AN074: TIME METERED DOSING USING A VOLUME CONTROL MODULE

1. INTRODUCTION

1.1. About this Application Note

This application note demonstrates a novel dispensing scheme – the Volume Control Module (VCM). VCM takes advantage of the high-precision pressure control of the Disc Pump.

The main advantage of the Volume Control Module dispensing over Time-metered dosing is that the dispensed liquid volume is independent of the liquid properties such as viscosity, flow restriction, liquid level, dispensing height. This is beneficial for dispensing applications with liquids that change viscosity with temperature or over time, applications using a single dispensing unit with multiple outputs or high precision applications that are sensitive to minute changes in the dispensed quantity.

This Application Note covers:

- System architecture
- The basic operating principles of Volume Control Module dispensing
- The main benefits – independence of liquid viscosity, high controllability and high accuracy
- How to fine tune the system to achieve the best results and to make it independent of external factors such as ambient pressure or temperature.

This note is meant to provide a helpful starting point for customers considering implementing this scheme in their own products.

Please note that The Lee Company does not design or manufacture manifolds for this scheme.

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3. BACKGROUND TO VCM DISPENSING SYSTEM

3.1. Advantages over Time-metered dosing

This novel dispense system improves on the traditional Time-metered dosing by introducing pressure feedback from the Volume Control Module. This feedback enables the system to automatically compensate for changes in:

- Liquid viscosity or flow restriction
- The liquid used
- Liquid level or dispensing height

While conserving the main benefits of Time-metered dosing:

- High accuracy
- High precision
- High controllability

This system can be used for dispensing applications with liquids that change viscosity with temperature or over time, applications using a single dispensing unit with multiple outputs or high precision applications that are sensitive to minute changes in the dispensed quantity.

The dispensing system utilizes The Lee Company's pulsation-free Disc Pump to generate the driving pressure for liquid dispensing. The Volume Control Module is a reservoir of known volume with a pressure sensor attached. When the liquid is dispensed it leaves a partial vacuum in the Volume Control Module. The pressure sensor measures the partial vacuum pressure, which is proportional to the volume of the dispensed liquid.

