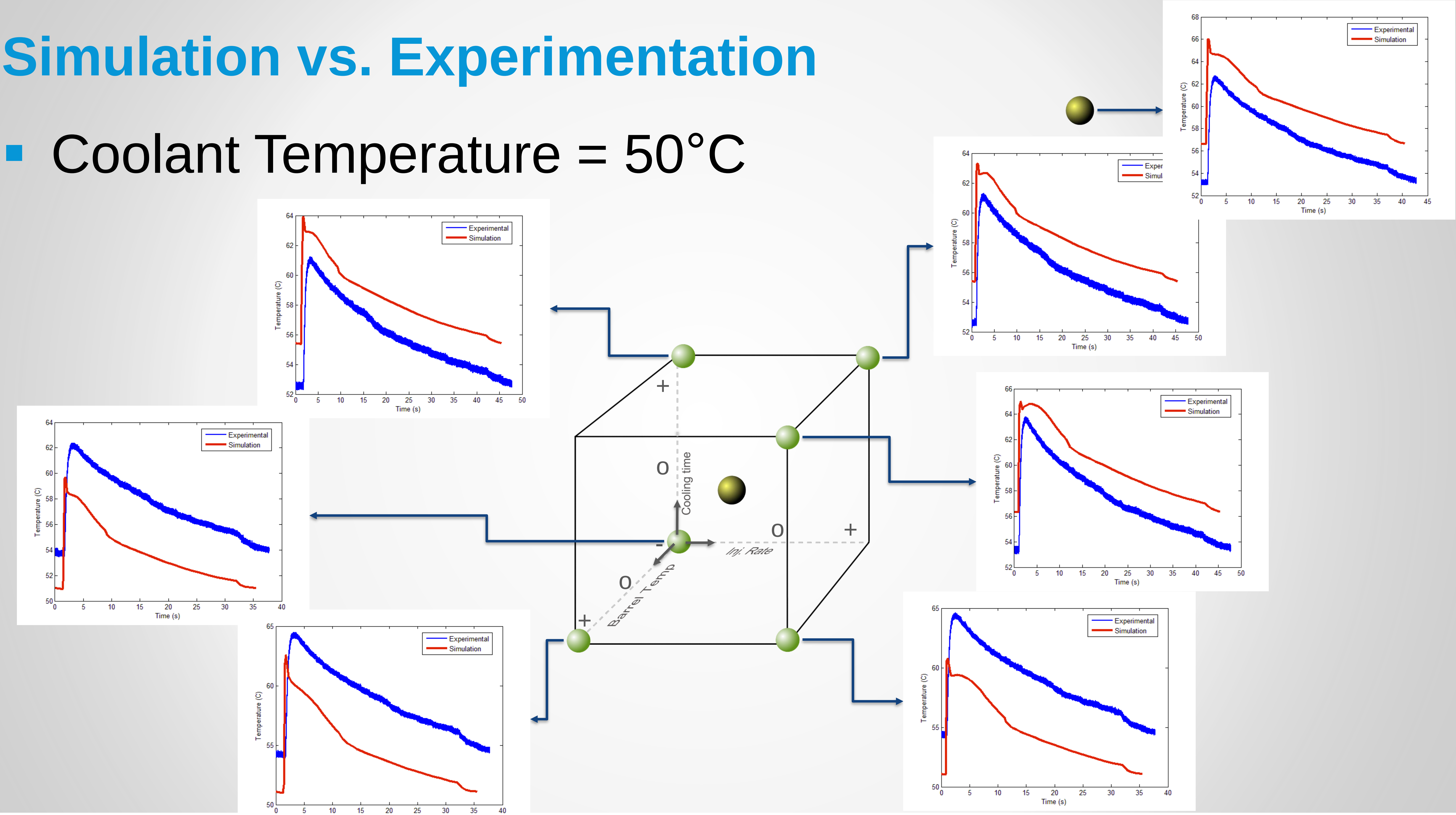
- Coolant Temperature = 35°C





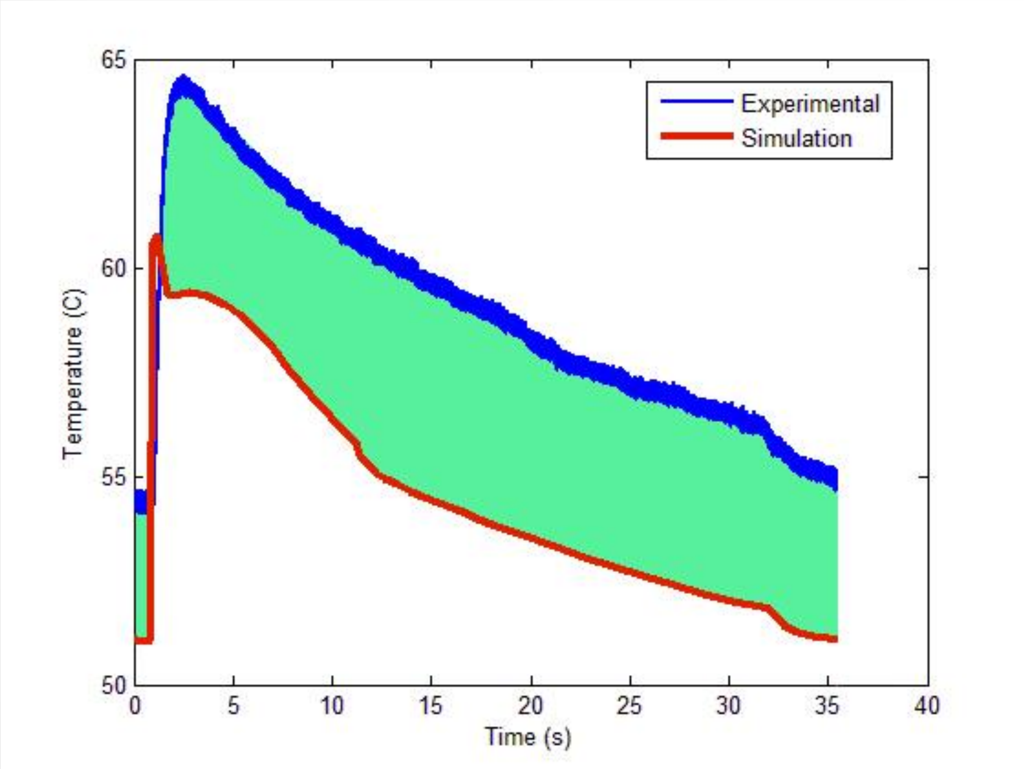
Simulation vs. Experimentation

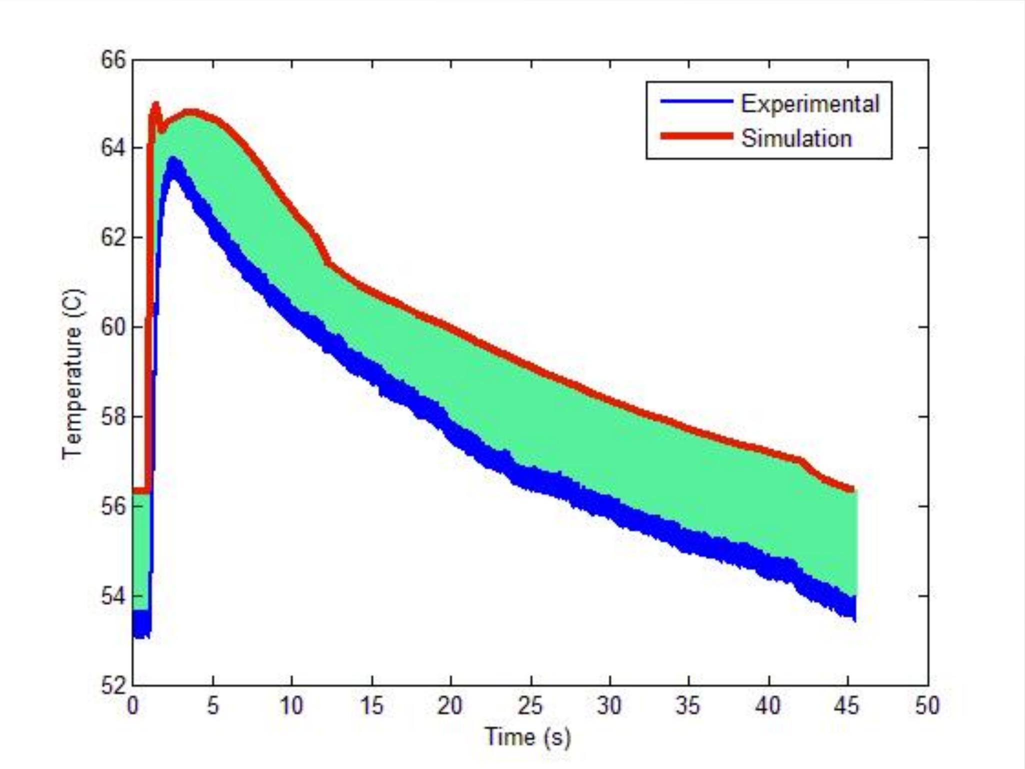
- Coolant Temperature = 50°C



Simulation vs. Experimentation

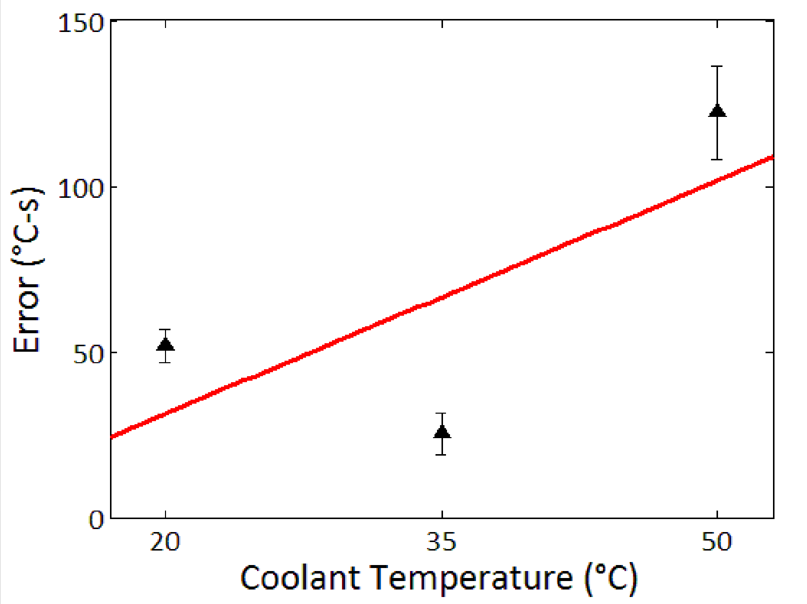
- Error
  - Deviation from experimental data estimated as the difference in the area under the curves

