

VII. Machine Rheology

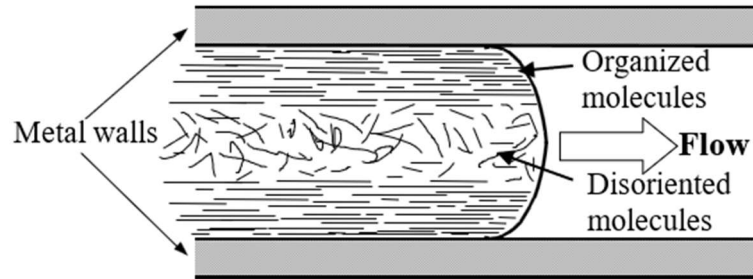
- **Plastic Melt Flow**
- **Shear Stress, Viscosity and Shear Rate**
- **Machine Rheology by Power**
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Plastic Melt Flow

The movement of material through a mold's cavities and its runners is better visualized if you imagine a 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 melt through two fixed metal faces.



VII-1. Orientation of molecules in a melt flow

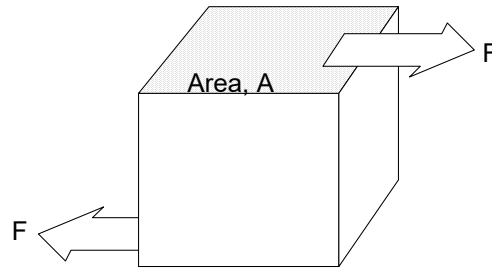
Molecules in contact with the metal tend to line up, and most stay in that direction after solidifying. The molecules that flow in the center are disoriented and remain that way after the melt solidifies.

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.



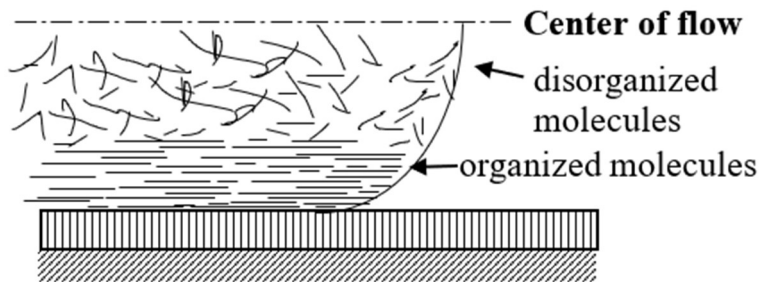
VII-2. Shear stress

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 .

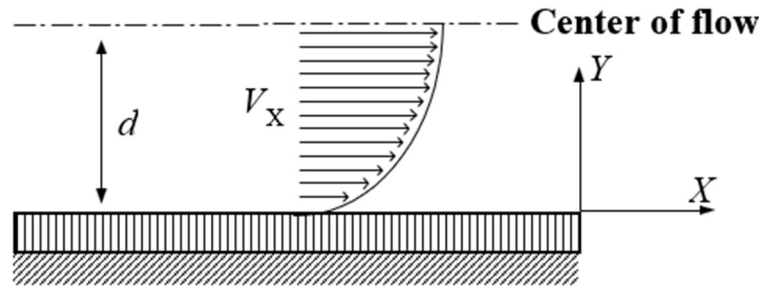
It was previously mentioned that thermoplastic melt resists flowing and will stick to the first static surface it finds along the way. It is this behavior that causes the shear effect of the melt. In order to simplify this explanation, let's consider only half the flow.



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 speed 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 extremes. 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:

$$\text{Shear rate} = \dot{\delta} = \frac{\text{change in speed}}{\text{distance}} = \frac{\Delta V_x}{\Delta Y}$$

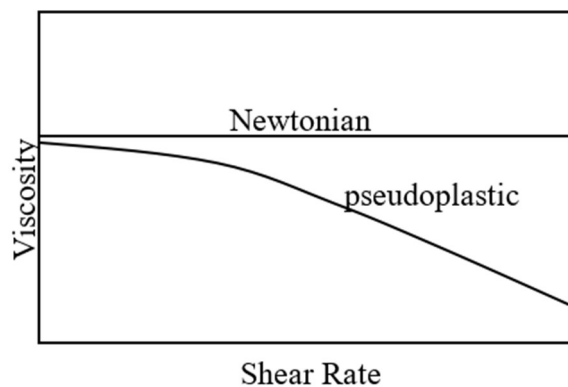
To describe the shear rate, imagine cars on a highway, one at normal speed (60 mph) being overtaken by other cars at an exaggerated speed (100 mph). Two scenarios, one car passes with a single lane separation and a second car with a separation of two lanes. In both cases, the change in speed (ΔV_x) is 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 :

$$\begin{aligned} \text{Shear stress} &= \text{viscosity} \times \text{shear rate} \\ \tau &= \mu \times \dot{\delta} \end{aligned}$$

Viscosity (μ) can be displayed as the opposition to the flow. Understand that if the viscosity increases then the opposition to flow, or shear stress (τ), 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 melt flow, distinct from Newtonian flow in which viscosity is not affected by shear rate.



