The results of the equation for T_r is rounded to the next whole number, since decimals represent the fraction of uninjected melt that will reside in the barrel for an additional cycle, and not a fraction of a cycle.

The unit of residence time is cycles since we are molding from the desk and do not know the final duration of the cycle. Once molding is complete and we know the optimized cycle duration, it could be converted into seconds.

Another method with equal results is to use the % of Utilization (U%).

$$T_r = \text{Rounded to the next integer of } 140/U\%$$

$$\text{Where: } U\% = [V_{required} / V_{max}]100\%$$

Example:
A 250.5cc barrel is used to mold two molds. One requires 150cc, the other 35cc. What would be residence T_r for each mold?

$T_r = 1.4V_{max}/V_{required}$	=	T_r (to the next whole num.)
1.4(250.5) / 150	2.3	**3 cycles**
1.4(250.5) / 35	10.02	**11 cycles**

VI-36. Table showing example of residence T_r

Or just use the table below:

$U_{\%}$	**T_r (# of cycles)**
1%	140
2%	70
3%	47
4%	35
5%	28
6%	24
7%	20
8%	18
9%	16
10%	14
11%	13
12%	12
13%	11
14% - 15%	10
16% - 17%	9
18% - 19%	8
20% - 23%	7
24% - 27%	6
28% - 34%	5
35% - 46%	4
47% - 69%	3
>70%	2

VI-37. Table of residence time, according to % of utilization

U% based on industry type	Min	Max
General Molding	10%	80%
Precision	20%	65%
Optical Applications	20%	80%
High Speed	15%	40%
Reinforced with Fibers	20%	65%
Rigid PVC	20%	85%

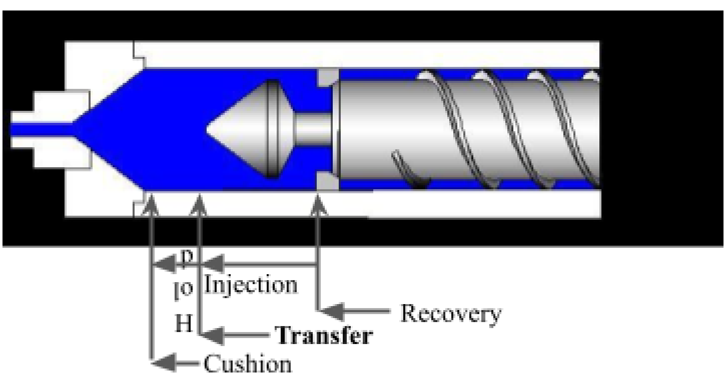
VI-38. Table showing % of Utilization according to industry type

Examples:

- The high-speed industry typically has limited recovery times. Consequently, it will require a low U% (between 15% to 40%), or what would be equal to, for example, high melt residence (4 to 10 cycles), so that the plastic has enough time to melt.
- The heat-sensitive materials industry, such as those which use rigid PVC, demands a high U%, or in other words, low residence times, to avoid material degradation.
- If the U% is very low you could have trouble controlling the cushion, as it would not have enough injection displacement to close the screw's check ring.

Transfer position

The transfer position is the position where the injection ends and hold begins. Remember that transfer is a screw position that corresponds to about 95% of the mold filled with compressible melt.



VI-39. Transfer position

Important facts:

- If the transfer position is too premature, the screw could create the bounceback effect.
- If the transfer position occurs too late, the screw can reach the end of the barrel, or rather zero cushion, and could create short pieces.
- What stops the screw after transfer is the melt in front of the check ring.
- From the barrel's point of view, the transfer position is reached when the injection volume is close to 95%. From the mold's point of view, at the instant at which the transfer position is reached, the volume that the melt occupies in the mold is less than what was injected. Remember that melt is compressible and will gradually expand.

After examining dozens of processes, interviewing multiple molders, and reviewing several manuals of various injection machines, the criteria used to determine transfer position was obtained through experimentation.

