AUTODESK **UNIVERSITY** 2014

Influence of Material Characterization and Modeling for Improved Pressure Prediction

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SM4977-P

Class Description

This class will show how to use Simulation Moldflow Insight software for modeling the injection molding process in order to provide more accurate predictions of injection pressures during molding. We will explore factors such as material characterization, mesh type, and process settings. We will look at how the measurement of juncture loss coefficients can influence the pressure prediction provided by Simulation Moldflow Insight software for several different materials, both semi-crystalline and amorphous. We will also examine how the incorporation of these coefficients influences the results between different mesh types (Midplane versus Full 3D). Additionally, we will present examples of actual projects where Simulation Moldflow Insight software was used to predict the injection pressure.

Learning Objectives:

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

- Discover the representation of the Cross-WLF coefficients and how they influence pressure predictions
- Understand the influence of juncture loss coefficients
- Discover how juncture loss coefficients influence pressure predictions in different mesh types
- Learn how to improve modeling of runner systems for more accurate pressure predictions

About the Speaker

Erik Foltz is a senior managing engineer at The Madison Group. Erik received his MS in mechanical engineering from the Polymer Engineering Center at the University of Wisconsin-Madison in 2008. As an Autodesk Certified Professional Simulation Moldflow consultant, Erik assists industrial clients to accelerate the product design process through the use of structural finite element analysis (FEA) and Simulation Moldflow Insight software. Through his analysis he helps to see that parts are durable and manufacturable. Erik has spoken at many venues in regards to the use of injection molding simulation, including as an instructor for University of Wisconsin-Milwaukee's Plastics Failure Analysis course. He is an active member of the Society of Plastic Engineers, where he serves as a board member on the Injection Molding Division, and has presented at the Annual Technical Conference (ANTEC). *erik@madisongroup.com*

Cross-WLF Viscosity Model

Injection molding simulation has become a prevalent tool for designers and engineers to evaluate their plastic part design. One of the most common objectives of injection molding simulation is determining the pressure requirement to manufacture the part for a given resin and set of process parameters. The reliability of pressure prediction is dependent on accurately modeling and predicting the material viscosity during this dynamic process. Autodesk Moldflow Insight uses the Cross-WLF equation to model this material property (Eq 1). This equation allows the viscosity of the melt to be described as a function of melt temperature, T, shear rate, $\dot{\gamma}$, and melt pressure, p.

$$\eta(T,\dot{\gamma},p) = \frac{\eta_0}{1+\left(\frac{\eta_0}{\tau^*}\right)^{1-n}} \quad \text{Eq. 1}$$

Where:

- η is the melt viscosity, with units of (Pa·s)
- η_0 is the zero shear viscosity, where the viscosity plateaus and appears to approach a constant at low shear rates.
- $\dot{\gamma}$ is the shear rate (s^{-1})
- τ^* is the critical shear stress at which the polymer starts to exhibit shear thinning behavior
- n is the power law index in the high shear rate regime

The zero shear viscosity, η_0, is described through a WLF representation (Eq. 2). This representation highlights that the zero shear viscosity is a function of both temperature and pressure. The coefficients in Equations 2-4 are all data-fitted from rheological measurements. The only coefficient in these equations that has a physical meaning is D_3, which represents the linear pressure dependence of T* of the resin.

$$\eta_0(T,p) = D_1 exp\left[-\frac{A_1(T-T^*)}{A_2+(T-T^*)}\right] \quad \text{Eq. 2}$$

$$T^* = D_2 + D_3 p$$

$$A_2 = \bar{A}_2 + D_3 p$$

The Cross-WLF relationship is commonly plotted on a log-log plot of shear rate vs. viscosity, Figure 1. Using this model is a much better representation of the material viscosity during processing as compared to melt flow rate testing, which is done as relatively low shear rates.

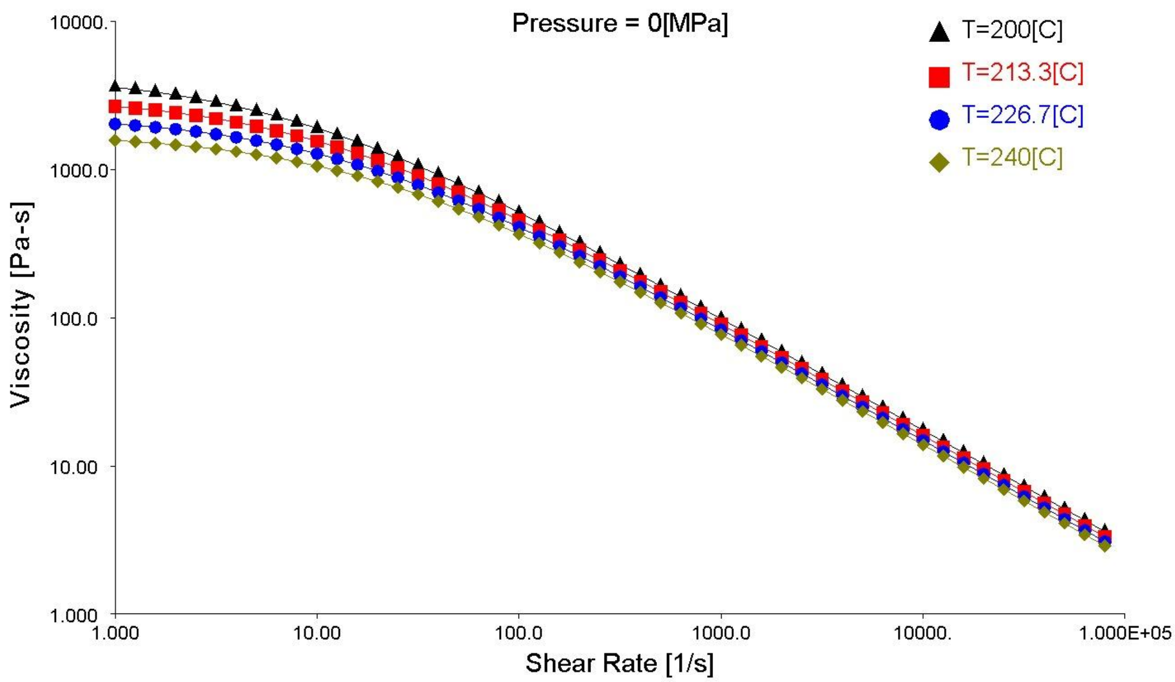


Figure 1 – Plot showing a typical rheological curve when viscosity data is fit to the Cross-WLF equation.