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 flow in contact with the hardened layer will experience a resistance, resulting in an increase in friction. If this 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.

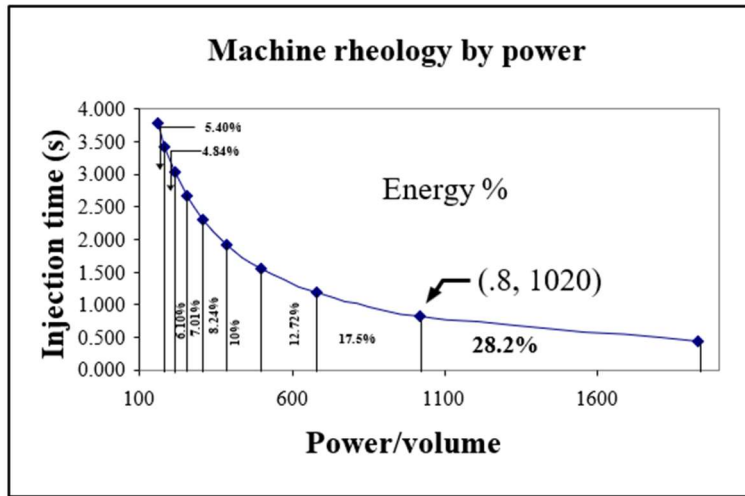
$$\text{Peak power} = \text{average injection flow} \times \text{pressure at the transfer position}$$

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

$$\text{Average injection flow} = \text{injection volume} / \text{injection time}$$

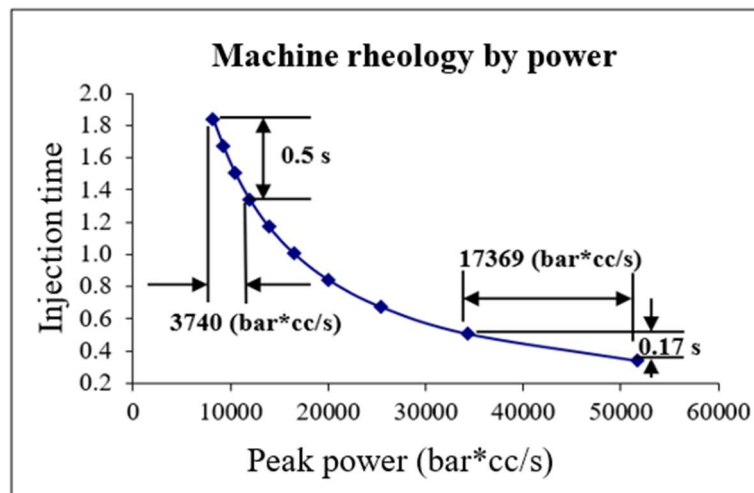
Injection volume – This represents the injected volume from the recovery position to the transfer position.

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.



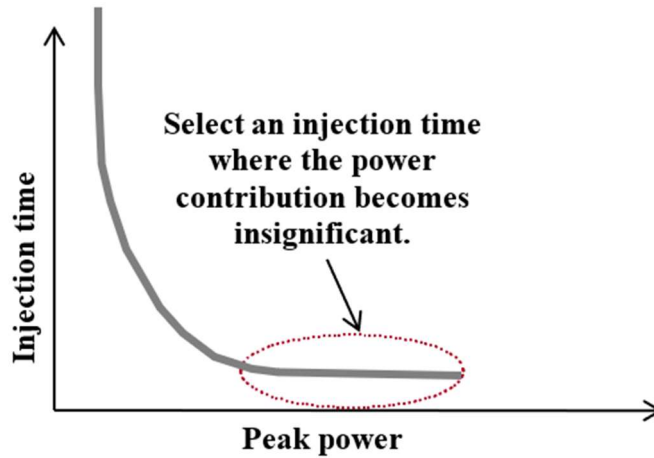
VII-6. Graph of machine rheology by power

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 speed 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 a fast injection, reducing the injection time by 0.17 seconds consumed 17369 bar*cc/s of power, 4.6 times more power for a insignificant reduction in injection time.



