PID TUNING LIQUID FLOW CONTROLLERS FOR FAST RESPONSE/STABILIZATION TIME

BY KATHY ERICKSON (MSP – A DIVISION OF TSI)

I. Higher Requirements for Liquid Flow Controllers

The ever-increasing performance requirements for microelectronic devices are driving higher performance demands for Liquid Flow Controllers (LFCs) used in semiconductor processing. Many of the LFCs in the microelectronic industry are used to vaporize liquid precursors for Chemical Vapor Deposition (CVD) or Atomic Layer Deposition (ALD). These state-of-the art processes require a high degree of accuracy and repeatability to ensure process recipes produce expected results for deposition rates, film composition and uniformity. Liquid flow control needs to be highly stable, with no variability from the first to the last wafer, enabling tight Statistical Process Control (SPC). SPC with tight tolerances allows the end users to determine more quickly if processes are trending out of control, so that actions can be taken BEFORE wafer yields take a hit. Stable liquid flow control also ensures stable chambers pressures – a must have for plasma processes to prevent arcing; important for thermal processes as well, to ensure consistent film quality for each nanometer of thickness. LFCs for semiconductor processing also need to perform reliably and predictably 24/7 365 as well, without requiring costly downtime due to either routine maintenance requirements or unscheduled field issues.

II. Importance of Fast Response/Stabilization Times

As more and more semiconductor processes run short processing times, liquid flow control response/stabilization times (time to reach and maintain ±1% of set-point) are increasingly becoming a gating factor of process time minimization and throughput maximization. Faster stabilization times in general increase throughput. For long processes, LFC response times can be a relatively small factor; in a 150 second process, a 3 second liquid flow stabilization time only adds 2% to the processing time - still significant, but perhaps not intolerable. However, for short process times, like short pulse CVD or ALD, the stabilization time of the LFC can become a much larger percentage of the processing time. For example, in a 6 second short pulse CVD process, a 3 second response time increases deposition times by 50%.

Long stabilization times also result in more time sending vapor to the diverter line – meaning more liquid waste. More liquid is consumed, pumps are exposed to more liquid, and remediation systems have a higher load. Increased liquid waste negatively impacts cost of ownership in increased liquid precursor source cost, reduced pump lifetime, and increased maintenance requirements. Additionally, it worsens the environmental impact of these semiconductor processes. If LFC stabilization times can be reduced from 3s to 0.3s, there can be a significant increase in throughput; reduction in waste; and increase in up-time.

III. Improving Liquid Flow Control Response Times - LFC Selection

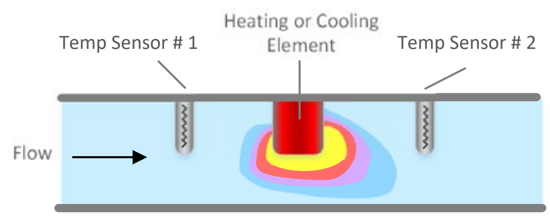
The keys to improving LFC response times are 1) proper selection of LFC and 2) optimization of PID tuning.

There are three primary techniques for measuring and controlling liquid flow rates: thermal, Coriolis, and differential pressure.

Thermal Flow Measurements

Thermal flow measurements are frequently used for semiconductor gas flow control (MFCs). In this method, the liquid is heated (or cooled) and the speed at which the liquid cools (or heats) can be calibrated to liquid flow rates. A primary benefit of this technique is that thermal sensors are inexpensive, providing a low cost LFC option. They are also reasonably accurate.