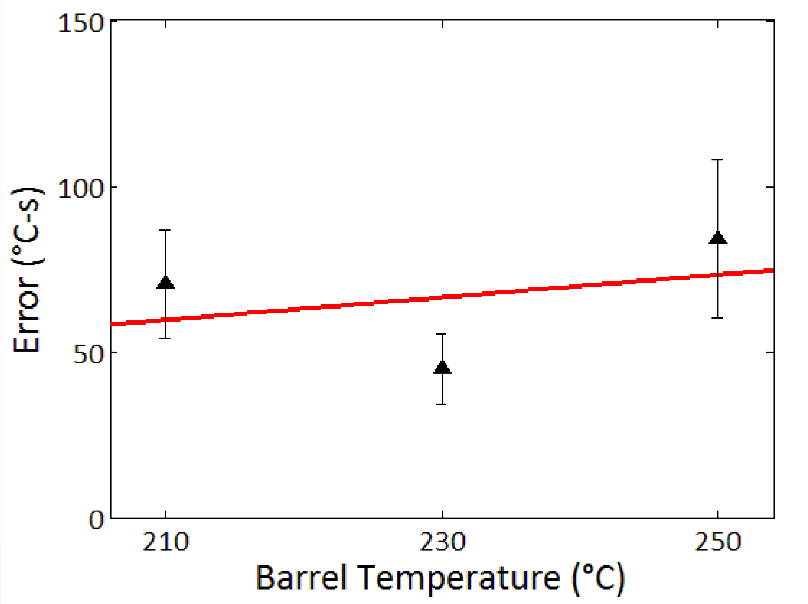


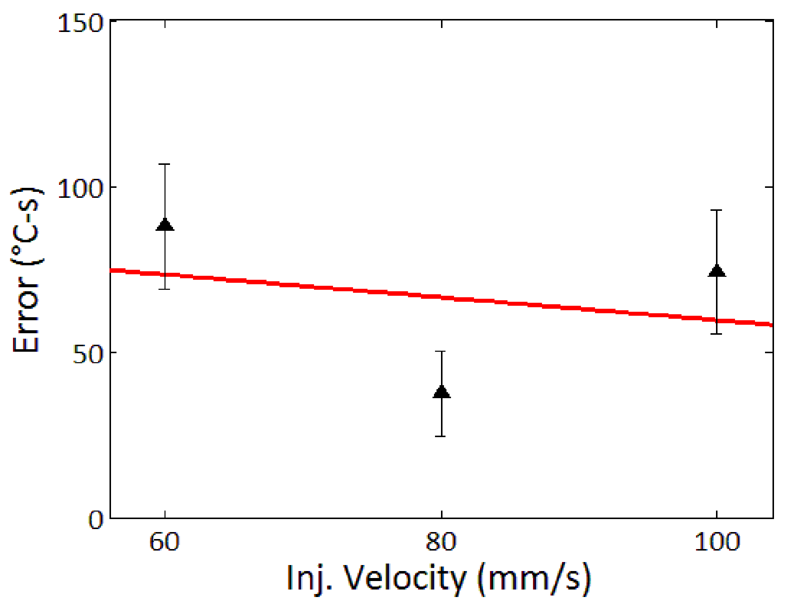


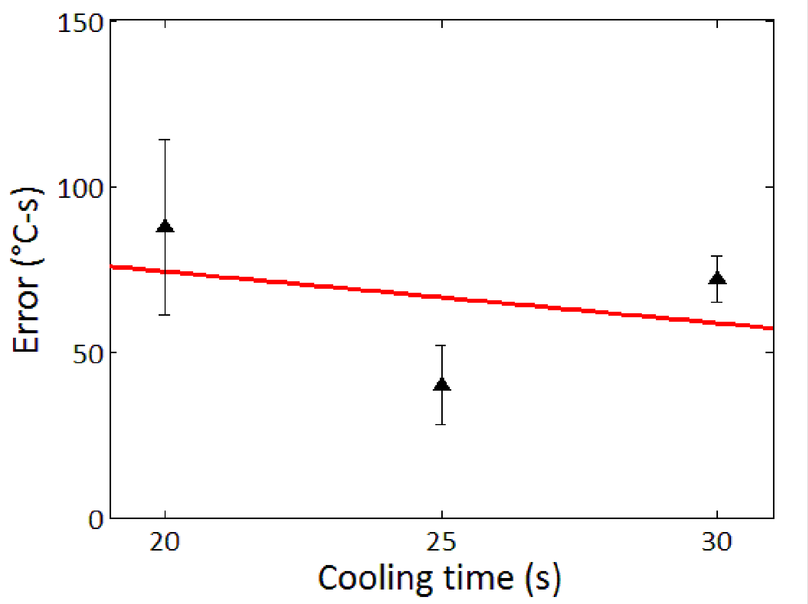
Simulation vs. Experimentation

- Error Main Effects
  - Largest error corresponds to the high coolant temperature runs.
  - No clear trends on the deviation was found for the barrel temperature, injection rate, or cooling time.
  - Smaller errors correspond to the medium level runs for all factors.

