

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

Gabriel Mendible

Graduate Student, University of Massachusetts Lowell

Stephen Johnston, Ph.D.

Assistant Professor, University of Massachusetts Lowell

Learning Objectives

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

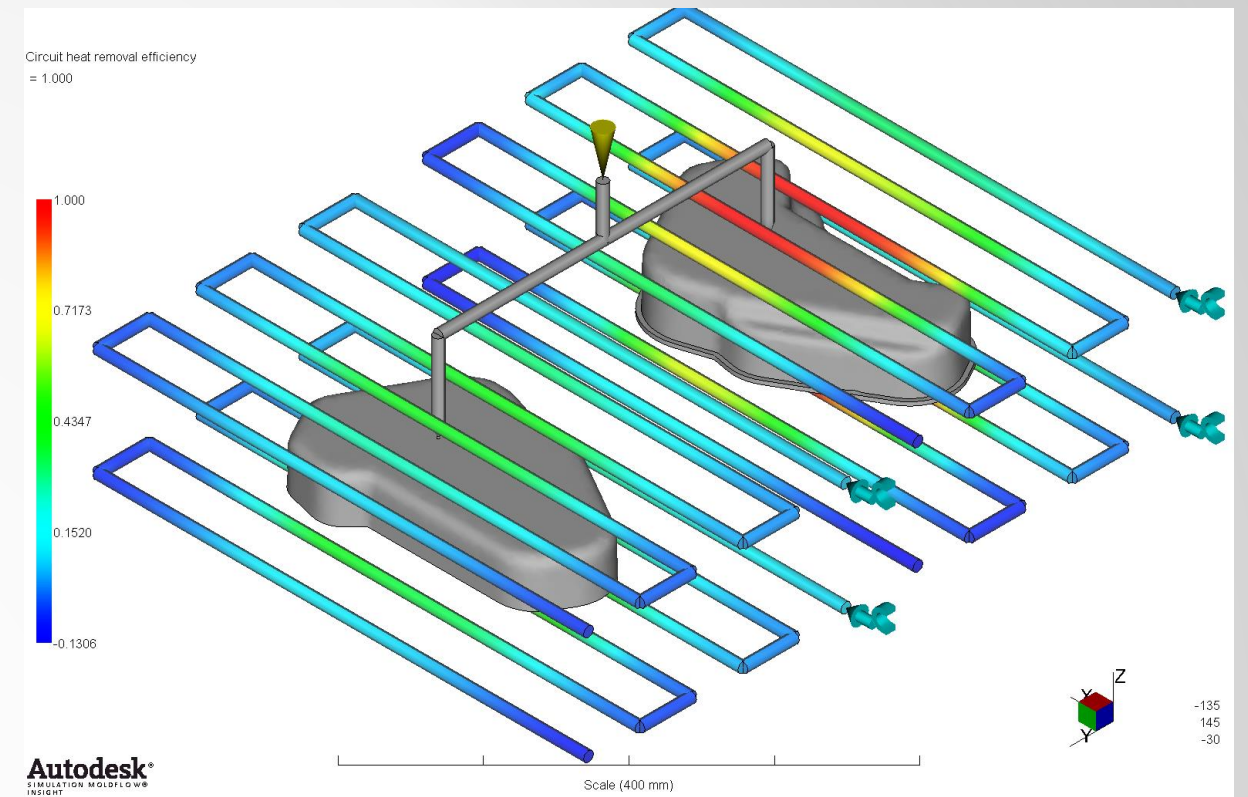
- List the variables that may affect the accuracy of the simulation results in the cooling analysis of Autodesk® Simulation Moldflow® Insight
- Identify improvements that can be performed to a model in order to increase its accuracy
- Describe the benefits of the transient cooling analysis
- Distinguish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

Introduction

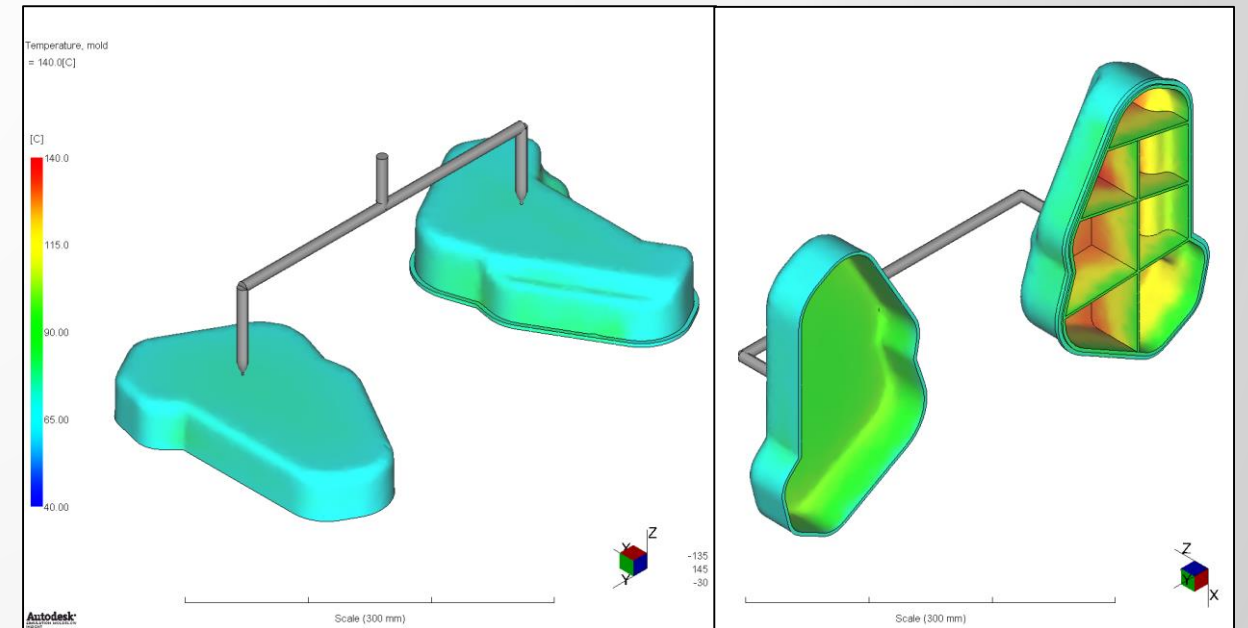
- Why cooling analysis?
 - Identify hot spots
 - Identify and reduce defects
 - Efficient design of cooling system
 - Reduce machining operations



<http://www.xcentricmold.com/>



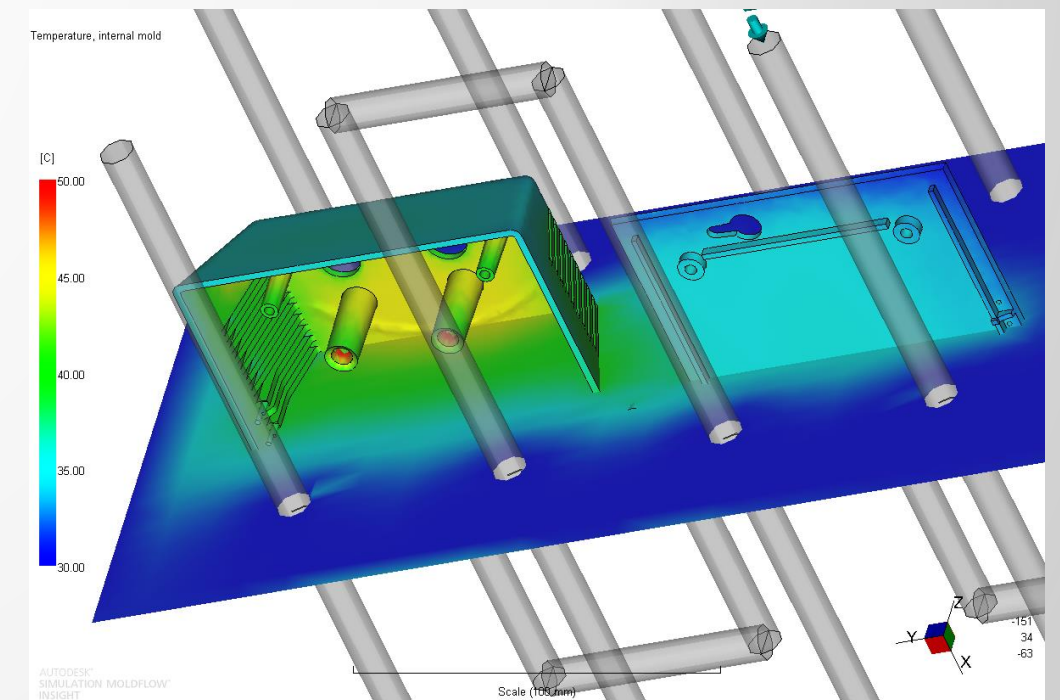
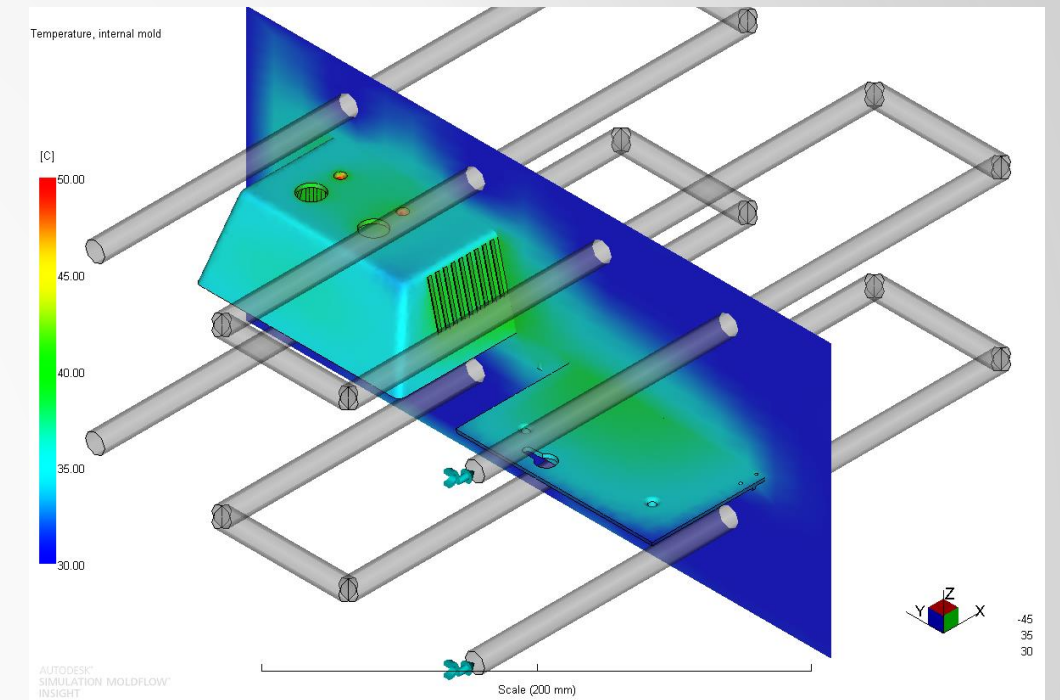
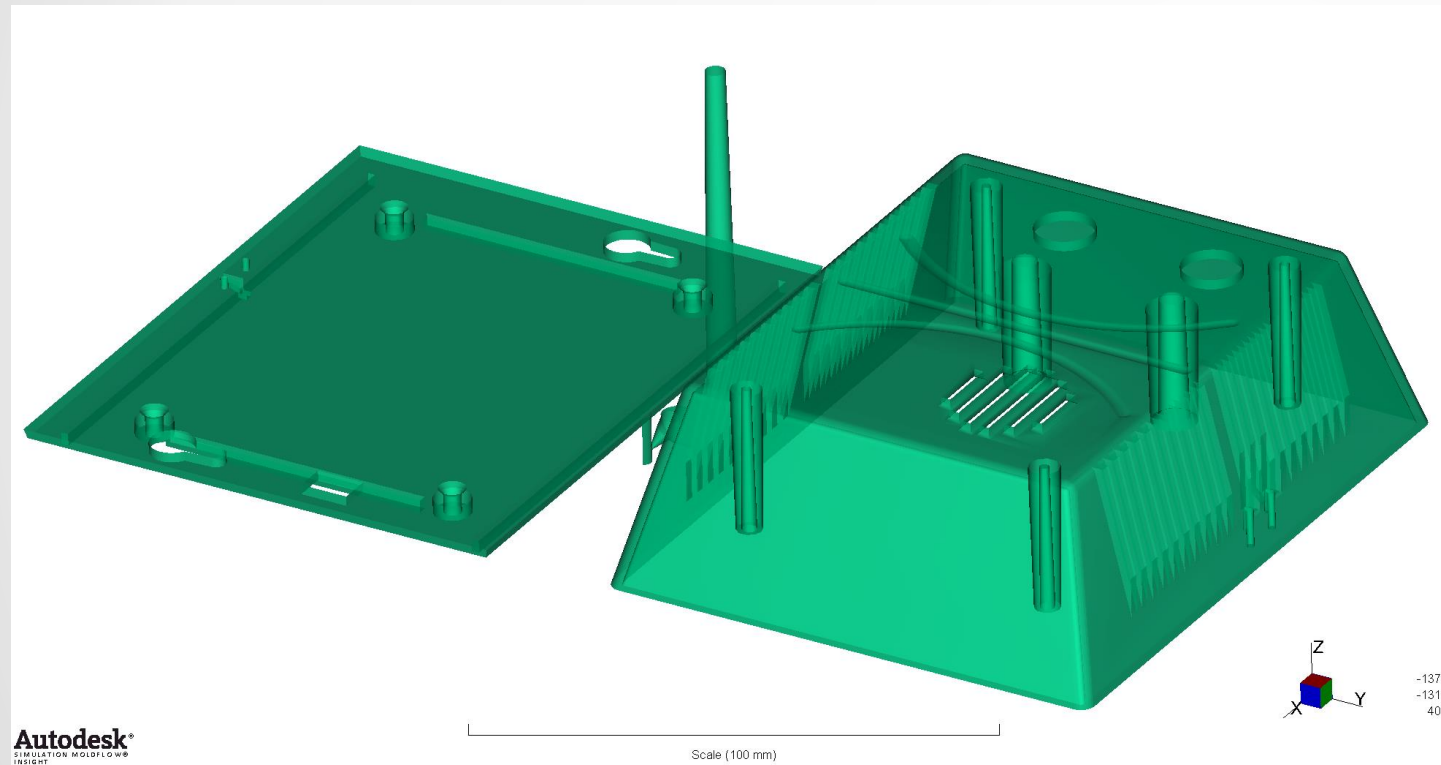
Circuit Heat Removal Efficiency



Mold Temperature

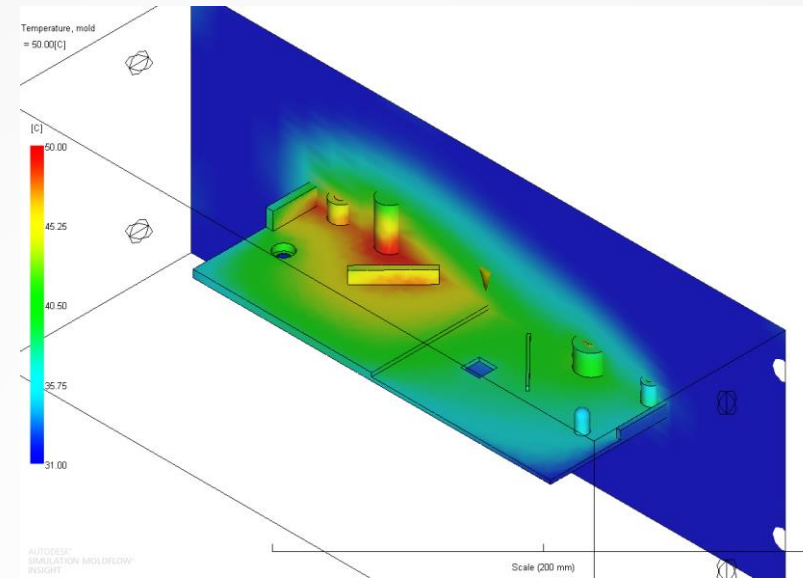
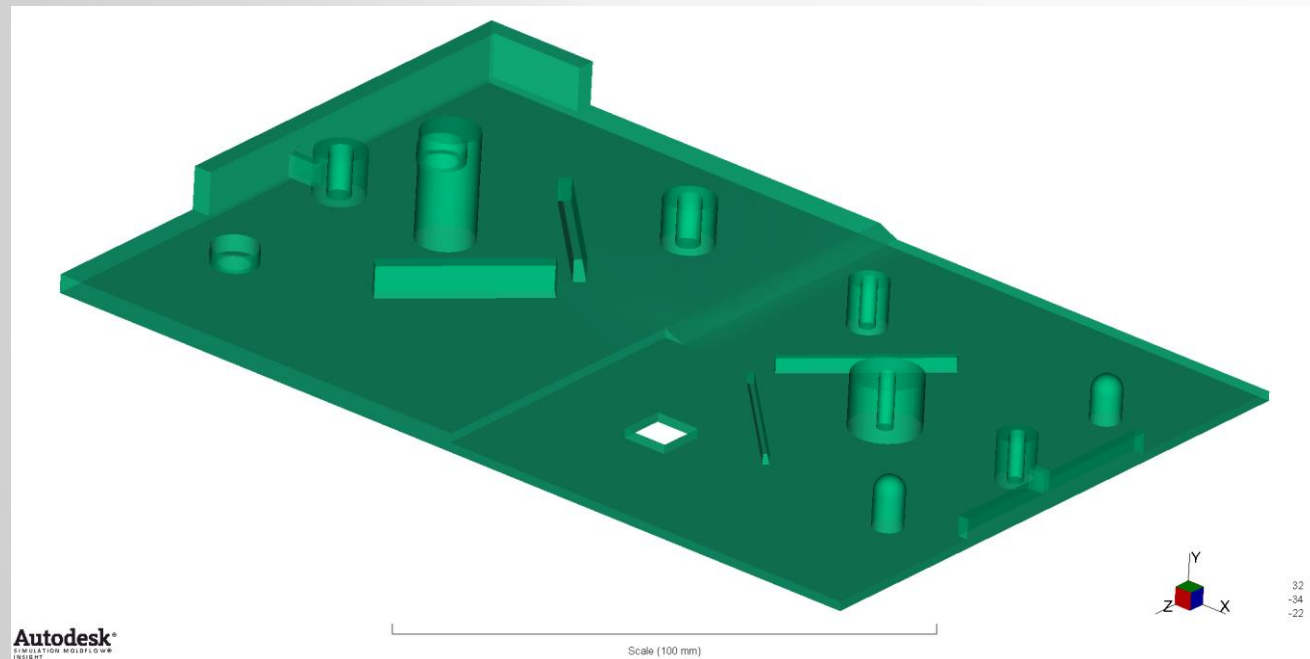
Introduction

- Hot spots due to inefficient cooling

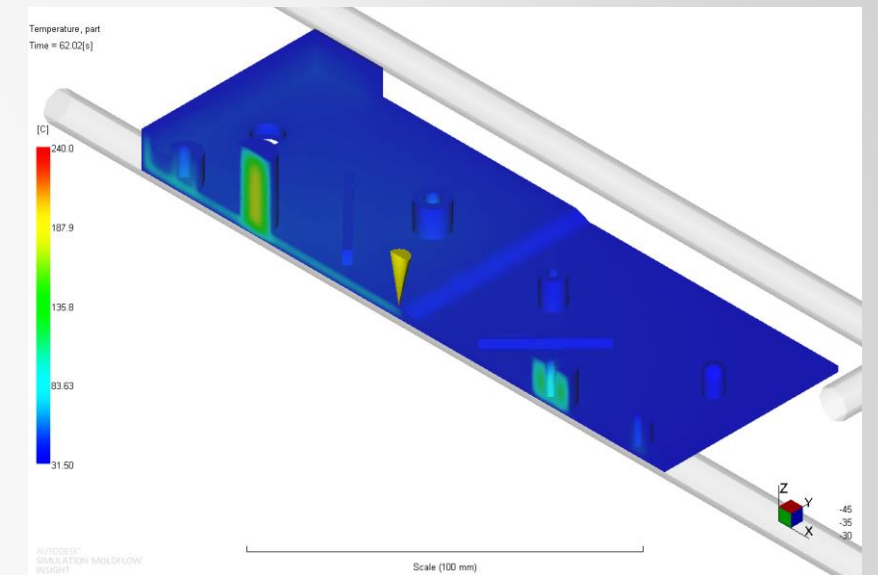


Introduction

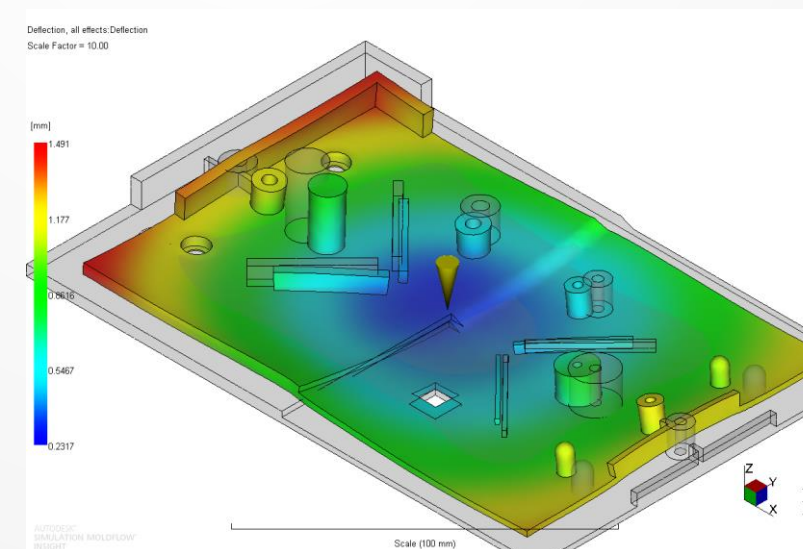
- Sink marks and warpage due to uneven part cooling



