DESIGN FOR INJECTION MOLDING:
USING DIMENSIONAL ANALYSIS TO ASSESS FILLABILITY

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ABSTRACT

This paper addresses the determination of wall thicknesses and gating schemes in the preliminary design of injection-molded plastic parts. Today, most of the existing design guidelines come in the form of experience-based qualitative rules. If the designers already have a detailed geometry of the part, the numerical process simulation program provides another form of design aid. There exists a huge gap between these two types of design aids; the experience-based guidelines are often too vague, while the process simulation programs come too late to impact preliminary part design. To fill this gap, this paper develops physics-based guidelines that utilize dimensional analysis techniques. Experiments and simulation studies can deduce non-dimensional relationships between flow length, thickness, material, and process parameters. The guidelines will aid plastic component designers in determining wall-thickness, gating schemes, and in selecting the material in the preliminary stages of part design. This paper describes the formulation of the non-dimensional charts for fillability assessment, and explains the use of these charts in part design. We further outline an ongoing experimental program to validate and refine our formulation.

1.0 INTRODUCTION

1.1 Background

The use of injection-molded plastics in engineering applications has increased dramatically over the last decade. The advantages of plastics include low density, superior corrosion resistance, integrated geometry features, and suitability for volume production. However, greater requirements on plastic part performance, the pressure of shorter development times, and continual development of new materials and processing technology place large demands on the designer. In addition, the designer must consider the entire product life-cycle during the preliminary stages of part design while attempting to meet the functional requirements for the application. The designer needs accurate and readily accessible design guidelines to produce world-class plastic part designs in a time- and cost-effective manner.

A critical decision parameter in injection molding part design is wall-thickness specification. Wall-thickness specification has an impact on part weight, material cost, gating configuration, choice of material, machine size, and process window. Designers must often resort to process simulation to determine feasible limits on wall-thickness. Unfortunately, designers perform process simulation at more detailed stages of the design process, at which time the designer has much less freedom to make significant changes. We feel that designers can benefit from a part design methodology that facilitates wall-thickness and gating configuration in earlier stages of the design process. Such a methodology will allow designers to explore a broader range of solutions before the designer has committed to any particular design.

1.2 Current Approach to Injection Molding Design

In industry, the majority of injection molding design guidelines originate from experiential knowledge while not necessarily from the process physics. The guidelines apply to many applications and features, but are often too specific in scope for designers to impact a specific design. The guidelines thoroughly cover detailed design of injection molding features (bosses, holes, snaps, etc.), but fail to incorporate variations in material, process, geometry, and type of application. Injection molding process simulation provides another excellent tool for designers when used in the proper context. Simulation can account for the thermo-mechanical behavior during the process and apply to general classes of geometry, material, and process. However, process simulation typically requires detailed information about the geometry, process, and material—a level of detail not usually known until well into the design process. At this stage, the designer has less freedom and is less willing to make the changes that the simulation might suggest.

In academia, many researchers have proposed concurrent engineering design as a means of incorporating tooling and process concerns in the early stages of product design. While many studies report on concurrent engineering in general (e.g. Barkan, 1988), only a few of them present a systematic methodology to help designers conduct the discipline. The most well developed concurrent engineering methodology is related to assembly as reported by Boothroyd and Dewhurst (1983). Dixon and his group have been the pioneers in applying AI to plastic part design (Dixon, 1986a). They have applied AI to evaluate extruded plastic parts (Duffey and Dixon, 1988) and injection-molded ones (Simmons and Dixon, 1985). Other groups working on design for injection molding are the Engineering Design Research Center at Carnegie-Mellon University (Pinilla, et al., 1989) and the Center for Design Research at Stanford University (Hanada, et al., 1989). These groups have concentrated their work on the representation schemes for part designs. There are also groups of researchers who focus on cost estimation at the early design stage (Poli, 1988a and b, Rosen, et al., 1992).

The largest shortcoming in the current approach to thermoplastic injection-molded part design is the lack of analytical tools that address whole-part design in the preliminary stages. Merhar, et al. (1993) describe a methodology that helps designers select a manufacturing process for engineering plastics. Beiter, et al. (1991) proposed a geometric index that predicts sink mark in ribbed injection-molded parts. Chong, et al. (1993) developed a procedure to simultaneously consider static and dynamic balancing and manufacturability concerns for injection-molded rotational parts. Overall, there is a lack of research focus on preliminary design of injection-molded thermoplastic parts.

