simform Easy Mold Cooling Prediction

Comparison of temperature and cooling time predictions with experimental mold trial results

Demonstrating the application of SimForm to a real-world plastic injection mold

Summary

SimForm is a thermal simulation tool used by tooling engineers and mold makers early in the design process to gain insight into the temperature distribution and hot spots within plastic injection molds. SimForm is continuously validated against standard thermal test cases and has been compared against proprietary mold trials. In this article, we compare the results of an experimental mold trial with the results from a SimForm simulation. We show that SimForm accurately predicts the plastic temperature distribution, and the temperature values within 2°C of sensor values. We also show that by modifying the cooling channels, we can lower the cooling cycle time to save on the unit cost of the plastic part.

SimForm makes several assumptions in order to be fast and convenient for mold designers:

- The injection of the plastic is not simulated; rather the plastic is injected “instantaneously”
- The injection and mold opening stages of the cycle are ignored
- There are no air gaps between plastic and metal (the heat transfer is ideal)

Yet, despite these assumptions, SimForm provides realistic and actionable temperature simulation results.

First, we will discuss the experimental mold trial, presenting the equipment used, the plastic part produced, the injection mold machine parameters, and the molding process.

Then, we will discuss the SimForm simulations, presenting the SimForm project definition, input parameters, and material properties, with a focus on the assumptions made by the software, and how it chooses the initial temperatures for the mold.

Finally, we will compare the measured temperatures at two specific sensor locations with the simulated temperatures at the same two locations, we will compare the overall temperature distribution on the part and mold to an IR camera measurement, and we will investigate the cooling time predicted by the software and how that could be improved.

Experimental Mold Trial

The objective of the experimental mold trial was to produce a sequence of plastic parts, while measuring the surface temperature at two specific sensor locations. Furthermore, we wanted to measure the impact of two key machine parameters: injection speed, and cooling water temperature.

The mold trial took place at the COALIA applied research centre[1]. COALIA specializes in minerals, materials science, and plastic technology, and seeks to innovate and improve upon industrial processes, in collaboration with businesses. Specifically, they are able to conduct plastic injection mold trials.

Equipment and Sensors

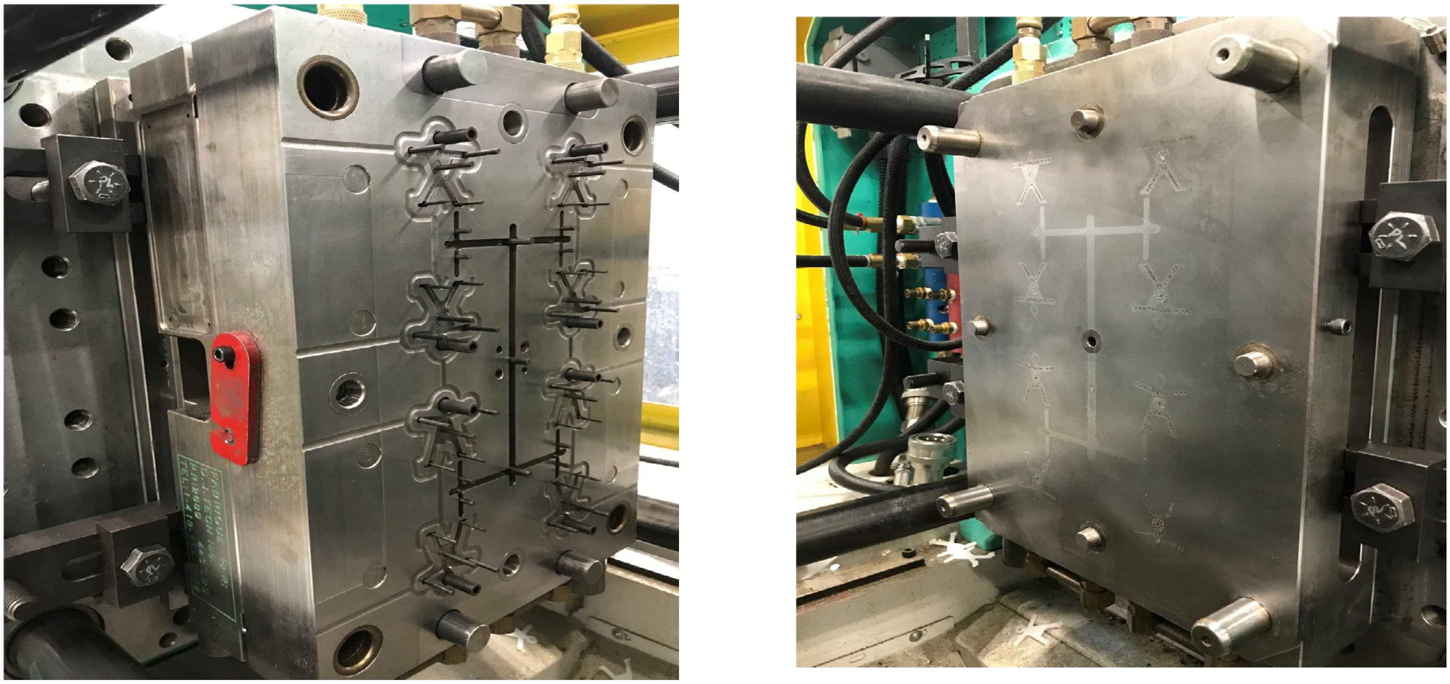
The mold trial was conducted using an Arburg Allrounder 370A injection molding machine[2] with a 66 ton clamping force.

The mold used in the trial was made in RAMAX HH, a chromium alloy stainless steel. Eight cavities of sample parts were distributed symmetrically in the mold and supplied by a cold runner.

Each of the cavity and core blocks have simple cooling channels passing through them, parallel to the parting line of the mold. The water passing through the cooling channels was maintained at near constant temperature by means of a Hamilton Plastic Systems Thermo-5 temperature control unit (HB-200Z2B).

Fig. 1: Arburg Allrounder at COALIA research facility

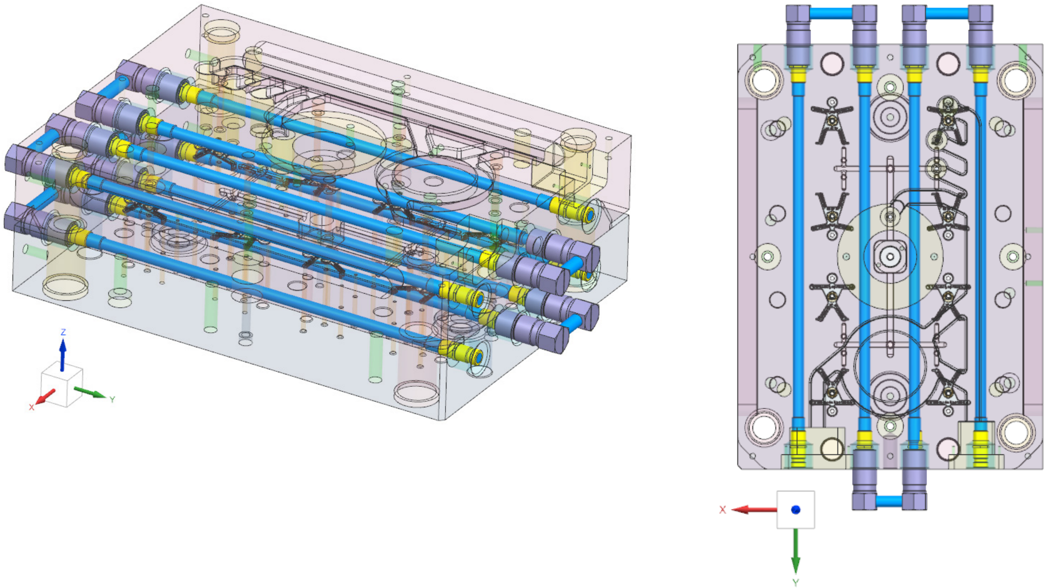
Fig. 2: Injection mold halves with 8 cavities