Figure 1: Thermal Flow Sensor Illustration



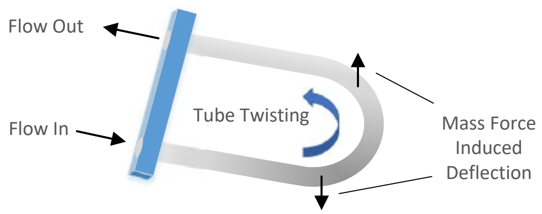
In general, however, thermal sensors are relatively slow. Since gases have low densities and low heat capacities, the thermal response is fast enough to be practical for most semiconductor applications. Liquids however, have a much higher heat capacity versus gases – meaning it takes more energy and time to change the temperature of a liquid compared to a gas. Because of this fundamental issue, thermal flow meters tend to be slow for liquids. Response/stabilization times are routinely ≥3 seconds. This slow sensor response not only results in a slow time to reach set-point initially (response/stabilization time), but also reduces the speed at which flow changes can be detected and compensated for via a control loop. This can result in less tightly controlled liquid flow rates.

Thermal LFCs are also liquid specific; meaning the LFC must be calibrated to the liquid being used. With a thermal flow meter, it is essentially impossible to calculate the change in sensor response to a different liquid due of the complex nature of the thermodynamic and fluid mechanic dynamics near the thermal sensor. This means in order to use a new liquid, thermal LFC users must wait for custom factory calibration. This can slow R&D and manufacturing build timelines. Finally, thermal sensors do not work for dual phase flows and can also be significantly affected by changes in environmental temperature and pressure – which can cause unpredictable accuracy and repeatability in real world semiconductor environments.

Coriolis Flow Measurements

Coriolis flow meters are based on the principle that the mass flow momentum of a fluid (liquid or gas) can physically deform tubes; and the degree of deformation can be directly related to mass flow rate. Lower mass flow rates create less of a deflection, higher mass flow rates create larger deflections.

Figure 2: Illustration of Coriolis Effect in Curved Tube



Simple illustration of the Coriolis effect in a curved tube which causes deflection and twisting. In practice, a vibration is often induced on the curved tube, and the frequency of the vibration as detected by optoelectrical sensors is related to mass flow rate.

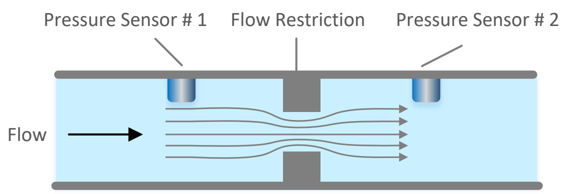
A key advantage of this technique is that the response is theoretically independent of liquid type. Coriolis flow meters do not need to be calibrated with the liquid being used. Coriolis flow meters can also be extremely accurate. These flowmeters need to sense physical deflection with high sensitivity and tend to be quite complex; so, they are typically relatively expensive, with a large footprint and sensitive to vibration. Additionally, Coriolis meters are slow. The detected deflections are small, and a relatively large number of movements must be measured to have reasonable accuracy – resulting in long response/stabilization times.

The biggest drawback to this technique tends to be ease of use in the field. These sensors have small long tubes, which create high pressure drops and cause liquid bubble issues which present as persistent, high magnitude drops in liquid flow rates (as the bubbles pass through the sensor). Most often Coriolis based LFCs need to be used with degassers to minimize this effect, but overcoming bubble issues in the field can be very problematic. Additionally, Coriolis sensors are prone to zero drift, which ultimately reduces the practical accuracy.

Differential Pressure Measurements

When speed is a primary consideration, differential pressure liquid flow meters are the go-to solution. Differential pressure liquid flow meters are based on the phenomenon that pressure drop across a flow restriction is a function of liquid flow rate.

Figure 3: Illustration of a Type of Differential Pressure Flow Sensor



Fundamentally, pressure changes can be sensed significantly faster than temperature changes or statistically meaningful Coriolis deflection measurements. In differential pressure flow controllers, measurements can literally be taken with good resolution at a frequency of 10ms. This not only leads to fast stabilization times, but also to faster control loops, providing tighter flow control.

Additionally, the fluid mechanics of differential pressure sensors are much more straight-forward compared to thermal sensors; enabling the use of a calculation to switch working fluids. This function enhances the sensor's flexibility, making it a convenient choice for process development where multiple liquids may be evaluated.

Differential pressure based liquid flow controllers can also be extremely accurate and are highly repeatable – making them a good choice for applications that cannot tolerate a high degree of variability. Finally, since these sensors are so fast, PID tuning of the control loop can be much simpler, making differential pressure liquid flow controllers easy to use in the field.

