XI. Determining Cooling Stage Parameters

- **Understanding Your Product**
- **Cooling Time**
- **Mold Temperature Optimization**
- **Other Parameters That Affect Cooling**
- **How is a Cooling Experiment Optimized?**
- **Summary**

Universal Molding™ is a discipline that promotes a structure of organized events.

- Auxiliary equipment should be properly installed and correctly operating.
- Temperatures should already be reached.
- Barrel adjustments should have been programmed.
- The required closing force should have been set.
- The platen openings, their movement, speeds, and mold protection should have been carefully and precisely adjusted.
- Extended cooling time should have been set, in order to prevent it from interfering with the determination of other parameters.
- The ideal injection speed should have been determined, adjusted and should be filling about 95% of the required fill for the mold.
- The injection pressure limit should have been determined and adjusted.
- The fill balance should have been verified and adjusted.
- The hold pressure and time should have been determined and adjusted.
- The remaining cooling time should have been adjusted.

Important -- only qualified personnel who have read the operational manuals of the equipment and understand the functionality of the equipment should operate and/or make adjustments.

Understanding Your Product

Optimizing the cooling stage will depend on the type of product. Before making decisions, ask yourself the following questions:

1. What effects am I looking to optimize in the cooling stage?
2. Is shrinkage significant in the product?
3. What factors or parameters must be evaluated that could contribute to the thermal effect or effects?

There are basically two parameters that should be optimized, cooling time and cooling temperature. There are also other parameters that could affect heat removal and, consequently, the thermal dimensions and the properties of the molded product. An example of this is melt temperature; hot melt will require more heat removal during cooling than a cooler melt would.

The melt temperature recommended by the resin manufacturer may require an adjustment. Molds that are difficult to fill may require increasing the melt temperature. Remember that changing the melt temperature means a change in viscosity. Filling cavities with thin walls could require more energy and less viscosity than cavities with thick walls, even when both are filled with the same thermoplastic.

Understand your product before deciding which parameters might be significant in the cooling stage. The thermal effect you are looking to optimize could be a function of one factor (mold temperature), two factors (mold temperature and cooling time) or three factors (mold temperature, cooling time, and melt temperature).

Cooling Time

We know that long operational cycles can be costly; consequently, the cooling time should be reduced as much as possible. To reduce the cooling time, it is recommended to carefully lower it until you get the minimum time needed to demold parts that are visually acceptable.

Extreme caution should be taken during this process; parts trapped inside the mold could result in costly damage.

In molds with cold runners, the runners could be used as a reference at the moment of demolding. The runner is usually thicker than the molded parts, and how it demolds could be used as a reference for the reduction of the cooling time.

Reducing cooling time is the first step; this does not mean that we have finished its determination. It will probably have to be modified to guarantee some dimension or property of the molded parts, even combining it with other parameters to achieve cooling optimization.

Optimization Using the Mold Temperature

This procedure is the simplest and probably where everyone should begin.

1. Determine the minimum cooling time.

Carefully, and without reaching the recovery time, reduce the cooling time until you get the least amount of time required to demold visually acceptable parts.

If the cooling time reaches the recovery time and the mold and material allow the cooling time to be further reduced, you should try to reduce the recovery time. If the process permits, reduce the recovery time by increasing recovery speed. Then, verify the melt temperature, which is likely to have increased.

Procedure for measuring melt temperature

1. Ensure that the process has operated normally for at least ten cycles.
2. Preheat an instrument to 25°C below the desired temperature. Digital mini-blowers are an economical option for preheating.
3. Stop the process (e.g., switch to semi-automatic mode). Once the mold opens, retract the injection unit and purge the melt. You can do this on a removable surface for easier access.
4. Adjust the instrument to maintain the highest recorded temperature. This eliminates subjectivity when searching for the melt stabilization temperature.
5. Submerge the instrument into the melt and agitate it. When you notice the temperature starting to decrease, remove the instrument and note the peak temperature obtained. Follow all safety rules.

