Scaling Approach for Thin Wall Injection Moulding by Dimensional Analysis

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Received 19 April 2005; accepted 12 November 2005

ABSTRACT

Thin-wall injection moulding has received increasing attention over the past few years due to economic and environmental concerns. However, due to the difficulties encountered in the thin-wall moulding process, systematic investigation is lacking in machine performance, mould design/manufacture requirement, moulding characteristics, computer aided engineering (CAE) simulation, part quality and part design criteria. Furthermore, the combination of viscoelastic materials, complex moulding geometry and cyclic processing conditions has generated some problems, such as flow marks, polymer degradation, sink marks and warpage, under high-speed and high-pressure injection moulding. So it is very important to design, operate, and control thin-wall moulding optimally to guarantee part quality as well as reduce cost. In thin wall injection moulding processes, parts thinner than 1 mm are produced using high injection pressures and velocities. Modelling has not been successful in predicting process physics during moulding. A dimensional analysis is performed, considering the most relevant variables of the process, the geometry and the non-linear material properties. Using similarity analysis with the material and process related dimensionless groups, the process is scaled by reducing the thickness. The scaled dimensionless groups are used to find relations between process conditions, material properties and other physical parameters, which lead to reasonable conclusions. Results fit experimental data well.

INTRODUCTION

Among the large number of polymer processing operations, injection moulding has found the widest application for making articles which could be put to direct use. Because of the superior manufacturability and the high degree of freedom of the form of plastics products, injection moulding is one of the most widely used processes for processing plastics. In injection moulding process, the polymer melt flows through a runner system and gates to fill the mould cavity. When the filling is
completed, more melt is packed into the mould to compensate for volume shrinkage. The cooling stage follows until the melt solidifies. Finally, the part is ejected from the mould.

Thin-wall injection moulding (TWIM) is conventionally defined as moulding parts that have a nominal wall thickness of 1 mm or less and a surface area of at least 50 cm² [1-2]. Thin wall is relative, however. It also can be named "thin-wall" as the flow length/thickness ratio is above 100 or 150 [3-4]. TWIM has been paid more and more attention, especially in computer, communication and consumer electronic (3C) industries, due to economic and environmental concerns. The reason is that thin-wall moulded parts could be made lighter, more compact, less expensive, and quicker because of fast cooling [5]. New environmental regulations require less plastic to be used at the source or in the initial stage of manufacturing [6]. Thus, TWIM is a viable option for reducing the weight and size of plastic components.

The difference between conventional injection moulding and TWIM is shown in Figure 1. The solidified "skin" layers are about 0.25 mm regardless of part thickness [2]. It means that the flow channel is very narrow and thus flow resistance is very high in TWIM. Reducing flow resistance can be reached by increasing the melt or mould temperature, reducing melt viscosity (increasing melt index), increasing injection pressure, or injection speed [1, 7]. However, high melt temperature may cause degradation and increases cooling time which are unacceptable. A rise in melt index shows a decrease in physical properties [7]. Therefore, high injection speed is preferred, and extremely high injection pressure, 200-250 MPa (30,000-40,000 psi), is required [8]. Due to the thin part, cooling is fast. Thus the combination of the fast cooling and high melt velocity (short fill time) significantly reduces the cycle time. The typical cycle time of TWIM is 6-20 s while the cycle time for conventional injection moulding is 40-60 s [9]. The shrinkage is also low because of the reduced part thickness [10]. TWIM is characterized as high flow rate, high pressure, high shear rate, high viscous heating, fast cooling and fast shrinkage. However, TWIM has some disadvantages. Due to the rapid cooling of the polymer melt, the operating window becomes narrower as the part becomes thinner [11-12]. Specialized material is also required to balance the trade-off between processability and physical properties [13], which means material should both flow easily (high melt index) and retain good physical properties. TWIM also makes design and process control more complicated. It is a big challenge to fill the mould with a high flow length/thickness ratio at a high speed under high pressure. For example, an additional accumulator is needed to maintain high pressure at a short fill time. However, the operation of the accumulator affects the moulding stability [14]. More robust control systems are required to control the moulding precisely and with a short response time [9, 15]. High injection pressure also needs high clamp tonnage which increases the capital investment of equipment.

Processing, material, tooling, and machine interact with each other and greatly affect the end results. For TWIM, systematic investigation about machine performance, mould design/manufacture requirement, moulding characteristics, computer aided engineering (CAE) simulation, part quality and part design criteria, is required [14]. However, the study is lacking due to the difficulty of thin-wall moulding process. Furthermore, the combination of viscoelastic materials, complex moulding geometry and cyclic processing conditions has generated some problems [16], such as flow marks, polymer degradation, high residual stress, sink marks and warpage, under high-speed, high-pressure injection moulding [17, 18]. So it is very important to design, operate and control thin-wall moulding optimally to guarantee part quality as well as reduce cost.