With machines under 400 metric tons

% of Utilization	**35% or less**	**65% or higher**	**between 35% and 65%**
Transfer	6 mm (0.25 in)	12 mm (0.5 in)	Interpolate

With machines larger than 400 metric tons

% of Utilization	**35% or less**	**65% or higher**	**between 35% and 65%**
Transfer	12 mm (0.5 in)	25 mm (1.0 in)	Interpolate

VI-40. Tables showing transfer position criteria

Once the transfer position has been obtained, convert it to volume (Universal unit).

Transfer volume

$$= \text{Transfer position x Screw area}$$
$$= \text{Transfer position x (Screw diameter}^2 \text{ x } 3.142 / 4)$$

The change must occur so that the screw's final position is greater than zero and less than the transfer position.

In the event of a defective mold requiring a transfer position other than the calculated one:

- if it is economically viable, repair the mold.
- if it is not, you will have to make the necessary changes and document them.

Examples:

1. A mold installed in a 160-ton press requires a fill volume of 120cc, and the barrel can be filled up to 160cc.

   Percentage of utilization = (120/160) x 100% = **75%**

   Since the % of utilization is greater than 65% and the press is less than 400 tons, the calculated transfer position would be 12mm.

2. A mold uses 50% of a barrel in a 200-ton press. To obtain the transfer position, you would have to interpolate between 6 and 12mm.

3. The recommended transfer position for a mold that uses 30% of the barrel would be 6 mm if the press is less than 400 tons and 12 mm if it is greater than 400 tons.

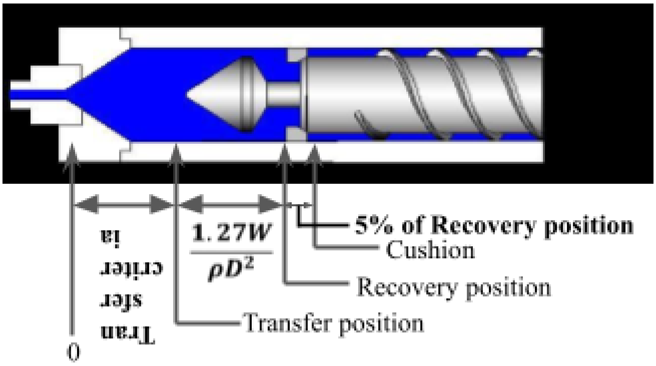
Summary

The screw positions are determined using the following:

Transfer position = use the transfer criteria table

Recovery position = Transfer position + $\frac{1.27W}{\rho D^2}$

Position of the cushion = add 5% to the Recovery position

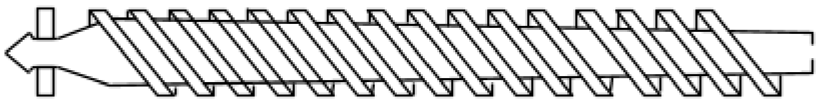


VI-41. Positions of the screw

Remember that you are molding from the desk, determining values that will be verified once the ***Universal Molding***^{TM} lab is performed.

Temperature profiles

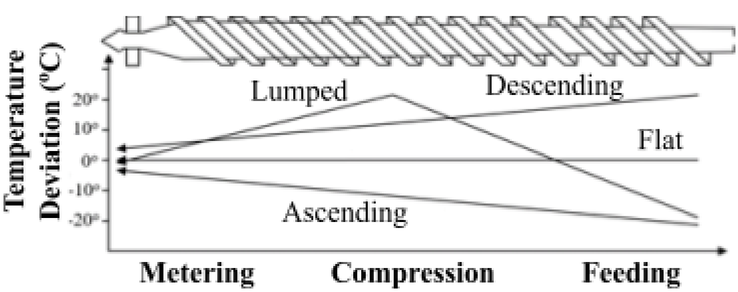
When we talk about temperature profiles, we mean the heat zones of the barrel. Heat zones are metering, compression, and feeding.