Note:

- Use safety equipment such as uniforms, gloves, and goggles.
- Adapt this protocol to your processes and ensure that everyone measures melt temperature in the same way.

Increasing the rate of recovery also increases friction, resulting in increased temperature and decreased melt viscosity. Two factors that could affect rheology are hold and fill balance. In other words, it would affect all laboratories carried out so far which is why, after increasing the rate of recovery, the temperature of the melt should be measured. If changed, you must adjust the heat zones of the barrel until reaching the temperature of the previous melt.

Again, avoid closing the mold with parts inside; this could cause expensive damage.

2. Organize and create a table for your experiment.

Select a range for your experiment, for example, 70 ± 4°F. This range can be obtained from the material data sheet, from the mold manufacturer, or from a trusted molder who has molded with this material or with a similar product. Decide how many times each experiment will be repeated. Do not overload the experiment, three to five repetitions should be enough.

Include the following in the table:

- the two temperature levels.
- the number of repetitions, three for each temperature.
- spaces for the random order in which the experiments will be performed.
- spaces for the molded parts' dimensions or attributes which are being evaluated.
- spaces for the averages of the measurements.

Temp.	**Rep.**	**Random order**	**Measure**	**Average**
T_{low}	1	4	M_4	$\frac{M_4+M_1+M_6}{3}$
	2	1	M_1	
	3	6	M_6	
T_{high}	1	3	M_3	$\frac{M_3+M_2+M_5}{3}$
	2	2	M_2	
	3	5	M_5	

XI-1. Mold temperature optimization experiment table

If the attribute you are measuring is a visual and subjective effect, set a judgement scale. For example, select a person who understands the effect being measured and ask them to evaluate the effect from 1 to 4, where:

1 = no defect
2 = insignificant defect
3 = notable defect
4 = unacceptable defect

Strange as it may seem, randomizing the temperature changes in the experiments gives results that are closer to reality than when using ordered changes in temperature. Randomized changes lessen the possibility of human error.

3. Write a protocol on how to perform the laboratory.
   Reduce any objectivity by writing specific procedures that everyone must follow.

Example of a simple protocol:

a) Verify that the cooling water source (chiller or cooling tower) that supplies the mold's water temperature control is at least 5°C (9°F) colder than the lowest temperature you expect to program.
b) Determine water temperature limits that correspond to the mold temperature limits. Remember that the water temperature to the mold is normally different from the temperature of the metal of the cavities.
c) Between experiments, stop the machine until reaching the adjusted temperature.
d) Once the temperature is reached and the machine is operating normally, wait 10 cycles to take the sample.
e) Measurements should be taken by the same person in the metrology laboratory with a calibrated instrument.
f) Measurements will be performed in order, for example, two hours after each demolding.

4. Perform the laboratory and enter the results in the table.
   Follow the protocol procedures that were approved for this laboratory and perform your experiments, complete the table, and calculate the corresponding averages.

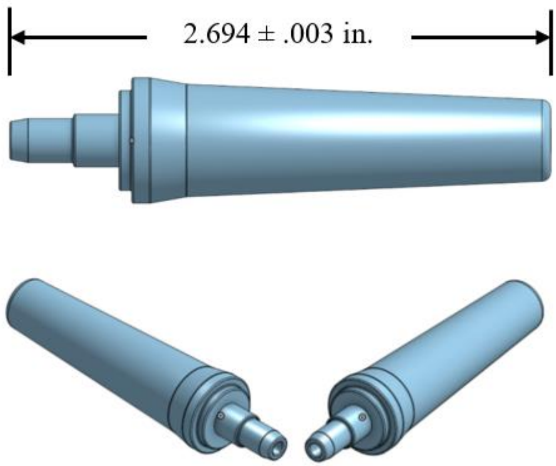
5. Evaluate the results.
   Evaluate the results and select a temperature range that guarantees the measurement of the parts or of the effect that you are looking for.

