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ALL THINGS FLOW

UNDERSTANDING PUMP DESIGN FLOW VARIANCES

Metering pump testing quantifies performance and use of excess chemical beyond molar calculated setpoint.

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ABSTRACT

This paper reports the results of testing four kinds of metering pumps: peristaltic metering, solenoid actuated diaphragm, stepper motor driven diaphragm and progressive cavity. Each pump was put through the same exercises to determine flow and excess chemical usage. The configuration of the test equipment was to operate the metering pump with a flooded suction of approximately 2.0 feet w.c. The purpose of testing was to determine the effect of pulsation on the quantity of a chemical required while operating the pump at 50 percent pump capacity. Half of the pump's capacity was chosen because this is where most metering pumps are sized at nominal process conditions. There are two types of statistical distributions that encompass the data sets collected using high-speed flow capturing. One of the distribution types is the normal distribution, also known as Gaussian distribution or bell curve. The other is non-normal distribution. Study of these data points and distributions allowed testers to determine the performance of each pump type. Enhancement of metering pump technology results in less chemical waste. Changes to design in order to eliminate pulsation will allow industries to move away from batch-related process and move toward continuous manufacturing methods that permit increased control in quality and fewer opportunities for contamination.

KEYWORDS
metering pump; chemical processing, manufacturing, water treatment, wastewater treatment, pulsation, reliability, chemicals, flow, molar setpoint, solenoid actuated diaphragm, peristaltic pump, stepper motor driven diaphragm, progressive cavity pump, batch process, continuous manufacturing, flow sampling, repeatability, linearity, flow variability, differential pressure

INTRODUCTION

In the current industrial manufacturing, chemical processing, water treatment and wastewater treatment markets, the use of chemicals, catalysts and additives are used to optimize processes, maintain quality and optimize operational efficiency. The number and variety of the chemicals used is almost as limitless as the processes that require additives. Some of these chemicals are expensive and usage can be strictly limited by local and federal regulation agencies. To precisely control the amount of chemicals used, metering pumps are used to inject these additives into process streams. Records of usage and discharge levels are manually or digitally sampled frequently, and records strictly kept in order to retain regulatory compliance. The limits of residual chemicals permitted must fall within an acceptable range that includes minimum and maximum criteria. Failure to meet these levels or exceed these levels can have dramatic effects of consumer health and far-reaching liabilities on the entities that use the chemicals.

The predominate features of an excellent metering pump might not be intuitively obvious. Typically, respondents would determine accuracy as the most important feature, but a closer look is required in order to determine what features determine accuracy. Does accuracy mean that the pump flow matches the curve exactly or does it mean that the pump is accurate to itself, or repeatable? Manufacturing variability makes this an impossibility to achieve accuracy to the curve more than 0.5 to 2.0 percent.

REPEATABILITY

Metering pump performance is really related to repeatability while minimizing flow variance as percentage of mean flow. If a pump has a high degree of repeatability, the flow is predictable, based on only a minimum of process parameters. If pressure does not affect the flow, pressure is no longer a dependent variable for feed rate.

LINEARITY

If a pump is highly repeatable, the next most important performance feature will be linearity. If an operator determines that the feed rate needs to be adjusted, linearity allows them to quickly interpolate the prescribed output based on present output. This means that an X percent increase/decrease in setpoint will correspond to X percent increase/decrease in chemical flow rate.

FLOW VARIABILITY

If a pump has a high degree of repeatability and linearity, the next most important measure of performance will be low flow variability as a function of differential pressure. This means that a large change in feed point pressure should result in very small change in chemical feed rate. This stability of flow in relation to pressure allows operators to feel assured that natural process pressure variations are not impacting the chemical feed rate.

The often overlooked, but most important, measure of a metering pump is the ability to minimize the variability of flow for a given setpoint. This is variability seen in a steady state flow without changes in process variables. In other words, how close is instantaneous flow to the mean flow rate? This last performance criterion has most significance to the plant operator's annual chemical budget. Variability in flow forces the use of higher feed rates to ensure compliance.

To sum the features up, a quality metering pump must:

1. Have a metered flow rate that is repeatable over long periods of time between calibrations.
2. Have a linear flow output that corresponds with setpoint increases/decreases.
3. $\frac{\Delta flow}{\Delta pressure} = \sim 0$ (flow change rate $\ll$ pressure change rate)
4. $\frac{\Delta flow}{\Delta time} = \frac{df}{dt} \sim 0$ as $\frac{d}{dt} => 0$ (flow variability should be small as possible)

Advanced plant process control is used to eliminate variability in the final product. Automation of this control has created a variety of analytical sensors to provide semi-real-time feedback of the subject process variable(s). The earlier in the process that critical process variables are measured, the sooner automated adjustments can be made to the chemicals that influence the process variable.

The challenge is that these automated controllers and analytical instrumentation do not operate in real-time. The control systems take periodic measurements, making process input variable changes and then repeating another measurement after a prescribed time interval. These time intervals can range from milliseconds to fractions of an hour. Examples include differential pressure measurements on the order of 100 msec. to free chlorine residual that can only update every 5 to 15 minutes. The longer time interval instrumentation uses a sample-and-hold method that usually requires chemical reagents.

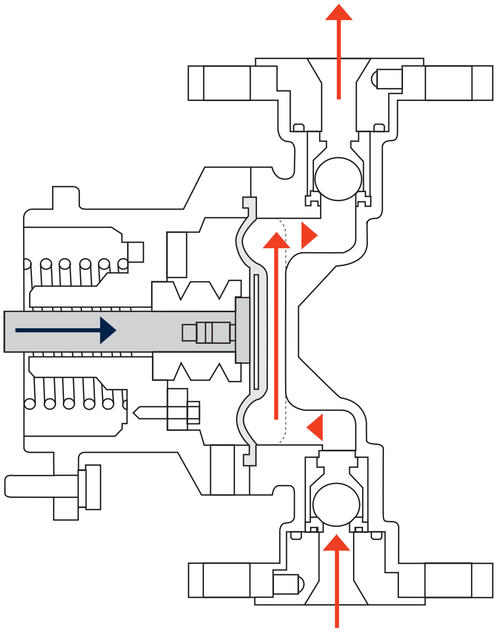
This is somewhat akin to taking a sample to a lab, titrating in order to determine pH and then making process adjustments based on that single sample. After the pre-selected time interval expires, a sample from the process stream is tested again. The biggest question is where and when will the analyzer sample the process variable? This also means that significant chemical is wasted to mitigate the probability that the analytical analyzer sample may be gathered when instantaneous flow was at a minimum value.

METERING PUMP DESIGN PRINCIPLES

As discussed above, chemicals are precisely injected into the process using metering pumps. Metering pumps come in varieties based on the technology used in their operation. Specific types include solenoid diaphragm pumps, motor-driven diaphragm pumps, peristaltic/hose pumps and progressive cavity pumps. Below, we will discuss the technologies in more detail.

Solenoid metering pumps utilize a strong electromagnetically driven piston and return spring to actuate the diaphragm in the pump. They also employ check valves on the suction and discharge to establish flow direction through the pump. This design does not require any shaft seal since there are no rotating components. This type of pump has a high peak instantaneous flow and points in the cycle where no flow is present. (see Figure 1)

FIGURE 1: Solenoid metering pump

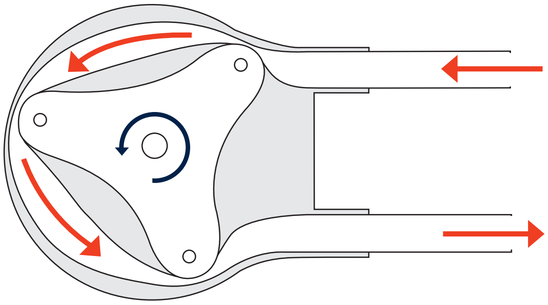


Motor-driven diaphragm pumps come in two types, lost-motion and full-motion. The electric motor is used to actuate the diaphragm. In a lost-motion pump, the diaphragm is driven by a rotating cam. The proximity of the piston position relative to the cam determines the duty-cycle and amplitude of the motion of the diaphragm. This design can be less preferred since the diaphragm motion is the product between a square wave and a sinusoidal wave. There are times within the pump cycle where diaphragm motion ceases to move. Some manufacturers have embraced the use of stepper motors to reduce the duty-cycle portion where forward flow does not happen.