However, the Cross-WLF equation is often simplified by not accounting for the pressure dependence of the resin viscosity. This is commonly done due to the fact that obtaining this data can be difficult, and there are few suppliers who can do it. Autodesk Moldflow Plastics Labs does have the capability of collecting this data and fitting the Cross-WLF equation. Previous publications[i] have shown that pressure dependent data becomes important when one or more of the following conditions exist:

- Flow length to thickness ratios are greater than 100
- Part wall thickness is less than 2 mm
- Injection pressures are greater than 100-150 MPa

Additionally, some resins, like polycarbonate, exhibit a strong pressure dependence on the viscosity of the material. If you are dealing with one of these geometric conditions, or have a material that exhibits strong pressure dependence of viscosity, then it may be worth it to have the resin characterized to account for this factor.

Juncture Loss Coefficients and Extensional Viscosity Model

The Cross-WLF model does a good job of describing the viscosity of the molten resin in shear flows. Shear flow is the dominate flow found in injection-molding cavities, where the wall thickness is in general thin and of constant cross section. However, the feed system, which conveys the plastic from the injection unit into the cavities does not include these geometric attributes. In general, the feed system consists of many geometric transitions, where the molten polymer experiences an elongational (stretching) flow as it passes from a large cross-sectional area to a small cross-sectional area. The work done on the polymer melt at these transitions results in an additional pressure drop. This is particularly prevalent at the machine nozzle, and at the gate(s). In order to account for this additional pressure drop, additional material models have been developed.

Juncture Loss Model (Bagley Correction)[ii]

One of the models used to help account for the additional pressure loss due to contraction in the flow path is the Juncture Loss Model. This model is used with the midplane, Dual Domain solvers. It is also used in a Full 3D analysis where the runner system is modeled with beam elements. This model is typically derived from performing a series of rheological studies using a capillary rheometer, where the L/D ratio of the die is varied. The direct pressure measurement, ΔP_m, from the rheometer is a combination of the pressure loss through the die, the entrance junction, and the exit junction, Eq 3.

$$\Delta P_m = \Delta P_e + \Delta P_d + \Delta P_{ex} \qquad \text{Eq. 3}$$

Where:

- ΔP_m is measured pressure loss
- ΔP_e is pressure loss at the entrance junction
- ΔP_d is pressure loss through the die
- ΔP_{ex} is pressure loss at the exit junction

Additional pressure losses, ΔP, are accounted for by relating the wall shear stress to pressure drop:

$$\Delta P = \Delta P_e + 4\frac{L}{D}\tau_w \qquad \text{Eq. 4}$$

Where:

- L is the length of the die
- D is the diameter of the entrance junction

By plotting the extra pressure loss versus the wall shear stress in the capillary, a single master curve can be generated for a given grade of material for various temperature and shear rates. Munstedt developed the Juncture Loss Model used within Autodesk Simulation Moldflow, Eq 5.

$$\Delta P_e = C_1 {\tau_w}^{C_2} \qquad \text{Eq. 5}$$

C_1 and C_2 are often referred to as the Bagley correction constants, or as the juncture loss coefficients. These coefficients are fit in conjunction with the coefficients of the WLF equation coefficients to the capillary data through an optimization procedure of a finite difference simulation. The coefficients are set when the root mean square deviation between the predicted and measured pressure drop is minimized.

Extension Viscosity

While the juncture loss model is useful for characterizing the elongation viscosity of the polymer melt in the feed system when the runner systems is modeled with beams, it is not incorporated into the solver when the feed system is modeled with tetrahedral elements. The additional pressure drop can still be accounted for in the full 3D solver if the extension viscosity model is characterized, and activated in the material data file. (Figure X shows the where the extension viscosity model can be selected on the rheology tab of the material database.)