1.3 Our Approach

To address the shortcoming in preliminary whole-part design guidelines, this paper proposes the use of non-dimensional charts. Non-dimensional charts can incorporate the important geometric, process, and material parameters that correspond to the physics of the process. Solutions to real problems involve a combination of analysis and experimental information. Dimensional analysis seeks a mathematical model that is simple enough to yield an applicable solution, yet capture the essence of the physical behavior. The injection molding process involves many parameters. Using conventional methods with dimensional values would require an excessive number of experiments to characterize the relationships among parameters and more importantly an excessive number of charts to represent the data to designers. Non-dimensional charts with appropriate dimensionless numbers can characterize relationships among these parameters very effectively. One method of developing dimensionless numbers is with the Buckingham Pi Theorem (Krantz, et al., 1971). The Buckingham Pi Theorem is a statement of the relation between a function expressed in terms of dimensional parameters and related functions expressed in terms of non-dimensional parameters. Using the Buckingham Pi Theorem allows us to develop the important non-dimensional parameters quickly and easily.

The Buckingham Pi Theorem states that for a given relation among n parameters of the form

$$f(q_1, q_2, ..., q_n) = 0 \qquad (1)$$

one may group n parameters into n-m independent dimensionless ratios, or Π parameters where m is the number of primary dimensions, expressible in functional form by

$$F(\Pi_1, \Pi_2, ..., \Pi_{n-m}) = 0 \qquad (2)$$

or

$$\Pi_1 = F_1(\Pi_1, \Pi_2, ..., \Pi_{n-m}) \qquad (3)$$

The functional relation among the independent, dimensionless Π parameters must be determined experimentally.

Non-dimensional charts thus obtained allow designers to determine feasible geometry and gating schemes without resorting to detailed process simulation programs. The power of this approach is that it incorporates manufacturability concerns, specifically fillability characteristics, into the preliminary stages of geometry synthesis. The designer will be able to start with a feasible preliminary design and more efficiently generate a detailed geometry without unnecessary iteration.

This paper describes our approach to develop filling guidelines applicable in the preliminary design stage through dimensional analysis. Section two covers fillability in injection molding, and addresses current fillability guidelines, the void in these guidelines, and our approach to fill this void. Section three addresses the experimental work we propose to develop fillability guidelines. Section four descusses simulation results, and finally, we describe a method for implementing the fillability guidelines in section five.

2.0 FILLABILITY IN INJECTION MOLDING

Fillability in injection molding is a critical manufacturability concern because it directly affects the entire part geometry and requires what we call a whole-part analysis. Whole-part analysis is generally more complex than design guidelines for isolated features such as bosses and holes. Effective fillability evaluation requires incorporating the effects of flow length, part thickness and geometry, process, and material properties.

2.1 Current Fillability Guidelines

Designers can perform detailed fillability analysis with injection molding process simulation. Process simulation can be a powerful tool if the designer uses the information correctly. However, an accurate process simulation requires detailed geometry and a time investment that the designer cannot always afford. The available design guidelines applicable to preliminary part design are limited.

2.1.1 Gate Design

There is little information on gate sizing. A common recommendation is to open up the gate as much as possible, or specify generic gate sizes based only on plastic material, while neglecting effects of geometric parameters. Design guidelines address gating schemes, i.e., number and location of gates to adequately fill a specific part, in a qualitative form. Gate design guidelines also discuss the various types of gates and their functions on a qualitative level. Below are some examples of gating design guidelines for location and geometry (Mehl, et al., 1993).

Location:

1. The gate location should be positioned in a way so the flow runs from the thick section to the thin section.
2. Position the gates so the knit lines are located in non-critical areas.
3. Position the gates in a non-critical strength and aesthetic area.
4. Gate location should take into consideration uniform filling of the cavities and venting of the cavities.
5. Position gates so that the polymer impinges against walls or other projections such as pins because of filling, jetting, and orientation concerns.