Full-motion, motor-driven diaphragm/piston pumps make sure that the diaphragm/piston is in motion the entire length of the pump cycle. Capacity of the pump is controlled by motor speed and/or overall stroke length (diaphragm amplitude). Although the diaphragm is in continuous motion, the flow is not continuous and is only present for 50 percent of the cycle time. This creates a high degree of pulsation in flow rates. Most manufacturers of diaphragm pumps make lost-motion and full-motion designs as part of their portfolio. Lost-motion designs have times where the diaphragm/piston motion stops in the pump cycle. In full-motion designs, the diaphragm and piston motion never stop during the pump cycle.

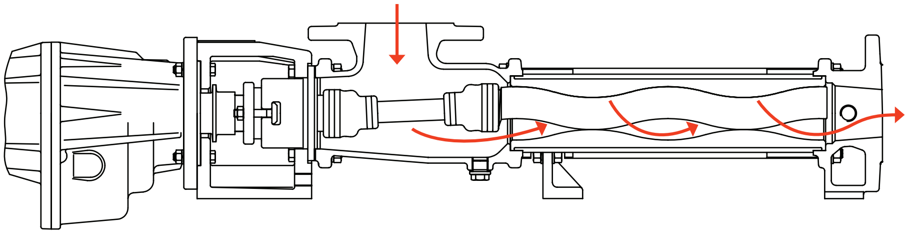
Peristaltic metering pumps use the properties of a flexible hose and cylindrical rollers to compress a hose in order to create multiple sealed cavities that are pushed along the hose to create flow. The precise control over the angular velocity of the rollers creates a flow progressing through the hose tangential to the roller wheel. There are no check valves required in this design. The flow from this design is more continuous than diaphragm pumps but can still have significant flow variation. (see Figure 2)

FIGURE 2: Peristaltic metering pump



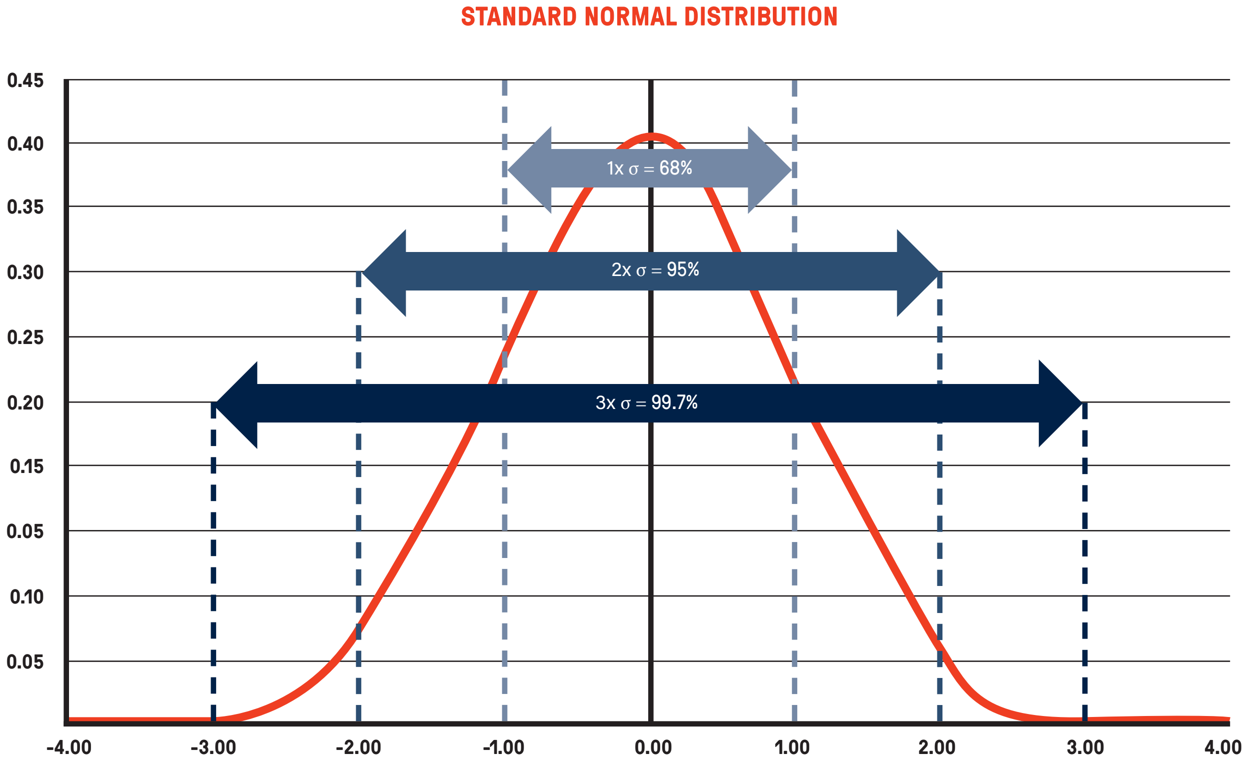
Progressive cavity pump technology has been used for the last 90 years. However, it has only been applied to metering pump design for the last 30 to 35 years. The technology utilizes a rubber stationary component that features an internal void in the shape of a double helix. The other major component is a rotor in the design of a single helix with two times the pitch length of the stator's double helix void. When the rotor is inserted into the stator, a cavity is formed between the rotors and the stator. When the rotor is rotated axially, the cavity formed between the rotor and stator progresses from one end of the stator to the other. The unique feature to this design is that a cross-sectional area of the cavity is constant over the length of the pump. This virtually eliminates pulsation during the operation of this pump. The pulsation is so slight that special instrumentation will be used to quantify it. (see Figure 3)

FIGURE 3: Progressive cavity pump



All of the above pumps have some degree of pulsation in their flow during operation. By definition, pulsation means that the instantaneous flow varies while operating at average flow target. As mentioned previously, instrumentation takes periodic samples of the process variable, analyzes the sample and records that data. The problem lies in the probability that an analyzer may sample the stream where a chemical metering pump's flow was below the mean flow. In practice, process owners slowly increase/decrease the chemical dosages until samples no longer appear outside operational limits. To establish the minimum amount that a user would need to adjust the chemical dosage, the variability of flow must be quantified. One of the common statistical measures of variability about the mean of a data set is standard deviation (σ) of a distribution of values. The standard deviation (σ) will allow the calculation of the minimum increase or decrease of feed rate to eliminate the probability that a sample would fall outside regulatory operational limits.

FIGURE 4: Normal distribution relationships.