Many investigators have studied thin wall injection moulding's problems experimentally [2, 18-22]. But a few models are available for these problems in literature. All of these models predict the pressure drop and velocity in TWIM with any processing parameters directly. None of them can predict the problems of TWIM well. In this work, we try to scale TWIM with application of the most important parameters that affect in TWIM. This work, do not give a model for TWIM. We try to relate the TWIM to conventional injection Moulding.

**EXPERIMENTAL**

**Procedure**

The problem under consideration is the mould cavity
filling process during injection moulding. A conventional process may be scaled down to a thin 8 wall injection moulding process, based on a dimensional analysis technique.

The viscosity of the melt depends on shear, temperature and pressure (eqn (2)), following the power law model:

\[ \eta = \eta_0 \exp(-a\Delta T) \exp(b\Delta P) \]  

where \( a \) and \( b \) represent the material's sensitivity to temperature and pressure, respectively.

We think that the variables related to the problem are:
- target quantities: \( \Delta P, v \);
- geometric variables: \( h, L \);
- physical or material properties: \( \eta, K, C_p, \rho \);
- process variables: \( \Delta T \);

where:
- \( \Delta P \): pressure difference between the gate and the cavity;
- \( h \): thickness of the part;
- \( L \): length of the part (flow length);
- \( \eta \): viscosity;
- \( K \): thermal conductivity;
- \( C_p \): specific heat;
- \( v \): injection speed;
- \( \Delta T \): temperature difference between the melt and the mould;
- \( \rho \): density of the melt.

There are nine (m) variables and four (n) dimensions. Therefore, \( n \) repeating variables are chosen: \( \eta, L, v \) and \( \Delta T \). These take into account all the dimensions, considering that one variable should not have exactly the same dimension as another.

A dimensionless matrix (Table 1) is set up locating the repeating variables on the first columns (to form a square core matrix) and the other variables on the remaining columns (to form a residual matrix). With algebraic operations between rows, the core matrix is turned into the identity matrix.

<table>
<thead>
<tr>
<th>( \Delta P )</th>
<th>( v )</th>
<th>( L )</th>
<th>( \Delta T )</th>
<th>( \rho )</th>
<th>( h )</th>
<th>( K )</th>
<th>( C_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>L</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>-1</td>
<td>-3</td>
<td>1</td>
</tr>
<tr>
<td>T</td>
<td>-1</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>-2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( \Theta )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

There are \( m-n \) dimensionless groups, each one being a fraction. The variable in the first column (to generate \( \Pi_1 \)) of the residual matrix is placed in the numerator. Each element in this column is the exponent of the repeating variable having one on that same row. The same process is followed to generate the rest of the \( \Pi \)-groups. Some \( \Pi \)-groups can be identified as known dimensionless numbers, even though they may not be directly found, requiring algebraic operations with other \( \Pi \)-groups. The following are the resulting dimensionless groups:

\[ \Pi_1 = \frac{\Delta P L}{\eta v} \]  

\[\Pi_2 = \frac{v p L}{\eta} \]  

\[\Pi_3 = \frac{h}{L} \]  

\[\Pi_4 = \frac{K \Delta T}{\eta v^2} \]  

\[\Pi_5 = \frac{C_p \Delta T}{v^2} \]  

Eqn (4) is the Reynolds number; eqn (6) is the reciprocal of the Brinkman number. The Prandtl number and the Euler number can, respectively, be obtained using the remaining dimensionless groups, by:

\[ \frac{\Pi_5}{\Pi_4} = \frac{C_p \eta}{K} \]
The thickness of the part is scaled down from \( h_1 \) to \( h_2 \), which corresponds to the thin-walled part thickness.

In any polymer process, viscous dissipation plays a significant role. For controlled viscous dissipation it is necessary that the Brinkman number remain constant, in which case it should be true that:

\[
\frac{\eta_1 v_1^2}{K_1 \Delta T_1} = \frac{\eta_2 v_2^2}{K_2 \Delta T_2}
\]

where \( \eta \) is defined according to eqn (1).

The following assumptions are made: \( \Delta T_1 = \Delta T_2 \); \( m_1 = m_2 \); \( K_1 = K_2 \); \( h_2 = R h_1 \), where \( R \) is the scaling factor.

