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

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SM2868-P   Autodesk® Simulation Moldflow® Insight is a powerful tool to simulate the different stages of the injection molding process. New capabilities of this tool include a transient mold thermal analysis. This type of simulation combines the mold filling and packing simulation with a heat transfer analysis, hence providing increased accuracy in the mold thermal solution. Attendees see the variables that influence the analysis results and improvements that can be done to the model to more closely correlate with the real life. For this purpose, simulation results are compared to experimental results over a design of experiments varying coolant temperature, injection rate, barrel temperature, and cooling time. The experimental results, obtained using an instrumented mold, include temperature and pressure data. Finally, the differences between the transient cooling analysis and the conventional cycle average solution are compared as well as their correlation to experimental results

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

- 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

About the Speakers

Prof. Stephen Johnston has his B.S. in Plastics Engineering Tech from Penn State Behrend and his M.S. and Ph.D. in Plastics Engineering from UMass Lowell. His industrial experience includes work at Moldflow Corp. (prior to acquisition by Autodesk), where he provided technical support and quality assurance testing. He also worked at Bausch & Lomb Inc. doing process validation and testing. Currently Prof. Johnston teaches classes and industrial seminars on Plastic Product Design and Injection Mold Design. Dr. Johnston's research interests include part design and mold design utilizing computer-aided engineering and manufacturing technology. He also works in the areas of process monitoring, process control, and process development for injection molding. His recent focus has been on the design and development of medical devices in collaboration with smaller medical device companies and innovators. *Stephen_Johnston@uml.edu*

Gabriel Mendible has his materials engineering degree from University Simon Bolivar, and his MS in plastics engineering from UMass Lowell. He has worked with simulation software for his undergraduate thesis and has done research in the same area during his MS. Gabriel's interests include part and mold design for injection molding using computer aided design and computer aided manufacturing technology. He is also interested in process control methods in manufacturing. Gabriel has worked as a Teaching Assistant at UMass Lowell involved in processing laboratories and mold design courses. He is a member of the Society of Plastics Engineers. He is currently a doctoral candidate at UMass Lowell working under the advisement of Dr. Stephen P. Johnston and his research is focused in injection molding simulation. *Gabriel_Mendible@student.uml.edu*

Mold Cooling Theory

Mold cooling analysis is based on the conduction equation. This equation is reduced to the following form if there is no heat generation:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T)$$

or,

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

where k is the thermal conductivity of the steel, ρ is the density of the steel, α is the thermal diffusivity of the steel, and Cp is the heat capacity of the steel.

Earlier forms of the cooling analysis, did not consider the time dependent side of the equation, assuming steady-state. In addition to conduction thermal conduction through the mold, a hydraulic analysis on the cooling lines is performed. The latter indicates heat removal efficiency and possible coolant stagnation issues [1].

Experimental Set-up

A 50 ton electric injection molding machine was used for the experimentation using a cold runner mold to produce ASTM test samples. The mold was instrumented with two unshielded type N thermocouples located near the end of fill in flex bar cavity as shown in Figure 1
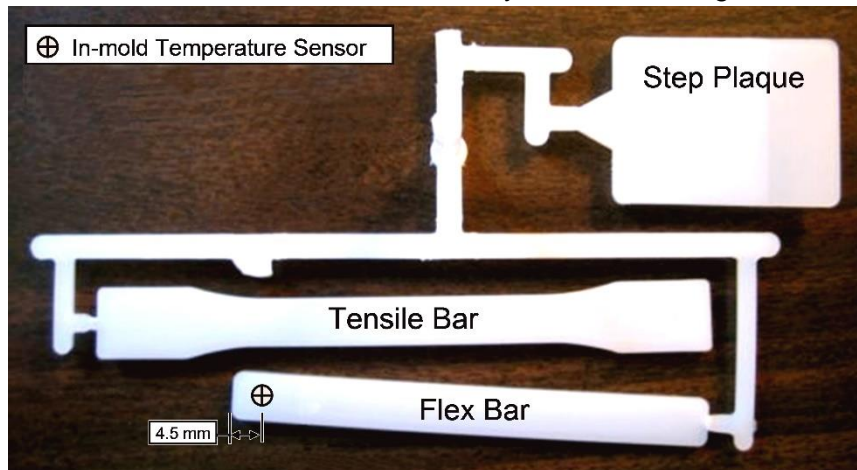

Figure 1. Sensor Location

A 21 run composite design of experiments was developed varying injection rate, coolant temperature, barrel temperature and cooling time. The molding trials were performed using a Braskem Polypropylene CP-201 HC.