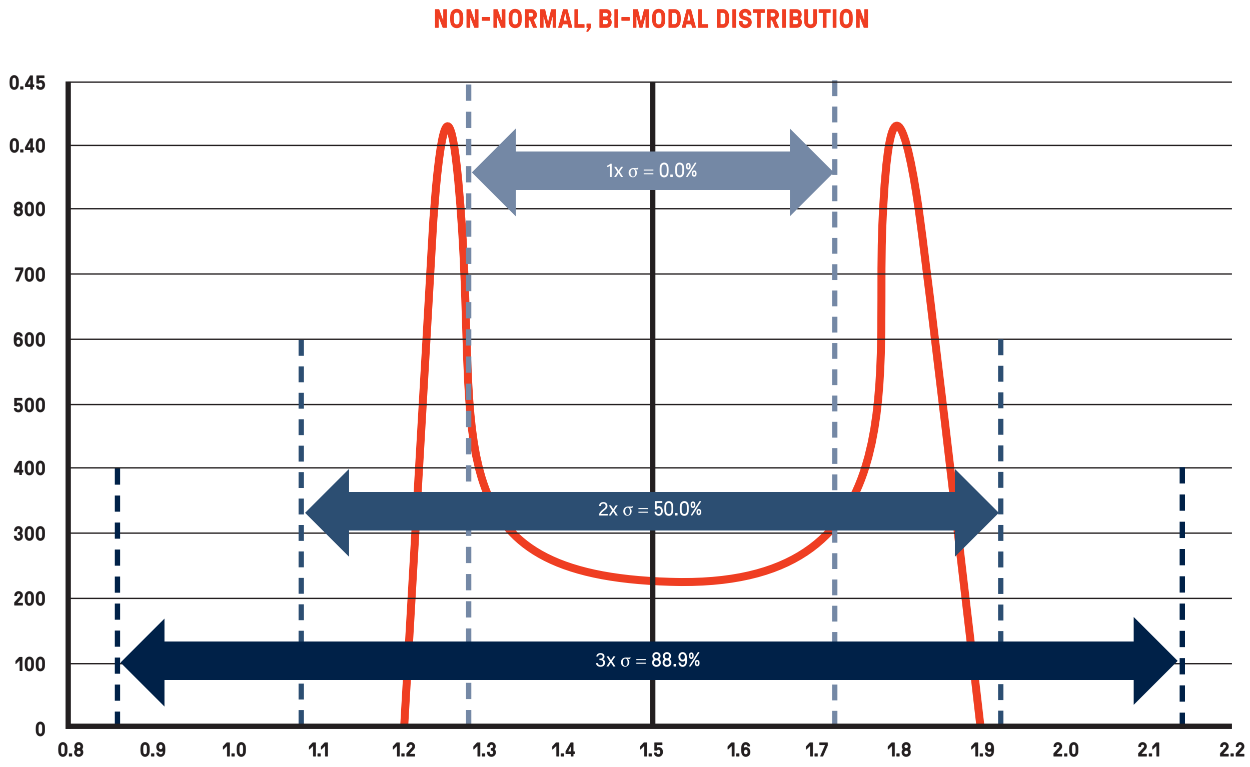
There are two types of statistical distributions that encompass the data sets collected using high-speed flow capturing. One of the distribution types is the normal distribution, also known as Gaussian distribution or bell curve (see Figure 4). The normal distribution is well defined and has been studied in great detail. Many natural and man-made phenomenon follows such distributions. Height of a population, grades on a test, dimensions of production components, blood pressure of a population and measurement errors all follow a normal distribution. The importance of a normal distribution is the statistical information that can be extracted related to the mean (μ) or average and the standard deviation (σ). If a data subset is distributed normally, we know the following things regarding the data set:

1. The data set will be symmetrical about the mean (μ).
2. From the data set, we can calculate the standard deviation (σ) and mean (μ).
3. The subset of data between ($\mu- \sigma$) and ($\mu+ \sigma$) will comprise 68% of the full set of data.
4. The subset of data between ($\mu- 2\sigma$) and ($\mu+ 2\sigma$) will comprise 95% of the full set of data.
5. The subset of data between ($\mu- 3\sigma$) and ($\mu+ 3\sigma$) will comprise 99.7% of the full set of data.

Where μ and σ are found by the following equations, where x are the sample values of n samples:

$$\mu = \frac{\sum_0^n x}{n} \qquad \sigma = \sqrt[2]{\frac{1}{n}\sum_0^n (x-\mu)^2}$$

FIGURE 5: Non-normal distribution relationships.



The second type of data distribution would be non-normal distribution (Figure 5 is an example), which can present in any shape that does not approximate or resemble a normal distribution. Although the above equations can still be used, the statistical correlation between μ and the σ is not as strong as in the normal distribution. The Chebyshev Theorem states that the correlation between μ and σ of a non-normal distribution is expressed by the following equation:

$$percentage\ of\ data\ within\ multiple\ k * \sigma\ of\ \mu = 100\left(1 - \frac{1}{k^2}\right)$$

The distribution shown in Figure 5 is bimodal, which means that it has two peaks that are significantly distant from the mean (μ), which creates a larger standard deviation (σ). This trait is indicative of any flow signal that has a significant amount of sinusoidal variation or pulsation. This also means there is high probability of sampling when flows are the farthest distance away from the mean flow. This gives us the following reference Table 1:

TABLE 1: Non-normal distribution probability based on standard deviation σ

k	1	2	3	4	5	6	7	8	9
Min % within k σ of the mean	0%	50%	88.9%	93.7%	96%	97.2%	98%	98.4%	98.8%
Max. % beyond k σ of the mean	100%	50%	11.1%	6.3%	4%	2.8%	2%	1.6%	1.2%

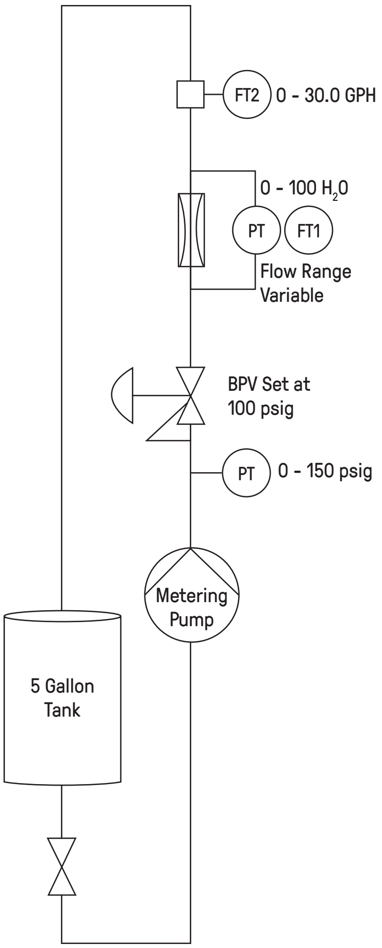
As you can see from table 1, it would be +/-5 x σ (96%) in a non-normal distribution to rival the certainty of 2 x σ (95%) of a normal distribution. The mean (μ) and the standard deviation (σ) of a pump's flow rate are the most statistically valid method to measure the average flow and variability of instantaneous flow. Using the instantaneous flow data captured during testing and applying statistical evaluation will give insight to the true performance of a metering pump and how it affects chemical usage.

In order to provide a means of measuring instantaneous flow rate, the experiment required a high sampling rate for data capture. Typical flow meter technology like magnetic flow meters and Coriolis-type flow meters can have too much internal dampening and insufficient sampling interval. To accurately measure instantaneous flow, two flow meters were utilized. One was a Coriolis flow meter to measure average flow rate and the other flow meter used differential pressure across an orifice plate to capture instantaneous flow rate.

The following items were used in testing:

- PT: Keller Valueline High-Accuracy Pressure transmitter, 0-150 psig, 4-20 mA, 0.1% Accuracy FS TEB – yellow data – channel #1
- Extech 382213 lab grade DC power supply
- Griffco CPVC ½" backpressure valve, set at 100 psig
- Multiple Signal Oscilloscope, 4-channel analog, 16-channel discrete, RIGOL, Model MSO1074Z / SNDS1ZC210200043 with variable capture rate
- FT2: Bronkhorst Cori-Flow Meter, M14-AGD-22-0-S rated for 0.0-30.0 L/hr. H_2O magenta data – channel #3
- FT1: Custom orifice type flow meter with 24mm body and ABB differential pressure transmitter scaled for 0.0-2540.0 mm H_2O with square root output signal transfer function in 4-20 mA DC – – Light Blue data – channel #2
- All 4-20 mA DC signals were placed across 0.1% precision, 250 Ohm resistor to convert signals to 1.0-5.0 VDC signal for the oscilloscope to capture.

FIGURE 6: Process diagram of the test equipment.