Geometry:

1. Gates should be just large enough to enable the cavity to fill relatively easy.
2. Gates should be as large as possible to permit high speed, low shear flow.
3. Ensure mold fills under realistic temperatures and pressures.
4. Gates should be radiused to reduce shear and facilitate flow.
5. Gate land should be as short as possible and no longer than 0.060".

2.1.2 Wall-thickness Guidelines

Standard nominal wall-thickness guidelines are more sophisticated than gating guidelines. Material suppliers and other institutions have conducted more research in this area due to the impact that part thickness can have on the final product. The thickness of a part can greatly influence cost, strength, and aesthetics. Thickness guidelines consist of nominal wall-thickness ranges for specific materials, and general rules on wall-thickness variations. Below are some examples of wall-thickness guidelines.

Nominal Thickness:

1. Wall thickness can usually range from 1/16" to 3/16" for rigid PVC.
2. Minimum thickness for most Polycarbonate parts is 0.050 inches.
3. Wall thickness should be as uniform as possible.
4. Thin parts are possible if melt flow is a shorter distance.

Transitions:

1. A gradual transition of a 3:1 ratio should be used for variations in wall thickness.
2. A wall-thickness variation of 25% is acceptable in a part made with thermoplastic having a shrinkage rate of less than 0.01 in./in..

More sophisticated thickness guidelines include flow length versus thickness curves. Material suppliers develop these curves for families of material within their company. Designers can trust the accuracy of these curves only to a relative measure within a companies materials.

2.2 What is Missing in Fillability Guidelines?

One cannot determine a gating scheme without incorporating thickness and material concerns. The lack of information in this area is understandable, considering the number of experiments required to quantify the process variables.

Melt front velocity is an important parameter in determining flow length, but is overlooked in standard flow length versus thickness curves. Standard flow length versus thickness curves confound two important factors that melt front velocity can capture. 1) How injection rate affects flow length. Injection rate contributes to maximum flow length via machine capacity, gate size, possible shear heating, and shear thinning. 2) How spiral mold size affects flow length. Companies developed the disc flow to approximate real life situations better than the spiral mold. The average melt front velocity in a disc flow is more typical of a production part. Melt front velocity will dictate the filling window in an injection-molded part. The lower bound of velocity will produce a short-shot and the upper bound will produce excessive shear, resulting in burning and degradation for a given geometry.

2.3 Geometry and Process Factors Affecting Fillability

To obtain an accurate filling model that applies to the generic injection-molded part, we must look at the physics behind the process, or how the filling is effected by the interdependent geometry, process, and material parameters. The filling model that we are proposing is flow length as a function of velocity, viscosity, and part thickness (Eq. 4)

$$fl = f(V, \eta, t) \tag{4}$$

The geometry that relates to our fillability model is thickness, melt front area, gate location, and number of gates. The process parameters that relate to the model are mold temperature, melt temperature, flow rate, and pressure at the gate. The material parameters include a temperature and shear-rate dependent viscosity.

2.4 Non-Dimensional Filling Guidelines

We feel that flow length as a function of velocity, viscosity, and part thickness (Eq. 4) will capture the physics of the filling process well enough to accurately predict the flow length of a material in a generic geometry. For the results to be applicable in the early stages of design we must eliminate detailed geometry information from the analysis.

2.4.1 Dimensional Analysis

We used the Buckingham Pi procedure to determine the dimensionless parameters. First we state all the parameters involved while listing the primary dimensions of each (Table 1). For simplicity we combined viscosity and density into a kinematic viscosity parameter which eliminates mass, a primary dimension, from the analysis, but will not change the outcome of the dimensional analysis. Previous research has found variable-density effects to not have a significant influence on the spiral flow-length (Hieber, 1994), so in effect, we are dividing the viscosity by a material constant.

Table 1. Dimensional Analysis parameters.