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

Here, the objective 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 by Viscosity

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

$$\text{Shear stress} = \text{viscosity} \times \text{shear rate} \\ (\tau = \mu \times \dot{\delta})$$

$$\text{Intensification ratio, } R_i = \frac{\text{plastic pressure, } P_p}{\text{hydraulic pressure, } P_H}$$

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

the hydraulic pressure in the injection unit. These are related by a constant called the intensification ratio, R_i .

Plastic pressure (P_P) is the result of the stresses that oppose injection. From this premise it can be said that the plastic pressure P_P 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:

$$\begin{aligned} \text{Relative shear stress} &= \\ \text{hydraulic pressure} \times \text{intensification ratio} \\ \tau_R &= P_H \times R_i \end{aligned}$$

Another assumed effect was simplifying the determination of shear rate ($\dot{\gamma}$) by assuming that it was equal to the reciprocal of injection time (T), which was renamed relative shear rate ($\dot{\gamma}_R$).

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

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

$$\text{Shear rate} = \dot{\gamma} = \frac{\text{change in speed}}{\text{distance}} = \frac{\Delta V_x}{\Delta Y}$$

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

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

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, they use the word “relative”, and we advise against using the values of $\dot{\delta}_R$ in any formulation other than injection machine rheology. This is why we **Universal** molders prefer rheology by power.

If we substitute the definition of relative shear stress ($\tau_R = P_H \times R_i$) and relative shear rate ($\dot{\delta}_R = 1/T$) into the equation for viscosity ($\tau = \mu\dot{\delta}$) and rearrange, we get:

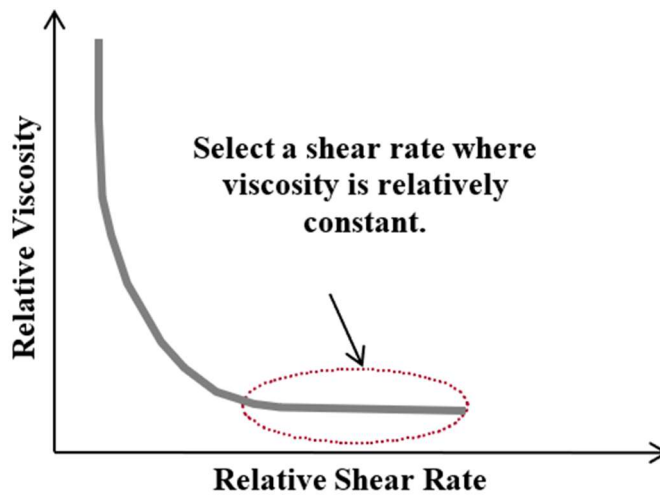
$$\mu_R = P_H R_i T$$

According to this equation, relative viscosity μ_R is simply determined by reading the hydraulic pressure and the injection time; then multiplying both by the intensification ratio.

Remember, if the injection unit reads plastic pressure and not oil (hydraulic) pressure, the equation would be:

$$\mu_R = P_P T$$

We then create a graph of viscosity versus shear rate and select a shear rate where the corresponding viscosity is relatively constant.



VII-9. Zone where the change in relative viscosity is minimal

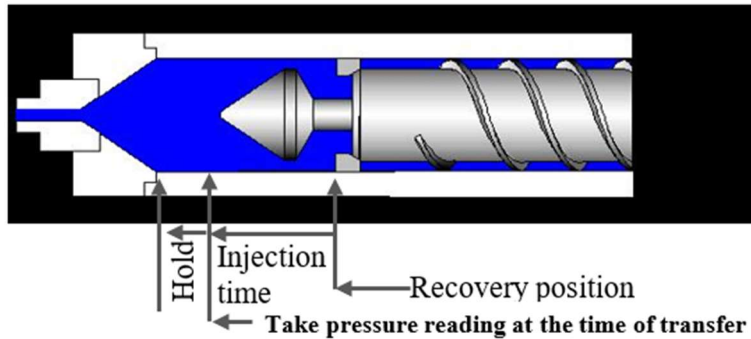
The idea is to select an injection time in which the melt is at its lowest viscosity and is relatively constant. The lower the viscosity the easier the melt flows and, as a result, the more efficient the fill.

