MELT MEMORY AND CORE DEFLECTION

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Abstract

When injection molding long slender hollow parts with closed ends, like test tubes, an unevenly advancing melt front around the cores results in core deflection, a pervasive problem especially when the parts are thin-walled. Accurately predicting core deflection problems is accomplished by considering the distributed load on the core caused by the normal stress distribution acting on the cores. In this paper, the effect of fluid elasticity on core deflection is explored by incorporating melt memory into the prediction of core deflection using the upper convected Maxwell model. The Deborah number is then used to represent the dimensionless amount of elasticity. We find that melt memory significantly worsens core deflection, and we provide a chart to help practitioners predict this.

Introduction

In the manufacture of long slender hollow parts with one closed end, the melt front advances unevenly around a cantilevered slender core, causing core deflection. Where this deflection causes the core to touch the cavity wall, the part can even perforate. To prevent this, mold designers are thus interested in estimating the maximum core deflection. In our previous study [1], an effective 3D numerical approach is developed to discuss the relation between volumetric flow rate of a Newtonian melt and core deflection, and the simulation agreed closely with a recent analytical solution (Giacomin and Hade, 2005) [2], especially at low flow rate, where core deflection varies linearly with the injection flow rate.

However, a number of important effects in the flow of polymeric liquids, such as rod-climbing, extrudate swell (also called die swell), tubeless siphon, and elastic recoil, demonstrate the effects of melt elasticity and specifically, of the normal stress differences in polymeric liquids [3]. One such significant normal stress effect is that polymeric fluids exhibit an extra tension along streamlines in addition to the shear stresses. This extra tension arises from the stretching and alignment of the polymer molecules along the streamlines. Their thermal motion makes the molecules tend to recoil to their equilibrium configurations, thus the extra tension. This tendency for polymer molecules to snap back like “rubber bands” demonstrates fluid memory, a manifestation of polymeric fluid elasticity.

Therefore, the effect of fluid elasticity on core deflection is to our interest. Since the amount of normal stress difference can be used to measure the elasticity in the fluid, it is suggested that melt memory arises an extra tension along the core owing to a nonzero normal stress difference, and that this may worsen core deflection. In this paper, a dimensionless group Deborah number, interpreted as the ratio of the magnitude of the elastic forces to that of the viscous forces, is adopted to determine the fluid elasticity.

Accurately predicting core deflection problems is accomplished by considering the distributed load on the core caused by the normal stress distribution acting on the cores. Here we explore the effect of fluid elasticity on core deflection by incorporating melt memory into the prediction of core deflection, to see how melt memory may affect core deflection. We then provide a chart to help practitioners predict this.

Conventional 2.5D CAE molding analysis adopts the mid-plane model, replacing the flow geometry with analysis along its mid-plane. This technology is now mature, computationally efficient and accurate, especially for thin-walled plastic parts. However, for the more complicated problem of core deflection, we prefer to depart from the mid-plane model. Here, we develop a 3-dimensional numerical approach to simulate the uneven flow and pressure around core components during mold filling and we further predict the corresponding core deflection.

Theory

Analytical Solution[2]:

Fig. 1 illustrates a cantilevered core of constant rectangular cross-section. We restrict our analytical solution to the Newtonian fluid, conservatively neglecting its solidification. Accordingly, we consider the mold filling very unevenly, with the polymer flowing down just one side of the mold. Giacomin and Hade studied this problem analytically and discovered that core deflection is governed by the dimensionless volumetric flow rate Q which they called *core deflectability*. The dimensionless core deflection Y and Q are related by:

$$\frac{d^5Y}{dX^5} = \frac{-12Q}{(1+Y)^3} \qquad (1)$$

where:

$$Q \equiv \frac{\mu QL}{EI}\left(\frac{L}{B_0}\right)^4 \qquad (2)$$

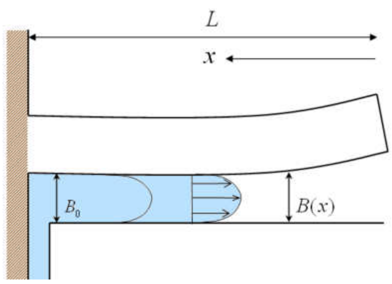
and where μ is Newtonian viscosity, Q is volumetric flow rate, L is core length, EI is the core stiffness, and B_0 is the gap between the mold wall and the core base.

