A New Way to Handle Changing Fluid Viscosity and the “Full-to-empty” Effect”

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And the "Full-to-empty" Effect"

Abstract

This paper explains how the Ultimus^{TM} V High Precision Dispenser and Optimeter^{TM} maintain consistent shot size in time-pressure dispensing processes as the fluid viscosity and volume of fluid remaining in the syringe change.

Introduction

Time-pressure dispensing is a widely accepted method of depositing small volumes of fluid such as the adhesives or encapsulating epoxies used to assemble many types of products, ranging from electronics such as cell phones, liquid crystal displays and power LEDs to medical devices like cardiac catheters and contact lenses.

These fluids are usually applied from a disposable syringe through a fine gauge dispensing needle using a precisely timed pulse of pressurized air. The duration and pressure of the air pulse are determined by a dispenser controller that regulates both the dispensing pressure and the timing of the pulse. The dispenser controller is connected to the syringe by a length of flexible tubing and a syringe adaptor. Figure 1 displays a block diagram of a typical time-pressure dispensing system.

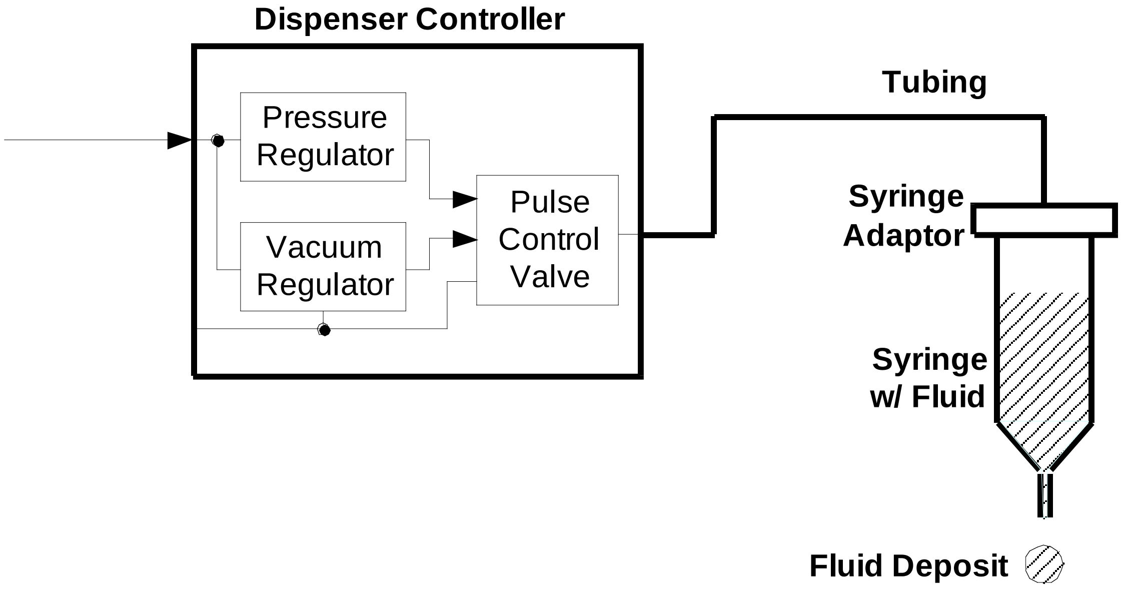


Figure 1: Typical Time-Pressure Dispenser Block Diagram

The pressure pulse applies a force on the fluid contained in the syringe, causing it to flow through the dispensing needle and produce a deposit. The duration of the pressure pulse determines the volume of fluid deposited. Maintaining the consistency of this volume from deposit to deposit is critical to the proper assembly of many products. For example, if an insufficient volume of fluid is applied, the product may not assemble properly and will be rejected. Alternatively, using too much fluid can be costly, or might interfere with the function of the product, such as preventing light from penetrating a camera phone lens.

There are several variables that affect the volume of the deposit. The most significant are the gauge of the dispensing needle, the magnitude of the pressure applied to the fluid, and the duration of the pressure pulse. The process engineer has control of these variables and will select the appropriate size and settings to meet the needs of the application.

Other factors that affect the amount of fluid deposited are changes in the viscosity of the fluid and the amount of fluid remaining in the syringe. Traditionally the process engineer compensates for these changing variables by periodically stopping the product assembly line to check the deposit size and adjust the timed pressure pulse accordingly. Such adjustments are often manual, and based on the engineer's knowledge and experience. However, stopping the assembly line decreases throughput, while manual adjustments increase the probability of rejects due to variations in the volume of fluid deposited.

This paper discusses how decreasing fluid volume in the syringe and time-related changes in a fluid's viscosity affect deposit consistency, and how the Ultimus V dispenser and Optimeter can be used to address these issues.

Full-to-empty Compensation

The overall volume of fluid remaining in the syringe will decrease with each deposit. As the volume of fluid decreases, the volume of air increases. The timed pressure pulse must pressurize the air volume to the set pressure in order to achieve the desired deposit size. However, as the air volume increases, the rate at which the pressure in the syringe changes decreases, so that more time is needed to (1) fully pressurize the air in the syringe to make the deposit and (2) vent the syringe after the deposit has been made.

With short pressure pulses, the air in the syringe may not reach the set pressure as the syringe empties of fluid and the air volume increases. This causes the deposit size to decrease as the amount of fluid in the syringe decreases, and is known as the "full-to-empty effect".

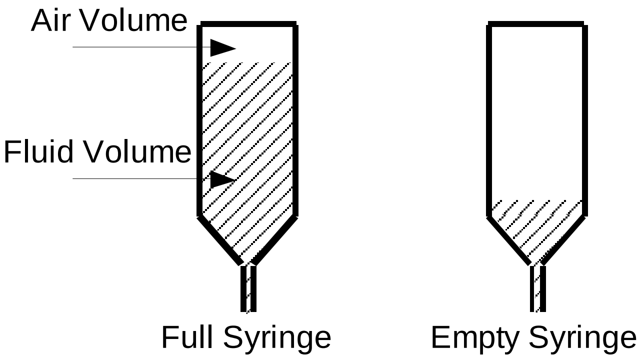


Figure 2: Changing Fluid Volume

To pressurize the air volume in the syringe, air must flow from the dispenser controller, through the flexible tubing and syringe adaptor orifice, and into the syringe. As more air flows into the syringe, the air pressure increases. The set pressure, the maximum mass flow rate from the dispenser controller, the syringe adaptor orifice area, and the volume of air in the syringe are the primary variables that affect the rate of pressure change in the syringe. Figure 3 is a basic diagram of the variables involved in pressurizing the syringe.