Backpressure valves and flow meters were placed in a vertical configuration in order to remove any compressible gasses from the pressure and flow paths

METHODS

The configuration of the test equipment was to operate the metering pump with a flooded suction of approximately 2.0 feet w.c. The outlet was equipped with a high-speed precision pressure sensor and artificial backpressure of 100 psig peak was created using a standard backpressure valve. After the backpressure valve, the flow passed through the instantaneous flow meter followed by the precision mass flow meter with flow averaging capability. After the flow passed through the last flow meter, it was directed back to a 5-gallon day tank. All instrumentation was specifically configured to push any and all entrapped air to escape by ensuring that metering pump flow experienced rising elevation from the pump discharge to the return line to the day tank. Please see Figure 6 for process drawing explanation.

Samples of pump technologies from several metering pump manufacturers were procured for testing. The purpose of testing was to determine the effect of pulsation on the quantity of a chemical required while operating the pump at 50 percent pump capacity. Half of the pump's capacity was chosen because this is where most metering pumps are sized at nominal process conditions. This method of sizing permits 200 percent of nominal capacity at maximum output and still easily permits operation 25 percent of nominal output. This range usually will cover the extremes of most process requirements.

During testing, the pump was permitted to achieve a steady state condition where the peak injection pressure was 100 psig. Pressure, instantaneous flow and average flow were recorded via process signals (4-20 mA DC) across precision 250 Ω resistor with 0.1 percent tolerance. The voltages were data logged using a 4-channel digital oscilloscope into a flat text file in CSV format.

Analysis of the data was completed and graphed using Microsoft Excel to determine pump performance using statistical methods described prior. Specifically, the instantaneous flow variability and the minimum amount that the operators would need to "tweak" the flow target to compensate for the flow variability were studied.

RESULTS

PERISTALTIC METERING PUMP

The first pump analyzed was a peristaltic metering pump. The selected pump had a maximum flow 6.5 LPH at a maximum pressure of 125 psig. The pump was operated at 50 percent capacity and the backpressure valve was adjusted until the peak pressure achieved was 100 psig. Below (Figure 7) is a screenshot of the oscilloscope data for this pump.

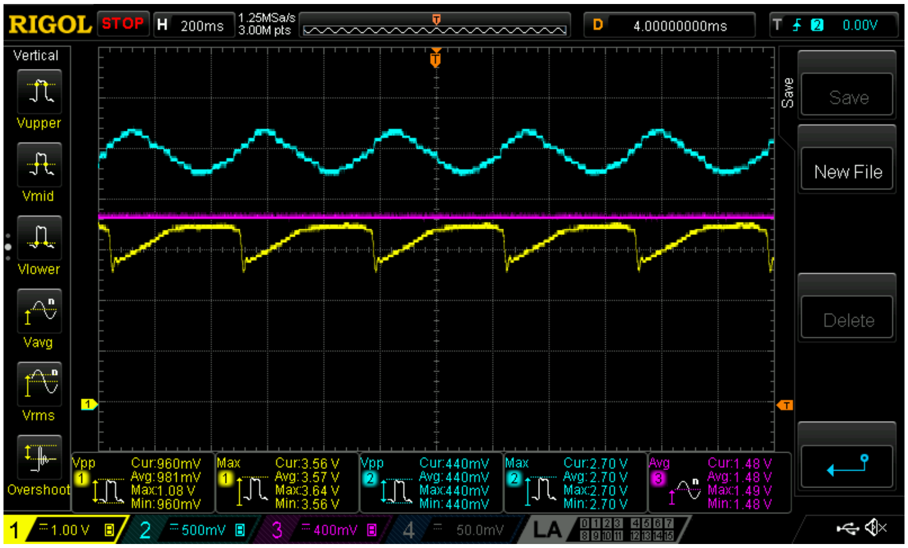


FIGURE 7: Oscilloscope traces of flow and pressure of peristaltic pump.

The first step was to determine what the distribution of captured flow data looked like. Was it normal or non-normal? At bottom left (Figure 8) is a histogram of the captured flow data. The data distribution certainly does not resemble a normal distribution, shown previously in Figure 4. In fact, the data seems to show that it is multi-modal with up to 9 peaks evenly spaced across the range of instantaneous flows.

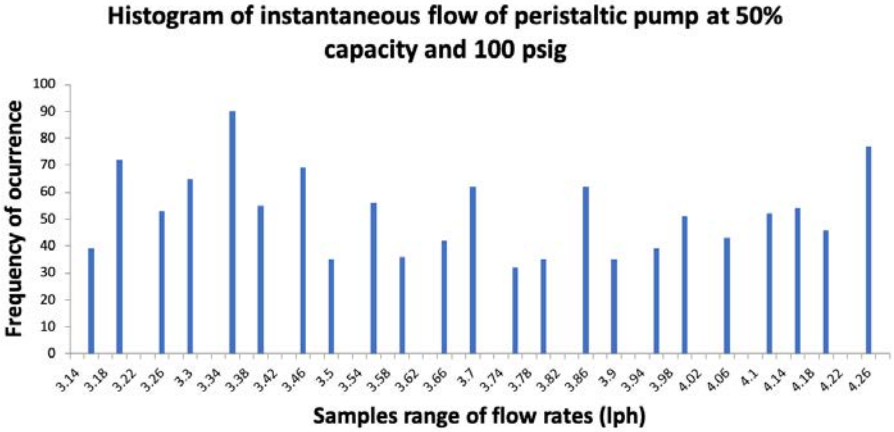


FIGURE 8: Histogram of sampled data of peristaltic pump.

The non-normal distribution shows that the natural frequency and harmonics managed to have a distribution with relatively small peaks, but many of them with a flow variability that ranged from 3.16-4.26 LPH with a relatively even probability of sampling any value from that range. The mean (µ), or average, flow was 3.68 LPH and the standard deviation (σ) of 0.35 LPH, which was almost 10 percent of the mean flow rate.

In this case, one standard deviation (σ) comprises 9.5 percent of the mean flow rate. Since the distribution is not a normal distribution, five times the standard deviation is required to achieve a statistical 96 percent certainty that the sampled feed rate will not fall below a desired minimum regulatory setpoint. This translates to a 47.5 percent increase in the mean chemical feed target to ensure that the instantaneous sampled flow rate will not fall below the flow rate dictated by molar demand. Let's take a close look at the graph of data with mean (µ) and multiple standard deviation (σ) lines graphed in Figure 9.

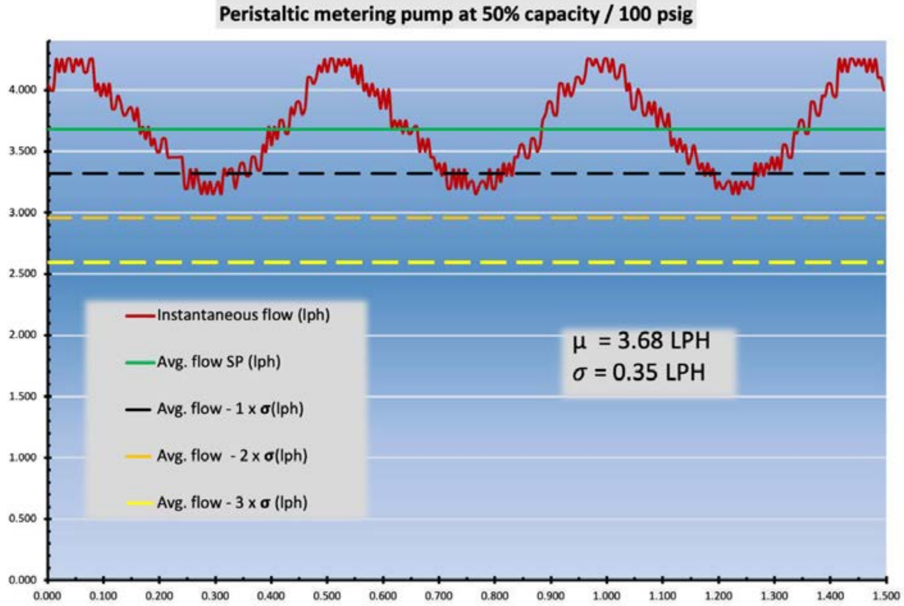


FIGURE 9: Graph shows instantaneous flow, average flow and standard deviations.