Parameter	Primary Dimensions
flow length, *fl*	L
thickness, *t*	L
velocity, *V*	L/T
kinematic viscosity, η/ρ	L^2/T

Number of parameters, $n = 4$
Number of primary dimensions, $r = 2$
Number of repeating parameters, $m = r = 2$
Number of non-dimensional groups = $n - m = 2$

We arbitrarily select the repeating parameters of t and V. The analysis for the first dimensional group is as follows:

$$\Pi_1 = (t)^a \cdot (V)^b \cdot fl = (L)^a \cdot \left(\frac{L}{T}\right)^b \cdot (L) \tag{5}$$

$$L: a+b+1 = 0 \tag{6}$$

$$T: -b = 0 \tag{7}$$

$$b = 0,\ a = -1 \tag{8}$$

Therefore, the first non-dimensional group is:

$$\Pi_1 = \left(\frac{fl}{t}\right) \tag{9}$$

We determined the other dimensionless parameter using the same procedure:

$$\Pi_2 = (t)^a \cdot (V)^b \cdot (\eta/\rho) = (L)^a \cdot \left(\frac{L}{T}\right)^b \cdot \left(\frac{L^2}{T}\right) \tag{10}$$

$$L: a+b+2 = 0 \tag{11}$$

$$T: -b-1 = 0 \tag{12}$$

$$b = -1,\ a = -1 \tag{13}$$

The second non-dimensional group is:

$$\Pi_2 = \left(\frac{(\eta/\rho)}{t \cdot V}\right) \tag{14}$$

The resulting dimensional analysis tells us that:

$$\Pi_1 = f(\Pi_2) \tag{15}$$

or

$$\left(\frac{fl}{t}\right) = f\left(\frac{(\eta/\rho)}{t \cdot V}\right) \tag{16}$$

We will determine this relationship between the normalized flow length and the normalized viscosity experimentally and determine whether this analysis is valid.

3.0 EXPERIMENTAL WORK

We are currently conducting experiments to establish an empirical relationship for the filling stage parameters in injection-molded parts. This characterization will aid designers in determining part thickness, gating schemes and material to adequately fill a part. We will use the various grades of our example material, PVC (Poly-Vinyl Chloride), in experiments to verify process simulation and develop further refined models. We will use a modified spiral mold with a variable thickness to determine the relationship between the thickness, gating scheme, material, and process.

3.1 Mold Design

The range of flow rate, velocity, and thickness constrain the spiral mold geometry. The flow rate should be between 0.5 and 4.0 in^3/sec., a range for a typical injection molding machine. A typical PVC part thickness ranges from 0.060" to 0.125". The flow velocity in most applications, calculated by (flow rate/melt front area) is typically in the range of 2 to 5 in/sec. A typical spiral mold generates too high of a velocity for practical applications; therefore, we must use a mold with a larger cross-sectional area. If we use a mold with a width of 1", the melt-front area will range from 0.060 to 0.125 in^2 under the desired thicknesses. The length of flow should be over 25". Figure 1 shows the cavity of the spiral mold we will use in the experiments. There are three cavities of thickness 0.060", 0.0925", and 0.125". The spiral mold is machined out of a 8" by 11" by 1.5" steel block with a total flow length of 30" and a width of 1". The gate is a fan gate of constant area and is 90% of the cavity thickness at the cavity entrance.

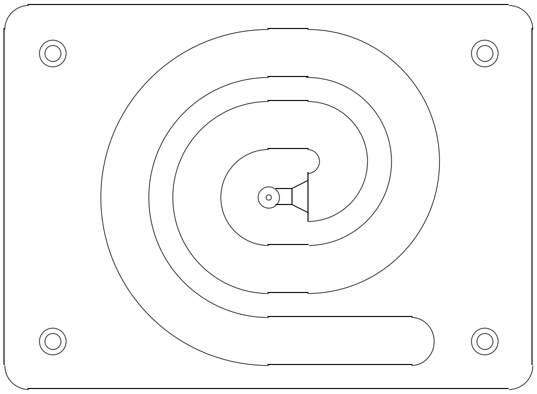


Figure 1. Fillability spiral mold.