A. Moving half

B. Fixed half

Fig. 3: CAD illustrating cavity and core cooling channels



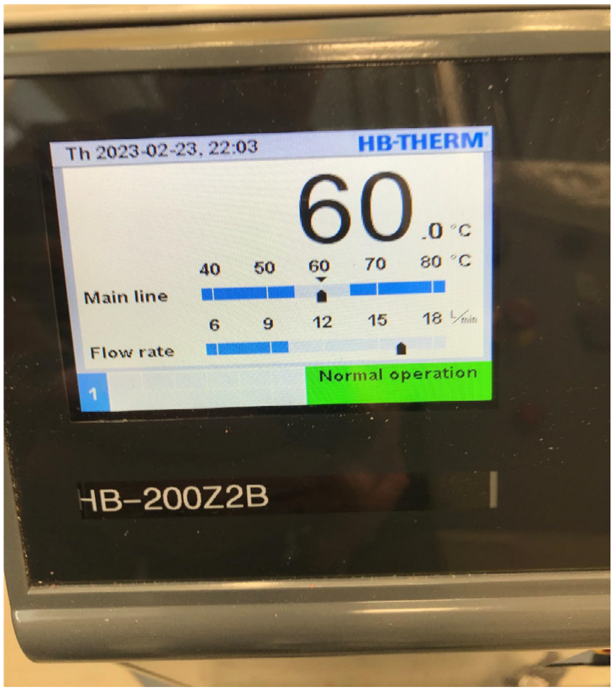


Fig. 4: Temperature control unit

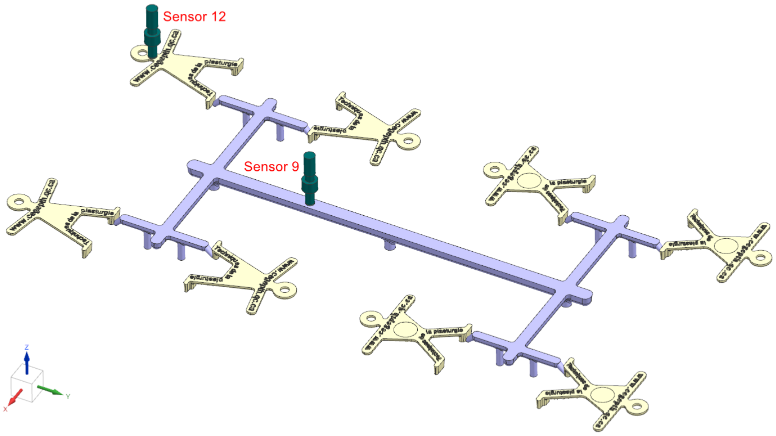


Fig. 5: CAD illustrating location of temperature sensors

Two combined cavity pressure and temperature sensors manufactured by Kistler were embedded within the mold cavity, in direct contact with the plastic, to measure the surface temperature. Sensor 9 measured the surface temperature of the cold runner, and Sensor 12 measured the surface temperature of the plastic part.

The 6190CA sensor[3] contains a Type K thermocouple. The sensors are interfaced to a Kistler CoMo Injection 2869 control and monitoring system.

Fig. 6: Control and monitoring system, measuring sensor temperatures and mold conditions

Plastic Part

The mold itself is for demonstration purposes, and so the plastic parts were just samples. However, they have a few interesting features: five ejector pin locations, an insert for the hole in the plastic figurine, a slightly thicker “foot” region, and detailed text on the surface. Eight parts were produced at a time, with a cold runner directing the plastic to the cavities. The samples were each roughly 1.67 mm thick, and the plastic used for the experiment was Profax 8623 polypropylene, manufactured by Lyondell-Basel.

Fig. 7: Close-up of plastic figurine

Mold Trial Runs

In total, three experimental runs were conducted to measure data while varying the speed of injection (either 35 cm^3/s or 50 cm^3/s), and the cooling water temperature (either 30°C or 60°C). At the start of each run, the mold was allowed to stabilize at the cooling water temperature, and then the injection cycles started.

For the first several cycles of an injection mold, the mold heats up due to the repeated introduction of hot molten plastic. Eventually, the temperature profile of the mold will reach a consistent, repeating pattern, representing the normal operating conditions. To properly account for this warming phase, in each experimental trial, 15 cycles were executed, all the while recording the sensor temperatures. As shown in Fig. 8, the recorded temperatures are repeating themselves within 2°C well before the 15th cycle, therefore the mold has easily reached its normal operating conditions.

Due to limitations in the data acquisition software, temperature could only be captured once within a limited set of pre-defined time intervals, and so the resolution is quite coarse.

After the 15th cycle, COALIA took an infrared thermal image of the parts still in the mold. This was done as close to the end of the cooling phase as possible, but did require halting the machine, and opening the bay to see into the machine with the mold halves open.