Dimensionless core deflection is defined by:

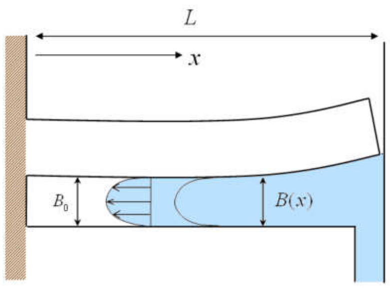
$$Y \equiv \frac{y}{B_0} \qquad (3)$$

where y is core deflection, and the dimensionless axial position along the core, X, is defined by

$$X \equiv \frac{x}{L} \qquad (4)$$



(a) Base-gated core



(b) Tip-gated core

Figure 1 – Base-gated (a) and tip-gated (b) core deflection models

Three-Dimensional Numerical Approach:

In this study, the melt flow pressure during filling is predicted by the following numerical solution. The governing equations to simulate transient, non-isothermal 3D flow are:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0\,, \qquad (5)$$

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{uu} - \boldsymbol{\sigma}) = \rho \mathbf{g}\,, \qquad (6)$$

$$\boldsymbol{\sigma} = -p\mathbf{I} + \tau \qquad (7)$$

$$\rho C_P\left(\frac{\partial T}{\partial t} + \mathbf{u}\cdot\nabla T\right) = \nabla(k\nabla T) + \frac{1}{2}\tau : (\nabla \mathbf{u} + \nabla \mathbf{u}^T), \qquad (8)$$

where $\mathbf{u}$ is the velocity vector, T is temperature, t is time, p is pressure, σ is the total stress tensor, ρ is the fluid density, τ is the extra-stress tensor, k, the thermal conductivity, and C_p, the specific heat. In the present work, τ is obtained by the constitutive equation of upper convected Maxwell model (UCM model):

$$\tau + \lambda \overset{\nabla}{\tau} = \mu(\nabla \mathbf{u} + \nabla \mathbf{u}^T) \qquad (9)$$

$$\lambda = \frac{\mu}{G} \qquad (10)$$

where λ is the relaxation time, $\overset{\nabla}{\tau}$ is the upper convected time derivative of τ, and G is the elastic modulus.

The Deborah number is a dimensionless measure of the amount of elasticity. It is the ratio of the fluid relaxation time, λ, to the characteristic process time (here, the filling time), t_p:

$$D_e = \frac{\lambda}{t_p} = \frac{\lambda Q}{B_0 L W} \qquad (11)$$

where W is the core width.

The melt pressure p during filling is governed by Eq. (7). Moreover, it exerts a net upward force on the core surface. Hence the core deflection can be obtained from the force balance:

$$\nabla \sigma + F = 0 \qquad (12)$$

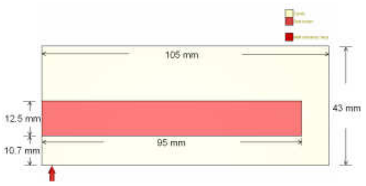
where σ is the stress and F is the body force from melt pressure.

The collocated cell-centered FVM (Finite Volume Method)-based 3D numerical approach developed in our previous work is applied in this paper [4,5]. The numerical method is basically a SIMPLE-like FVM with improved numerical stability. Furthermore, the volume-tracking method based on a fixed framework is incorporated in the flow solver to track the evolving melt front during molding.

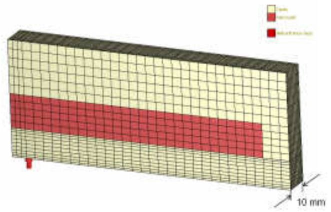
Results and Discussions

In our previous work, the simulated core deflection has been validated by an analytical solution proposed by Giacomin and Hade for a Newtonian melt. Likewise, since the analytical solution employs several assumptions, we simplify our 3-dimensional simulation accordingly, first by adopting a symmetric pressure distribution along thickness direction during filling. We then restrict our analysis to a temperature-independent Newtonian melt. Since polymer flowing down just one side of the core was considered in the analytical solution, we use the stress loading when the mold fills with the polymer just flowing beneath the slender core for our stress analysis. Since solidification was neglected in the analytical solution, we output the simulation results of filling analysis to the sequential stress solver. Eq. (8) incorporates heat transfer between the hot melt and the cold mold (including the cold core), whereas the analytical solution is for the much simpler isothermal problem. Finally, whereas Eq. (8) accounts for viscous heating, the analytical solution to which our results are compared does not.

Fig. 1 illustrates our 3-dimensional model whose specific dimensions are chosen arbitrarily (see Fig. 2 (a) and (b)) for comparison with a dimensionless analytical solution for core deflection. Table 1 lists the core material, its elastic modulus and its moment, along with the molding conditions. We use these data as the simulation conditions for filling and core deflection analysis, and then vary the filling time to explore different flow rates.



