Computer Flow Simulations

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Chapter Objective

The provided chapter will provide technicians understanding of what flow simulation can do for them, their role in the running the flow analysis and interpreting the results, and a flowchart/ worksheet to assist them in the area.

Introduction

Competitively designing and manufacturing plastic molded products can be difficult. There are many performance requirements on a molded part, including high stiffness, good appearance, and tight tolerances, among others. Profits, however, drive the need to reduce costs continually, through reduced material consumption, lower tooling cost, and faster cycle times. In injection molding, there is a big trade-off between performance and cost. Knowing the behavior of a material in a molding application can impact such major design decisions as wall thickness, number of gates per cavity, number of cavities per mold, molding machine selection, and even long-term plant-level capacity planning.

Making the best decisions regarding material selection, mold design, and processing conditions is challenging for several reasons. First, the process is complex. The molten plastic is flowing in three dimensions and the flow rates, temperatures, and pressures are always changing. Second, it is not possible see everything that is going on inside the mold when the process is operating. Third, the material is compressible (it shrinks under higher pressure and expands with higher temperature) and its viscosity changes with temperature and flow rate. Fourth, there are many conflicting design and processing requirements: higher melt and mold temperatures, for example, will facilitate filling the mold but may increase the cycle time.

Now, you or your local expert may think that they have seen it all and know all the answers (or at least enough to get by); however, incorrect or inaccurate estimates of the process will cost your company big profits. There are so many trade-offs between performance and cost that incorrect assumptions can drastically change the profitability of a molding job. Given the risk and uncertainty that exists in plastics molding, an external review of the situation may be very valuable.

What Is Flow Analysis?

Have you ever wished that you could undo a major bad decision? Have you wished that after a bad day, you could have avoided your problems or had somebody else solve them? Injection molding process simulations (mold flow analysis) may be able to assist you. These simulations have been developed over the past 30 years to provide critical information so that the best decisions get

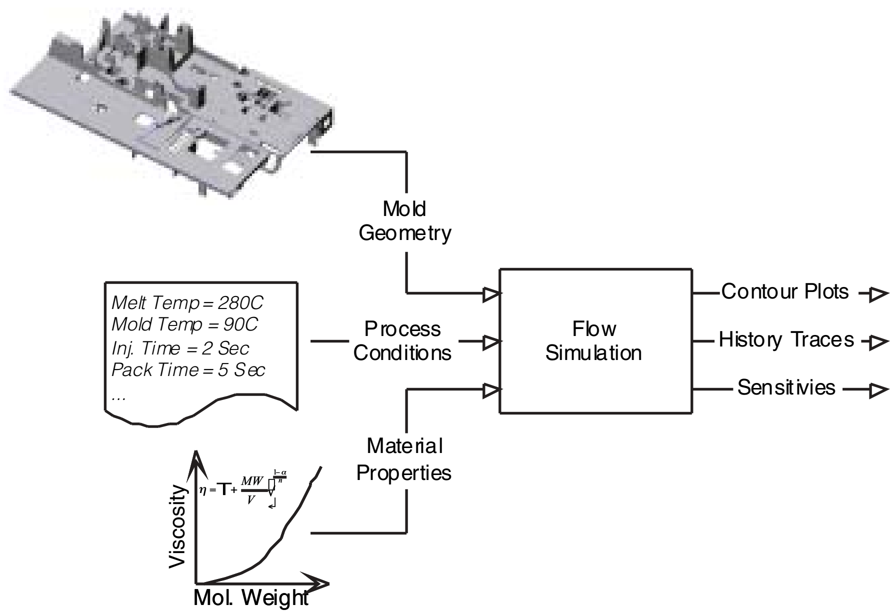


Figure 1. Inputs to flow simulation.

made. Through the early 1990s, these analyses had fairly limited capability and were quite expensive to use; however, significant progress has been made in process modeling, material characterization, and computational power. Today, simulations are extremely powerful and inexpensive, with results being available within hours or sometimes minutes.