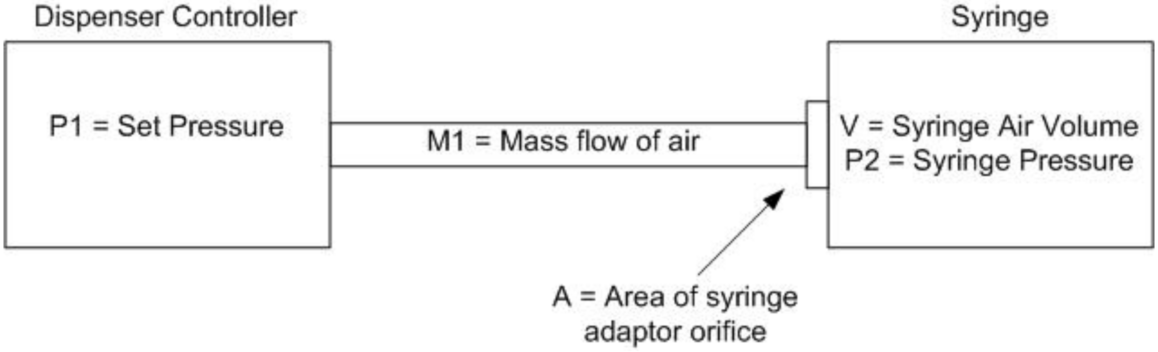


Figure 3: Syringe Pressure Variables

Equation 1 describes the rate of pressure change inside the syringe during a dispensing cycle. K_1 is a constant, V is the syringe volume and M_1 is the mass flow rate though the syringe adaptor orifice. This equation is integrated to get the pressure in the syringe over time.

$$\frac{dP}{dt} = K_1 * \frac{M_1}{V} \tag{1}$$

The mass flow rate of air through the syringe orifice (M_1) is governed by equations 2 and 3. Equation 2 describes the mass flow rate while pressurizing the syringe and equation 3 describes the mass flow rate when the syringe is venting. K_2 is a constant, P_{DC} is the pressure set by the dispenser controller, P_S is the syringe pressure and A is the area of the syringe adaptor orifice. Equations 4 through 6 tell the outcome of C_m based on the ratio of pressures. K3 through K5 are constants.

$$M_1 = K_2 * P_{DC} * A * C_m \tag{2}$$

$$M_1 = K_2 * P_S * A * C_m \tag{3}$$

When $\frac{P_S}{P_{DC}} < 0.528$ for pressurizing or $\frac{P_A}{P_S} < 0.528$ for venting (P_A is the ambient pressure), the air flow is sonic; therefore C_m is the sonic velocity of air,

$$C_m = 0.0404 \tag{4}$$

When $\frac{P_S}{P_{DC}} \geq 0.528$, the pressurizing air flow is sub-sonic so,

$$C_m = \sqrt{K_3 * \left[\left(\frac{P_S}{P_{DC}} \right)^{K4} - \left(\frac{P_S}{P_{DC}} \right)^{K5} \right]} \tag{5}$$

Also when $\frac{P_A}{P_S} \geq 0.528$, the venting air flow is sub-sonic and C_m is

$$C_m = \sqrt{K_3 * \left[\left(\frac{P_A}{P_S} \right)^{K4} - \left(\frac{P_A}{P_S} \right)^{K5} \right]} \tag{6}$$

Initially while the pressure ratio is less than 0.528, the mass flow rate is sonic and therefore constant. The mass flow rate diminishes exponentially as the pressure differential reduces to zero. For simplicity, assume that the mass flow rate is sonic and thus linear. Figure 4 shows a pressure pulse with and without this assumption.

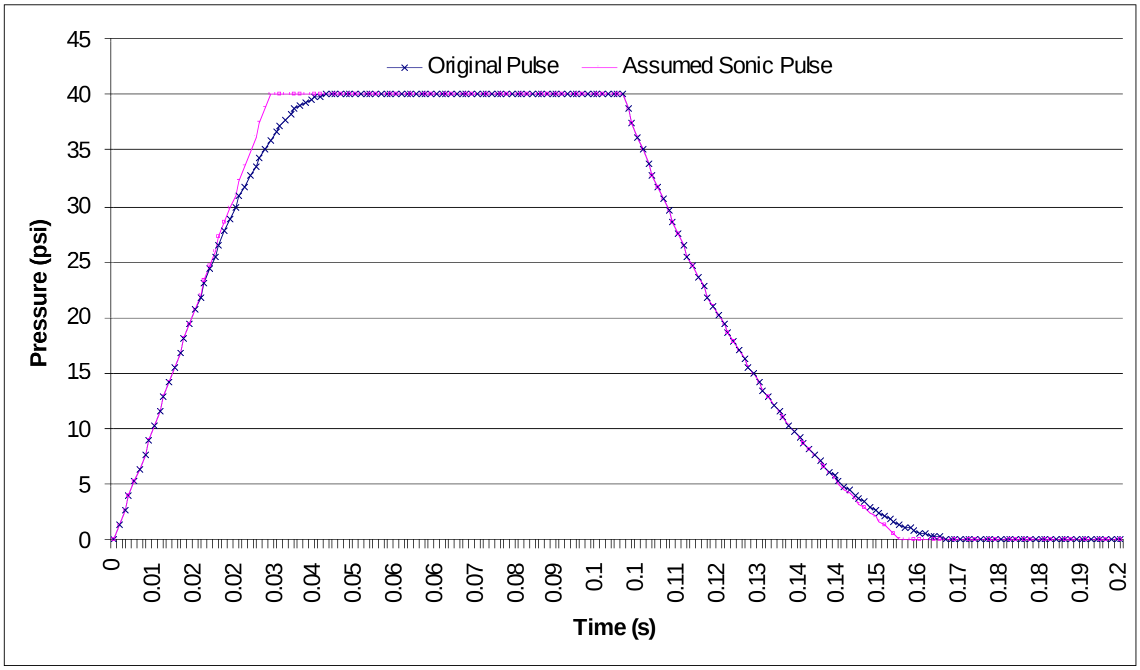


Figure 4: Pressure Pulse Sonic Assumption

Using the sonic flow assumption it is clear that when pressurizing the syringe, the dispenser controller pressure (P_{DC}) and the syringe adaptor orifice (A) are the controlling variables determining the air mass flow rate into the syringe (2).

Also note that during the venting portion of the pressure pulse, the mass flow through the syringe adaptor reverses. In this case, the dominant variables are the pressure remaining in the syringe (P_S) and the syringe adaptor orifice area (3). Equation 7 is formed by substituting equation 2 into equation 1 and combining the constants. Equation 8 is formed by substituting equation 3 into equation 1 and combining the constants. From equations (7) and (8), it can be seen that the rate of pressure change is inversely proportional to the volume of the syringe. Therefore it takes longer to pressurize or vent the syringe as the syringe empties of fluid and the air volume becomes larger.