Metering **Compression** **Feeding**

VI-42. The barrel's heat zones

These zones are fixed in the barrel, and do not move with the screw. Each zone measures the temperature of the metal. These zones are adjusted to ensure the most significant temperature, the temperature of the melt. The temperature profile for each material should be recommended by the material manufacturer. There are four basic temperature profiles: descending, ascending, lumped, and flat.



The vertical coordinate indicates the temperature deviation, and the horizontal coordinate corresponds to the heat zones.

Ascending profile - Temperatures go from low to high, and this profile is regularly used in situations where the residence time of the plastic is extremely high (% of utilization less than 30%), so that it avoids premature or extended heating of the material.

Descending profile – Temperatures go from high to low, and this profile is recommended for materials with additives and hard-to-melt materials. It is also recommended in operations where residence time is small, with a % of utilization greater than 65%.

Lumped Profile – The initial temperature is low, rises considerably in the compression zone, and lowers in the metering zone. This profile, although little used, is suggested for materials without additives for which the residence time is moderate to high, with a % of utilization from 40% to 65%.

Flat Profile – Here all temperatures are set the same. This could be used with materials with no fillings or additives, in which the residence time is moderate.

Remember that this is a reference, consult with your resin supplier for the most suitable profile for your material. Another reference of information could be the screw and barrel supplier. For example, barrier screws are commonly used with highly semi-crystalline materials, and a descending profile would be recommended in this case.

It is typical for resin manufacturers to provide temperature ranges for each heat zone in the barrel. The high variety of screw types and sizes forces most manufacturers to provide minimum and maximum temperature ranges for each heat zone.

During our molding from the desk, we assign temperatures for each heat zone, considering factors such as the type of material and the residence time.

We use the barrel's percentage of utilization (U%) as our significant variable. If U% is excessively high, we use the upper temperature limit. Inversely when U% is small, we would use the lower temperature limit.

Let's see:

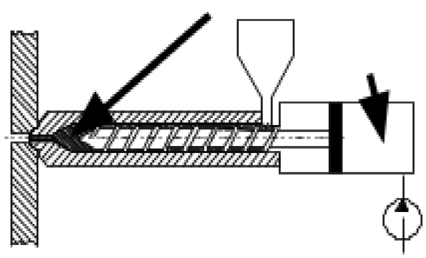
- If the percentage is equal to or less than 35%, use the lower temperatures in each range.
- If the percentage is equal to or greater than 65%, use the upper temperatures in each range.
- If the percentage is between 35% and 65%, interpolate.

Important:

- Thermocouples in the barrel's temperature zones read the temperatures of the metal.
- The most significant temperature is the temperature of the melt.
- Verify the temperatures with the resin supplier or the screw and barrel manufacturer.

Intensification ratio

It is imperative that the relationship between hydraulic pressure and plastic pressure be understood. Plastic pressure is intensified to a ratio of about 10 times the hydraulic pressure.



Hydraulic pressure, P_H
Plastic pressure, P_P

VI-44. Intensification ratio

The intensification ratio (R_i) represents the relationship between hydraulic pressure (P_H) and plastic pressure (P_P).

$$R_i = P_P / P_H$$

Other definitions are:

$$R_i = \frac{P_P}{P_H} = \frac{A_H}{A_P} = \frac{D_H^2}{D_P^2}$$

Where:

A_H = area of the hydraulic piston
A_P = area of the injection barrel
D_H = diameter of the hydraulic piston
D_P = diameter of the injection barrel

Important: Before molding, or making any adjustments to the injection machine, initial calculations must be done.

Machine labeling

Label your equipment with values that represent their capacities. This concept facilitates the understanding and use of your Universal factory.