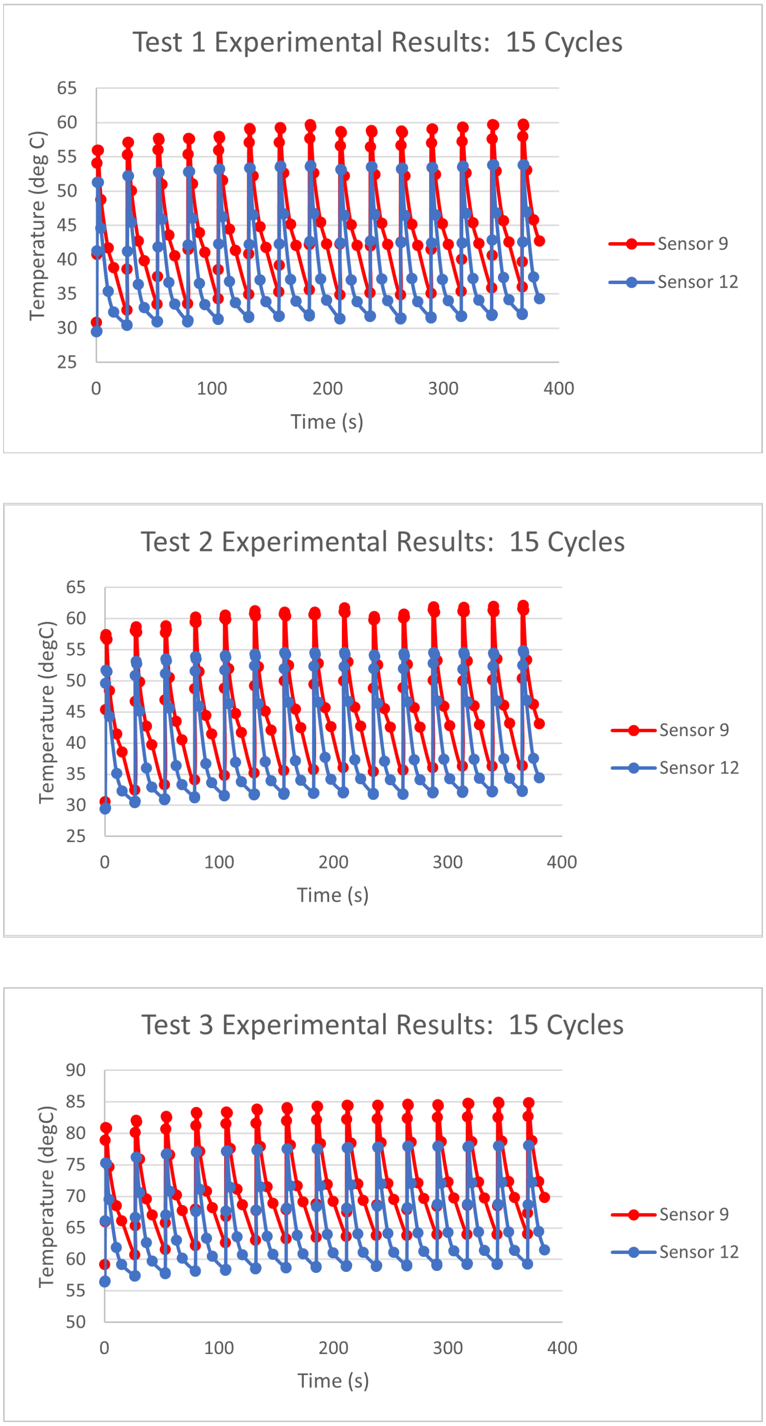


Fig. 8: Temperature evolution of mold over 15 initial injection cycles

A detailed summary of the machine conditions for each test is shown in Table 1. Pertinent values are highlighted in orange.

Table 1: Machine conditions for each experimental test

	Test 1	Test 2	Test 3
Temperature Set Point (°C)	30	30	60
Measured Sensor Temperatures at Start of Test (°C) - Fixed Mold Half	29.9/29.5	29.9/29.5	57.4/54.4
Measured Sensor Temperatures - Moving Mold Half	29.4/29.2	29.4/29.2	57.3/53.3
Injection Pressure (bar)	840	910	830
Speed Injection (cm^3/s)	35	50	35
Injection Time (s)	0.76	0.54	0.76
Hold Pressure (bar)	600	600	600
Speed of hold (cm^3/s)	30	30	30
Hold Time (s)	10.5	10.5	10.5
Cooling time (s)	10	10	10
Spindle Rate (RPM)	120	120	120
Total Volume (cm^3)	29	29	29
Total Cycle Time (s)	26.28	26.06	26.37
Melt Temperature (°C)	210	208	211

SimForm Simulations

The objective of the SimForm simulations was to mimic the mold trial runs, and ultimately compare the simulation temperatures to the measured temperatures. We ran simulations with two different cooling water temperatures. We also simulated cases where we let SimForm predict a cooling cycle time.

Project Setup

COALIA provided a near-complete CAD representation of the mold. In an external CAD package, we manually reconstructed the cold runner geometry and introduced solid geometry to represent the cavity and core cooling channels. The entire CAD model was imported into SimForm.

We selected all metal parts in contact with the plastic or the water for consideration in the simulation. SimForm performs automatic meshing of the mold and plastic parts, relative to the size of the parts, using a voxel-based mesher. For the COALIA mold, the resulting voxel mesh sizes were as shown in Table 2.

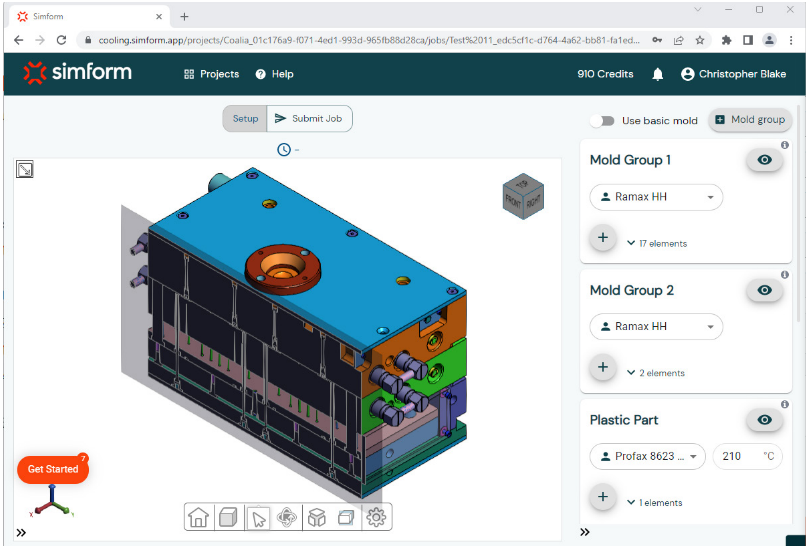


Fig. 9: Project setup in SimForm

Table 2: Voxel mesh sizes

Plastic Parts / Runner	0.28 mm
Mold / Metal Components	0.56 mm

SimForm does not consider a thermal contact resistance between parts, meaning the voxel mesh is a continuous mesh, without any gaps.

Thermal material properties were assigned, as shown in Table 3.

Table 3: Thermal material properties

	Ramax HH[4] (Mold Components)	Profax 8623 Polypropylene (Plastic)
Density (kg/m3)	7700	900[5]
Specific Heat (J/kg-°C)	460	3100
Thermal Conductivity (W/m-°C)	24	0.15
Ejection Temperature (°C)	-	90

Typically, the specific heat of thermoplastics varies with temperature – strongly near the glass transition temperature. In the absence of further detail from the manufacturer, standard values for polypropylene were used.

Normally, SimForm will simulate the cooling of the plastic parts until a specified wall thickness has dropped below the safe ejection temperature, rendering the part solid enough to eject. To properly mimic the experimental conditions, the cooling phase was simulated for the same amount of time, 10.5 s of hold and 10 s of cooling, for a total simulation time of 20.5 seconds. The injection time is not considered (0.76 s or 0.54 s), nor is the time to open, eject, or close the mold (roughly 5s). This was repeated for a total of 15 cycles, like in the mold trial. The temperatures calculated at the sensor locations were reported for the final cycle.

The initial temperature for the plastic parts and runner at the start of each cycle was uniformly set to 210°C – assuming essentially an instantaneous injection of the plastic. This is an approximation of what occurs in reality: despite the injection time being less than 1 second, because the plastic part is thin, we know that a relevant frozen layer compared to the thickness of the part will begin to develop as the plastic is injected.

The initial temperature of the mold at the first cycle was uniformly set to the measured sensor temperatures (30°C / 57.5°C) rather than the control unit set point; the mold temperatures were then allowed to evolve with each cycle. A summary of the simulation cases run is shown in Table 4.

Table 4: Conditions for each simulation

	Simulation 1	Simulation 1 – 20%	Simulation 1 – Full	Simulation 3	Simulation 3 – 20%
Initial Plastic Temperature (°C)	210	210	210	210	210
Initial Mold Temperature (°C)	30	30	30	57.5	57.5
Water Temperature (°C)	30	30	30	57.5	57.5
Simulated Cycle Time (s)*	20.5	20% thickness target	Fully solidified	20.5	20% thickness target
Ambient Temperature (°C)	30	30	30	57.5	57.5
Number of cycles	15	15	15	15	15

Since SimForm does not consider the injection time, simulations of Test 1 and 2 were deemed the same. In addition to simulating the full cycle from the experimental trials, we also simulated cases where the plastic parts were ejected once the solid wall thickness target was achieved, thus predicting a cooling cycle time.