Another way to look at it is that as the air volume increases, the amount of air mass needed to pressurize that air volume also increases. But because the flow of air is constant through the syringe adaptor orifice, more time is needed to allow the air to flow into the syringe to bring it up to the set pressure. Figure 5 shows several pressure pulses in a syringe with various air volumes. It is clear that as the air volume in the syringe increases, the amount of time the syringe is at the set pressure decreases. This reduced pressure pulse is what causes the decrease in deposit size.

$$\frac{dP}{dt} = K_6 * \frac{P_{DC} * A}{V} \qquad (7)$$

$$\frac{dP}{dt} = K_6 * \frac{P_S * A}{V} \qquad (8)$$

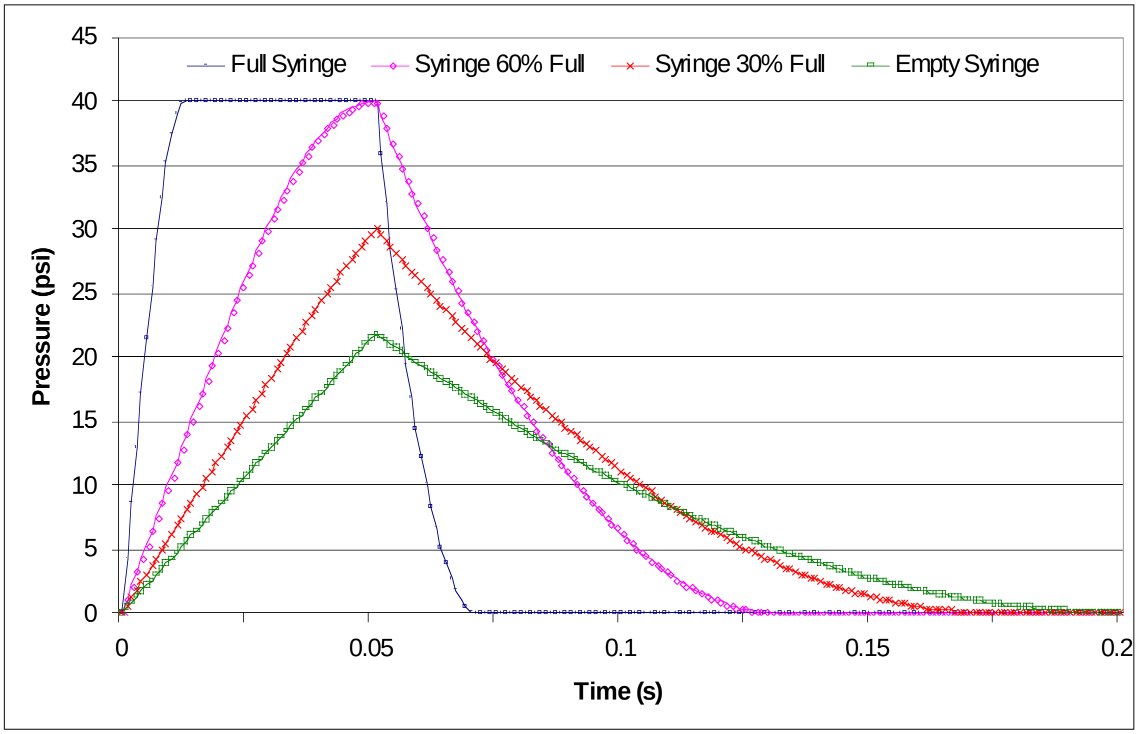


Figure 5: Uncompensated Full-to-empty 30cc Pressure Pulses

One method of automatic compensation is to increase the dispense time as the syringe empties. While this method does allow the syringe to be at the set pressure for a fixed period, the overall cycle period increases considerably due to the increase pressurizing and venting times.

Figure 6 shows a full syringe and an empty syringe that uses dispense time compensation. Here it is shown that the dispense time began at 50ms with a full syringe and ended at 175ms when the syringe is empty. The total time to pressurize and then vent an empty syringe was 350ms when venting time is considered. Having a variable dispense time is undesirable when the dispenser controller is part of an automated assembly system that is operating at a high rate and relies on a consistent cycle rate.