(a) Part shape and thickness



(b) Solid mesh of cavity and slender core

Figure 2 – Model geometry: (a) Part shape and thickness (b) Solid mesh of cavity and slender core

Table 1 – Polymer, core properties and molding conditions

Molding Conditions	
Polymer	ABS STYLAC VA29
Core Material	Copper
Melt Temperature	225℃
Mold Temperature	60℃
Core Elastic Modulus	1.15×10^{12} dyne/cm^2
Core Moment of Inertia	0.16276 cm^4

Since the effect of fluid elasticity on core deflection is our main concern in this study, the Deborah number, De, is incorporated in our prediction of core deflection. By increasing De, which means lengthening the relaxation time for a specific filling time, more elasticity is obtained. Therefore, we adopt De = 1, 10, 100 as the index of fluid elasticity, and De = 0 denotes no fluid elasticity. Since elasticity was not considered in our previous simulation, the predicted core deflection can be regarded as the results of De = 0.

From Eq. (10), we can see that increasing elastic modulus G for a specific viscosity decreases the relaxation time. This thus affects the amount of calculated flow-induced residual stress τ in Eq. (9), and then contributes to total stress σ exerted on the core according to Eq. (7). After the model constants and the mechanical properties of the core are fixed, we can then select G to fix De and then sweep through a set of interesting core deflectabilities, see Table 2.

Table 2 – Computational Domain

Core Deflectability (Ω)	Deborah Number (De)	Elastic Modulus (G: dyne/cm^2)
0.0001	1	9.54E+00
	10	9.54E-01
	100	9.54E-02
0.001	1	9.54E+01
	10	9.54E+00
	100	9.54E-01
0.01	1	9.54E+02
	10	9.54E+01
	100	9.54E+00
0.1	1	9.54E+03
	10	9.54E+02
	100	9.54E+01
1	1	9.54E+04
	10	9.54E+03
	100	9.54E+02
10	1	9.54E+05
	10	9.54E+04
	100	9.54E+03
100	1	9.54E+06
	10	9.54E+05
	100	9.54E+04

The finite De results in flow-induced residual stress contributing to total stress σ exerted on the core.

Consequently, normal stress effects can be explored in core deflection. In our flow system, we call the polymer flow direction beneath the deflecting core the "*x*" direction (see Fig. 1); the direction normal to the surface of the deflecting core the "*y*" direction; and remaining neutral direction the "*z*" direction. $\tau_{xx} - \tau_{yy}$ is thus the first normal stress difference N_1, and $\tau_{yy} - \tau_{zz}$ is the second, N_2. For a shear flow and UCM model, $|N_2|$ is much smaller than $|N_1|$, therefore, only N_1 is considered in the total stress exerted on the core in our calculation. As the polymer filling just one side of the mold reaches the end of the slender core, the pressure loading on the core exerted by this fluid plus N_1 is output as the boundary condition for the subsequent stress analysis.

Here we consider the two most common cantilevered core conditions. Case 1 is with a free core tip, gated near this tip. Case 2 is also with a free core tip, but gated near its base. Were these cores undeflected, for both Cases 1 and 2, the stress loadings on the slender cores would mirror one another. Thus, to approach the analytical solution, we use the two constraints shown in Fig. 3 to simulate Cases 1 and 2 in the stress analyses. After these stress analyses complete, the maximum core deflection arising at the core's free end is obtained for each different flow rate.

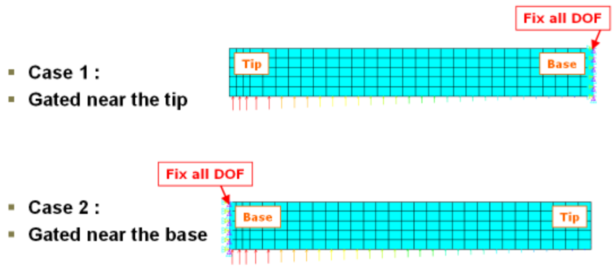


Figure 3 – Settings of fixed boundary condition and stress loading on undeflected cores in Cases 1 and 2

Fig. 4 summarizes our previous work, comparing core deflection between the simulation and the analytical results where De = 0, and shows that these agree closely in the linear regimes, where $Q \leq 0.1$. In this study, melt memory is incorporated into the prediction of core deflection, and the predicted core deflection for both core base and tip gating, for De = 1, 10, 100, are listed in Table 3. Comparing these to results in Fig. 4 and plotting in Fig. 5 and Fig. 6 respectively for case base and tip gating yields the main results of this paper. We can see that the core deflection increases with increasing De for fixed core deflectability both from Fig. 5 and 6, demonstrating that melt memory significantly worsens core deflection. The effect of fluid elasticity on core deflection amplifies with increasing Q. This is because at low shear rate, N_1 is proportional to shear rate squared, thus there is hardly any normal stress difference effect on core deflection at very low Q. With the increase of Q, implying increasing shear rate during filling, the melt memory effect emerges with a remarkable increase in core deflection. By using Fig. 5 and 6, practitioners can estimate core deflection according to their specific Q and De.