Molding Machine:

- Maximum clamping force (US-ton, Metric-ton, kN, ...)
- Injection unit capacity (in^3, cm^3, liters, ...)
- Maximum opening (in, mm, cm, ...)
- Minimum opening (in, mm, cm, ...)
- Space between tie-bars, horizontal (in, mm, cm, ...)
- Space between tie-bars, vertical (in, mm, cm, ...)
- Pattern of the ejectors on the platen (ex. 2x16in horizontal)

Dryer:

- Air flow (CFM, liter/min, m^3/min, ...)
- Dryer hopper volume (ft^3, liters, m^3, ...)

Water circulator:

- Water flow (gpm @ psi, liters/min @ kPa, ...)

Questions

1) The nozzle hole is
   a. greater than the diameter of the sprue bushing hole.
   b. less than the diameter of the sprue bushing hole.
   c. equal to the diameter of the sprue bushing hole.

2) The contact radius of the nozzle is
   a. less than the contact radius of the sprue bushing.
   b. greater than the contact radius of the sprue bushing.
   c. same as the contact radius of the sprue bushing.

3) A material that degrades easily will be injected with a barrel larger than recommended. Since there is no smaller injection unit, what would be the recommended profile?
   a. Ascending or lump
   b. Descending or flat

4) It is known that a fast process is less than 6 seconds. For a fast process with a material that does not degrade easily, it is recommended to use
   a. a descending or flat profile with a larger barrel than normal.
   b. an ascending profile with a barrel utilization of 70%.
   c. a flat profile with 70% utilization.

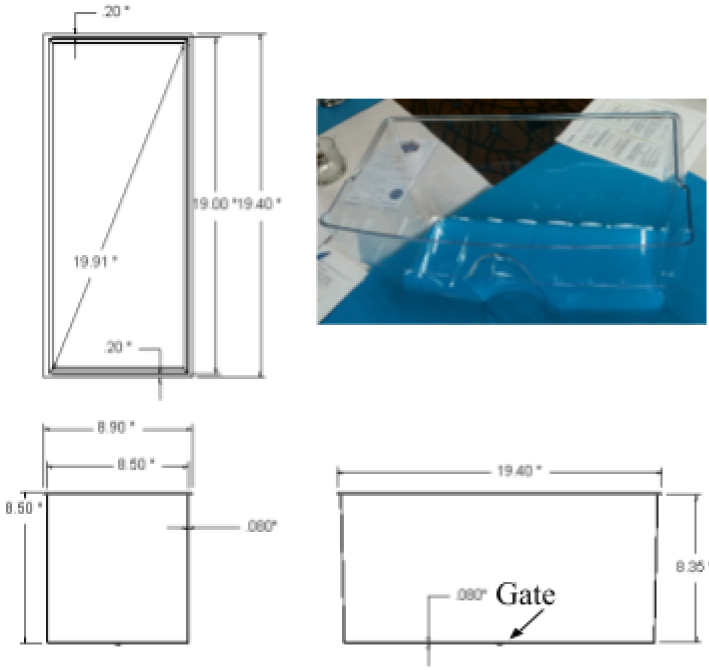
5) What would be the recommended transfer position, from injection to hold, for a mold that uses 50% of the barrel in a 150-ton press?
   a. Interpolating would give us a number between 6 and 12mm.
   b. A number less than 6mm.
   c. A number greater than 12mm.
   d. 6mm.

6) What would be the recommended transfer-to-hold position for a mold that uses 30% of the barrel?
   a. Interpolating would give us a number between 6 and 12mm.
   b. 12mm if the press is less than 400 metric tons.
   c. 6mm if the press is less than 400 metric tons, and 12mm if it is greater than 400 metric tons.
   d. 6mm.

7) What would be the recommended transfer position for a mold that uses 50% of the barrel in a 150-ton press?
   a. Interpolating would give us a number between 6 and 12mm.
   b. A number less than 6mm.
   c. A number greater than 12mm.
   d. 6mm.