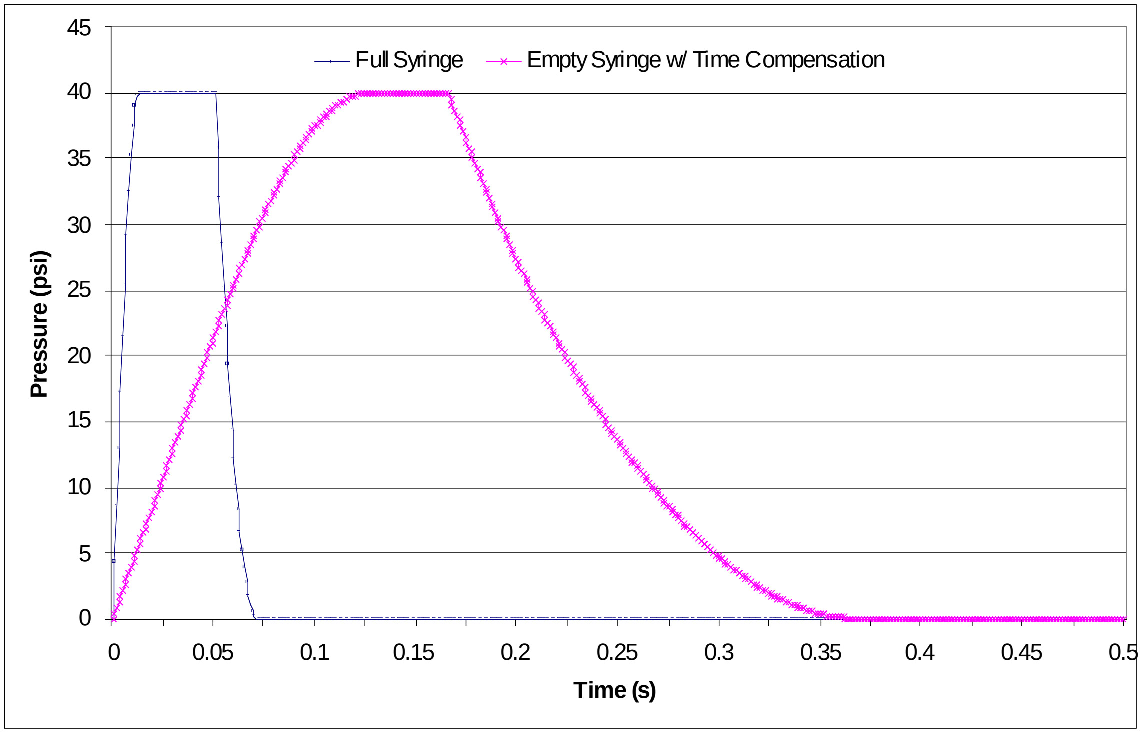


Figure 6: Varying Time Full-to-empty Compensation

Another method of compensating for the full-to-empty effect is to increase the dispensing pressure as the syringe empties. By increasing the dispensing pressure, the flow rate of the fluid through the dispense needle will also increase, resulting in larger deposits. But as shown in Figure 7, the venting time is still significant when the syringe is empty because the air mass still needs to vent from the syringe. Increasing the set pressure increases the total air mass and will ultimately increase the venting time. This long vent time may cause fluid to drool from the dispensing needle as the automated system is moving the syringe and dispensing needle to the next location.

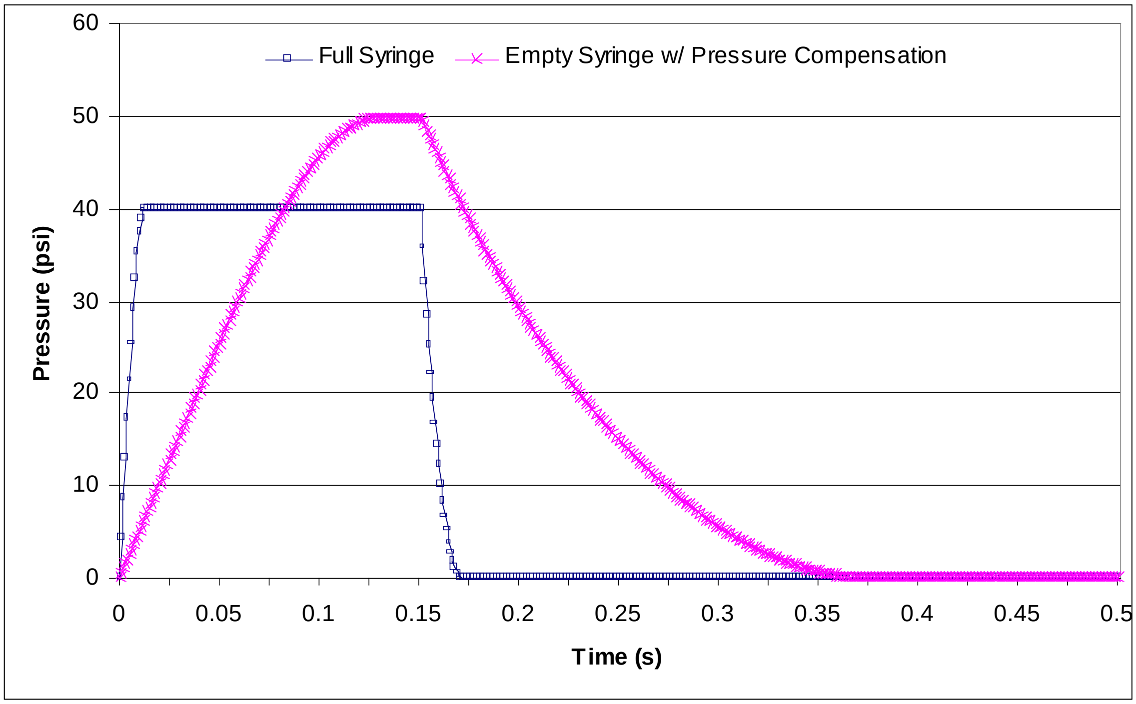


Figure 7: Varying Pressure Full-to-empty Compensation.

The Ultimus V combined with the Optimeter negates the full-to-empty effect by varying the orifice diameter of the syringe adaptor. As shown in equations 7 and 8, the pressure pulse rate can remain constant when the area of the syringe adaptor orifice changes in proportion to the change in air volume inside the syringe. Increasing the size of the adaptor orifice increases the flow rate through the orifice. This allows a greater flow of air into the syringe, allowing it to pressurize more quickly. The venting portion of the dispense cycle is controlled in a similar manner.

The Optimeter automatically tracks the air volume of the syringe and adjusts the size of the adaptor orifice appropriately. This capability, combined with the Ultimus V's hybrid precision electronic pressure regulator, allows the pressure pulse to remain consistent regardless of the volume of fluid in the syringe. Since the Optimeter automatically adjusts the orifice to compensate for the full-to-empty effect, the process engineer is free to focus on compensating for the changing fluid viscosity. Figure 8 shows actual test data for compensated and uncompensated dispensing systems.