Table 1. Design of Experiments Parameters

Run	Inj. Velocity [mm/s]	Coolant Temp. [°C]	Barrel Temp. [°C]	Cooling time [s]
1	60	20	210	20
2	100	20	210	20
3	60	50	210	20
4	100	20	250	20
5	60	50	250	20
6	100	50	250	20
7	60	20	210	30
8	60	50	210	30
9	100	50	210	30
10	60	20	250	30
11	100	20	250	30
12	100	50	250	30
13	60	35	230	25
14	100	35	230	25
15	80	20	230	25
16	80	50	230	25
17	80	35	210	25
18	80	35	250	25
19	80	35	230	20
20	80	35	230	30
21	80	35	230	25

Transient (FEM) Cooling Analysis

The Moldflow® cooling analysis, until the 2012 release, was performed using a boundary element method (BEM). The BEM solves the thermal equation assuming steady state conditions during the cycle. Hence, the mold temperature results are average values throughout the cycle. Besides the cooling channels and part models, only a surface mesh of the mold boundary is needed for this analysis.
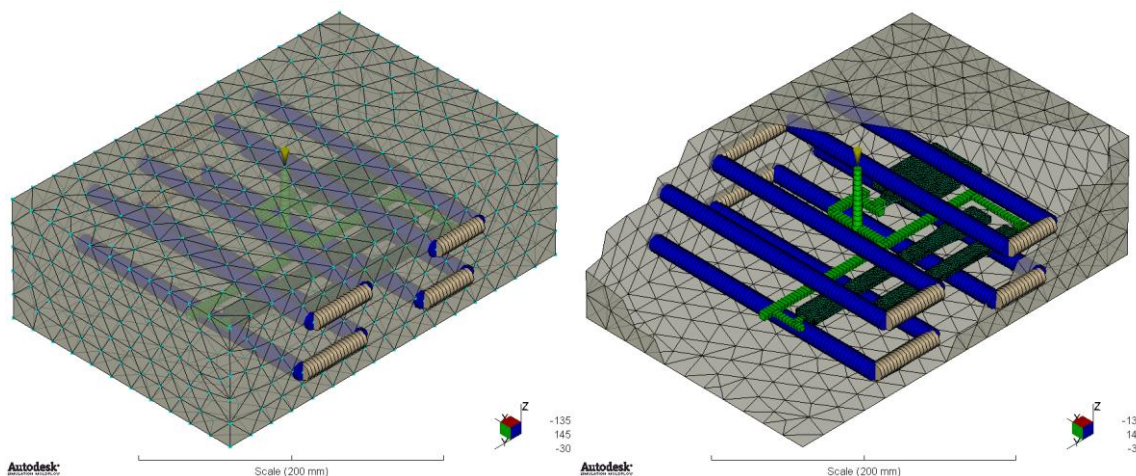