As shown in Figure 1, there are three separate inputs needed to run a flow analysis: (1) mold geometry, (2) material properties, and (3) processing conditions. On the inside, the flow analysis decomposes the complex three-dimensional geometry of the injection mold to a mesh of triangles or pyramids (tetrahedrons) that are easier to handle numerically. Because the injection molding process is dynamic, the flow simulation progresses in a series of many small time steps. At each time step, the simulation calculates the position of the polymer melt in the mold, the pressure distribution throughout the mold, and the temperature drop between the core and the skin everywhere in the part. The simulation can end once the mold has been filled, continue to simulate the packing of the mold, or predict the shrinkage and end-use of the molded part(s).

Why Use a Flow Analysis?

The general reason to use a flow analysis is to improve our understanding of the molding process. Flow analyses are sometimes performed as standard operating procedure for marketing purposes or to verify design feasibility. To be more specific, however, analyses can be used to support critical decisions during the design, tooling, and processing stages of the molded part development process. Table 1 provides an overview of the top three uses of flow analysis.

There are two very important notes that should be mentioned about the use of flow analysis. First, flow analyses should be performed before most critical decisions are made. Running a flow analysis after most of the decisions are made will incur the same analysis costs, but have little positive impact on the molding application. Second, computers do not make decisions—people do. If a computer simulation provides a recommendation regarding wall thickness or a processing condition, a person must consider the quality of the recommendation and decides about its acceptance. Remember that computers cannot be fired and people are accountable for their decisions. For this reason, it is important to know both when to use flow analysis, and how to verify and use the results.

Application	Description
Mold/runner design	Multiple-mold and runner designs can be analyzed to ensure moldability, properly balance flow, position knit-lines, estimate clamp tonnage or shrinkage rates. Key decisions that are supported include wall thickness, number and location of gates, runner and gate layout, number of cavities per mold, and machine selection.
Unknown material	For a fixed mold design, multiple materials can be characterized and simulated for a fixed mold design to provide comparative estimates of fill pressure, clamp tonnage, cycle time, and shrinkage. Compared with melt flow indexes, flow analysis can provide significantly more accurate results for comparisons. Key decisions that are supported include selection of specific grades from a family of materials, or across multiple families of materials.
Sensitivity analysis	For a fixed mold design and material selection, multiple-flow analyses can be performed to provide the effect of such critical processing conditions as melt temperature, mold temperature, injection velocity, pack pressure, pack time, and cooling time on peak fill pressure, clamp tonnage, shear rates, and shrinkage rates. Key decisions that are supported include relative changes in most processing conditions.

Table 1. Top three uses of flow analysis

Running a Flow Analysis

Despite significant advances in the capability of flow analysis, only little progress has been made with direct integration of flow analysis with molding machine controllers. The reasons are simple: (1) flow analysis requires significant information that may not be readily on the production floor, and (2) simulation technology is not currently capable, and may never be capable, of precisely producing optimal machine settings in a reliable manner. There are several significant sources of error. For instance, the simulation may not model some fundamental process phenomena (e.g., three-dimensional flow effects or uncharacterized complex material behavior). Moreover, even if one assumes a perfect simulation, there are many physical aberrations that can induce error. Such instances may include unmodeled mold geometry, shut off and leakage of the melt back into the screw during injection, tuning-dependent and unmodeled molding machine dynamics, and so on.

As a result, the design and manufacturing team must work together to ensure that the analysis is using the correct set of mold designs, material properties, and process conditions. Assumptions and issues surrounding each of these three areas will next be discussed. Afterward, the module will describe how the team can interpret and use the analysis results.

Geometry Assumptions

A big advantage of flow analysis is that it allows virtual molding for molds that have not been created. The computer models the flow through the mold with a mesh made up of triangles or pyramids, called *elements*. By using many small elements as shown in Figure 2, the mesh can approximate the true complex three-dimensional geometry of the mold design.

The accuracy of the results will generally improve as the number of elements increases. The computation time required to perform an analysis, however, increases significantly with the number of elements. The conversion of the part's computer-aided design to a discrete finite element mesh occurs in a step called *preprocessing*. Many flow analyses now have automatic preprocessing for automatic generation of the finite element mesh; however, the quality of the mesh should be verified to ensure that the geometry is correctly represented and essential features of the product have not been deleted.