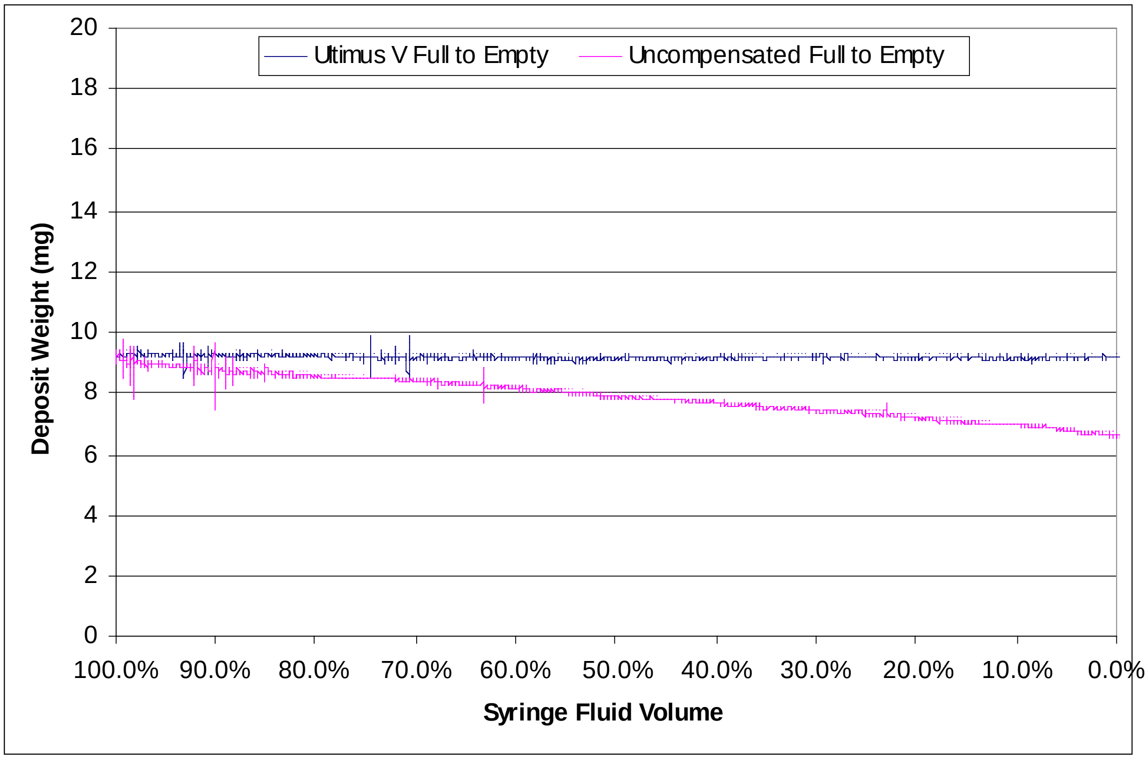


Figure 8: Actual Deposit Mass from Full-to-empty

Viscosity Compensation

Many of today's applications involve dispensing two- or three-part epoxies that cure and harden over time. As the viscosity of these fluids increases as they cure over time, the amount of fluid dispensed decreases, unless some form of compensation is used. The process engineer can either increase the dispense time or increase the dispense pressure. Other methods use temperature to slow down the fluid's cure rate, but ultimately the viscosity of the fluid will increase and the size of the fluid deposits will decrease.

Poiseuille's equation (9) can be used to demonstrate how increasing the syringe pressure is a way to offset the increase in viscosity. Poiseuille's equation calculates the volumetric flow rate of a fluid through a pipe or needle with an inner radius (R) and length (L), a viscosity (μ), and pressure differential (P2 – P1), where P1 is the ambient pressure and P2 is the pressure inside the syringe.

This equation assumes that flow through the dispensing needle is laminar (not turbulent) and the pressure drop of the fluid in the syringe is negligible compared to the pressure drop across the dispensing needle. These assumptions mean that the pressure pulse is fully applied across the dispensing needle. Substitute the integral of equations 7 and 8 for P2 in equation 9, and then integrate equation 9 over time to determine the volume of the deposit.

$$\frac{dV}{dt} = \frac{\pi * R^4 * (P_2 - P_1)}{8 * \mu * L} \tag{9}$$

In a typical dispensing system, the dispensing needle's diameter and length are fixed. Given that, it is clear that to maintain a constant fluid flow rate the syringe pressure needs to increase in proportion to the changing fluid viscosity.

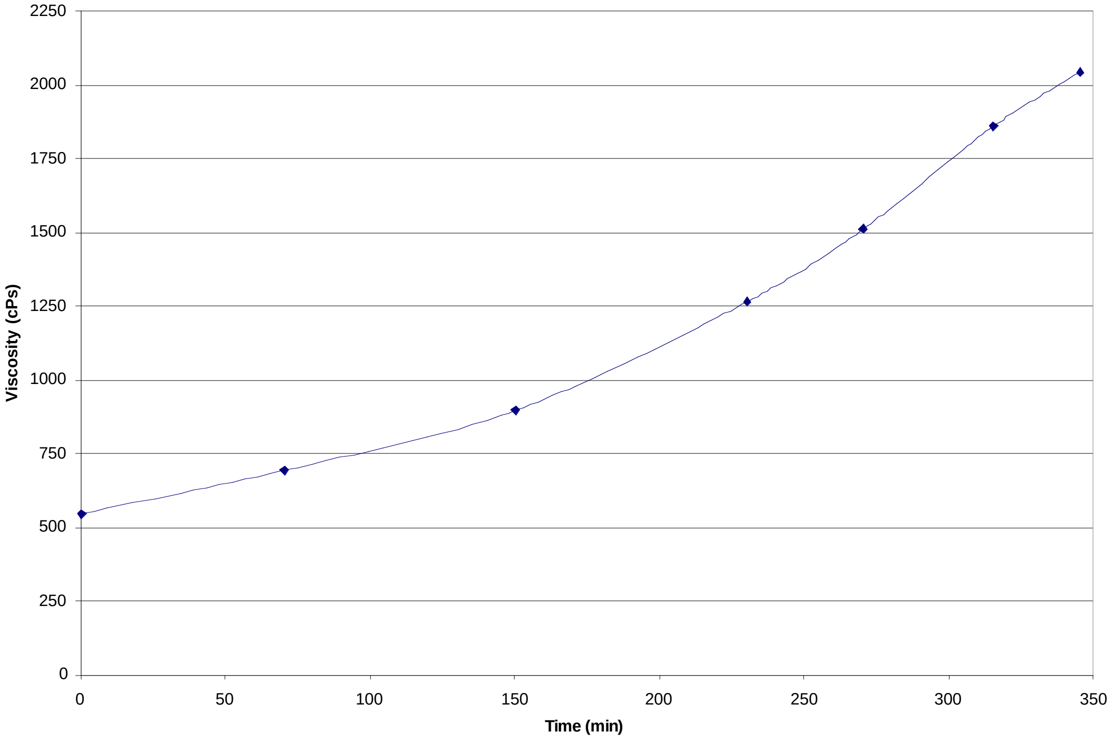


Figure 9: An Example of a Viscosity-changing Fluid

For illustration, the viscosity curve of a fluid as it cures is shown in Figure 9. Notice that the viscosity change of the fluid is not linear. There are many possible curves for a curing fluid. These curves can be linear, exponential or, in the case of Figure 9, a polynomial. Applying equation 9 to the viscosity curve shows that the needed change in pressure over time is nonlinear. Therefore using a dispensing system that compensates for changing viscosity in linear step intervals will result in inconsistent deposit sizes as the fluid cures (Figure 10).