Figure 2. Mold boundary mesh used in BEM cooling analysis

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The transient analysis uses a full 3D mesh of the mold geometry. The temperature equation is solved using a finite element method. In contrast to the BEM, the transient term is included for the solution calculation.
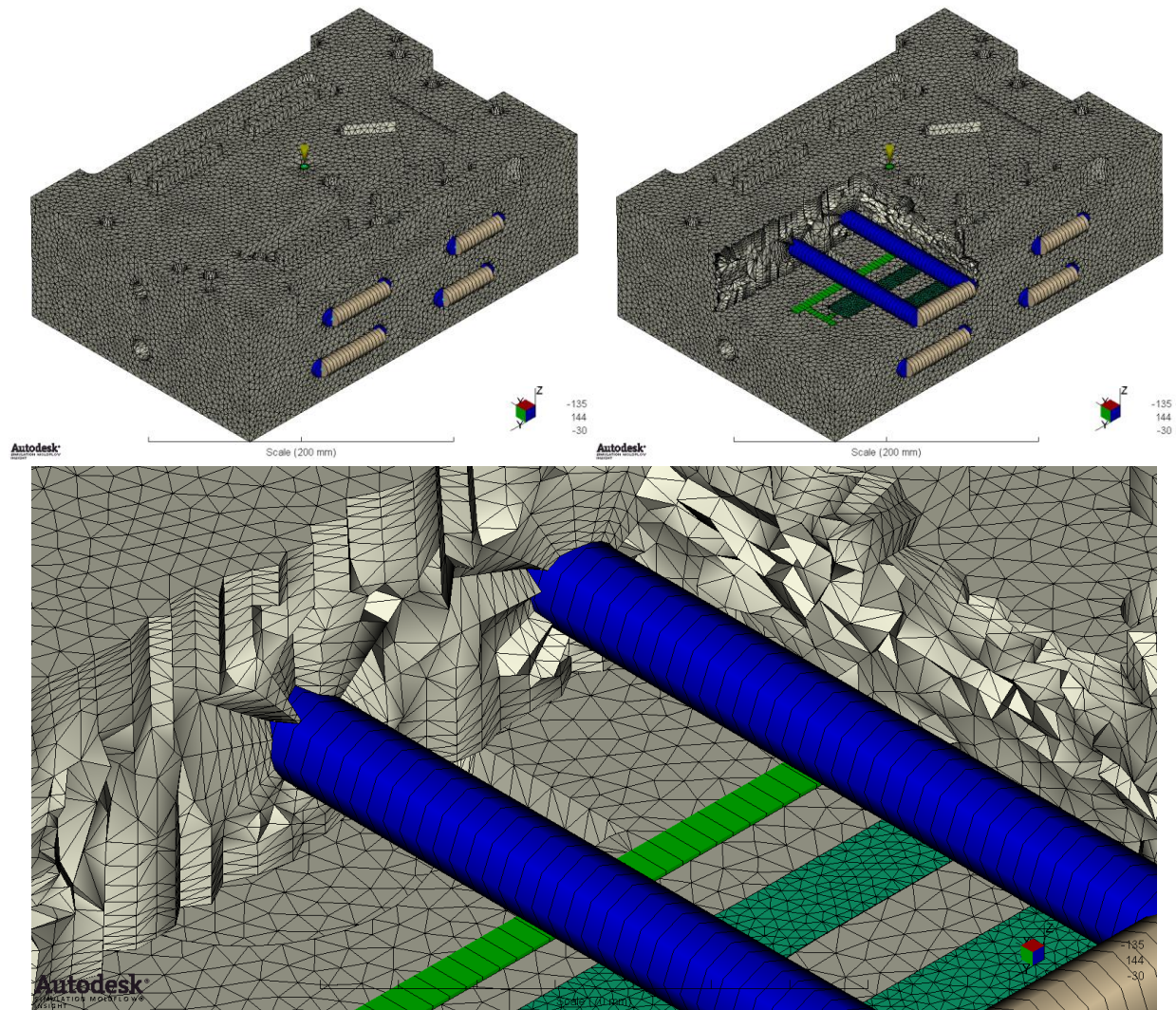

Figure 3. Mold 3D Mesh used in Transient Cooling Analysis

There are three temperature options in the transient analysis: average within cycle, transient within cycle and transient from production start-up. The first provides a solution equivalent to BEM, it assumes steady state conditions, providing results based on average temperatures during the cycle. The second performs a non-steady-state analysis throughout one cycle. The third option considers the entire heat transfer and accumulation history from production startup until steady-state is achieved.

There are two solvers for the FEM cooling analysis: the conduction solver and the flow analysis on every iteration. The conduction solver takes the melt temperature as the initial cavity temperature, i.e. it assumes that the cavity is filled immediately at the start of the analysis. The flow analysis on every iteration considers the viscous dissipation and heat transfer effects during filling.