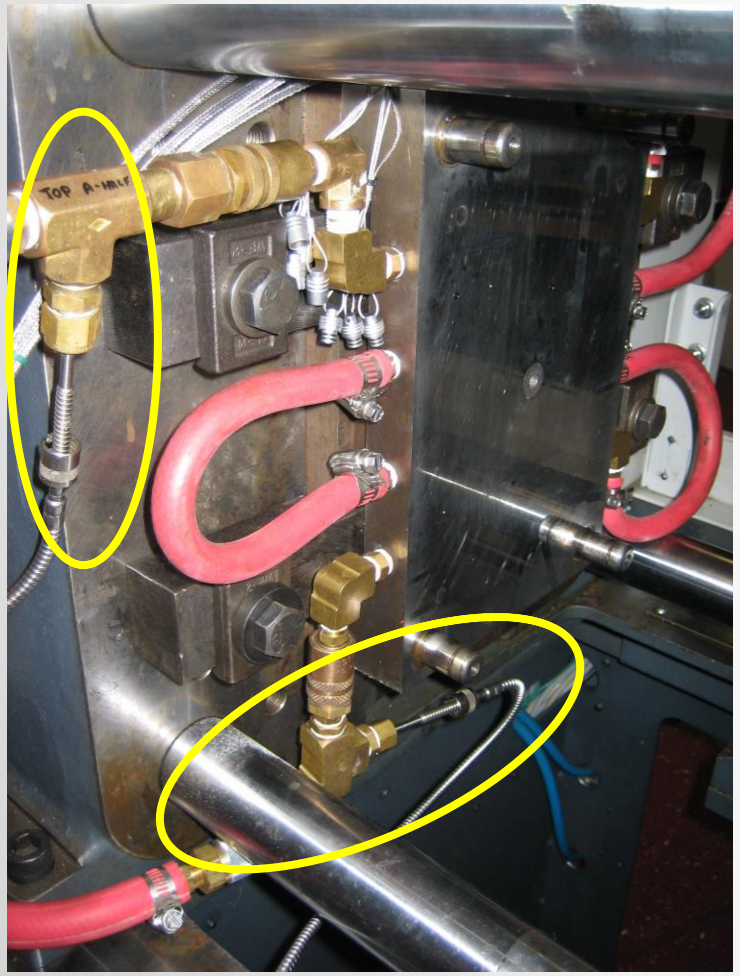


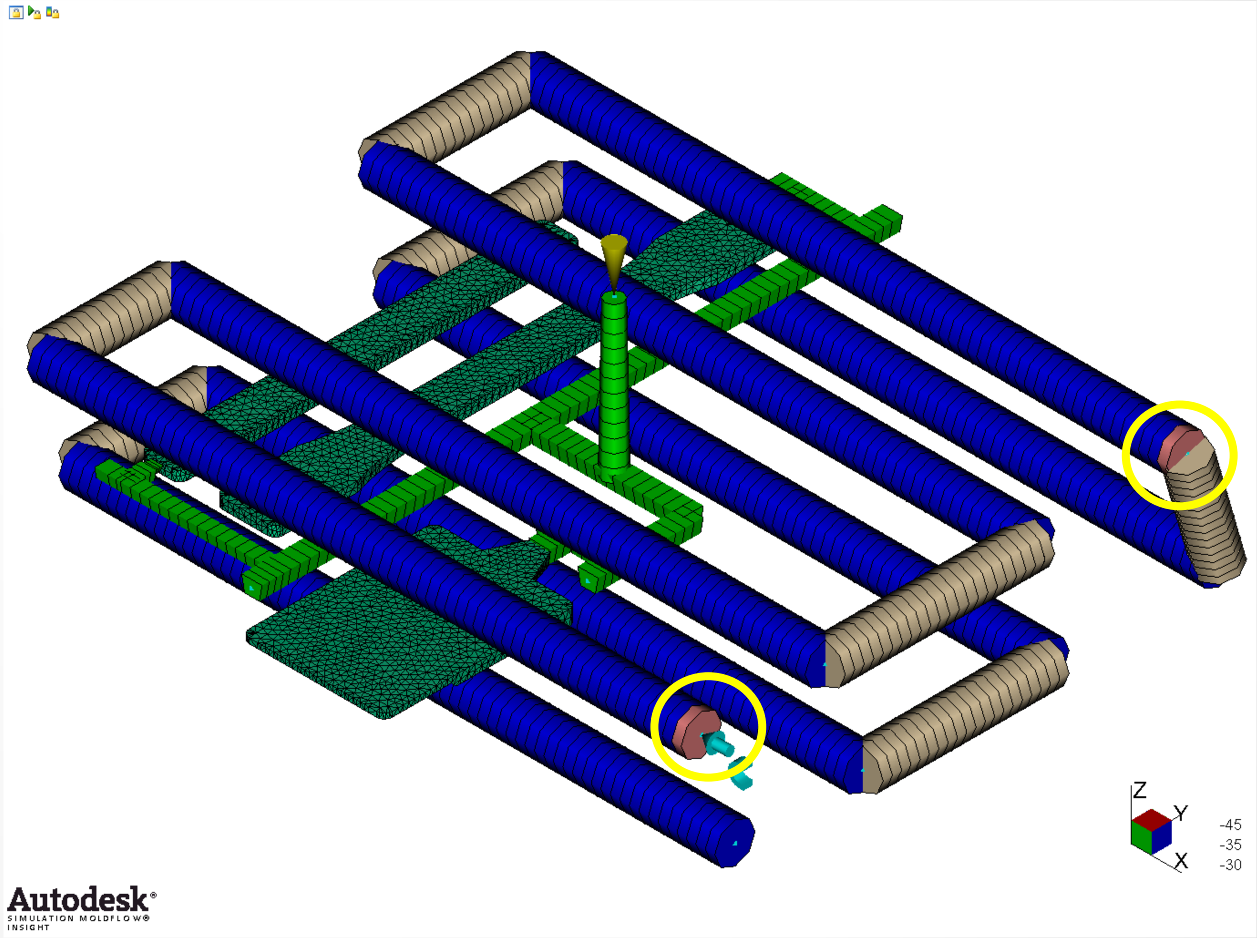






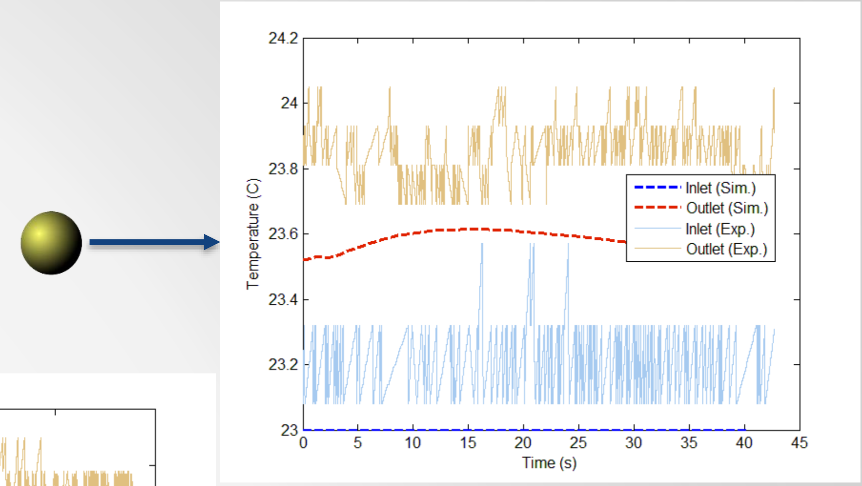
Coolant Temperature

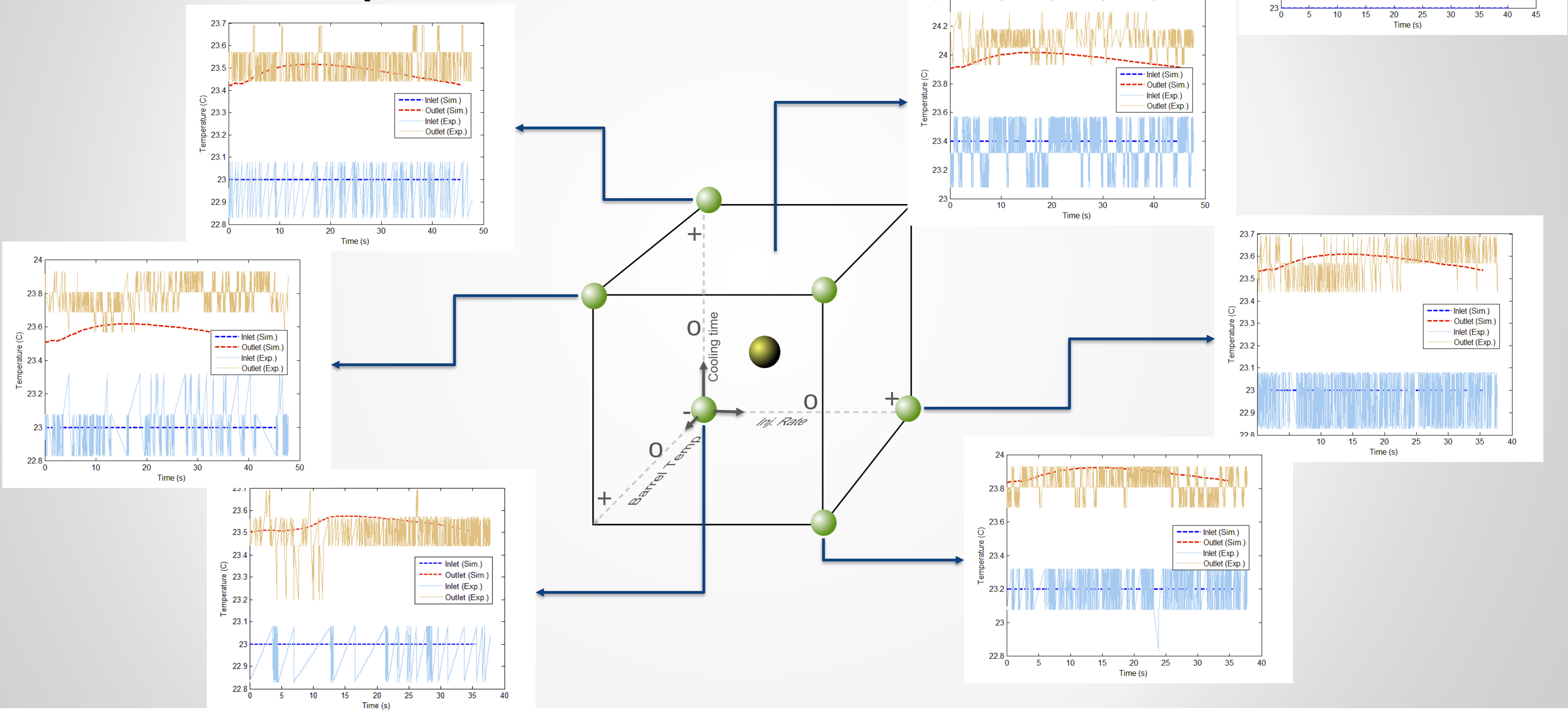




Simulation vs. Experimentation

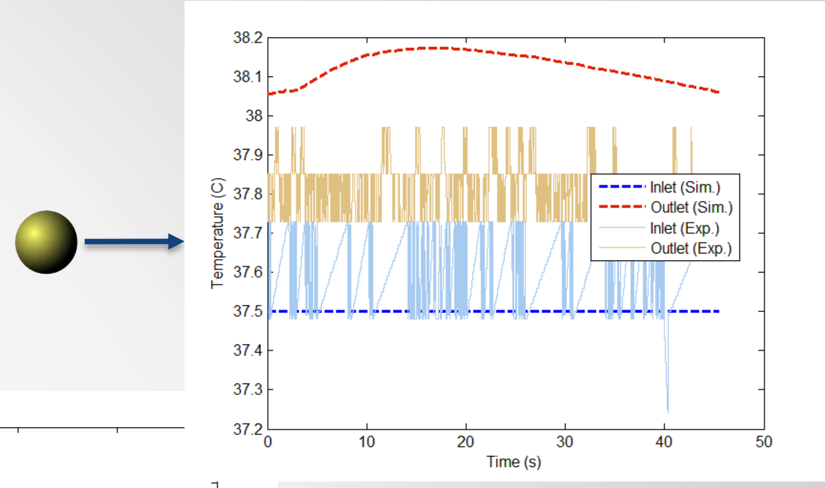
- Coolant Temperature = 20°C

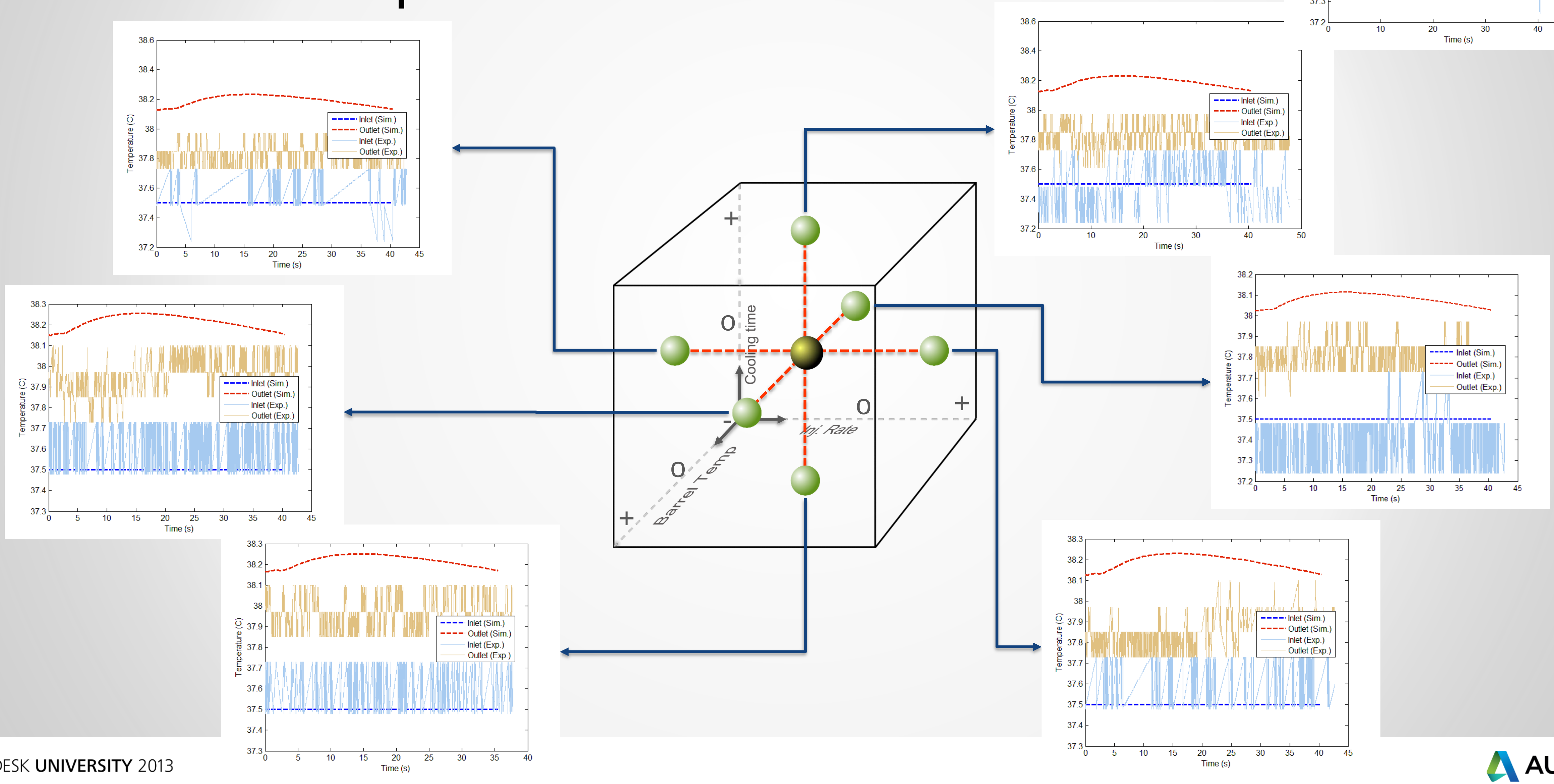




Simulation vs. Experimentation

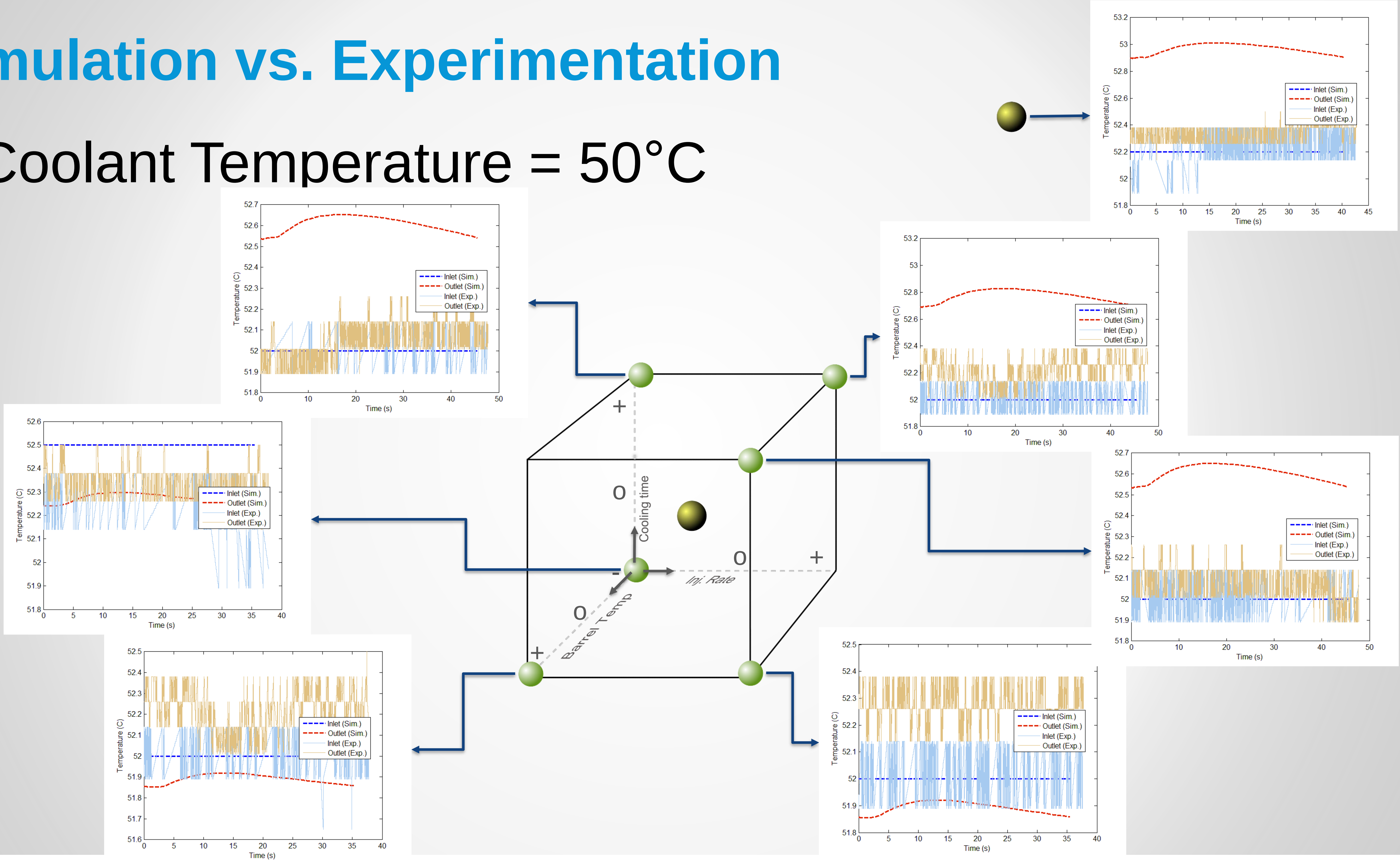