3.2 Design of Experiments

If the mold temperature proves to be insignificant, we will run a full-factorial experiment with thickness, material viscosity, melt temperature, and ram speed as variables. We will use these four variables to determine our fillability model of flow length as a function of melt front velocity, material viscosity, and part thickness. Thickness and melt temperature will contain three levels, ram speed will contain four levels, and material will contain one. The full factorial consists of 72 experiments. We expect this to be enough to characterize the relationship among the dimensionless parameters. We will use two rigid PVC materials from The Geon Company, 87241, a general purpose molding compound, and 85890, a high-flow compound. The ranges for the other three variables are:

0.060 in	<	Thickness	<	0.125 in
380 deg F	<	Melt Temperature	<	410 deg F
0.50 in^2/s	<	Ram Speed	<	3.5 in^2/s

The experimental results will provide a testbed for validation of the commercial process simulation programs. If the experimental result agrees with the simulation model, it can extend the scope of our design guidelines.

4.0 SIMULATION RESULTS

We utilized C-FLOW, Version 3.1 (AC Technology, 1992) for our commercial process simulation package. We tried to simulate our experiments closely in an attempt to verify the fillability predictions of C-FLOW. We ran the initial simulations using the same estimated ram-speed profile for each simulation. We will obtain the correct ram-speed profile for every experimental run and re-run the simulations. We used the same experimental design to run simulations except with five levels of thickness, resulting in a full-factorial experiment of 90 simulation runs. We also ran 18 simulations at the mid-level thickness range with a five inch wide plaque in order to avoid confounding width within our fillability model of equation 4.

Initial results from the simulation are represented in Figure 2. Thickness is the most pertinent factor with ram speed, material variation and melt temperature also as contributing factors (Figure 2). The contribution of thickness to flow length is the dominant factor. However, at each thickness, the variation of flow length due to other factors was significant. To be able to predict the fillability of a part, we must quantify the velocity and viscosity effects on flow length as well as thickness.

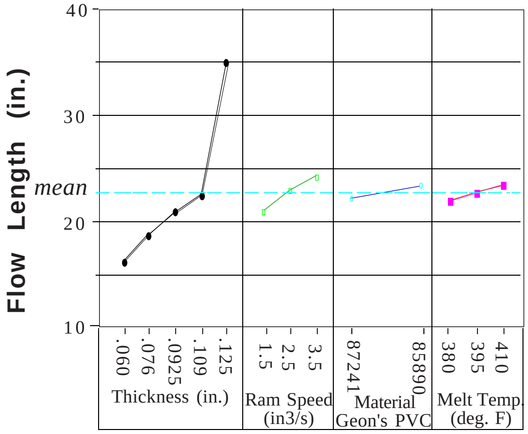


Figure 2. Factor effects on flow length from simulation.

4.1 Fillability Model

We have seen the various factors influence on flow length. To represent the information in terms of the physical parameters, velocity, viscosity, and thickness (equation 4), we need to characterize the simulation data in terms of a non-dimensionalized function. The Buckingham Pi Analysis suggests that we represent the information as a normalized flow length as a function of normalized viscosity (Equation 16). The model was able to capture the viscosity variation over two materials and a range of melt temeraptures and shear-rates. Likewise, the model captured the influence of velocity variation over a range of ram speeds and flow front widths. The model was unable to characterize thickness. By multiplying the dimensionless flow length by thickness, we eliminate the thickness dependence from one axis in our model representation and let a third dimension capture the thickness relationship (Figure 3).

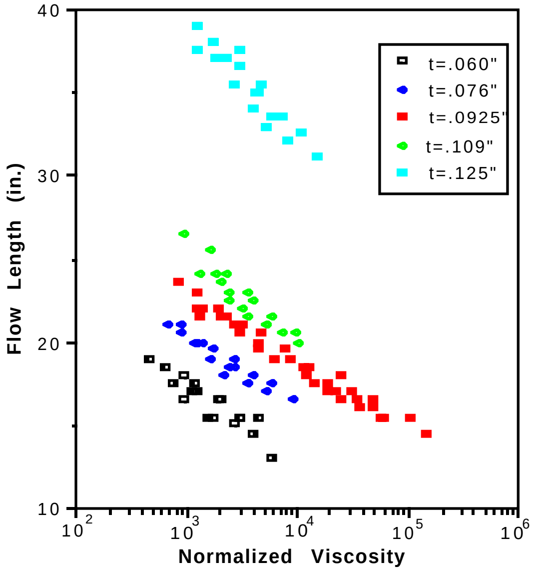


Figure 3. Flow length as a function of normalize viscosity over a range of thicknesses.