Statistically, the peristaltic pump would need to feed almost 48 percent more chemical, but there is another way to look at the data to quantify the excess chemical that would be required. For discussion purposes, this method will be referred to as the observational method. The observational method is a study of the graphed instantaneous flow sampled over time. On the same graph, the average flow and multiples of standard deviation can be graphed to give a better visual relationship between the calculated values. Instantaneous flow can be observed and how does that compare to the mean (µ) flow, plus or minus k multiples of standard deviation (σ).

In the above graph (Figure 9), instantaneous flow (red), average flow (green), average minus 1 x σ (black dashed line), 2 x σ (orange dashed line) and 3 x σ (yellow dashed line) have been charted to show the visual relationship between minimum flows, mean flow and mean flow minus multiples of standard deviation. It can be observed that all of the flow data points fall within 1.5 to 2.0 standard deviations (σ) of the mean (µ) or 14.25-19.0 percent. Combining the statistical method with the observational method, the additional chemical added for peristaltic-style metering pump can range from 14.25 (observational method) to 47.5 (statistical method) percent based solely on the operating principle that creates the pulsation.

SOLENOID ACTUATED DIAPHRAGM

The capacity of the tested solenoid actuated diaphragm pump was for 2.3 LPH at a maximum of 232 psig. Testing was again completed at 50 percent of maximum capacity and at 100 psig. This pump automatically controls stroke rate and stroke length based on the desired capacity setpoint. The maximum stroke rate of the pump was 200 strokes per minute.

In Figure 10, the oscilloscope screen capture shows sudden spikes in instantaneous flow and instantaneous pressure. Figure 11 shows the range of instantaneous flow rates of the captured data from the oscilloscope. The sampled data ranged from 1.19 LPH to 1.53 LPH and the distribution is a bimodal non-normal distribution. Additionally, the mean (μ) flow was 1.36 LPH and the standard deviation (σ) was 0.11 LPH. The standard deviation comprised 8 percent of the average flow.

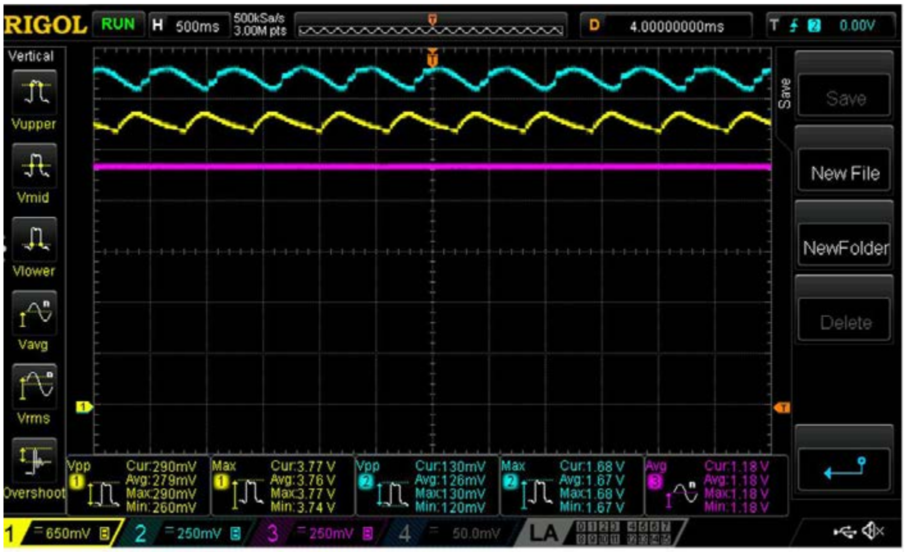


FIGURE 10: Oscilloscope screen capture of flow and pressure of solenoid driven pump.

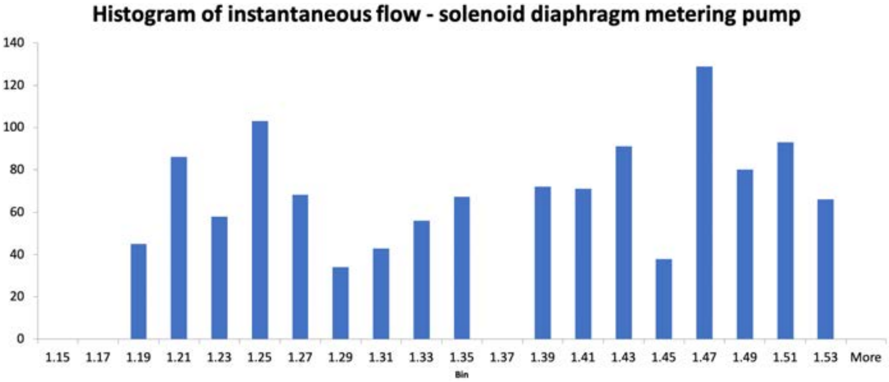
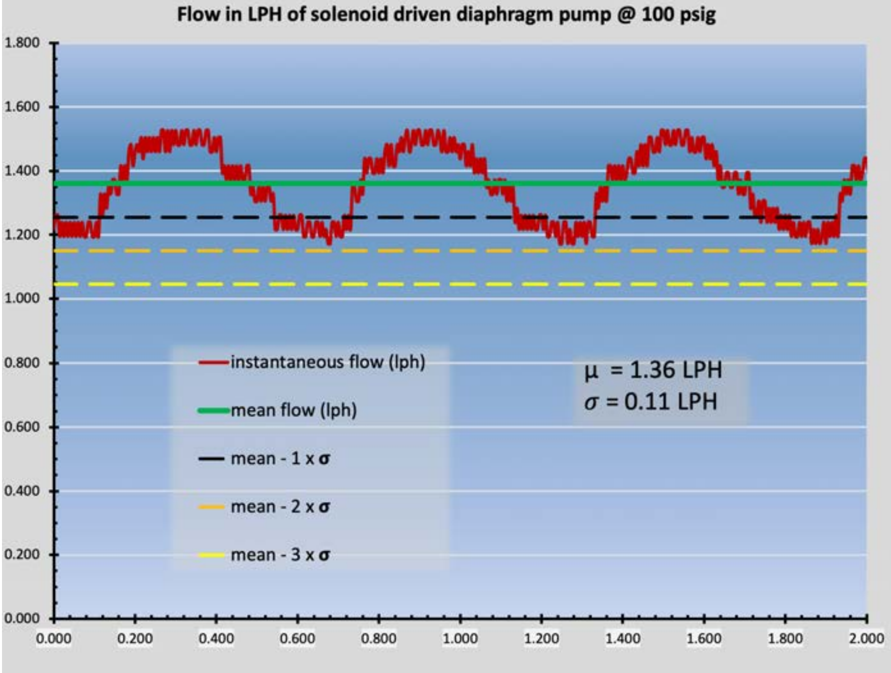


FIGURE 11: Visual representation of instantaneous flows sampled from a solenoid actuated diaphragm pump.

Evaluating the data statistically results in requiring five times standard deviation (σ) in order to have a 96 percent certainty that any analytical instantaneous flow sample will not fall below minimum limits. This results in in a minimum statistical excess chemical consumption of 40.4 percent of the molar chemical target.