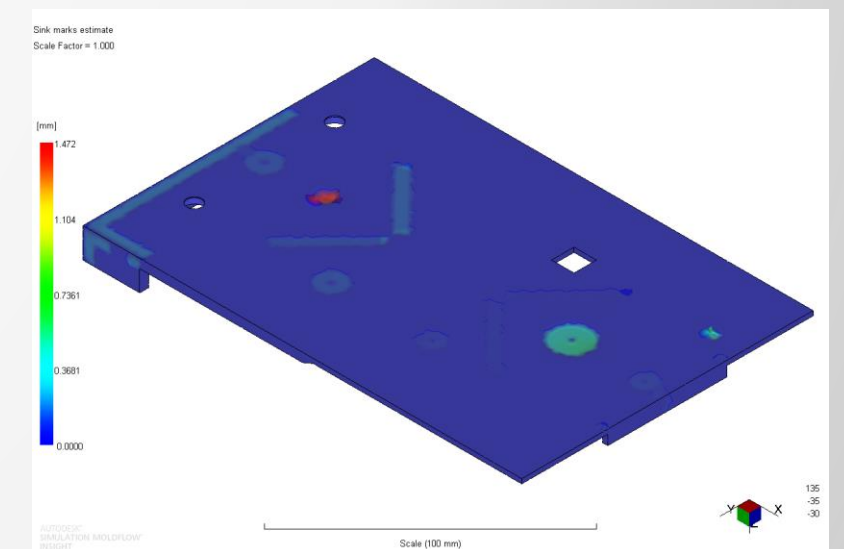
Mold Temperature



Part Temperature



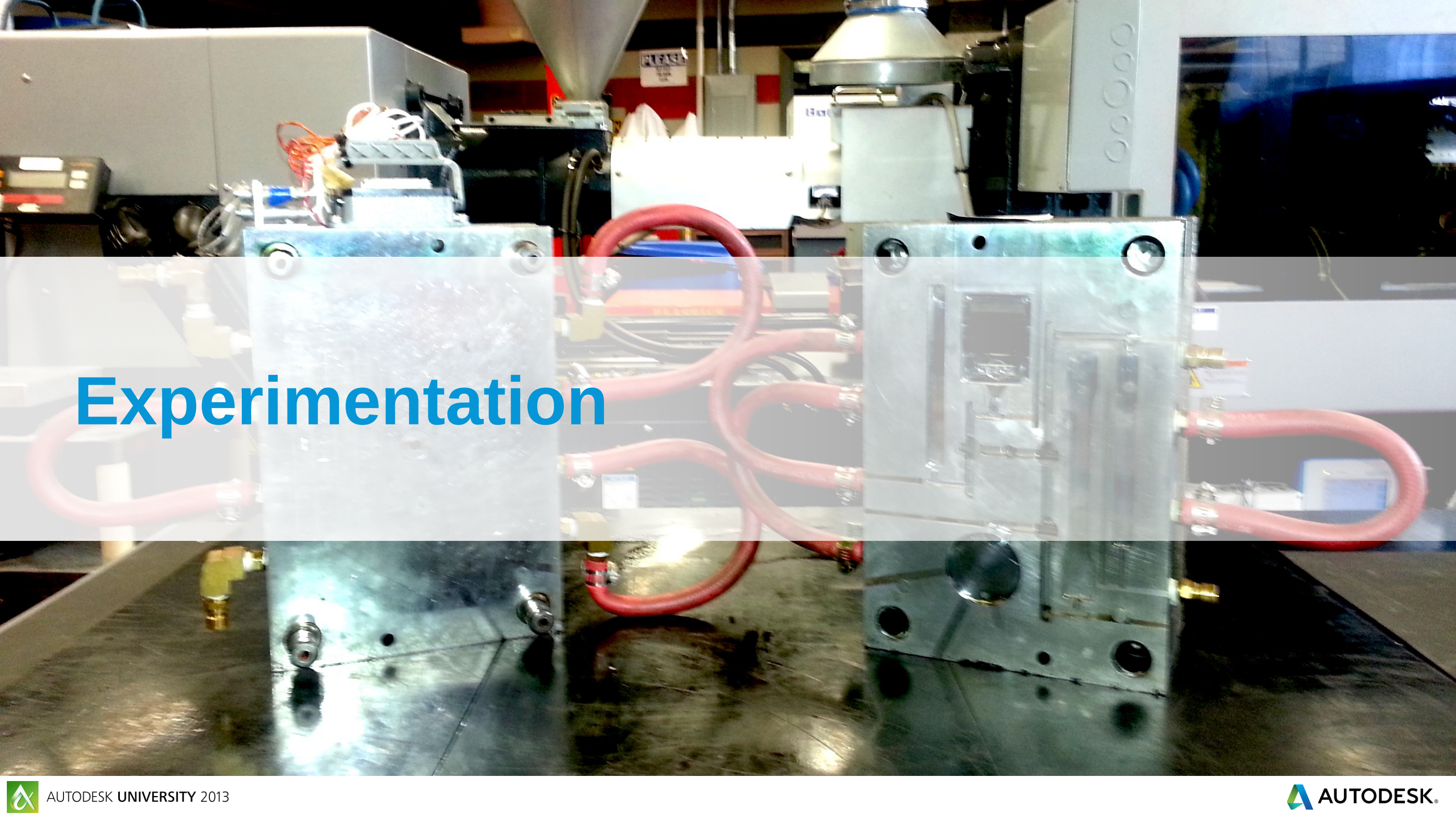
Warpage



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

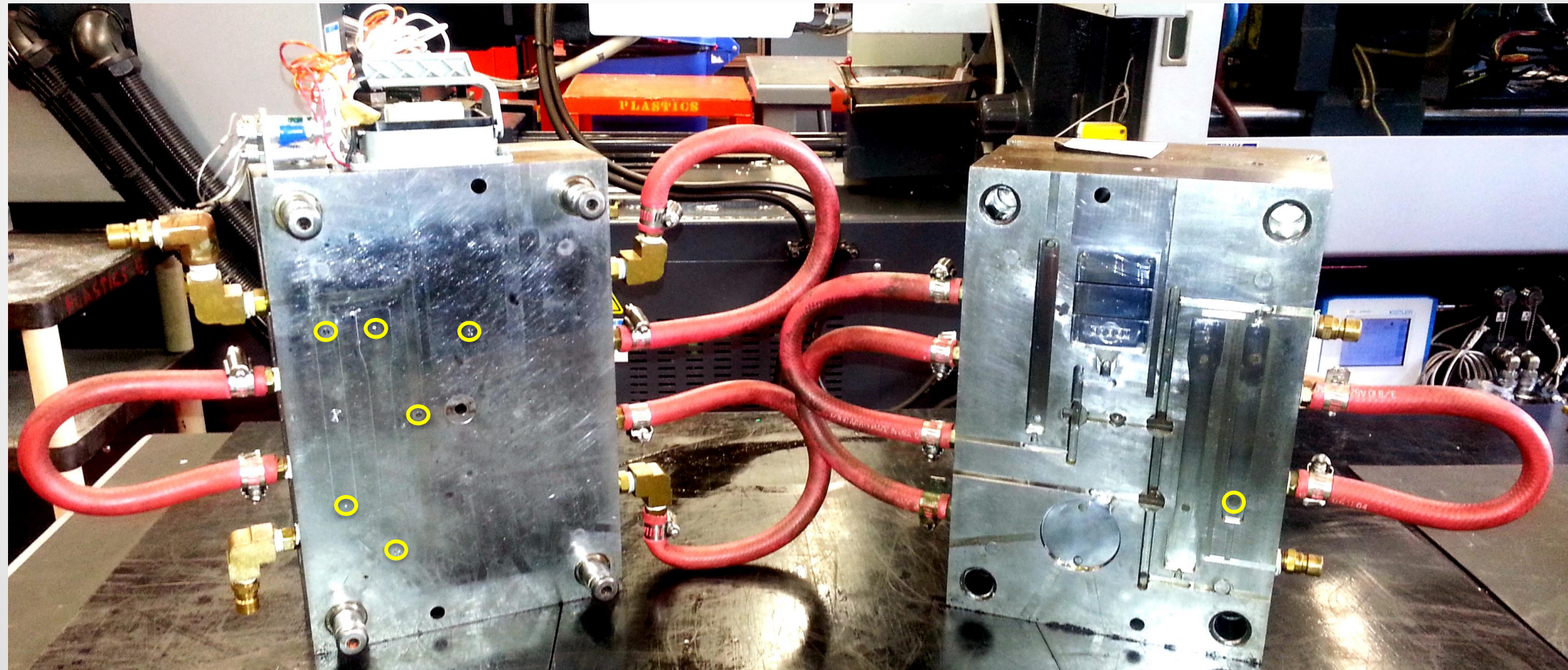
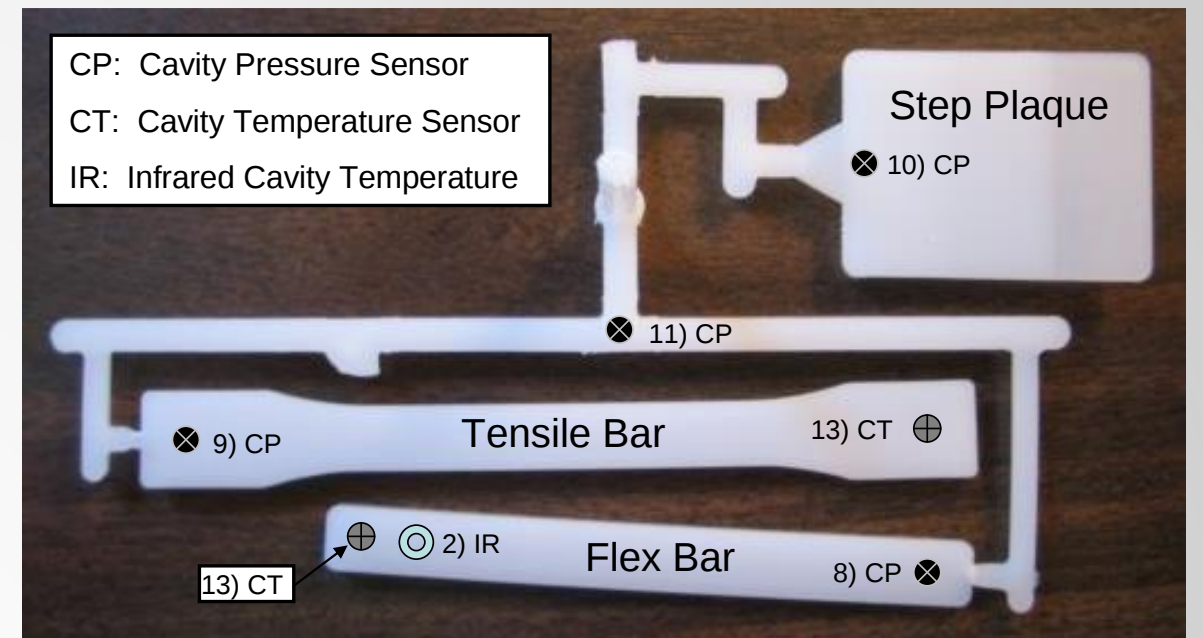
The background image shows a complex industrial setup, likely a laboratory or manufacturing environment. It features two large, rectangular metal blocks, possibly heat exchangers or fluid reservoirs, connected by several thick red hoses. The hoses are coiled and looped between the blocks. In the background, there are various other pieces of equipment, including a control panel with a digital display and some wiring. A semi-transparent white rectangular box is overlaid on the center of the image, containing the word "Experimentation" in a bold, blue, sans-serif font.

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



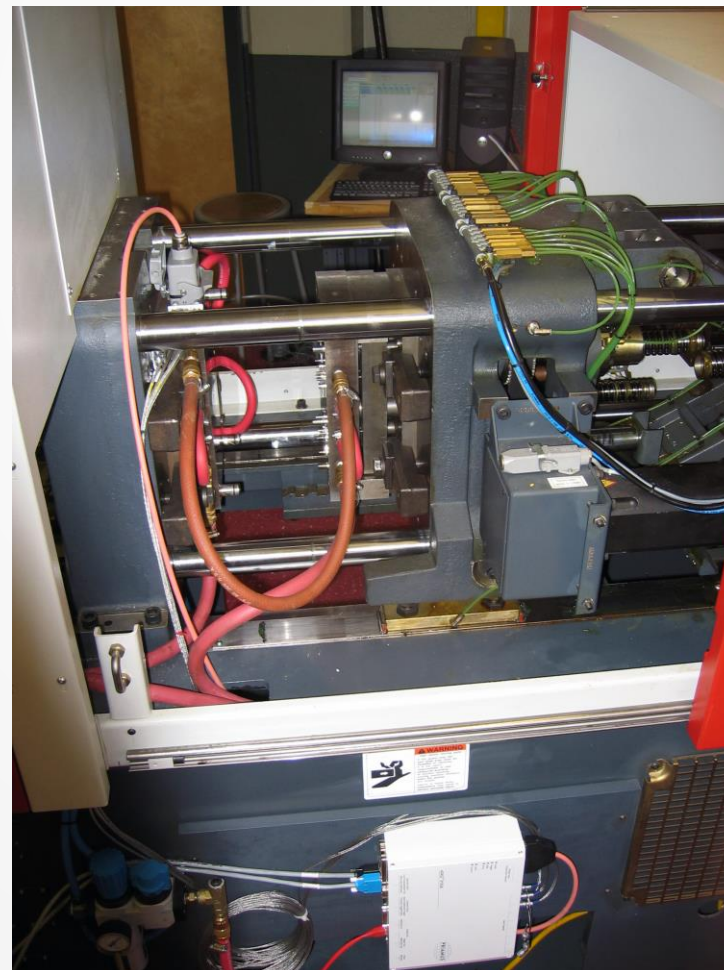
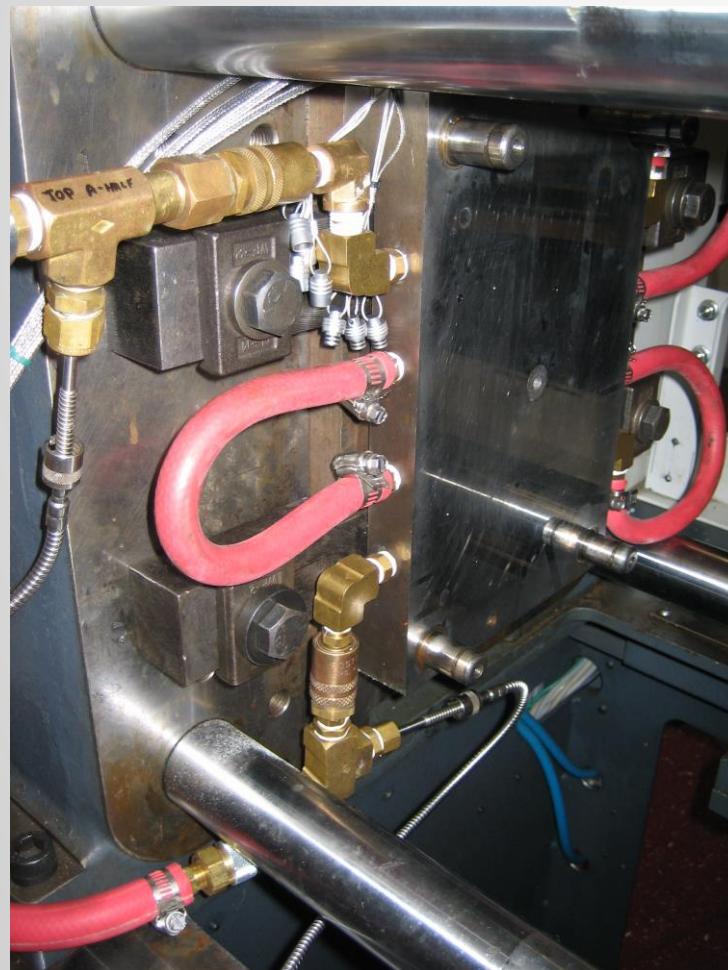
■ Data Acquisition Systems

- RJG eDART®
 - Machine signals
 - Cooling lines thermocouples
- Priamus® eDAQ 8102A
 - Cavity pressure and temperature sensors



Experimentation

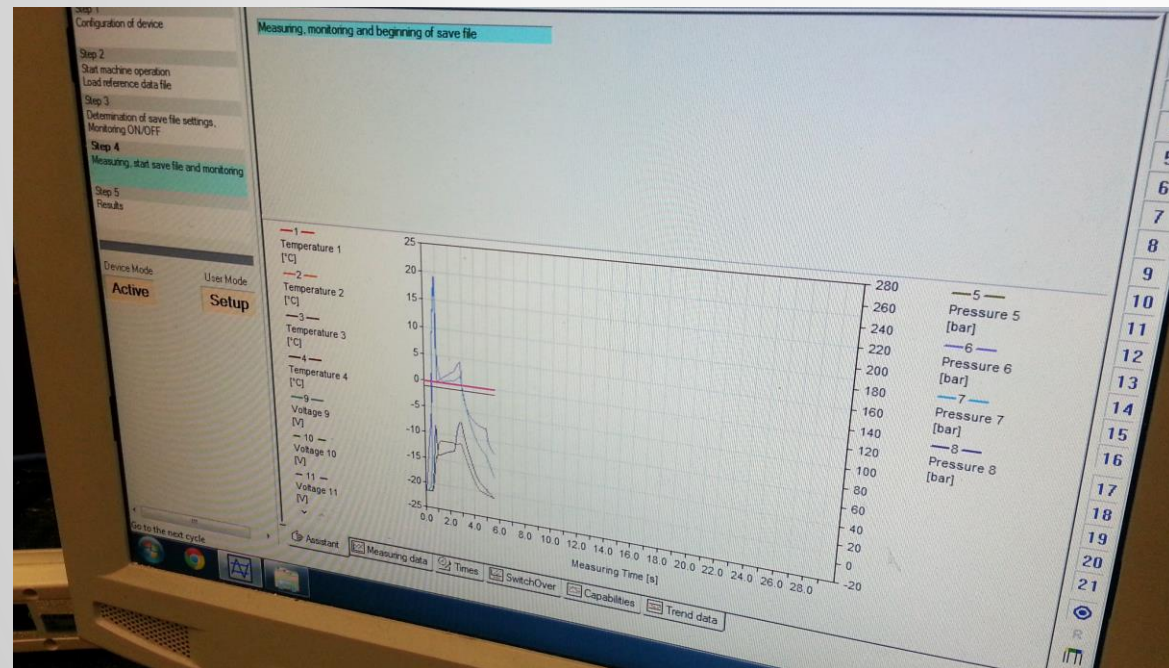
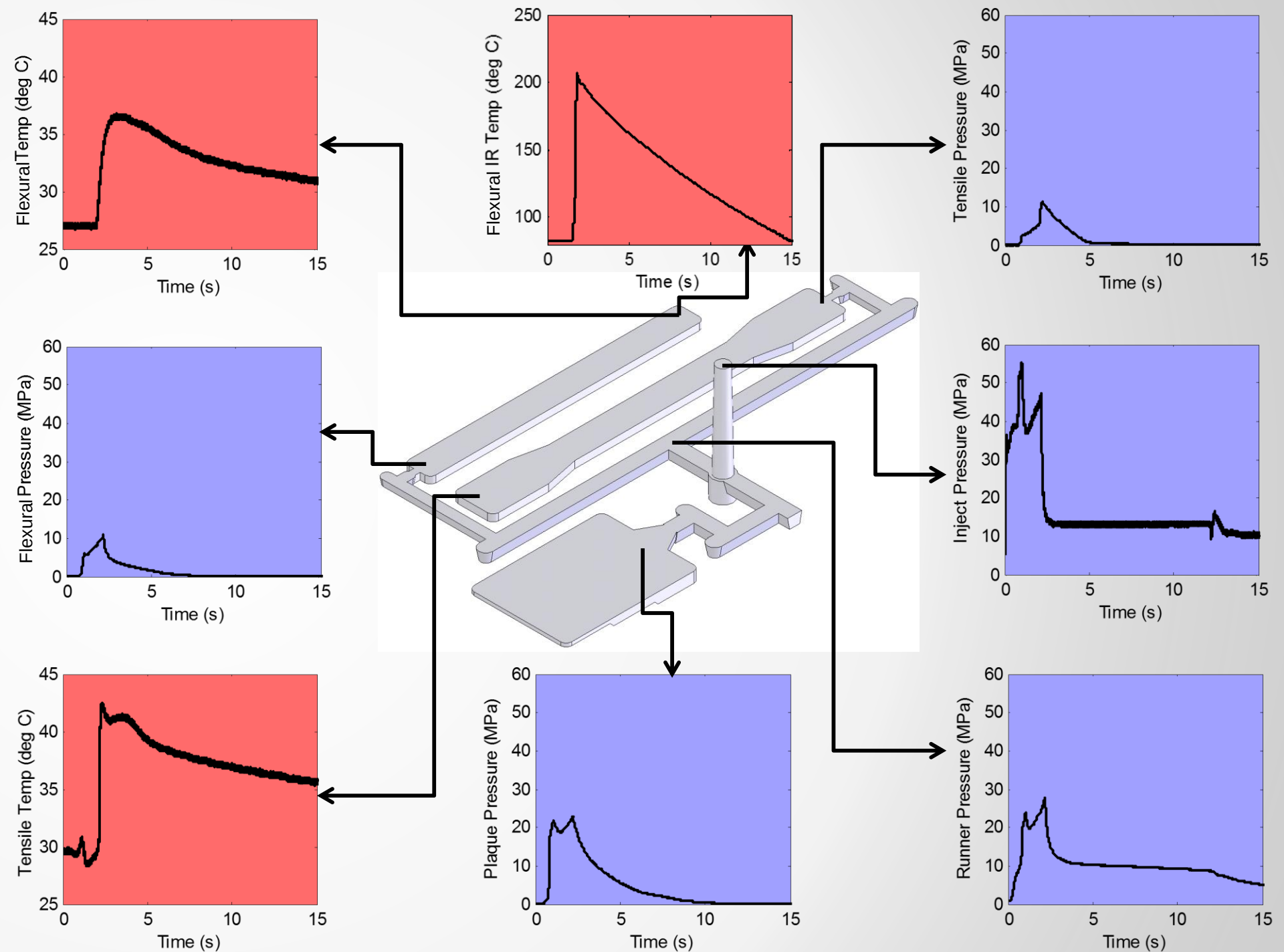
- Electric Injection Molding Machine
 - Ferromatic Milacron Elektra 50 ton
 - Braskem CP201HC Polypropylene



<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

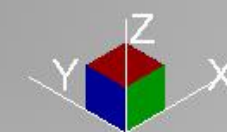


Guthrie Gordon, UMass Lowell

Circuit metal temperature
= 34.66[C]

