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From lab to production, providing a window into the process

Closed Loop Pressure Control for the Extrusion Process

Extrusion is a continuous process and successful economic production depends on maintaining stable output and melt quality at an accurately controlled rate.

Current screw design technology, the use of DC drives, computerized controllers and raw material testing help to deliver the melt to the extrusion die at a relatively constant temperature, pressure and viscosity. However, even the slightest variation in the raw material or process will affect product dimensions. The manufacturing of small diameter tubing which must be held to ± 0.001" or less dimensional tolerances, is particularly sensitive to process instabilities.

In the production environment, variations in the raw material and process do occur. Mechanical parts wear. Monitors vary in speed, temperatures go above and below setpoint and ambient conditions change. Some plastic materials are sensitive to moisture and storage temperature. All these conditions are subject to change and they all affect the stability of the extruder output and the product quality (1).

The extruder screw is the one item that most influences the quality and quantity of the melt produced by the machine.

The most common extruder screw design has a feed zone, transition zone and metering zone. Each of these zones within the extruder must perform a specific function simultaneously to achieve stable output.

Extrusion Zone	Function
Feed Zone	Solids Conveying
Transition Zone	Melting/Pressurization
Metering Zone	Pumping

To achieve stable output of the extrudate, the flow rate through each of the three zones must be equal. In the extrusion, melting and pressurization occur simultaneously and inconsistency in either process will influence the other (2).

Random disturbance in both the mechanism of solid feeding and melting, results from inherent process and raw material variation, which cause unstable conditions within the extruder. Instability in the extruder output tends to increase in both frequency and severity with increased screw speed (3).

The output of the extruder is a function of drag flow and pressure flow:

Output = drag flow - pressure flow

Quantitatively expressed as:

$$Q = AN - \frac{BP}{H} \qquad (1)$$

Q	=	net volume rate of discharge
AN	=	vol. open discharge rate of melt
BP	=	volumetric back flow rate of melt
N	=	screen speed
P	=	pressure at head of extruder
A	=	screw constant based on screw geometry
B	=	screw constant based on screw geometry
π	=	apparent viscosity of melt in the metering section

The output and pressure of the melt delivered to the die by the extruder increases with increased screw speed. Output and pressure increase of the melt to the die is somewhat less than the increase in extruder screw speed due to an increase in the pressure flow portion of extruder output, but in practice, this effect is usually small.

The output instability or surging of the extruder is related to the melt pressure at the die. Not direct interrelationship between output and melt pressure exists due to melt viscosity fluctuations, but in practice, die pressure fluctuations do correlate with output changes (4).

The amount of pressure at the entrance to the die determines the flow rate through the die. The die, by definition is a pressure-flow device. Die output is presented in a form similar to the pressure-flow portion of the extruder output relationship:

$$Q = \frac{KP^{1/n}}{\pi}$$

Q	=	flow rate from the die
P	=	pressure drop through the die
K	=	die constant based on die geometry
n	=	power law index of the melt
π	=	apparent viscosity of melt in the die

The screw shows the output and pressure relationship of the extruder and die and the die characteristic curves (see Figure 1). The intersection of the screw characteristic curve and the die characteristic curve represents the operating point for the system under the particular combination of conditions. For a given screw geometry, an increase in extruder output will shift the screw characteristic curve to the right, a decrease will shift the curve to the left (see Figure 2). Changes in extruder output can be detected by monitoring the pressure at the entrance to the die. Adjustments in the extruder screw speed based on pressure at the die can be used to compensate for fluctuations in extruder output.

A head pressure variation of 1% is roughly equivalent to an extruder output variation of 1-3% depending on the theological behavior of the polymer melt (5). This relationship between pressure variation and output is shown by the die output expression, equation (2).

For a given die and melt system, K, π and n are constant. The relationship between pressure fluctuation and change in output from the die can be expressed as:

$$\frac{Q_2}{Q_1} = \left(\frac{P_2}{P_1}\right)^{1/n}$$

Values of n for several plastics and a Newtonian fluid are given below:

LDPE/PP	0.35
HDPE	0.50
Nylon 6	0.60
FEP	0.70
Newtonian fluid	1.00

Table 1 shows the calculated theoretical effect of die pressure variation on output for a given thermoplastic melt as well as a Newtonian fluid.

Table 1. Pressure Variation

	1%	2%	5%	10%
Variation in Output				
LPDE	2.9%	5.8%	15%	31%
PP	2.9%	5.8%	15%	31%
HDPE	2.0%	4.0%	10%	21%
Nylon 6	1.7%	3.3%	8.5%	17%
FEP	1.4%	2.8%	7.2%	14%
Newtonian Fluid	1.0%	2.0%	5.0%	10%

From a material such as LDPE/PP, a variation in die pressure could result in three times as much variation in output. Note that these are theoretical values and in actual practice, the output variations will differ due to many factors affecting the pressure. But, in all cases, the output variations of non-Newtonian plastics will be a multiple of the pressure variation at the die. It is, therefore, essential to know the pressure variation of the process even more so than the dimensional variation of the extrudate.