3.2. Architecture

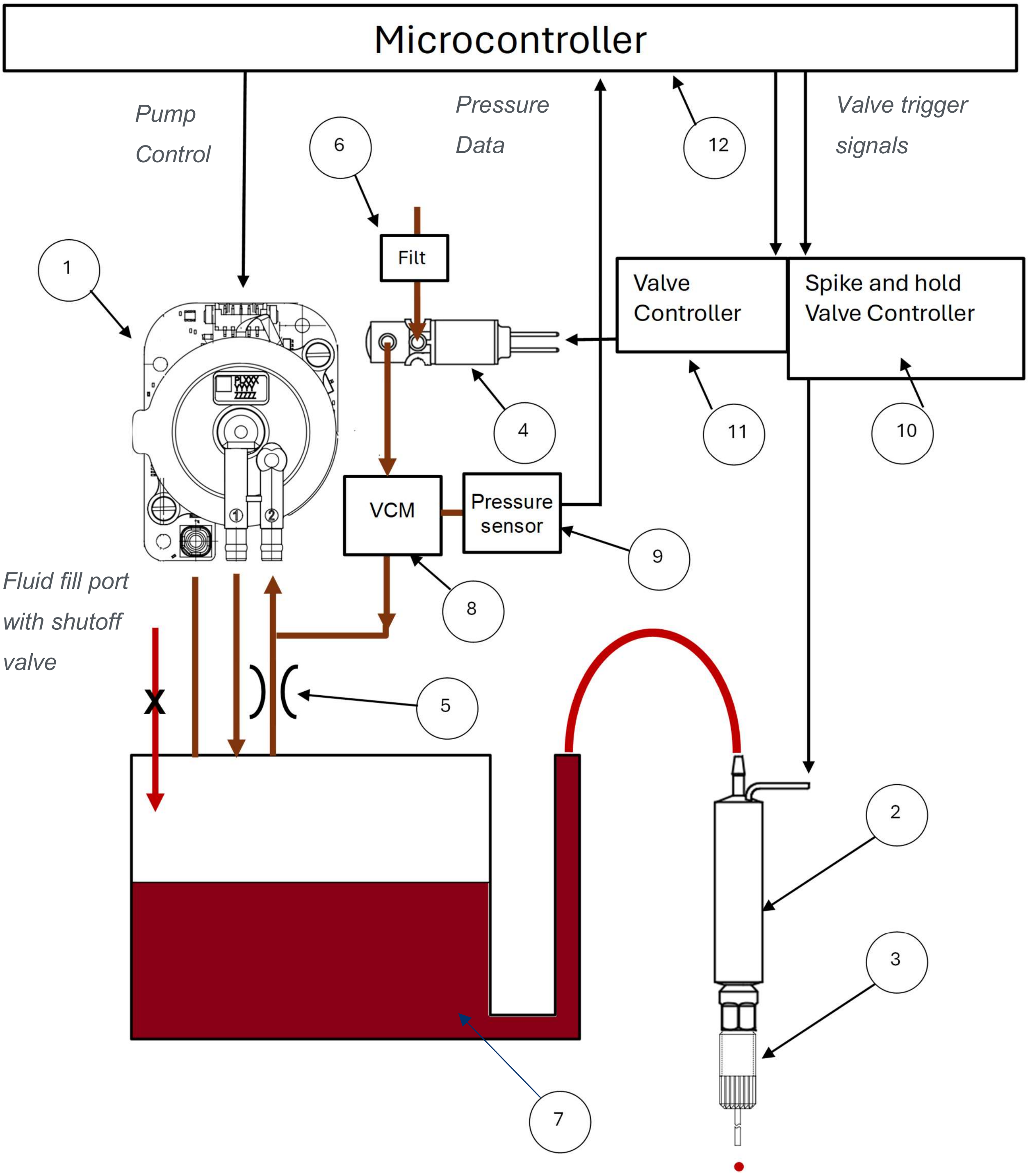

Table 1 Prototype components

Component	Description	Product code	Source
1	Smart Pump Module	UBLC5400200A	The Lee Company
2	VHS Valve – for liquid dispensing	INKX 0508000A	The Lee Company
3	Dispensing Nozzle	INZA3100914K	The Lee Company
4	HDI Valve – for air intake	LHDA1233115H	The Lee Company
5	Orifice	RPGF2554300S	The Lee Company
6	Filter	3μm pore size or less	
7	Fluid Reservoir	Bespoke SLA	
8	VCM control volume	Bespoke SLA	
9	Differential pressure sensor 1psi	HSCDLND001PGAA5	Honeywell
10	Spike and Hold valve controller	IECX 0501350A	The Lee Company
11	Valve controller	Simple "Basic transistor" valve driver	
12	Microcontroller	Arduino Mega 2560 Rev3	Arduino

3.3. Principle of operation

The Volume Control Module dispense system goes through the following steps in its operation:

1. The Smart Pump Module, which is comprised of the Disc Pump, drive electronics and sensors (1), is turned on and pressurises the Fluid reservoir (7). The Smart Pump Module (1) uses closed loop pressure control to precisely control the pressure in the reservoir.
2. A small delay is introduced for pressure and temperature to equalise (see Section 6.3)
3. The air intake HDI Valve (4) is closed, shutting off air supply to the Volume Control Module (8).
4. The VHS valve (2) is opened to start dispensing liquid.
5. As the liquid is dispensed, the Disc Pump (1) draws air from the Volume Control Module (8) into the Fluid reservoir (7). This creates a partial vacuum in the Volume Control Module (8).
6. The partial vacuum in the Volume Control Module is measured with the Pressure sensor (9). As the dispensed liquid volume is linearly dependent on the partial vacuum pressure, the system waits until a target negative pressure is reached.
7. Once the target VCM negative pressure is reached, the VHS valve (2) is closed to shut off the liquid output.
8. The Disc Pump (1) is stopped and the air intake HDI valve (4) is opened.

4. KEY OPERATING PRINCIPLES

To a first approximation the dispensed liquid volume V_{out} is:

$$V_{out} = \frac{\Delta P_{VCM}}{P_R} \times V_{VCM} \qquad \text{Eq. 1}$$

Where ΔP_{VCM} and V_{VCM} are the partial vacuum pressure and the volume of the Volume Control Module respectively, and P_R is the absolute pressure in the Fluid reservoir. Note that by design the volume of the Volume Control Module (V_{VCM}) is a calibrated quantity.

4.1. Independence of liquid viscosity and liquid level height

The main advantage of the Volume Control Module dispensing over Time-metered dosing is that the dispensed liquid volume is independent of the liquid properties such as viscosity, flow restriction, liquid level or dispensing height.

The variability of liquid viscosity was explored for both a Volume Control Module dispensing system and a Time-metered dosing application. The liquid viscosity was simulated by placing different orifices in the liquid's flow path. As show in Figure 1, the Volume Control Module dispensing system can compensate for the variability in the flow resistance, while the Time-meter dosing system dispenses less fluid at higher flow resistance.

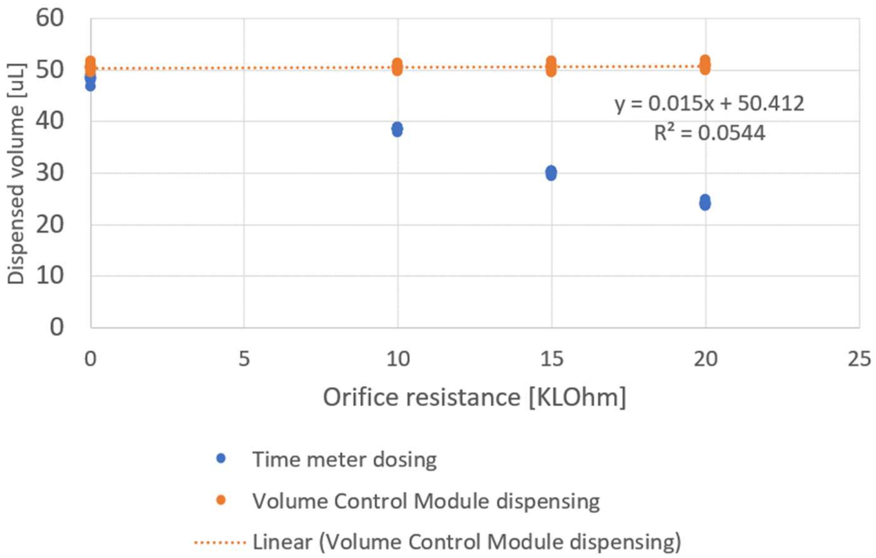

Figure 1 Liquid viscosity simulation – Volume Control Module dispensing vs Time-metered dosing

4.2. High controllability

The linear relationship between the pressure drop in the Volume Control Module and the dispensed volume, allows the system to be easily controlled. Figure 2 shows this close correlation.