6. Corroborate the ranges of the selected temperatures.

Inside the limits of the selected temperature, take multiple samples at distinct periods, and verify that the results comply with the prediction of the effect that is being studied.

Example:
This exercise was performed by students at the University of Puerto Rico, Mayagüez campus. The material used is low density polyethylene (LDPE) with a two-cavity mold.

The laboratory was performed in order to evaluate the effect of the mold's temperature on shrinkage. Students decided on the following critical measurement:



XI-2. Example of parts of a two-cavity mold

The resin manufacturing data sheet listed a range of 70°F to 90°F for the mold temperature.

Experiment protocol:
- Two temperature levels, 70°F and 90°F.
- Three repetitions per temperature level.
- Each experiment was randomized.
- Cooling time was set to 18 seconds.
- The machine was stopped between experiments until it reached the adjusted temperature.
- Once it began operating, the sample was taken after the 10th cycle.

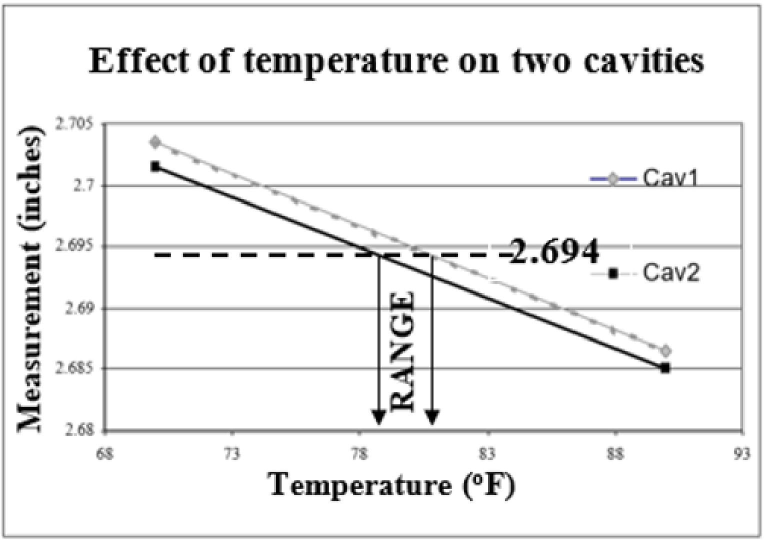
- Measurements were taken in order, two hours after demolding.
- The same person took all the selected measurements.
- An operator verified that the mold never closed with parts trapped inside the cavities during the experiment.

Experiment results:

Mold Temperature (°F)	Average Length (inches)	
	Cavity 1	Cavity 2
70	2.7035	2.7015
90	2.6865	2.6850

XI-3. Table with effects of mold temperature on critical measurement

To understand the effect, graphs of temperature versus dimension were created, one for each cavity.

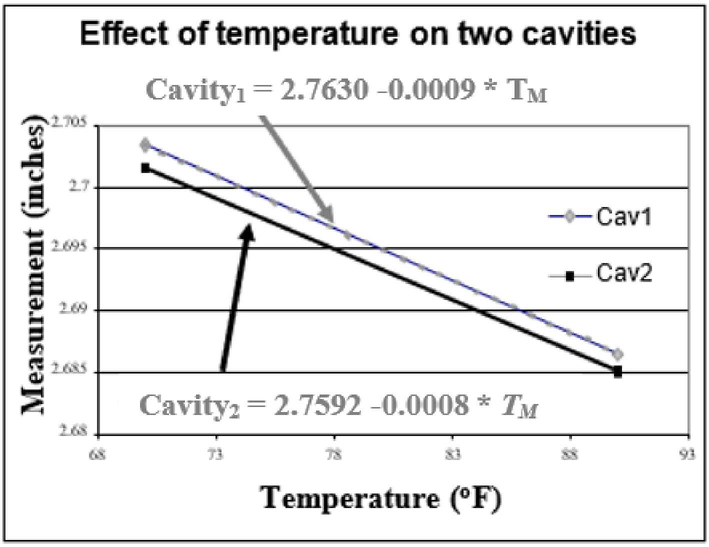


XI-4. Graph of mold temperature effect on critical measurements

The graph of length vs. temperature reveals a clear effect of the temperature on the length of the pieces. By drawing a line at the average length of 2.694 inches, we can predict that Cavity 2 should be around 78°F and Cavity 1 should be around 80°F to ensure the average length.