Variations in pressure and, therefore, output are constantly occurring due to variations in the raw material and process. A closed loop feedback system which adjusts screw speed to maintain a constant die pressure is the most effective method o control both short term and long term pressure fluctuations caused by extruder surging. If the extruder is slaved to the downstream equipment, no downstream changes will be required.

Test Method

Test results are presented in Table 2 and plotted on graphs shown in Figures 3 through 6, which demonstrate the effectiveness of closed loop feedback pressure control in minimizing output variations.

Tests were made on a 2½" extruder processing 100% LDPE regrind at screw speeds of 35, 50, 70 and 100 rpm. Use of 100% LDPE regrind simulates the worst surging conditions. The tests were made utilizing a melt pressure transducer mounted in the die and a microprocessor-based pressure controller. The PID output of the controller was fed to the extruder drive. The output of the controller was used to continually adjust the screw speed in order to maintain a constant die pressure.

- Graphs with broken lines indicate product linear weight over time with no pressure control (fixed screw speed).

- Graphs with solid lines indicate product linear weight over time with control of die pressure (continually adjusted screw speed).

The TABLE 2. Test Results

Extruder Speed with and without Pressure Control	Polymer Pressure at Die			Product Linear Weight			
	Avg	Variation	% Variation (B)	Avg	Variation	% Variation (A)	Change in Product weight (A) Change in Pressure (B)
35 RPM Nominal w/o pressure control w/ pressure control % reduction	 1685 1870	 85 90	 11 4.8 56%	 1.075 1.14	 0.325 0.0875	 30 7.77 74%	 2.70 1.62
50 RPM Nominal w/o pressure control w/ pressure control % reduction	 1625 1695	 275 155	 17 9.1 46.4%	 1.9 2.09	 0.5 0.29	 26.3 13.9 47%	 1.55 1.53
75 RPM Nominal w/o pressure control w/ pressure control % reduction	 1775 2030	 445 190	 25.1 9.4 62.5%	 1.905 2.575	 0.805 0.375	 40.6 14.6 64%	 1.62 1.55
100 RPM Nominal w/o pressure control w/ pressure control % reduction	 2650 2850	 160 70	 6.0 2.5 58%	 2.53 3.22	 0.32 0.132	 12.6 4.2 66.7%	 2.10 1.68

Results

Linear weight output variation was 153% to 270% (1.53 to 2.70 times) of the pressure variation. Based on the pressure variations, which occurred during the tests, output variations were not as large as theoretically predicted in Table 1. However, in all cases linear weight output variation was greater than the pressure variation.

The reduction in product linear weight output variation ranged from 47% to 74% (see Column A, Table 2). This suggests that as a minimum, variations in output can be cut in half using closed loop pressure control.

Closed Loop Pressure Control for Melt Pump Extrusion

Melt pump assisted extrusion is gaining popularity as a method of stabilizing the extrusion process. The literature states that a gear pump helps to eliminate unexpected surges and drifting output rates from the extruder (2) (6-9).

Gear pumps are positive displacement devices that deliver polymer melt to the extruder die at a relatively constant rate. In gear pump extrusion, the primary function of the extruder is to act as a plasticating unit to deliver a homogeneous melt to the gear pump inlet.

The gear pump which is mounted between the extruder and the die, buffers the die from the extruder surges and drifts in output, but the inlet of the gear pump itself is subject to these extruder output variations. Since the pump requires a constant flow of plastic within certain pressure levels for lubrication, a prolonged low-pressure condition could cause damage to the pump. Over pressurization at the pump inlet, caused by a sudden surge of melt from the extruder, will change the melt condition and in extreme cases, can be dangerous to the equipment and operator.

For these and other reasons, a closed loop pump inlet pressure control system that changes the extruder screw speed to maintain a constant gear pump inlet pressure offers a number of processing advantages.

A study conducted by Dynisco and the University of Lowell concluded that control system of this type simplifies and improves process operations by completely eliminating long term inlet pressure drift, significantly reducing short term inlet pressure fluctuation, reducing the average inlet melt pressure, and increasing the safety of operation (2).

The following is a brief summary of the results:

Short Term Inlet Pressure Stability

Large fluctuations in the inlet pressure dictate that a higher average inlet pressure should be used to avoid dropping below minimum inlet pressure. Even a temporary loss of inlet pressure will show on the discharge side of the pump. The higher average pump inlet pressure increases the energy input to the material, increasing the average melt temperature. Figure 7 shows pump inlet and discharge pressures for both manual and closed loop operation at a pump inlet pressure setpoint of 350 psi. Figure 8 shows that short term inlet pressure variations were reduced 70-80%.