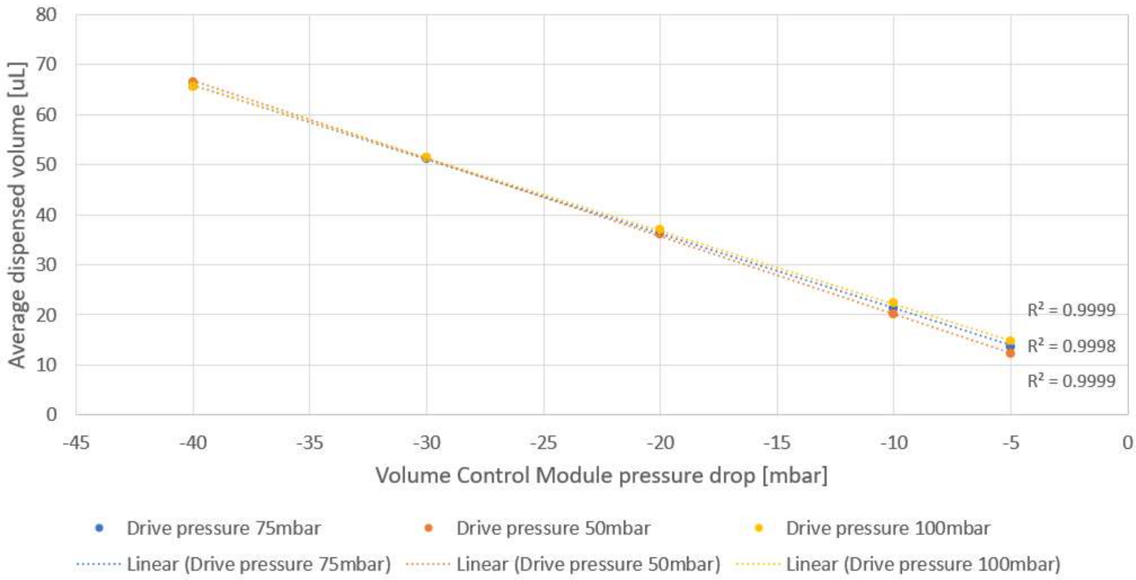

Figure 2 Dispensed volume vs VCM Pressure drop.

The other factor contributing to the dispensed volume is the drive pressure in the Fluid reservoir. Figure 3 shows the theoretical relation of $V_{out} \propto \frac{1}{P_R}$ holds closely. Note that for small variations in drive pressure, the 1/x relation can be approximated as a linear relationship.

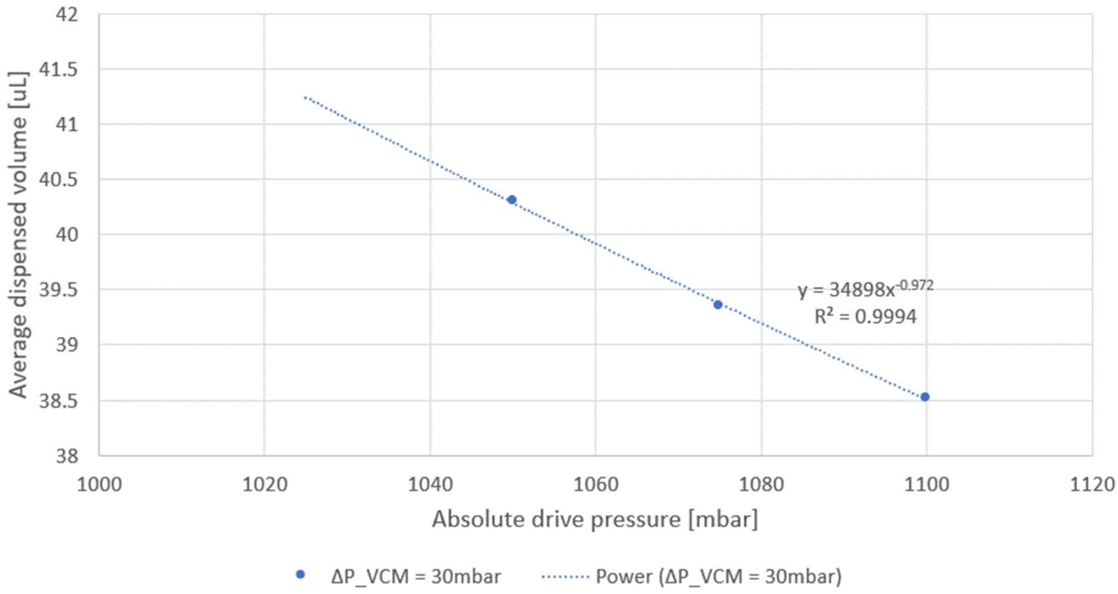

Figure 3 Dispensed Volume vs Drive pressure

4.3. High accuracy and precision

High accuracy and precision are important for dispensing applications. Figure 4 shows the coefficient of variation (CV = standard deviation / mean) for different dispensed volumes. The Volume Control Module dispensing system can reliably achieve less than 5% CV and less than 1% CV for larger dispensed volumes of about 50uL. This precision is in line with most industrial applications and shows the viability of using Volume Control Module dispensing in applications that typically make use of Time metered dosing. The precision of the system for dispensing smaller quantities can be explored with better measurement equipment in future.