Looking at the graphed captured data in Figure 12, we observe that the minimum flow rate almost touches the orange dashed line, which represents two standard deviations (σ) below the mean flow (µ). In most cases, the operator's tweaking would come close to three standard deviations (σ) because the distribution shows tendencies of samples to be near the ends of the recorded instantaneous flow spectrum in lieu of being closer to the mean (µ) flow. Calculating excess chemical usage observationally with two standard deviations (σ) results in 16.2 percent excess chemical feed, and three standard deviations results in a 24.3 percent minimum increased chemical demand resulting solely from pulsation. Combining these results with the previously statistically calculated results show that a solenoid diaphragm pump will require 16.2 to 40.4 percent more chemical than a metering pump instantaneous flow and average flow were identical.

FIGURE 12: Instantaneous flow, average flow and multiple sigma lines-r solenoid metering pump.



ENHANCED FULL-MOTION, STEPPER MOTOR-DRIVEN DIAPHRAGM PUMP

The previous solenoid metering pumps pulsated because the flow stops for half of the pump cycle to fill the volume of the diaphragm. This next pump uses a stepper motor to drive the diaphragm. The advantage is that the stepper motor can quickly change speeds and control diaphragm motion and position. This is used to create a high-speed suction stroke and a lower-speed discharge stroke. The result allows the pump to have a forward flow duty cycle greater than 50 percent. The selected pump was rated for 6.0 LPH at 145 psig.

Below in Figure 14 is a graph of the recorded instantaneous flow versus time. The instantaneous flow versus time graph shows the large variability of the flow with respect to the average flow. There is more than +/- 0.80 LPH instantaneous flow variability on a 2.2 LPH average flow synonymous with molar setpoint.

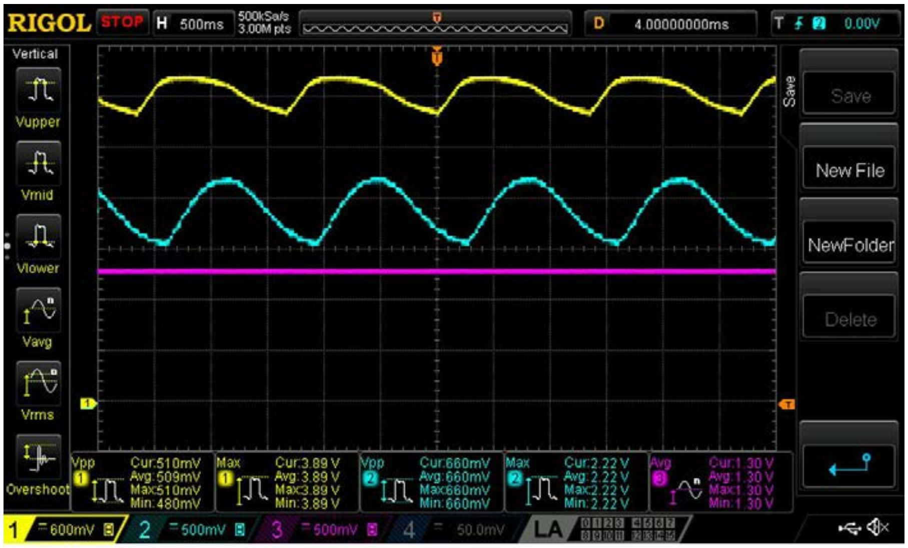


FIGURE 13: Oscilloscope screen capture of enhanced diaphragm pump data.

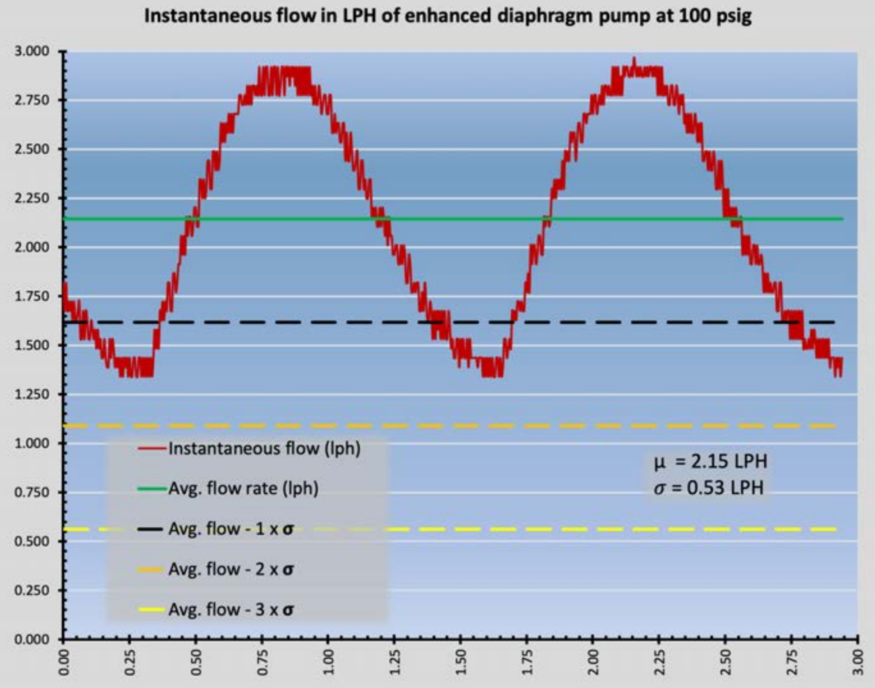


FIGURE 14: Graph of instantaneous flow samples of enhanced diaphragm metering pump.

FIGURE 15: Histogram of instantaneous flow data for enhanced diaphragm pump

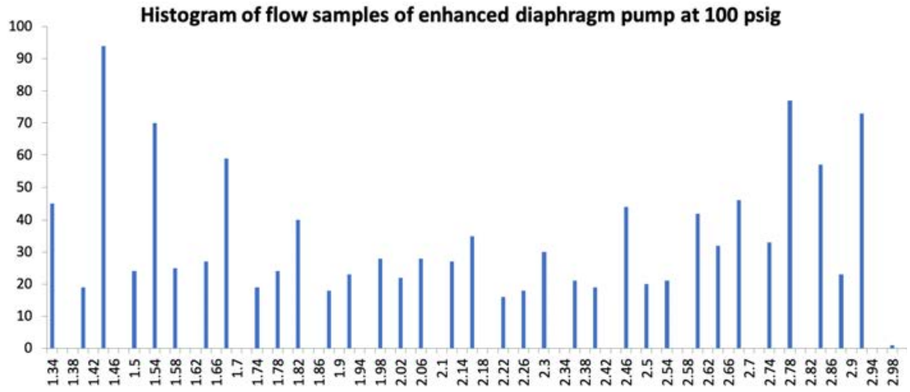


Figure 15 shows this instantaneous flow variability in a clear fashion. The sampled flows varied from 1.33 LPH to 2.92 LPH and the histogram shows the greatest frequency of the sampled flows were at the extreme limits, farthest away from the mean flow rate of 2.15 LPH. If a greater portion of the instantaneous flow rates fall in the regions at the extreme of the distribution, the standard deviation (σ) of the sampled data will be large. Furthermore, the histogram of sampled data also shows that the volume of instantaneous flow rates near the flow extremes far outnumber the volume of samples closest to the mean flow rate. This weighting of samples indicates that the probability of plant process variable sampled data being near the extremes would far outweigh the probability of sampling process data closer to the mean values. This disparity in sampled data favoring the extremes would certainly cause a process owner to raise the desired process mean flow rate setpoint much higher to attain a larger safety factor above and beyond the molar flow rate. This would be the only way that a process owner could increase his absolute certainty that any sampled data would fall within the range of acceptable limits.

Evaluating the captured data for the enhanced diaphragm metering pump, we find a standard deviation (σ) of 0.53 LPM on a 2.15 LPM setpoint within the distribution. A single standard deviation (σ) comprises 24.6 percent of the mean (μ) value, which is synonymous with molar setpoint value. A statistical evaluation of the captured data requires five times the standard deviation for 96 percent certainty that an instantaneous flow sample will not fall below the desired molar setpoint, which would result in 123.0 percent chemical overfeed required above and beyond the molar feed rate.
If we evaluate the enhanced diaphragm metering pump data from an observational perspective, the pump requires a minimum of 1.5 standard deviations above the mean of 2.15 LPM. This results in raising the setpoint target 0.79 LPM or a 36.7 percent increase in the flow setpoint to ensure that the process variable never falls below a 2.15 LPM instantaneous flow minimum.