- Coolant Temperature = 35°C





Simulation vs. Experimentation

- Coolant Temperature = 50°C



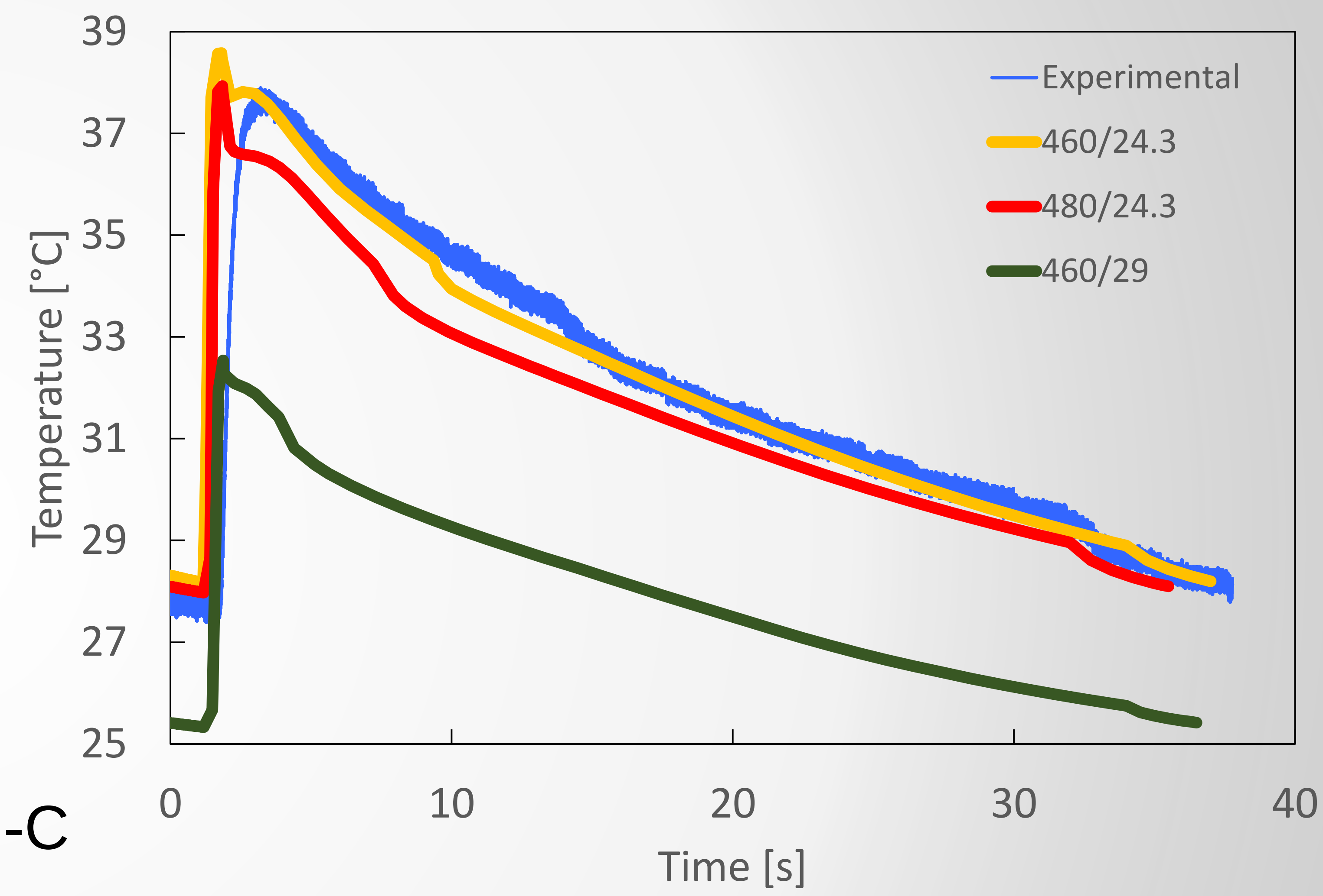
Factors that affect the analysis

Factors that Affect the Analysis

- Material Properties
  - Mold
    - Heat capacity (Cp)
    - Thermal conductivity (k)
  - Resin
    - Heat capacity (Cp)
    - Thermal conductivity (k)
    - Rheological properties
  - Mold-melt interface
    - Heat transfer coefficient (HTC)