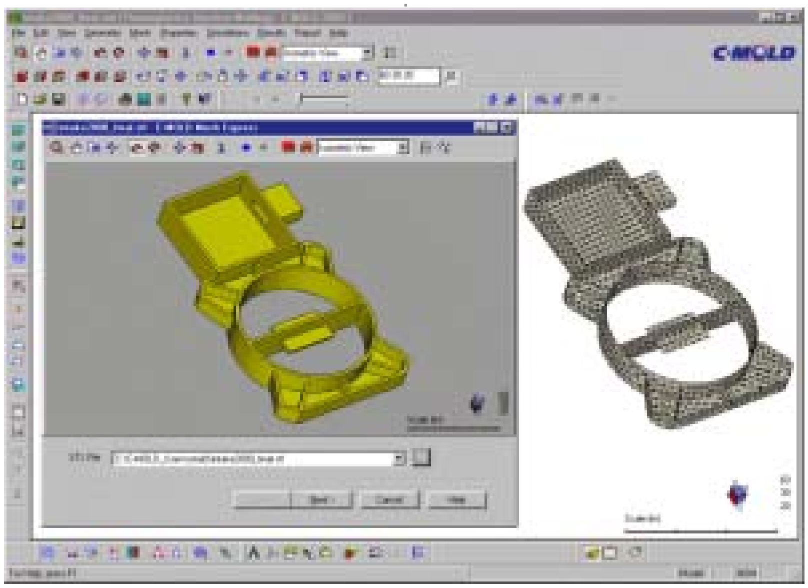


Figure 2. Finite element mesh. *[Courtesy of Moldflow Corporation.]*

The flow analysis will assume that the mesh perfectly represents the three-dimensional geometry of the mold. All commercial analyses assume that the mold is perfectly rigid with no deflection, and that the thickness of the mold and geometry of the gates are correct. Problems with flow analysis often stem from two common errors in the geometric modeling:

1. *Feed system not modeled.* Many flow analyses assume that the melt is directly injected from the nozzle into the center of the part. This assumption is made because the gate locations, gate size, and runner layout are unavailable. Without the feed system, however, the analysis cannot properly predict the pressure drop through the feed system, or the proportion of flow going through each of the gates. Always question results that were generated without a feed system, and request another set of analysis runs with a reasonable estimate of the feed system.

2. *Mold geometry inaccurate.* Because analysis can be performed throughout the plastic part development, the computer design used for the analysis may not accurately reflect the geometry of the final tooling. Change orders specifically are frequently made to gate location, gate size, and even wall thickness that are never fed back to the flow analysis. Always verify that the computer design of the mold matches the actual mold design.

Material Assumptions

Flow analyses require a significant amount of information about material behavior. The behavior includes thermal properties (e.g., thermal conductivity, specific heat, and density) as well as rheological properties (e.g., viscosity). Depending on the type of flow analysis that is required, highly specialized material characterization experiments may be required to generate data to model the material behavior.

For the most commonly used materials, it is likely that all the material models required by the flow analysis exist. Problems with flow analysis, however, often stem from two common errors in the material modeling:

1. *Use of incorrect material.* If a molding job requires a flow analysis for a material that has been not been characterized, properties for a similar material are frequently utilized. For instance, it may be a reasonable assumption to use an existing viscosity model for similar grades of polypropylene. Always verify that the material model is representative of the material to be used for

molding. Using grades with similar names will frequently lead to errors because the grades have different filler contents or operating ranges!

2. *Incorrect material characterization.* Even when the exact material to be used in a molding job has been characterized, significant errors may occur when the material was characterized at process conditions that do not reflect those of the molding process. To be specific, the range of melt temperatures should go from 20ºC below the lower processing temperature up to the upper processing temperature.

Processing Assumptions

Flow analyses also require estimates of the machine set-points at which to process the material. Knowledge of the exact process conditions are unfortunately, not precisely known before the mold is trialed at the machine. Even worse, there is sometimes no direct correlation between the flow analysis parameters and the machine set-points. Melt temperature, for instance, is assumed as a constant in the analysis, but it is really a complex function of the barrel temperature, screw rotational speed, and backpressure during plastication.