IV. Improving LFC Response Times - PID Tuning

A fast differential pressure liquid flow controller, like the MSP Turbo™ 2950 Liquid Flow Controller, can provide fast stabilization using factory default PID values depending on the flow rate and application. Response times ~1-2 seconds are typical default performance – meaning field PID tuning may not be necessary for many processes. However, if response/stabilization times <1s to ±1% of set-point is desired, PID control loop parameters must be optimized.

PID Basics

PID is a real-time sensor feedback control loop that is widely utilized in controllers. PID are constants that can be entered in the control algorithm to adjust the control response for different application requirements and setpoints. P = Proportional, I = Integral, D = derivative.

P: (Proportional) is often referred to as proportional gain. It is a function of the difference between the set point and the measured value. P is a multiplier of the difference. It allows an 'exaggeration' of the difference. When P is increased the control system will go faster, but too high of P can cause oscillation.

I: (Integral) sums the difference between the set point and measured value over time. If I is > 0 even small differences between the set point and measured value will cause an adjustment in the control loop eventually. The higher the I value, the faster the adjustments based on the error.

D: (Derivative) is proportional to the rate of change of the measured value. High D will cause the control loop to react more violently to changes in measured value. This can speed up the response, but can also throw the control loop into a sinusoidal oscillation; where it is constantly adjusting up and down.

Controllers typical come with default PID constants inputted into the device. These values can be updated to improve or adjust response as needed by the application. Typically, PID values can be adjusted using digital communication interfaces (like EtherCAT or RS485) or custom controller interface software packages.

The PID parameters control how the flow is adjusted based on measure flow values. In the MSP Turbo™ 2950 Liquid Flow Controller (LFC), flow is measured approximately every 11ms, and the PID control loop continually adjusts the flow control to ensure the flow is tightly controlled to the set-point.

PID Zones

If your process has multiple liquid flow setpoints – for example 1g/min, 5g/min, 15g/min and 30g/min; for completely optimized response times you would set unique PID parameters for each of these set-points using 'zones'. PID values are typically loaded into a device using a 'recipe table' (Table 1). In a recipe table, there are 'zones' of control. For optimized response, it is best to set the PID parameters specific to the set-point. In the recipe table, a 'zone' is defined by the top % F.S. (Full Scale) value (see Table 1 Column 2 - Threshold). The zone includes all flow rates less than the Threshold value and everything above the Threshold value of the previous zone. For example, if the Zone 0 Threshold value is 5 (5% F.S.), then for a 30g/min full scale unit the first zone would include set-points from 0 – 1.5g/min. If the second zone had a threshold value of 10% F.S., then the second zone would run from 1.51 – 3.00 g/min.
In the Turbo™ 2950 LFC, there are 8 zones that can be configured. These zones do not need to be spread evenly across the full scale. Ideally, you would have one zone for each unique set-point if you are looking for optimized response.

Table 1: PID Recipe Table Example

Zone	Threshold (% F.S.)	Example values (g/min)	Bias/ Offset (V)	Example Valve Position	Bias/ Offset Time (ms)
0	5	0 -1.50	2	98% open	200
1	10	1.51 - 3.00	2	98% open	200
2	15	3.01 - 4.50	2	98% open	200
3	20	4.51 - 6.00	2	98% open	200
4	30	6.01 - 9.00	70	30% open	200
5	70	9.01 - 21.00	60	40% open	200
6	75	21.01 - 22.50	40	60% open	200
7	90	22.51 - 30.00	90	10% open	200

Bias/Offset

The bias/offset options determine how quickly the LFC initially reaches the set-point. Essentially, these options can allow the user to control the shape and speed of the initial flow response.