Characteristic results of the *transient from start-up* analysis are shown in Figure 4. The initial mold-cavity interface temperature at production start-up is set by the user. From this point on, the software calculates the temperature changes in the cycle and uses the final temperature as the initial condition for the subsequent cycle. The iterations continue until the specified steady-state criteria (temperature tolerance) is achieved.

Figure 5 presents mold cavity interface results for the *transient within cycle* analysis using the *flow analysis on every iteration* solver for a node close to the end of fill of the flexural bar cavity. It is noticed that the rise in temperature is not instantaneous, it corresponds to the melt arrival time at the examined location. On the other hand, results for the same analysis but using the *conduction solver,* presented in Figure 6, exhibit an almost instantaneous increase in the cavity interface temperature. This is due to the assumption of the melt temperature as the initial condition for the cavity immediately at the start of the analysis.
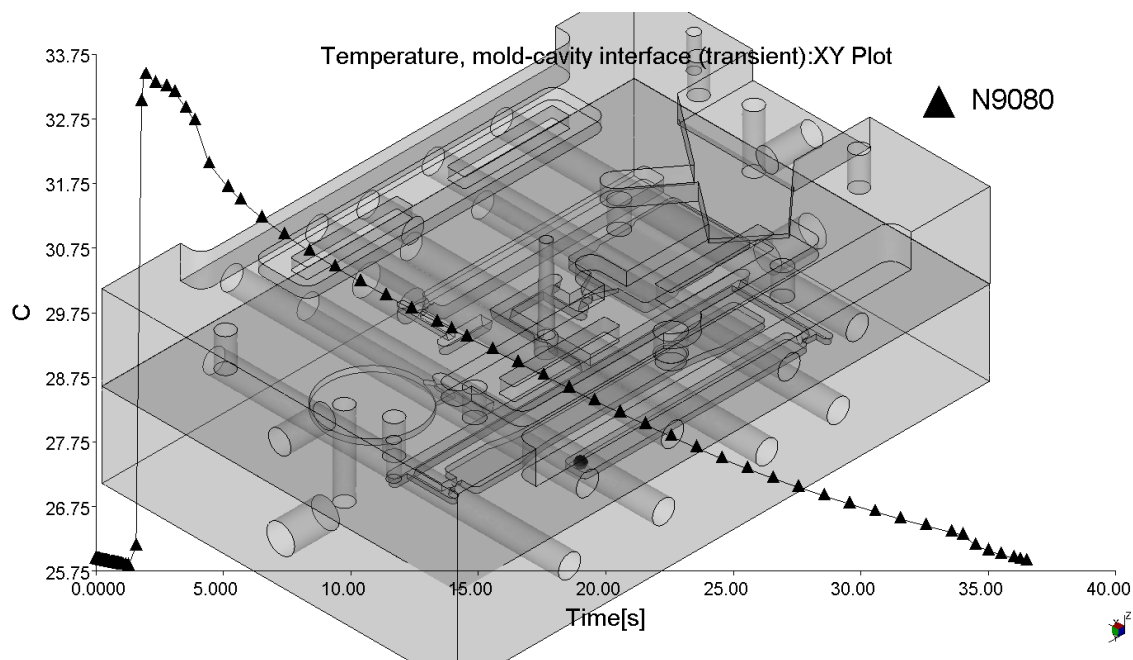