Factors that Affect the Analysis

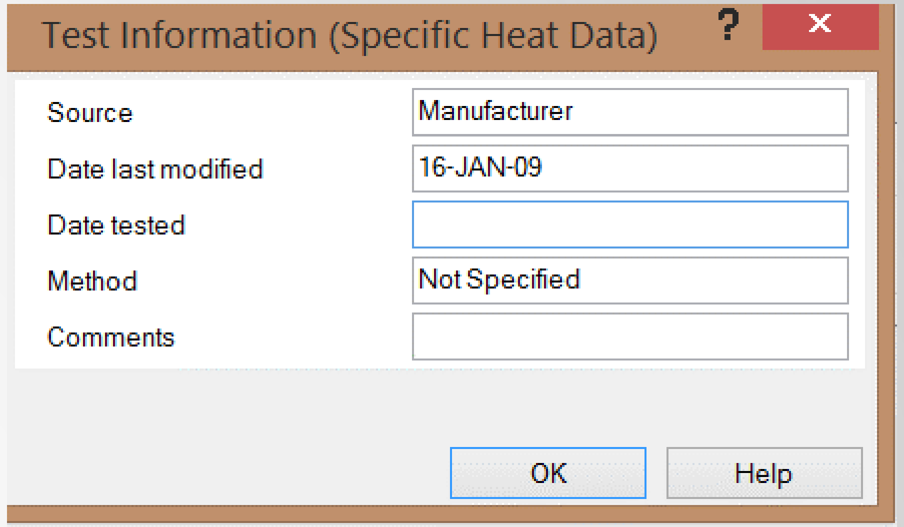
- Material Properties
  - Mold Thermal Properties
    - Heat Capacity (Cp)
      - Default value: 460 J/kg-C
      - Tested value (DSC): 480 J/kg-C
    - Thermal Conductivity (k)
      - Published values vary
      - Default value: 29 W/m-C
      - Other published value used: 24.3 W/m-C
      - Testing could not be performed due to equipment limitations