If bias/offset is used, when a set-point is received, the flow controller tells the control valve to move to a pre-determined position for a fixed amount of time (typically milliseconds). Valve position is determined by voltage (Column 4 in Table 1), and Bias/Offset Time (Column 6 in Table 1) is the amount of time the controller will hold at this fixed voltage before engaging the PID control loop. In the 2950 LFC, ~100 - 120V is fully closed and 0 V is fully open. Columns 4 and 5 provide a rough guide of how voltage relates to valve position (not absolute – example only; application/hardware specific).

On one end of the spectrum, bias/offset can be used to 'jump-start' the flow; by opening the valve ~100% for a short period of time to quickly establish flow (Figure 4), before then moving into the PID control loop. In this case, a low bias/offset voltage would be applied. Doing this can significantly improve the time to set-point, but also likely results in some 'overshoot' as well (particularly if the bias/offset time is too long).

Figure 4: Bias/Offset Voltage Illustration: Overdrive - Fast Response

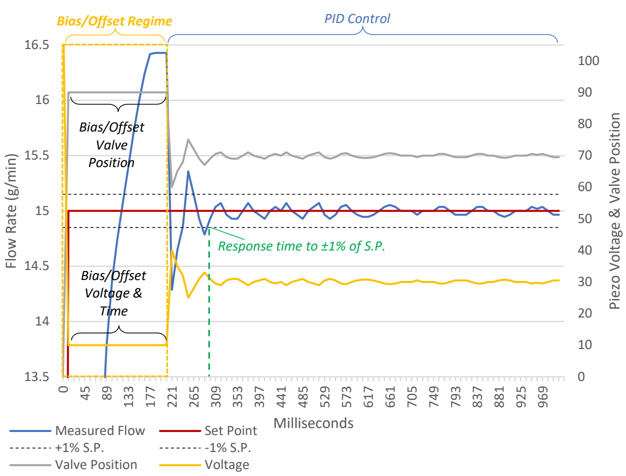


Figure 4 is an illustration of a flow pulse (flow set-point event: start to finish). The red line is the flow set point signal, the blue line is the measured flow rate (both left axis). The grey line is the valve position and the yellow line is the piezo voltage (both the right axis). The piezo voltage to valve position is very application specific and is just an example for discussion purposes. The left part of the graph is the bias/offset region. Shown is the bias voltage and valve position and the time they stay at these set-points (bias/offset time). After the bias/offset regime, PID control takes over (middle/right of the graph). In this example, the bias/offset is set to overdrive the liquid flow to bring the flow to set-point quickly; similar to how the Recipe Bias/Offset voltage is set in Zones 0,1,2 & 3 in Table 1.

On the other end of the spectrum, bias/offset could be used to ensure the valve does not open too far initially – to prevent ANY overshoot. In this case a bias/offset voltage of 80-100V would be used.

Figure 5: Bias/Offset Voltage Illustration: Conservative - No Overshoot

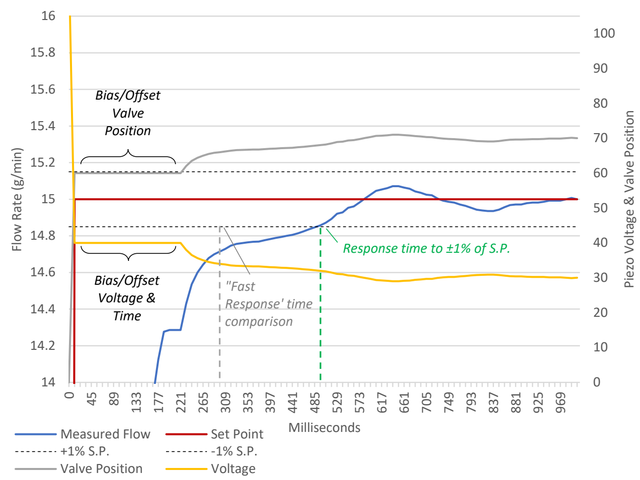
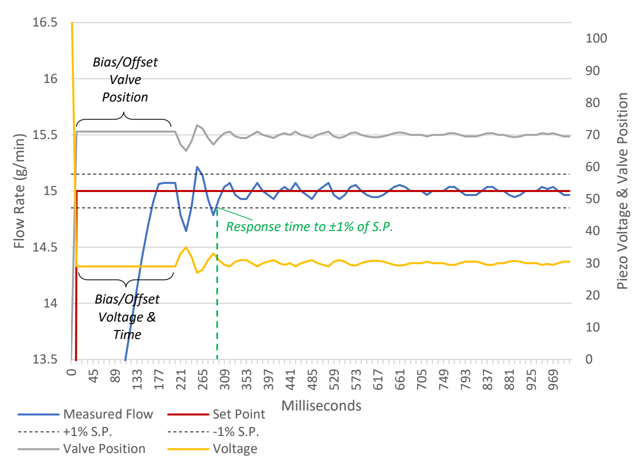