Figure 4. Cavity temperature results in transient from start-up analysis
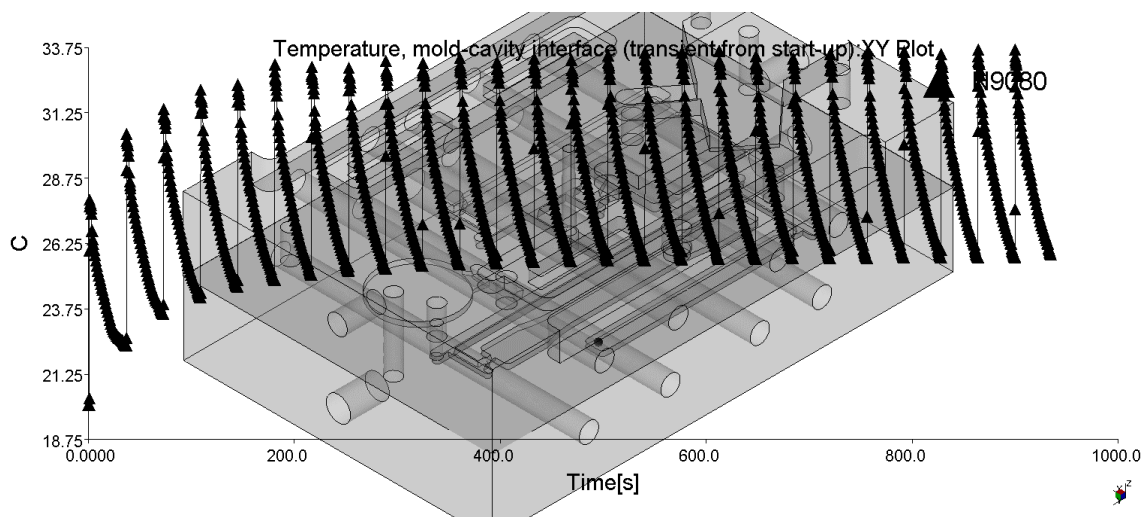
Figure 5. Cavity temperature results in transient within cycle analysis (Flow analysis on every iteration solver).
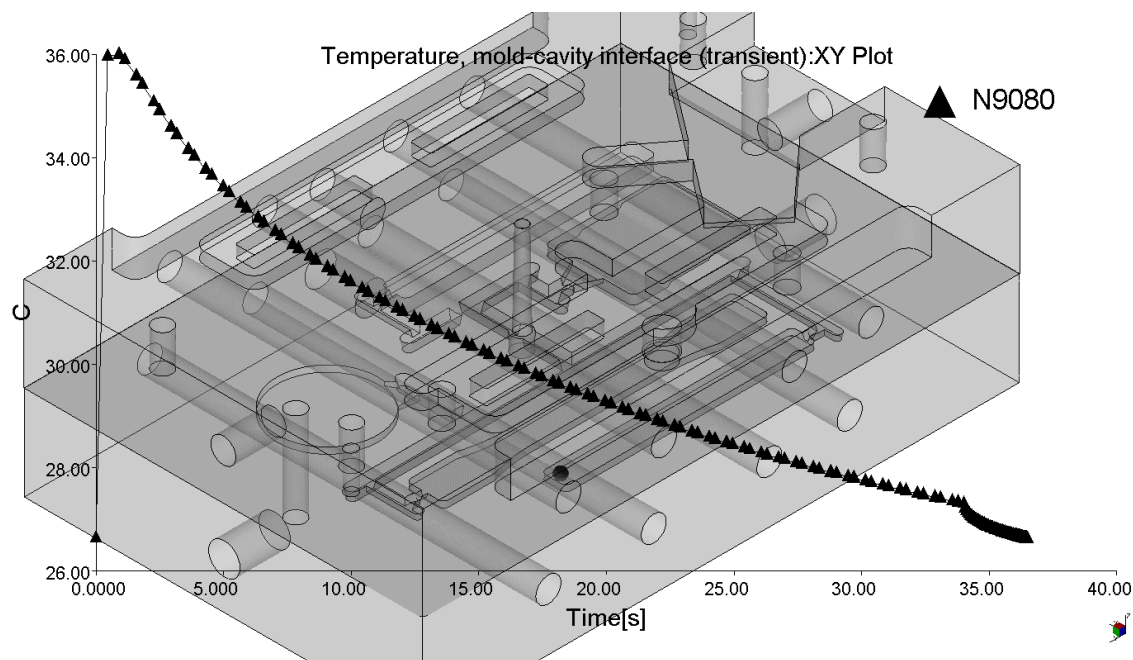

Figure 6. Cavity temperature results in transient within cycle analysis (Flow analysis on every iteration solver).