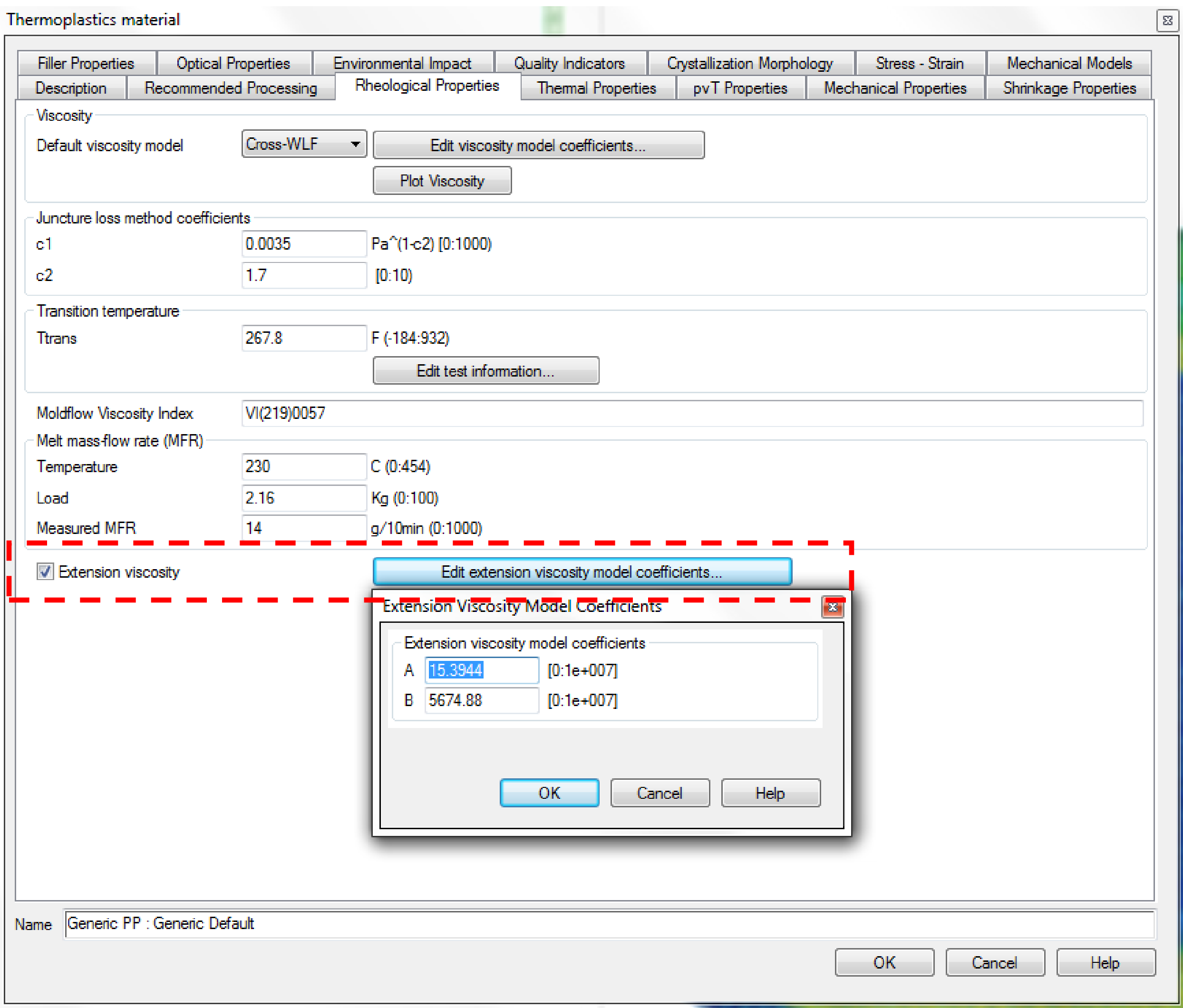


Figure 2 – Image showing the location of the extension viscosity model selection for use with Full 3D analysis.

Like the juncture loss model, the extension viscosity model works in conjunction with the Cross-WLF equation as shown in Equations 6-7. The shear viscosity, η_s , is calculated from the Cross-WLF equation, and the extension viscosity model scales the shear viscosity to account for the strength of the extension flow.

$$\overline{\eta}(T, p, \dot{\gamma}, \dot{\varepsilon}) = f(\dot{\varepsilon})\eta_s(T, p, \dot{\gamma}) \quad \text{Eq. 6}$$

$$f(\dot{\varepsilon}) = 1 + \frac{A\dot{\varepsilon}}{B + \dot{\varepsilon}} \quad \text{Eq. 7}$$

Where:

- $\overline{\eta}$ is the unified viscosity (Pa-sec)
- η_s is the shear viscosity (Pa –sec)
- $\dot{\varepsilon}$ is the extension rate (sec^{-1})

A and **B** are data-fitted coefficients from the capillary studies performed. **A** represents the importance of the extension stresses, and is unitless. **B** represents the extension rate of the transition to strong extension stresses, and is also unitless. These coefficients are fit using the same data that was collected for the juncture loss model. Therefore, no additional testing needs to be performed to obtain this data.

Comparisons of Different Viscosity Models to Experimental Results

A correlation study was performed to evaluate the importance of the different material characterization levels on the predicted injection pressure required to fill a plaque mold. The resin selected for the study was Moplen EP301K, a medium flow impact copolymer polypropylene resin. The study varied the characterization level of the rheological data to see how the incorporation of pressure effect, D3, and the inclusion of extensional viscosity models, Juncture Loss Model or Extension Viscosity, influenced the predicted injection pressures for the simulations across different mesh types.

The mold used for this study consisted of a cold runner system feeding a tunnel gate, which produced a 150 mm X 75 mm X 3 mm plaque. There were a total of six different pressure sensors located within the mold, which allowed the pressure to be monitored through each of the molding cycles, Figure 3. There was one sensor at the machine nozzle, two within the runner system, and three within the cavity. The mold was selected due to the restrictive gate design of the gate, which should highlight the importance of the extensional viscosity models integrated into Autodesk Simulation Moldflow.

While the mesh type was varied across the simulations, the entire mold design was modeled for all iterations. The machine nozzle and cooling line layout was incorporated into the studies, Figure 4. A Cool+Fill+Pack analysis was performed for each study.

The physical experimental data on injection pressure was collected by performing several molding trials that varied the melt temperature, mold temperature, and set flow rate. One run out of each molding parameter was selected to be replicated, and those process settings are highlighted in Table 1. All molding trials were performed using an Arburg All-rounder 520 Selogica with a 40 mm barrel.

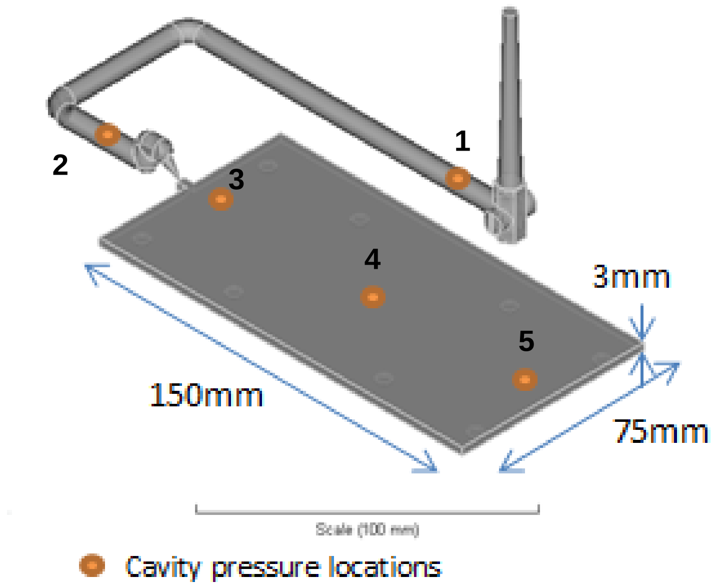


Figure 3 – Schematic showing the location of the pressure sensors within the plaque mold.