SimForm assumes that water flows through each channel network at a rate to guarantee turbulence, i.e. a Reynolds number of 10,000. For this mold, the flow rate was calculated by SimForm to be 1.1 gpm (4.12 L/min). The heat transfer coefficient of 4500 W/m^2-K between the water and channel walls was calculated by SimForm based on a forced convection correlation, assuming fully-developed flow.

Simulated temperature results at the sensor locations were sampled every 1/10th of a second.

Initial Conditions

Rather than assign a constant mold temperature, SimForm simulates the evolution of the mold temperature throughout the cycle, which provides insight into the effectiveness of the cooling channel design. In order to do this, a starting temperature distribution on the mold must be specified. SimForm provides two methods for estimating this starting temperature on the mold:

1. Steady State Approach (Old Method): SimForm holds the plastic at the target ejection temperature and determines the temperature distribution in the mold. This approach is conservative, as in an actual cycle, the plastic surface temperature will be lower than this target, to ensure that the interior is sufficiently cool to be ejected.
2. Multi-Cycle Approach (New Method): SimForm starts the mold at the same uniform temperature as the cooling channels, and then simulates a number of cycles that warm up the mold with each injection. This is a more time-consuming approach, but more closely estimates the temperature distribution on the mold under normal operating conditions.

This experiment used the “Multi-Cycle Approach”, as it corresponds with the experimental conditions. We tried both 5 and 15 initial cycles and demonstrated that with more cycles, not only did the mold absorb more heat, but a temperature difference between the two sensor locations was predicted, like in the mold trial.

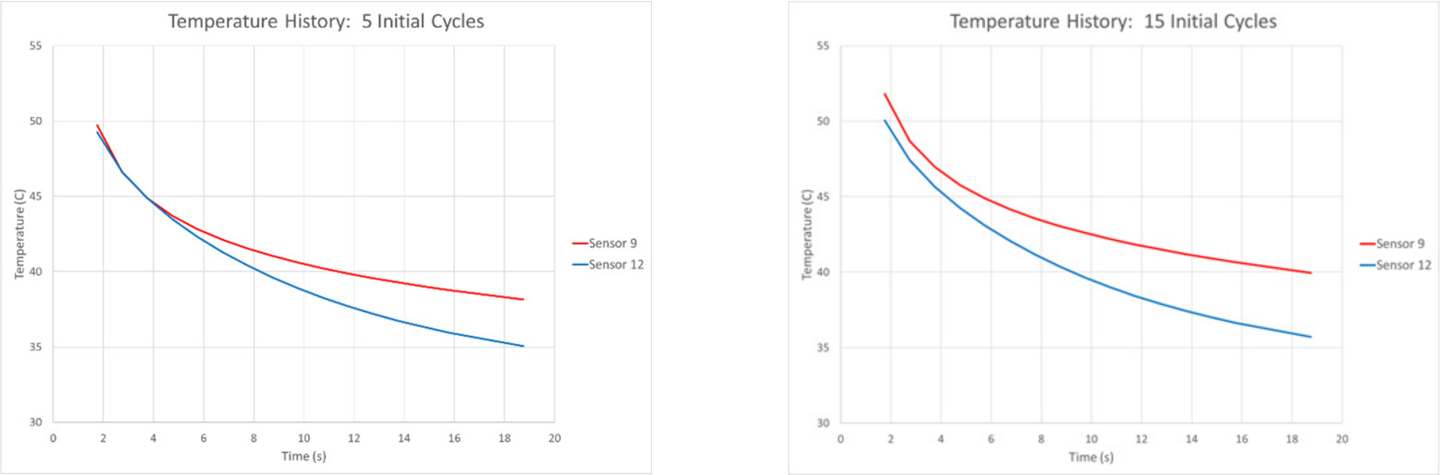


Fig. 10: Evolution of sensor temperatures after initial injection cycles

SimForm simulates the heat loss from the plastic to the mold, but under the assumption that the plastic starts out at a uniform melt temperature, implying an instantaneous injection. In reality, the injection takes time, and there can be multiple gates – especially for larger parts. During the injection phase, the frozen layer begins to develop, meaning the surface temperature is cooler. Shear heating in the boundary layer of the plastic, also causes the temperature of the plastic within the part to rise. Ultimately, close to the wall, the plastic temperature is not uniform.

Because simulating the plastic flow can be computationally intensive, SimForm elects to ignore the injection phase so that mold designers can run informative simulations more quickly and easily.

Discussion of Results

SimForm enables designers to look at the temperature distribution on the plastic part and on the mold to analyze whether the cooling approach is adequate and where improvements can be made. Using SimForm's post-processing features, we compared the results from the three experimental trial runs with the results of the two SimForm simulations.

Simulation 1

Sensor Results

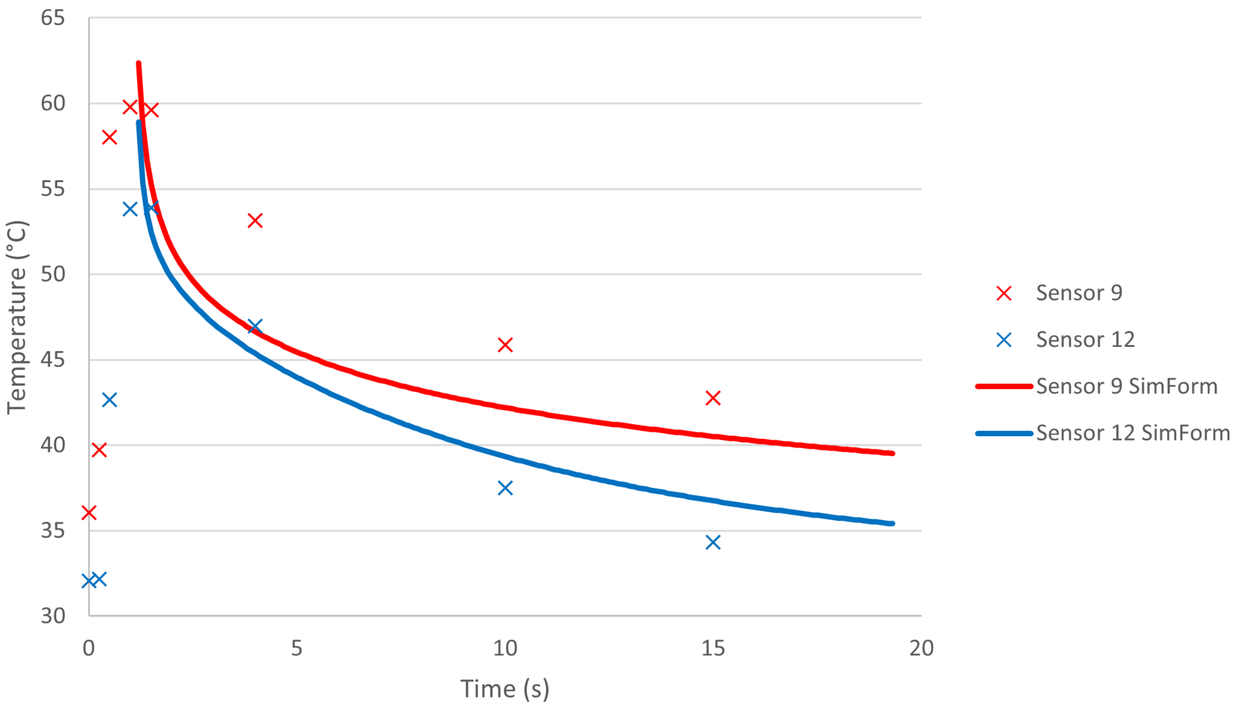


Fig. 11: Simulation 1 – temperature history

In Fig. 11, we can see the experimental results for the final injection cycle, plotted with X-markers. The sensor temperatures begin at a value near the cooling channel temperature of 30°C, but are slightly higher due to the accumulated heat from the previous cycles. In the first 0.75 seconds, the plastic is injected into the mold, and the temperature increases. The sensors don't record any temperature near the melt temperature of 210°C. Presumably, by the time the plastic has reached the sensor location and a value has been captured at the coarse sampling resolution, a thin frozen wall has already started to form.