5.0 DIMENSIONAL CHART APPLICATION

A designer can use the fillability chart to determine optimal gating schemes, minimum part thickness, material, and velocity at which to fill the part. Obviously, the designer is also concerned with strength, shrinkage, and other design issues, but this chart can provide a starting point. The designer can get a qualitative feel for which parameters are going to effect the design by the chart's functional relationship. The designer can determine a minimum thickness while adequately filling a part by varying the gating scheme, material, and flow rate. The chart will allow for quick solutions to a number of parameters giving the designers a good feel for the gating scheme, thickness, material, and required flow rate for a part.

Access to a tool early in the design stage based on the physics of the process will provide designers with more knowledge earlier in the design process. The designer can incorporate this knowledge when designing each feature on the part. For example, if the designer knows the gating scheme going into the detail design stage, they can utilize ribs as flow leaders, determine the geometry of the ribs and bosses as a function of distance from gate to minimize sink, and locate knit lines in non-critical strength and aesthetic areas. This will ultimately lead to less design iterations and process simulation down stream in the design stage.

There are certain assumptions in the filling analysis that the designer must be aware of when using such a chart. The designer must use an average value for part thickness and flow width, flow length, flow rate, viscosity, and density. The viscosity will be dependent on shear rate and temperature, however. The most difficult and crucial parameter to quantify is width. The average width will determine the average velocity.

The width is the actual width of the melt front as the plastic is flowing into the mold. In a rectangular plaque mold, the width of the melt front increases as the plastic flows radialy and then stays fairly constant as the plaque fills. If the melt front width is relatively constant during the filling stage, then using a time averaged width would be a valid assumption.

Using a non-dimensional chart, we can follow a series of steps to converge on a preliminary design.

Step 1: Specify initial gating scheme for part to determine flow length.
Step 2: Specify flow rate from the machine capabilities and nominal (η/ρ).
Step 3: Use fillability chart to determine initial minimum thickness.
Step 4: Use the initial thickness, flow rate, and melt front width (determined from gating scheme) to determine the modified shear rate dependent viscosity assuming no slip at the wall and a linear velocity distribution (equation 18).

$$\dot{\gamma} = \frac{dv}{dt} = \frac{(Q/w \cdot t)}{(t/2)} \tag{18}$$

Step 5: Use the modified viscosity value, and determine a modified thickness value from the dimensionless chart.
Step 6: Repeat steps 4 and 5 until you converge on a minimum thickness.
Step 7: Repeat steps 1 through 6 with alternate gating schemes until a good preliminary design in complete.

We illustrate a simple example of the dimensionless chart application by using a qualitative filling example not considering the upper constraint of excessive shear stress of the filling window.

Objective: Determine minimum thickness, *t*, to fill a 24" x 6" x 1" housing.

Constraints: Machine capable of a ram speed of 4 in/sec with a 1” diameter barrel.

Design Analysis 1:

First we start by choosing a gating scheme for our part. We initially choose a single sprue gate (Figure 4a).

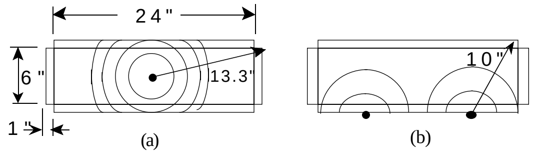


Figure 4. Possible gating schemes for a 24" x 6" x 1" housing, (a) sprue gated part, (b) two edge gates

Flow length, *fl*: This gating scheme gives a required flow length of approximately 13.3".

Width, *w*: We can approximate the average flow front width to be 6" x 2, or 12".

Flow rate, *Q*: Injection speed x barrel area = (4 in/sec.)(π/4) = 3.14 in^3/sec.

η/ρ: We will use a grade of PVC from The Geon Company - 87241 Rigid PVC.