Long Term Pressure Drift

With manual control, it was necessary to periodically adjust screw speed, producing the result shown in Figure 9. With closed loop pressure control (Figure 10) some short-term inlet pressure instability was observed but long-term pressure drift was completely eliminated.

Process Output Change

A smooth, well-coordinated change in output rate was difficult to achieve with manual control. An increase in pump speed required simultaneous and coordinated increases in extruder speed, often resulting in excessive pressurization at the pump inlet. Closed loop inlet pressure control simplified the operation considerably. An increase or decrease in pump speed was automatically followed by the extruder (Figure 11).

Safety

Closed loop inlet pressure control incre3ases operator and equipment safety. If, during manual operation, the pump ceases rotation and the extruder continues to pump polymer, pressure at the pump inlet reaches dangerous levels in a matter of seconds. Mechanical rupture plugs, electrical interlocks or high inlet pressure limits relays (a feature of some controllers) should be used.

Summary

Although modern extruder drives and take-off devices provide constant, drift-free operation, variations in the raw material and process occur which causes the output of the extruder to change. The output instability of the extruder is related to the melt pressure at the die. The output variations of the extrudate will be a multiple of the pressure variation at the die. A closed loop feedback system, which adjusts screw speed to maintain a constant die pressure, is the most effective method to minimize variations in extruder output.

Closed loop inlet pressure control for gear pump extrusion reduces inlet pressure instability, as well as the average minimum inlet pressure. Reducing the inlet pressure variations assures a more uniform melt temperature at the die, thus improving the consistency and quality of the extrudate.