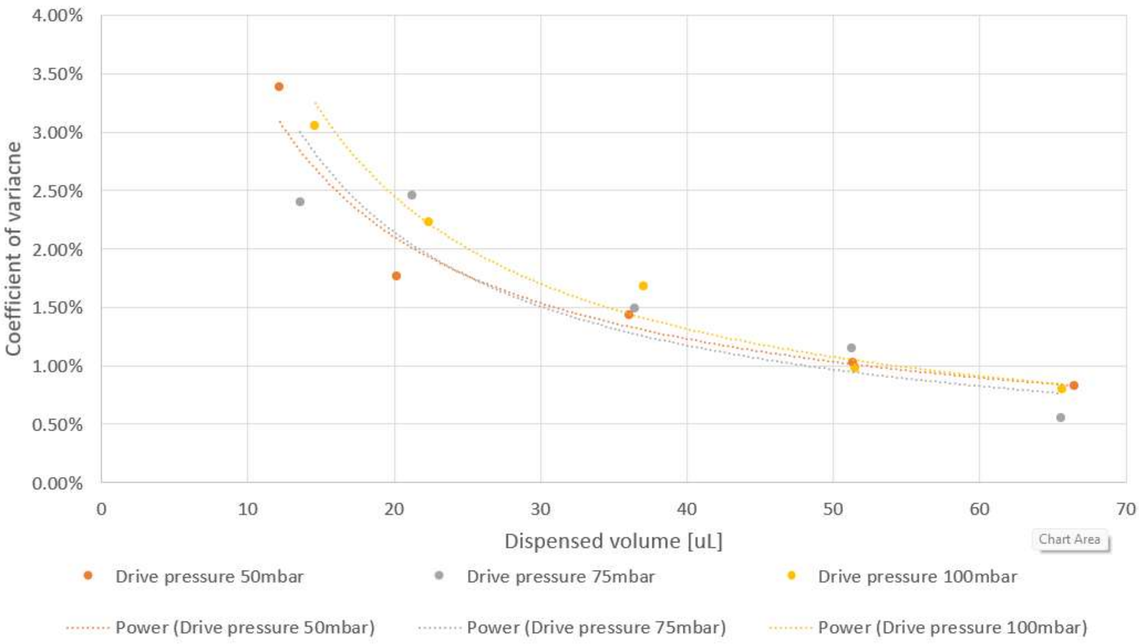

Figure 4 Coefficient of variation vs Dispensed volume

5. NOTES ON THE EXPERIMENTAL DATA PRESENTED IN THIS REPORT

Measuring microliter volumes of a liquid is challenging dictated, in part, by the sensitivity of the of the measurement equipment (typically measuring scales) and external factors such as evaporation or even air movement. To improve the accuracy and precision of the measurements in this report, the dispensed liquid volumes were estimated by integrating the flow measurements of a high precision liquid flow sensor.

Water was used for all experiments as the liquid flow sensor was factory calibrated for water measurement. Due to the limitation of using water, various liquid viscosities were simulated by placing a flow restrictive orifice in the fluid's path. While an orifice does not have the same flow characteristics as a viscous liquid, the end goal of varying the liquid velocity is achieved .

To minimise variability due to external factors such as ambient temperature or pressure, the experiments were performed in a temperature-controlled environment in a short span of time. The effects of these factors are explored independently in the following sections of this report.

6. FINE TUNING

There are many variables that affect how well a Volume Control Module performs. A well-designed system can be made independent of variations in ambient pressure and temperature and other internal parameters such as control loops and self-heating. The rest of this section will go through these variables, explore the effects they have on the system and how to compensate for them.

6.1. Theoretical derivation

The system equations can be derived from considering the ideal gas law for the combined system of the Fluid reservoir and the Volume Control Module. In this equation the change:

$$\frac{P_{VCM} \times V_{VCM}}{T_{VCM}} + \frac{P_R \times V_R}{T_R} = const = \frac{(P_{VCM} + \Delta P_{VCM}) \times V_{VCM}}{(T_{VCM} + \Delta T_{VCM})} + \frac{(P_R + \Delta P_R) \times (V_R + \Delta V_R)}{(T_R + \Delta T_R)} \qquad \text{Eq. 2}$$

Where:

V_{VCM} is the volume of the Volume Control Module

P_R and ΔP_R are the absolute starting pressure and the pressure change in the Fluid reservoir.

T_R and ΔT_R are the starting temperature and the temperature change in the Fluid reservoir.

V_R is the volume of the Fluid reservoir at the start of the dispense.

ΔV_R is the change in the volume of the Fluid reservoir. Which is the dispensed volume V_{out}.

P_{VCM} and ΔP_{VCM} are the absolute starting pressure and the pressure change in the Volume Control Module.

T_{VCM} and ΔT_{VCM} are the starting temperature and the temperature change in the Volume Control Module.

is the volume of the Volume Control Module. As noted, before this is a calibrated quantity.

To a second approximation the dispensed volume is:

$$V_{out} = \frac{\Delta P_{VCM}}{P_R} \times V_{VCM} \times \frac{T_R}{T_{VCM}} \cong \frac{\Delta P_{VCM}}{P_R} \times V_{VCM} \qquad \text{Eq. 3}$$

$$\text{if } P_R \neq const \quad + \frac{\Delta P_R}{P_R} \times V_R \qquad \text{significant because } V_R \gg V_{VCM} \qquad \text{Eq. 4}$$

$$\text{if } T_R \neq const \quad - \frac{\Delta T_R}{T_R} \times V_R \qquad \text{significant because } V_R \gg V_{VCM} \qquad \text{Eq. 5}$$

$$\text{if } T_{VCM} \neq const \quad - \frac{\Delta T_{VCM}}{T_{VCM}} \times \frac{T_R}{T_{VCM}} \times \frac{P_{VCM}}{P_R} \times V_{VCM} \cong \frac{\Delta T_{VCM}}{T_{VCM}} \times \frac{P_{VCM}}{P_R} \times V_{VCM} \qquad \text{Eq. 6}$$

Note that the starting temperatures for the Volume Control Module and the Fluid reservoir are typically both the same as the ambient temperature ($T_{VCM} = T_R$). Also note that for a typical system the volume of the Fluid reservoir is much bigger than the volume of the Volume Control Module ($V_R \gg V_{VCM}$).

6.2. Fluid reservoir pressure control ($P_R \neq const$)

The pressure in the Fluid reservoir needs to be very well maintained. Small variations in the Fluid reservoir pressure can lead to large errors in the dispensed volume, as in most systems $V_R \gg V_{VCM}$ (see Eq. 4). The effects of poor pressure control are shown in Figure 5. These can lead to both error in dispensed volume (the vertical difference between the two tunings) as well as deviations from the theoretical relation for driving pressure (the poor fit to the $V_{out} \propto \frac{1}{P_R}$ line).