8) ABS, with density of 0.97 g/cc plasticized at 270ºC and 50 bars, will fill a mold with a total weight of 147 gr. The ABS manufacturer recommends a barrel utilization between 40 and 60%. What would be the most appropriate barrel?
   a. 147gr/(0.97gr/cc)
   b. 147gr/(0.97gr/cc) x 52%
   c. 147gr/(0.97gr/cc) x 40%
   d. between 147gr/(0.97gr/cc)/60% and 147gr/(0.97gr/cc)/40%

9) In a molding from the desk example of a refrigerator drawer made of high impact polystyrene, in a single cavity mold with a hot sprue bushing:
   - Total shot weight = 1100 gr
   - Injection machine is 500 US tons with a 90mm injection unit ($2480cm^3$).
   - Material is high impact polystyrene (PS) with a plasticizing density of 0.92 gr/cc.
   - PS cooling factor = 50lb/hr/ton of cooling
   - Total expected cycle = 50 seconds
   - Estimated cooling time = 15 seconds
   - Drying data: 100% virgin, drying time = 2 hours at 190ºF and bulk density = $35lb/ft^3$, flow factor = 0.75 cfm/(lb/hr)
   - Clamping force factor = from 1.5 to 2.5 $USton/in^2$



9a. Determine the projected area in in^2.
9b. Determine the thin wall value and force factor.
9c. Determine the required clamping force.
9d. Determine the total material consumption in lb/hr.
9e. Determine the volume required by the part in cm^3.
9f. Determine the percentage of utilization of the barrel (%U).
9g. Determine the cooling tons.
9h. Determine the water required from the chiller in gpm, assuming a Delta of 3°F.
9i. Determine the transfer position.
9j. Determine the recovery position.
9k. Recommend a plastic backpressure in psi.
9l. Recommend a decompression.
9m. What is the temperature, in °F, of the recommended melt?
9n. Recommend a temperature profile for the heat zones of the barrel.
9o. Determine the residence time in cycles and seconds.
9p. Determine the volume of the drying hopper.
9q. Determine the flow required for the dryer in cfm.

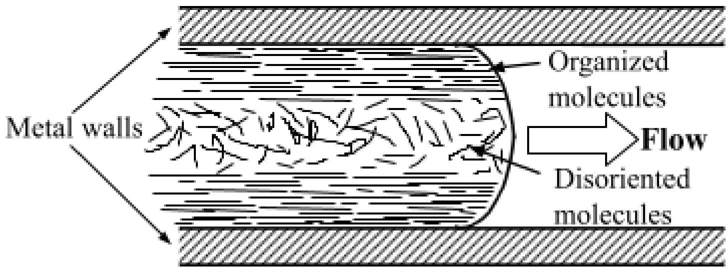
VII. Machine Rheology

- **Plastic Melt Flow**
- **Shear Stress, Viscosity and Shear Rate**
- **Machine Rheology by Power**
- **Machine Rheology with Apparent Viscosity**
- **Approximated Rheology**
- **Equation to Predict Injection Time**

Plastic Melt Flow

The movement of material through a mold's cavities and its runners is best described as the flow of short, fine strings suspended in a melt. These strings are polymer chains that float freely, and their orientation depends upon the direction of the flow. These strings are molecules that conform to a specific orientation, which is determined by the flow once the material solidifies in the mold.

Organized molecules
The illustration shows the flow of molten plastic through two fixed metal faces.



VII-1. Orientation of molecules in a melt flow

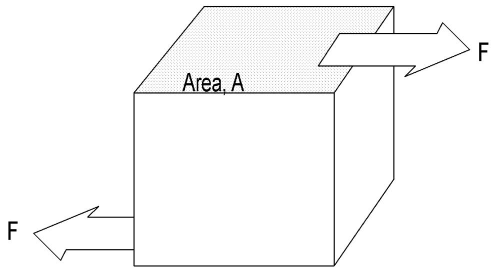
Molecules in contact with the metal tend to line up, and most stay in that direction after solidifying. The molecules that flow in the center are disoriented and remain that way after the melt solidifies.