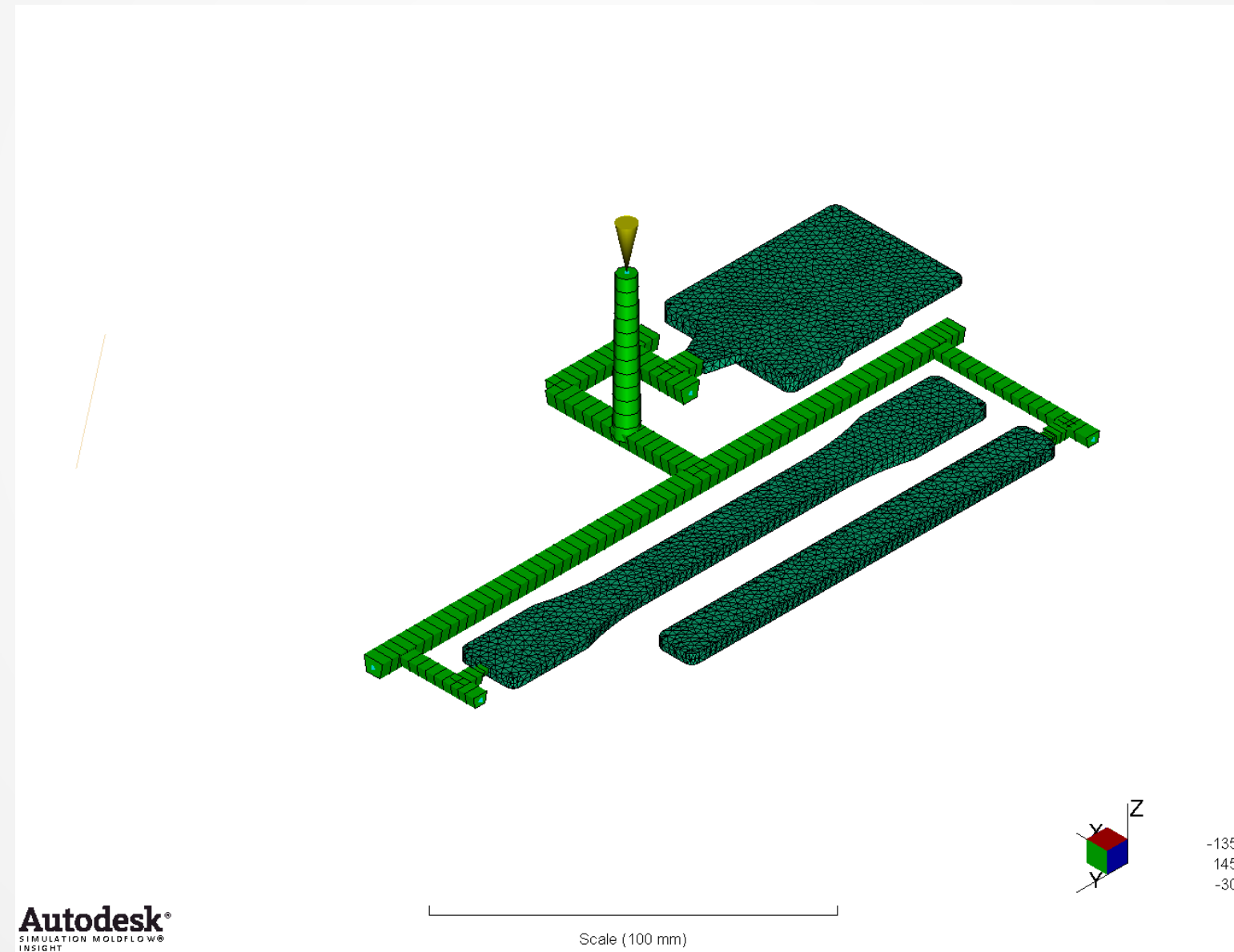


Cooling Analysis



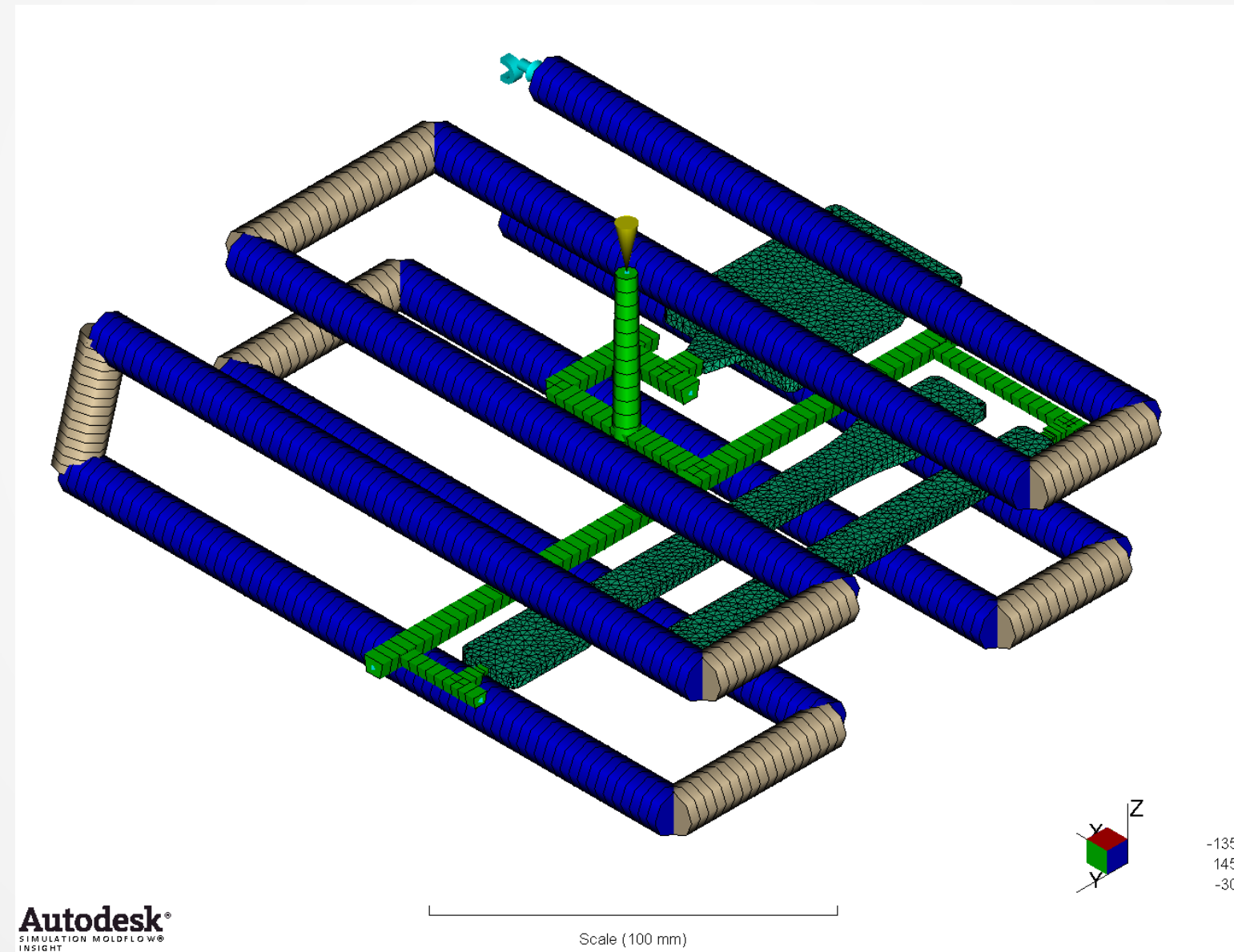
Model Setup

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



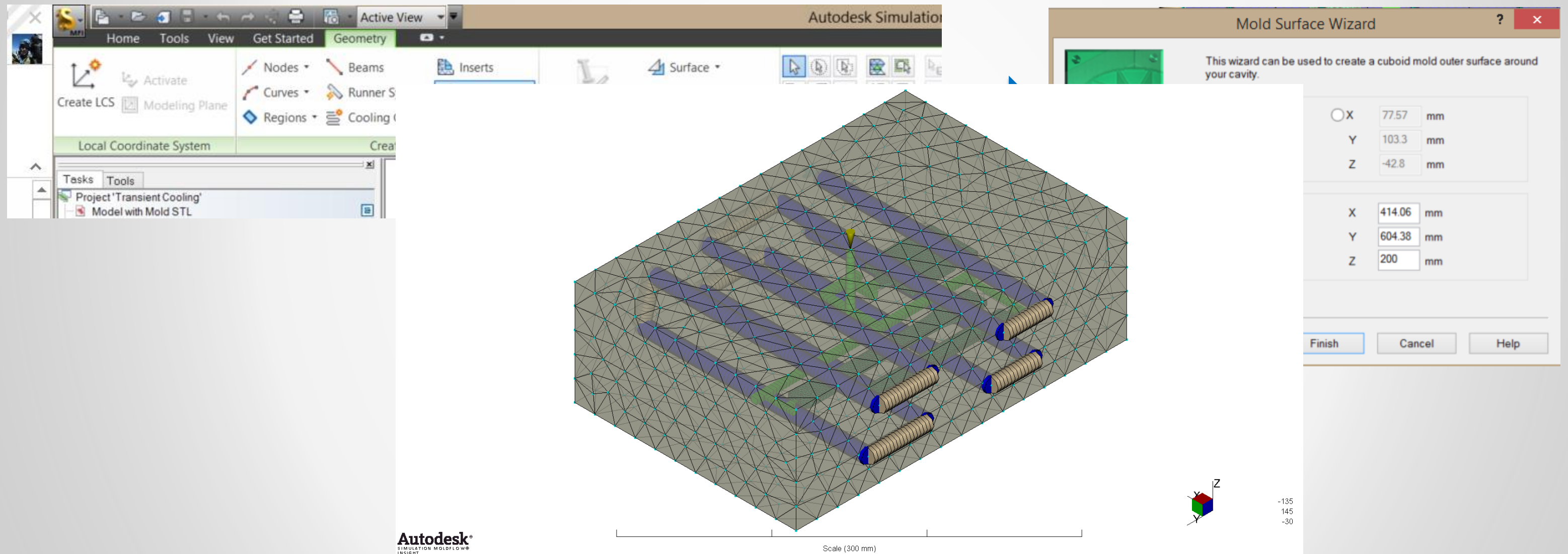
Model Setup

- Model cooling system with beam elements



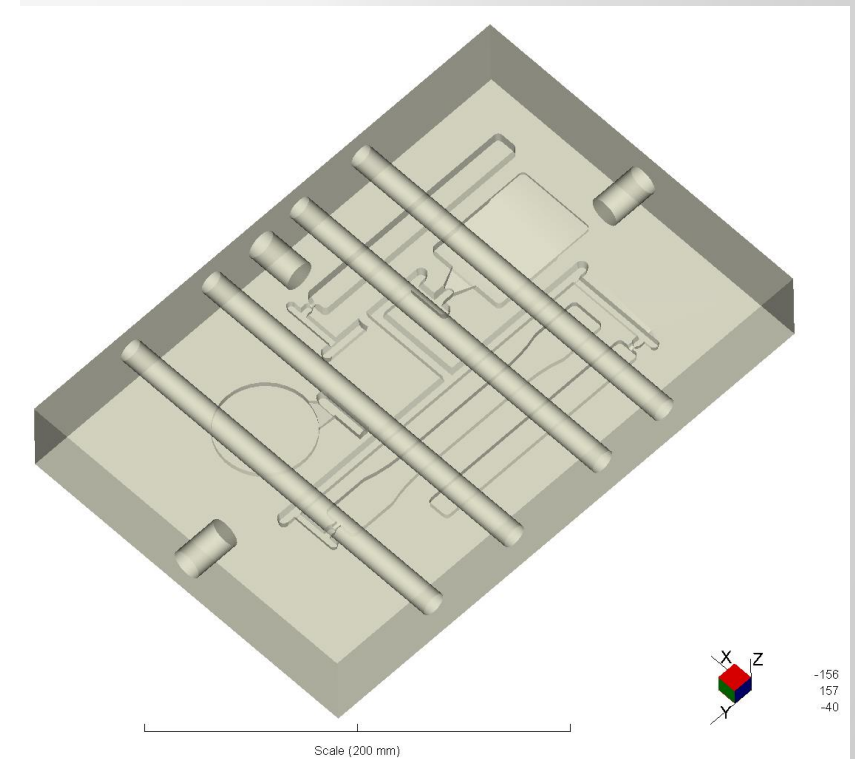
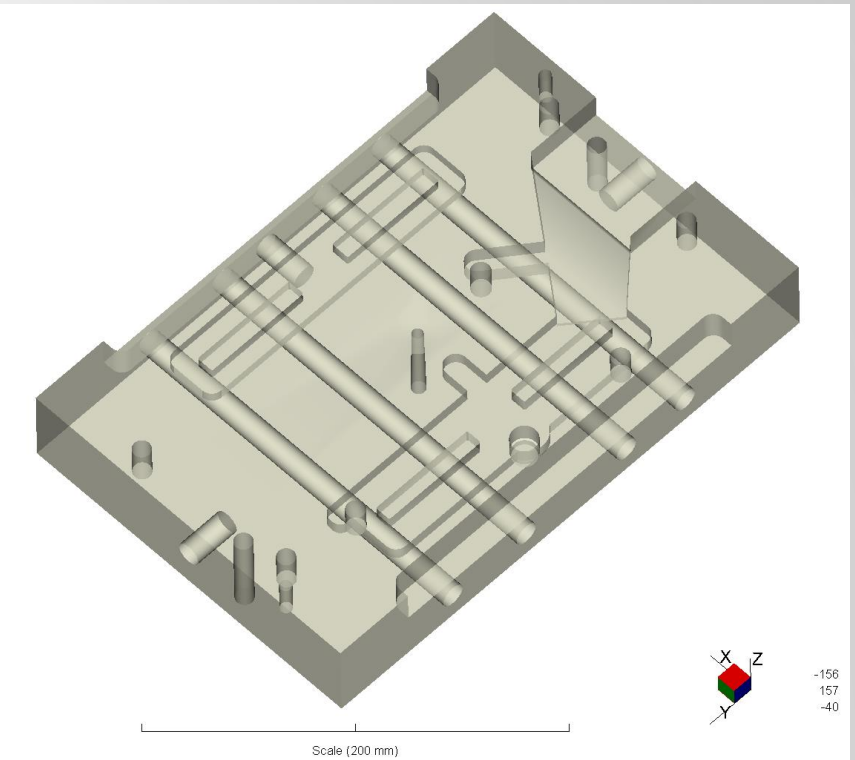
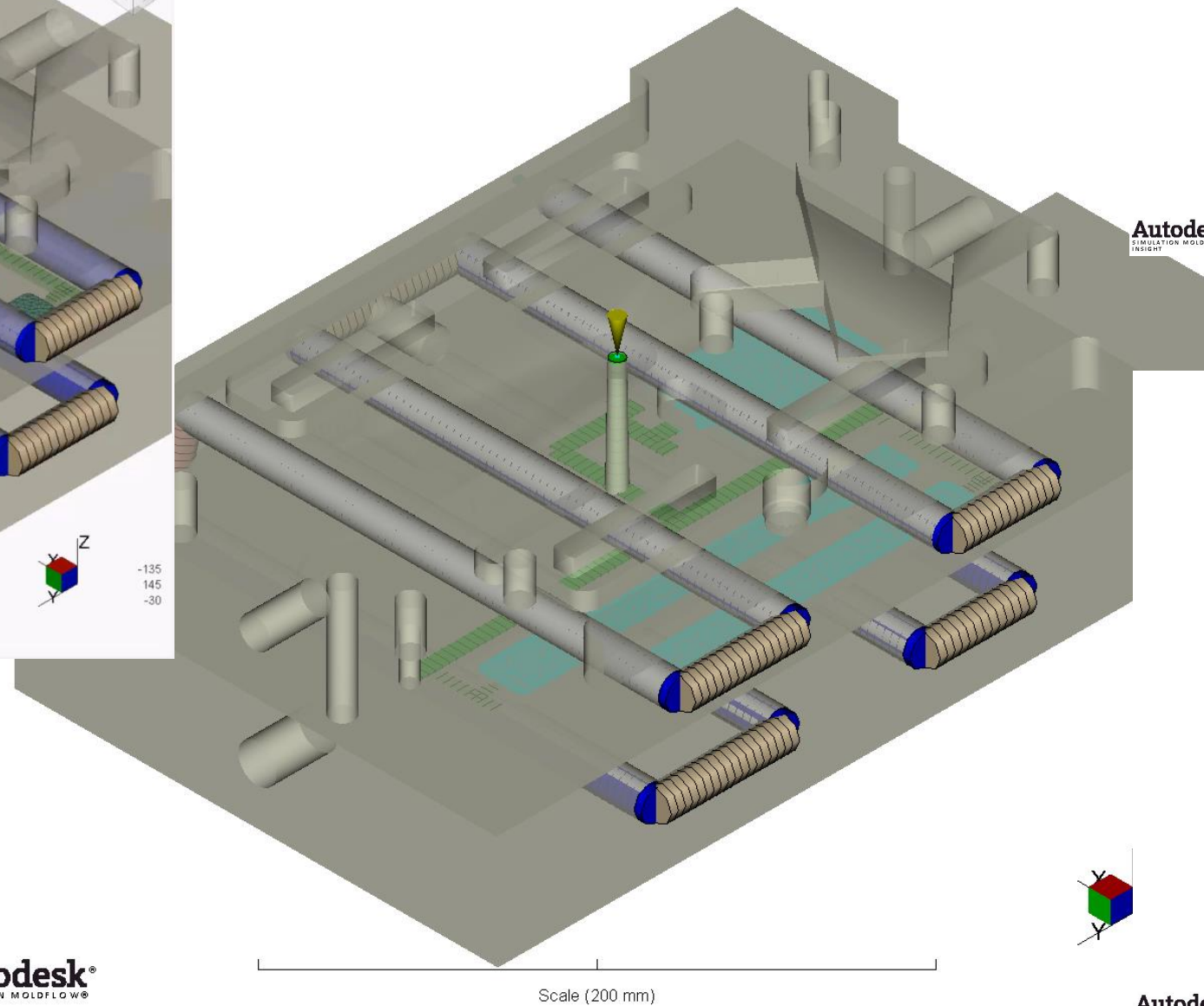
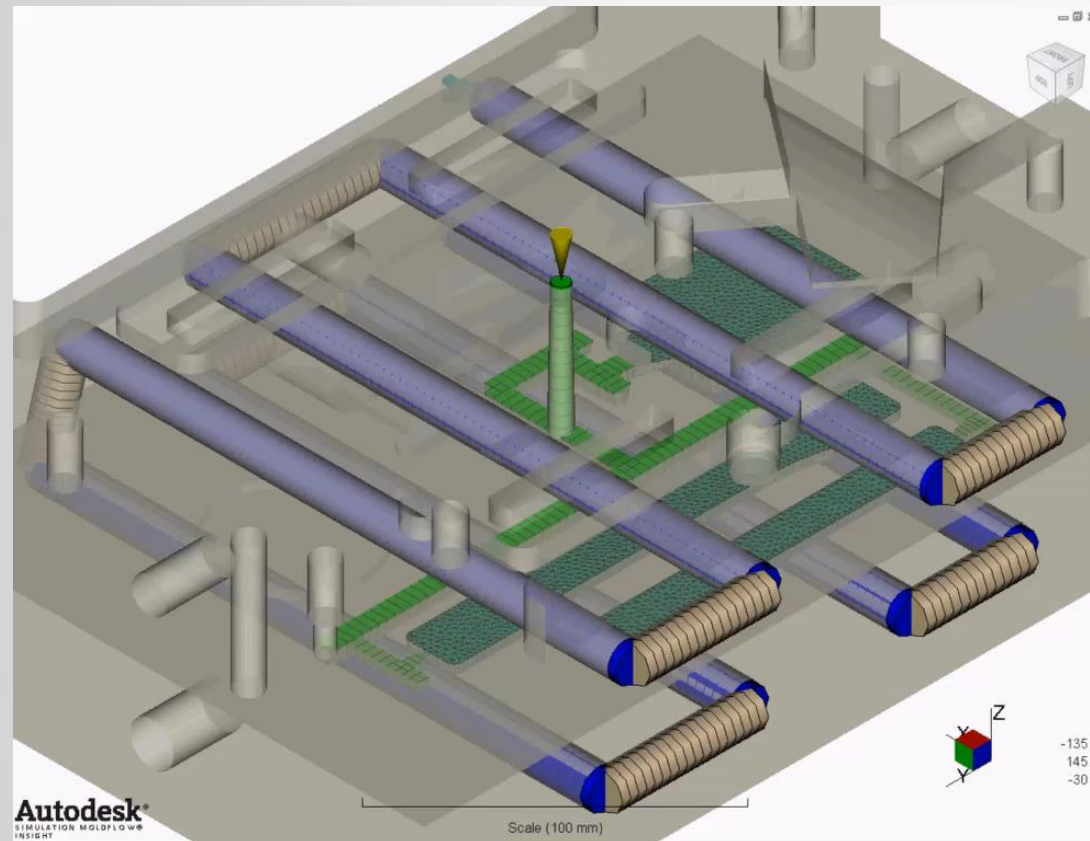
Model Setup (BEM)

- Create mold surface mesh



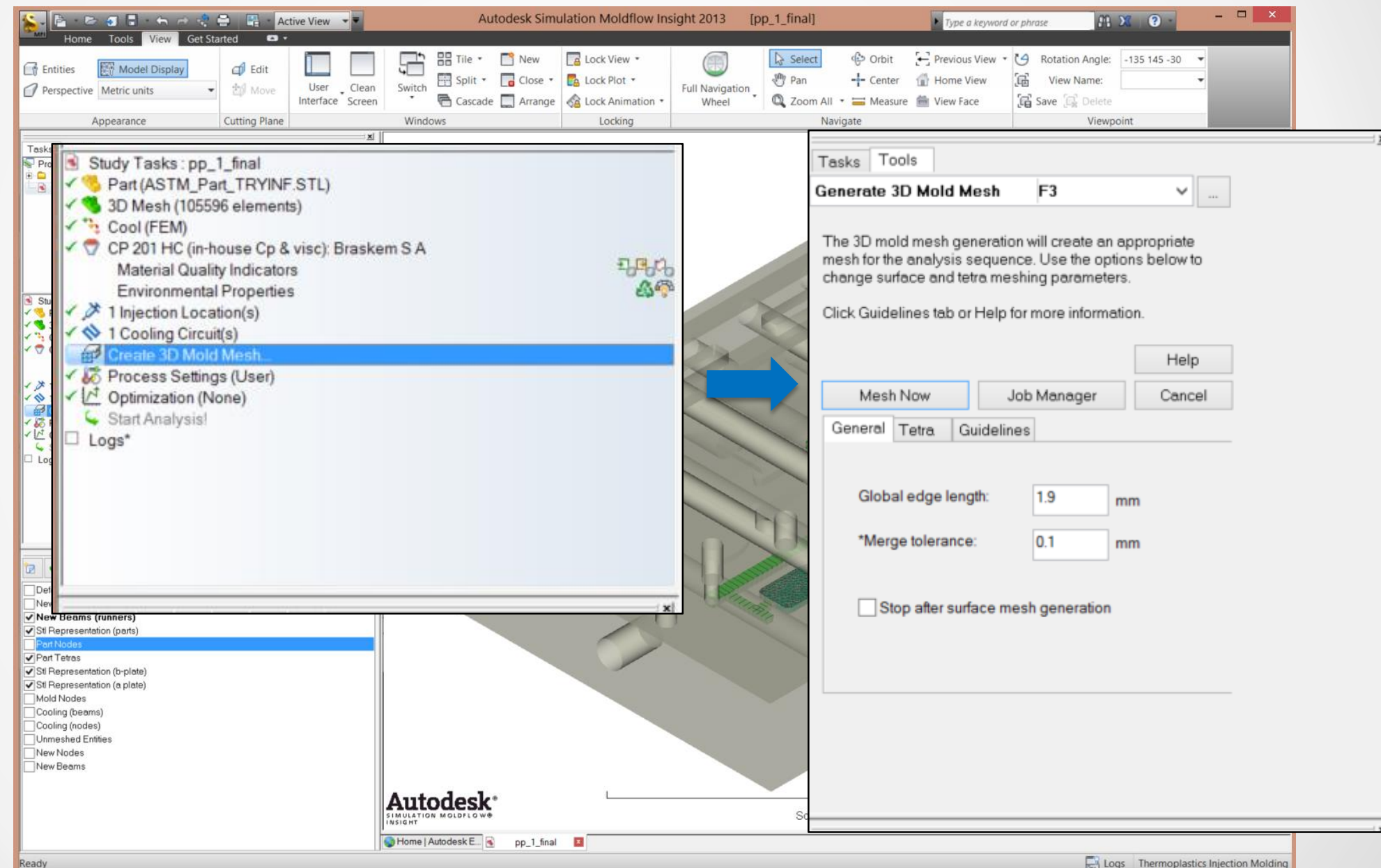
Model Setup (FEM)

- Import mold plates from models



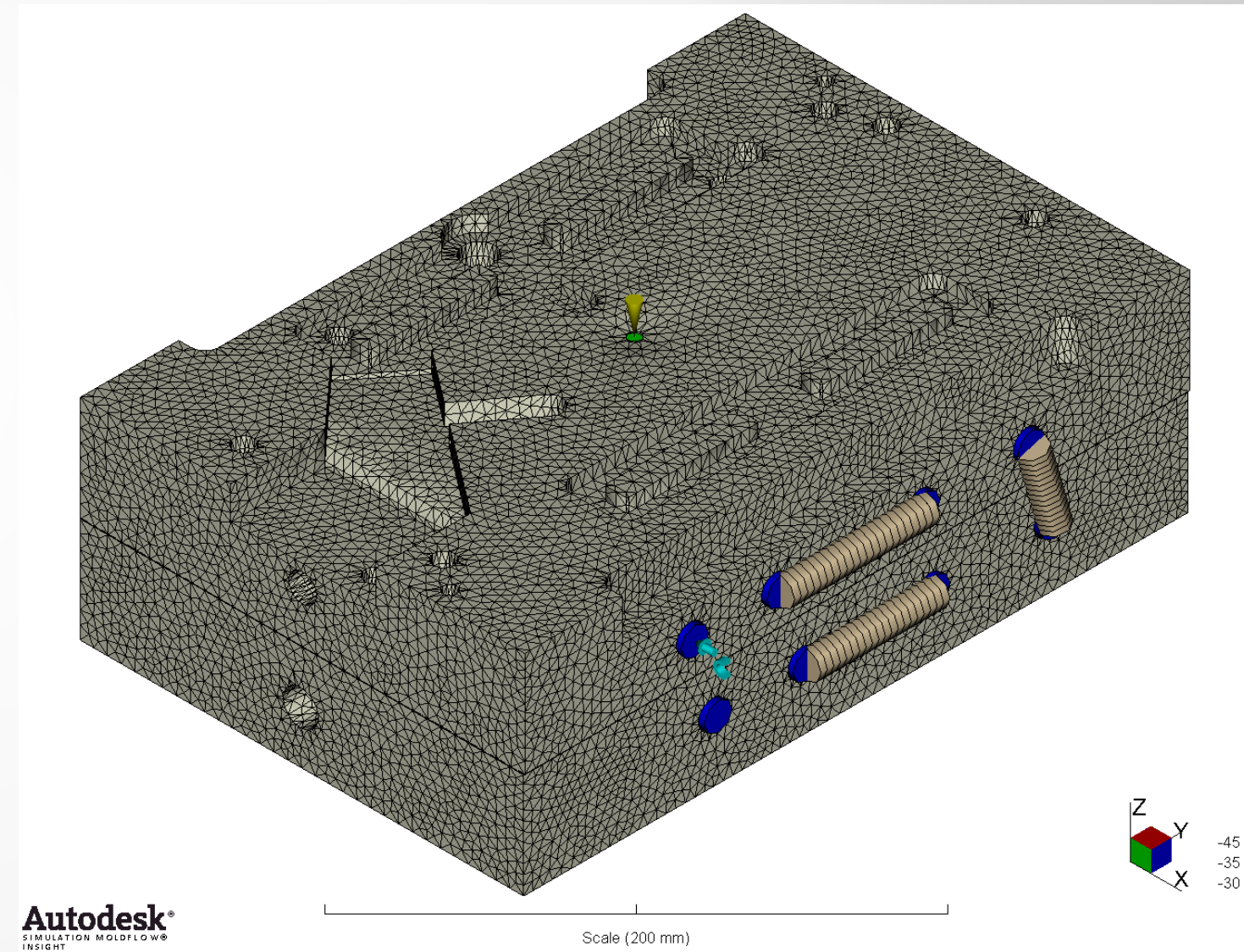
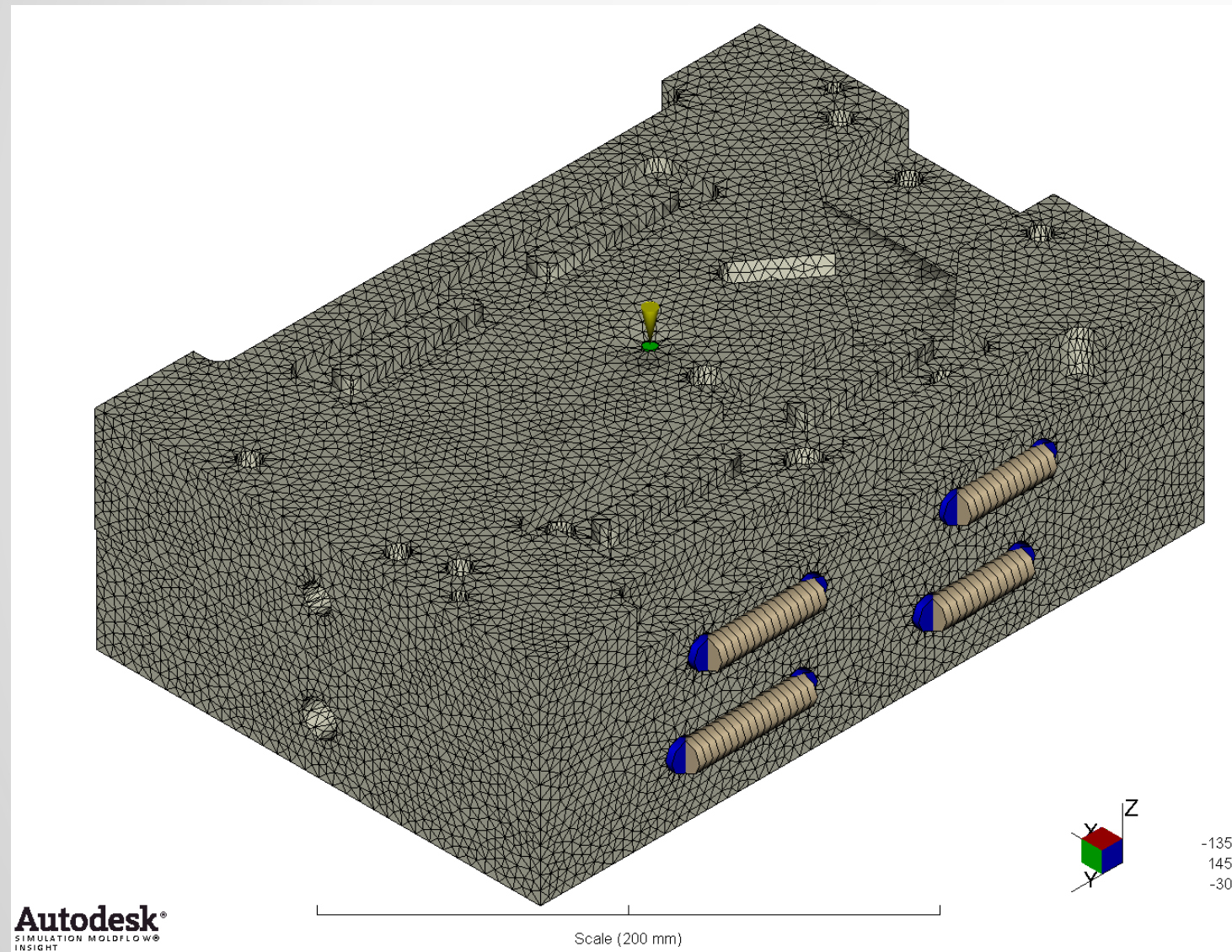
Model Setup (FEM)

- Create mold mesh



Model Setup (FEM)

- Create mold mesh



What is BEM and FEM?

- Conduction Equation
 - Heat transfer through mold steel

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) \quad \xrightarrow{\text{constant } k \text{ for steel}} \quad \overbrace{\frac{\partial T}{\partial t}}^{\text{Transient Term}} = \alpha \nabla^2 T$$

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

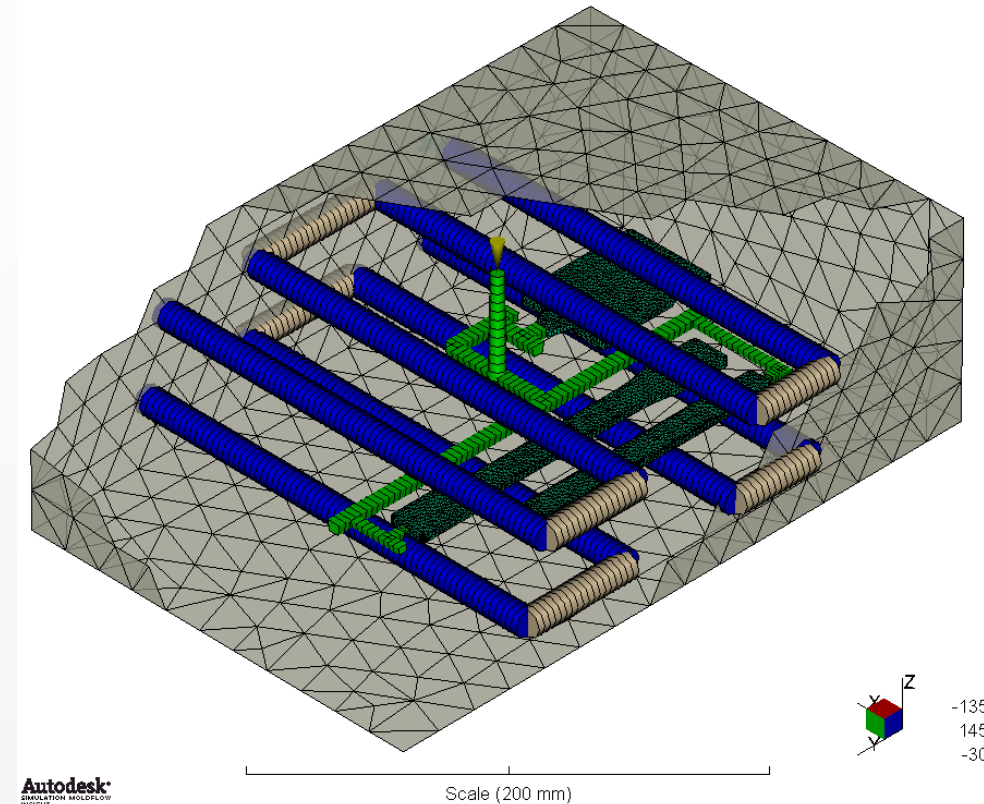
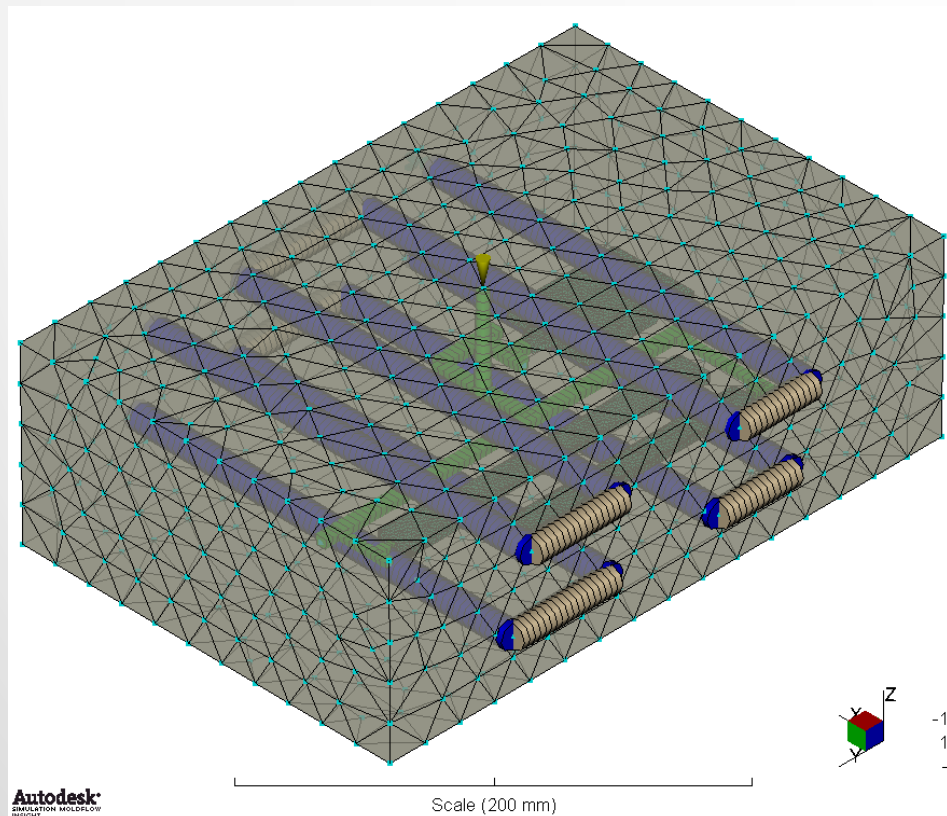
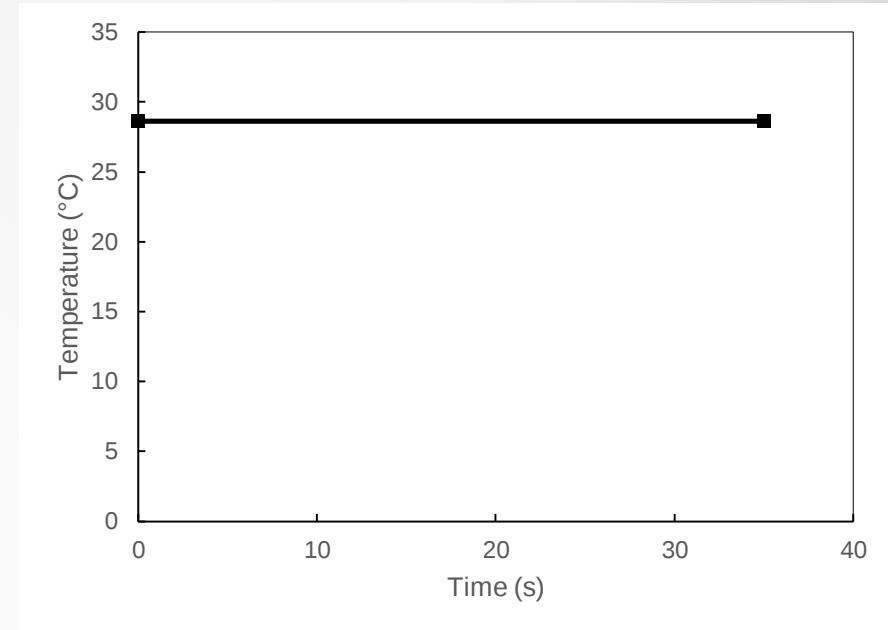
BEM Cooling Analysis