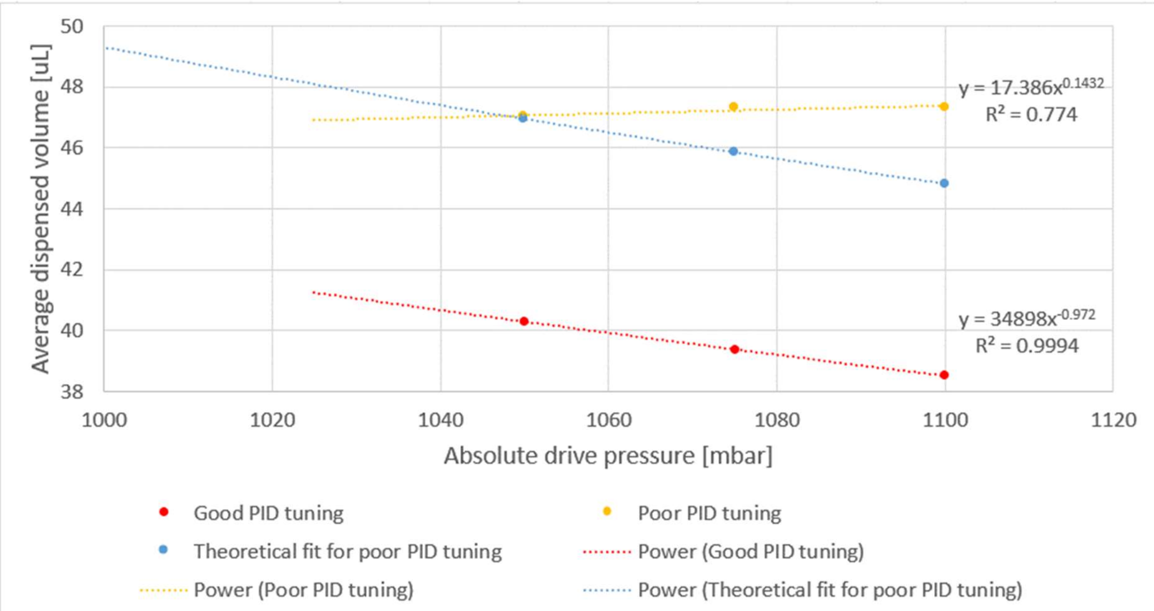

Figure 5 Dispensed volume vs Drive pressure for different PID tuning

It is worth pointing out that a PID (Proportional, Integral and Differential) control loop cannot fully compensate the pressure drop due to dispensing, especially for long dispenses. This is a fundamental limitation of control systems which states that a system can achieve steady state error only if the control system has at least one-degree higher control loop than the system to be controlled.

As shown in Figure 6, a simple proportional control cannot achieve zero steady state error for a step input, but a first order integral control can achieve zero steady state error for the same step input system.

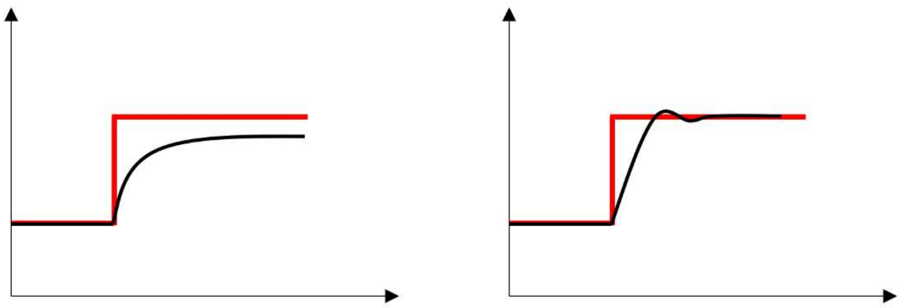

Figure 6 Step input (0^{th} degree) - Proportional control (P) steady state error (left) and Integral (I) control no steady state error (right)

Similarly, in Figure 7 a first order PID control cannot achieve zero steady state error for a ramp input system, but a control loop with a double integral can. Dispensing a liquid is equivalent to a ramp input to the system because the dispensed liquid creates a constant change int the air volume of the reservoir. This phenomenon is usually not a problem with short dispense times as the steady state error is a small contributor to the pressure tracking but can be pronounced for long dispenses.

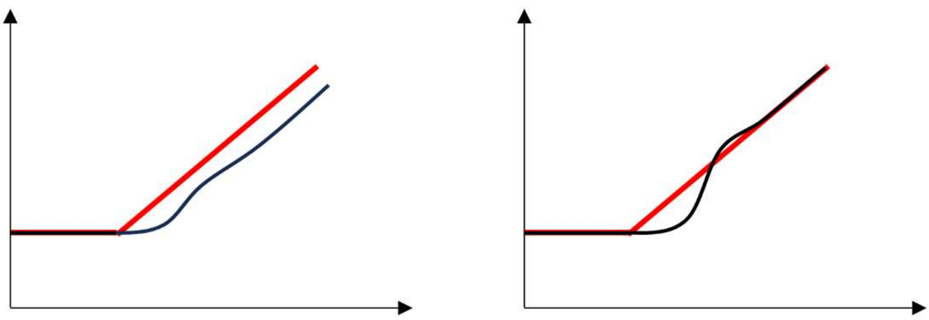

Figure 7 Ramp input (1^{st} degree)– Integral (I) control steady state error (left) and Integral squared (I^2) control no steady state error (right)

An alternative way of compensating would be to measure the pressure drop in the Fluid reservoir and calculate and compensate for the dispense volume error term via Eq. 4. The downside of this approach is the reliance on a known volume in the Fluid reservoir, which varies with the liquid level.

6.3. Ambient temperature

The system is independent of ambient temperature if all parts of the system are at the same temperature, because the temperature terms cancel out ($T_{VCM} = T_R$). However, when the ambient temperature changes rapidly (around 1°C/min), there is a large effect on the dispensed volume as shown in Figure 8.