The number of molecules that will remain oriented depends on how the polymer is cooled and its molecular weight. The longer the molecules or chains, the higher the molecular weight. The longer the molecules, the more difficult they are to orient and, consequently, the more they will restrict the melt flow.

Shear Stress, Viscosity and Shear Rate

The opposition to flow is better known as viscosity. Before defining viscosity, we must define other terms such as shear stress.

Shear stress can be defined as shear force per unit area. Imagine a cube with surface area, A, upon which two opposing forces of magnitude F try to tear the cube apart.



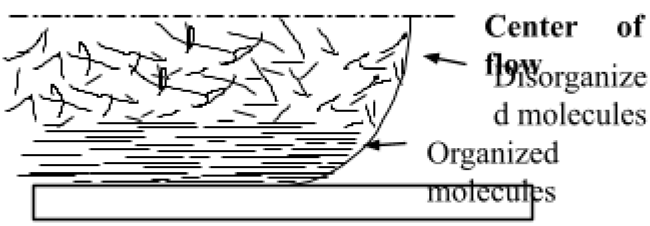
VII-2. Shear force

This effect is defined as shear stress, **τ**.

$$\tau = \frac{F}{A}$$

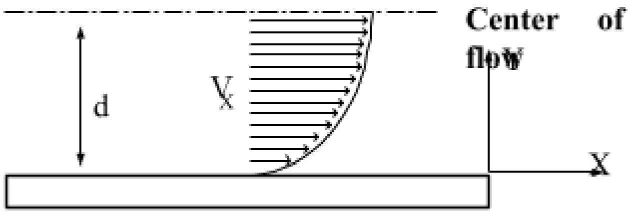
Now try to imagine that the cube is a small mass of thermoplastic melt exposed to two opposing forces, of magnitude F.

Previous chapters mentioned that thermoplastic melt resists flowing and will stick to the first static surface it finds along the way. It is this behavior that causes the shear effect of the melt. In order to simplify our explanation, let's consider only half the flow.



VII-3. Half of the melt flow

Likewise, the melt against the metal plate will experience an effort that opposes the movement of the melt. This effort is the result of disoriented molecules opposing their orientation. Now let's set our coordinates; X is in the direction of the flow and Y is perpendicular to the flow.



VII-4. Velocity vectors in a melt flow

The molecules near the plate move at a different rate than those at the center of the flow. The speed profile V_x, in the direction of X, illustrates a maximum speed when Y = d (center of the flow).

If you could microscopically see these molecules moving, you would see a gradual change of speed between both ends. This velocity gradient in the vertical direction is defined as shear rate.

This change in speed V_x, in the direction of Y, is defined as:

$$\text{Shear rate} = \frac{\text{Change in speed } (V_x)}{\text{Distance } (y)}$$

To describe the shear rate, imagine cars on a highway, one at normal speed (60 mph) being overtaken by other cars at an exaggerated speed (100 mph). Two scenarios, one car passes with a single lane separation and a second car with a separation of two lanes. In both cases, the change in speed (ΔV_x) is equal to 40 mph. However, when we consider the distance (Δy) of the car passing with only one lane of separation, the wind effect will be more noticeable. The relationship between shear stress and constant change is viscosity, μ:

$$\text{Shear stress} = \text{Viscosity x Shear rate}$$

$$\tau = \mu \text{ x } \dot{\delta}$$

Viscosity can be displayed as the opposition to the flow. Understand that if the viscosity increases then the opposition to flow, or shear stress, also increases.

Definition: a Newtonian flow is one in which viscosity is constant and independent of shear rate. The opposite would be a non-Newtonian flow, in which viscosity is a function of shear rate. Unfortunately, the molten plastic flow is non-Newtonian, which is why viscosity changes with shear rate. In a simplified form, *viscosity changes with injection speed*.