When processing conditions are missing, the analysis may estimate them from the material characterization ranges and/or the size of the part. Always verify that the process parameters used in the flow analysis closely match the process conditions to be used during actual molding. It is amazing how well materials seem to flow 50ºC greater than their specified temperature range, when in fact these set-points are nowhere near a feasible process window.

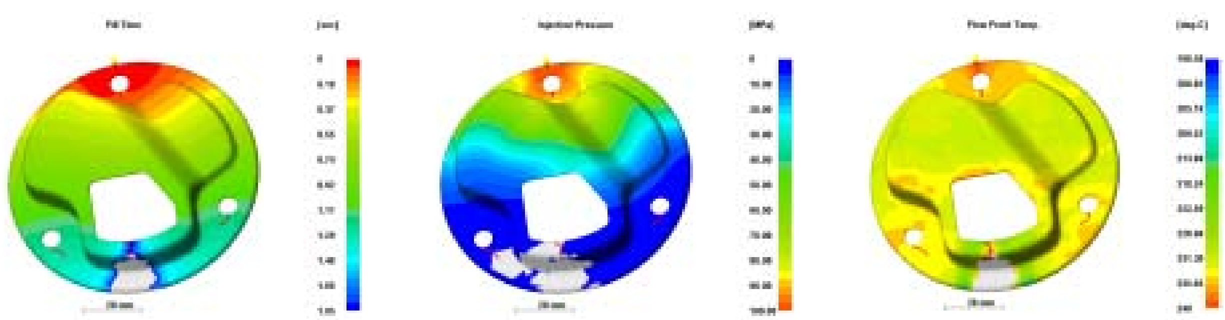
INTERPRETING RESULTS

Flow analysis can provide estimates of any process variable, anywhere in the mold, at any time during the molding cycle. There is so much information that sometimes many of the results will go unused. It is therefore important to know what purpose the flow analysis is serving, and to review the right type of results output. There are typically three different kinds of output results: (1) contour plots, (2) history traces, or (3) sensitivity graphs. The interpretation of each of these outputs will next be discussed, prior to concluding the module with a discussion of best practices.

Contour Plots

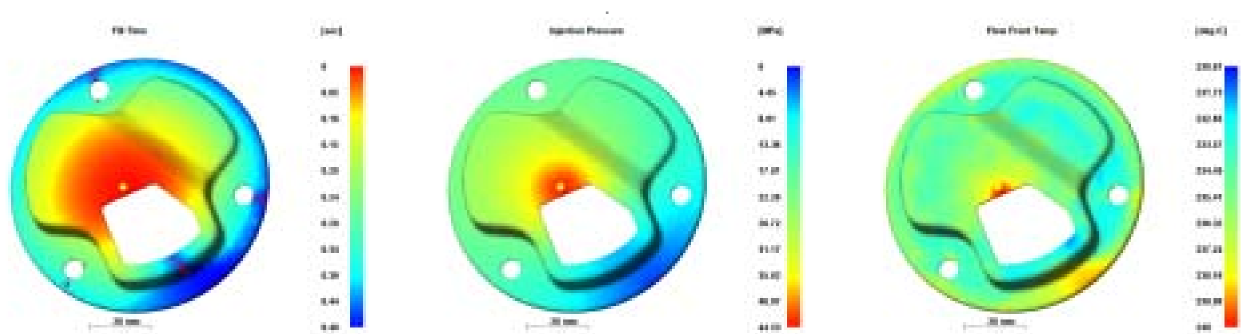
Contour plots are those red, green, and blue three-dimensional pictures that look like the molded part, as shown in Figure 3. Contour plots are typically used to indicate the distribution of fill time, pressure, temperature, or other process variables across the molded part. In general, each banded region represents the magnitude of the process variable.

The three most common contour plots are melt front advancement, cavity pressure, and bulk melt temperature. In Figure 3(a), the fill time contour plot indicates the location of the melt at different moments in time—each contour line corresponds to the melt front in increments of



(a) fill time　　b) cavity pressure　　c) melt front temperature

Figure 3. Common contour plots.



(a) fill time b) cavity pressure c) melt front temperature

Figure 4. Contour plots for revised design and process.