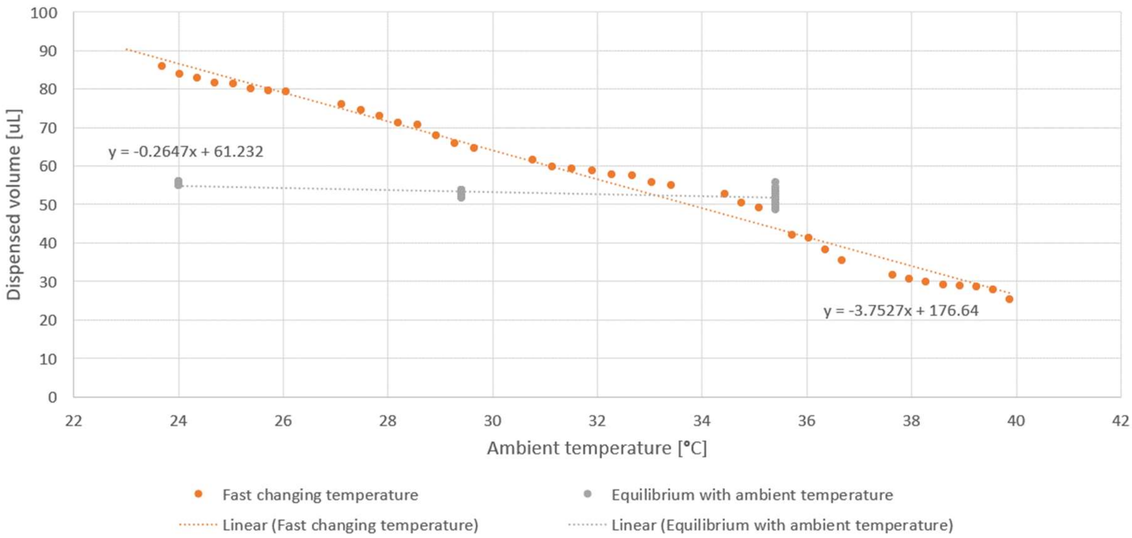

Figure 8 Dispensed volume vs temperature for different temperature-time gradients. Note that the data is noisy due to imprecise temperature measurements.

This effect happens when air of different temperature to the system (the housing and air in the system) is drawn in. New warm air is drawn in while the rest of the system is at a lower temperature. As the air intake valve shuts off air supply to start the dispensing, the warm air cools down to reach equilibrium with the surroundings as shown in Figure 9. The cooling down results in dropping pressure which drastically affects the dispensed volume (effectively changes ΔP_{VCM}, which is the main system control, see Eq. 3).

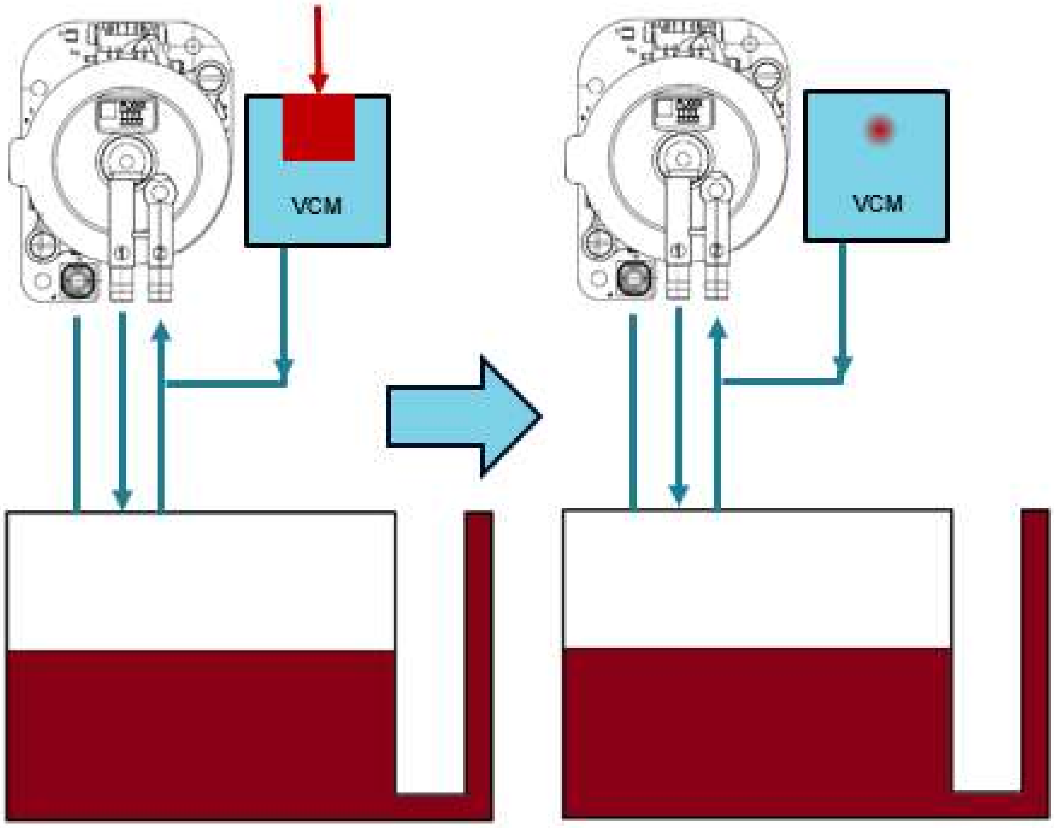

Figure 9 Warm air entering the system. As the air cools down, it creates a partial vacuum.

The simplest way to compensate for this effect is to wait for a couple of seconds (with the air intake valve open) after the liquid reservoir has reached pressure. This additional time allows the new warm air to equilibrate with the system and draw additional air in (which prevents the drop in pressure). The effects of implementing this waiting period can be seen in Figure 10.