Figure 1. Output and Pressure Relationship of the Extruder Die

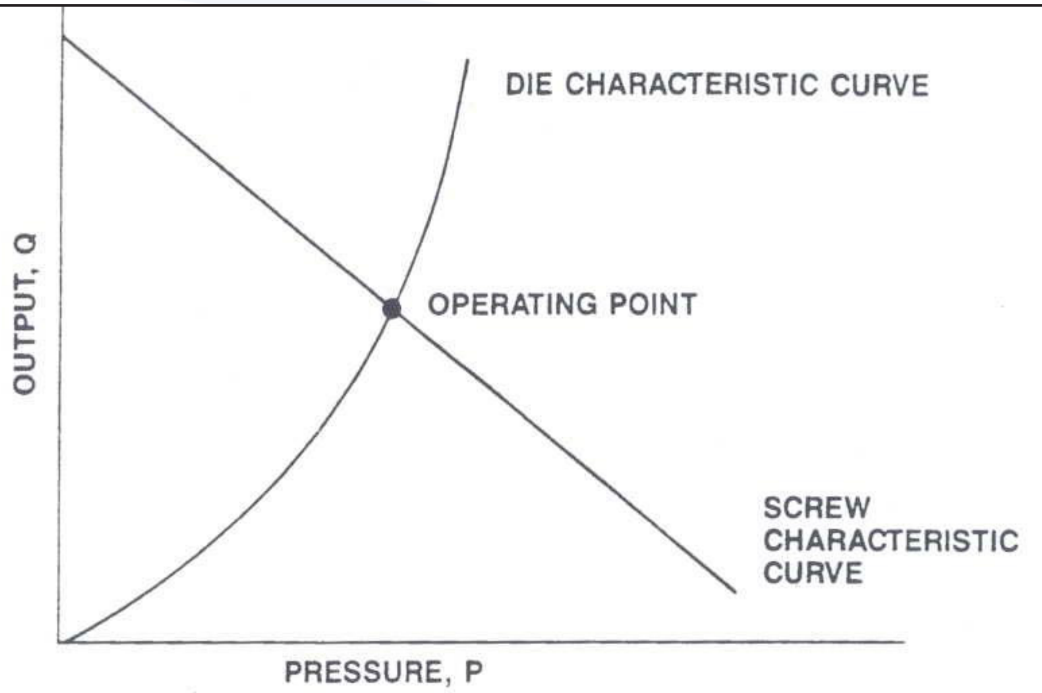

Figure 1. Output and Pressure Relationship of the Extruder and Die

Figure 2. Effect of Changes in Extruder Output on Die Pressure

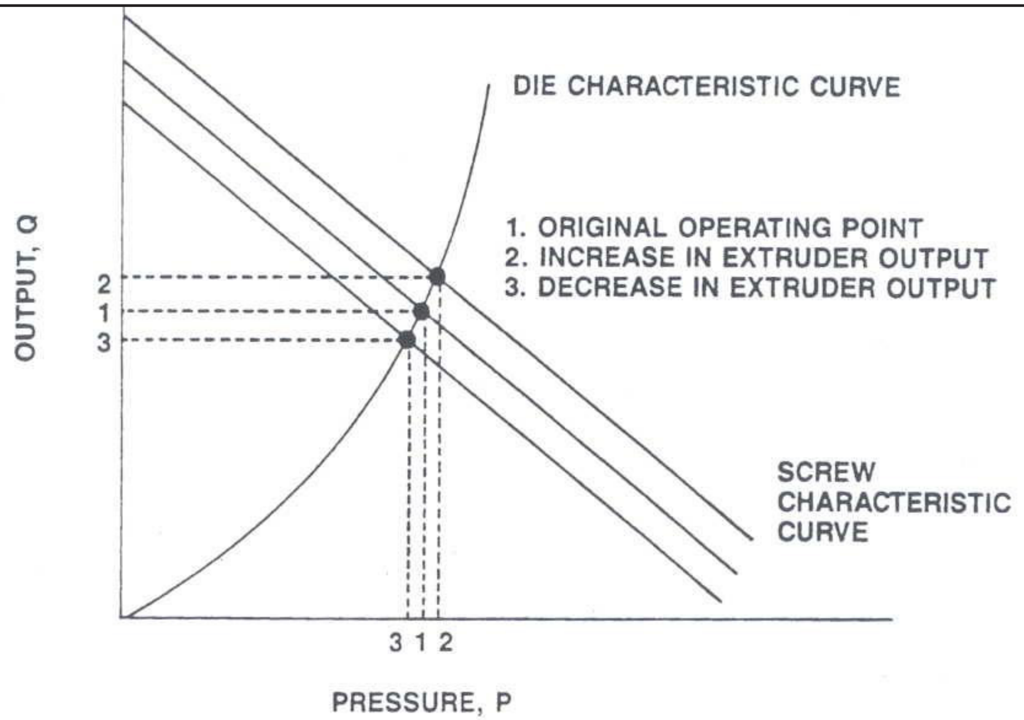

Figure 2. Effect of Changes in Extruder Output on Die Pressure

Figure 3.

Figure 3.

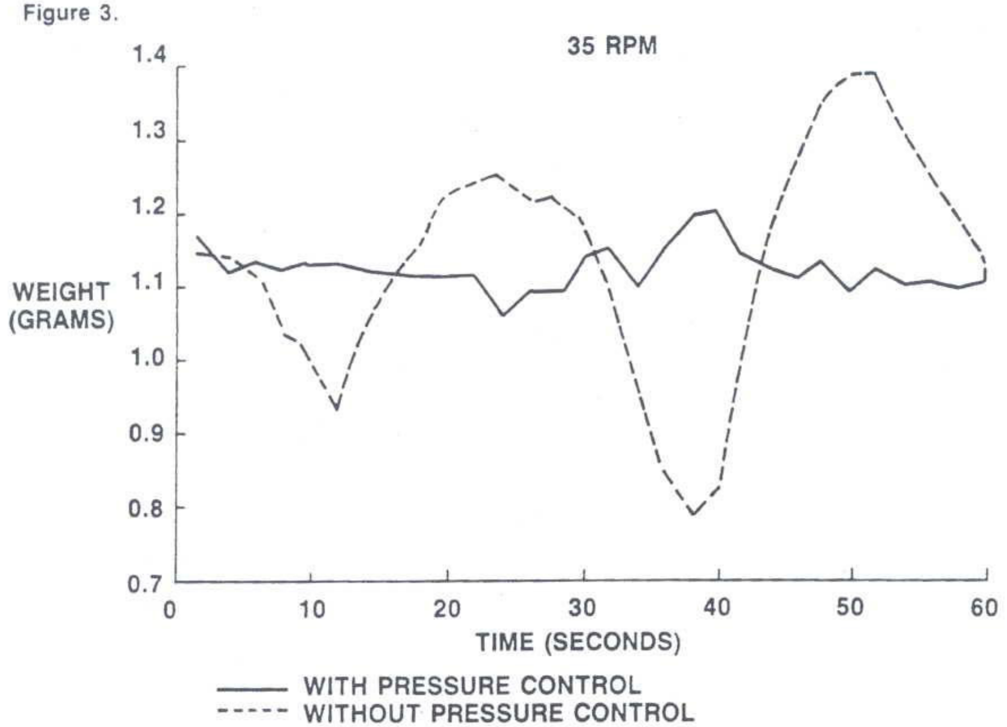

Figure 4.