- Boundary Element Method

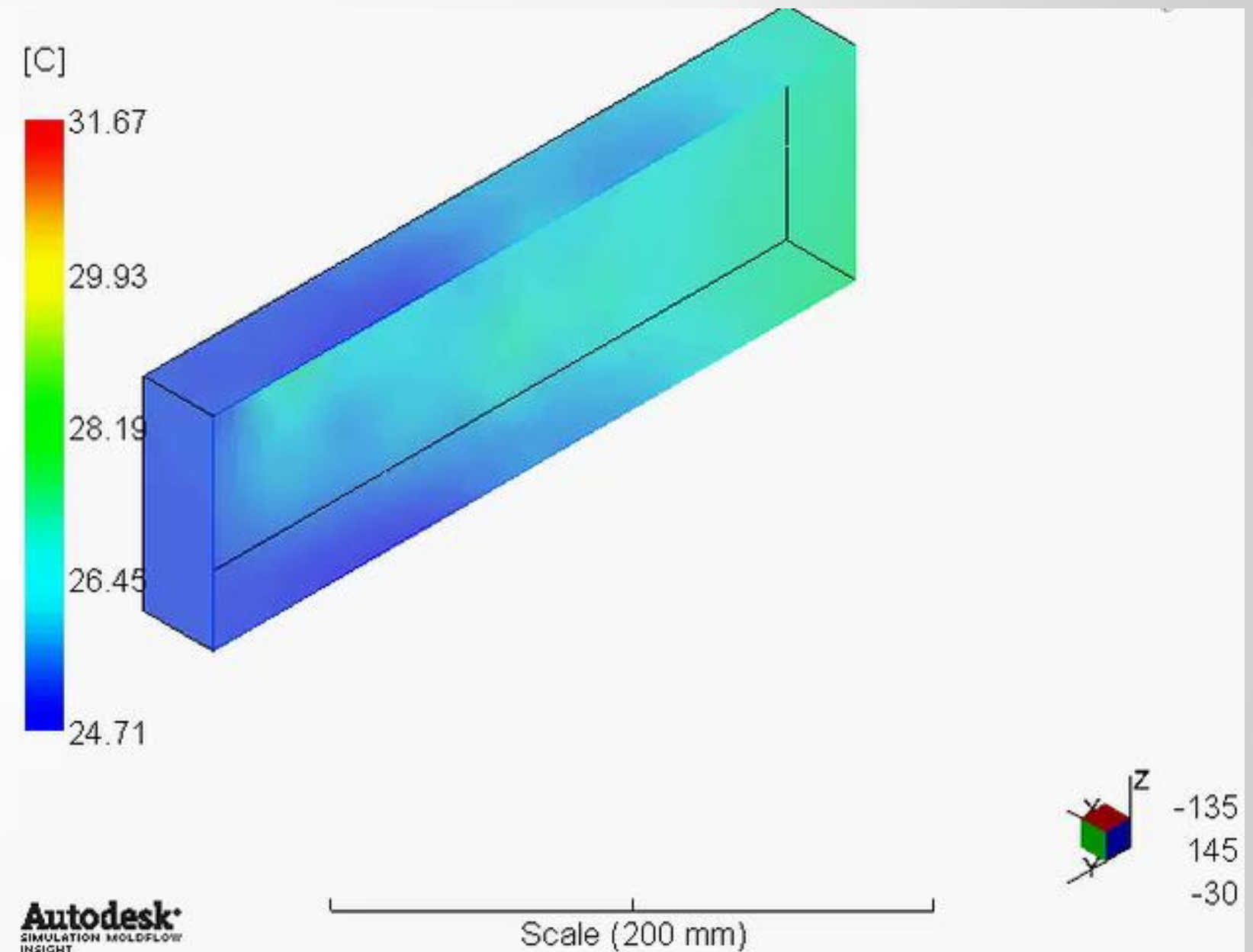
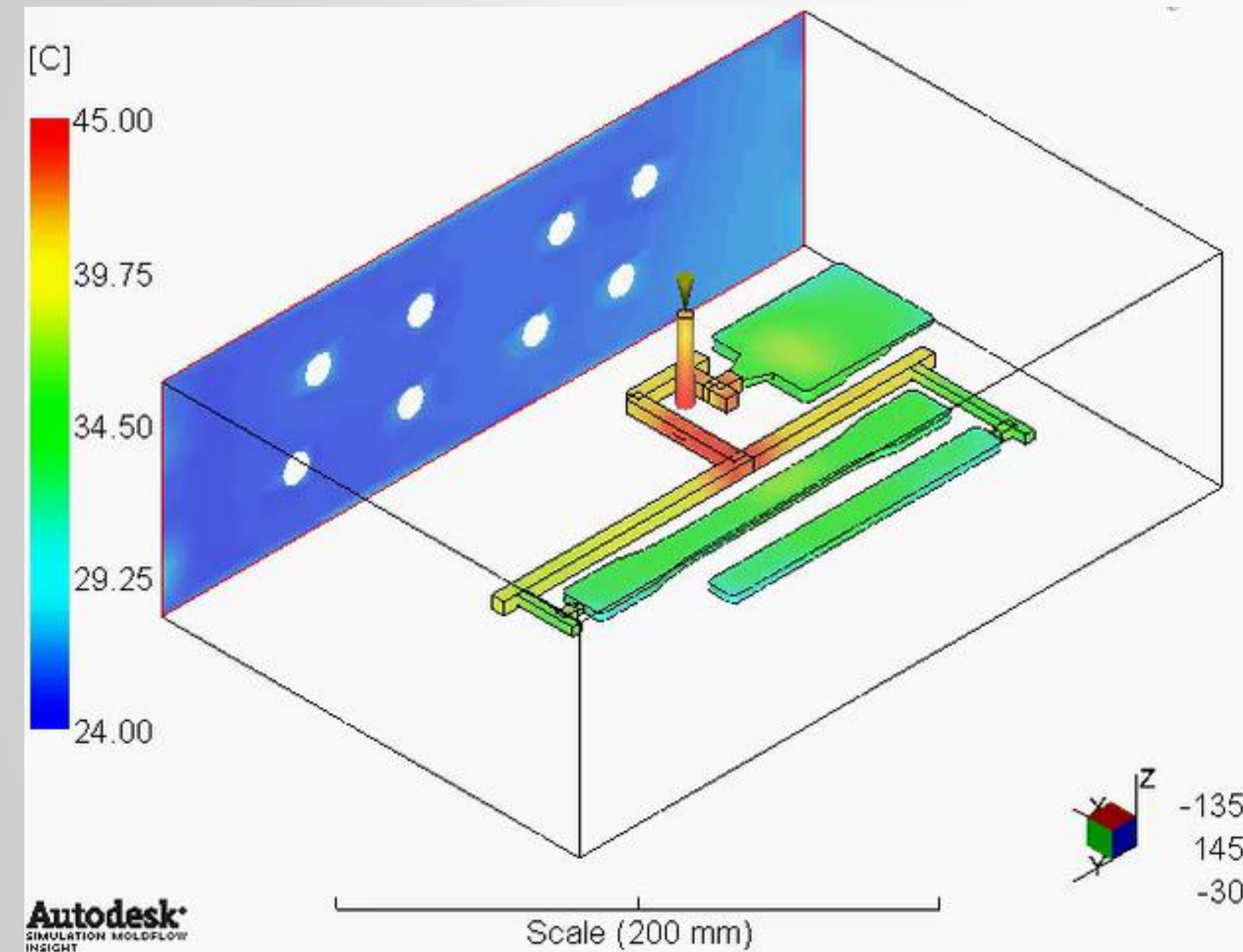
- Steady-state solution

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

- Surface mesh of the mold boundary

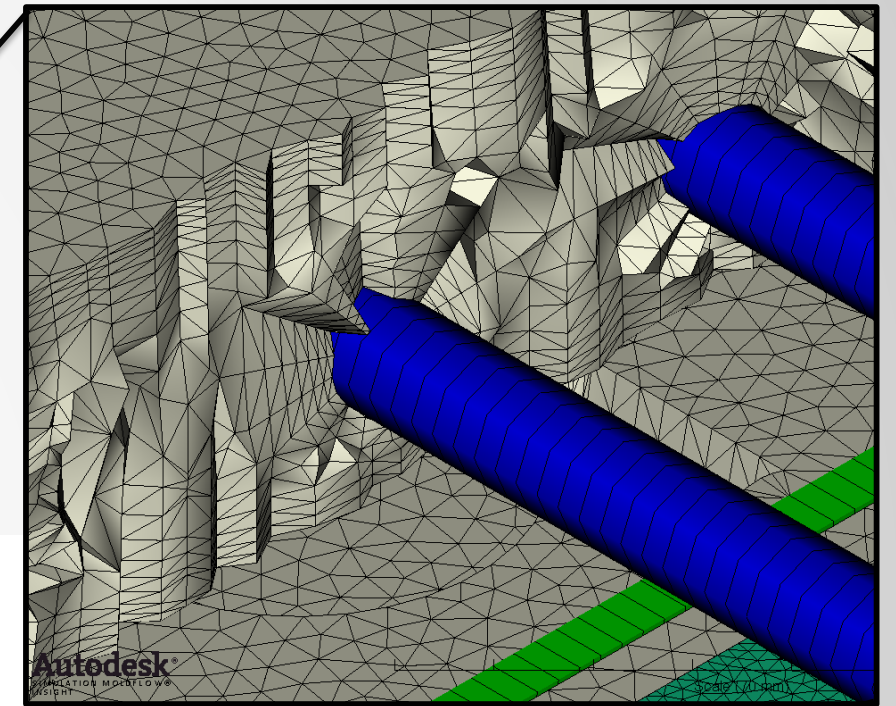
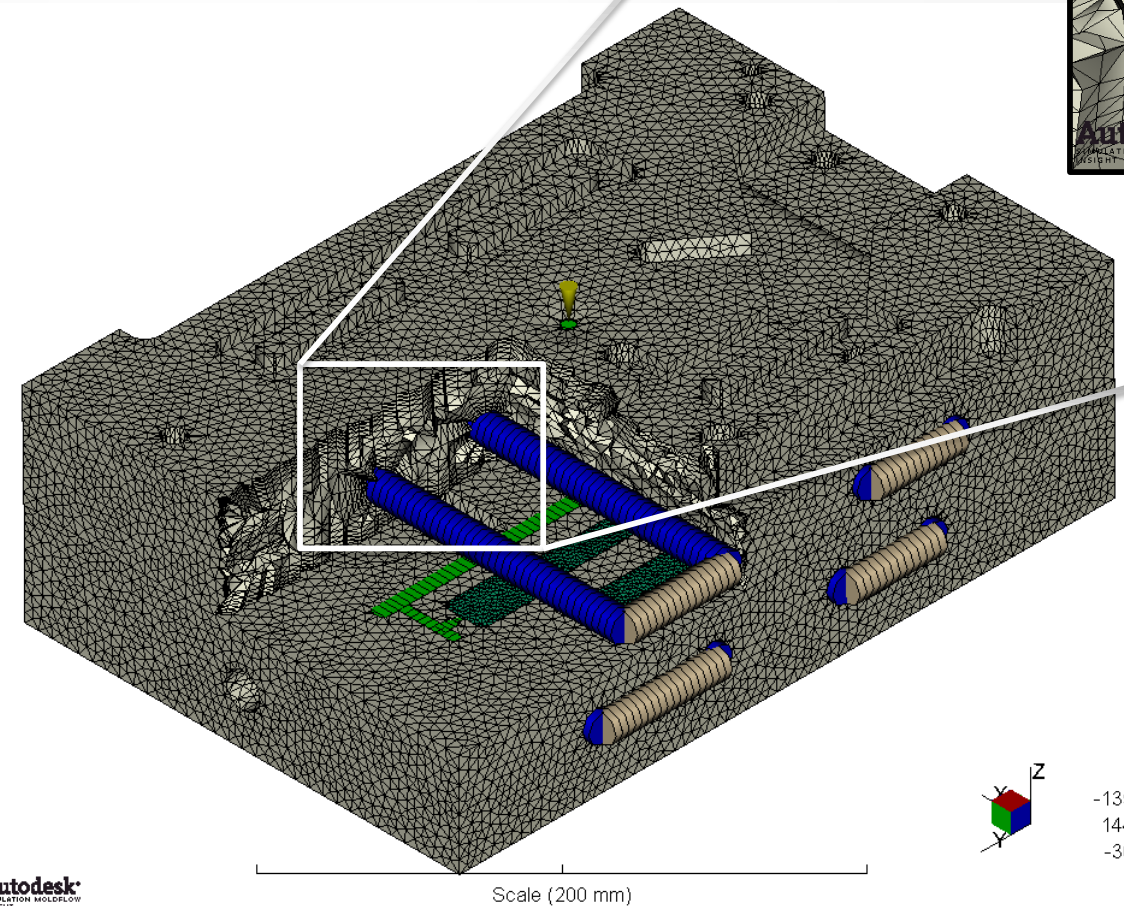
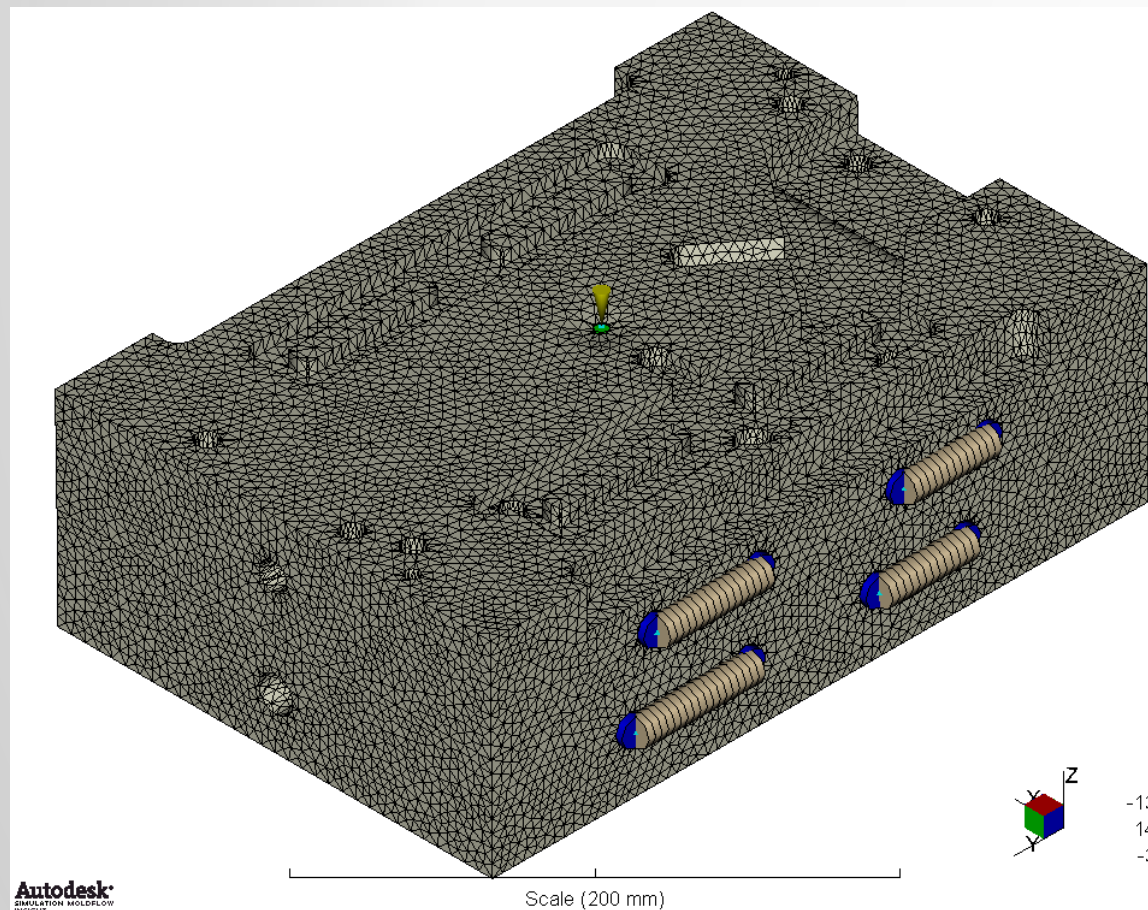


BEM Cooling Analysis

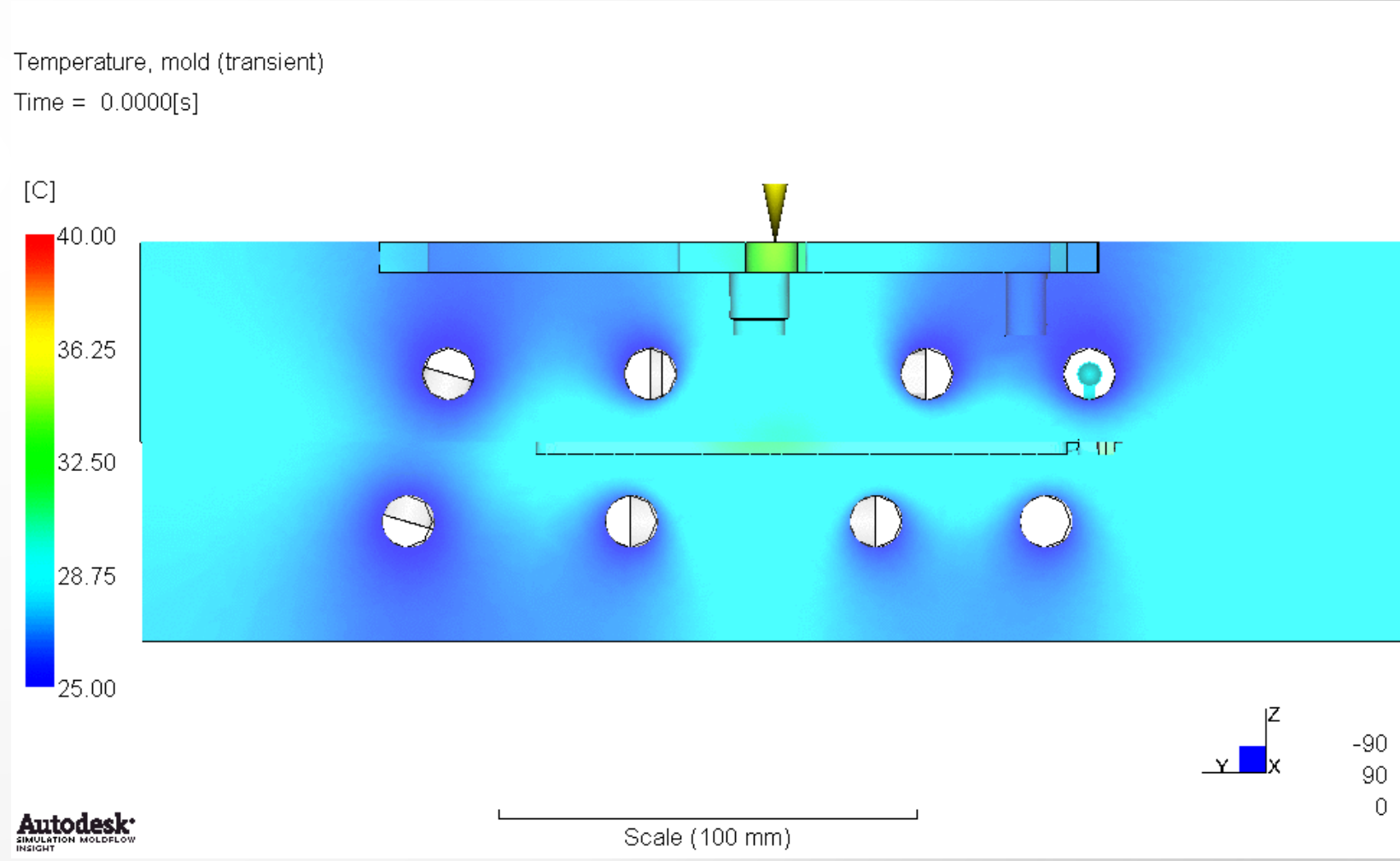
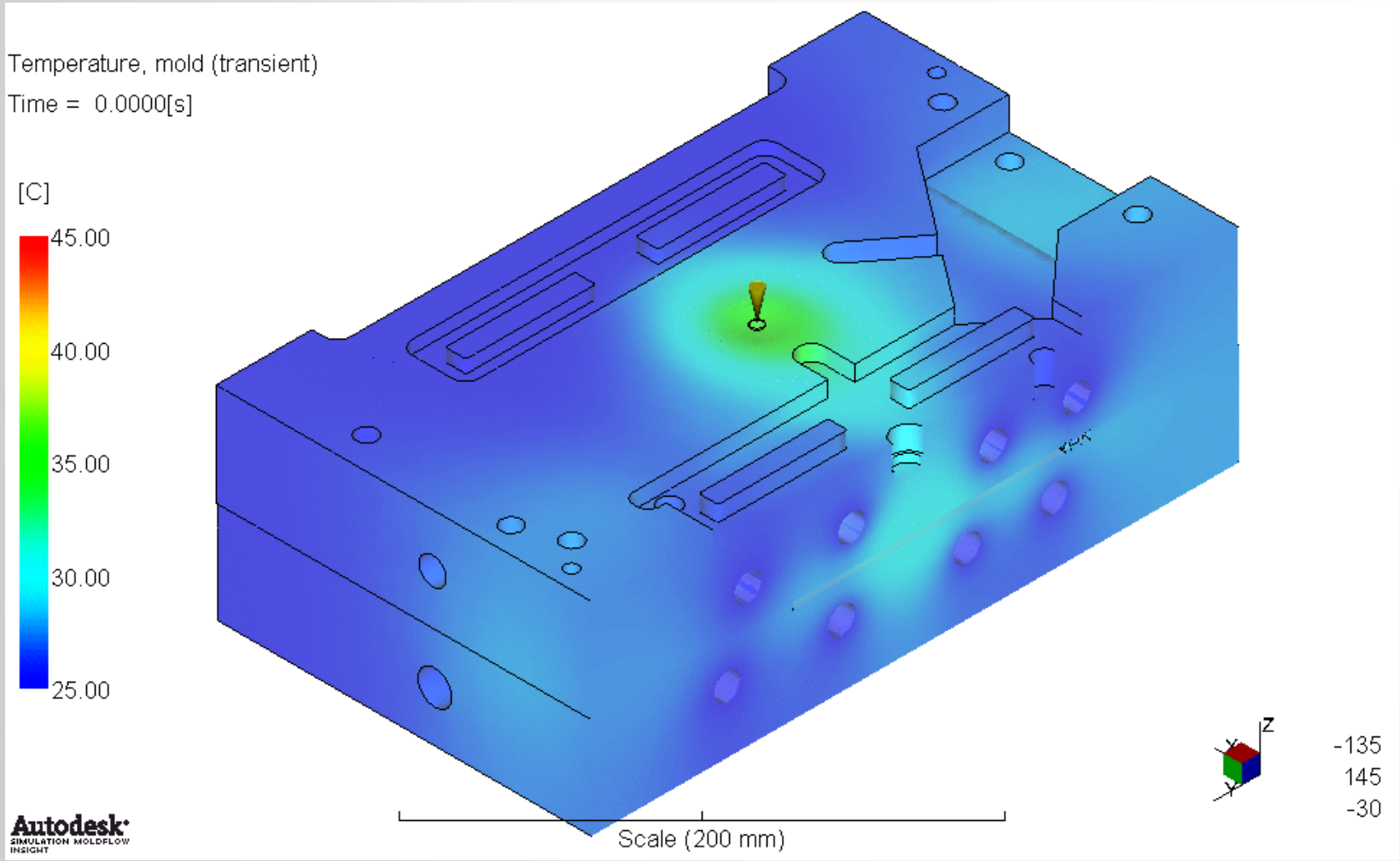
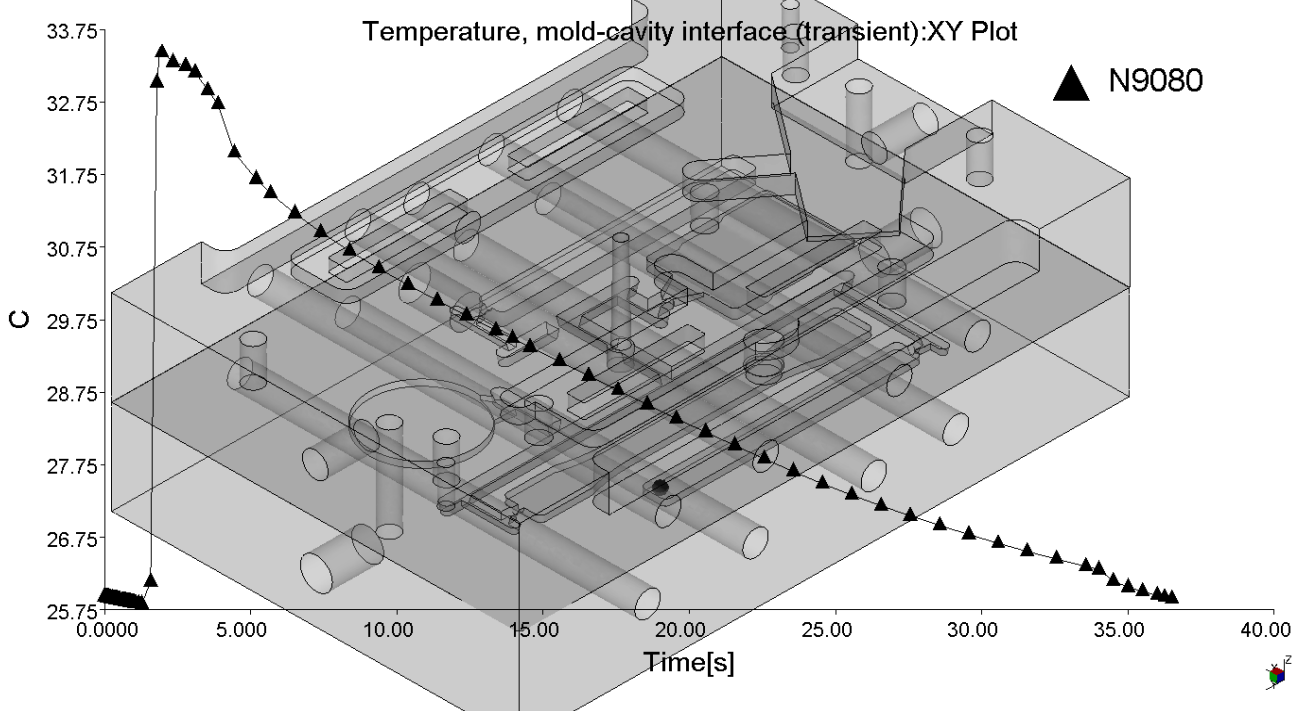


FEM Cooling Analysis

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



FEM Cooling Analysis



When to use FEM or BEM?