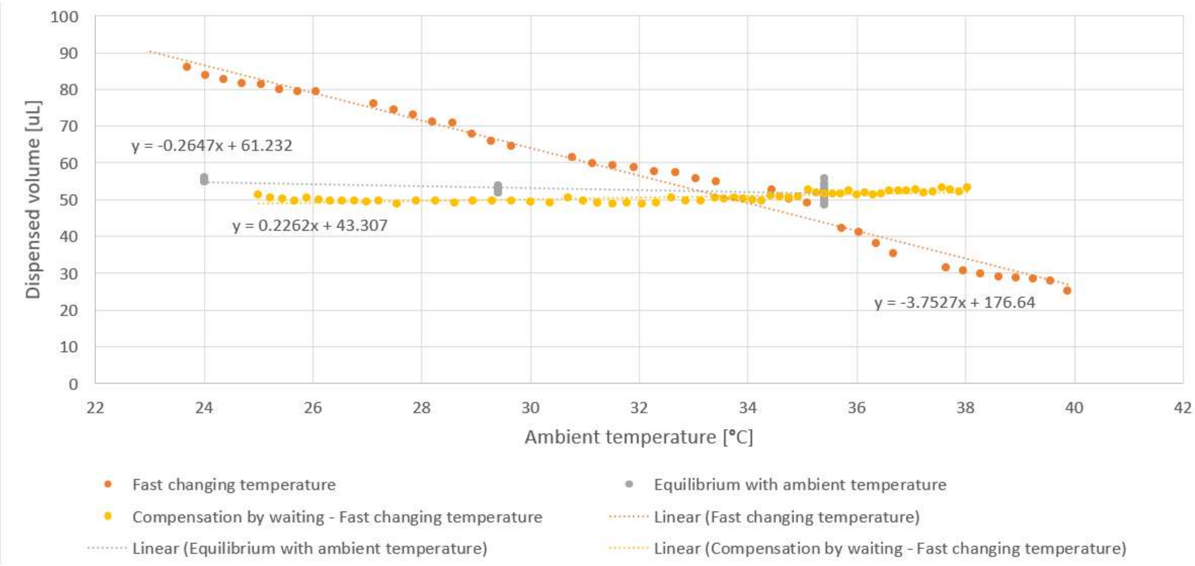

Figure 10 Dispensed volume vs temperature for different temperature-time gradients, with and without wait period upon air intake. Note that the data is noisy due to imprecise temperature measurements.

There could be alternative solutions:

- Mechanical system to pass the incoming air through the housing allowing it to equilibrate before entering the air intake valve (this would likely require the manifold to be fabricated from a conductive material).
- Allowing some of the orifice feedback air from the liquid reservoir to go to the VCM to accelerate mixing.
- Temperature control system.

6.4. Ambient pressure ($V_{out} \propto \frac{1}{P_R}$)

The dispensed volume is dependent on the pressure in the Fluid reservoir ($V_{out} \propto \frac{1}{P_R}$) as expressed in Eq. 3. Typically, the Fluid reservoir pressure is measured using a differential pressure sensor and thus the reservoir pressure changes with ambient pressure. Ambient air pressure can vary by about 3% daily, and greater still in clean room environments due to extraction systems. This variation can be compensated for either by using an absolute pressure sensor as shown in Figure 11 or by measuring the atmospheric pressure.

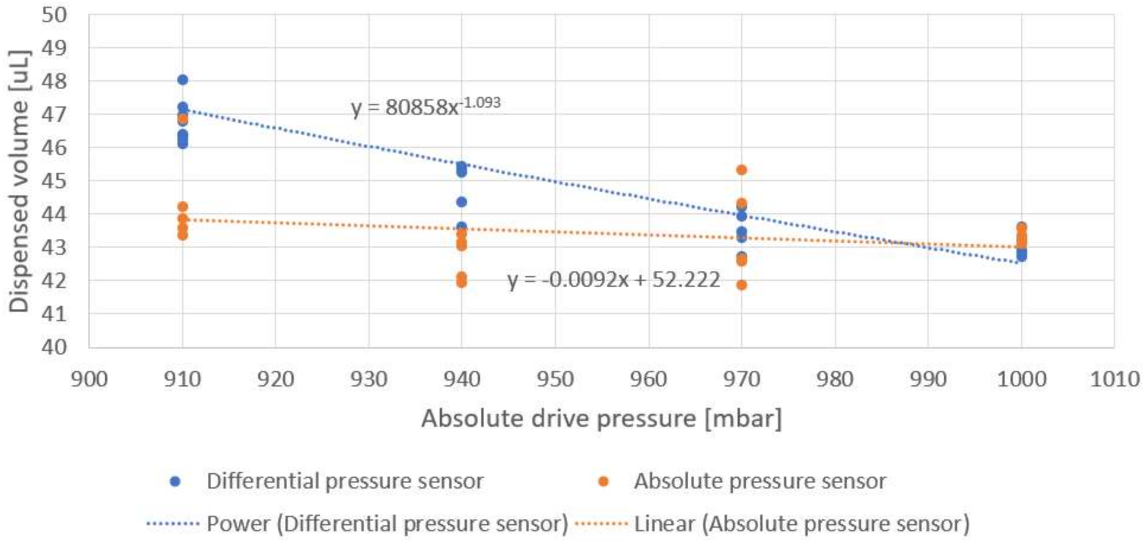

Figure 11 Dispensed volume vs ambient pressure for differential and absolute pressure sensor. The changes in atmospheric pressure were achieved using a vacuum chamber. Note that the data is noisy due to imprecise pressure control in the vacuum chamber.

6.5. Self-heating (T_R and $T_{VCM} \neq const$)

The system is prone to self-heating due to the pump running which can affect the dispensed volume as expressed in Eq. 5 and Eq. 6. In the experimental setup presented it was difficult to directly measure due to the small size of the components ($V_R \sim 1 - 3cm^3$ and $V_{VCM} \sim 0.8cm^3$). Instead, the direct impact of self-heating was observed by measuring the pressure of the Volume Control Module when both the air intake and liquid output valves were closed. The change in Volume Control Module pressure can be seen in Figure 12.