To calculate a temperature and shear-rate dependent viscosity, we first assume a melt temperature of 376 deg. F. The shear-rate can be calculated using equation 19 assuming an initial nominal thickness of 0.100". We can iterate of this thickness to converge on the solution later.

$$\dot{\gamma} = \frac{dV}{dt} = \frac{Q/(w \cdot t)}{t/2} = \frac{2Q}{w \cdot t^2} = 53 \text{ (1/s)} \tag{19}$$

The temperature and shear-rate dependent viscosity is

$$\eta = 2000 \text{ (Pa} \cdot \text{s)} \tag{20}$$

Dividing by the density to attain a kinematic viscosity gives

$$(\eta/\rho) = 23440 \text{ (in}^2\text{/s)} \tag{21}$$

We can eliminate thickness from the x-axis by using equation 22 for average velocity in equation 23.

$$V = \frac{Q}{w \cdot t} \tag{22}$$

Therefore, the x-axis value for Figure 5 can be calculated from equation 24.

$$\frac{(\eta/\rho)}{t \cdot V} = \frac{(\eta/\rho) \cdot w}{Q} = 89580 \tag{23}$$

We can now attain a first approximation of minimum thickness of approximately 0.085" from the fillability chart (Figure 5). We can now check the initial shear-rate approximation with the new thickness value. The new shear-rate is

$$\dot{\gamma} = 73 \text{ (1/s)} \tag{24}$$

The shear rate value propagates down to the normalized viscosity value.

$$\frac{(\eta/\rho)}{t \cdot V} = 80618 \tag{25}$$

The modified shear-rate value, represented by the dotted line connecting to the 13" mark, changes the minimum thickness by a few thousandths (Figure 5).

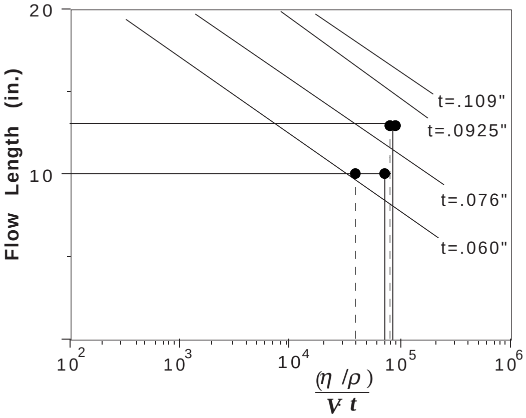


Figure 5. Qualitative non-dimensional filling chart.

Design Analysis 2

Now we want to determine the minimum achievable thickness by using two edge gates (Figure 4b). We can analyze one half of the part from symmetry. We will use the same material and melt temperature as in Design Analysis 1.

Flow length, *fl*: This gating scheme gives a required flow length of approximately 10".

Width, *w*: We can approximate the average flow front width to be πr using a radius of about 5" resulting in a *w* value of 15.7"

Flow rate, *Q*: 1.57 in^3/sec.

η/ρ: Again, assuming an initial nominal thickness of 0.100".

$$\dot{\gamma} = 63 \text{ (1/s)} \tag{26}$$

The temperature and shear-rate dependent viscosity is

$$\eta = 1900 \text{ (Pa} \cdot \text{s)} \tag{27}$$

Dividing by the density to attain a kinematic viscosity gives

$$(\eta/\rho) = 22267 \text{ (in}^2\text{/s)} \tag{28}$$

The x-axis value (Figure 8) can be calculated from equation 29.

$$\frac{(\eta/\rho)}{t \cdot V} = 70914 \tag{29}$$

The first approximation of minimum thickness value is approximately 0.070" from the solid line connecting the 10" flow length on the fillability chart. Checking the initial shear-rate approximation with the new thickness value. The new shear-rate is

$$\dot{\gamma} = 128 \text{ (1/s)} \tag{30}$$

The adjusted normalized viscosity value is

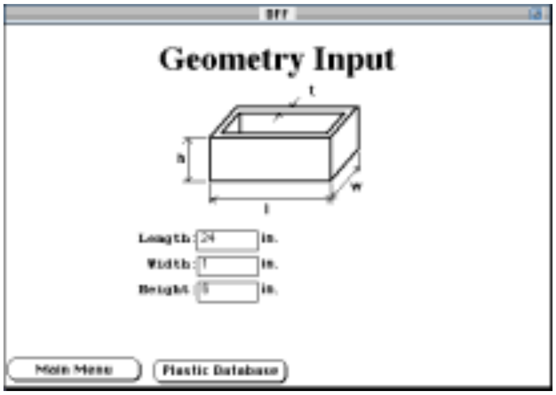
$$\frac{(\eta/\rho)}{t \cdot V} = 44787 \tag{31}$$

Here, the resulting thickness is significantly decreased by to about 0.063". Further iterations do not alter the minimum thickness significantly.