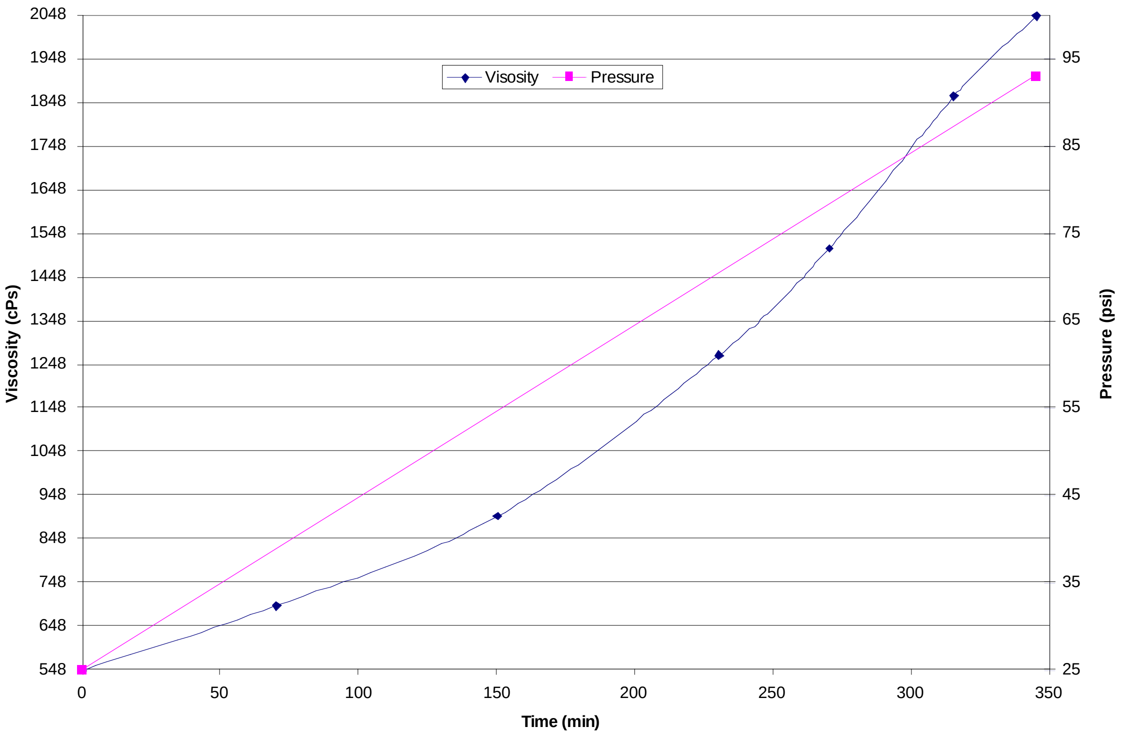
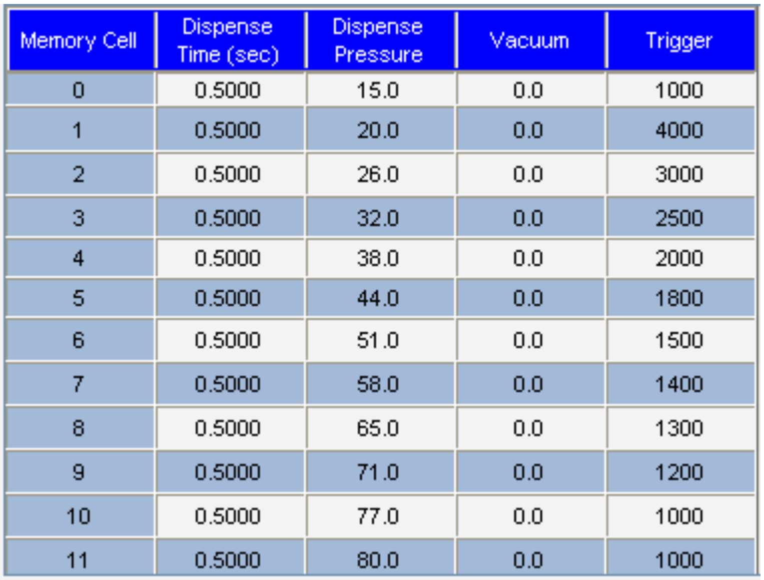


Figure 10: Viscosity Compensation w/ Linear Pressure

In contrast, the Ultimus V dispenser has the ability to store up to 400 dispensing parameters into memory cells, each one storing Set Pressure, Dispense Time, Vacuum and Trigger values. The Ultimus V Auto Increment feature is then used to automatically set the dispensing parameters based on the Trigger value and the Auto Increment Mode. The Trigger value can be set to either the number of dispense cycles that occur during each interval (Count Mode) or to the number of seconds that elapse during each interval (Timer Mode). The Ultimus V and Optimeter enable the process engineer to alter the dispensing pressure as well as the time intervals at which pressure is changed.

As each interval time expires, the Ultimus V transitions to the next pressure setting. The Ultimus V is unique in that it allows this time interval to be different for each step, which simplifies the setup process by reducing the number of steps to be calculated. With dispensing systems that have a fixed time interval step, the time step has to be the smallest needed to fit the changing viscosity curve. The pressure curve must then be broken into these small intervals. This can result in many adjacent memory cells being loaded with the same pressure settings, thus wasting memory cells. Reducing the number of intervals needed for each viscosity curve allows more curves to be stored in the 400 memory cells in the Ultimus V.

Table 1 shows a sample of a dispensing parameter profile that could be loaded into the Ultimus V to compensate for the changing fluid viscosity. Figure 11 shows the dispensing pressure compared to the changing viscosity. (Note how the time interval changes as the rate of viscosity change increases.)



Memory Cell	Dispense Time (sec)	Dispense Pressure	Vacuum	Trigger
0	0.5000	15.0	0.0	1000
1	0.5000	20.0	0.0	4000
2	0.5000	26.0	0.0	3000
3	0.5000	32.0	0.0	2500
4	0.5000	38.0	0.0	2000
5	0.5000	44.0	0.0	1800
6	0.5000	51.0	0.0	1500
7	0.5000	58.0	0.0	1400
8	0.5000	65.0	0.0	1300
9	0.5000	71.0	0.0	1200
10	0.5000	77.0	0.0	1000
11	0.5000	80.0	0.0	1000