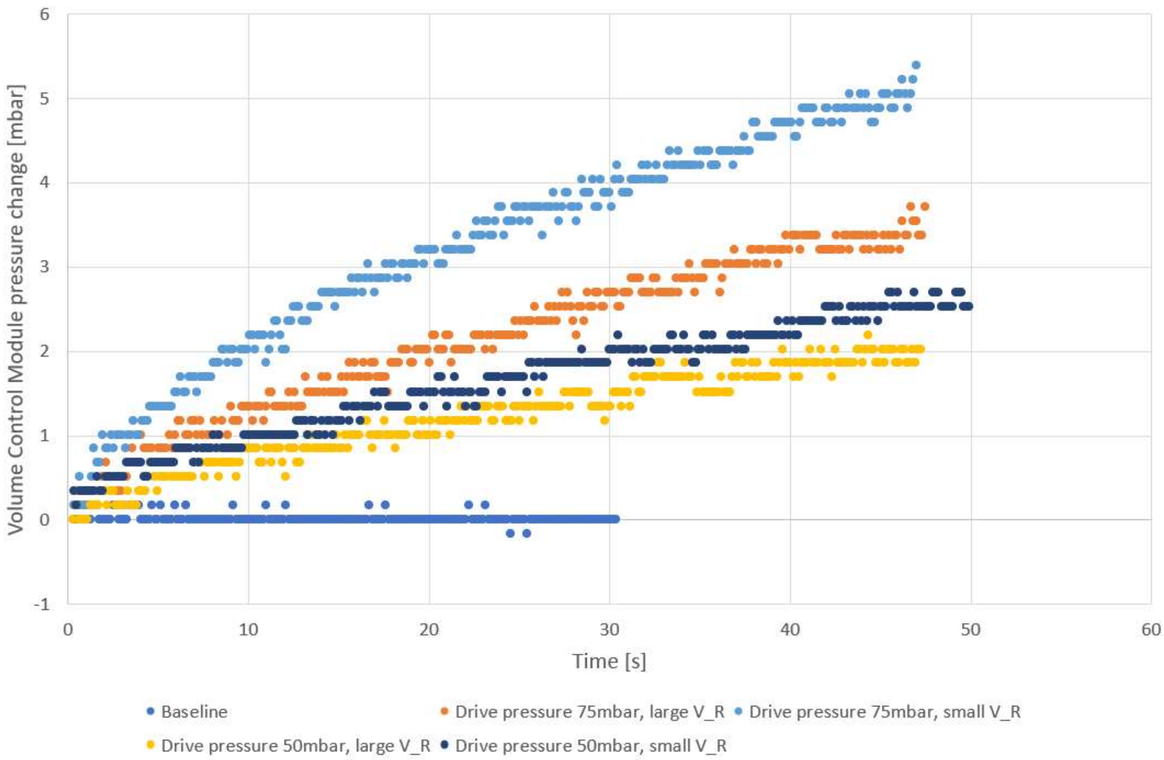

Figure 12 Changes in the pressure of the Volume Control Module due to self-heating. Data presented for various Fluid reservoir volumes and pressures (corresponds to different pump power).

The self-heating effect is stronger for smaller fluid reservoir volume (higher liquid level) and higher fluid reservoir pressure due to the pump working harder.

Overall, the self-heating effect is small as dispense times are typically between 0.12s and 1.2s and typical target ΔP_{VCM} is between 10 and 50mbar. It is still recommended to turn the pump off between dispenses to minimise or avoid self-heating.

6.6. Leaks

The Volume Control Module dispensing system relies on measuring the system pressure precisely and is therefore highly susceptible to any leaks (whether air is leaking into or out of the system). The acceptable leak rate can be estimated by considering that a typical dispense (1s dispense + 2s of waiting of 50ul) has an average output flowrate of about 1000ul/min. The leak rate should be <1% of the flowrate of the system and is therefore recommended to be kept below about 10ul/min. Note that this value is for reference use only and would be highly dependent on the application. A standard method for detecting leaks in the system is to pressurise it (or reduce the pressure below ambient) and observe if the pressure decays over time. The leak rate can be calculated from the system volume and pressure decay time.

6.7. Valve and control system response time

Small dispense volumes require short dispensing times (e.g. under 100ms). Any delays in the Volume Control Module pressure sensing or slow valve actuation can cause the system to overshoot the target dispense volume or generally introduce inaccuracy and variation. To minimize this effect, it is recommended to use an external microcontroller that is dedicated to sensing the Volume Control Module pressure. Additionally, the valve opening and closing times should be minimised by using high speed valves and drive electronics such as the system used in this report - a Lee Co. VHS valve driven by a spike and hold circuit to provide millisecond response time.

6.8. Compliance and thermal expansion

There needs to be careful consideration of the design and choice of materials, for instance it is possible for the reservoirs to flex under the applied pressure. Any changes in the capacity of the Volume Control Module would affect the dispensed volume (see Eq. 3). This can be highly problematic when trying to achieve high precision as the changes will be nonlinear with the internal pressure and other external factors. A similar problem can occur with thermal expansion of the reservoirs. This could happen because of either change in ambient pressure or self-heating of the system under prolonged dispensing cycles.

7. CONCLUSION

Volume Control Module dispensing is a novel system that provides numerous advantages over traditional Time Metered Dosing. With Volume Control Module the dispensed liquid volume is independent of the liquid properties such as viscosity, flow restriction, liquid level or dispensing height, while maintaining high precision and controllability of the dispensing.

There are many considerations when implementing the Volume Control Module dispensing for the system to achieve its potential. A well implemented system can be made independent of ambient pressure and temperature as shown in this report.

8. ADDITIONAL SUPPORT

The Lee Company Website provides advice on:

- Getting Started
- Applications
- Development Process
- Downloads (including datasheets, application notes, case studies and 3D models)
- Frequently Asked Questions

Visit: www.theleeco.com/discpumps

The Lee Company is happy to discuss next steps beyond prototyping, including system design. If you would like to discuss this with us, or for any other additional support, please contact your Lee Sales Engineer.

9. REVISION HISTORY

Date	Version	Change
21/05/24	V02	Reformat
06/10/2023	V01	Document created