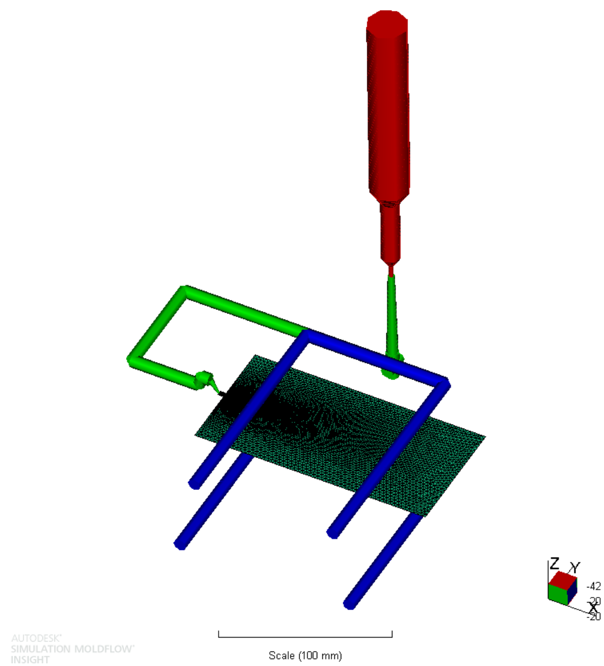


Figure 4 – A representation of the midplane model used for the analysis, which modeled the entire mold design including the machine nozzle (red) and cooling circuits (blue).

Table 1: Process Parameters Used In Correlation Study

Cycle	Melt Temperature	Mold Temperature	Flow Rate
105	**230 °C**	**40 °C**	**40 cm^3/sec**
237	**230 °C**	**40 °C**	**80 cm^3/sec**
385	**230 °C**	**60 °C**	**40 cm^3/sec**
570	**200 °C**	**60 °C**	**40 cm^3/sec**

Midplane

Reviewing the results of the midplane analyses show that the injection pressure prediction is greatly improved when the juncture loss model is incorporated into the simulation. Most of the simulated cycles showed very good correlation with the measured data. Without accounting for the juncture losses the injection pressure is severely under predicted. However, Cycle 570 was under predicted in all instances, with the model simulating the pressure dependent viscosity still exhibiting a 25% error in the injection pressure prediction. From the three accurate simulations, it appears that the juncture loss coefficients had a more significant impact on increasing the injection pressure than the pressure dependent viscosity. However, this is not unexpected since the pressures remained low, and polypropylene is typically not a pressure sensitive material.

Cycle 105

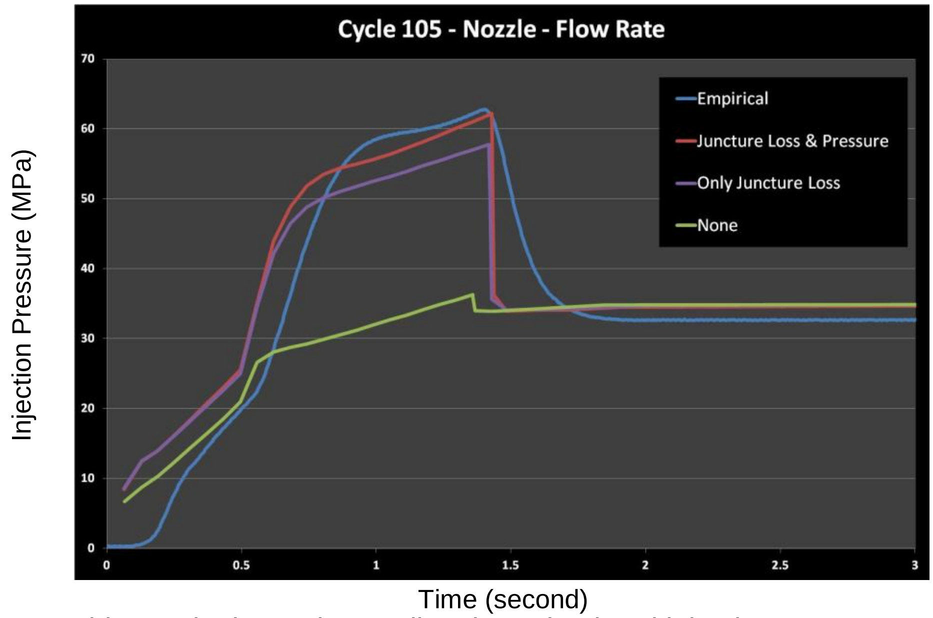


Figure 5 – This graph shows the predicted vs. simulated injection pressure profile for the different material characterization levels of the resin for the Midplane solver of cycle 105.