Figure 5 is an illustration of a bias/offset and PID set to reduce/eliminate overshoot. In this case, bias/offset voltage is set high – corresponding to a more closed valve position, similar to how the Recipe Bias/Offset voltage is set in Zone 7 in Table 1. This ensures the initial flow set-point will not overshoot. Additionally, PID values in this example are set to makes small changes to flow errors; again, to reduce/prevent overshoot. Note the response time is slower versus Figure 4 Bias/Offset Voltage Illustration: Overdrive - Fast Response

Bias/Offset levels can be set aggressive - 'jump-start' shown in Figure 4; conservative - 'creep-up' approach shown in Figure 5, or somewhere in between - as illustrated by Figure 6 below and in the recipe bias/offset voltage value examples in Table 1 zones 4, 5, & 6.

Figure 6: Bias/Offset Voltage Illustration: Just Right – Bias/Offset Voltage very close to control voltage



There are several different bias/offset methods to provide flexibility for application requirements and user preferences in the Turbo™ 2950 LFC.

Recipe Bias/Offset Method

When Recipe Bias/Offset Method is used, every time a set point is given, a fixed predetermined valve position will be used for a pre-determined time. The bias/offset voltage (valve position) and bias/offset time are inputted in the recipe table for each zone (see Table 1). For example, if bias/offset voltage is 2V (for example only: valve position ~98% open) for 200ms for Zone 0, every time a setpoint from 0-1.5g/min is received, the control will set the valve to 98% open for 200ms. After the bias/offset time elapses, the PID calculation starts, and the piezo drive voltage is adjusted accordingly. The measured value will be adjusted every 11ms according to the measured flow value.

Dynamic Bias/Offset - Current Method

Dynamic bias/offset options are a type of machine learning function. When one of these modes are selected, the LFC 'learns' the best starting valve position from previous experience at the same set-point. Dynamic bias/offset is most useful when the same set-point is used several times consecutively.

Figure 7: Dynamic Bias/Offset Illustration

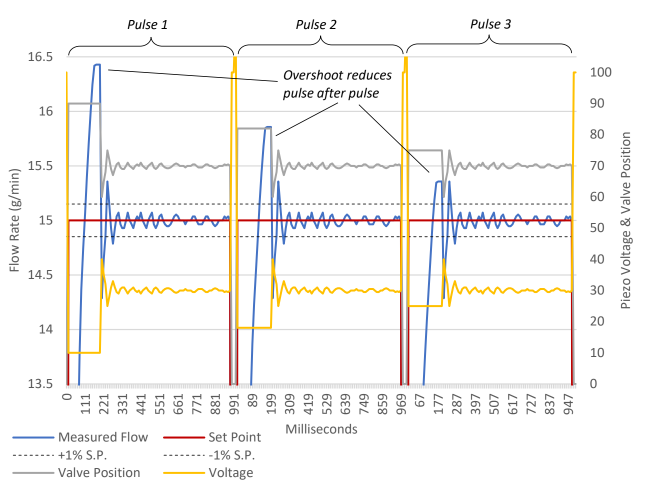


Figure 7 is an illustration of dynamic bias. From pulse 1 to 3, the measured flow (blue line) overshoot lessons, the valve position (grey) and piezo voltage (yellow) change to become closer to the correct starting point for that set-point. Note: only the bias/offset regime is changed. The PID control region is not changed.