Notes:

- These viscosity and shear rate equations should only be used in rheology for injection molding machines. Do not use these values for other calculations or other scientific work.
- If the injection unit provides the melt pressure, shear stress τ_R is equal to the pressure reading of the plastic melt, or $R_i = 1.0$.
- Although these equations do not represent the effects of viscosity and shear rate, they have standardized the determination of injection time. If you are not comfortable with these equations, use rheology by power.

Reading the values

Pressure is read at the time of transfer (change from injection to hold), and time is equal to the duration of the injection stage.



VII-10. Readings of transfer pressure and injection time

We use transfer pressure for convenience. The average pressure would be more representative; however, very few machines provide that reading.

These graphs are traditionally created by injecting at various injection speeds. For each injection speed, injection time and injection pressure readings are taken at the time of transfer. Then their corresponding coordinates are calculated.

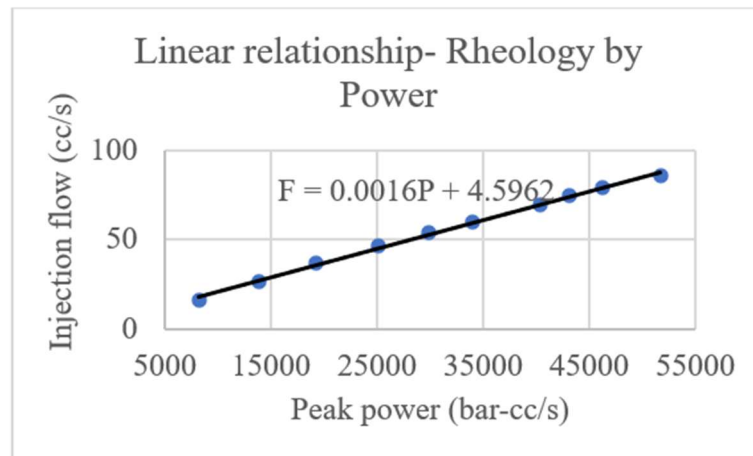
During the development of *Universal Molding™*, it was established that the determination of the injection process parameters would use standardized procedures and corroborated equations. The next chapter will discuss the recommended procedures in detail.

Developing these graphs takes time and resources. We have developed a more efficient method called “approximated rheology”. Students from the University of Puerto Rico at the Mayagüez campus, under the supervision of Dr. Ivan Baigés, were the ones who initiated this simple technique.

Approximated Rheology

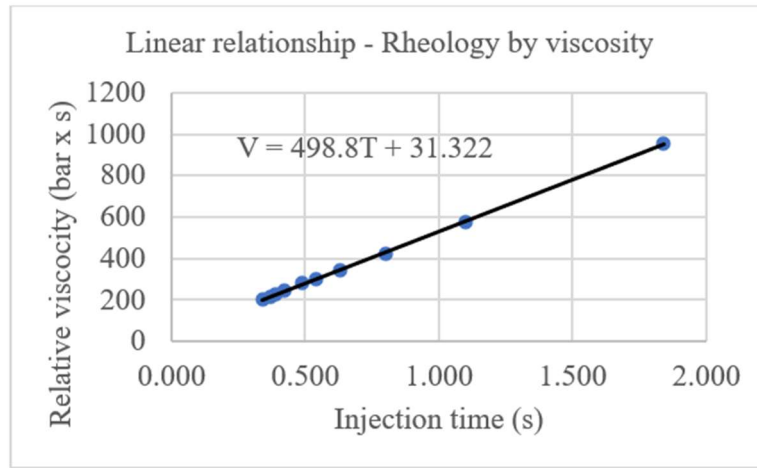
Developing a rheology lab in an injection machine consumes time and resources. With approximated rheology, a mathematical prediction technique, the laboratory is performed in less than a 3rd of the time. Let's see how.

If you work with rheology by power, you will notice that there is a relatively linear relationship between injection flow and peak power.



VII-11. Graph of linear behavior between injection flow and peak power

If you work with rheology by viscosity, there is a linear relationship between relative viscosity and injection time.



VII-12. Graph of linear behavior between relative viscosity and injection time

Both graphs reveal that the intermediate points on the graph can be approximated by the simple function of the equation of a line, $Y = Y_o + MX$. Let me explain, by knowing slope M and the intercept Y_o on the Y axis, we can predict intermediate points.