Cycle 237

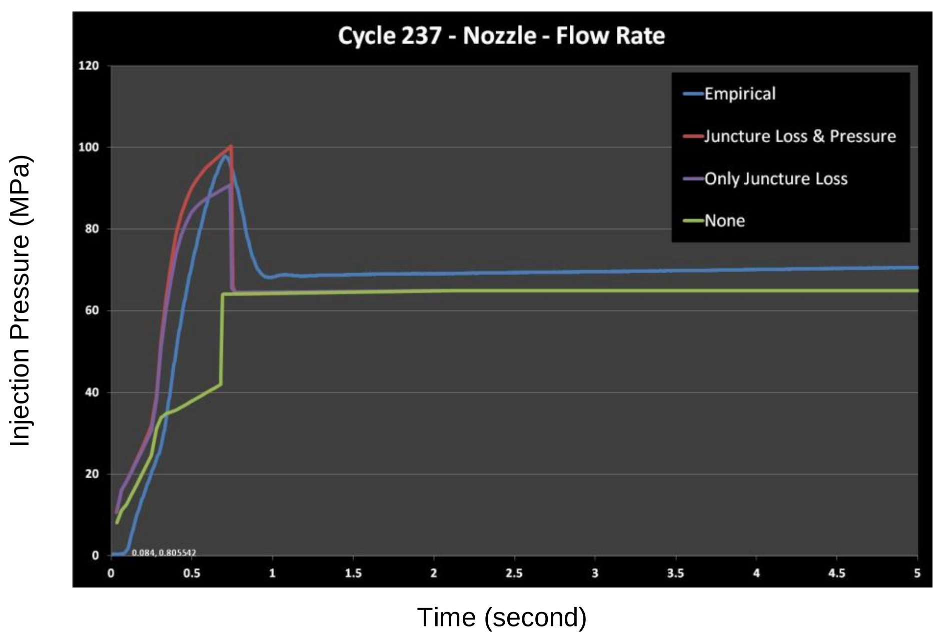


Figure 6– This graph shows the predicted vs. simulated injection pressure profile for the different material characterization levels of the resin for the Midplane solver of cycle 237.

Cycle 385

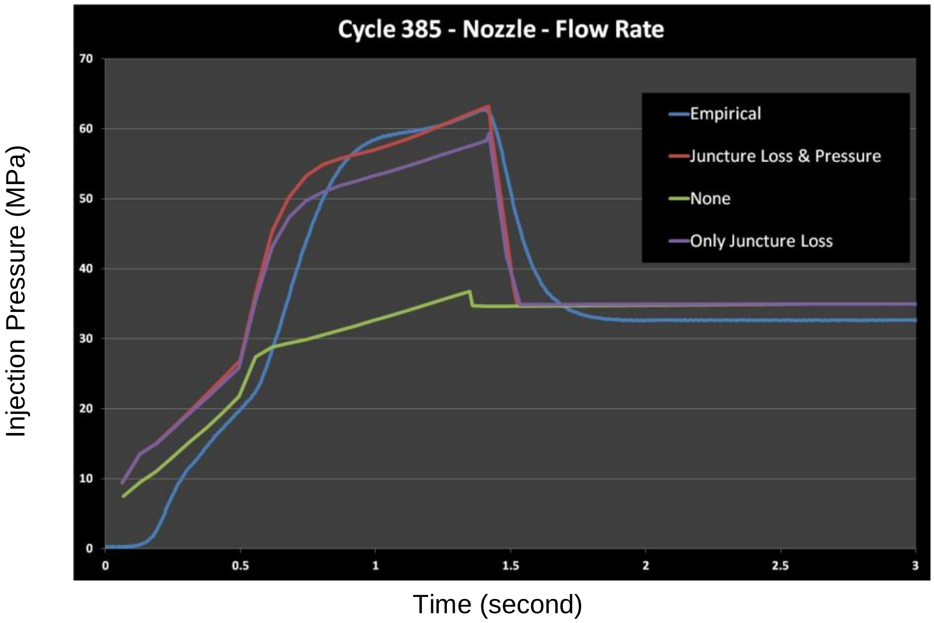


Figure 7– This graph shows the predicted vs. simulated injection pressure profile for the different material characterization levels of the resin for the Midplane solver of cycle 385.

Cycle 570

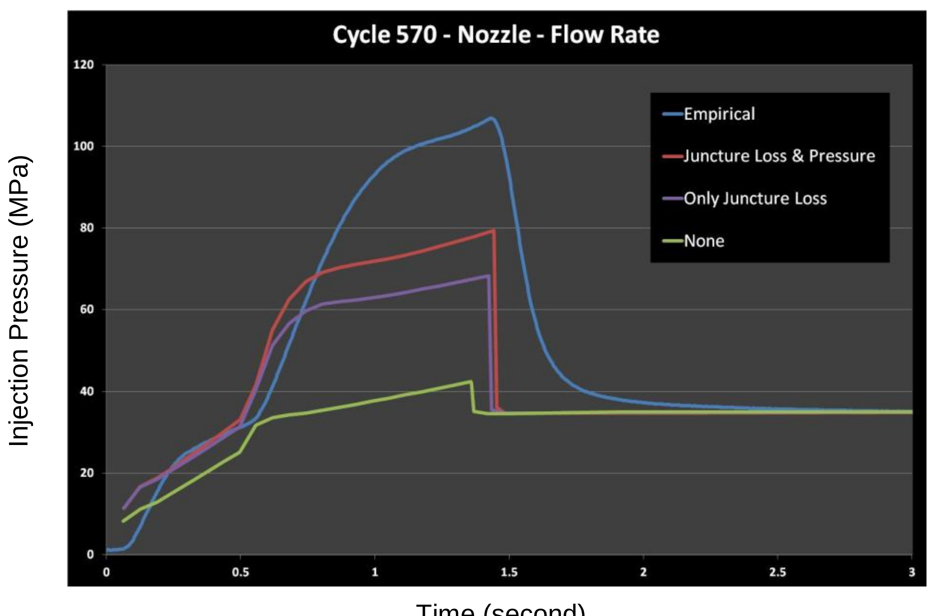


Figure 8– This graph shows the predicted vs. simulated injection pressure profile for the different material characterization levels of the resin for the Midplane solver of cycle 570.

3D

The analyses that evaluated modeling both the runners and the cavity with tetrahedral meshes revealed that the pressure was in general under predicted. Except for Cycles 105 and 385, which essentially had the same process parameters, the other pressures were under predicted. The incorporation of the extension effects did improve the pressure prediction but in general remained very low. The mesh refinement was increased, but did not appear to make a significant difference. The full 3D solver appears to be more sensitive to the changes in the injection rate or in the temperature as compared to the midplane solver.