Since the SimForm simulation does not consider the injection phase, we offset the SimForm results ahead by 0.75 seconds. SimForm successfully predicts the cooling history at the sensor on the plastic part, Sensor 12, to within 2°C of the experimental results. This is an important result, because obtaining a good prediction of the temperatures on the part allows the designer to draw conclusions about the cycle time, and the relative performance of one cooling design versus another.

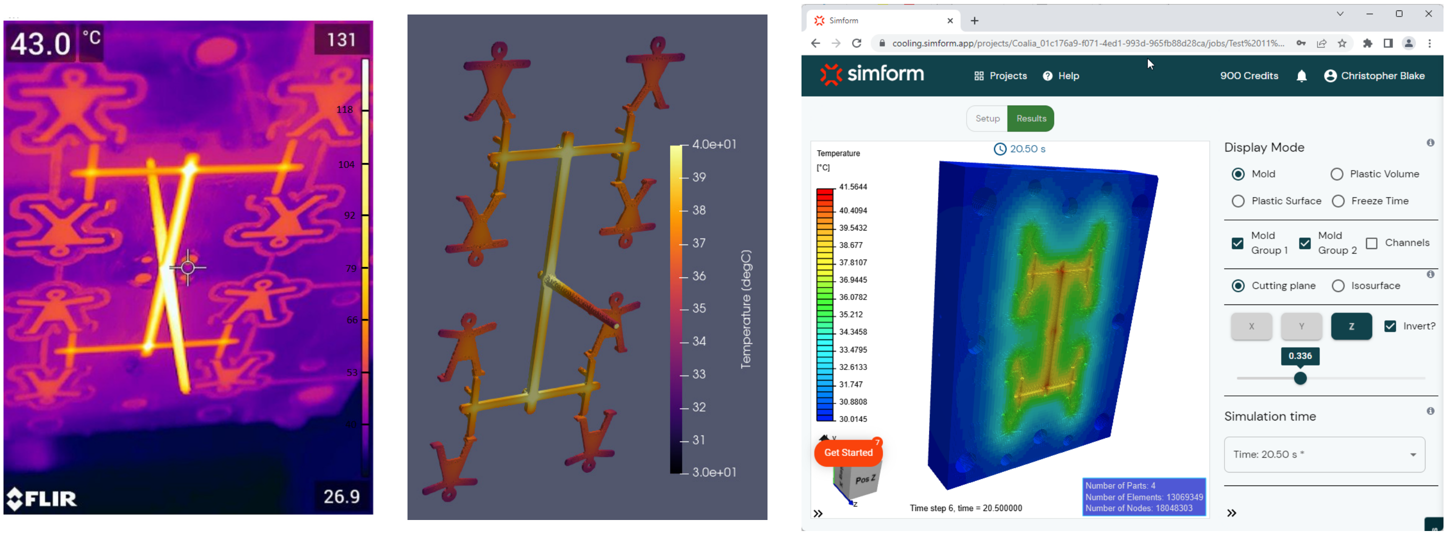
SimForm does predict a faster cooling rate at Sensor 9 on the runner, though this can be explained by the following:

- The plastic volume is much thicker at Sensor 9. Given there is additional thermal mass, the cooling rate may be more greatly affected by temperature-dependent density and specific heat, keeping the plastic at the glass transition temperature longer as it solidifies.
- Shear heating during the injection phase will raise the plastic temperature on the runner. This effect will be less pronounced at Sensor 12, which is at the extremity of the mold cavity.

The effectiveness of the heat transfer between the plastic and the mold also has an impact on the predicted temperatures. As the plastic cools, it shrinks and pulls away from the metal walls, leading to poorer heat transfer. The pack phase after injection partially compensates for this by forcing additional plastic into the mold. Once gate freeze occurs, any additional shrinkage will lower the heat transfer effectiveness. In thicker areas of the part, such as here on the runner, this can lead to higher surface temperatures. SimForm aims to support specifying imperfect contact between plastic and metal in a future release.

The measured temperature difference between Sensor 9 and Sensor 12 is roughly 8°C. SimForm predicts a lower temperature difference, but this can be explained by the fact that the SimForm does not consider the injection phase, which results in a surface temperature gradient along the path of the melt. SimForm assumes a uniform starting temperature for the plastic, which is a conservative assumption.

Fig. 12: Simulation 1 – Plastic and mold surface temperature comparison



cooling.simform.app/projects/Coalia_01c176a9-f071-4ed1-993d-965fb88d28ca/jobs/Test%2011%...

Display Mode: ● Mold ○ Plastic Volume ○ Plastic Surface ○ Freeze Time

☑ Mold Group 1 ☑ Mold Group 2 ☐ Channels

● Cutting plane ○ Isosurface

☑ Invert?

Simulation time: Time: 20.50 s *

Time step 6, time = 20.500000

Number of Parts: 4
Number of Elements: 13069349
Number of Nodes: 18048303

A. Experimental IR image after mold opening

B. Plastic and runner surface temperatures at t=20.5s

C. Mold surface temperatures at t=20.5s

Infrared Camera Results

Comparing now the FLIR image of the mold to the simulation results, we see in Fig. 12 that the gradient across the runner and the plastic parts is present in both images. Despite not simulating the injection phase, SimForm predicts warmer temperatures on the runner, due to the additional thickness, and peaks at the bifurcation points in the runner – both of which we see in the FLIR image. Qualitatively, the temperature predicted by SimForm are in good agreement with the experimental data measured by the FLIR camera.

There are two noticeable differences: (1) the vertical runner path is hotter, and (2) overall, the plastic is much hotter in the FLIR image. This is partly due to reheating: during the few seconds that the mold is opened, the heat within the molten center of the plastic travels to the exposed plastic surface and raises the surface temperature. SimForm reports the instantaneous temperature at the end of the cooling cycle and doesn't consider an opening phase where the reheating would occur. At the same time, as is known in the industry, we must take the accuracy of the FLIR results with a grain of salt, as they are highly dependent on calibration and surface finish. There is a reflected IR signature of the vertical runner on the mold surface, and the temperature on the vertical runner itself is unrealistic, as it is somehow reported as higher than the solidification temperature of the polypropylene.

Safe Ejection Time

In addition to recreating the full cycle from the experimental trial, two additional simulations were conducted in SimForm, halting the cycle once the plastic part reached a solid wall thickness target deemed to mean the part is safe to eject. SimForm reports the time to reach this target.