It has been experimentally demonstrated that viscosity decreases when the flow or injection speed increases. This behavior is called pseudoplastic, distinct from Newtonian flow in which viscosity is not affected by shear rate.

Shear Rate
Viscosity
Pseudoplastic
Newtonian

VII-5. Newtonian and pseudoplastic melt flow

This effect is called "shear thinning", increasing fluidity by friction. During the injection process the melt near the walls will harden, as a result of the heat exchange between the melt and the metal.

The melt in contact with the hardened layer will experience a resistance to the flow, resulting in an increase in friction. If friction reflects in the form of heat, then we can say the following: if the speed increases, the friction increases; the heat will increase as well and, consequently, the viscosity will decrease.

Machine Rheology by Power

The plastic industry uses machine rheology to get the ideal injection time. We Universal molders use machine rheology by power, in which injection time and peak injection power are graphed.

Definitions:
Peak power – The maximum power reached by the injection unit, usually at the transfer position (change from injection to hold). This is obtained by multiplying the average injection flow by the pressure at the transfer position.

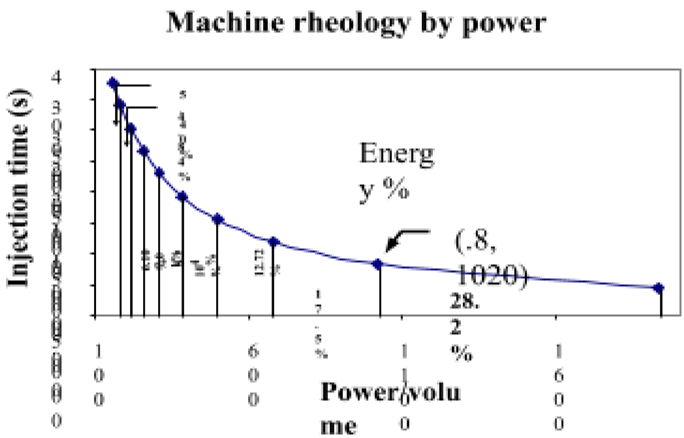
$$\text{Peak power} = \left\{ \begin{array}{c} \text{Average} \\ \text{injection} \\ \text{flow} \end{array} \right\} \text{X} \left\{ \begin{array}{c} \text{Pressure at the transfer} \\ \text{position} \end{array} \right\}$$

Average injection flow – This flow is a function of the volume injected during the injection stage and the injection time.

$$\text{Average injection flow} = \frac{\text{Injection volume}}{\text{Injection time}}$$

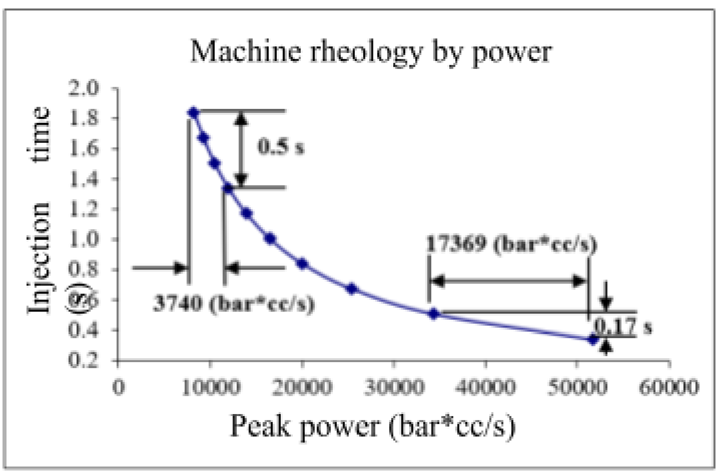
Injection volume – Represents the injected volume from the recovery position to the transfer position.

Injection time – This is the time it takes to inject from the recovery position to the transfer position. The injection time decreases with an increase in injection speed.