The enhanced speed of the suction stroke created a negative effect on the variability of flow within the diaphragm metering pump's cycle. The pump variability and minimum flow rate in the operational cycle would force an operator to feed anywhere from 36.7 percent to 123.0 percent of excess chemical feed volume to have greater than 94 percent confidence that instantaneous flows would never fall to less than 2.15 LPM, the molar setpoint.

PROGRESSIVE CAVITY METERING

The final pump being tested is a pump that utilizes the progressive cavity principle of metering. The progressive cavity pump design uses a single-helix rotor within a double-helix stator constructed of rubber. The design is such that two cavities are formed between the rotor and stator when the rotor is rotated. These cavities are positioned so the sum of the cross-sectional area of the cavities is constant through a single rotation cycle. This has an effect of creating a flow with minimal pulsation. In most cases, the pulsation of flow would be imperceptible without sophisticated equipment used in this testing. Figure 16 shows the oscilloscope readings of instantaneous flow (cyan), average flow (magenta) and discharge pressure (yellow). Note that the scaling differences exist between the instantaneous flow meter and average flow meter in order to allow the traces to not overlap one another. Visually, we cannot observe any pulsation in instantaneous or average flow. There is a slight pulsation visible on the discharge pressure, which confirms that the there is a very small variation in flow. This is further illustrated in the histogram of instantaneous flow shown in Figure 17.

FIGURE 16: Oscilloscope traces of average flow (magenta), instantaneous flow (cyan) and discharge pressure (yellow) for a progressive cavity metering pump.

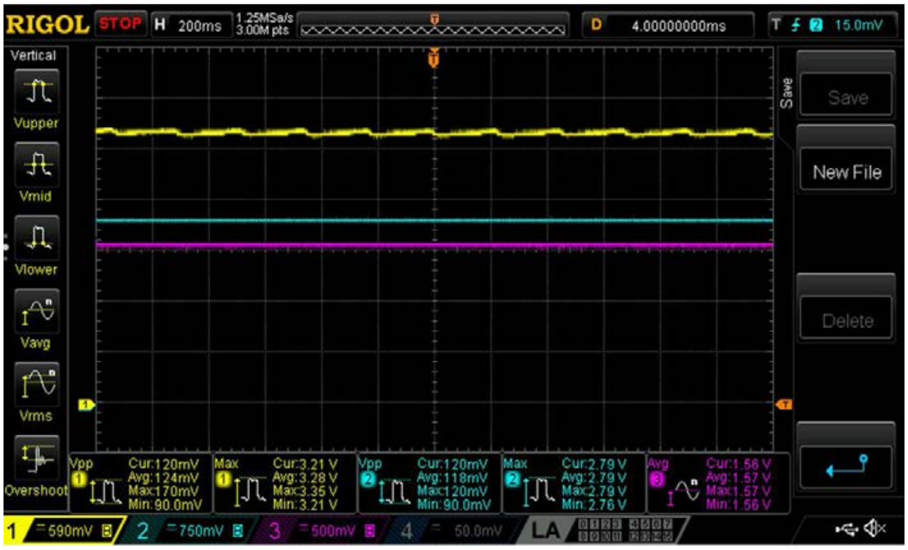
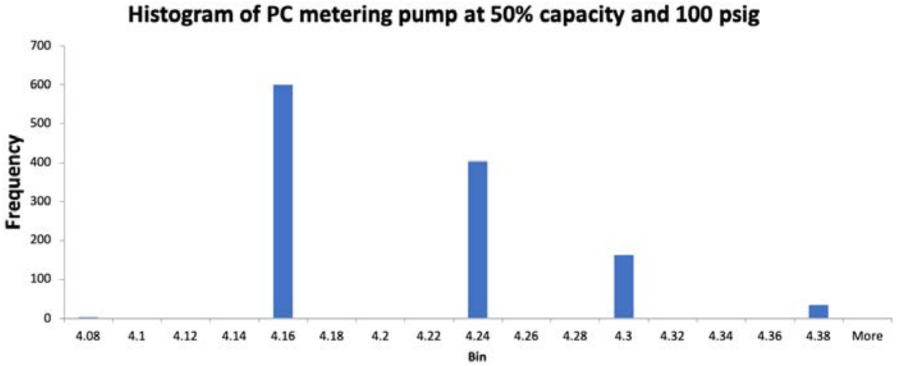


FIGURE 17: Oscilloscope traces of average flow (magenta), instantaneous flow (cyan) and discharge pressure (yellow) for a progressive cavity metering pump.



The histogram shows the variability of flow data captured was limited to only four separate bin values of captured instantaneous flow rates within 1200 samples of data. All of the captured flow data only varied from 4.16 LPH to 4.38 LPH. The mean (μ) flow of 4.20 LPH had a minimum flow variance of 0.04 LPH and a maximum flow variance of 0.18 LPH.

We can also notice that the distribution for the progressive cavity metering pump seems different. It looks like half of a unimodal normal distribution. This phenomenon occurs when the mean (μ), median and mode are in close proximity on the histogram of bin values. Additionally, this phenomenon is shown when variability is limited to flow rates that exceed the mean value. The mean (μ) value of a distribution has been covered extensively in the analysis thus far, but median and mode may need some definition. Mode is the sampled value occurring most often within a set of sampled values. In our example (Figure 17) histogram above, the mode is 4.16 LPH. The median is the center value if the samples are arranged from smallest to largest. In the sample set in Figure 17, the median is actually 4.19 LPH, which is extremely close to the mean of 4.20 LPH. The mean, mode and median all fall within 0.04 LPH. When selecting a metering pump, this is exactly what the primary focus should be in selecting metering pump technology. When the mean (μ), median and mode are very close together, the standard deviation (σ) will be very small. That means that no matter when an instantaneous flow sample is taken, the probability is that the value will be extremely close to the molar value setpoint.

FIGURE 18: Instantaneous flow rate data of PC pump including dashed lines depicting multiples of standard deviation about the mean value.

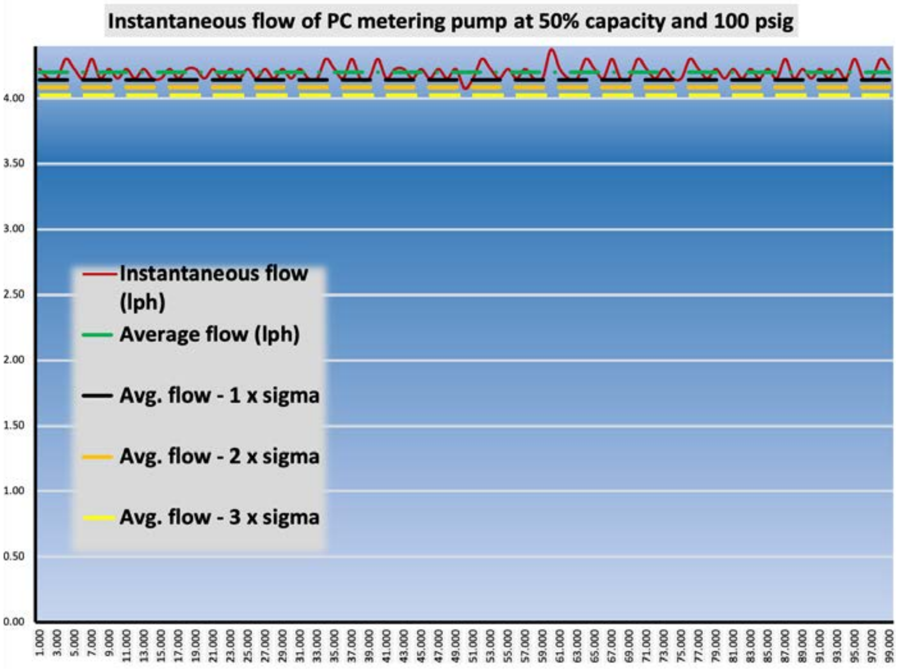


Figure 18 shows visually how the progressive cavity metering pump compares to the previous metering pumps showing the full range of instantaneous flow from zero to 4.5 LPH. It also shows how the multiples of standard deviation (σ) almost overlap one another on the graph. In order to better understand the relationship to mean (μ) and standard deviation (σ), we must zoom in on the graph to better see the relationships of instantaneous flow rates, average flow rates and multiples of standard deviations around the mean.