Table 5: Simulation 1 – safe ejection time predictions

Solid Wall Thickness Target	Safe Ejection Time
20% of part thickness	6.2 seconds
Part completely solid	19.7 seconds

For a solid outer layer of plastic that is 20% of the part thickness, it takes 6.2 seconds of cooling after injection is completed. In SimForm, we can examine which areas of the part take the longest to solidify. Fig. 13 shows a "freeze time plot", which is the estimated time at which each area of the plastic part is safe to eject. There is a potentially problematic area in the thicker part of the "foot" of the plastic figurine, especially where the runner connects to the part. However, the predicted freeze time is almost the same as the top surface of the part.

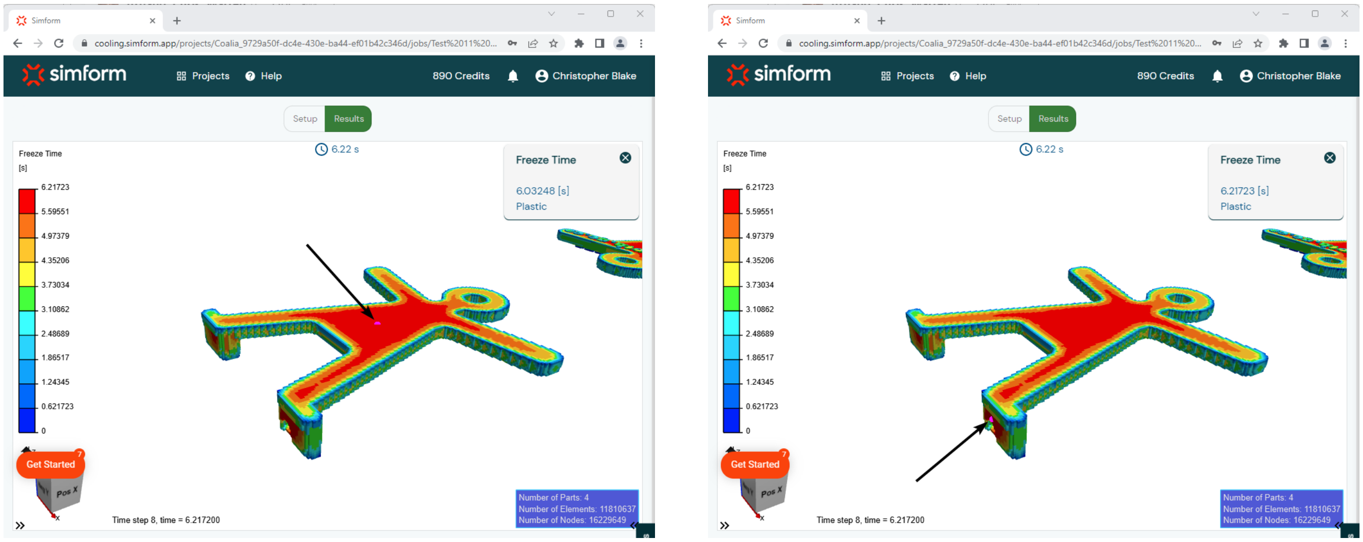
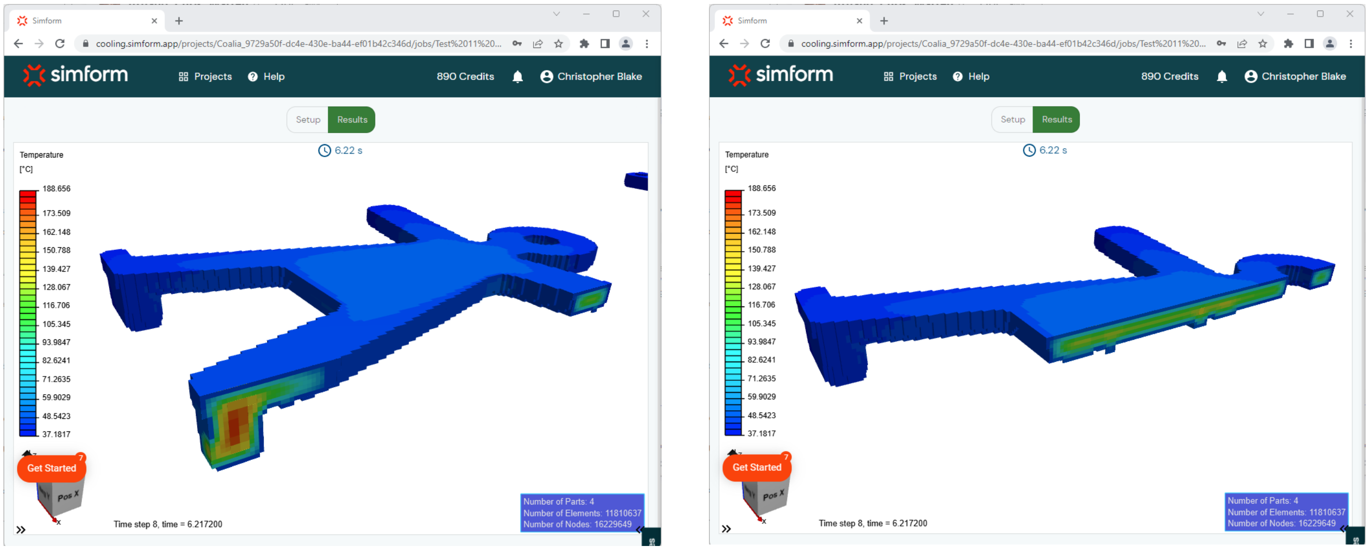


Fig. 13: Simulation 1 – freeze time plot

If we look at a cross section of the temperature, through the "foot" and through the middle of the part, we see that the frozen layer is pretty consistent throughout the part. In order to reduce the cooling cycle time, we would need to move the cooling channels closer to the parts.

Fig. 14: Simulation 1 – cross sectional views of temperature through plastic part



A. Maximum internal temperature location

B. Center of part

To ensure the part is entirely solidified requires 19.7 seconds. Both predicted freeze times are below the fixed pack-hold-cool time of 20.5 seconds set in the experimental trial, meaning we could have specified a shorter cycle time. By exploring the simulation results in SimForm, a designer can make an informed decision on how to improve the cooling design in order to reduce that cycle time.