Table 1: Dispensing Parameters for a Viscosity-changing Fluid

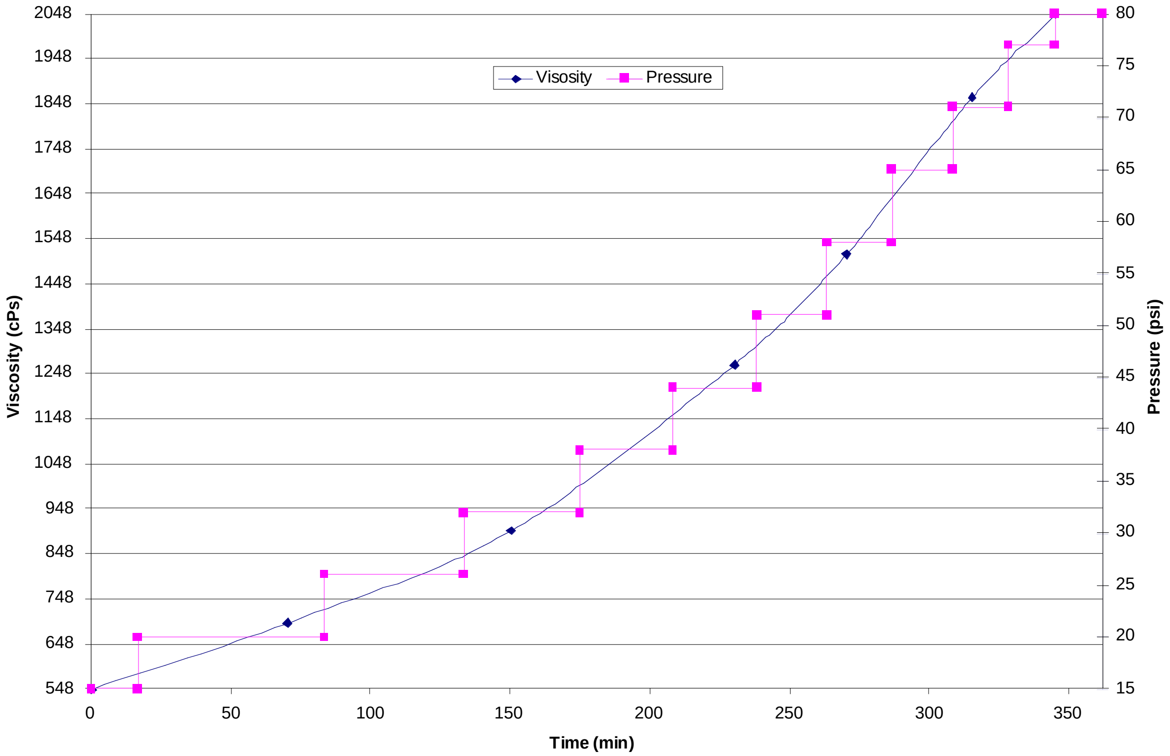


Figure 11: Viscosity Compensation Using the Ultimus V

Figure 12 details the volumes of the deposits made using the pressure profiles given in Figures 10 and 11 for the given fluid. Note that the linear pressure compensation has a greater range of error than the compensation used by the Ultimus V. Also consider the full-to-empty effect discussed above.

As pressure increases with increasing air volume, the pressure pulse increases significantly, leading to the possibility of fluid drooling from the dispensing needle on automated assembly equipment. Altering the set pressure and dispense time to compensate for the full-to-empty effect while simultaneously altering those parameters to compensate for changing viscosity can be difficult. Other variables, such as the volume of fluid contained in the syringe at startup, can further complicate the process.

The assembly machine may also pause for a short time due to a jam or part changeover. While this will not be an issue for viscosity compensation, which is based on total time and is independent of the assembly machine cycle rate, full-to-empty compensation does depend on the machine's cycle rate. Any unscheduled pauses in the cycle rate can invalidate any calculations for the combined compensation, which can lead to even more inconsistent deposit sizes. The combination of the Ultimus V and the Optimeter allow the process engineer to easily compensate for both the full-to-empty effect and changing fluid viscosity, without worrying about many of the issues described above.

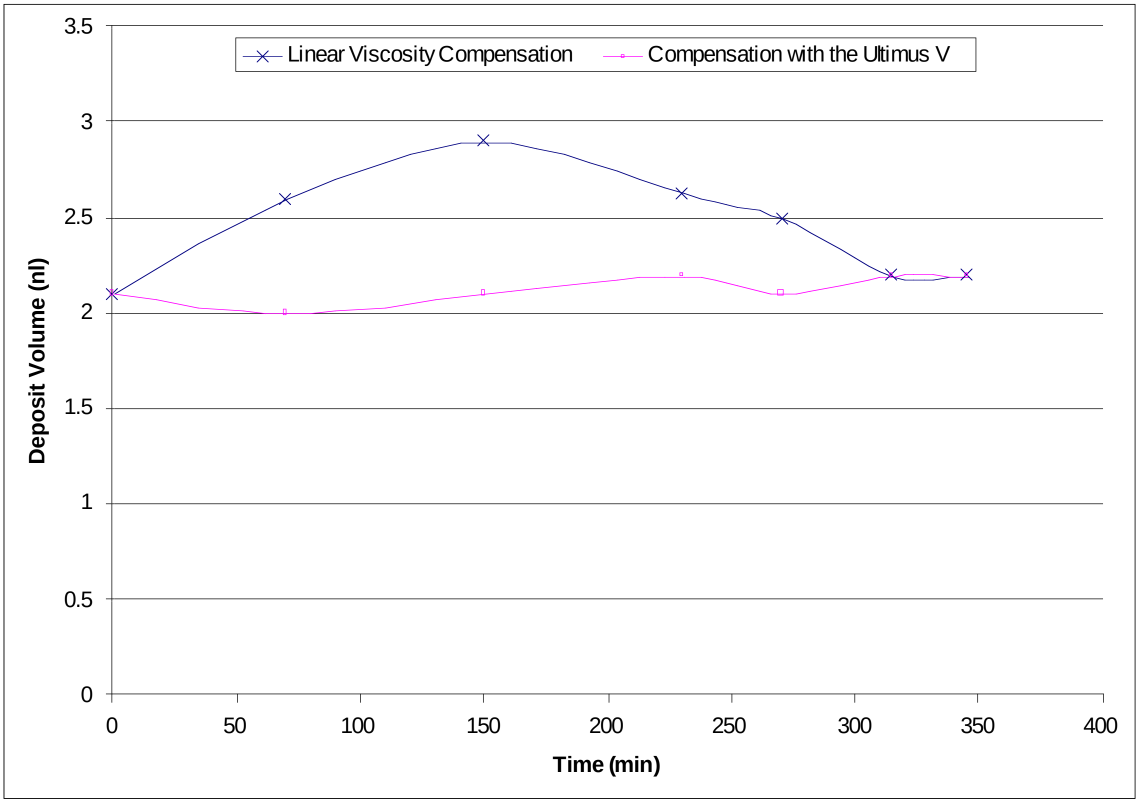


Figure 12: Deposit Volumes with Viscosity Compensation

Other Compensation

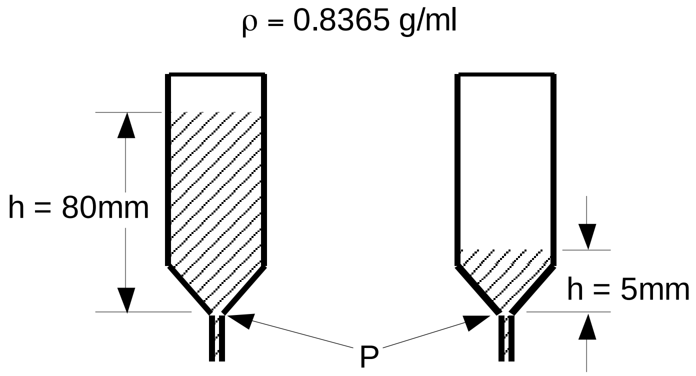
Processes that use fluids with stable viscosities can also benefit from the capabilities of the Ultimus V dispenser.