In this example of determining minimum thickness required for adequate filling, we determine the second design analysis of a double gated part to allow the designer to attain the thinner wall section. With the information, the designer can ultimately assign a nominal wall thickness after considering burning, degradation, knit line, strength, impact, shrinkage, and other issues. This example shows the potential benefits of exploring various gating schemes early in the design stage.

6.0 DEPLOYMENT OF TOOLS/KNOWLEDGE

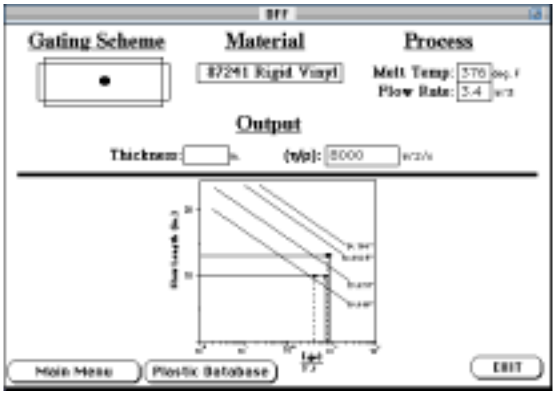
Designers must have quick access to our fillability design guidelines. Otherwise, they will bury the result along with volumes of other design handbooks. Dimensional analysis allows us to represent a significant amount of information in one chart. A designer could use this information more readily if the calculations and iterations in the design were automated. Our project will implement the empirical information from the filling stage analysis into a software package for designers to use as a design tool. The inputs to the analysis will be geometry, material, and molding machine parameters. The program is linked to a plastics database that contains material selection data for determining optimum material for a particular application. The geometry can be represented in a generic form (Figure 6) for analysis in the early design stages.



Length: 24 in.
Width: 7 in.
Height: 5 in.

Figure 6. Geometry input for the Fillability Design Tool.

Designers have the freedom to represent any gating scheme on a geometry figure that is drawn on a scaled version of the actual size (Figure 7). The program calculates the flow length and flow-front width when the designer selects a gate location. The designer can specify a suitable flow rate for a particular part or from a specific machine and specify an initial melt temperature. The program contains a shear-rate, temperature dependent viscosity model to calculate kinematic viscosities for a particular material under the geometry and process. With the geometry, material, and necessary process information entered, the program can calculate an initial minimum thickness value using the initial thickness value, the program will automatically determine a new value of shear-rate-dependent viscosity and converge on a minimum thickness.



87241 Rigid Vinyl

Melt Temp: 376 deg. F
Flow Rate: 3.4 in^3/s

Thickness: in.
(η/ρ): 5000 in^2/s

Figure 7. Design analysis for the Fillability Design Tool.

7.0 CONCLUSION

This paper develops a design aid for determining part thickness and gating schemes. We proposed dimensionless numbers that incorporate flow length, thickness, flow velocity, and material viscosity. These dimensionless numbers capture the relationship between gating scheme, thickness, flow rate, and material. This approach fills the gap between two types of existing design aids: experience based design rules and numerical process simulation. Our approach allows designers to apply physics-based design guidelines at the preliminary stages of part design. We explained in systematic fashion how designers can use these dimensionless numbers.

This paper also described the ongoing experimental study that will provide flow length data and verify the dimensionless relationship. The experiments utilize a variable-thickness spiral mold to determine flow length as a function of thickness, velocity, and material viscosity.

We described a computerized design aid that incorporates the dimensionless numbers in the design of plastic parts. The program provides a graphical interface for specifying candidate gating schemes, part envelope, and material selection, and yields minimum part thickness.

Future challenges include:

a) Integrating the material burning and degradation model to place an upper limit of the filling window for a generic part.
b) Integrating this model with other injection molding part quality models such as strength and cycle time and establish an iterative design procedure.
c) Apply the dimensional analysis methodology to evaluate other performance issues in injection-molded parts, such as stiffness and dimensional accuracy.

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