Simulation 2

Sensor Results

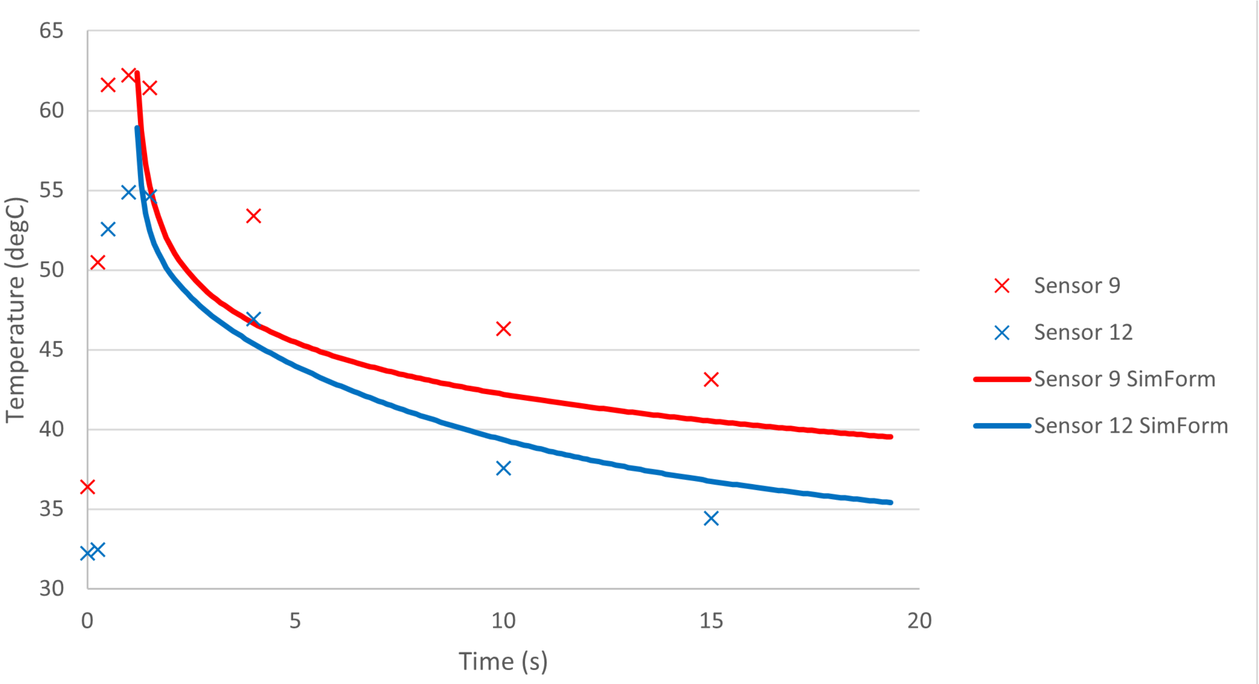


Fig. 15: Simulation 2 – temperature history

In Simulation 2, the injection speed was increased, and so the injection time was lowered to 0.54 seconds. Even with that slight drop in time, the frozen layer is affected, and the experimental plastic surface temperatures are 1-2°C higher near the beginning of the trial. Further on into the trial, the temperatures are not significantly different, and so the comparison between the experimental results and SimForm is similar.

Simulation 3

Sensor Results

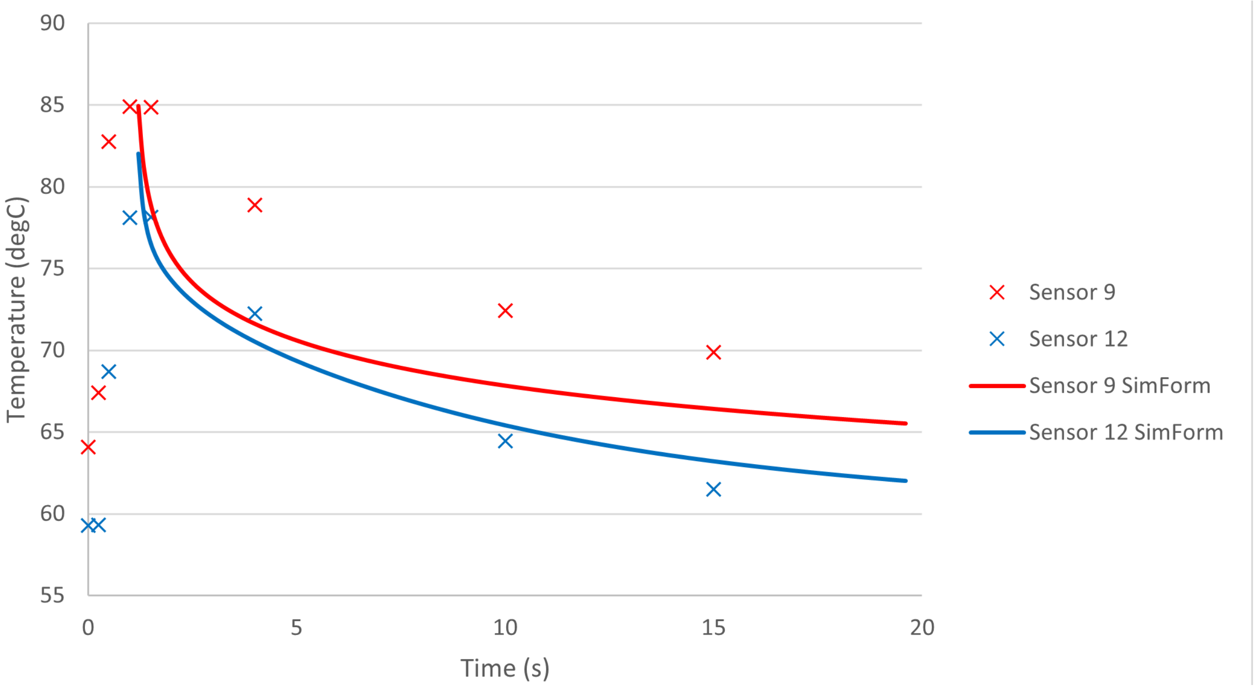


Fig. 16: Simulation 3 – temperature history

In Simulation 3, the injection time is returned to 0.76 seconds, but with a set cooling temperature of 60°C. SimForm successfully predicts the cooling history at the sensor on the plastic part, Sensor 12, to within 2 degrees of the experimental results. Obtaining a good prediction of the temperatures on the part allows the designer to draw conclusions about the cycle time, and the relative performance of one cooling design versus another.

SimForm predicts a faster cooling rate at Sensor 9 on the runner, and a lower temperature difference between Sensors 9 and 12, which can be explained by the additional thermal mass on the runner and the effect of shear heating, as discussed earlier.

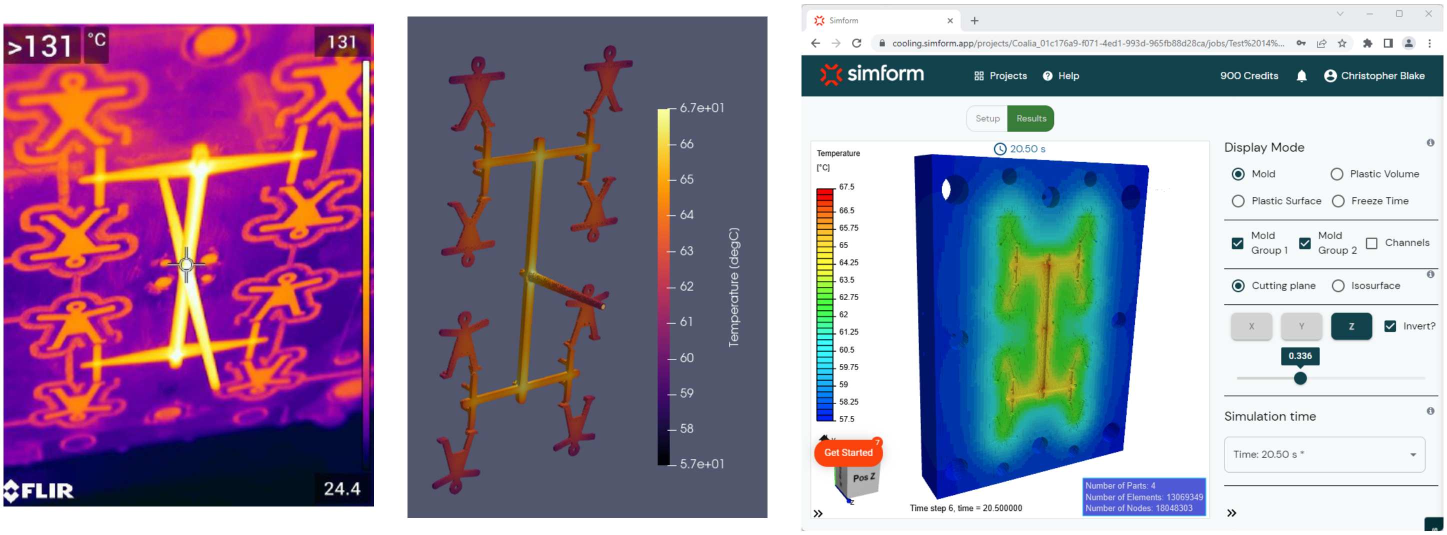
Infrared Camera Results

The plastic and runner surface temperatures at the end of the simulated cycle are similar to in Simulation 1, except that the range is shifted higher by 30°C. Interestingly, a corresponding shift is not observed in the FLIR image, calling the accuracy of that image into question. SimForm reports the instantaneous temperature at the end of the cooling cycle and doesn't consider an opening phase. During the experiment, the open mold surface would have started to cool while exposed to the ambient air.