With a prediction equation for each cavity, we can simplify the selection of an acceptable temperature range. In this example, the equation is simple since it is the equation of a line; $Y = Y_o + MX$, where Y is the measurement of the part, Y_o is the intercept of the measurement coordinate, M is the slope, and X is the temperature of the mold. The value of these constants can be found using simple mathematics or with Excel.

Normally two points are enough, but if you suspect that the results are not linear, intermediate points can be used.



XI-5. Graph showing linear equations using temperatures and measurements of a two-cavity mold

By solving for temperature, we get:

$$T_{M1} = (2.7630 - \text{cavity length}_1) / 0.0009$$
$$T_{M2} = (2.7592 - \text{cavity length}_2) / 0.0008$$

Substituting the dimensional limits (2.694 $\pm$ 0.003) of 2.697 inches and 2.691 inches in both equations, we obtain the following:

	Upper dimension 2.697 in.	Lower dimension 2.691 in.
Cavity 1 temperature range	73 °F	80 °F
Cavity 2 temperature range	78 °F	85 °F
Operational Range	**78 °F**	**80 °F**

XI-6. Table with temperature limits at critical measurements of two parts

Let's evaluate the results: if the mold temperature is set to 73°F, Cavity 2 will be outside of the range, since its minimum is 78°F; if the temperature is set to 85°F, Cavity 1 will be outside of the range since its maximum is 80°F. The operational range would then be between 78°F and 80°F.

Other Parameters that Affect Cooling

Although the cooling stage's control parameters are cooling time and mold temperature, we must recognize that the melt temperature contributes as well.

Imagine that, after performing the previous mold temperature laboratory, a product requires better thermal dimensional control. A decision was made to optimize these thermal dimensions by evaluating the contribution of three factors:

T_M = temperature of the mold
t = cooling time
T_m = temperature of the melt

The critical dimensions could be represented by the following linear equation:

$$\text{Critical dimension, } D_C = \bar{D}_C + \beta_0 T_M + \beta_1 t + \beta_2 T_m + \beta_3 T_M t + \beta_4 T_M T_m + \beta_5 t T_m + \beta_6 T_M T_m t$$

where:

$\bar{D}_C$ = average measurement
$\beta_o T_M$ = effect of the mold temperature
$\beta_1 t$ = effect of the cooling time
$\beta_2 T_m$ = effect of melt temperature
$\beta_3 T_m t$ ……$\beta_6 T_M T_m t$ = combined effects
and the symbols β_o to β_6 are constants.

This type of exercise assumes that the behavior is linear. If the ***Universal Molding***[TM] laboratory is performed in the recommended order, those who have a good understanding of the morphology of thermoplastics, thermal dimensions, and mass dimensions will be able to select reasonable experimental ranges for each factor.

If the experimentation ranges are very large, e.g. $\pm 10^{o}$F for the melt temperature, you can be sure that the results would be nonlinear, and a more complex equation would be required.

The selection of factors is important; assigning an effect to multiple factors, such as temperature of the mold, cooling time, temperature of the melt, and hold pressure, without fundamentals would complicate and make the laboratory more expensive. Most effects are corrected by experimenting with a single parameter. For example, a critical dimension in a semi-crystalline material is likely to be controlled with the temperature of the mold. Avoid complicating the cooling laboratory.