FIGURE 19: Same as Figure 18 with 10X on the X-axis.

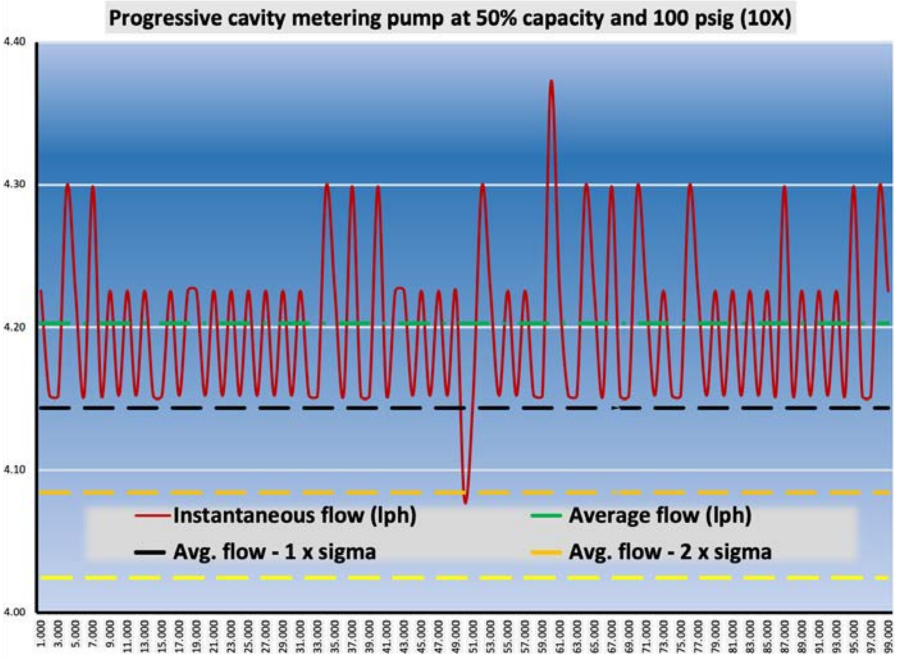


Figure 19 shows a magnified and truncated range from 4.0 LPH to 4.4 LPH (10X) to better illustrate the mean flow rate as it relates to instantaneous flow rates. Figure 19 really shows how the previously discussed statistical variables of mean and multiples of standard deviation are the excellent indicators of metering pump technology performance. In the case of the progressive cavity metering pump, the variability of instantaneous flow rates falls within a single multiple of standard deviation with extremely high regularity. However, there was a single instantaneous flow sample that ventured slightly more than two standard deviations. Since the histogram of the flow rates is not a normal distribution, we must apply the same statistical methods that were previously applied to the previous metering pumps to get a statistical and observational chemical overfeed required.

Statistically, the distribution was not a normal distribution, just like the other pumps that were examined. As we investigated previously, a non-normal distribution requires a difference of five times the standard deviation (σ) from the mean (μ) in order to have a 96% certainty that any sample taken will be within the regulatory acceptability range. The standard deviation for the progressive cavity metering pump was 0.06 LPH for a setpoint of 4.20 LPH. The standard deviation of the instantaneous flow rates with respect to the mean was only 1.4 percent. Five times the above standard deviation is 0.30 LPH and this corresponds to a statistically required 7.14 percent increase in feed setpoint to have a 96 percent certainty that instantaneous flows will not fall below the minimum molar treatment limits.

If we evaluate the progressive cavity metering pump data from an observational perspective, the pump requires a minimum of 2.1 standard deviations (σ) above the mean (μ) of 4.20 LPM. This results in raising the setpoint target 0.126 LPM or a 3.0% increase in the flow setpoint to ensure that the process variable never falls below a molar setpoint of 4.20 LPM.

The progressive cavity metering pump instantaneous flow variability and minimum instantaneous flow rate in the operational cycle would require an operator to feed anywhere from 2.80 to 7.14 percent of excess chemical feed volume in order to have greater than 96 percent confidence that instantaneous flows would never fall to less than the molar flow setpoint.

CONCLUSIONS

Using statistical methods to determine the level of performance of individual metering pumps and metering pump technology was the goal of this testing. Additionally, it was observed that variance in flow rates also forces operators to increase metering pump feed rates to reduce the probability of randomly sampling process data that falls below true regulatory levels. Looking at the mean flow rate and the standard deviation of flows gives an excellent picture of the metering pump performance and provides a means to quantify the excess chemical required beyond the molar calculated setpoint as a result of pump design flow variances. Identifying the mean and standard deviation and then applying either Normal Distribution theory or the Chebyshev Theorem allows a mathematical interpretation of performance and helps quantify chemical waste based on pulsation.

TABLE 2: Quantifying excess chemical required based on pump technology

PUMP TYPE / PUMP TECHNOLOGY	**STANDARD DEVIATION** (% mean)	**MIN. EXCESS CHEMICAL FEED** (Observational / % mean)	**MAX. EXCESS CHEMICAL FEED %** (Statistical / % mean)
Progressive Cavity Metering Pump	1.40%	3.00%	7.10%
Solenoid Driven Metering Pump	7.60%	15.20%	38.00%
Peristaltic Metering Pump	9.40%	14.10%	47.00%
Stepper-driven Diaphragm Metering Pump	24.60%	36.90%	123.00%

In Table 2, we can see the results of the empirical testing of the pump technologies that were tested. The progressive cavity pump was deemed to waste the least amount of chemicals in order to meet regulatory compliance or molar calculated setpoints. Using the progressive cavity pump as the basis pump and comparing the other technologies to it, the solenoid driven metering pump and peristaltic metering pump wasted 5-times more chemical than the progressive cavity pump. The stepper driven diaphragm metering pump wasted over 13-times the chemical of the progressive cavity pump.

Regulatory compliance is mandatory in many processes such as wastewater treatment, water treatment, petroleum refining, boiler water conditioning, chemical production and chemical end-users. More and more regulations are targeting not only maximum limits, but minimum limits as well. Maintaining processes within these strict limitations requires precision control with relatively fast-acting algorithms to optimize system performance and profitability. Improving process speed and performance can make systems subject to high-frequency instability. Ideally, you want your process to stabilize and require small changes through the use of feed-forward and feedback process controls. Dosing chemicals in slugs by pulsation creates process variability that is reflected in variation of end product. Removing this variation from pulsation requires operators to implement SCADA-based discrete filtering, making control lethargic, or having large process residence times through the use of large holding vessels. The large holding vessels allow the final product output to attain homogeneity through holding time. Having large storage areas makes some industries susceptible to nefarious contamination by terrorist or other criminal activities.

The refinement of metering pumps to eliminate pulsation will allow industries to move away from batch-related process and move toward continuous manufacturing methods that permit increased control in quality and less opportunities for contamination. One of the largest advantages of continuous manufacturing is that the process machinery and required area for the same production is reduced up to a factor of 10 or more. This advantage has been realized already by the chemical manufacturing industries but can be applied to almost any batch-related process with fluctuating demand.

ALL CONTENT, GRAPHS, TABLES AND ILLUSTRATIONS BY:

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