Cycle 105

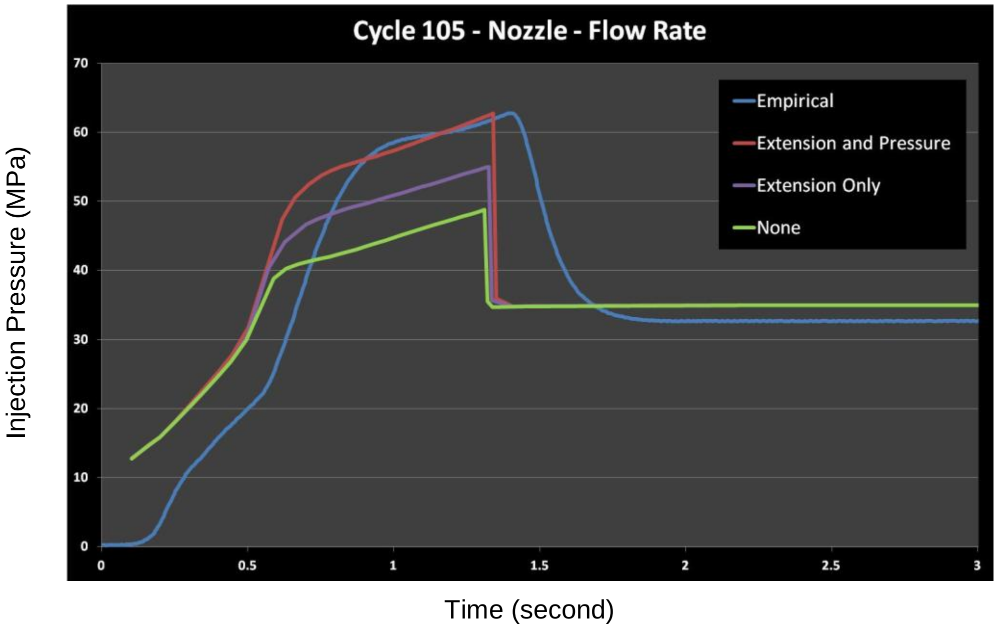


Figure 9– This graph shows the predicted vs. simulated injection pressure profile for the different material characterization levels of the resin for the Full 3D solver of cycle 105.

Cycle 237

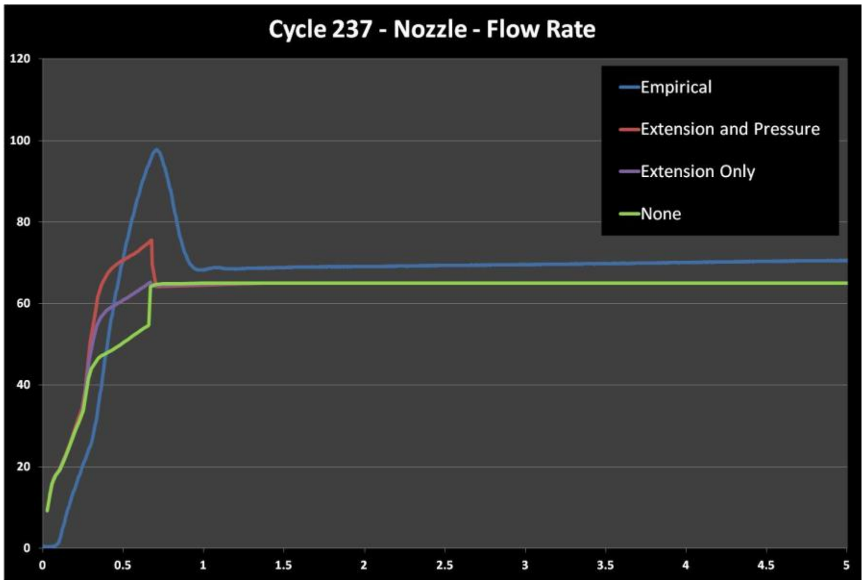


Figure 10– This graph shows the predicted vs. simulated injection pressure profile for the different material characterization levels of the resin for the Full 3D solver of cycle 237.

Cycle 385

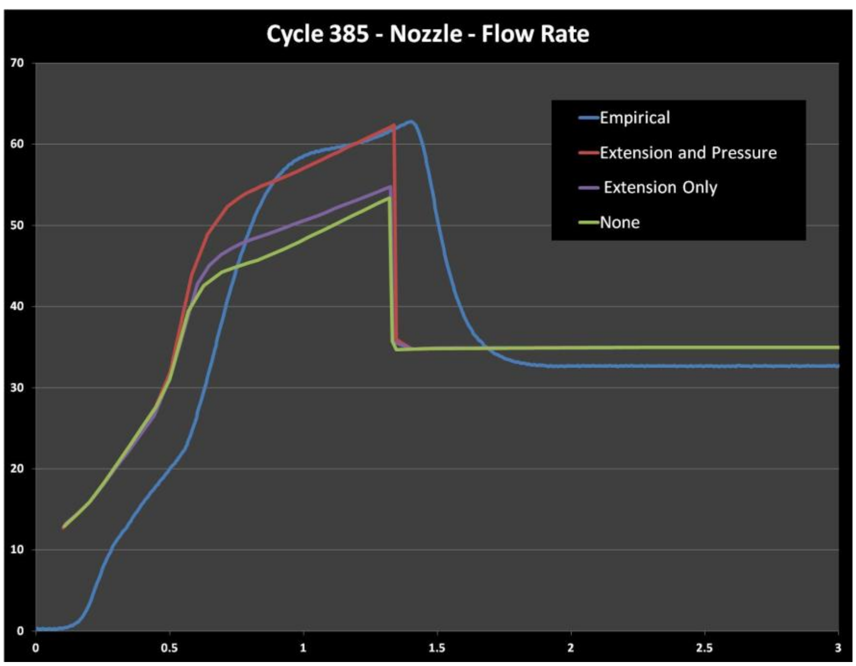


Figure 11– This graph shows the predicted vs. simulated injection pressure profile for the different material characterization levels of the resin for the Full 3D solver of cycle 385.