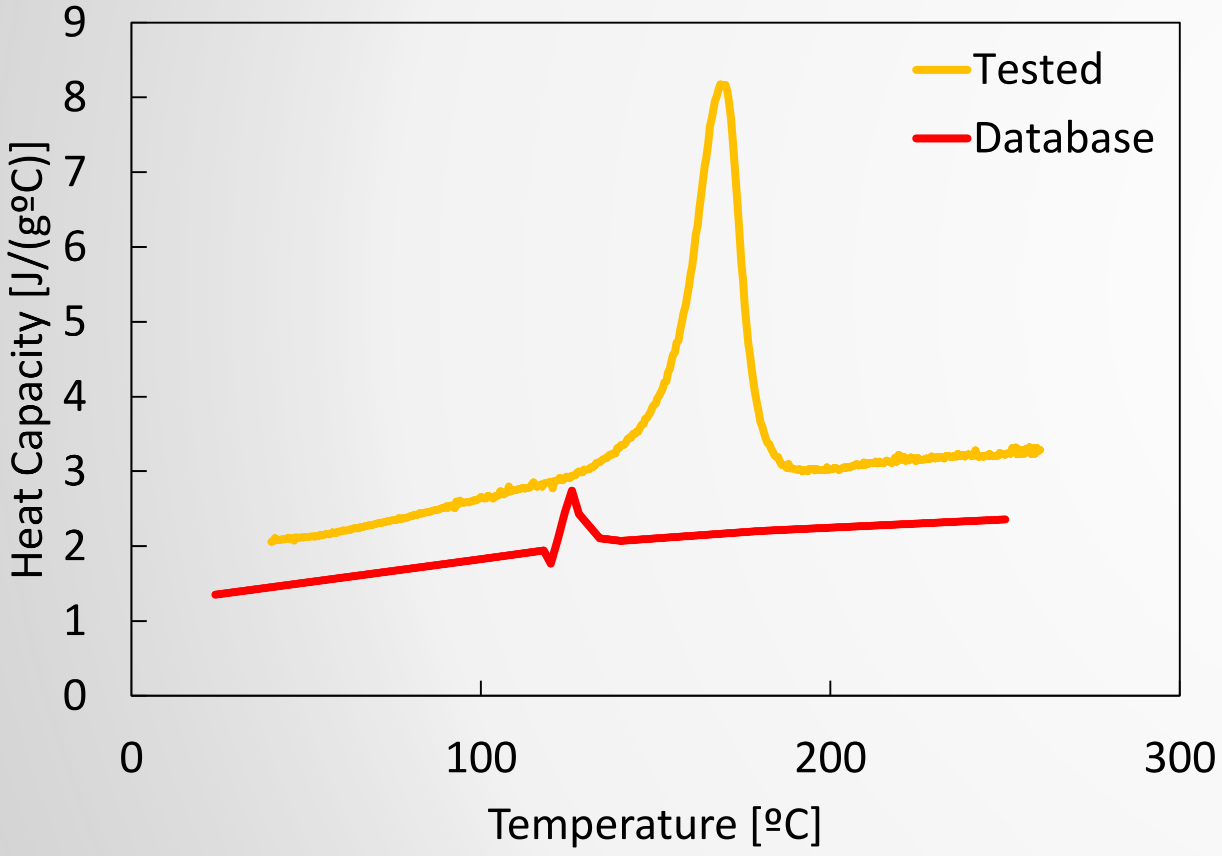


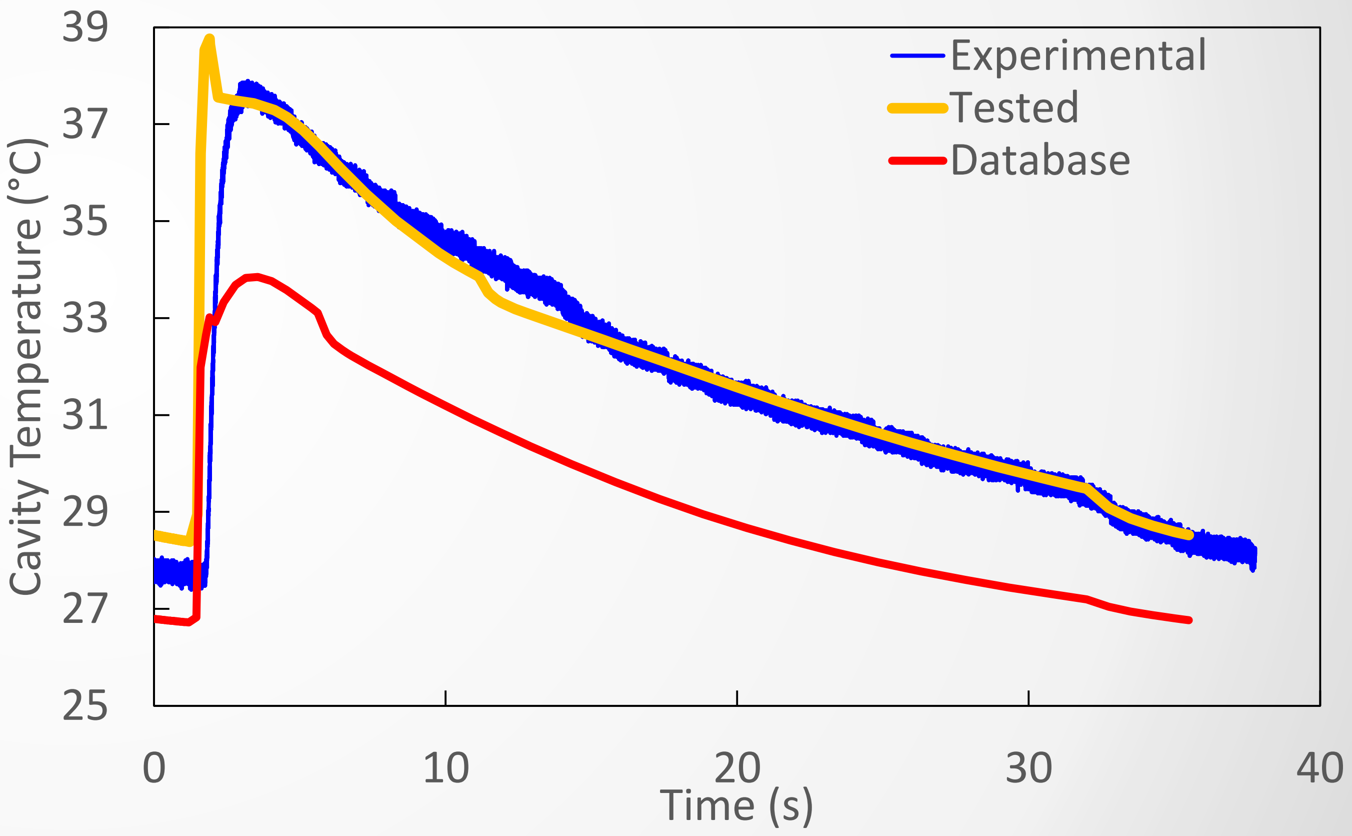
Selected values:
Cp=480 J/kg-C k=24.3 W/m-C

Factors that Affect the Analysis

- Material Properties
  - Resin Heat Capacity (Cp)