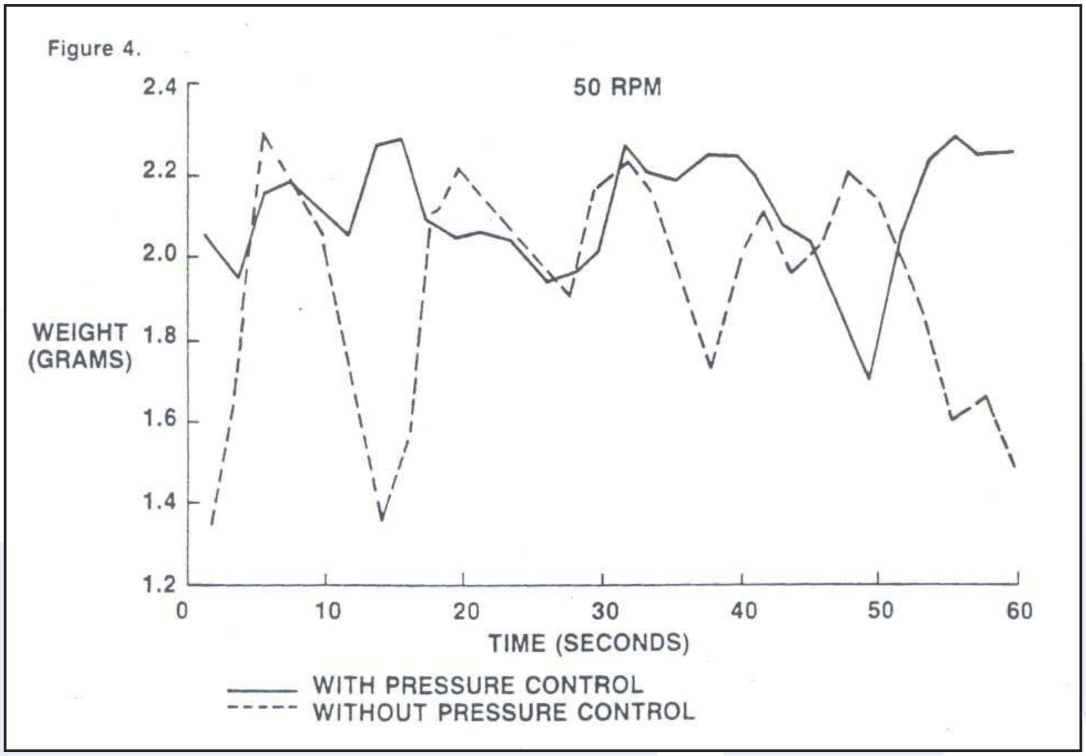

Figure 5.

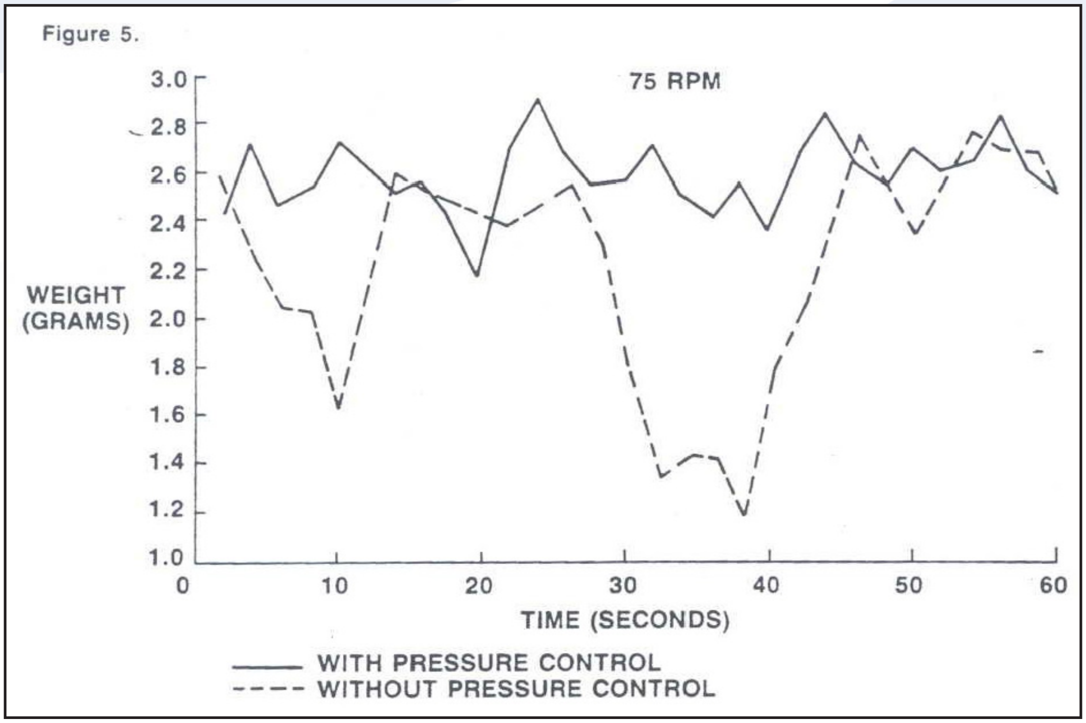

Figure 6.