In 'Current' Dynamic Bias/Offset (default mode for Turbo™ 2950 LFC), the valve position at the end of the last set-point command/ flow pulse (trailing edge) will be used as the starting point for the next flow pulse.

Figure 8: Dynamic Current Bias/Offset & Dynamic Alternate Bias/Offset

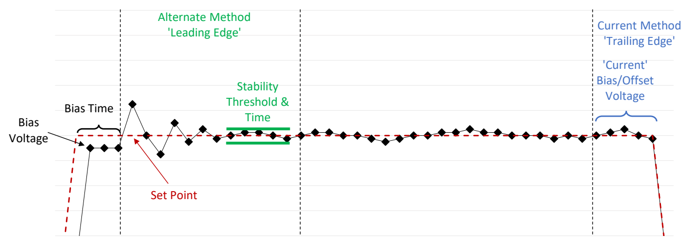


Figure 8 is an illustration of how bias/offset voltage is calculated when using either Dynamic Bias/Offset Current or Dynamic Bias/ Offset Alternate. In Dynamic Bias/Offset Current method, the bias/ offset voltage for the next pulse is determined by the last few points of the previous pulse set-point. In Dynamic Bias/Offset Alternate method, the bias/offset voltage for the next pulse is determined on the leading edge of the pulse after a user defined stability threshold and stability interval is satisfied.

Since valve position can be dependent on environmental parameters and valve lifetimes, the dynamic bias/offset function ensures that the initial valve position will be as close as possible based on the latest set of information. It is important to note that when using either Dynamic Bias/Offset Method, the PID values are not changed. The only thing changing is the initial valve position - bias/offset voltage. This typically provides a better jumping off point, resulting in faster stabilization times. Because Dynamic Bias/Offset Current leads to the best response times for most applications it is the default mode of the Turbo™ 2950 LFC.

Dynamic Bias/Offset - Alternate Method

A second Dynamic Bias/Off Method is Alternate. While Current Dynamic Bias/Offset is best for most applications, occasionally Alternate Dynamic Bias/Offset may be used. In the Alternate Method, the bias/offset voltage (i.e. initial valve setpoint) is determined by using the leading edge of the previous set-point - versus the Current Method which is trailing edge (Figure 8). When using Alternate Dynamic Bias/Offset, two other parameters must be determined: stability threshold, and stability time.

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In Alternate Dynamic Bias/Offset, the bias/offset voltage is set at the beginning of the set-point pulse as soon as the stability threshold (± x% of setpoint) has been achieved for the stability time (x ms). Dynamic Alternate Bias/Offset would be considered during very short pulses where the fluid flow may not reach a steady state. Or conversely for long pulses with long "no flow" time between pulses. Long liquid pulse times can cause hardware cooling. If the next pulse occurs very soon after the cooling, this is not an issue because the hardware temperature doesn't return to steady state. On the other hand, after many minutes of "no flow" the hardware can warm up and temperature gradients can occur which can affect the piezo voltage/valve position – perhaps making the end of the pulse not representative of the condition at the start of the pulse.

All of the Bias/Offset Methods are merely tools to allow users to control the initial shape of the flow set-point pulse. They can be used to overdrive and get to set point quickly or can be used to ensure a conservative valve position initially to prevent overshoot – essentially the flow slowly creeps up to the setpoint. These 'knobs' allow you to control the LFC response the way you need to for your application.

'Tuning' the PID Values

After you determine the bias/offset options you want to use, the next step is to tune the PID values. Before modifying these values, best practice is to set the flow rate to zero - telling the control valve to close and resetting PID calculation. Next run the default PID settings and monitor the flow response. Note: any time you change any of the tuning parameters set the flow rate back to zero to reset it. Then after the flow is reduced to zero retype the flow rate that is under testing to run the new values.