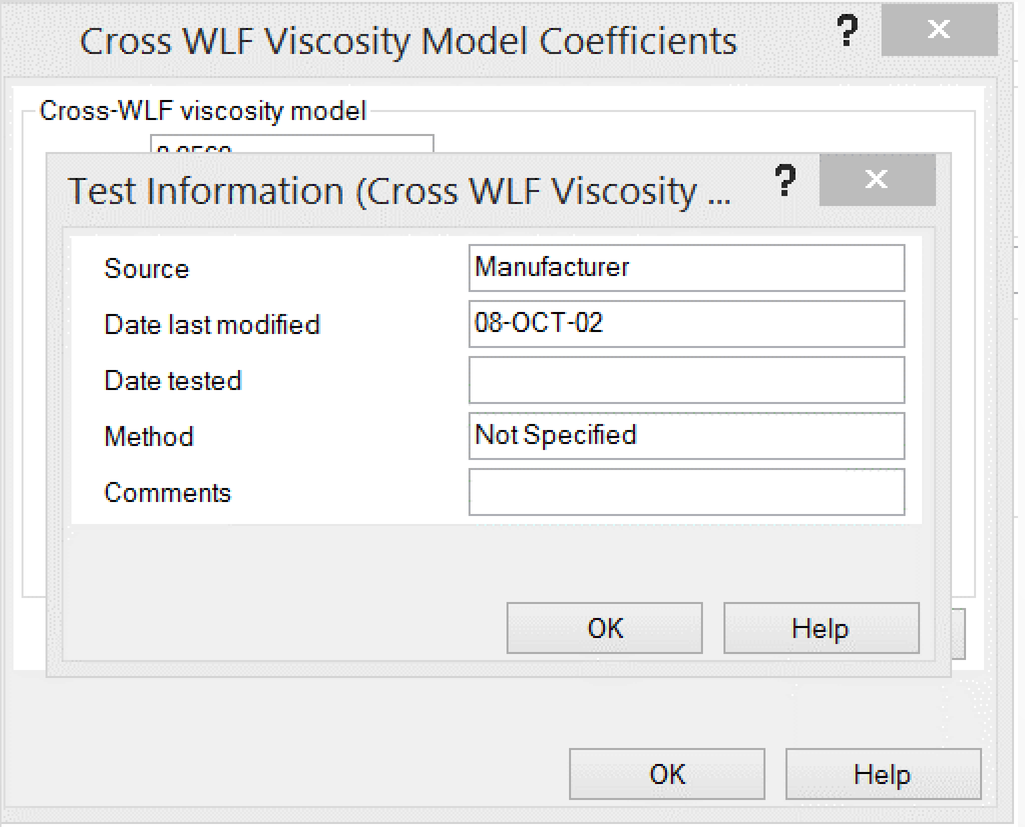


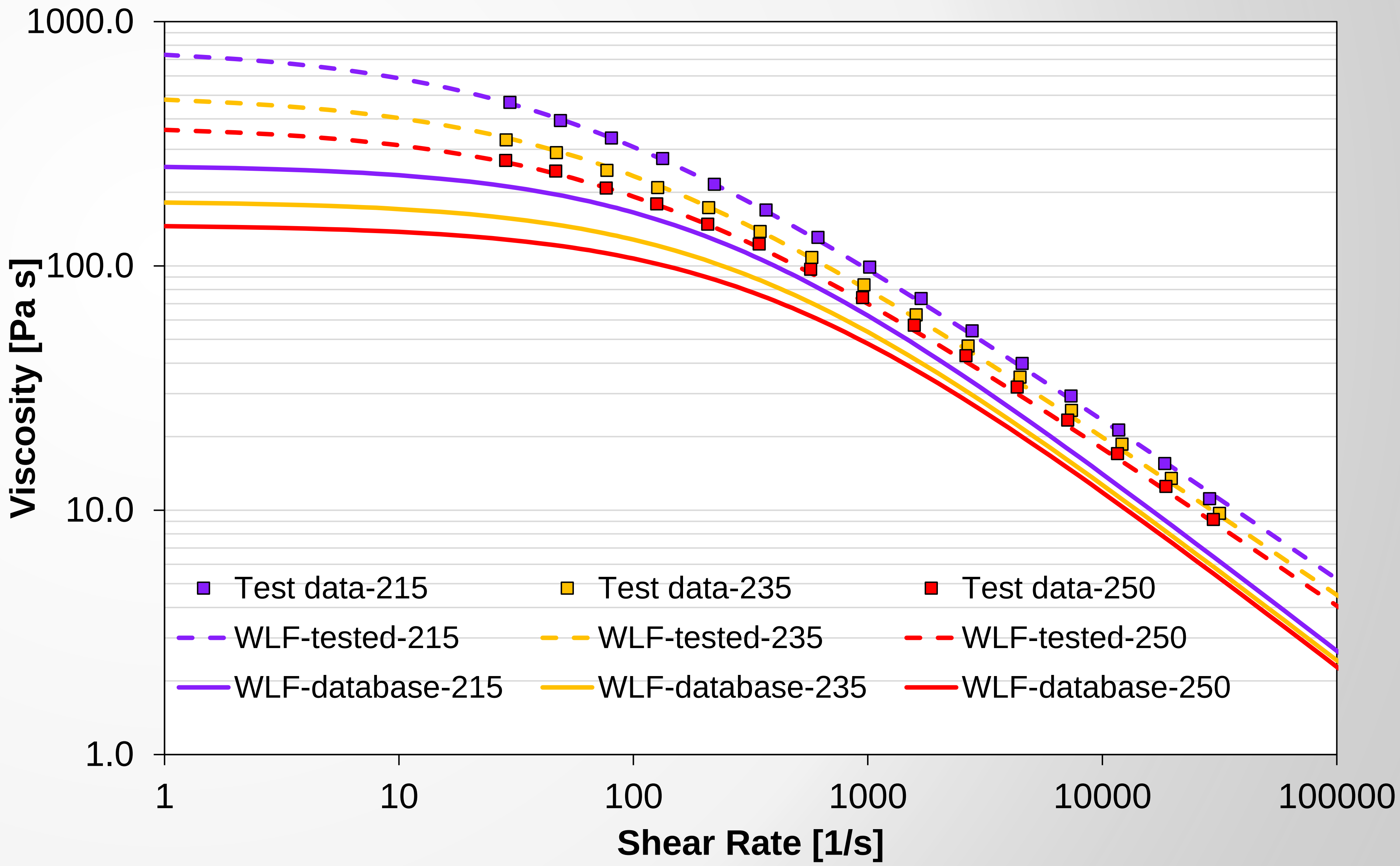




Factors that Affect the Analysis

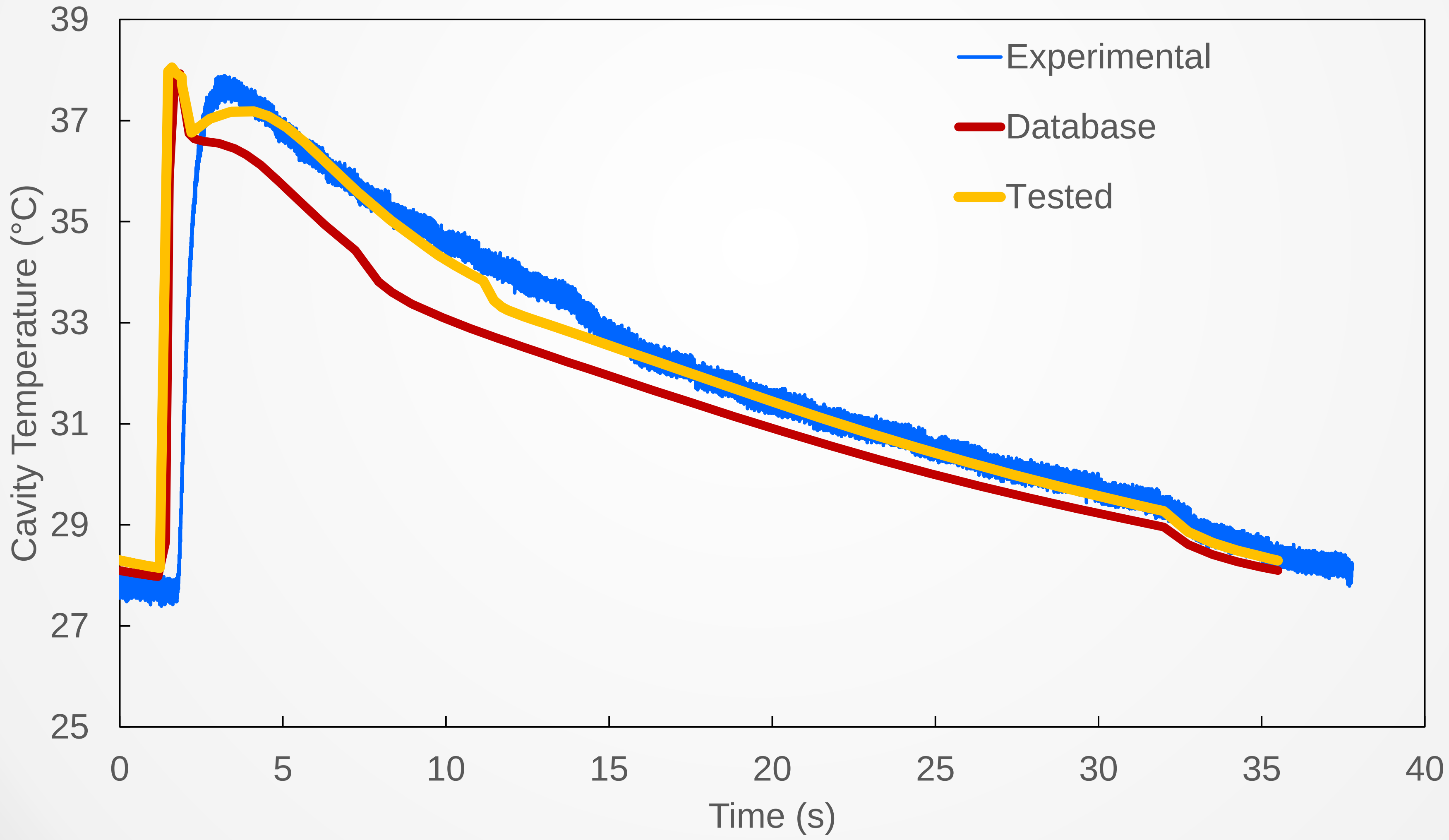
- Material Properties
  - Resin rheological properties