Cycle 570

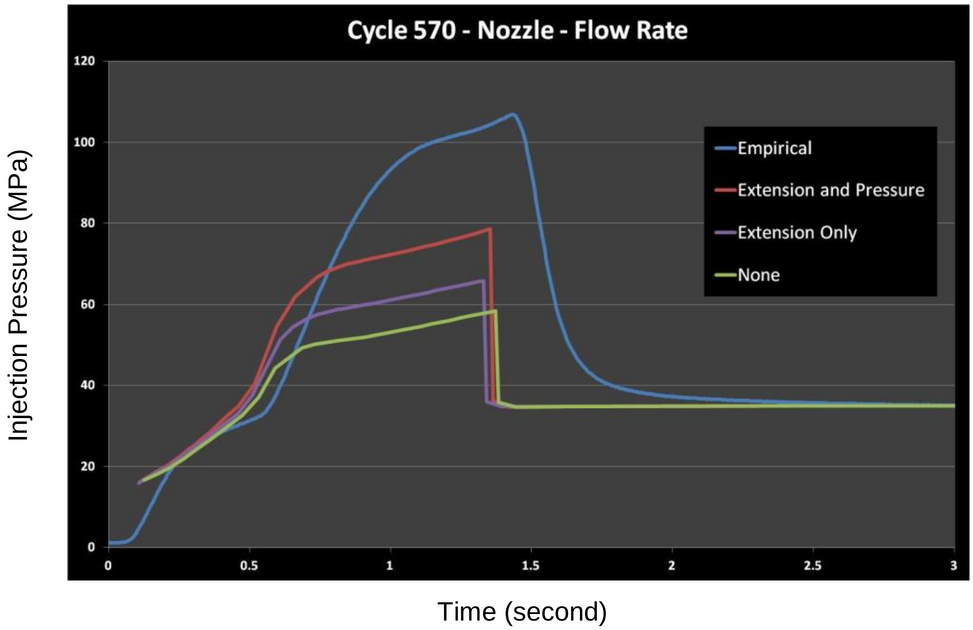
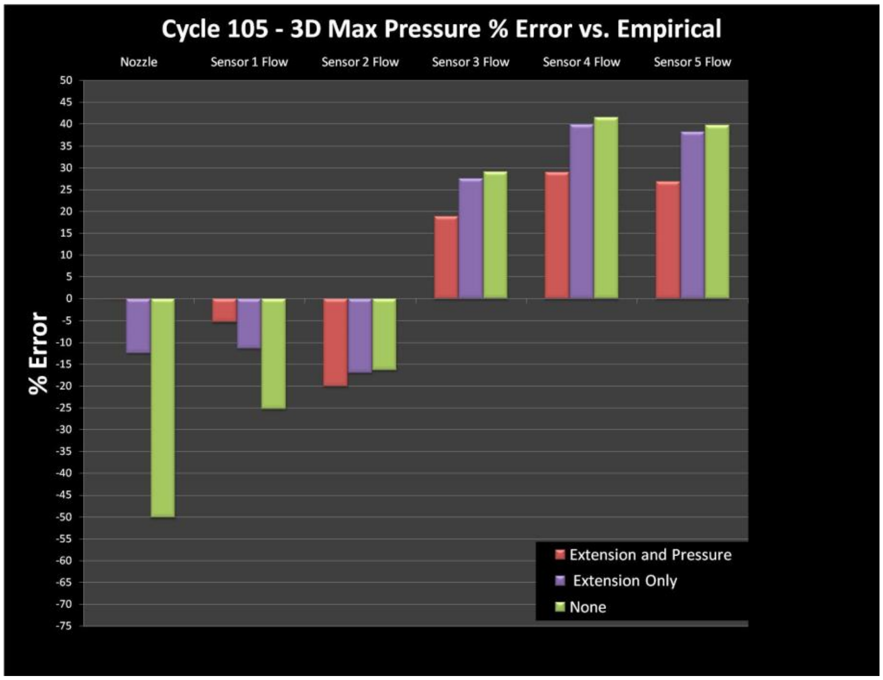


Figure 12– This graph shows the predicted vs. simulated injection pressure profile for the different material characterization levels of the resin for the Full 3D solver of cycle 570.

Runner Pressure Drop Comparison

The final section of this paper attempts to look at how the modeling of the runner system influences the predicted injection pressure. The focus at this point will be on whether modeling the runner system in Full 3D or with beams with the Full 3D solver influenced the overall pressure decay through the feed system. To examine this the difference between the maximum predicted injection pressure at each of the sensors was compared. Since only Cycle 105 and Cycle 385 produced reliable results, they are the only cycles examined. These cycles are essentially the same except for the mold temperature. Therefore, it becomes difficult to draw many conclusions. However, examining the overall trends suggests that modeling the feed system with beam elements better represents the pressure decay through the feed system. Additionally, modeling the feed system with beams provides a slightly better pressure prediction after the gate in the cavity (Sensor 3).