1. Start with I

For a fast response controller, PID values of 1,1,0 are a good place to start (default values for the Turbo™ 2950 LFC). If faster response times are desired, a good start is to slowly increase the I values. It is not unusual to run I values as high as 15. Note, flow hunting could occur at higher I values. Flow hunting is the process in which the controller over corrects for an error resulting in a new error of greater magnitude in the opposite direction. If this occurs reduce the I value until the problem resolves.

2. Move to P if Needed

If adjusting the I value does not provide fast enough response the P value can be slowly increased. Increasing P will shorten time to reach set-point, but it can also lead to oscillation issues where the controller adjusts with too much magnitude, and consistently overshoots and undershoots set-point. Since the P gain value is "proportional" to the error, its affect is minimized when dynamic bias/offset is working. For example, if using recipe bias/offset, and the bias/offset voltage is large versus the setpoint (i.e. 100 volts vs 75 volts), the resulting error would be large and the P gain value would have the most immediate effect on the piezo voltage.

3. Consider D

If set-point overshoot is a persistent problem, or if the application cannot allow any overshoot; D value can be slowly increased. Increasing the D value frequently causes the system to move out of control and should only be used if it is absolutely needed.

4. Run set-point multiple times

Once satisfactory values for all three tuning parameters have been set, run the controller a few times at those values to confirm they are correct.

5. Move to next set-point

After the first set point value has been successfully tuned, move to the next set-point and see if the other desired flow rates fall into the same zone - meaning that the PID controller will produce the desired response time and shape while using the same tuning parameters as the first flow rate. If the parameters don't allow the new flow rate to fall within the specifications a new zone must be created and the tuning process repeated.

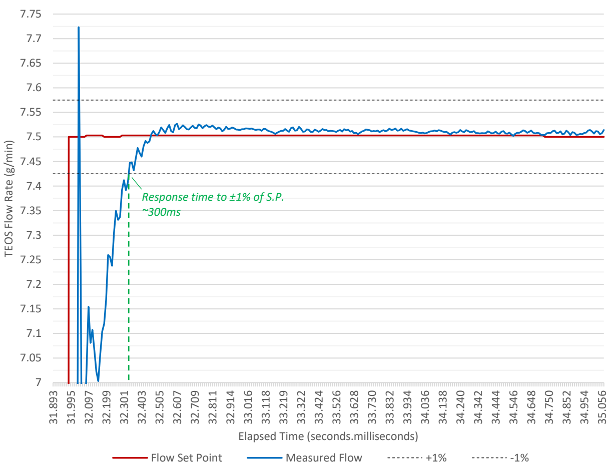
When tuning a second zone it is easiest to start with the tuning parameters from the previous zone and increase or decrease them from there. When tuning a lot of zones, a pattern can arise in the tuning parameters. For example, as the setpoint is increased the value for I could consistently decrease.

The most common PID problem is flow oscillation. Tuning the controller too 'tight' might look good initially but can result in oscillation after running for a longer time. Ambient conditions also can cause oscillation. Temperature and pressure will cause the most oscillation if they fluctuate, so it is best to control them as tightly as the application allows.

V. Summary

Significantly improving Liquid Flow Controller (LFC) response/ stabilization times can reduce processing times, increase throughput and reduce waste. By choosing a fast response LFC and by optimizing PID tuning, response times ≤ ±0.3s to 1% of set-point can readily be achieved (Figure 9).

Figure 9: Turbo™ 2950-30 Liquid Flow Controller Response Time



The Turbo™ 2950 LFC is a high-speed liquid flow controller designed for use with MSP Turbo™ Vaporizers to provide unmatched liquid source delivery performance for microelectronic process applications like CVD and ALD. The 2950 contains a custom engineered high-precision differential pressure flow sensor which features exceptional accuracy and repeatability measured by SEMI E561 . The 2950 has flexible communication options including EtherCAT, RS485 and analog options. Additionally, the 2950 configuration software allows users to easily tune the PID and switch working fluids in the field. Visit our website for more information on the MSP Turbo™ 2950 LFC, visit.

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5910 Rice Creek Parkway, Suite 300
Shoreview, Minnesota
55126, U.S.A.
Tel: 651.287.8100