0.18 seconds. The contour lines can be used to estimate the position of knit-lines, where two melt fronts come together. In this example, there are four knit-lines formed by the windowed sections of the part and identified by the lines in the fill time contour plot.

Figure 3(b) shows a pressure contour plot at the end of fill for the same molding job. Because the cavity pressure varies during the molding cycle, it is necessary to specify the time at which to examine the pressure distribution. The pressure at the end of the filling stage is most frequently used to indicate a balanced fill. If one area of the mold cavity fills before the rest of the mold, the stagnating flow will generate high local pressures that may cause flash, high residual stress, or dimensional defects. In this example, the pressure is very high near the gate.

Figure 3(c) shows a bulk temperature plot at the end of the filling stage. Because the temperature of the plastic varies from the skin (very cold) to the core (very hot), the bulk temperature is simply an average of the temperatures across the thickness. Variations in bulk temperature from one area of the part to the other have been shown to cause significant warpage. Such bulk temperature variations are normally caused by poor gate locations, processing conditions, and significant wall thickness variations in the part. In this example, the pressure-limited fill causes the melt front to cool significantly before filling the part.

In the previous example, the previous gate selection and process parameters were poor. The contour plots shown in Figure 4 were achieved by moving the gate to the center of the part and decreasing the fill time. The results indicate that the knit-lines have been moved to the exterior edge of the part, the pressures are lower and more uniform, and the melt front temperatures are nearly uniform. These changes would likely increase the quality of the part while allowing for more cavities per mold and faster cycle times.

There are other types of contour plots that can also be generated, including orientation, residual stress, shrinkage, shear stress, and others. Contour plots are very useful for supporting critical design and processing variables (e.g., number and location of gates, wall thickness, and approximate processing conditions).

History Traces

Contour plots are useful for showing a process variable across the mold cavity at an instant in time; however, they do not show the process history at a given location throughout the molding cycle. For this reason, it is useful to plot history traces. The most common history traces plot injection and cavity pressure as a function of time throughout the molding cycle. These traces can be used to identify critical process events (e.g., when the melt reaches the gate or when the mold cavity is filled). As such, flow analysis can provide information at any point or any location that could otherwise only be received with a sensor.

Figure 5, for example, shows the injection pressure and cavity pressure for the molding of a part similar to that shown in Figure 3. Note how the injection pressure climbs quickly as the melt

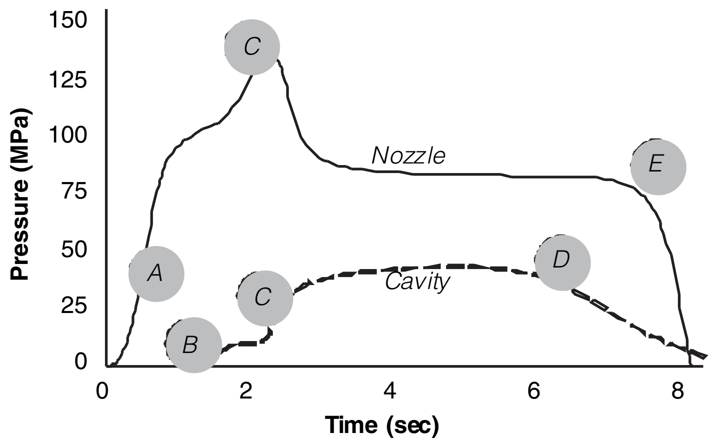


Figure 5. Pressure history traces at nozzle and cavity.

pushes through the gate (A), then again toward the end of the cycle (C). The cavity pressure (B) similarly indicates that there is a loss of 70 MPa (10,000 psi) going through the runner system, that the cavity begins filling at 1.5 seconds, that the cavity is completely filled (C) at 2.25 seconds, and that the gate freezes around 6.0 seconds (D). Such results can be very helpful when adjusting gate design, choosing the packing time, or understanding the processing behaviors.

Sensitivity Analysis

By running many analyses for different mold designs, material types, or process conditions, flow analysis can be used to understand the potential sensitivity of process performance. Such analysis is vital when selecting nominal wall thickness, choosing between multiple materials, or optimizing process conditions. Figure 6, for example demonstrates the required clamp tonnage of molding a part for two different materials.