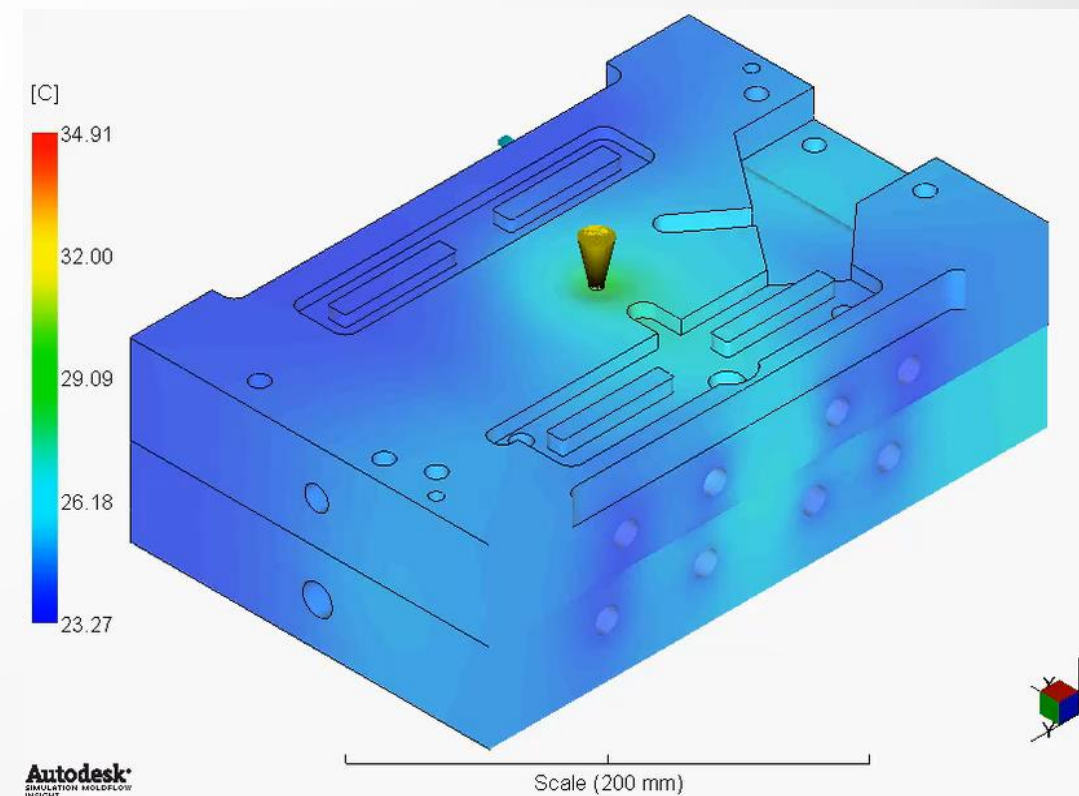
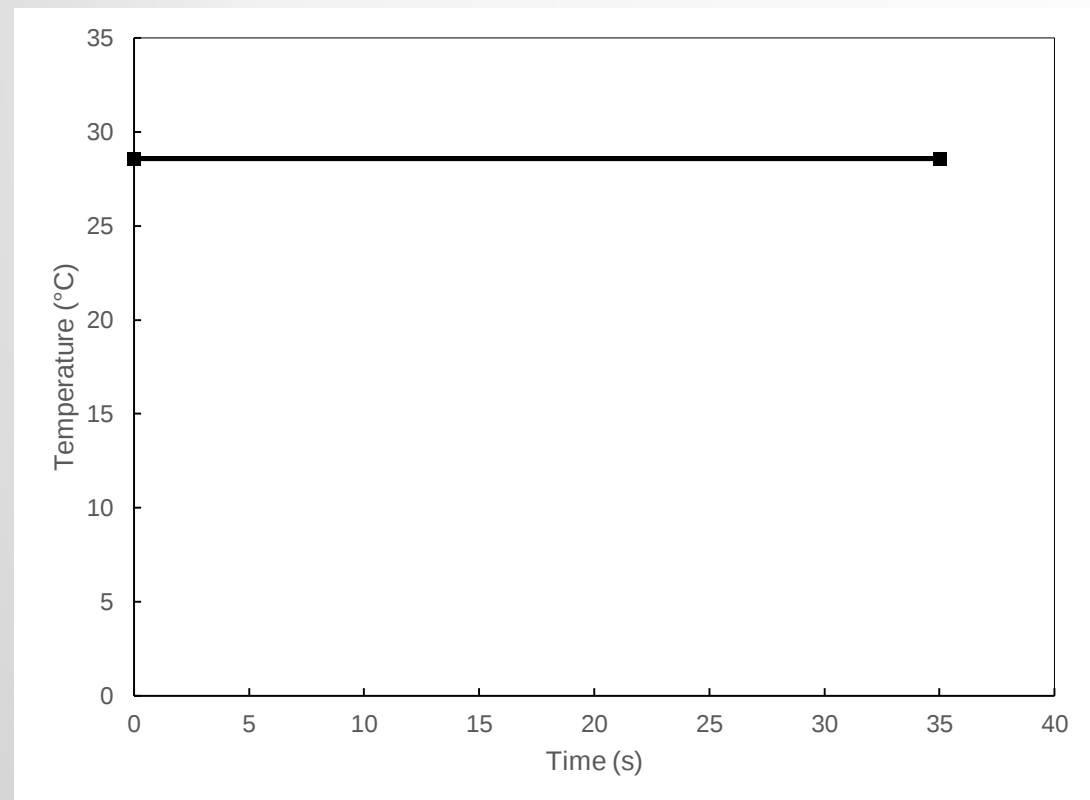
- FEM provides a time-dependent thermal solution of the mold
 - Heat transfer during the cycle
 - Heat accumulation between cycles
- FEM can determine time to reach a thermally stable cycle
 - Provides information about heat transfer rates in the mold
- BEM provides an average temperature useful to identify 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

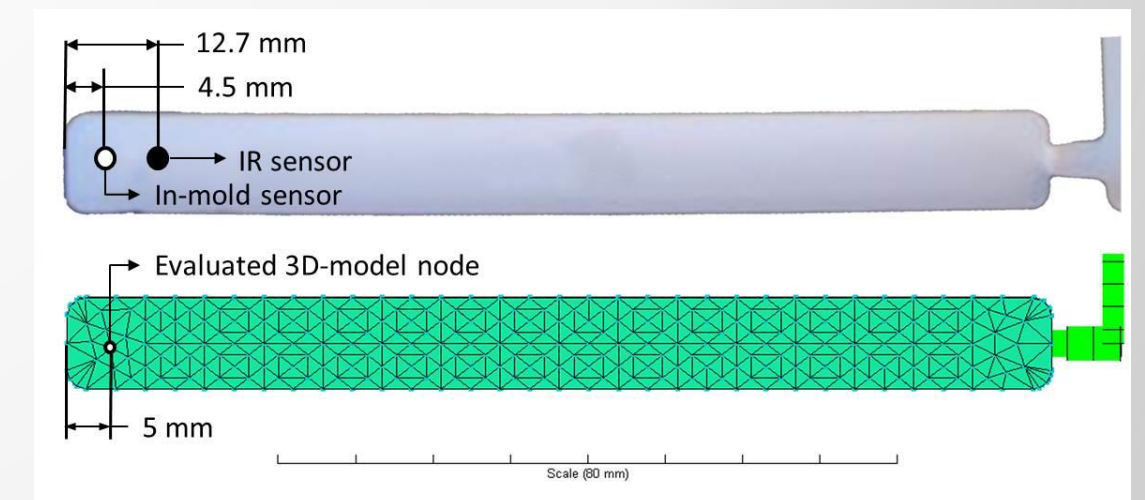
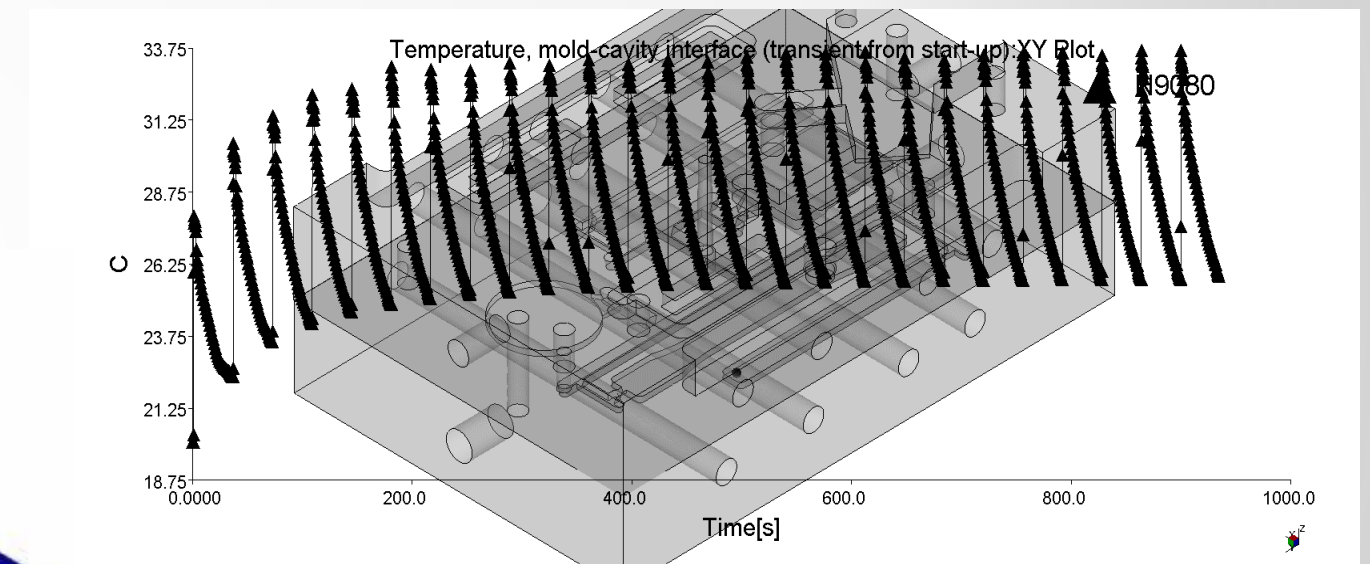
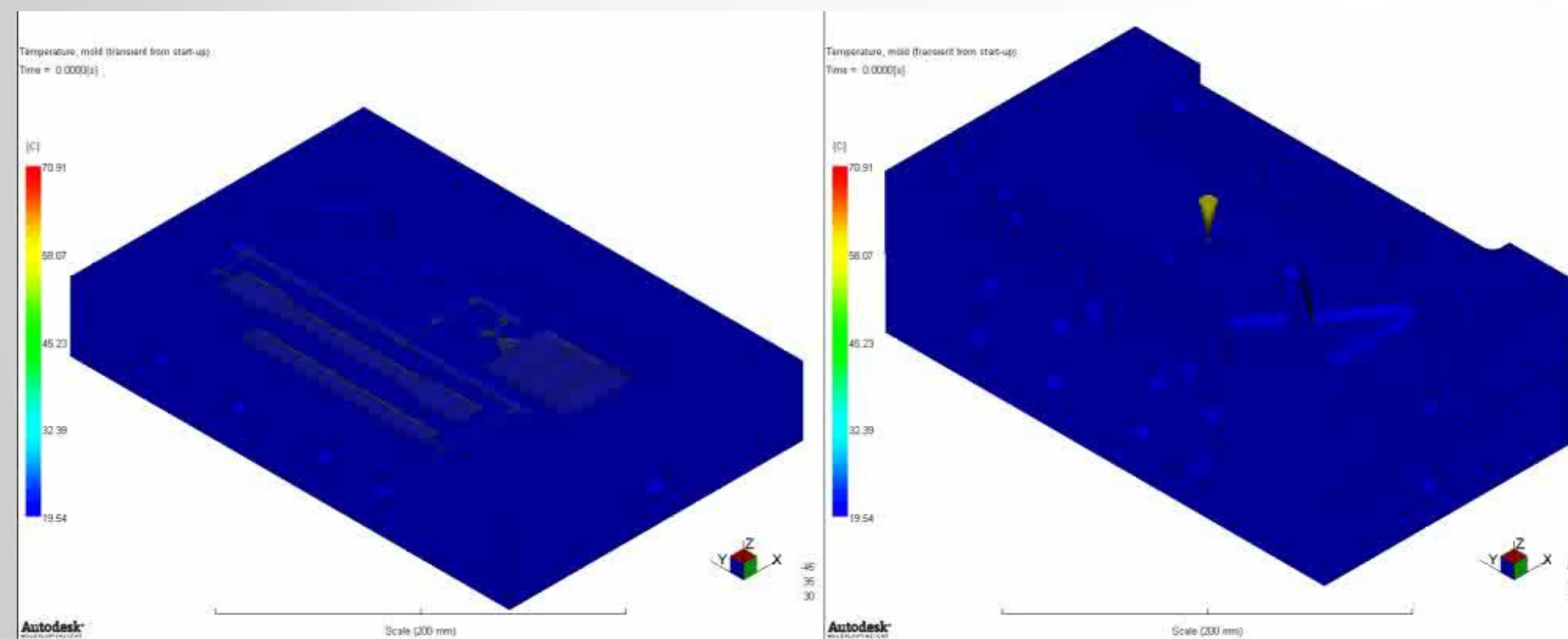
Mold Temperature Options

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



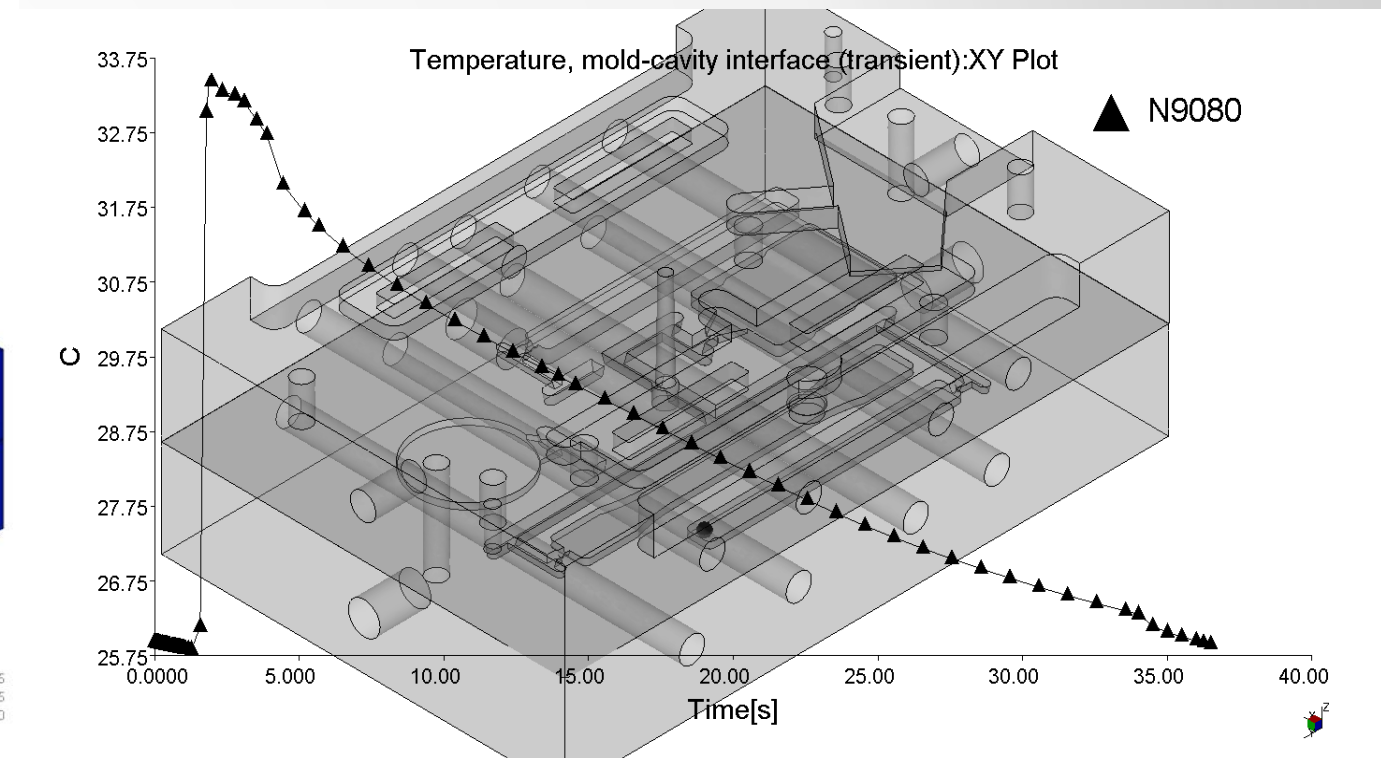
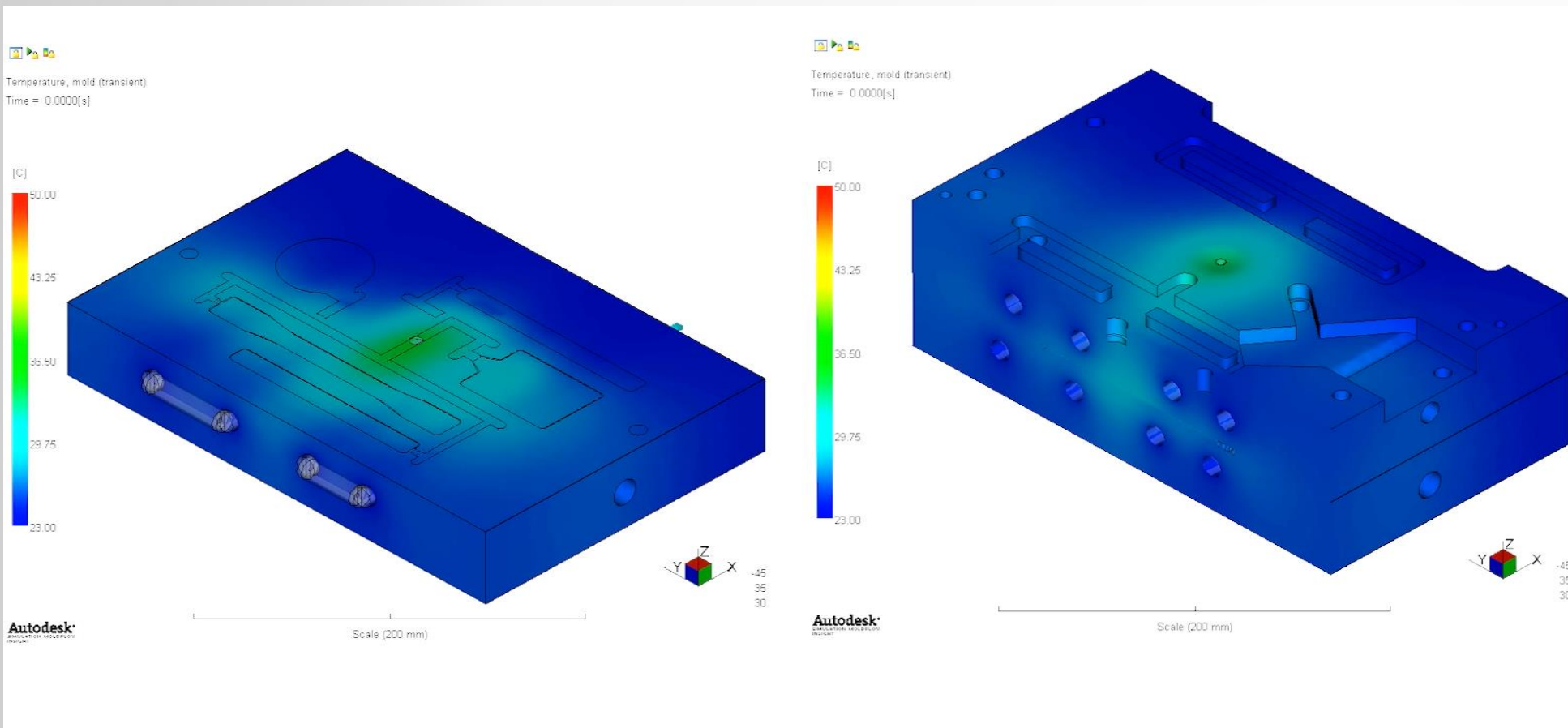
Mold Temperature Options

- 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

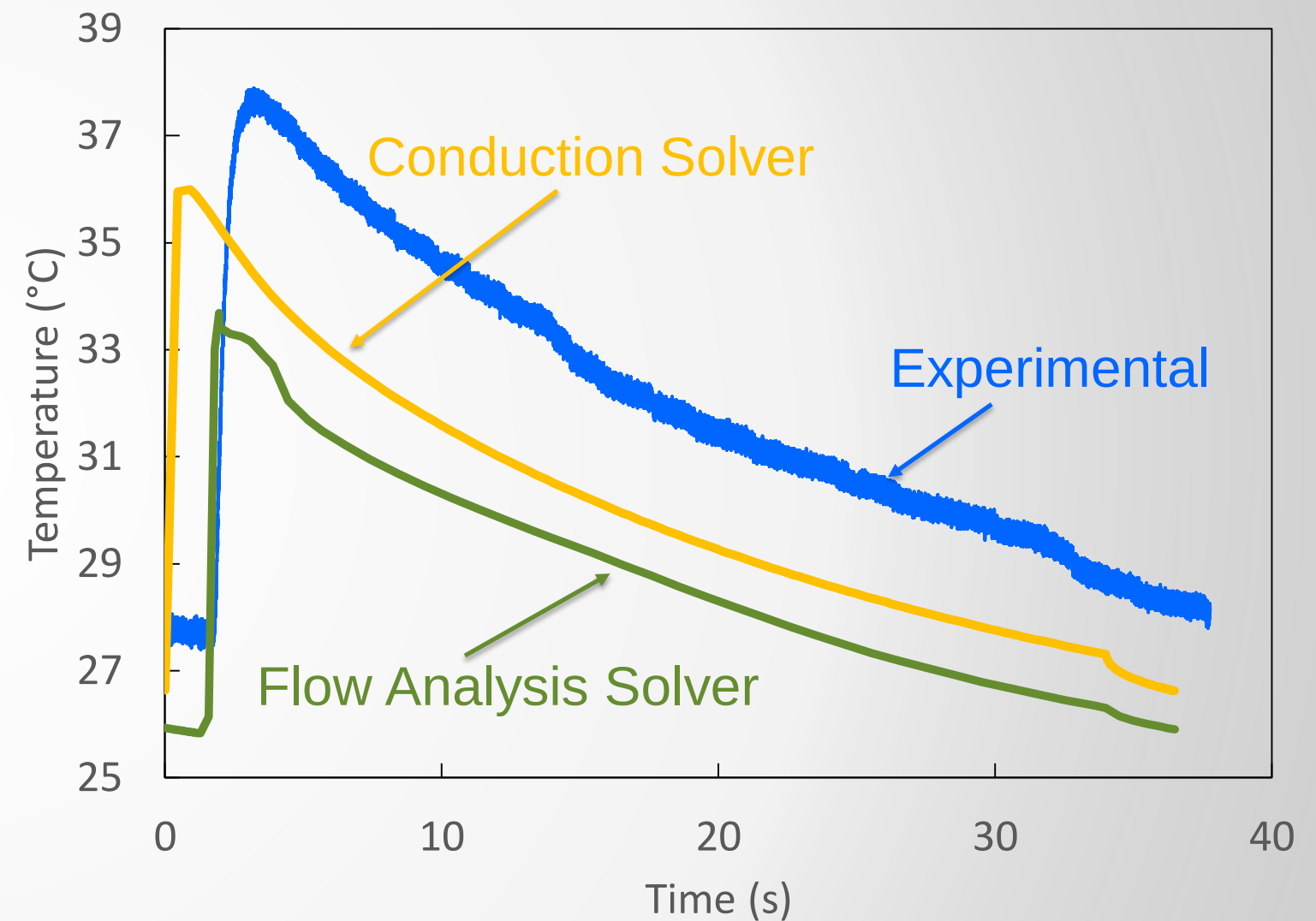


Solver options

- 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

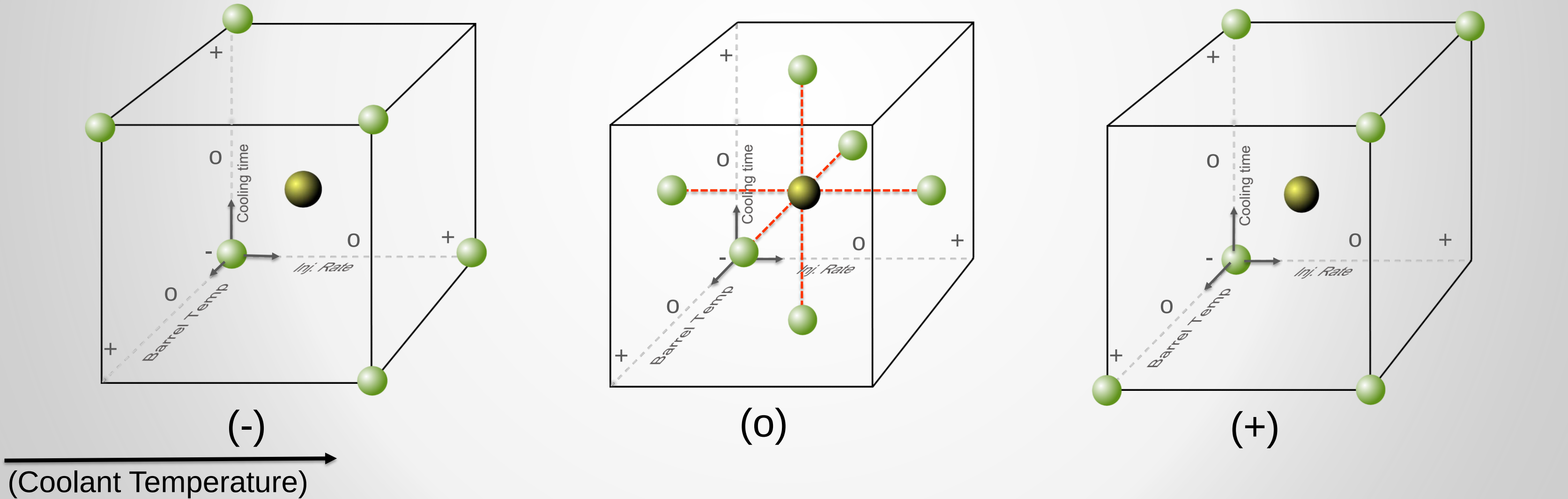
A photograph of a complex industrial machine, likely a mold or a specialized manufacturing component. The machine is constructed from polished metal blocks with various ports and fittings. Several thick red hoses are connected to the machine, looping around it. The background shows a workshop environment with other equipment and a bright light source.

Experimental and Simulation Results

Design of Experiments (DOE)

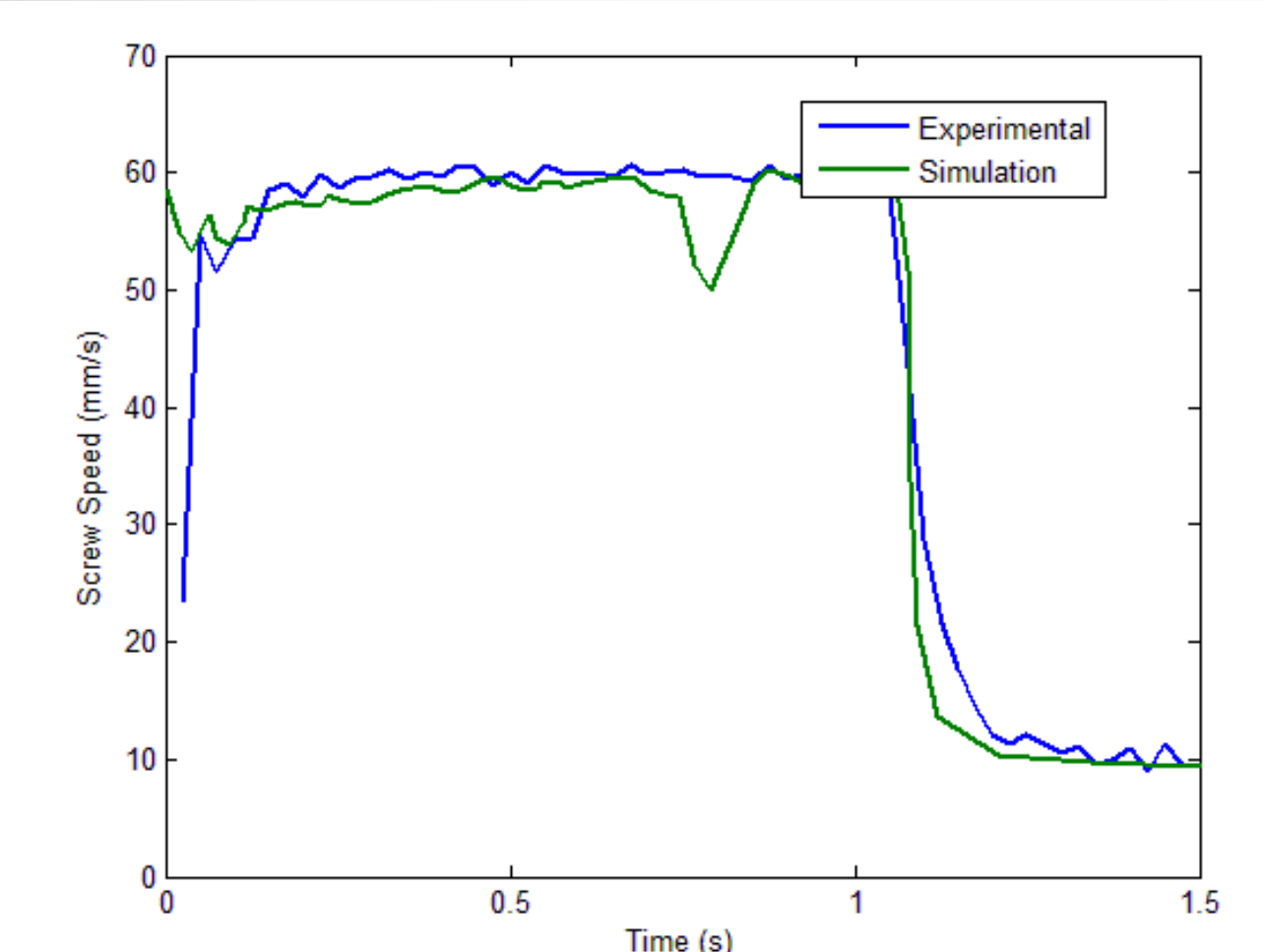
- Central composite design (21 runs)
 - Each run simulated with transient from startup using flow analysis solver

Level	Barrel Temp.	Coolant Temp.	Injection Rate	Cooling Time
-	210 °C	20 °C	60 mm/s	20 s
0	230 °C	35 °C	80 mm/s	25 s
+	250 °C	50 °C	100 mm/s	30 s