Example:

In the optimization of a process injecting a volume of 29.17cc, the injection time and transfer pressure readings were obtained at two injection speeds:

Vel (mm/s)	T_{inj} (s)	P_{tran} (bar)
193	0.34	602.7
19	1.84	518.5

VII-13. Example of injection times and transfer pressures

Using the equations shown above:

Average injection flow =
injection volume / injection time

Peak power =
average injection flow x pressure at the transfer position

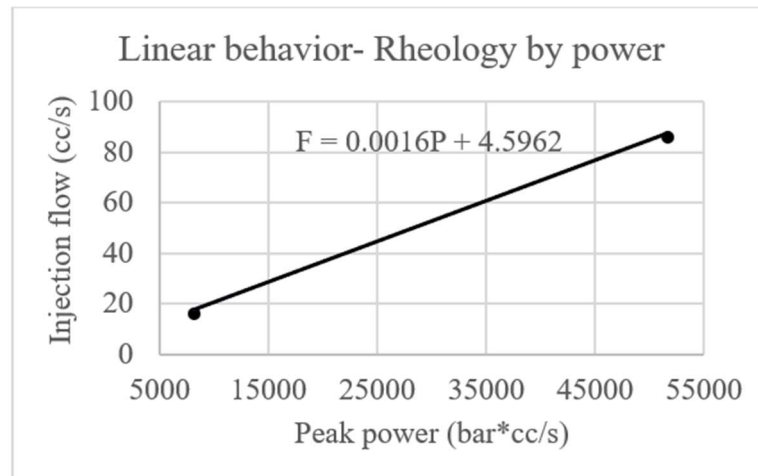
Relative viscosity = plastic pressure x injection time

$$\text{Relative shear rate} = \frac{1}{\text{injection time}}$$

We calculate and add the values in the following table:

Inj. Vol. = 29.17 cc			Rheo. by Power		Rheo. by Viscosity	
Vel. (mm/s)	T_{inj} (s)	P_{Tran} (bar)	Flow (cc/s)	Power (bar*cc/s)	V_{shear} (1/s)	Visc. (bar*s)
193	0.34	602.7	85.79	51708	2.94	204.9
19	1.84	518.5	15.85	8220	0.54	954.0

VII-14. Examples of rheology values



VII-15. Graph of the linear effect between average injection flow and peak power

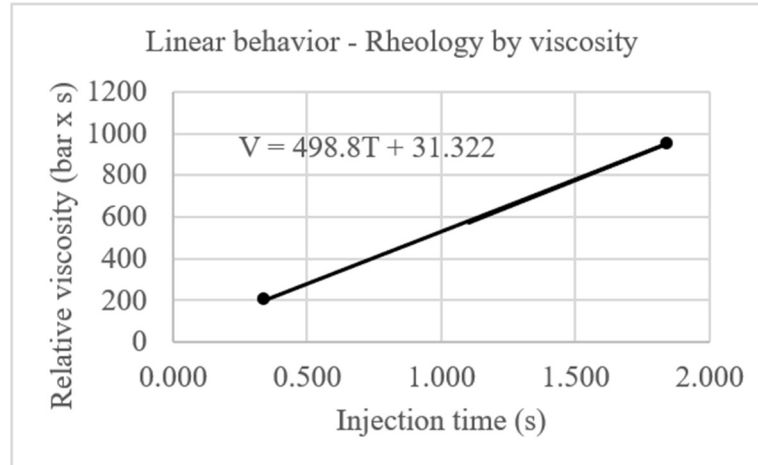
The linear equation of rheology by power would be:

$$\text{Flow} = (0.0016 \times \text{power}) + 4.5962$$

or

$$\text{Power} = (\text{flow} - 4.5962) / 0.0016$$

Now let's look at the linear equation of rheology by viscosity:



VII-16. Graph of the linear effect between relative viscosity and injection time

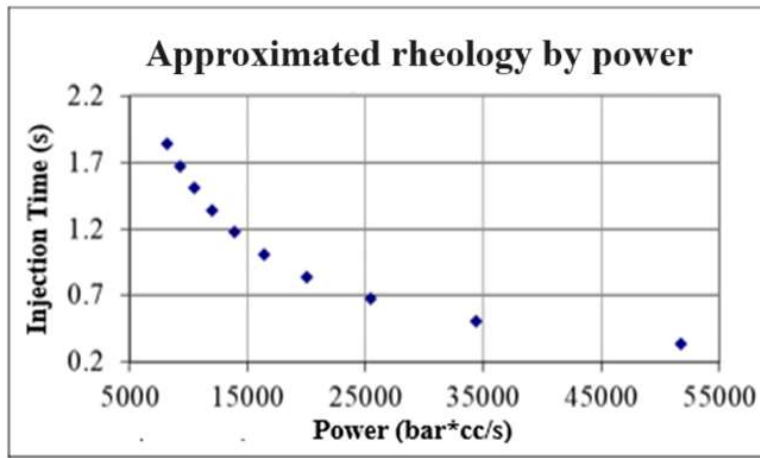
The equation would be:

$$\text{Viscosity} = (498.8 \times \text{injection time}) + 31.322$$

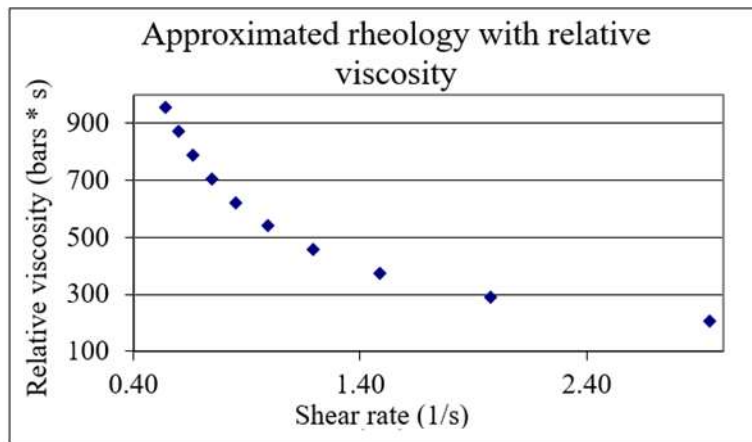
The next step is to determine eight injection times equidistant between the existing times, T_{inj} , then complete the calculation of the corresponding average injection flow and shear rate for each injection time added.

Inj. Vol. 29.17 cc			Rheo. by power		Rheo. by viscosity	
Vel (mm/s)	T_{inj} (s)	P_{Tran} (bar)	Flow (cc/s)	Power (bar*cc/s)	V_{shear} (1/s)	Visc. (bar*s)
193	0.34	602.7	85.79	51708	2.94	204.9
	0.51		57.57	34337	1.97	284.0
	0.67		43.32	25430	1.49	367.2
	0.84		34.73	20058	1.19	450.3
	1.01		28.98	16465	0.99	533.4
	1.17		24.86	13892	0.85	616.6
	1.34		21.77	11960	0.75	699.7
	1.51		19.36	10455	0.66	782.8
	1.67		17.43	9249	0.60	866.0
19	1.84	518.5	15.85	8220	0.54	954.0

VII-17. Table including 8 equidistant injection times

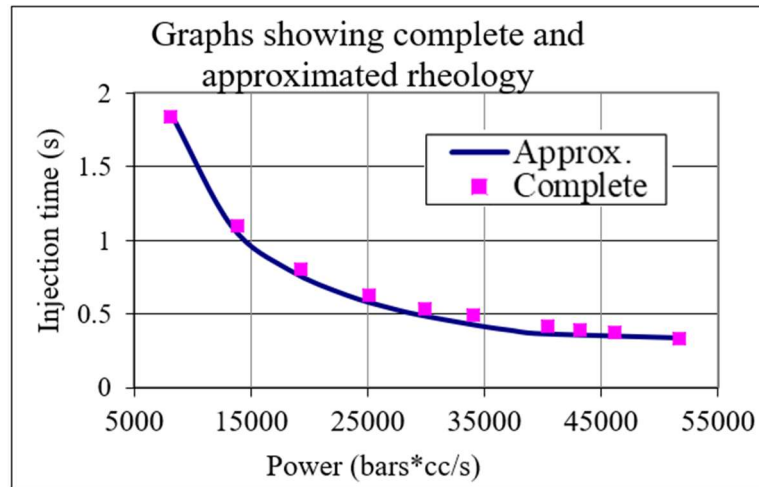


VII-18. Graph of approximated rheology by power



VII-19. Graph of approximated rheology using relative viscosity and shear rate

Now let's superimpose the graph of an approximated (two-point) rheology with the graph showing a complete (ten-point) rheology.



VII-20. Superimposed graphs of complete and approximated rheology

This graph shows that approximated rheology is very close to complete (ten-point) rheology, which makes it a timesaving, beneficial option.