If a molder needs the job to run on a 300-ton machine, the sensitivity analysis indicates that the minimum wall thickness is 3 mm for material A and 3.5 mm for material B. Because a thinner material is desired if stiffness is not an issue (i.e., less material consumption and lower cycle time), then material A may be selected with a wall thickness of 3.2 mm and may be specified to leave some margin for error.

After selecting the material and wall thickness, the molder may wish to minimize cycle time by ensuring that the maximum fill pressure is less than 100 MPa (14,500 psi). To support this decision, the sensitivity of fill pressure to melt temperature and mold temperature may be investigated as shown in Figure 7. As such, the molder chooses to utilize as

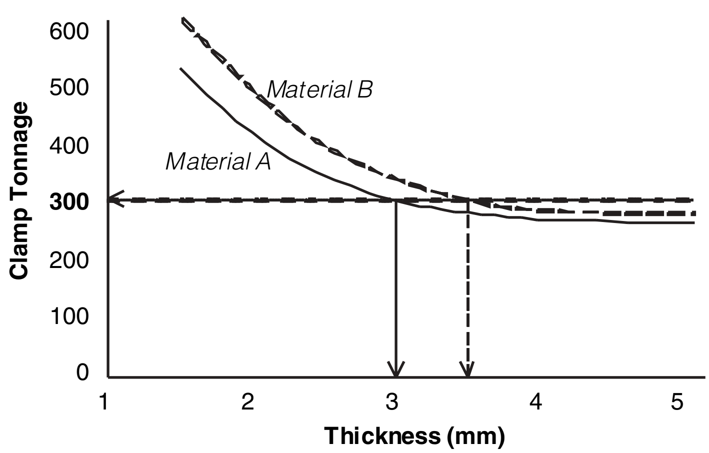


Figure 6. Using sensitivity plot to choose thickness for 300-ton machine.

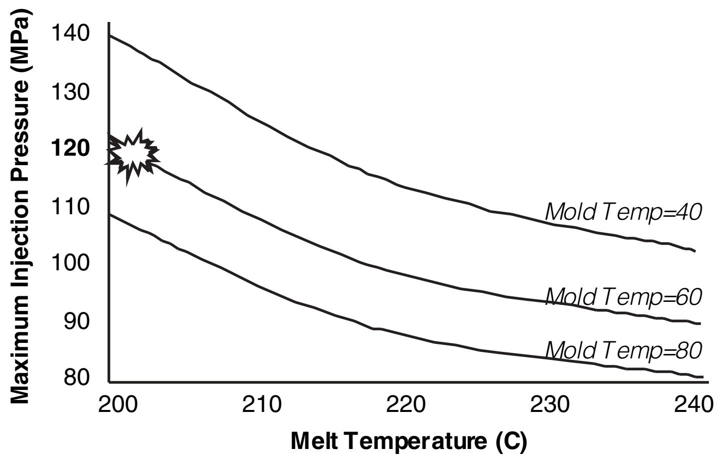


Figure 7. Using sensitivity plot to choose temperature for 120 MPa injection pressure.

low a melt temperature as possible with a moderate mold temperature.

BEST PRACTICES

Know When and How To Use Flow Analysis

Flow analysis cannot be used to do the impossible, but it can help to support critical decisions about the mold design, material selection, and process optimization. It is important to understand the capabilities and limitations of flow analysis. To be specific, the best practitioners of flow analysis:

- use analysis early and frequently in the mold tooling and processing stages
- know exactly why they want a flow analysis and what they can get out of it
- understand how to convert the simulation results (temperature, pressure, etc.) to estimates of part quality (short shot, flash, dimensions, appearance, etc.) that they can use in their shop

Make Sure The Analysis Was Run Correctly

Flow analysis makes many assumptions about the mold design, material behavior, and process conditions. These are really idealized and may not represent the actual state of the molding job. The best practitioners of flow analysis:

- always verify that the computer design of the mold matches the actual mold design
- always verify that the material model is representative of the material to be used for molding
- always verify that the material was characterized at temperatures from 20ºC below the lower processing temperature up to the upper processing temperature
- always verify that the process parameters used in the flow analysis closely match the process conditions to be used during actual molding

Using Results

Flow analysis can provide estimates of most processing variables at any point in the mold at any time during the molding cycle. Knowing what results are important, how to use the results, and questioning their accuracy is vital to utilizing flow analysis effectively. The best practitioners of flow analysis:

- always question results that were generated without a feed system, and request another set of analysis runs with a reasonable estimate of the feed system
- use contour plots to indicate the process variable across the mold at an instant in time
- make sure that contour plots use similar scales when doing direct comparisons

- use history traces to track the value of a process variable (like injection pressure) at a given point during the molding cycle
- use history traces to explain critical events during the molding cycle
- use sensitivity plots to make critical decisions about mold design, material selection, and process optimization
- use a reasonable factor of safety to ensure a margin for error—reducing the maximum allowable injection pressure or using temperatures lower than the known upper limit are two methods to leave room for process adjustment

Staying in the Loop

Finally, the best practitioners of flow analysis:

- document the flow analysis results
- convert the flow recommendations into action items
- implement the actions
- report back on the outcome of the actions, share in the team success, or suggest corrective action when things go wrong

FLOW ANALYSIS WORKSHEET

Application: ____________________

Responsible Personnel

Part Design & Company: ____________________
Tooling Designer & Company: ____________________
Process Engineer & Company: ____________________
Flow Analyst & Company: ____________________

Geometry Inputs

Wall Thickness: ____________________
Size (Width x Length x Depth): ____________________
Number of Gates: ____________________
Runner Layout: ____________________
Number of Cavities Per Mold: ____________________

Processing Condition Ranges

Melt Temperature: ____________________
Mold Temperature: ____________________
Max. Injection Pressure: ____________________
Injection Time (or Ram Velocity): ____________________
Pack Pressure: ____________________
Pack Time: ____________________

Critical Performance Parameters

- ❏ Aesthetics
- ❏ Balanced Flow
- ❏ Clamp Tonnage
- ❏ Cycle Time
- ❏ Flow Length/Fillability
- ❏ Knit Line Location
- ❏ Shrinkage/Tolerances
- ❏ Strength
- ❏ Other: ____________________
- ❏ Other: ____________________

Type of Analysis to Be Run

- ❏ Mold Design
- ❏ Material Selection
- ❏ Sensitivity Analysis
- ❏ Other: ____________________

Notes Regarding Need for Analysis:

Schedule & Responsibility

Part Design Completed
❏ ____________________

Mold Design Completed
❏ ____________________

Material Selected
❏ ____________________

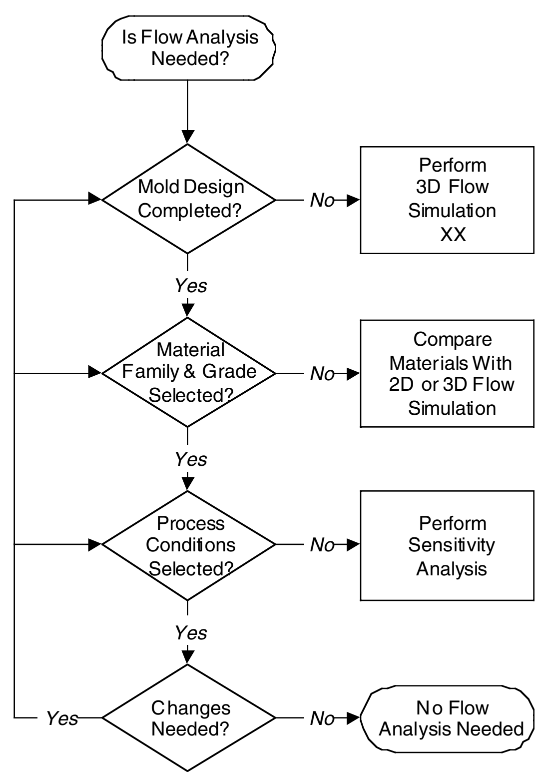
Process Conditions Verified
❏ ____________________