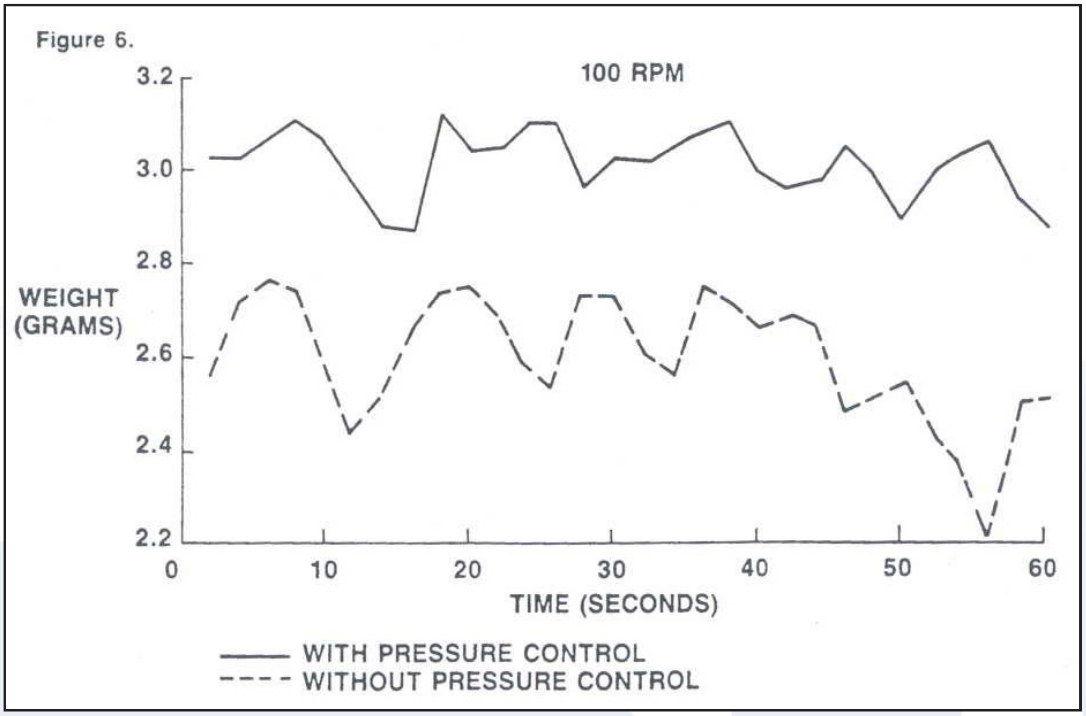

Figure 7. Short-Term Inlet Pressure Stability @ Pump Speed: 35 RPM (Approximately 105 RPM Extruder Screw Speed): Manual and Closed Loop Operation.

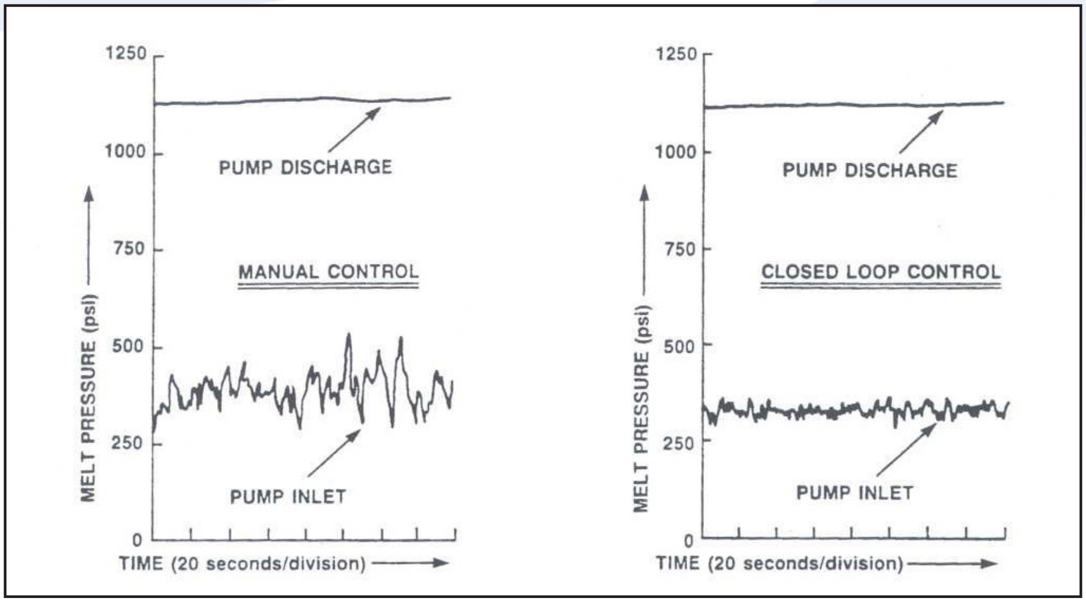

Figure 8. Short-Term Pump Inlet Pressure Stability vs. Pump Speed: Manual and Closed Loop Operation.