Factors Affecting the Analysis

Choosing the appropriate solver for the analysis can make a significant difference, not only in the results but also in the calculation time. However, these are not the only parameters that would affect the results. Similar to the other simulation sequences, accurate modeling of the geometry under study is crucial for the results. Also, thermal properties of the resin and the mold material are quite important for the accuracy of the analysis due to its dependence on them. The resin rheological properties gain importance when using the flow analysis solver.

Another parameter that should not be neglected is the heat transfer coefficient for the melt-mold interface. This parameter characterizes the convective heat transfer between the melt and the cavity wall. Measuring this parameter represents a challenge since it varies during the cycle. Heat convection will be higher during filling. It will decrease as the material starts to solidify during packing, and it will be the lowest when the part shrinks away from the cavity forming a gap between the plastic and the steel. Results illustrating the effect of the different parameters on the analysis results will be shown in this section, as well as the evaluated parameters. The results are followed by a discussion on the parameters effect.

Heat transfer coefficient (HTC)

Table 2. Heat transfer coefficients used to evaluate the parameter effect

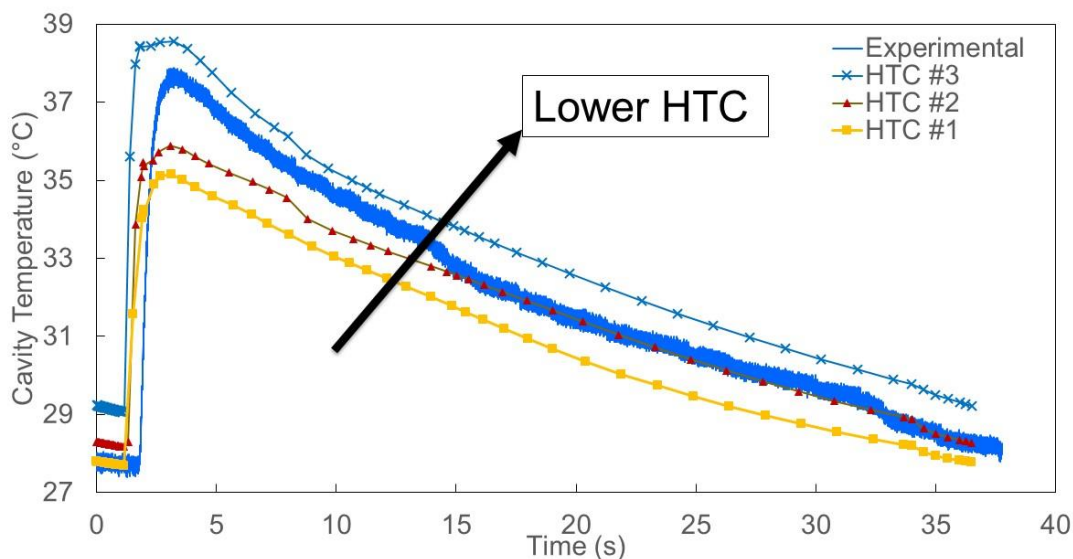| Condition	HTC $\left[W/_{m^2C}\right]$		
	Fill	Packing	Detached
HTC #1	20,000	10,000	5,000
HTC #2 (Default)	5,000	2,000	1,250