Analyses Performed
❏ ____________________

Analyses Verified
❏ ____________________

Decisions Implemented
❏ ____________________

Feedback Provided
❏ ____________________



Analysis Recommendations

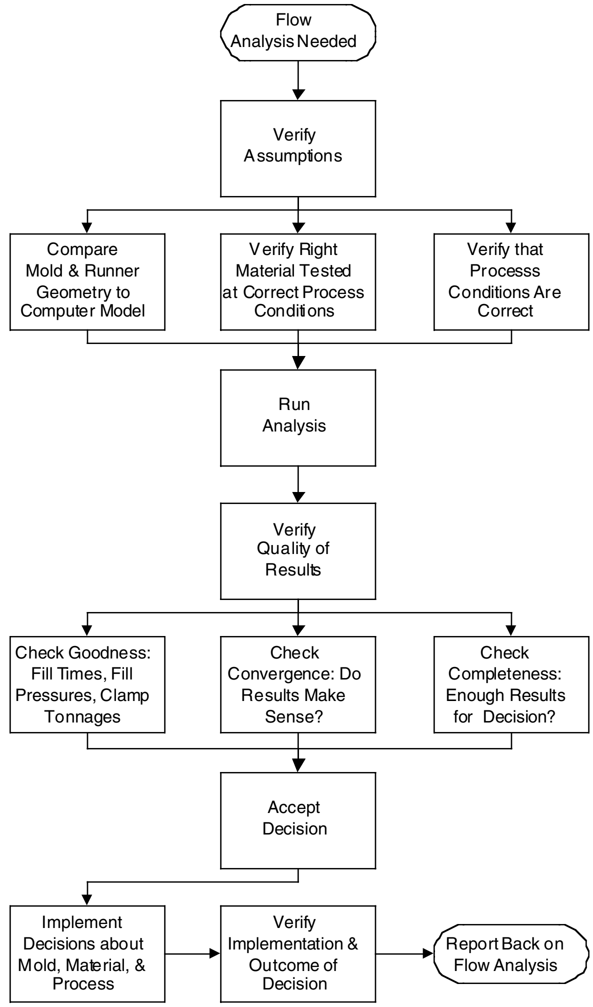
Final Decisions

Decision Implementation & Outcome

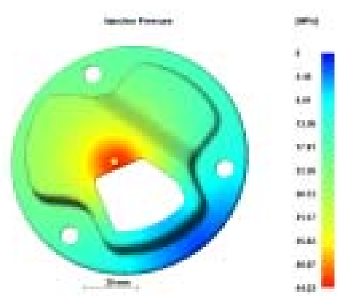
Feedback to Team

Interpreting Results

Flow analysis can provide estimates of most processing variables at any point in the mold at any time during the molding cycle.

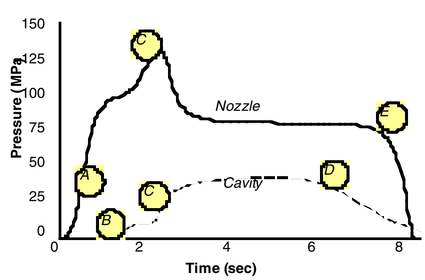


Contour Plots



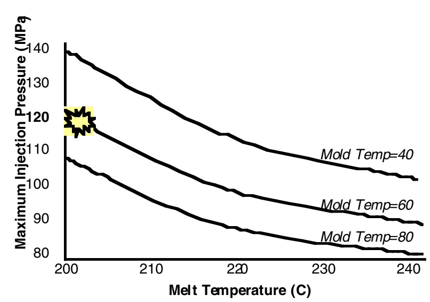
Use contour plots to examine the process variable across the mold at an instant in time. Contour plots support critical design and processing variables such as number and location of gates, wall thickness, and processing conditions.

Time History Traces



Use history traces to track the value of a process variable (like injection pressure) at a given point throughout the molding cycle. Traces support adjustments in gate design and packing time, or help to understand the processing behaviors.

Sensitivity Plots



Use sensitivity plots to show the effect of process variables on process performance. Sensitivity plots support critical decisions about mold design, material selection, and process optimization. Use a reasonable factor of safety to ensure a margin for error.