Cycle 105



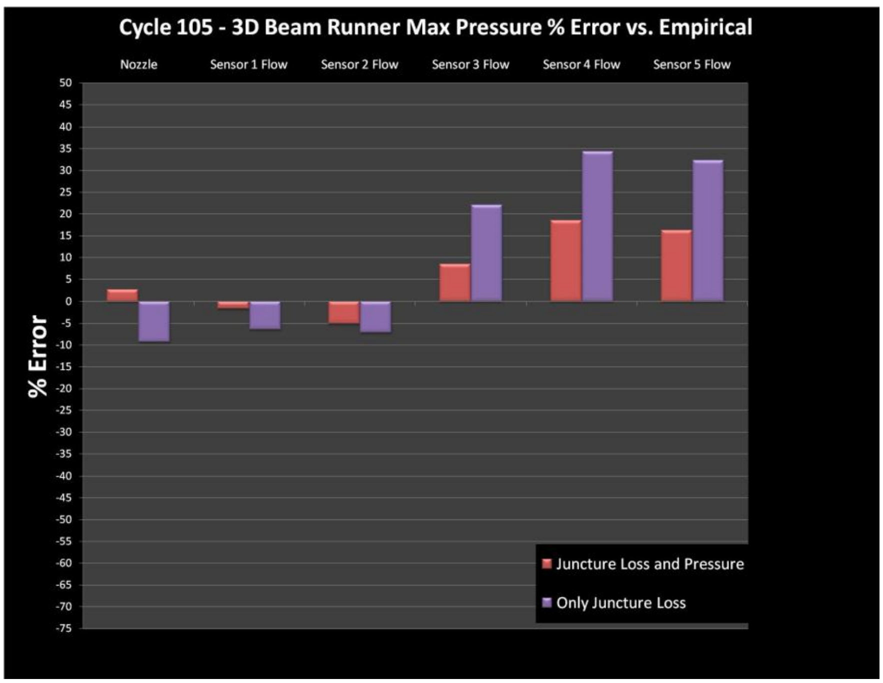
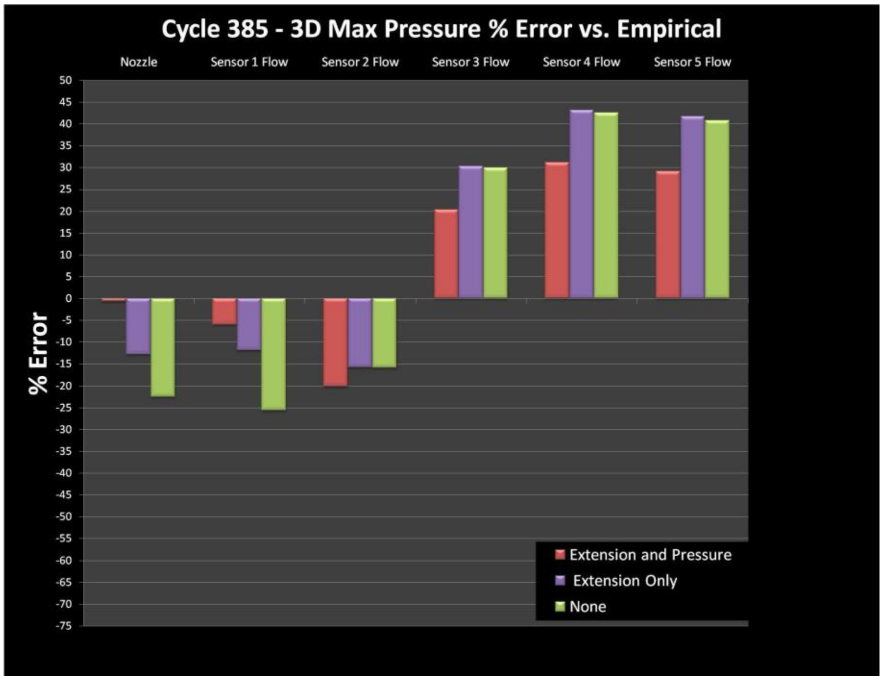


Figure 13 – These graphs highlight that modeling the feed system with beams in a full 3D analysis (bottom graph) can help improve the pressure drop through the feed system and in the cavity

Cycle 385



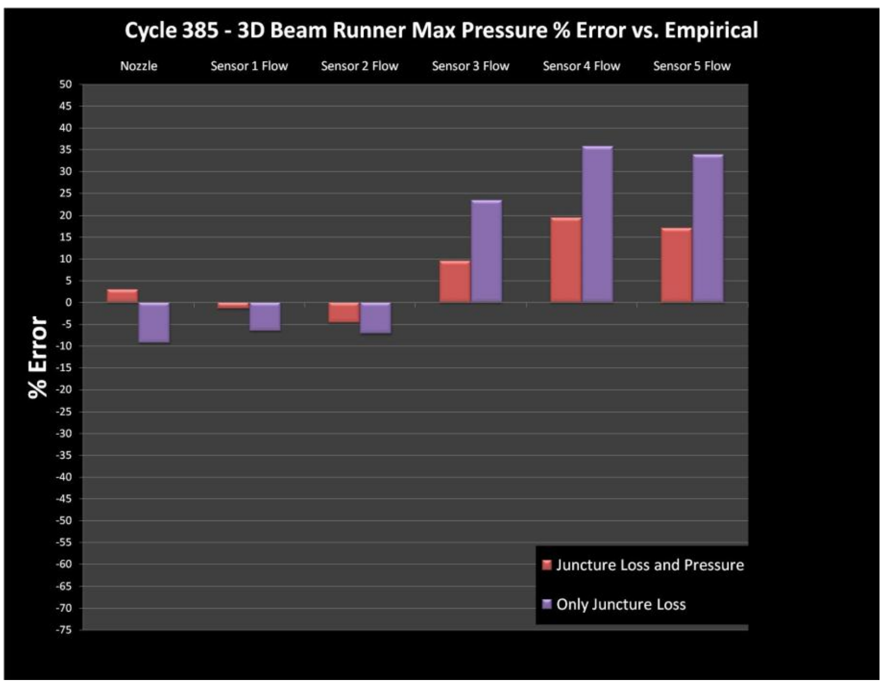


Figure 14 – These graphs highlight that modeling the feed system with beams in a full 3D analysis (bottom graph) can help improve the pressure drop through the feed system and in the cavity.

Conclusions

After reviewing the results of this correlation study, it is clear that accounting for both the elongation flow and shear flow behavior of the resin can help improve the accuracy of the maximum injection pressure required to fill the mold. The midplane models still appear to exhibit some sensitivity to temperature, but consistently provided more reliable injection pressure predictions than the full 3D solver. The full 3D models appear to exhibit sensitivity for both temperature and variation in injection rates. However, including the pressure dependence and extension viscosity model did improve the injection pressure prediction for all cases analyzed. When full 3D analysis is used, it appears that modeling the feed system with beams rather than with tetrahedral elements could provide a more accurate pressure drop through the feed system. Although this last claim is only loosely supported by the comparison between these studies since the two studies that provided reliable injection pressure predictions only varied the mold temperature.

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[i] Mahishi, M., ANTEC Proceedings 1998, *"Material Characterization for Thin Wall Molding Simulation"*
[ii] Autodesk Moldflow Insight 2015 Online Help Section