Let's look at another example where we suspect that the hold pressure has a significant effect on the dimensions of the product. In this laboratory, it is assumed that the critical dimensions, in addition to being a thermal function, are also a function of the quantity of material (mass dimensions) and should consider two factors:

T_M - temperature of the mold
P - hold pressure

Critical dimension, $D_C = \bar{D}_C + \beta_0 T_M + \beta_1 P + \beta_2 T_M P$

Where:

$\bar{D}_C$ = average measurement
$\beta_o T_M$ = effect of mold temperature
$\beta_1 P$ = effect of hold pressure
$\beta_2 T_M P$ = combined effect

A combined effect is when two or more factors, or parameters, join to influence the effect being evaluated. A hypothetical example: two employees work separately, doing the same job. Their job is packing molded products into boxes, and each employee packs 50 boxes a day. One day they decide to work as a team; one assembles the boxes and fills them with product, the other seals them closed and stacks them. At the end of the day, they pack 120 boxes. The combined effect was to pack 20 more boxes per day. This also happens when two parameters combine and create an effect on the molded product.

How is a Cooling Experiment Organized?

1. Establish an objective and the effect, or effects, to be measured.

2. Identify which factors or parameters are presumed to have some effect and how they are related to the effect to be examined. Selecting these factors is probably the most delicate part of this process. Include only those factors that have a high probability of influencing the effect being evaluated on the molded product. An exercise of more than one parameter or factor consumes time and resources; be careful with your design or you could end up with inconclusive results. Most cooling laboratories are carried out with a single factor, mold temperature.

3. Select the limits, or ranges, of each factor. Here you must be quite judicious; too large a range could create nonlinear results, create inconclusive results, or could complicate the experiment. Too small a range could reveal no contribution to the effect, even though some may exist.

4. Create a table for your results; include spaces for the variables of the effects and their combinations, the number of repetitions, and number of experiments.

	Process Factors		**Repetitions**		
	T_M (°C)	**t (s)**	**I**	**II**	**III**
1	20	4	1	2	3
2	20	12	4	5	6
3	25	4	7	8	9
4	25	12	10	11	12

XI-7. Table of cooling parameters (temperature and time), with their combinations and their repetitions

5. Write a protocol on how to perform the lab.

6. Perform the laboratory, and take samples as indicated in the written protocol.

7. Evaluate the data and obtain results. If the laboratory uses two factors (ex: cooling time and mold temperature) with a mold that contains only a few cavities (four or less), data analysis could be performed with Excel. However, when there are more than two variables and more than four cavities, you will need to use a statistical program.

Results should reveal significant and insignificant factors, as well as significant and insignificant interactions.

Summary

- Begin the optimization of the cooling stage by finding the minimum cooling time that produces parts that can be demolded and are visually acceptable.
- The first laboratory should only be performed with the mold temperature.
- Consider a second factor only when the cooling stage cannot be optimized with the mold temperature.
- When the effect is an attribute, for example, a visual or physical defect, select one person who knows how to evaluate the effect, and establish some numerical evaluation system that represents the criteria for acceptance.
- In order to reduce the possibility of objectivity on the part of those performing the laboratory, create a written, step-by-step protocol that must be followed.
- If the laboratory is for two factors (e.g. cooling time and mold temperature) with a mold that only has a few cavities (four or less), data analysis can be created in Excel; with more than two factors and more than four cavities, use a statistical program.

Questions

1) When optimizing the cooling stage,
   a. the cooling time is set so it is equal to the hold time.
   b. the pressure and hold time have been determined and adjusted.
   c. the melt temperature remains fixed since it does not affect heat removal or thermal dimensions.

2) When organizing a mold temperature optimization experiment, include more than ten repetitions per experiment in order to obtain more accurate results.
   a. True, the experiment improves when the number of repetitions is increased.
   b. False, do not overload the experiment; three to five repetitions should be enough.