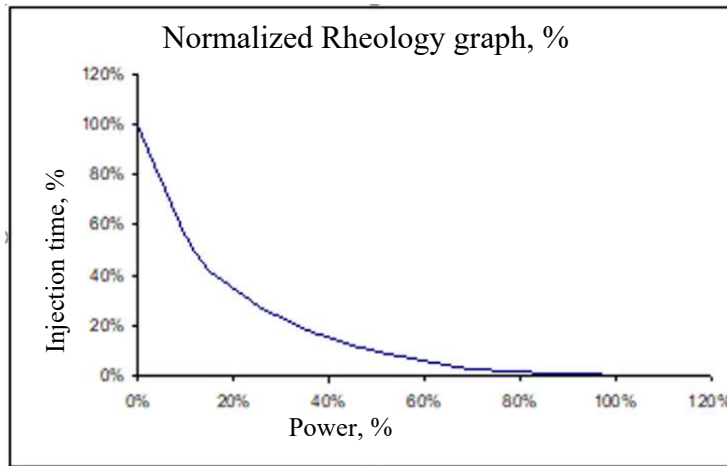
Again, we **Universal** molders prefer rheology by power because the definitions describe the effect with more conviction. You can use the method which makes you feel more comfortable; both rheologies lead to good results.

Equation to Predict Injection Time

During the development of **MUTM** it was established that all parameters must be determined by clear procedures and equations. This was done to guarantee similar results between molders.

If the selection of injection time depended on individual criteria, then it would be impossible to obtain similar results between molders. Using the criteria of multiple molders, who have a clear understanding of machine rheology, this situation was resolved. With rheology graphs with their coordinates normalized in percentages and simple statistics, the selection trend of some **Universal** molders was determined.

With several graphs such as the one illustrated, the following question was formed: Where does the plateau begin?



VII-21. Graph of standardized rheology in %

The average of this entire group was evaluated, and the following formula was obtained:

$$T_{plateau} = T_{min} + (T_{max} - T_{min}) / 9$$

Where:

- T_{min} - injection time corresponding to the maximum injection speed
- T_{max} - injection time corresponding to the minimum injection speed
- $T_{plateau}$ - injection time where the plateau starts on the graph

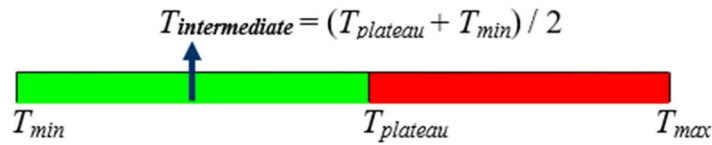
This equation calculates injection time, where the rheology curve begins to be relatively constant. Based on this simple calculation, we determine that the ideal injection time should be less than that obtained by the equation.

$$T_{Ideal} < T_{min} + (T_{max} - T_{min}) / 9$$

The ideal injection time will depend on the type of industry. Conventional molding industries should select an ideal injection time in the center of the plateau. Industries that mold materials sensitive to friction as a result of high injection rates, such as the rigid PVC fittings industry, should be close to $T_{plateau}$. High-volume injection industries, such as cap manufacturers, should be close to T_{min} .

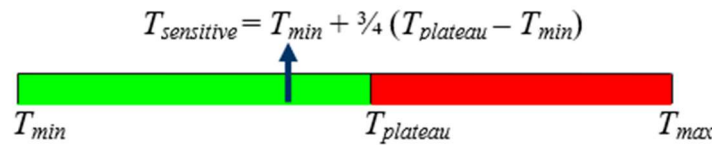
Let's take a closer look:

Conventional molding industries: Select an ideal injection time between $T_{plateau}$ and T_{min} .



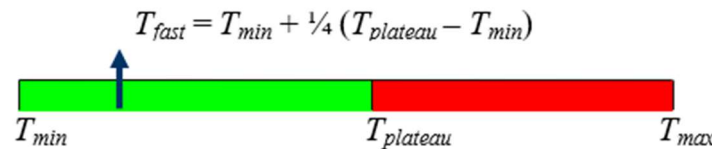
VII-22. Injection time for conventional molding industries

Industries that mold friction-sensitive materials (such as manufacturers of rigid PVC fittings): For materials that degrade at high speeds, select an ideal injection time near $T_{plateau}$.



VII-23. Injection time for industries that mold friction-sensitive materials

Industries with a high volume of production (such as cap manufacturers): Select an ideal injection time near T_{min} .



VII-24. Injection time for high-volume injection industries

T_{fast} is also used with parts that are very difficult to fill, like in micromolding.