Simulation vs. Experimentation

- Injection rate



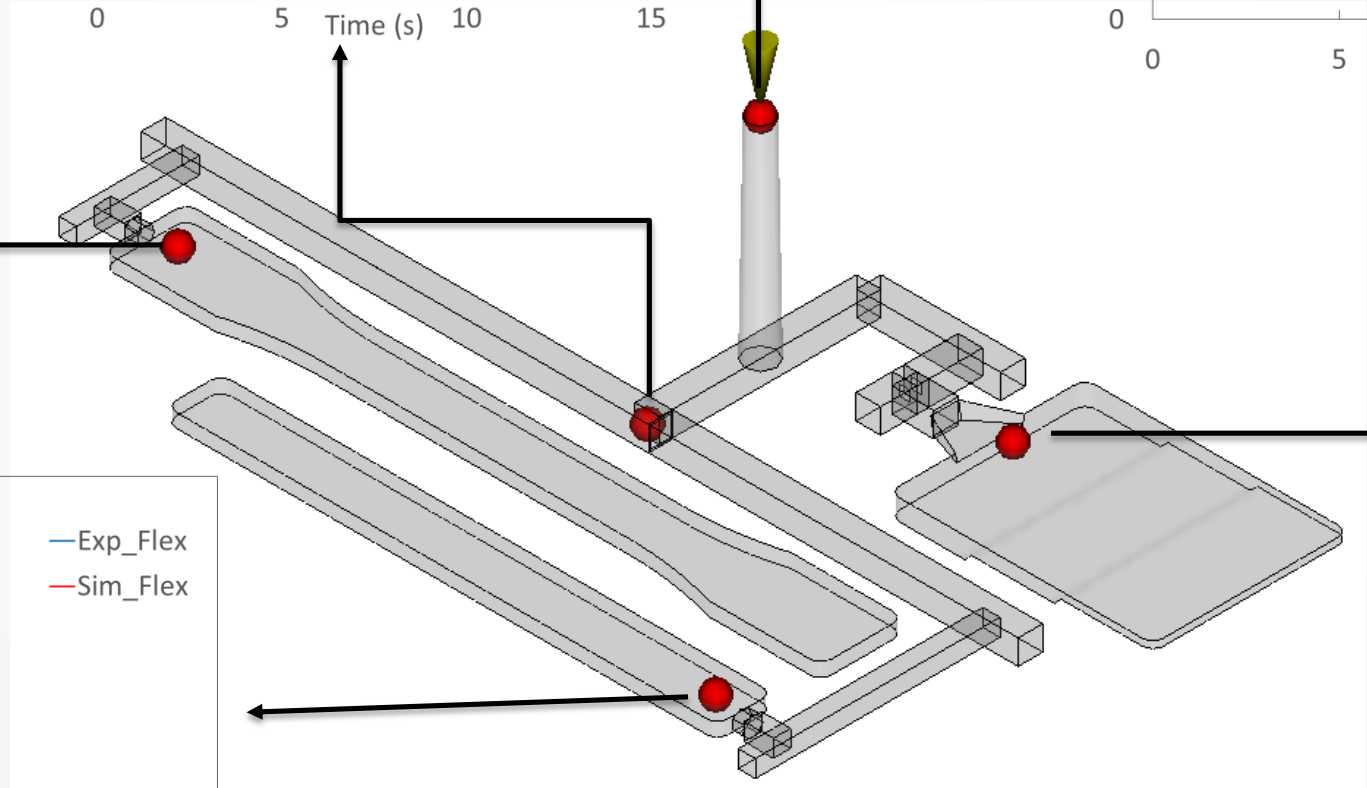
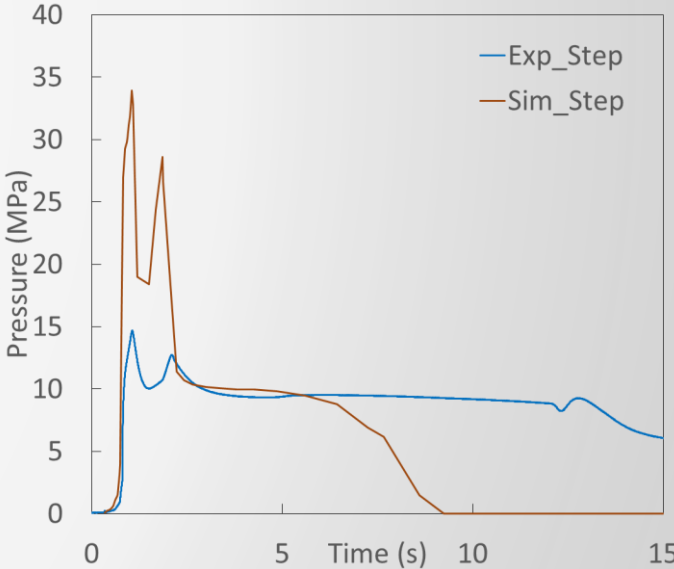
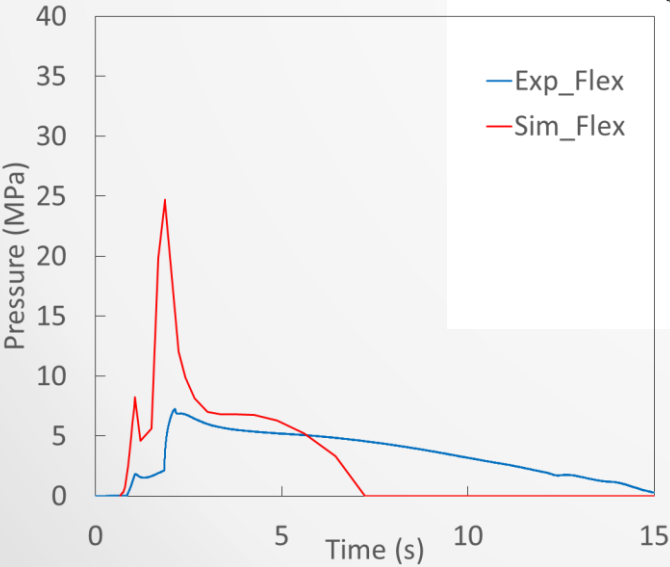
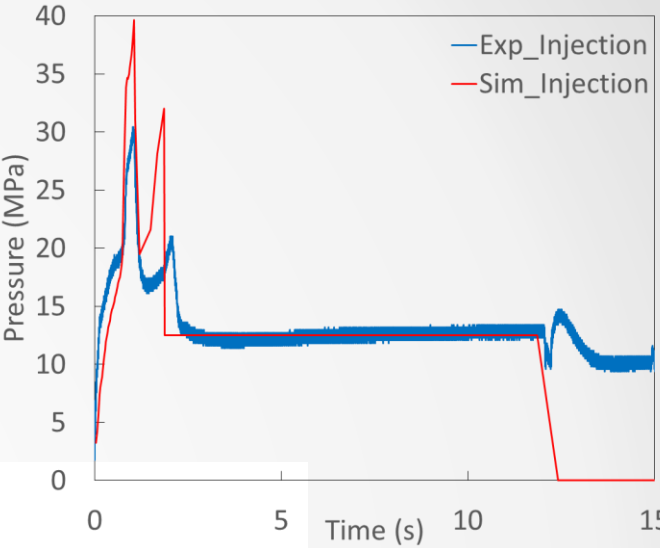
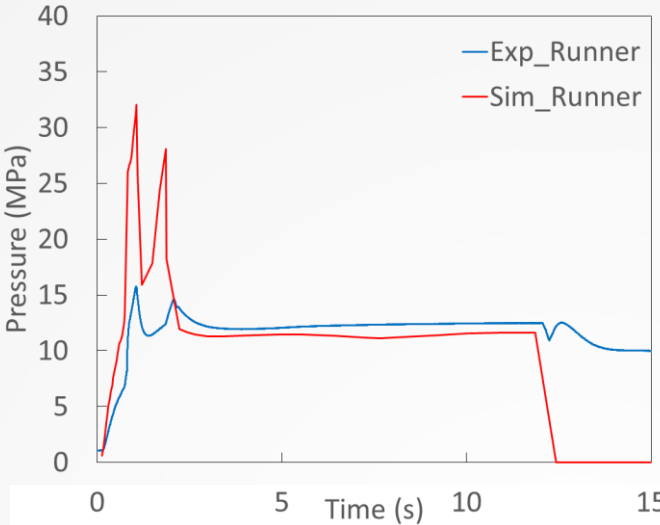
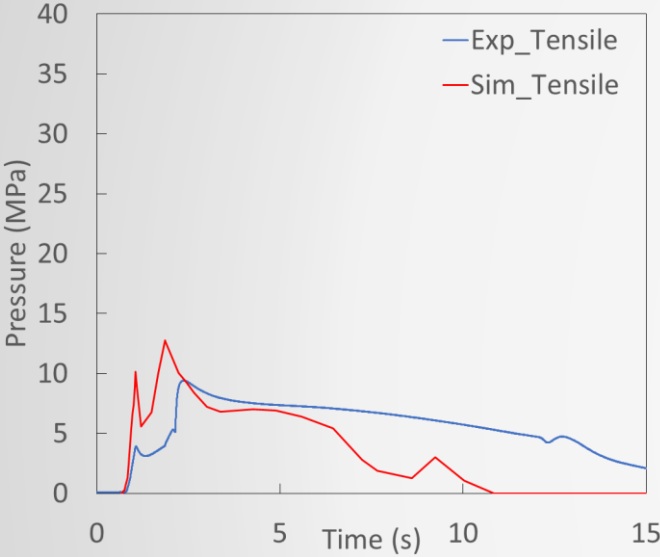
Filling Phase: Status: U = Velocity control U/P = Velocity/pressure switch-over P = Pressure control						
Time (s)	Fill Vol (%)	Inj Press (MPa)	Clamp F (tonne)	Flow Rate (cm ³ /s)	Frozen Vol (%)	Status
0.022	1.754	2.049e+00	0.00e+00	28.745	0.00	U
0.039	3.259	3.239e+00	0.00e+00	26.952	0.00	U
0.062	4.869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

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

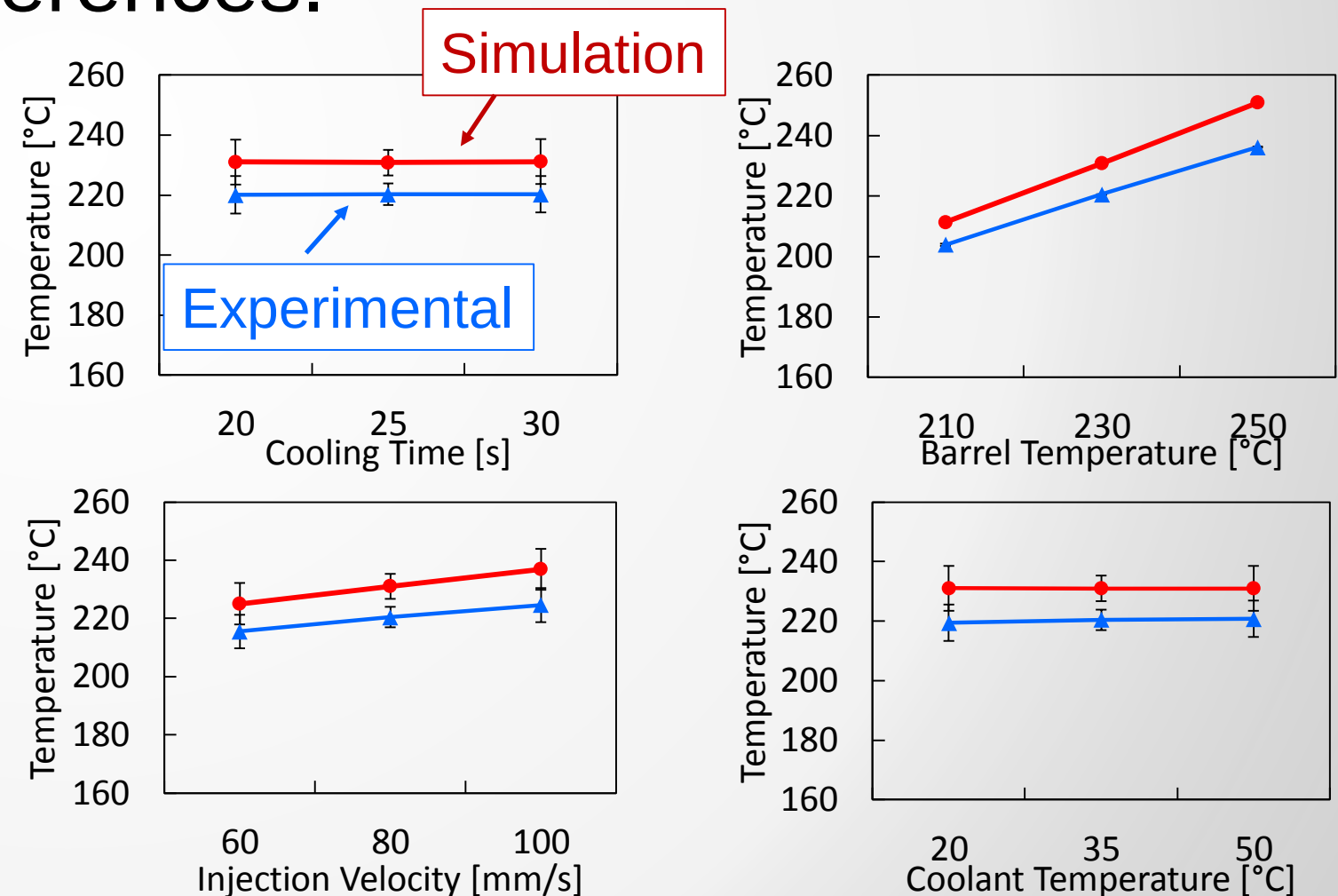
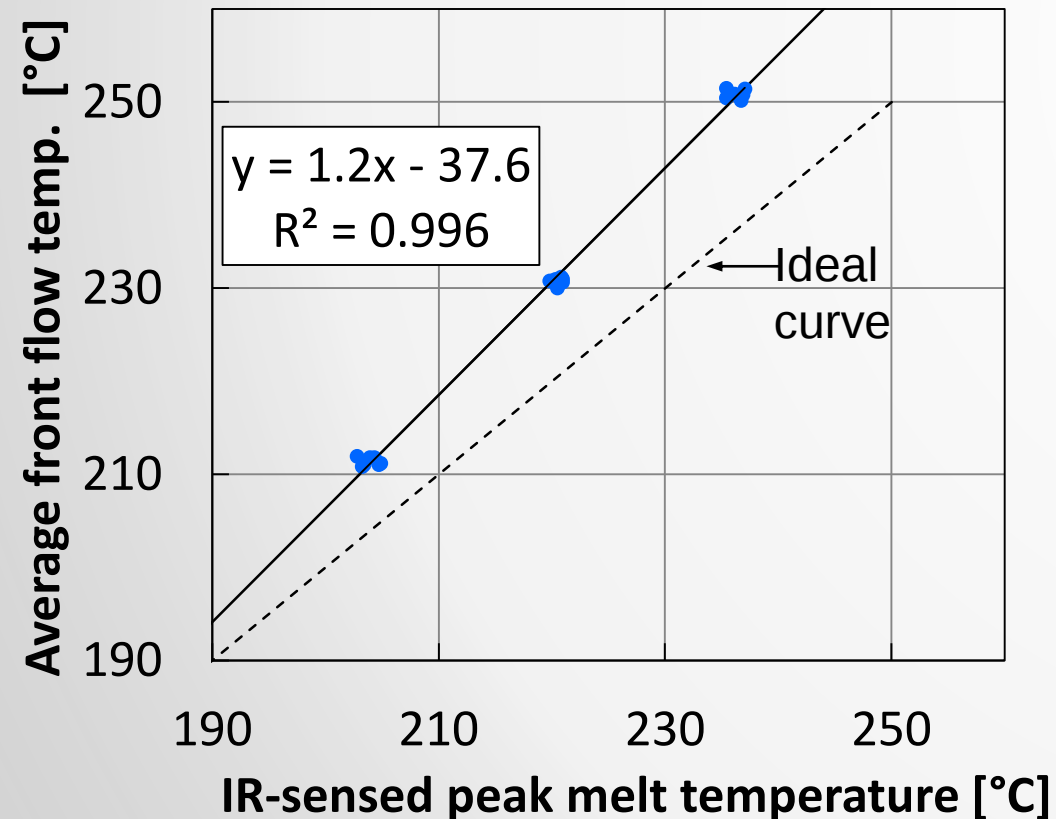


Run 1	Barrel Temp.	Coolant Temp.	Injection Rate	Cooling Time
	210 °C	20 °C	60 mm/s	20 s

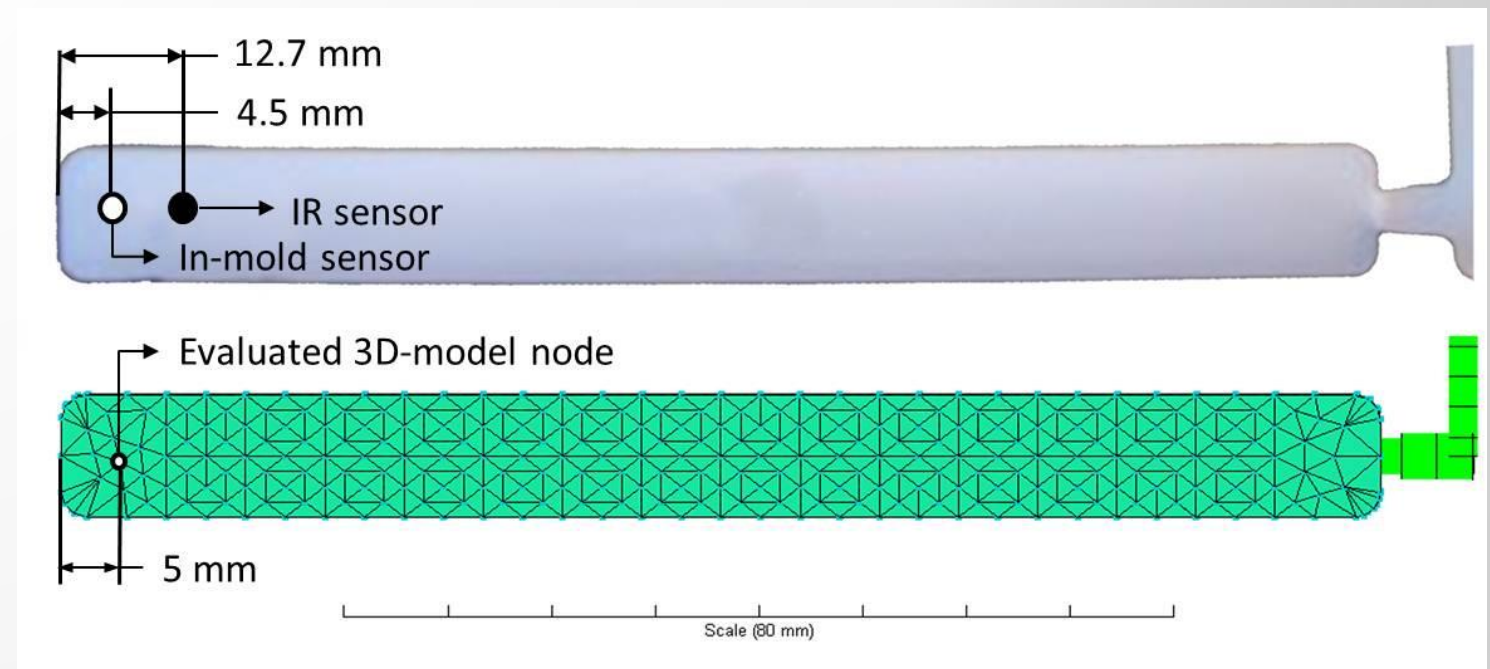
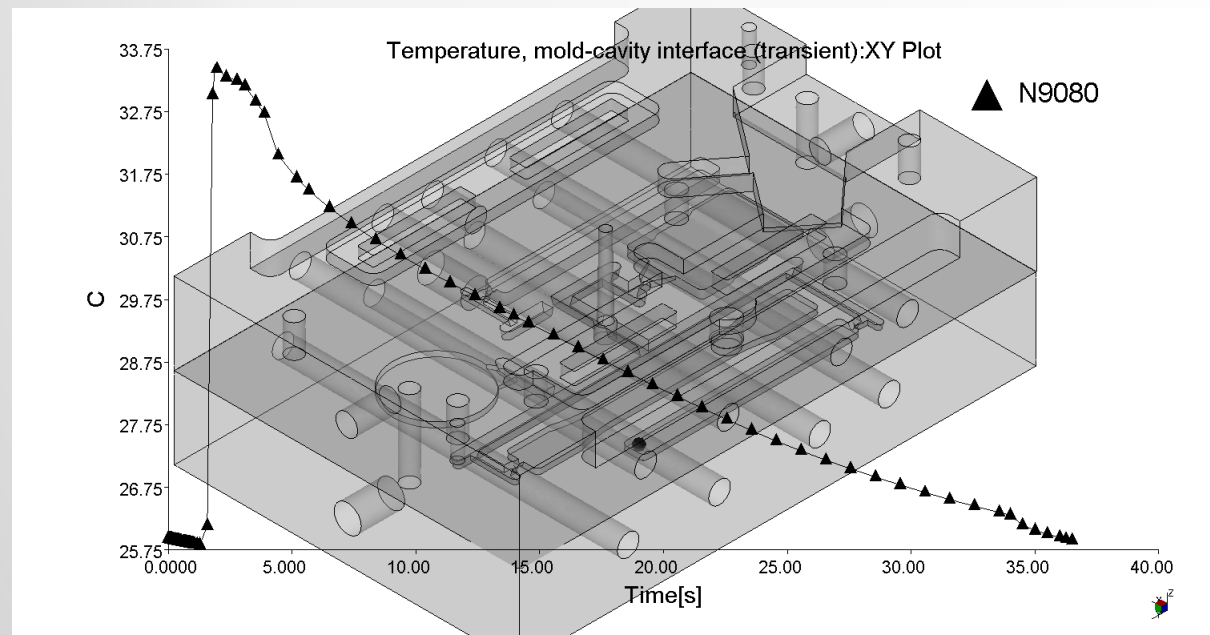
Simulation vs. Experimentation

■ 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.