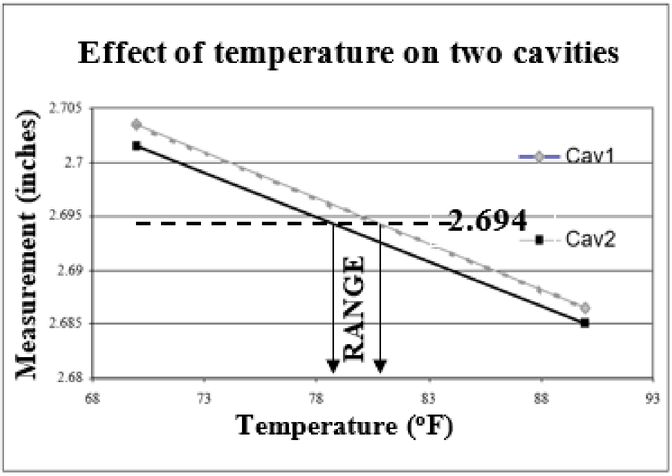
3) Select all the correct statements. While optimizing the cooling stage,
   a. long operational cycles could be costly; consequently, cooling time should be minimized while still guaranteeing demolding and part quality.
   b. extreme caution should be exercised because parts trapped inside the mold can cause costly damage.
   c. in a conventional mold, you must ensure that the cooling time is always greater than the recovery time.
   d. All the above.

4) In a cooling optimization experiment, parameter adjustments made during data compilation should be randomized.
   a. True, since random changes lessen errors as a result of human convenience.
   b. False, since random changes complicate the laboratory and do not contribute to the experiment.

5) Select all the correct statements. In a cooling optimization experiment,
   a. the chiller or cooling tower that supplies water to the temperature control of the mold must be at least 5°C (9°F) cooler than the lowest temperature you expect to program.
   b. the temperature of the water for the mold is normally equal to the temperature of the metal in the cavities.

c. you should verify the results with values outside of the operational ranges obtained from the experiment.

6) The graph demonstrates the effect of the mold temperature on one dimension of the molded parts. For a dimension of 2.694 inches, what would be the recommended temperature?



a. 80°F
b. 83°F
c. 73°F

7) If you decide to optimize cooling dimensions by evaluating the contribution of three factors,
   a. a laboratory of three parameters or factors consumes time and resources; be careful in your design or you could end up with inconclusive results.
   b. when one of the factors is hold pressure, you should assume that the evaluated dimension is a function of mass dimensions.
   c. when one of the factors is melt temperature, you should assume that the evaluated dimension is a function of mass dimensions.
   d. both a and b are correct.

8) In a two-factor experiment for mold temperature (T_M) and melt temperature (T_m),

Critical dimension, $D_C =$

$$\bar{D}_C + \beta_0 T_M + \beta_1 T_m + \beta_3 T_M T_m$$

It was found that mold temperature (T_M) and melt temperature (T_m) were significant and that their combined effect was not significant. The equation could then be reduced to

a. $D_C = \bar{D}_C + \beta_1 T_m + \beta_3 T_M T_m$
b. $D_C = \bar{D}_C + \beta_0 T_M + \beta_1 T_m$
c. $D_C = \beta_0 T_M + \beta_1 T_m$

9) In an experiment with three factors, mold temperature (T_M), melt temperature (T_m), and cooling time (t), the following linear equation is used:

Critical dimension, D_C =

$$\underbrace{\bar{D}_C}_{(\ \ )} + \underbrace{\beta_0 T_M}_{(\ \ )} + \underbrace{\beta_1 t}_{(\ \ )} + \underbrace{\beta_2 T_m}_{(\ \ )} + \underbrace{\beta_3 T_M t + \beta_4 T_M T_m + \beta_5 t T_m + \beta_6 T_M T_m t}_{(\ \ )}$$

Write the number of each description below its corresponding component of the equation.

1. average measurement
2. effect of cooling time
3. combined effects
4. effect of melt temperature
5. effect of mold temperature