If we replace the definition of the plateau time ($T_{plateau} = T_{min} + (T_{max} - T_{min}) / 9$) within each of the three previous equations and simplify, we get:

Conventional molding industries

$$T_{intermediate} = T_{min} + (T_{max} - T_{min}) / 18$$

Industries that mold sensitive materials

$$T_{sensitive} = T_{min} + (T_{max} - T_{min}) / 12$$

High-volume injection industries

$$T_{fast} = T_{min} + (T_{max} - T_{min}) / 36$$

After selecting the application type, select the corresponding equation, replace the values of T_{min} and T_{max} , and determine the ideal injection time.

Example: Using the calculated rheology for $T_{min} = 0.24$ seconds and $T_{max} = 1.58$ seconds, the corresponding injection times would be:

Average application:

$$T_{intermediate} = T_{min} + (T_{max} - T_{min}) / 18 = 0.24 + (1.58 - 0.24) / 18 \\ = \mathbf{0.31 \text{ seconds}}$$

Sensitive material application:

$$T_{sensitive} = T_{min} + (T_{max} - T_{min}) / 12 = 0.24 + (1.58 - 0.24) / 12 \\ = \mathbf{0.35 \text{ seconds}}$$

High volume application:

$$T_{fast} = T_{min} + (T_{max} - T_{min}) / 36 = 0.24 + (1.58 - 0.24) / 36 \\ = \mathbf{0.28 \text{ seconds}}$$

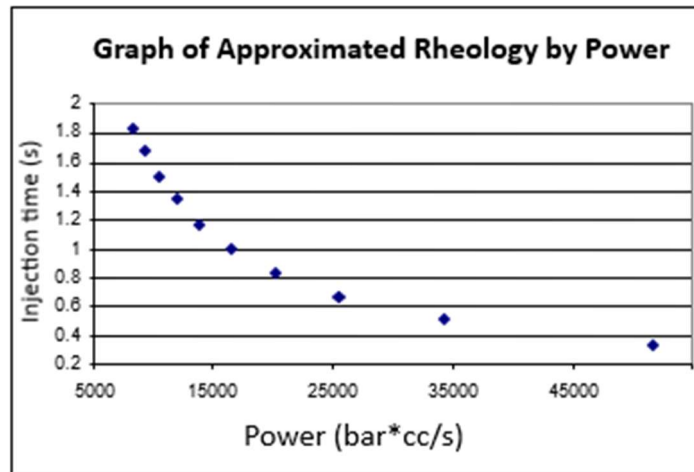
Procedures for obtaining these minimum and maximum injection times will be discussed later.

Questions

- 1) Using calculated rheology, you can determine the ideal injection time without having to create a graph. For example, depending on the type of industry, the injection time should be less than $T_{min} + (T_{max} - T_{min})/9$. For a T_{min} of 0.24 seconds and a T_{max} of 1.58 seconds, the ideal injection time should be
 - a. Shear rate = $0.24 + (1.58 - 0.24)/9$
 - b. $T_{ideal} < 0.24 + (1.58 - 0.24)/9$
 - c. 4 seconds.

- 2) For a process with a total cycle of 3.5 seconds, we use the approximated rheology equation
 - a. $T_{intermediate} = T_{min} + (T_{max} - T_{min})/18$
 - b. $T_{sensitive} = T_{min} + (T_{max} - T_{min})/12$
 - c. $T_{fast} = T_{min} + (T_{max} - T_{min})/36$

- 3) In the graph of approximated rheology by power below, an ideal injection time would be
 - a. 1 second.
 - b. greater than 1 second.
 - c. 0.4 seconds.



- 4) **Universal** molders prefer machine rheology by power
- a. because shear rate is graphed versus injection power.
 - b. because it is graphed with parameters that truly describe the effect being measured, injection time versus peak power.
 - c. because viscosity versus injection power is graphed here.
- 5) Peak power
- a. is calculated by multiplying average injection time by the pressure at the time of transfer.
 - b. is the maximum plastic pressure reached by the injection unit, usually at the time of transfer.
 - c. is obtained by multiplying the average injection flow by the pressure at the time of transfer.
- 6) Average injection flow
- a. is a function of injection time and the volume of melt filled in the injection stage.
 - b. is the maximum plastic pressure reached by the injection unit, usually at the time of transfer.
 - c. is obtained by multiplying the average injection flow by the pressure at the time of transfer.
- 7) The injection volume represents the volume filled from the recovery position to the transfer position.
- a. True
 - b. False