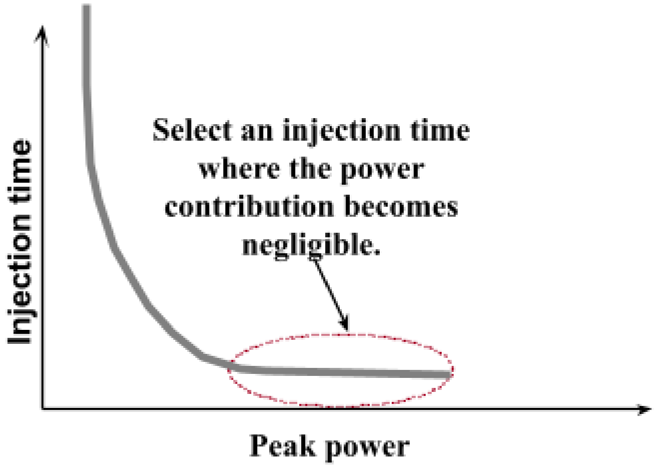
VII-6. Graph of machine rheology by power

The graph demonstrates the effect of the injection time on power, where the area under the curve represents the percentage of energy consumed by each decrease in injection time. This graph shows that the power increases when the injection time is decreased, or when the injection rate is increased. It also reveals that the energy consumed by the injection unit is more significant at low injection times.



VII-7. Graph of injection time versus peak power

In the above graph, with a slow injection, reducing the injection time by 0.5 seconds consumed 3740 bar*cc/s of power. Now, with fast injection, reducing the injection time by 0.17 seconds consumed 17369 bar*cc/s of power, 4.6 times more power for a negligible reduction in injection time.



VII-8. Zone where the change in injection time is minimal or where the power stopped contributing

The objective of this graph is to select a point on the graph where the change in injection time is minimal or, rather, a point where the contribution of peak power becomes insignificant.

Machine Rheology with Apparent Viscosity

The plastic industry also uses rheology with viscosity in order to obtain the ideal injection time, using the equations previously defined with some assumptions.

$$\text{Shear stress} = \text{Viscosity x Shear rate}$$

$$(\tau = \mu \times \dot{\delta})$$

$$\text{Intensification ratio } (R_I) = \frac{\text{Plastic pressure } (P_P)}{\text{Hydraulic pressure } (P_H)}$$

The intensification ratio was described previously and establishes the relationship between the melt pressure and the hydraulic pressure in the injection unit.

Plastic pressure is the result of the stresses that oppose injection. From this premise it can be said that the plastic pressure is apparently equal to the sum of all stresses opposing the melt flow entering the mold. This is why the plastics industry assumed:

$$\text{Plastic pressure } (P_P) = \text{Relative shear stress } (\tau_R)$$

Substituting the intensification ratio equation, we get:

$$\text{Relative shear stress} = \text{Hydraulic pressure x Intensification ratio}$$
$$\tau_R = P_H \text{ x } R_i$$

Another assumed effect is simplifying the determination of shear rate ($\dot{\delta}$) by assuming that relative shear rate ($\dot{\delta}_R$) is the reciprocal of injection time (T).

$$\dot{\delta}_R = \frac{1}{T}$$

Note that $\dot{\delta}$ and $\dot{\delta}_R$ have the same units (1/s) and seem to be equal; however, **they are not**. This simplification by the industry is based on unit cancellation; let me explain.

$$\text{Shear rate} = \frac{\text{Change in speed } (\Delta V_x)}{\text{Distance } (\Delta Y)}$$

If we replace units (mm and seconds) in the shear rate equation and then cancel those units, we get:

$$\frac{\cancel{\text{mm}}/\text{second}}{\cancel{\text{mm}}} = 1/\text{second}$$

Until now we are correct, the wrong thing to do would be to say that, according to this result (1/second), the equation is reduced to 1/time. The distance component of the numerator is in the direction of X and the distance component of the denominator is in the direction of Y, and those cannot be cancelled. For this reason, we use the word "apparent" and advise against using the values of $\dot{\delta}_R$ in any formulation other than