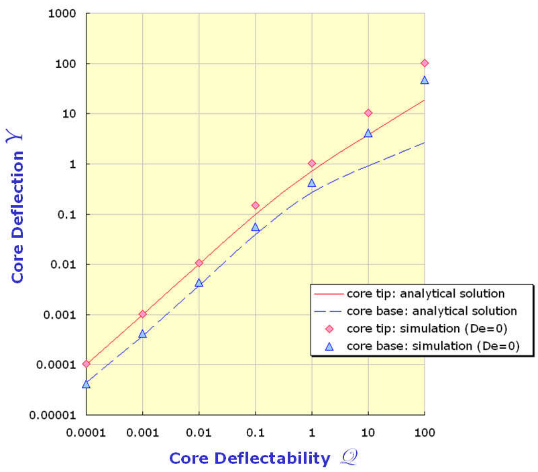


Figure 4 – Comparison of core deflection between numerical simulation and analytical solution when De = 0

Table 3 – Predicted core deflection of core base and tip gating for De = 0, 1, 10, 100

Core Deflectability (Q)	De	Y (Core base)	Y (Core tip)
0.0001	0	3.913E-05	9.645E-05
	1	4.935E-05	1.117E-04
	10	4.935E-05	1.117E-04
	100	4.505E-05	1.087E-04
0.001	0	3.934E-04	9.681E-04
	1	5.102E-04	1.141E-03
	10	5.102E-04	1.141E-03
	100	7.315E-04	2.072E-03
0.01	0	4.126E-03	1.007E-02
	1	6.415E-03	1.752E-02
	10	6.415E-03	1.752E-02
	100	2.430E-02	3.993E-02
0.1	0	5.314E-02	1.387E-01
	1	1.325E-01	2.267E-01
	10	1.325E-01	2.267E-01
	100	2.512E-01	4.638E-01
1	0	3.911E-01	9.640E-01
	1	7.571E-01	1.461E+00
	10	1.076E+00	2.684E+00
	100	2.766E+00	5.207E+00
10	0	3.913E+00	9.642E+00
	1	4.511E+00	1.087E+01
	10	7.561E+00	1.815E+01
	100	1.936E+01	3.267E+01
100	0	3.960E+01	9.660E+01
	1	4.599E+01	1.187E+02
	10	4.561E+01	1.187E+02
	100	6.898E+01	1.314E+02

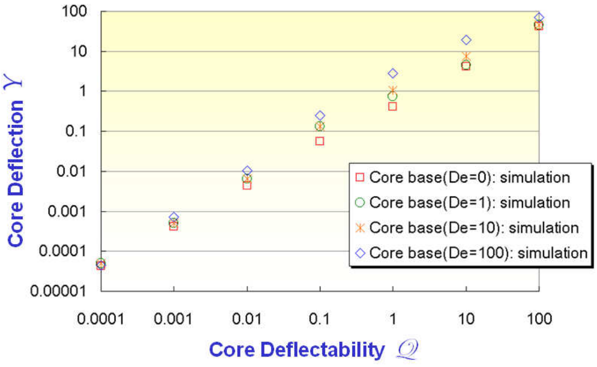


Figure 5 – Predicted core deflection at different De for core base gating

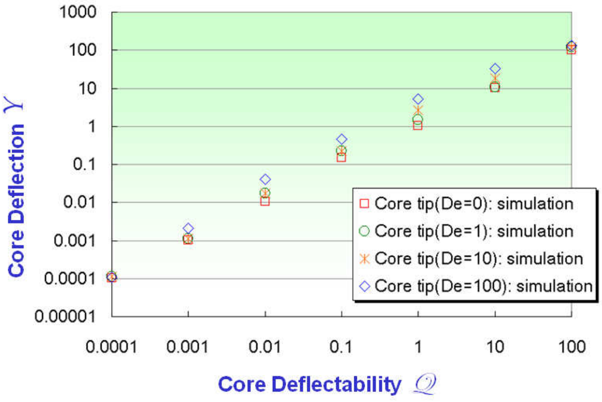


Figure 6 – Predicted core deflection at different De for core tip gating

Conclusion

In this paper, the normal stress effects in polymeric liquids are demonstrated by exploring the effect of fluid elasticity on core deflection. We use the upper convected Maxwell model to explore flow-induced normal stress, and use the Deborah number to represent the dimensionless amount of elasticity. We find that melt memory significantly worsens core deflection, and we provide a chart to help practitioners predict this.

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