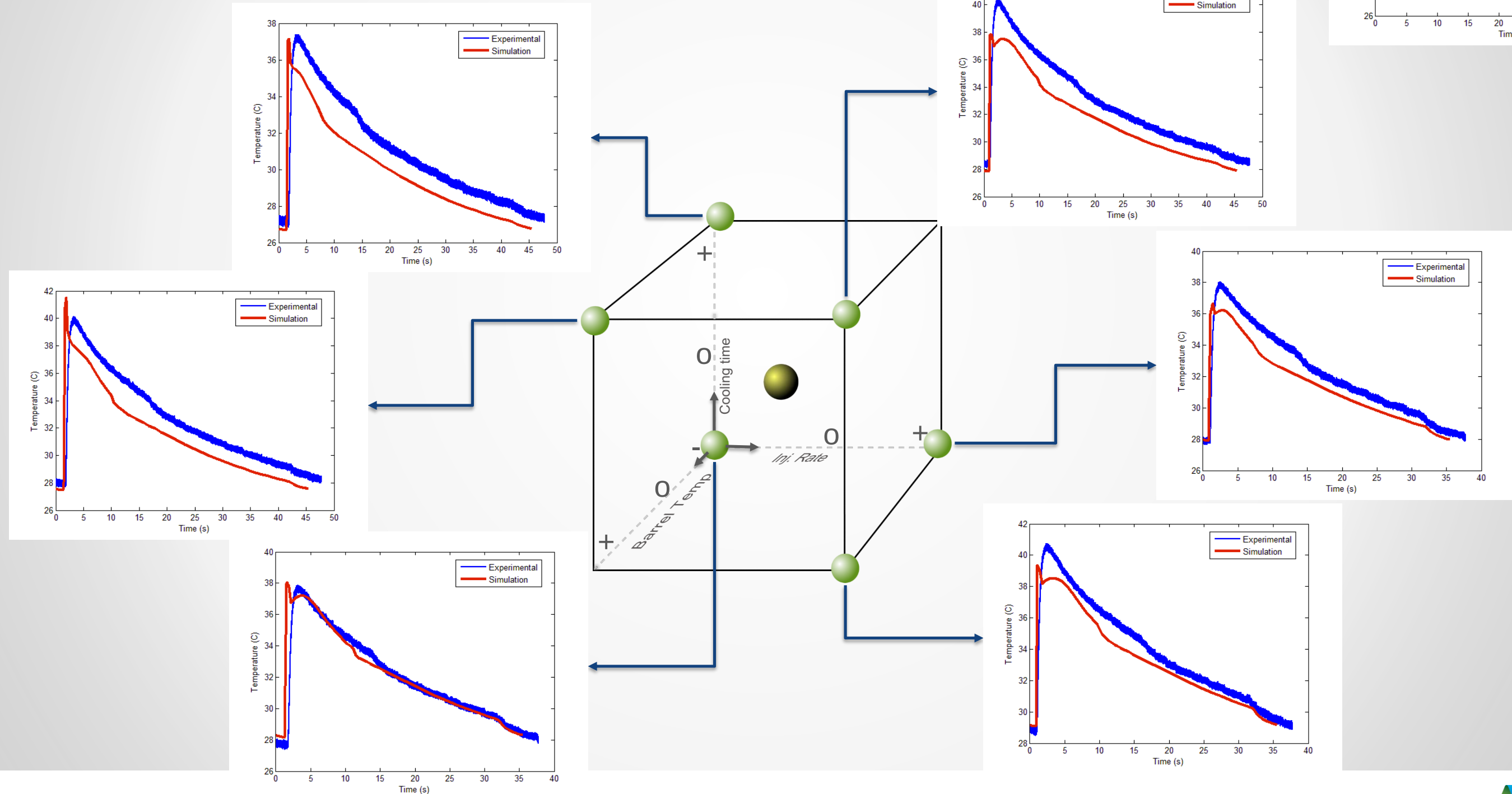


Melt-Cavity Interface Temperature



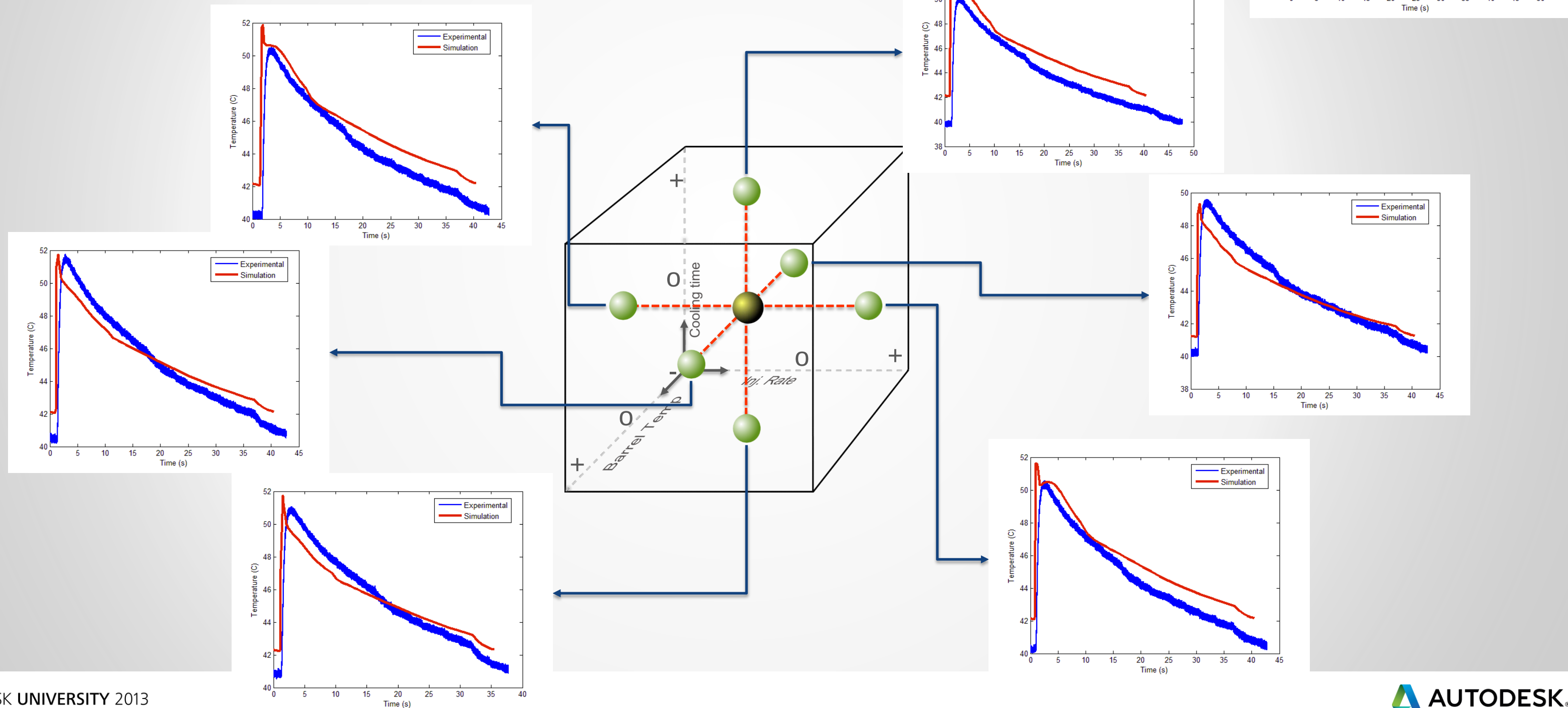
Simulation vs. Experimentation

- Coolant Temperature = 20°C



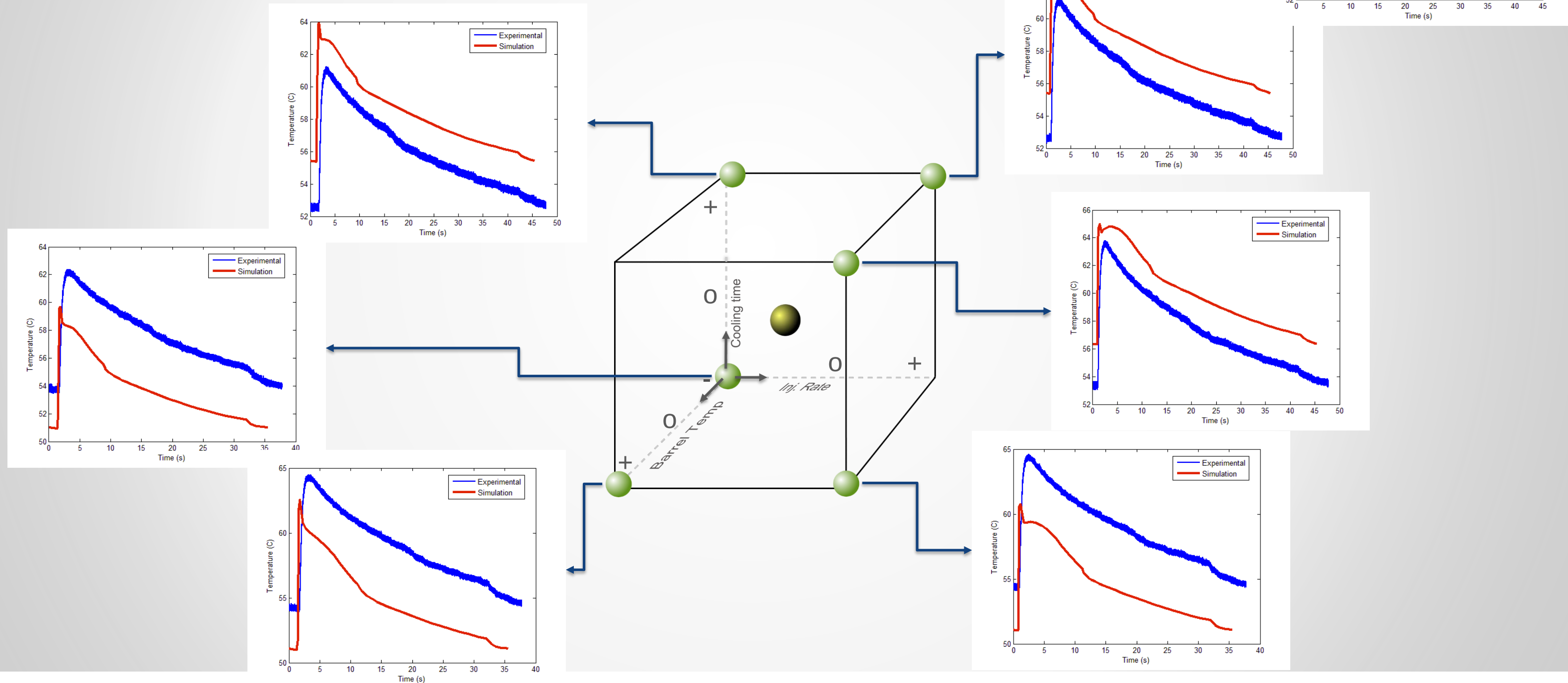
Simulation vs. Experimentation

- Coolant Temperature = 35°C



Simulation vs. Experimentation

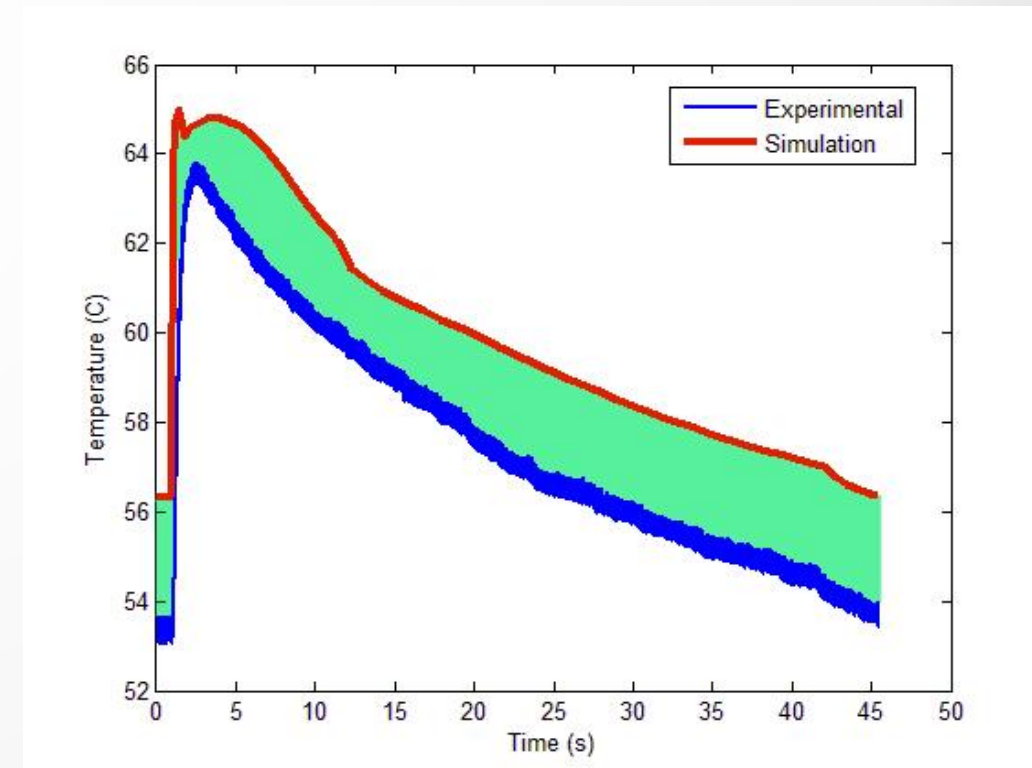
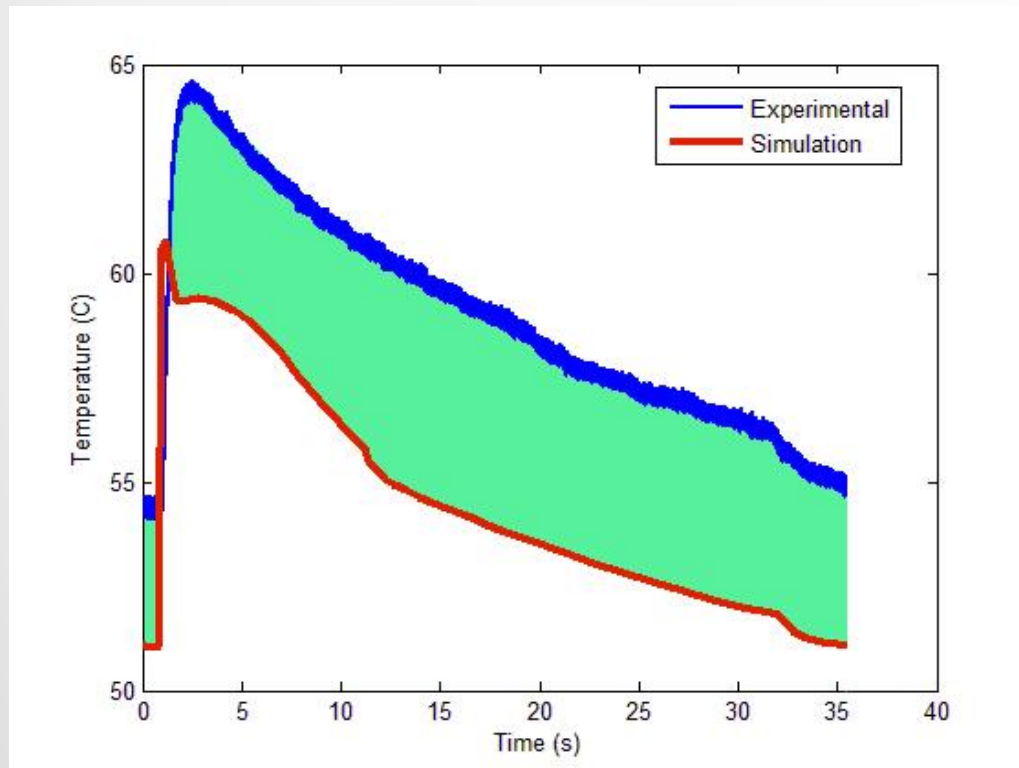
- Coolant Temperature = 50°C



Simulation vs. Experimentation

- Error

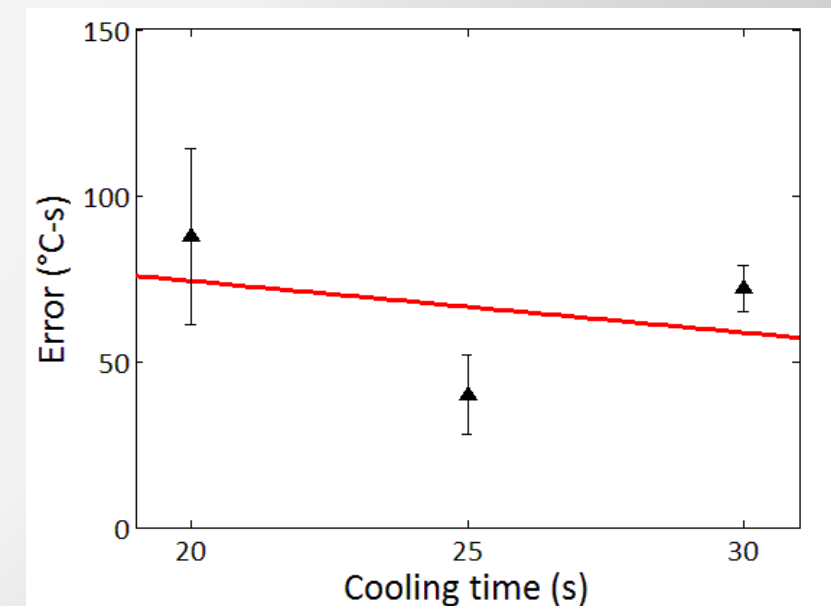
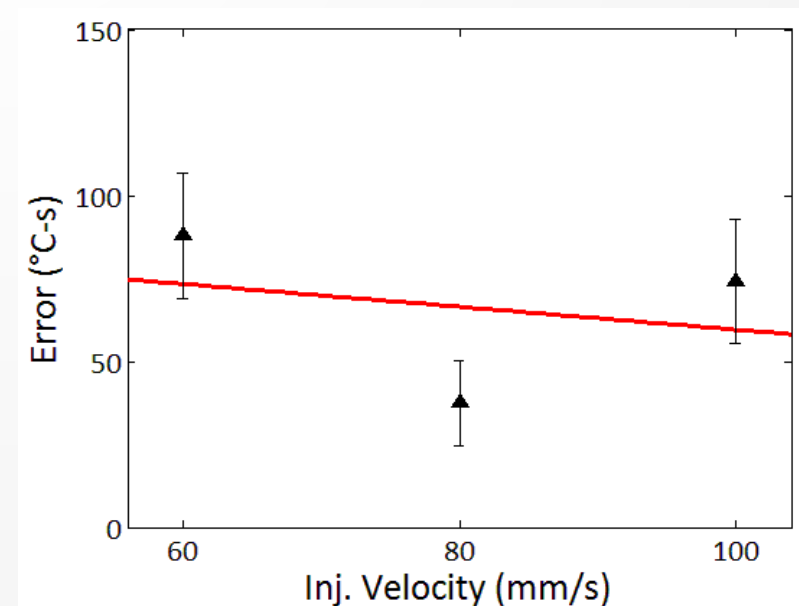
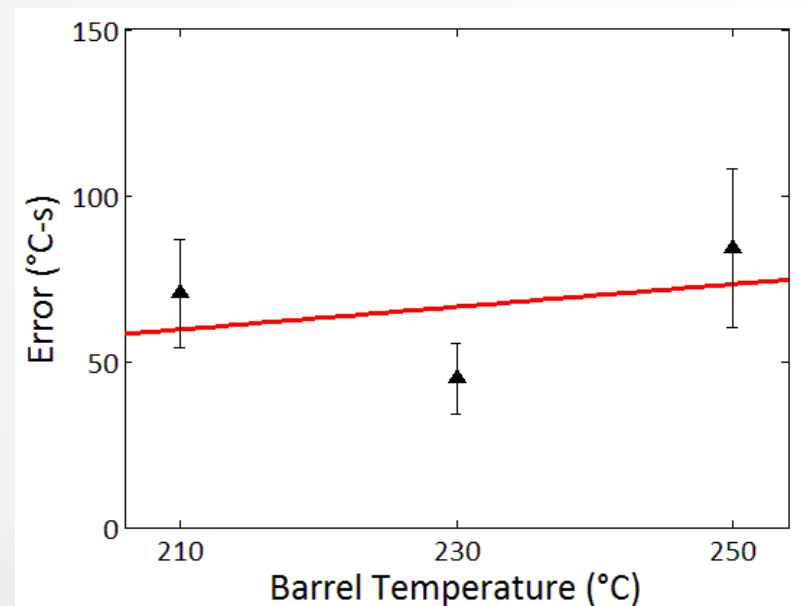
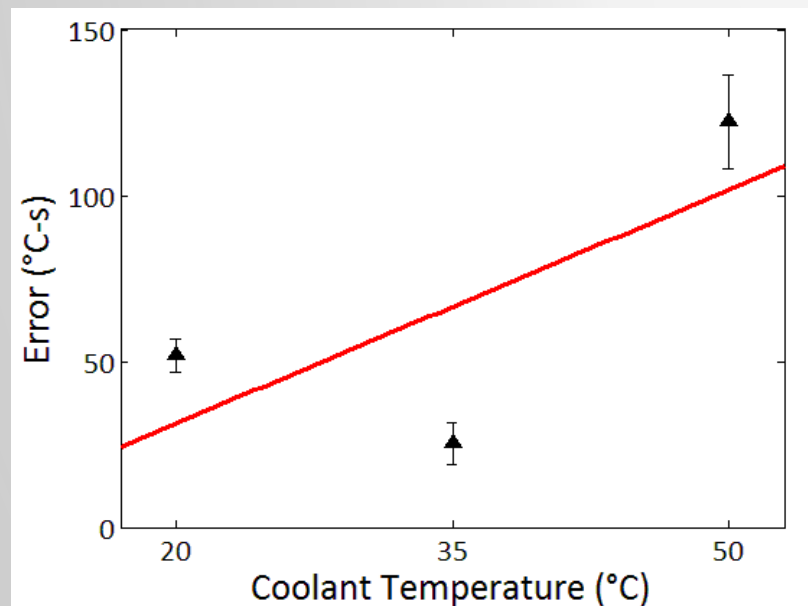
- Deviation from experimental data estimated as the difference in the area under the curves



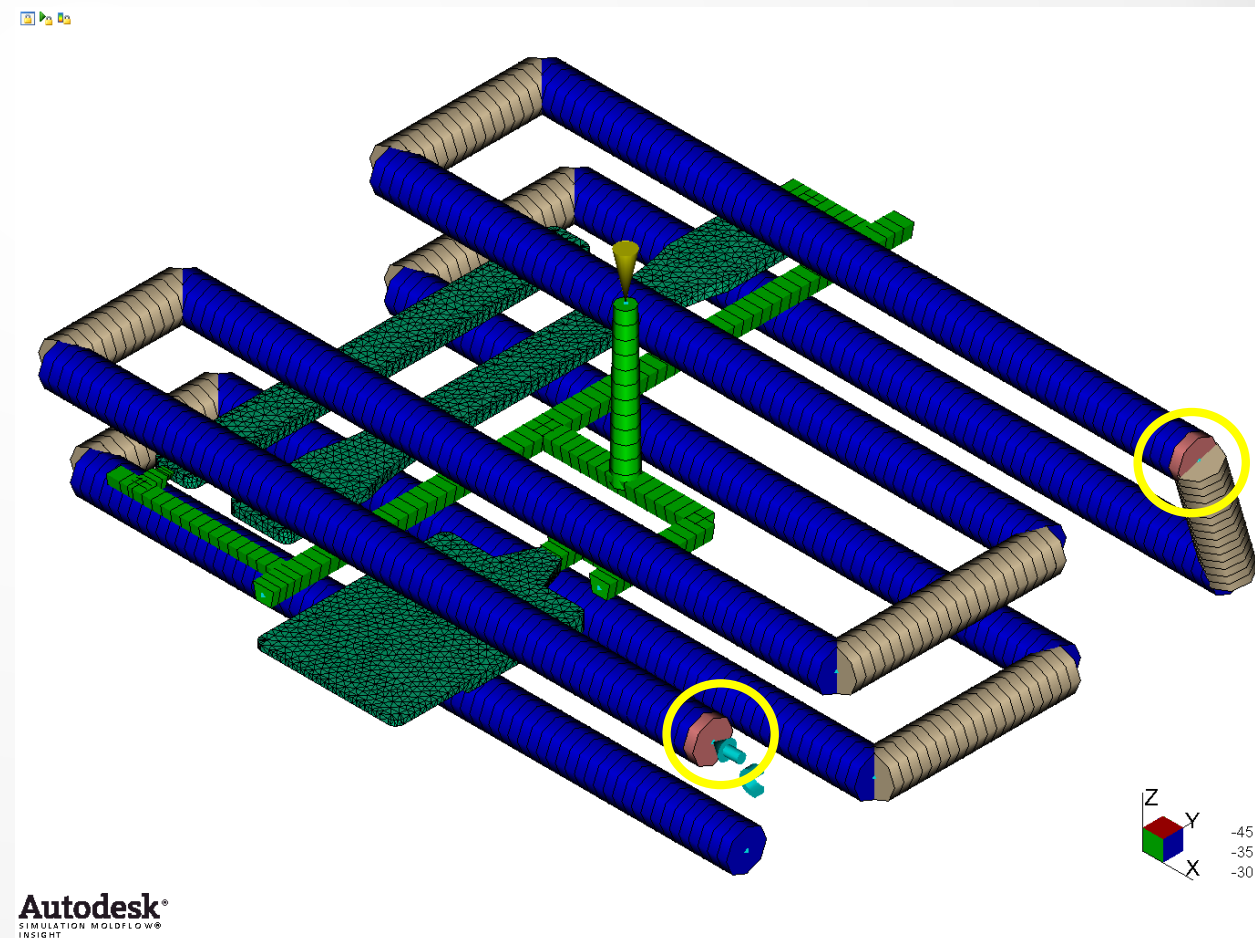
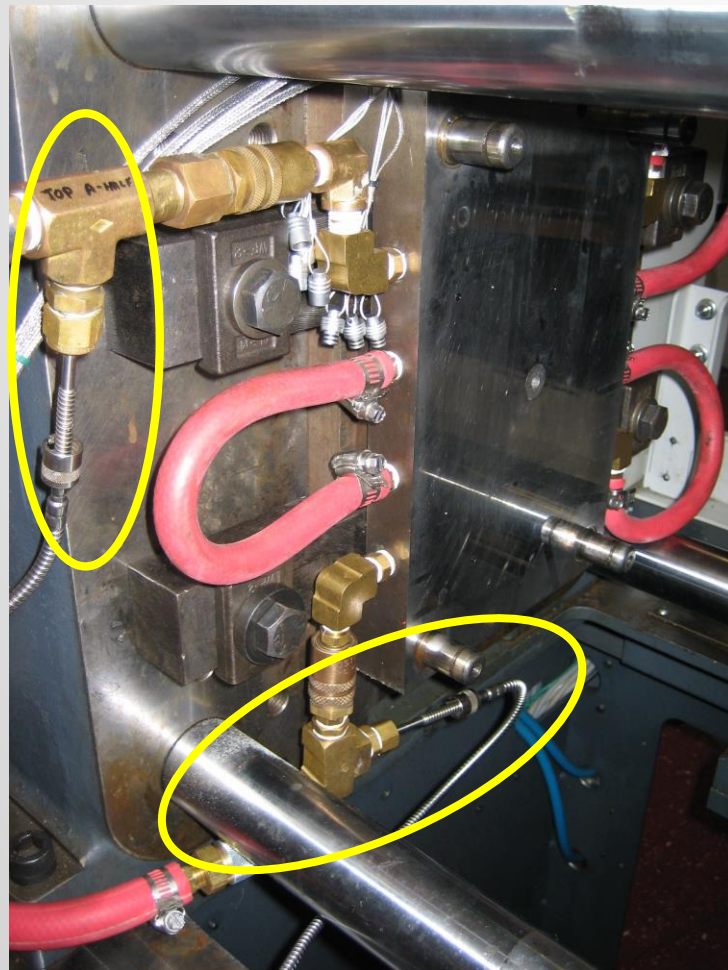
Simulation vs. Experimentation

■ 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.