Comparing the FLIR image to the simulation results, we see that the gradient across the runner and the plastic parts is present in both images. Despite not simulating the injection phase, SimForm predicts warmer temperatures on the runner, due to the additional thickness, and peaks at the bifurcation points in the runner - both of which we see in the FLIR image.

Again, the plastic is overall much hotter in the FLIR image. This is partly due to reheating, but the accuracy of the FLIR results remain questionable due to the reflected image and the very high temperature measured on the runner.

Fig. 17: Simulation 3 – plastic and mold surface temperature comparison



Time step 6, time = 20.500000

Number of Parts: 4
Number of Elements: 13069349
Number of Nodes: 18048303

Display Mode
● Mold ○ Plastic Volume
○ Plastic Surface ○ Freeze Time
☑ Mold Group 1 ☑ Mold Group 2 ☐ Channels
● Cutting plane ○ Isosurface
☑ Invert?

Simulation time
Time: 20.50 s *

A. Experimental IR image after mold opening

B. Plastic and runner surface temperatures at t=20.5s

C. Mold surface temperatures at t=20.5s

Safe Ejection Time

In addition to recreating the full cycle from the experimental trial, one additional simulation was conducted in SimForm, halting the cycle once the plastic part reached a solid wall thickness target deemed to mean the part is safe to eject. SimForm reports the time to reach this target.

Table 6: Simulation 3 – safe ejection time predictions

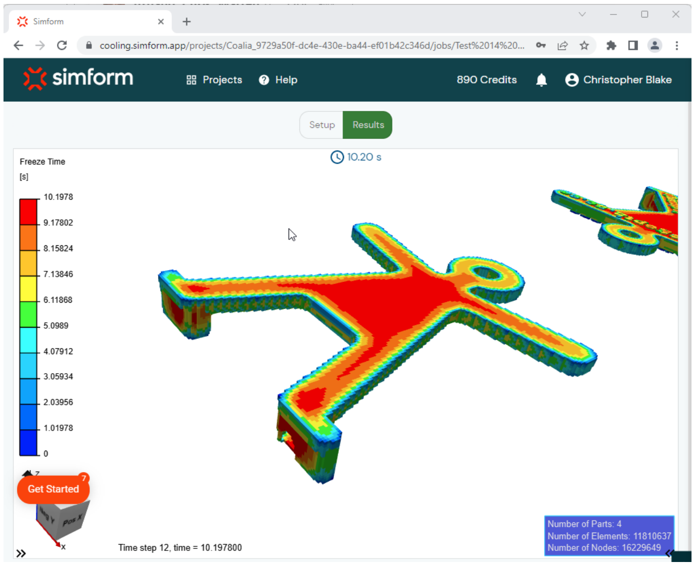
Solid Wall Thickness Target	Safe Ejection Time
20% of part thickness	10.2 seconds

For a solid outer layer of plastic that is 20% of the part thickness, it takes 10.2 seconds of cooling after injection. In SimForm, we can examine the freeze time, which has a similar distribution to Simulation 1.

If we look at a cross section of the temperature, it is interesting to note that the temperature at the centre of the plastic is actually lower than that predicted in Simulation 1.

There are competing forces at play here. The cooling lines are at a higher temperature, and so are slower to solidify the outer layer of plastic, but because the part is in the mold longer, the central temperature of the part is lower at ejection time.

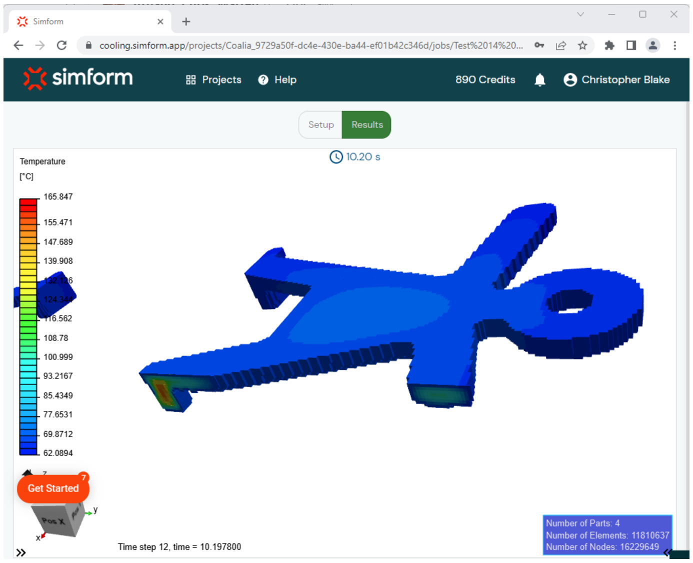
The predicted freeze time for a 20% solid wall is below the fixed pack-hold-cool time of 20.5 seconds set in the experimental trial. However, it was not possible to solidify the part completely within that time, meaning that without a cooling channel re-design, we would require at least the full specified cycle time. By exploring the simulation results in SimForm, a designer can make an informed decision on how to improve the cooling design, and when it is safe to eject the plastic part.



Time step 12, time = 10.197800

Number of Parts: 4
Number of Elements: 11810637
Number of Nodes: 16229649

Fig. 18: Simulation 3 – freeze time plot



Time step 12, time = 10.197800

Number of Parts: 4
Number of Elements: 11810637
Number of Nodes: 16229649

Fig. 19: Cross sectional view of temperature through plastic part

Conclusion

In this article, we compared temperature results from an experimental mold trial with temperature results computed by SimForm. We showed that SimForm's prediction of the temperature history at two sensors mounted within the mold captured the trend observed during the experimental trial. Certain assumptions are made by SimForm:

- The injection of the plastic is not simulated; rather, the plastic is injected "instantaneously"
- The injection and mold opening stages of the cycle are ignored
- There are no air gaps between plastic and metal (the heat transfer is ideal)

Yet, despite these assumptions, SimForm provides realistic and actionable temperature simulation results. SimForm is able to accurately predict the temperature distribution and the temperature values within 2°C of the experimental data measured.

By running a fast front-end simulation with SimForm, we were able to estimate the time to safe ejection, and determine that we could shorten the cycle time chosen in our injection mold machine parameters. By moving the cooling channels and improving the design, we can drive down the cycle time even more and save on the unit cost of the plastic part.

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1. https://www.coalia.ca/en/
2. https://www.arburg.com/media/daten/publications/technical_data/electric_machines/ARBURG_ALLROUNDER_370A_TD_526447_en_GB.pdf
3. https://kistler.cdn.celum.cloud/SAPCommerce_Download_original/000-680e.pdf
4. http://www.uddeholm.gr/Storage/Media/Shared/SteelBrochures/Ramax%20HH/PB_Uddeholm_ramax_hh_english.pdf
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