Many processes that involve very low-viscosity fluids apply vacuum to prevent fluid from dripping from the dispensing needle between dispensing cycles. For these processes, the vacuum level must be set to support the column height of the fluid. With too much vacuum, fluid is drawn back through the dispensing needle and bubbles appear in the syringe, while vacuum that is too low will cause fluid to flow out of the dispensing needle. Both of these conditions affect deposit consistency. As the fluid volume in the syringe decreases, the amount of vacuum needed to prevent the fluid from dripping also decreases. Therefore, a vacuum setting that prevents dripping with a full syringe may cause bubbles in a syringe that is nearly empty.

Examining Poiseulle's equation (9), in order to prevent any flow from the dispensing needle, the syringe pressure (P2) must equal the ambient pressure (P1). The amount of fluid in the syringe and the effects of gravity generate a pressure inside the syringe, which can be calculated using equation 10, where P1 is the pressure of the fluid at the dispensing needle (kpa), P2 is the pressure at the top of the fluid inside the syringe (kpa), ρ is the fluid's density (Kg/L), g is the acceleration due to gravity ($m*s^2$) and h is the height of the fluid inside the syringe (m). The greater the density of the fluid and the greater the height of the fluid, the greater the pressure at the dispensing needle, so that more negative pressure is needed to hold the fluid. However, as the height of the fluid in the syringe decreases, the pressure generated is also reduced.

$$\Delta P = P_2 - P_1 = \rho * g * h \qquad 10$$

The Ultimus V can compensate for the changing fluid height and corresponding changing vacuum requirements by using the Auto Increment function in Count Mode. The process engineer can determine the number of intervals needed to step down the vacuum setting and the number of deposits for each interval. The number of deposits then becomes the trigger value for each interval. Figure 13 shows an example of how vacuum requirements change as a syringe empties.



$$P = \rho * h * g$$
$$= 0.8365 g/ml * 80 mm * 9.8 m/s^2$$
$$= 0.65 kpa \approx 2.6\text{''}H2O$$

$$P = \rho * h * g$$
$$= 0.8365 g/ml * 5 mm * 9.8 m/s^2$$
$$= 0.04 kpa \approx 0.2\text{''}H2O$$

Figure 13: Example of Vacuum Needed for a Fluid

Conclusion

As this paper explains, there are many variables that affect fluid deposit size and consistency deposit from dispense cycle to dispense cycle. Many of these variables, such as dispensing pressure, dispense time and needle gauge, are directly controllable by the process engineer, size. However, some dispensing variables are not directly controllable and will change as the syringe empties. The changing fluid volume in the syringe causes a “full-to-empty” effect that has a negative impact on the consistency of the fluid deposits. Fluids that cure and change their viscosity over time can also have an undesirable effect on deposit size consistency.

Standard dispensing systems that feature automatic compensation but do not address both the full-to-empty effect and changing fluid viscosity often fail or have other undesirable effects, such as longer cycle time or drooling between deposits. The Ultimus V dispenser controller and Optimeter resolve these issues by addressing them concurrently.

The Ultimus V dispenser also has a custom electronic pressure regulator that is specially designed for high-precision dispensing. Being able to electronically control the dispensing pressure, coupled with the Ultimus V’s variable trigger feature, increases the process engineer’s ability to accurately dispense fluids that change viscosity.

The Optimeter is used to proportionally control the amount of flow of air into and out of the syringe. This ensures that the pressure pulse maintains the same characteristics from when the syringe is full to when it is empty.

Consistent pressure pulses result in consistent fluid flow from the dispensing needle, which in turn ensures consistent deposits. Combining the Ultimus V dispenser and Optimeter provides an easy-to-use solution that will deliver consistent fluid deposits in the most demanding applications.

Frequently Asked Questions

1. What are the advantages of using the Ultimus V dispenser compared to a positive displacement syringe system?

   Positive displacement systems often use a stepper motor and a threaded rod as the system actuator. These actuators are long and the stepper motor is heavy, making positive displacement systems difficult and cumbersome for manual dispensing applications. In contrast, the Optimeter features a lightweight aluminum body and very flexible air supply hose that make it suitable for both hand operations and mounting on a robot.

   Positive displacement systems also tend to be slower than time-pressure dispensers like the Ultimus V. Positive displacement systems have a maximum flow rate that is limited by the mechanical actuation of the displacement system.

   Also, many positive displacement systems retract the piston to keep fluid from dripping from the dispensing tip. Again, this rate is limited by the mechanical actuator. The Ultimus V dispenser does not have this restriction—the process engineer has the ability to change the dispense tip, dispensing pressure and dispense time to achieve the desired deposit size and cycle rate, while maintaining a high level of deposit size consistency.

   Another advantage of the Ultimus V dispenser over positive displacement systems is that the Ultimus V can be used to make a variety of deposit types and sizes with a single dispenser while maintaining the same accuracy for all of the deposits. Its sequencing capability allows the process engineer to generate repeatable patterns such as large deposits, small deposits or beads. A positive displacement system, on the other hand, would require the use of multiple units in order to achieve such variety at acceptable cycle rates.

2. Can I use the Optimeter with dispensers other than the Ultimus V?

   No. The Ultimus V's custom-built electronic pressure regulator and the Optimeter were specifically designed to work together to produce consistent fluid deposits.

3. How do I develop a dispensing parameter profile to load into the Ultimus V dispenser?

   The easiest way to develop a dispensing parameter profile is to use the Ultimus V Interactive Software included with the dispenser. This software provides convenient tools for gathering and displaying empirical dispensing parameter data, as well as tools for generating a dispensing parameter profile.

4. Can I store multiple fluid profiles in the Ultimus V dispenser?

   Yes. There are a couple ways of doing this. The Ultimus V contains 400 memory cells for storing dispensing parameters. If the total number of memory cells for the multiple profiles is less than 400, then the profiles can be stored in increasing memory cell addresses. The operator would then need to adjust the START and END addresses in the Auto Increment mode to appropriate memory cell addresses.

   The other method is to use the Ultimus V Interactive software 'Load Jobs' feature. Up to four dispensing parameter profiles can be loaded into the Ultimus V dispenser using the 'Load Jobs' feature. Each of the parameter profiles can use up to 400 memory cells. In addition, each parameter profile can be named according to the application to reduce the chance of an incorrect setup being used in a process. .

References

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