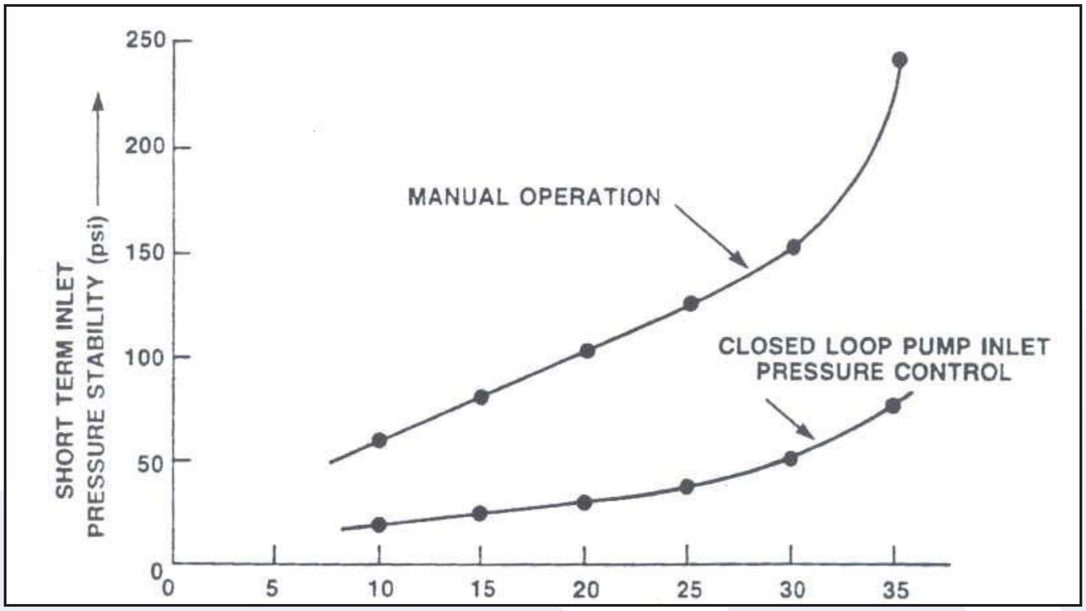

Figure 9. Long-Term Inlet Pressure Drift: Manual Adjustment in Extruder Screw Speed.

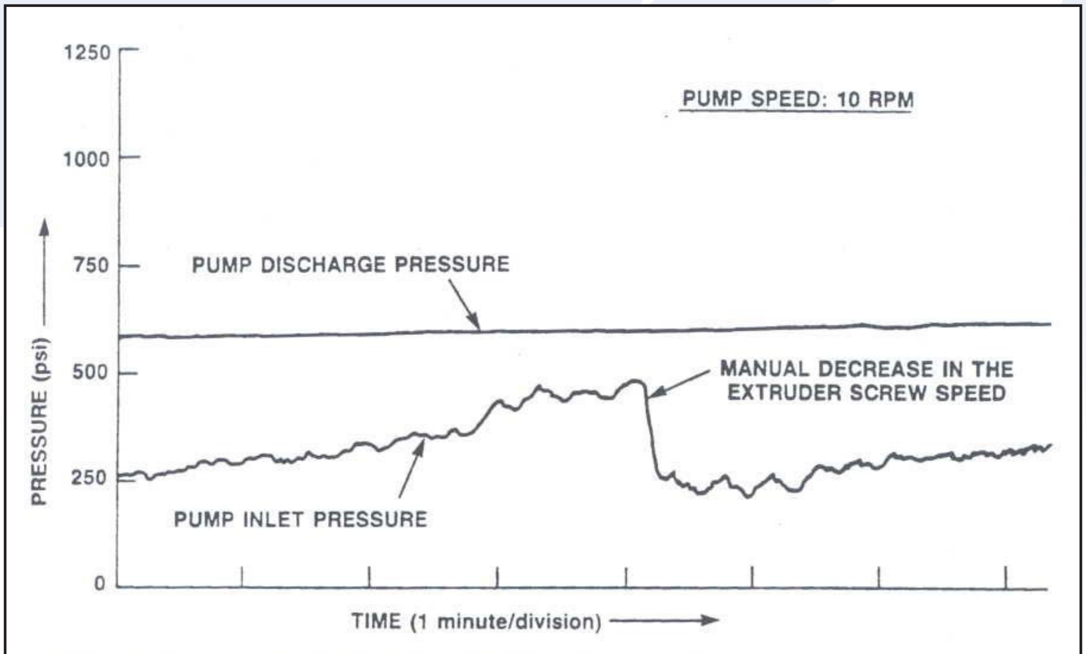

Figure 9. Long Term Pump Inlet Pressure Drift: Manual Adjustment in Extruder Screw Speed.

Figure 10. Long-Term Inlet Pressure Drift with Closed Loop Inlet Pressure Control.