The slit flow equation [17] is used to find a relationship between the two velocities as:

\[
v = \left( \frac{h \Delta P}{2 m \exp(-a \Delta T) \exp(b \Delta P)} \right)^{1/2} \cdot \frac{1}{h^{1/2}} \cdot \frac{1}{2} \left( \frac{n+1}{n} \right)^{1/2} \cdot \frac{1}{n+2} \cdot \frac{1}{n+1}
\]

\[
v_1 = \frac{h_1^{1+n/n} \Delta P_1^{1/n} \exp((b \Delta P_1)/n)}{h_2^{1+n/n} \Delta P_2^{1/n} \exp((b \Delta P_2)/n)}
\]

The velocities \( v_1 \) and \( v_2 \) in eqn (12) are equivalent to the velocities found in eqn (12).

By manipulating the above equations the following expression was obtained:

\[
\frac{\Delta P_2^{1/n} R^{3/(n+1)}(n^2+n)}{\Delta P_1^{1/n} \exp\left(\frac{(\Delta P_2 - \Delta P_1)((n+1)b+b)}{n(n+1)}\right)}
\]

Solving for \( \Delta P_2 \), it is seen that as \( R \) decreases (for thinner parts), the pressure for the thin system increases. Similarly, eqn (15) presents the effect of power-law index \( n \), and pressure dependence of the viscosity, \( b \).

The various effects of scaling, material behaviour and processing conditions are captured and shown in Figures 2 and 3. The obtained results are compared with experimental data from Xu [2].

**RESULTS AND DISCUSSION**

For HIPS and HDPE, and the conventional injection pressure set to 70 MPa (700 bar), Figure 1 was obtained for various values of \( R \) and \( b \) (bar\(^{-1}\)) of \( 1.2 \times 10^{-4} \) and \( 2.5 \times 10^{-4} \). It is shown that the injection pressure required for thin-walled parts increases as the value of \( R \) decreases. For the least values of \( R \), it increases three-fold. However, the corresponding values for \( R \) are further from reality as they approach zero. For smaller values of \( b \), less pressure is required, since the material will have a lower viscosity.

For HIPS and HDPE, and the conventional injection pressure set to 100 MPa (1000 bar), Figure 2 was obtained for various values of \( R \) and \( b \) (bar\(^{-1}\)) of \( 1.2 \times 10^{-4} \) and \( 2.5 \times 10^{-4} \). Even for materials that require lower injection pressures (700 bar), as for example PE, the
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Figure 2. Obtained results from this model and experimental data [2]. Experimental data at $\Delta P_2 = 700$ bar.

Figure 3. Obtained results from this model and experimental data [2]. Experimental data at $\Delta P_2 = 1000$ bar.

injection pressure requirements increase for thinner parts and reflects a relatively large effect of pressure dependent viscosity (Figure 1). Figure 2 presents the same results as seen in Figure 1 but for materials with higher injection pressure (1000 bar) requirements, such as HIPS. It is here that the pressure dependence of the viscosity significantly affects the required pressures for injection moulding of thin parts.

CONCLUSION

Dimensional analysis is a technique that can be used to approach physical systems and scale them to a higher or lower level by searching for similarity between them. Based on a constant Brinkman number in the scaling process, a relationship between the injection pressures for conventional and thin-wall injection moulding was found.

The results found here were plausible, and point to the pressure dependence of the viscosity as one of the more important factors that affect moulding of thin parts. It is therefore important that complex simulation of injection moulding include this effect. This poses a major problem, due to the fact that these data must be measured at least for the materials that are typical of thin-walled injection moulded parts.

Symbols and Abbreviations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$a$</td>
<td>Material's sensitivity of viscosity to temperature</td>
</tr>
<tr>
<td>$b$</td>
<td>Material’s sensitivity to viscosity to pressure</td>
</tr>
<tr>
<td>$L$</td>
<td>Length of the part (flow length)</td>
</tr>
<tr>
<td>$K$</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Specific heat</td>
</tr>
<tr>
<td>$m$</td>
<td>Power law viscosity model coefficient</td>
</tr>
<tr>
<td>$n$</td>
<td>Power law viscosity model index</td>
</tr>
<tr>
<td>$R$</td>
<td>Scaling factor</td>
</tr>
<tr>
<td>$v$</td>
<td>Velocity of mould material</td>
</tr>
<tr>
<td>$h$</td>
<td>Part thickness</td>
</tr>
<tr>
<td>$P$</td>
<td>Pressure</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Viscosity</td>
</tr>
<tr>
<td>$\gamma'$</td>
<td>Shear rate</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
</tr>
<tr>
<td>$\Pi_i$</td>
<td>Dimensionless group i</td>
</tr>
</tbody>
</table>

REFERENCES

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