Factors that Affect the Analysis

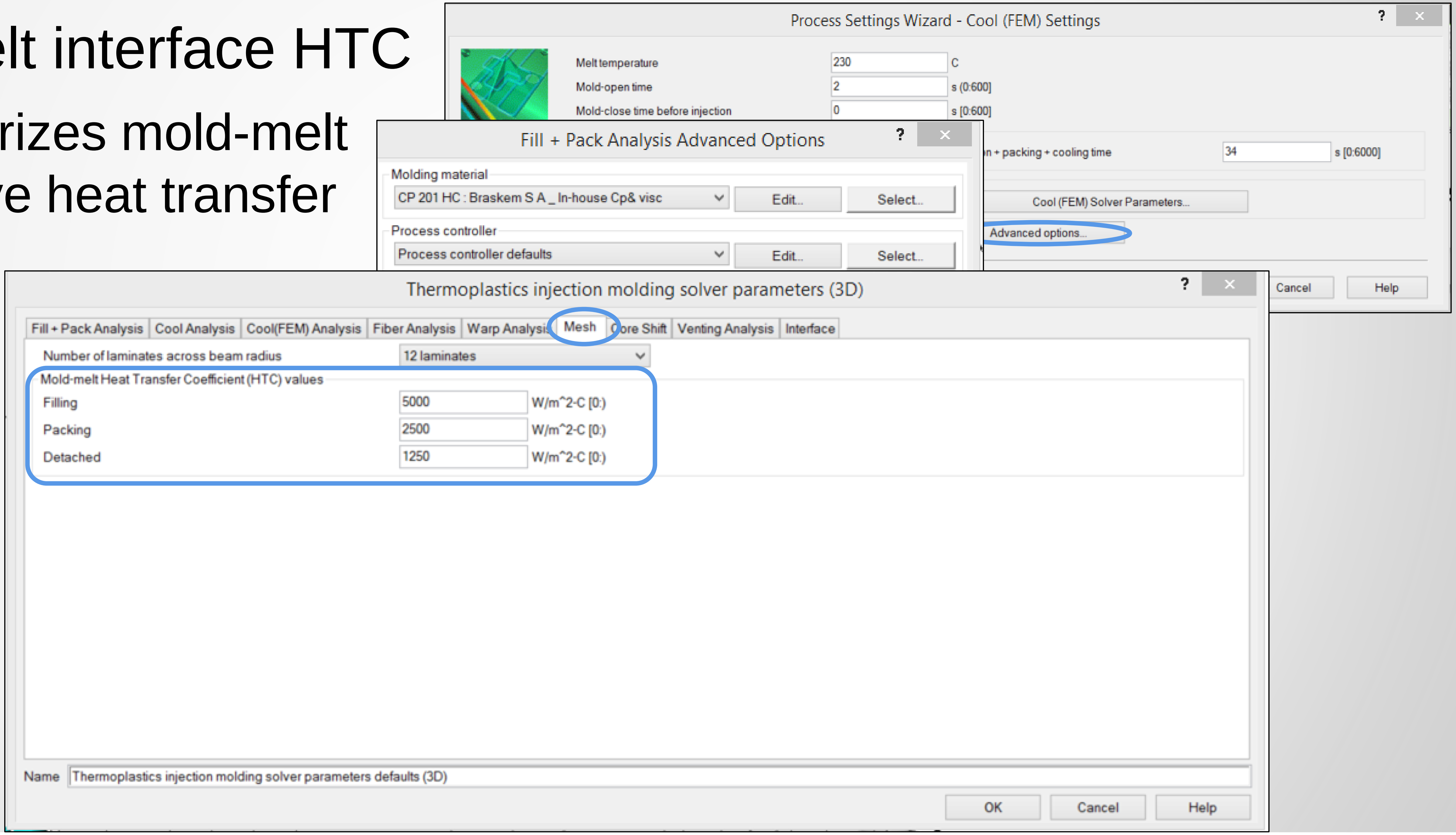
- Material Properties
  - Resin rheological properties



Factors that Affect the Analysis

- Material Properties
  - Mold-melt interface HTC

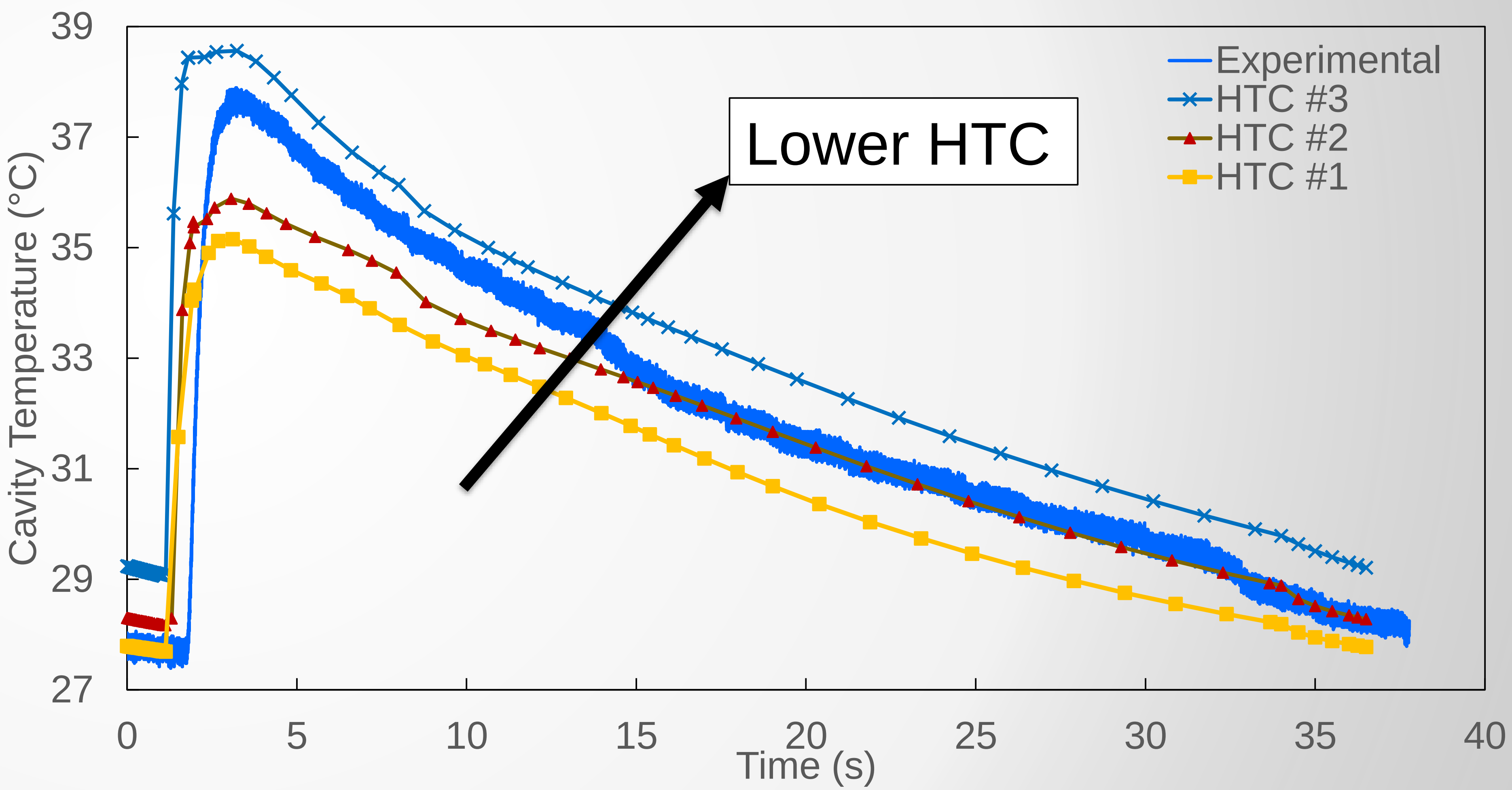
    Characterizes mold-melt convective heat transfer



Factors that Affect the Analysis

- Material Properties
  - Mold-melt interface HTC

Condition	HTC $[W/m^2C]$		
	Fill	Packing	Detached
HTC #1 (High)	20,000	10,000	5,000
HTC #2 (Default)	5,000	2,000	1,250
HTC#3 (Low)	3,000	2,500	1,250



Summary
Steps to Improve the Simulation Results

- Check solid model
- Validate steel and resin properties when possible
  - Heat capacity
  - Thermal conductivity
  - Viscosity
- Determine type of analysis that best suits your requirements.

Potential Sources of Further Improvement

- Model the nozzle of the molding machine
  - Melt temperature distribution from machine still unknown
- Validate cooling system efficiency
  - Flow rate of coolant
  - Fowling of cooling lines
  - Length of connecting hoses
- Continue to update material properties
  - Thermal conductivity of the materials
  - Validate PVT data of resin
- Consider 3D elements for runners

Conclusions

- FEM cooling analysis provides very insightful information on the cycle.
- Temperature and solver options must be set to provide desired data efficiently.
- Simulations were ALL within 3°C of the experimental data. In many cases, they were much closer.
- Thermal properties are critical for the analysis.

Acknowledgements

- The presenters would like to thank Clinton Kietzmann for helpful discussions and support regarding software capabilities.

- The presenters would also like to acknowledge Autodesk's support of the software and facilities at UMass Lowell which have made this research possible.