Figure 7. Effect of the HTC on the analysis results
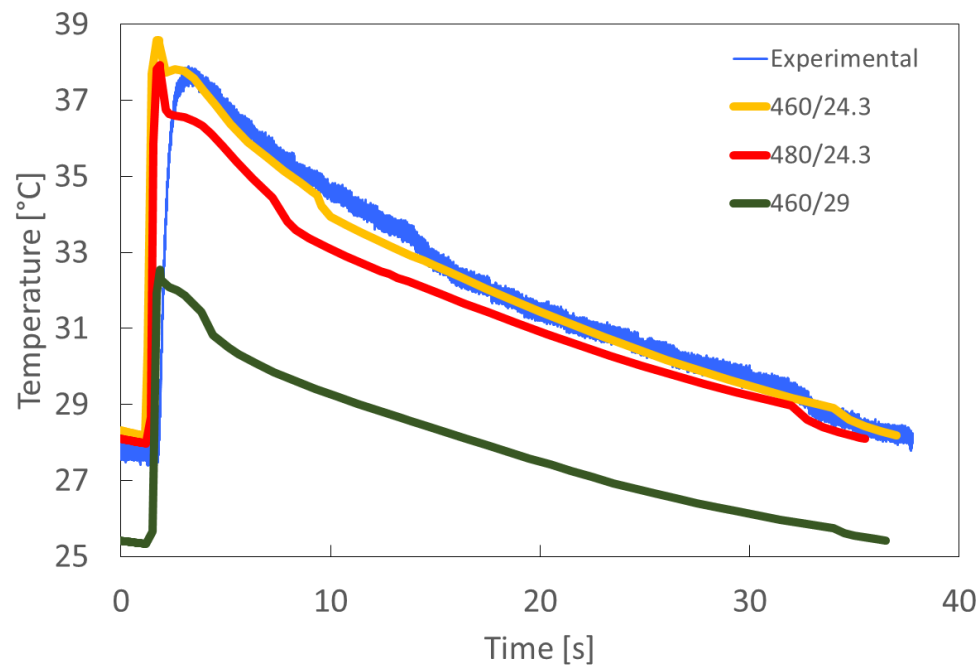
Mold Steel Properties

Figure 8. Results obtained using different mold material thermal properties.
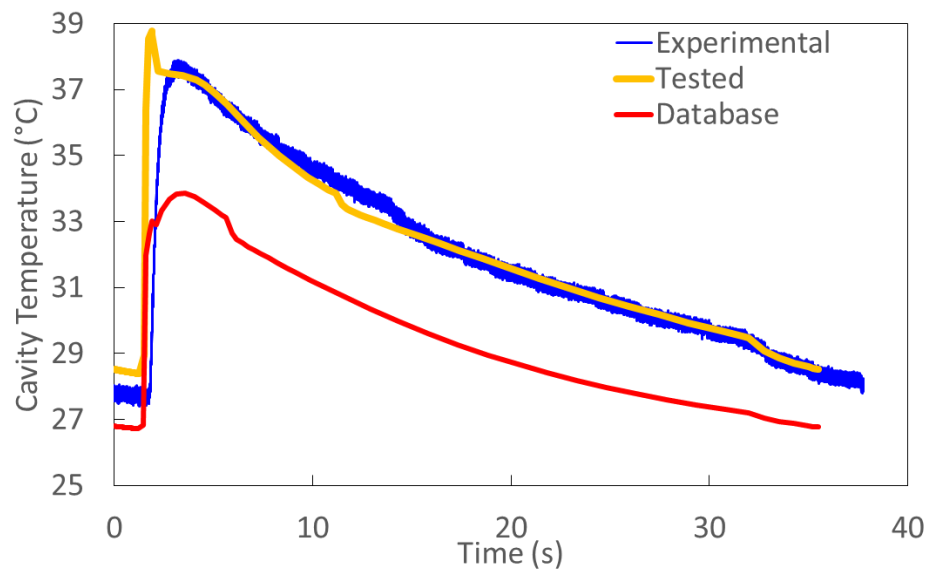
Resin Thermal Properties

Figure 9 Results obtained using published and in-house measured heat capacity data of the resin.

Discussion

After running the analysis with different parameters and comparing the results with experimental data it was clear that the thermal properties (heat capacity and thermal conductivity) of the resin and the mold steel play a very important role on it. In many cases, there is limited availability of these properties for the specific material that is being used. The use of generic values may be sufficient depending on the required accuracy.

Comparison of Experimental and Simulated Data

Within the limitations of equipment available, the properties of the resin and mold steel were tested and input to the software. A subset of the results is presented as follows showing screw speed, coolant temperature at the inlet and outlet and temperature at the mold-cavity interface. Four runs representative of the high and low values of the DOE are shown.