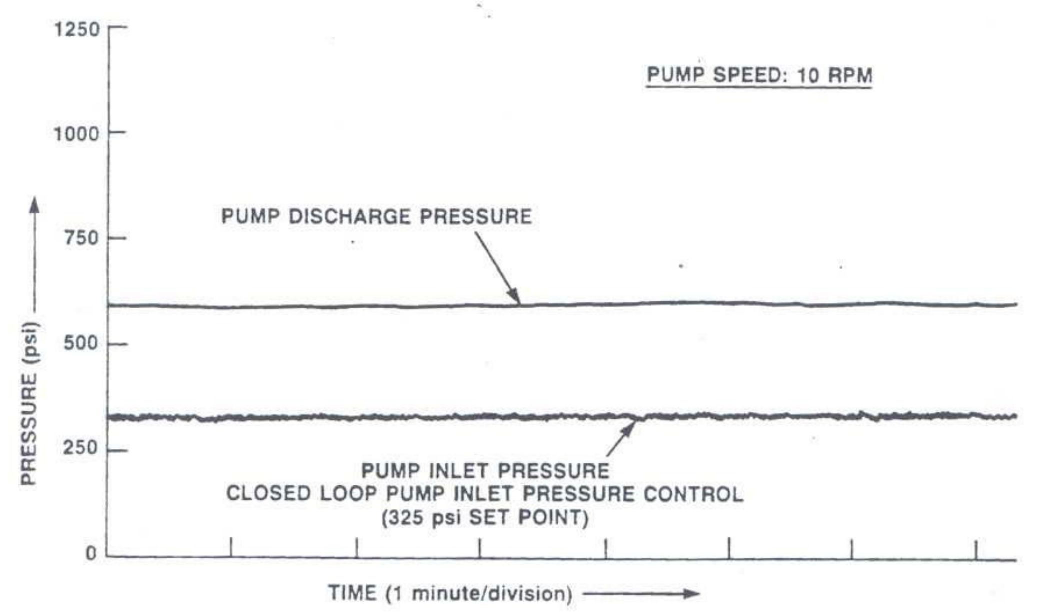

Figure 10. Long Term Inlet Pressure Drift With Closed Loop Inlet Pressure Control.

Figure 11. Closed Loop Pump Inlet Pressure Response to a Pump Speed Change.

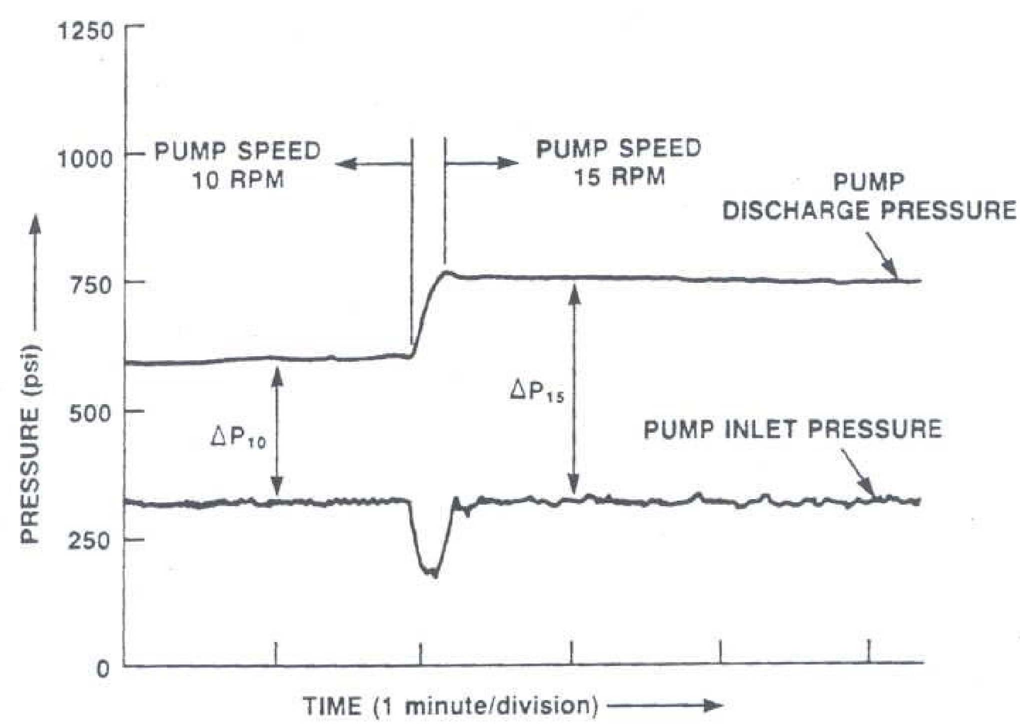

Figure 11. Closed Loop Pump Inlet Pressure Response to a Pump Speed Change.

References

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