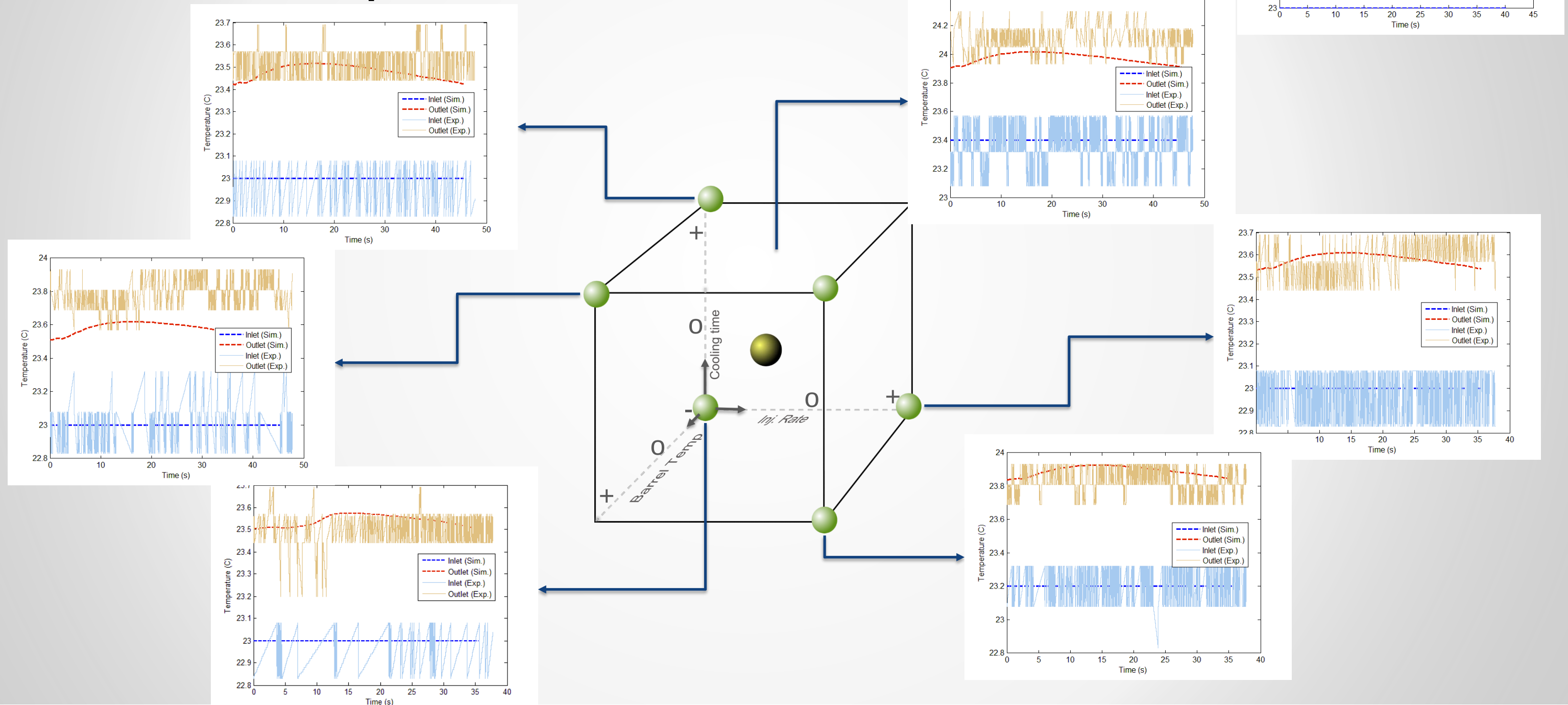


Coolant Temperature



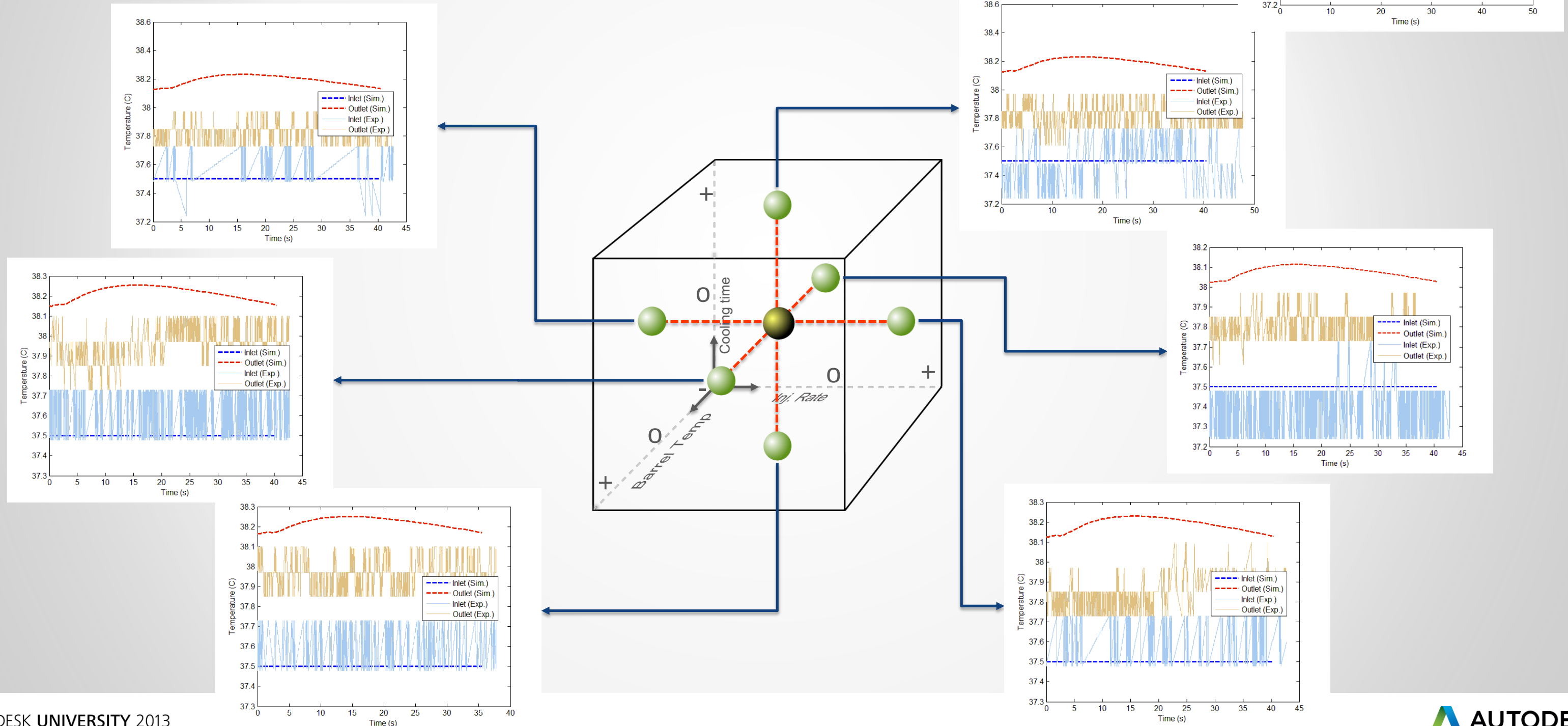
Simulation vs. Experimentation

- Coolant Temperature = 20°C



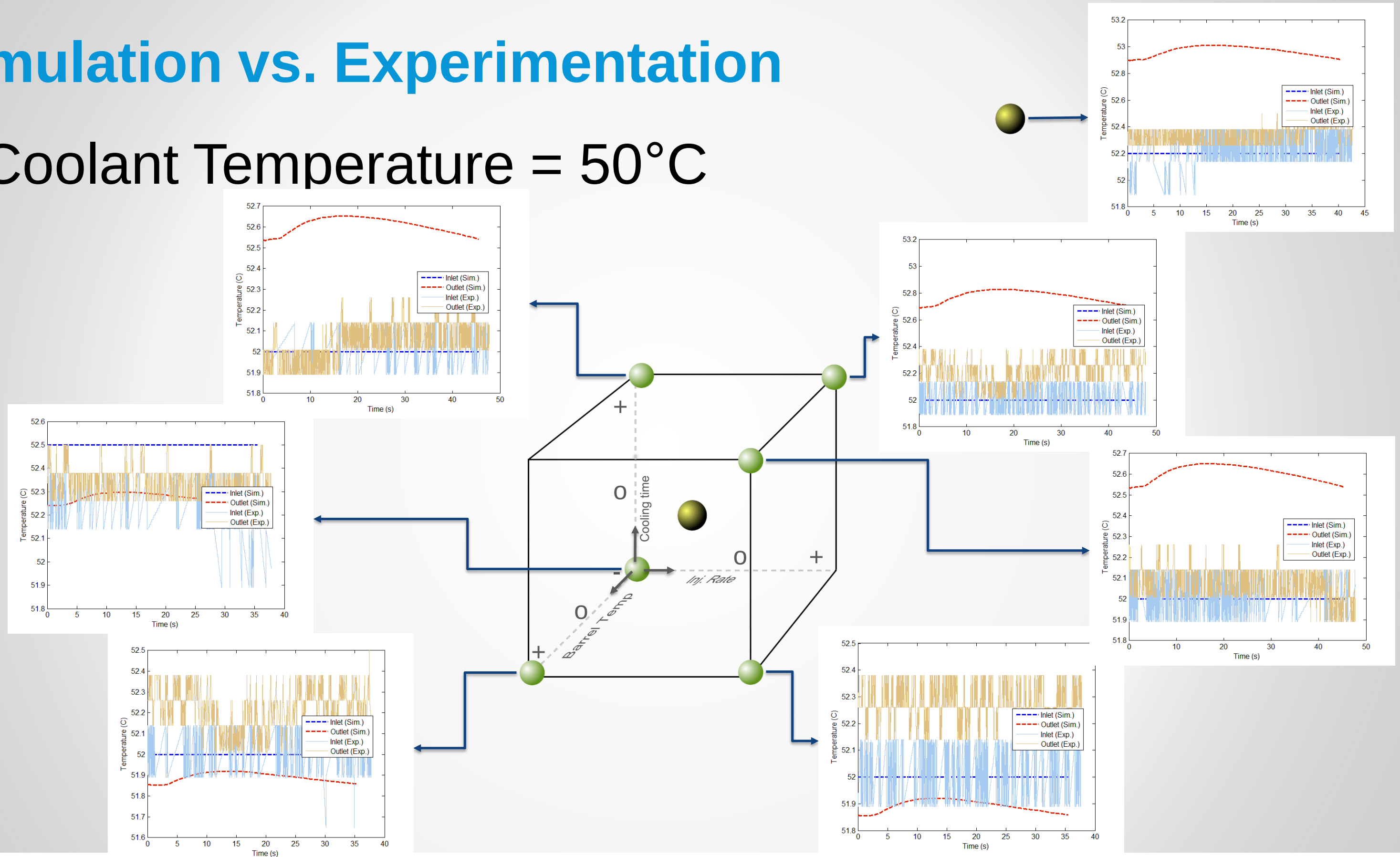
Simulation vs. Experimentation

- Coolant Temperature = 35°C



Simulation vs. Experimentation

- Coolant Temperature = 50°C



Factors that affect the analysis

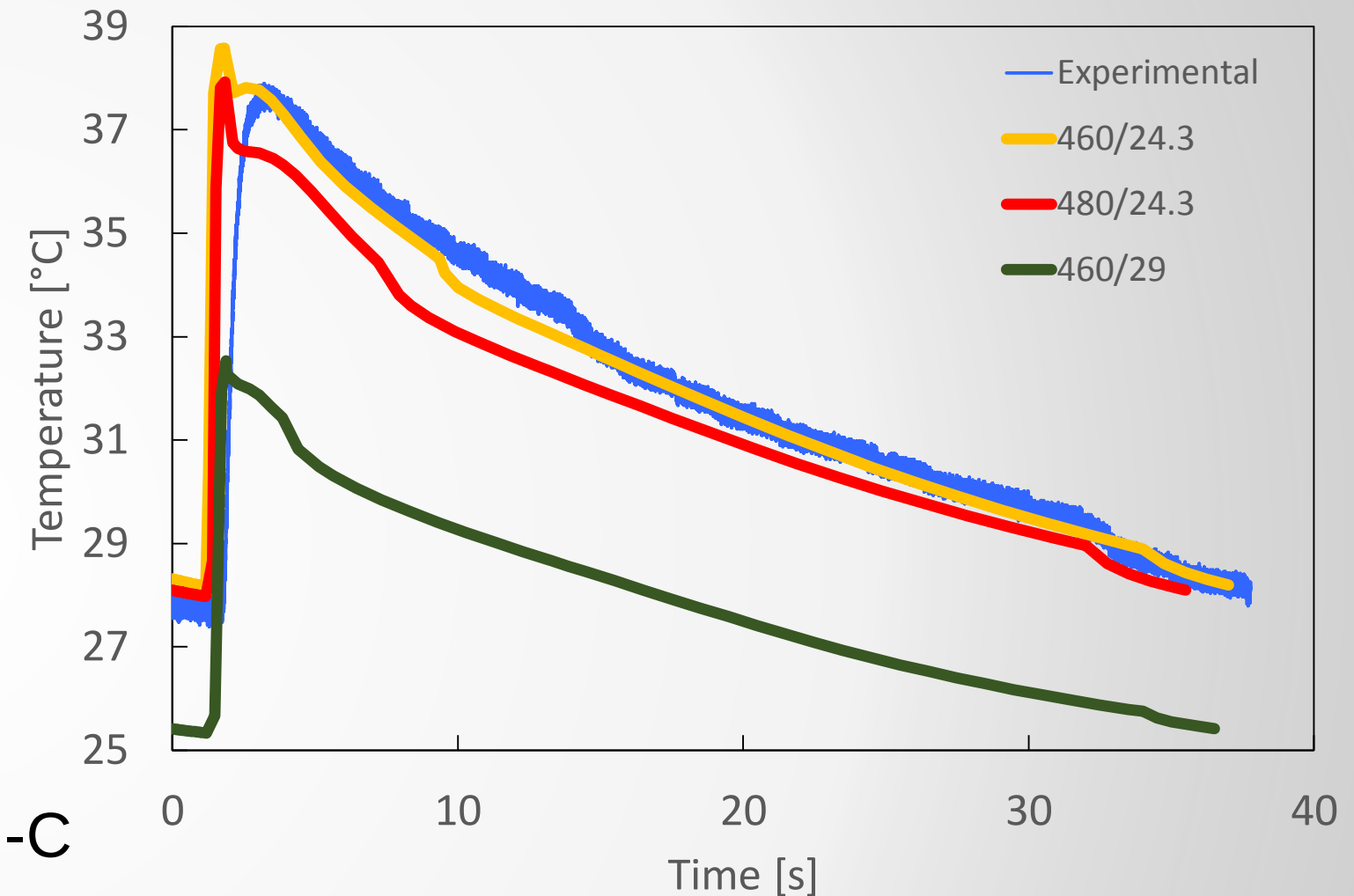


Factors that Affect the Analysis

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

Factors that Affect the Analysis

- Material Properties
 - Mold Thermal Properties
 - Heat Capacity (C_p)
 - 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

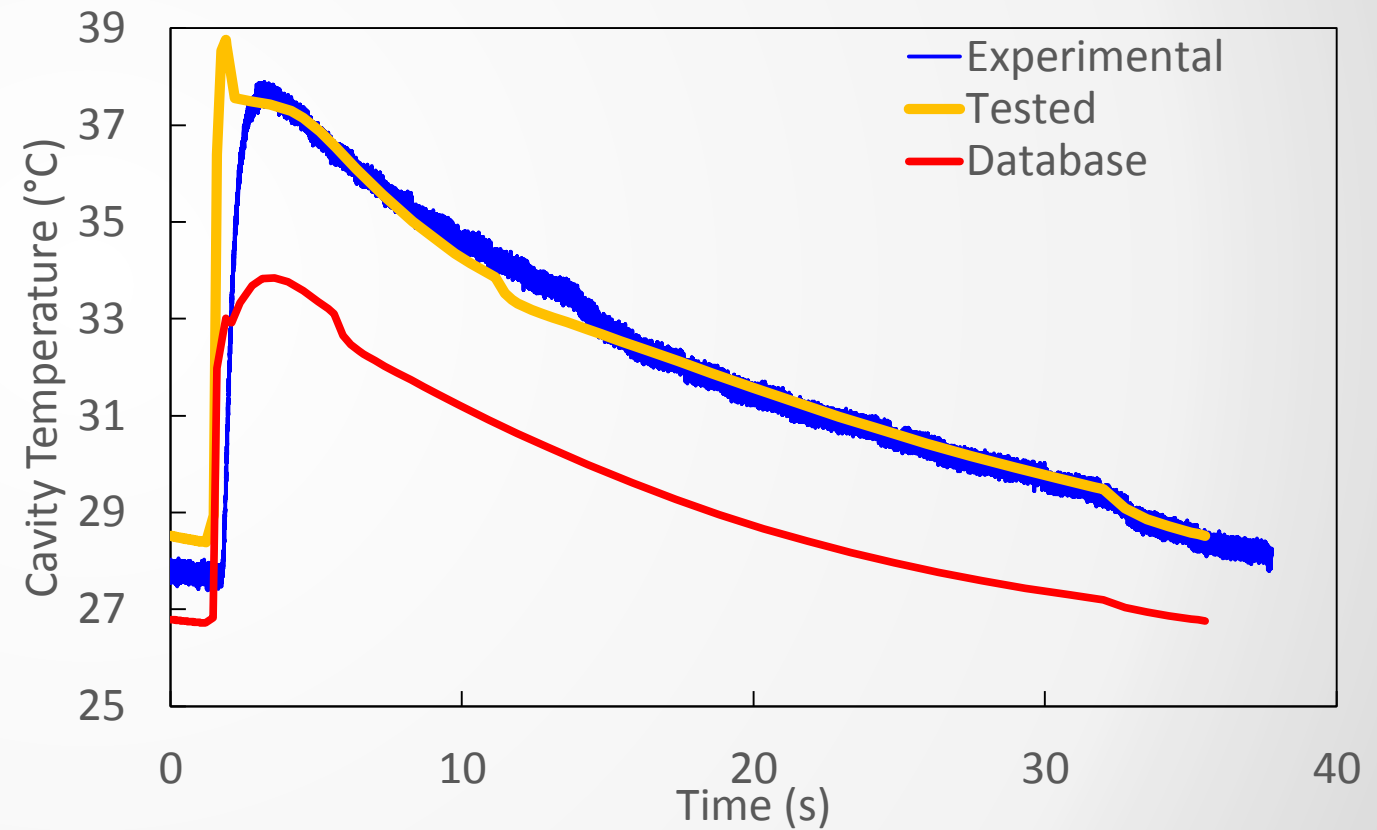
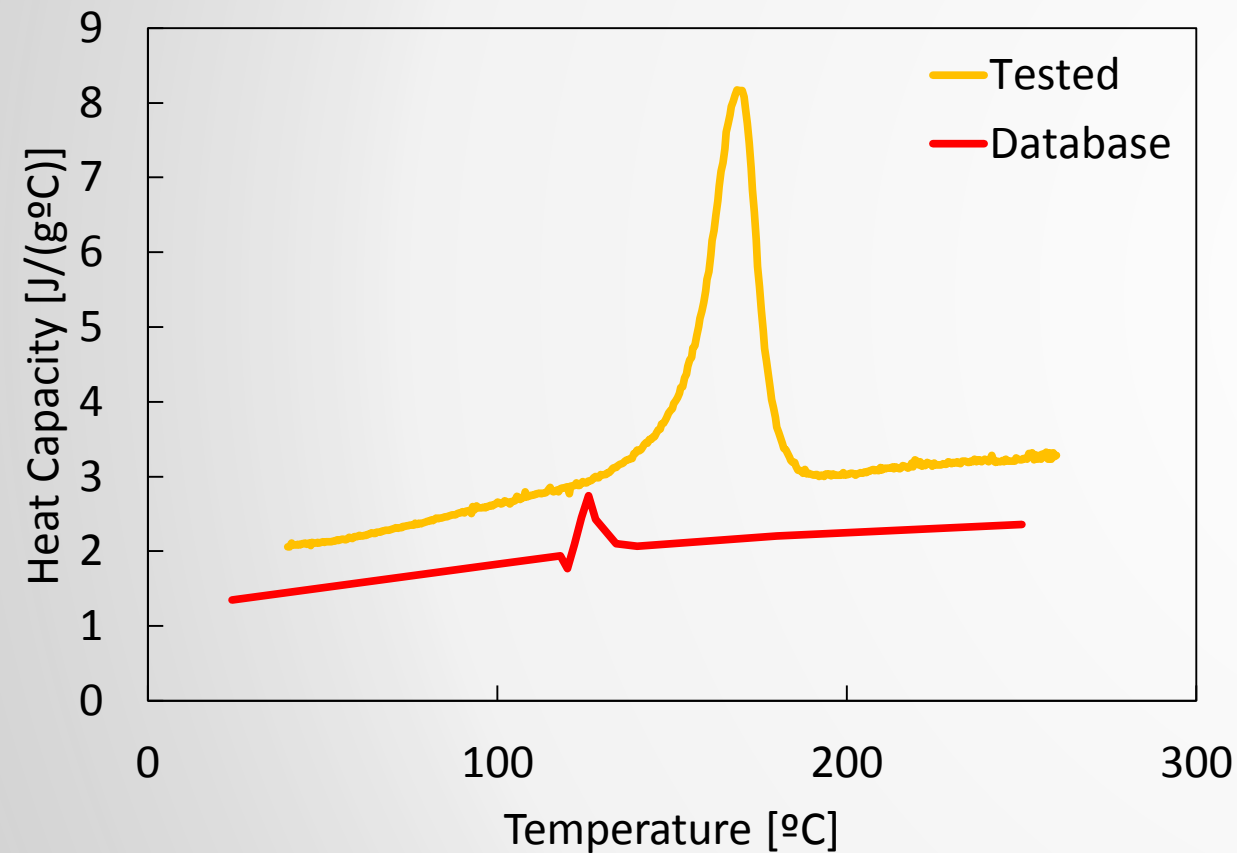


Selected values:
 $C_p=480$ J/kg-C $k=24.3$ W/m-C

Factors that Affect the Analysis

- Material Properties
 - Resin Heat Capacity (Cp)

Test Information (Specific Heat Data) ?	
Source	Manufacturer
Date last modified	16-JAN-09
Date tested	
Method	Not Specified
Comments	
OK Help	



Factors that Affect the Analysis

- Material Properties
 - Resin rheological properties

Cross WLF Viscosity Model Coefficients

Cross-WLF viscosity model

Test Information (Cross WLF Viscosity ...)

Source: Manufacturer

Date last modified: 08-OCT-02

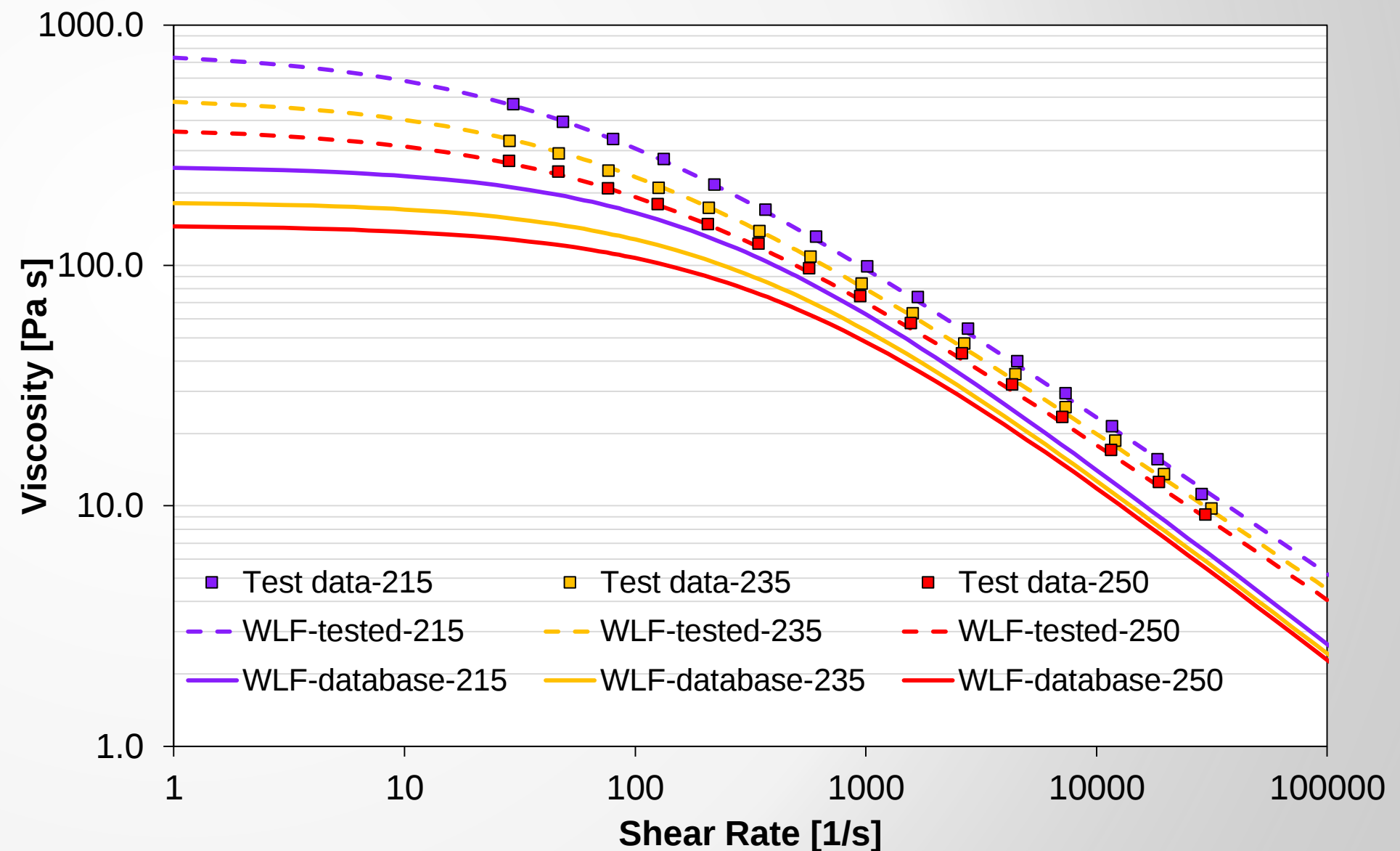
Date tested:

Method: Not Specified

Comments:

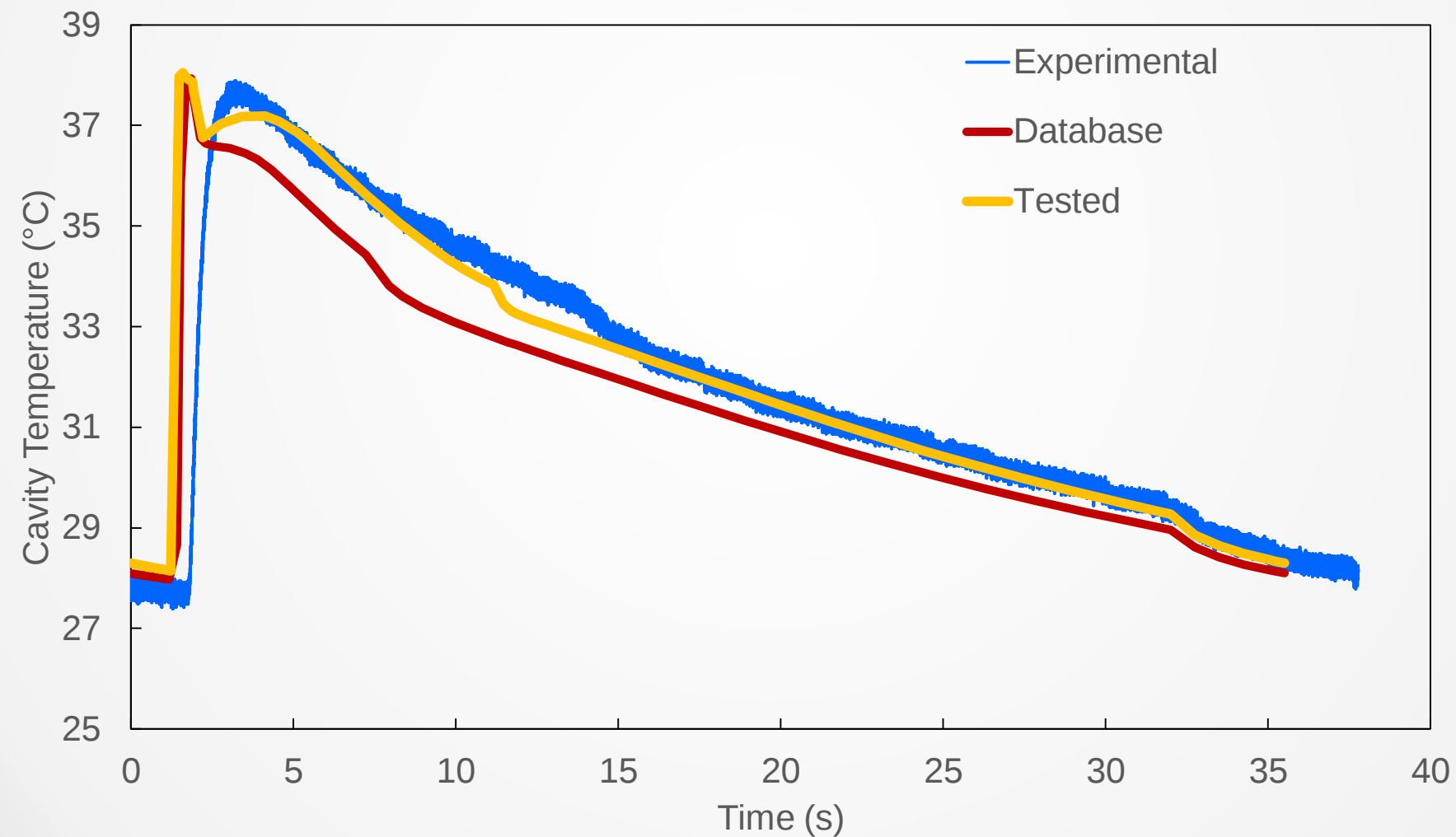
OK Help

OK Help



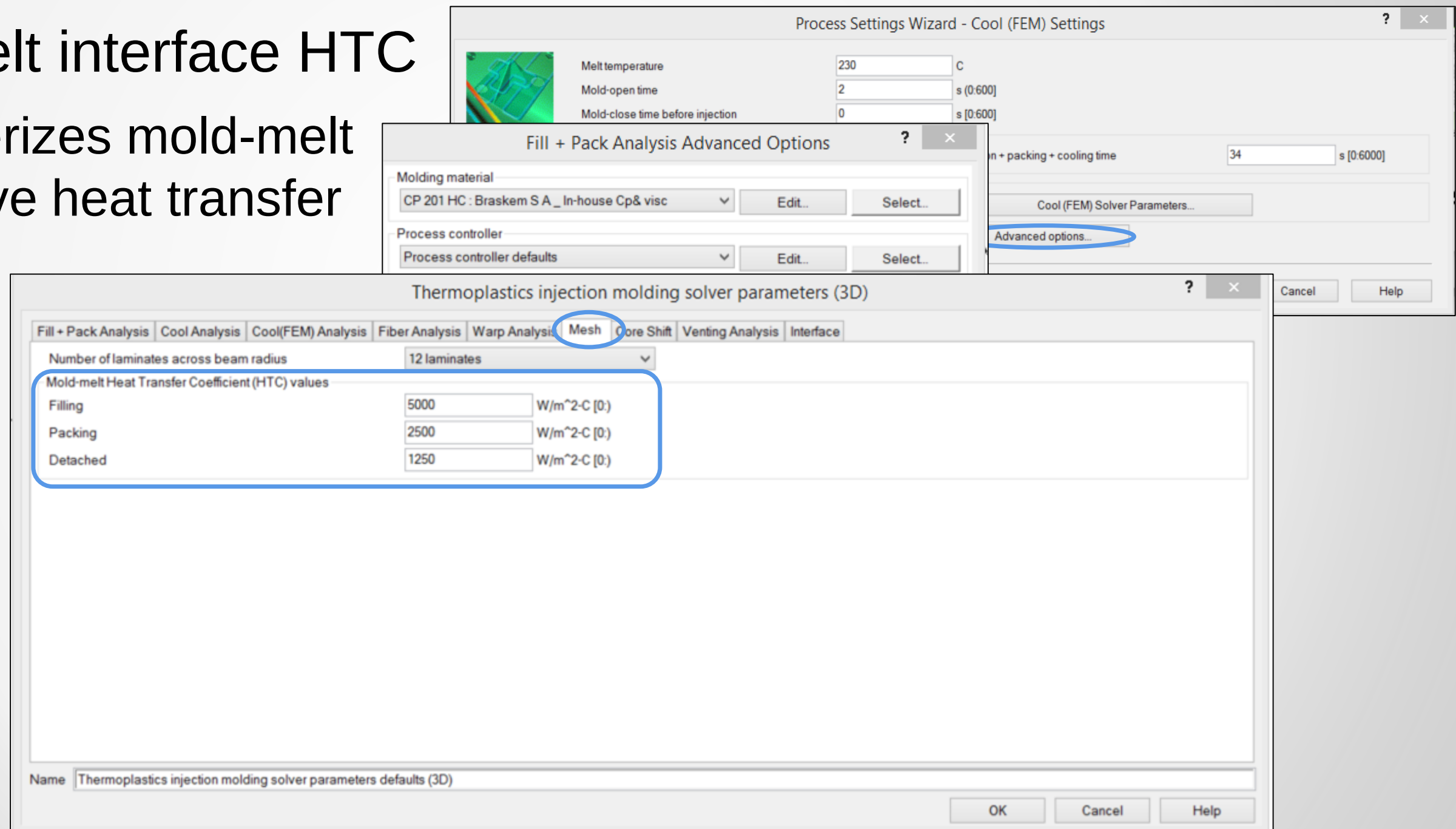
Factors that Affect the Analysis

- Material Properties
 - Resin rheological properties



Factors that Affect the Analysis

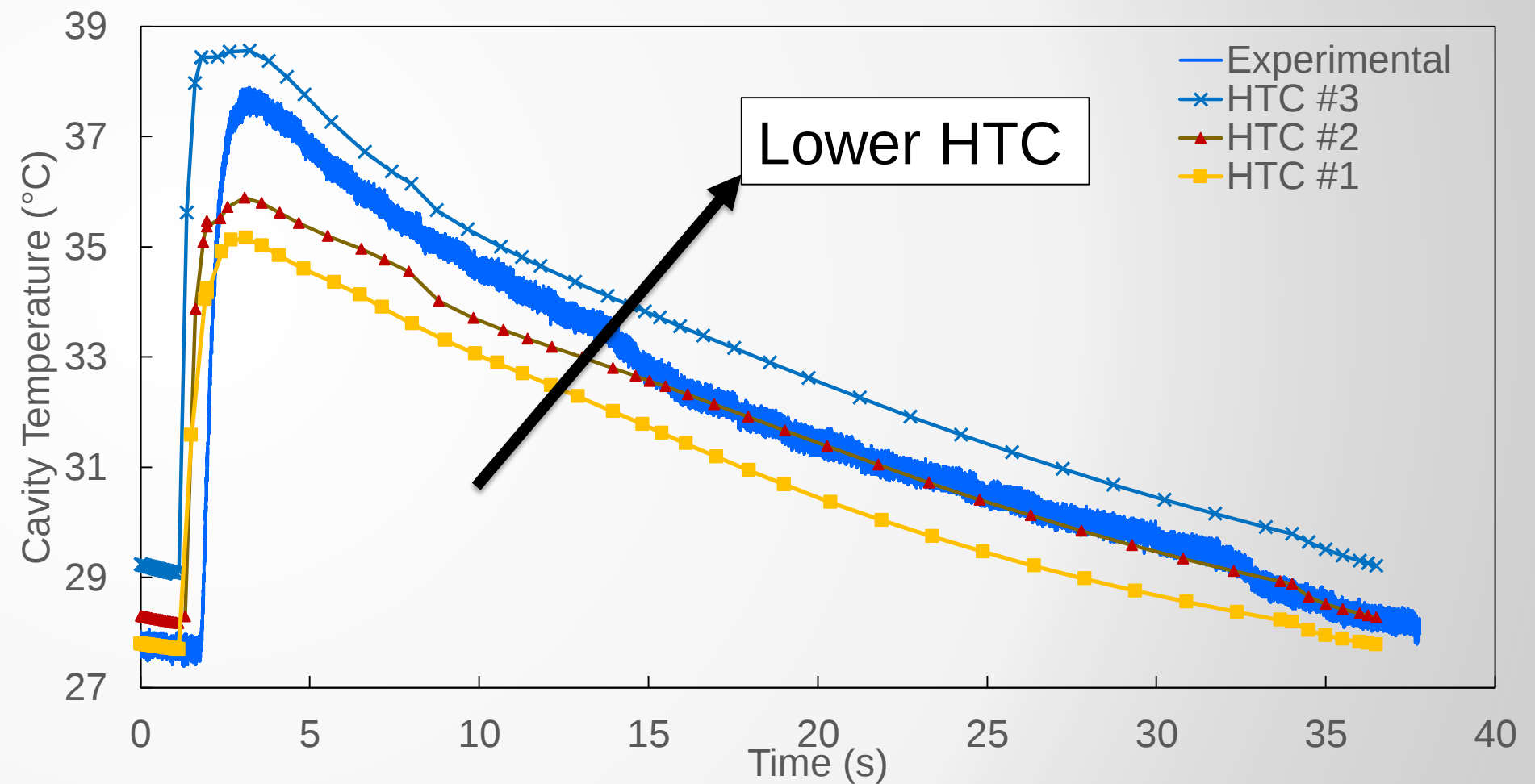
- Material Properties
 - Mold-melt interface HTC
- Characterizes mold-melt convective heat transfer



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
 - Fouling 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.