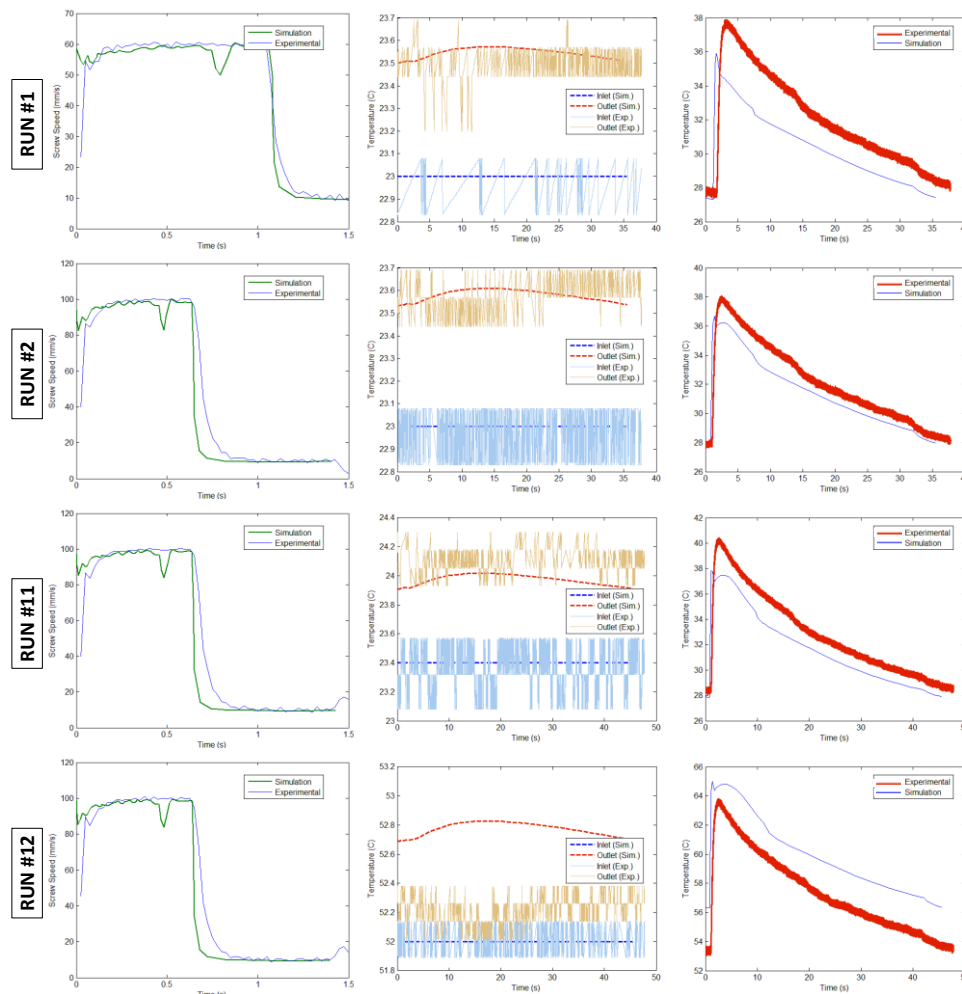Note: The screw speed data is truncated at the V-P switchover.

Figure 10. Comparison of simulation to experimental results

Conclusions

The transient cooling analysis provides a new set of tools to the mold designer and to the process engineer providing more insight information about the process. Each of the analysis options and solvers has its pros and cons. Their selection ultimately depends on the type of results required. For example, if time to reach a steady process is needed, the transient from startup analysis would be most suitable versus a transient within cycle analysis. The computation time is an important factor to consider on the selection. The flow analysis solver requires more time to solve than the conduction solver; however, it consider shear heating and flow history. Novel tools such as cloud computing are available and can be very useful when running transient cooling analysis due to the computing power required.

The simulations performed were capable to represent the process data in a very accurate manner for most of the cases. Difference in the mold-cavity interface temperatures were in all cases within 2°C. Furthermore, the analysis was found to very closely predict the coolant inlet and outlet temperatures. For the low coolant temperature the difference between simulation results and experimental data is negligible due to the signal noise. For the medium temperature the difference is within 0.2°C and for the higher value is within 1°C.

The simulated flow rate (when available) was compared to the experimental screw speed to verify this aspect of the simulation. The prediction followed the experimental values for all the conditions evaluated.

Acknowledgement

References

[1]   P. Kennedy and R. Zheng, *Flow Analysis of Injection Molds*, 2013.