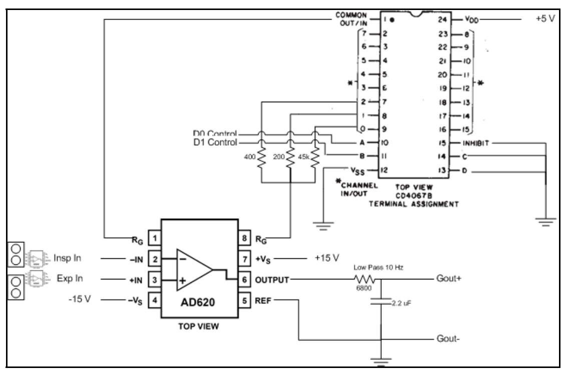
Differential Vaporizer Research

2007 - 2008



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1.0 Introduction

GE Healthcare currently has two different vaporizers in its product line, the Tec series and the electronic Aladdin series. The Tec series vaporizers have no electronic components and deliver agent through a manual dial. This manual dial controls the amount of flow that goes into the sump, which in turn, controls the amount of agent delivered. The electronically controlled Aladdin series uses valves and a proportional valve to control the flow into the cassette. The Aladdin system has removable agent cassettes that allow agent swapping. However, the Aladdin cassette has a number of challenges that make it desirable to find a better solution. First, the Aladdin cassette is not cost effective because of the components, materials, sensors, and mechanical parts. Second, the Aladdin cassette also has a closed loop feedback control to the AC board which causes slow response. When changing gas flows through the vaporizer, it takes a number of seconds for the control algorithm to get the agent concentration correct. For a circle system, this is not a problem due to the large volume, however it does when trying to design a smaller system like a semi-open Mapleson/Bain system. (See the Universal Compact Anesthesia Machine documentation for direct application that requires fast response). Next, the Aladdin vaporizer does not have any form of manual override. A form of manual agent control would give the clinician another way to deliver agent under system problems, power failure, or to allow the clinician to focus better on the patient. Clinicians that are active users of manual control would feel more comfortable with the transition to an electronic system if it had a manual adjustment mechanism. Finally, the Aladdin cassette holds less agent than the Tec vaporizers, which causes the clinician to refill the cassettes at a faster rate.

In attempt to find a solution to all of the above challenges, it would be necessary to redesign the vaporizer with the problems in mind. The Tec vaporizer is used on the Avance, Aestiva, and Aespire, therefore compatibility with these modules would be desired. An ability to control the agent concentration quickly would make the vaporizer functional in semi-open systems and open up new opportunities. Optional manual control would ease the transition for clinicians from manual to electronic while still giving them flexibility in certain circumstances. A larger sump would allow clinicians to focus on treatment, rather than maintaining the machine. Finally, cost savings is an important factor due to the currently high electronic vaporizer cost. In order to encourage the development of a new system, the solution cost would need to be less than the current electronic system.

This research project targets a concept that could assist in meeting all of the above objectives. To reduce the cost of the system, just measuring inflow and outflow would help reduce the number of valves, sensors, and brass needed. If the sensitivity and correction could be fast, the inflow and outflow agent calculation could be very fast and able to adjust a manual valve rapidly. With this, the manual valve could have an external control for setting the diverted amount manually. In packaging the whole system together in a Tec series vaporizer, the vaporizer could be electronic, manual, compatible, longer life due to less mechanical parts, and lower cost. Keeping a similar sized sump as the Tec has would also keep the agent volume the same, reducing the rate of filling. However, in order for this to happen, the inflow outflow measuring system needs to reliably and safely deliver agent.

2.0 Description

The vaporizer research project consists of two orifice plate flowmeters, one measuring inbound flow, and one measuring outbound with agent pickup. The orifice plate flowmeters were designed as bypass restrictors in the Tec 7 vaporizer and pressure taps were added before and after the restrictor and passed to Honeywell DCXL10DS pressure transducers. The pressure transducer differential output connects to AD620 instrumentation amplifiers to increase the usable range. The output from both instrumentation amplifiers is then connected differentially to either labview or another instrumentation amplifier stage for signal conditioning and amplification. The difference between these measurements is being used to attempt agent concentration calculations. Temperature and gas characteristics are held constant in order to reduce the complexity of the system.

Differential pressure transducers measure the force required to stop a gas from expanding, and is usually stated in terms of force per unit area. A pressure sensor generates a signal related to the pressure imposed. The DCXL10DDS uses a silicon micromachined sensing element with a stress concentration-enhanced structure to improve the pressure linearity. An instrumentation amplifier that has manual span adjustment then amplifies the differential pressure transducer voltage. The span potentiometer is adjusted to minimize the difference between the inbound and outbound flow sensor across the desired flow range. Analog outputs and a calibration table for removing common mode noise at common flows control the zero offset of this instrumentation amplifier. The signal from these instrumentation amplifiers then extends to another differential amplifier to amplify the difference for calculation. The final differential amplifier has digitally controlled resistor selections through an analog MUX for varying the gain.

The procedure for this project progressed as challenges were discovered. The project began by adding a Tec 7 vaporizer between the flow meters. Challenges with resistance caused a number of variants in order to isolate the behavior. The project continued progressing with testing a two mixer system, utilizing a two way diverter valve, and other mechanical tests. Circuit signal conditioning progressed over the course of the project in order to maximize the signal and reduce the drift substantially. Finally it was determined that for a specific flow range, agent estimation could be possible ending the project with an agent calculation algorithm which was tested in this flow range. In order to extend the calculation to the low flow range, it was determined that the effect of absolute pressure in the system would need to be compensated and/or the system would need to be designed with a constant resistance.

2.1 Interpolation with Calibration and Application Design

Figure 1 shows an initial diagram for a means of implementing the application behavior. This diagram was enhanced over the project to the sequence diagrams below.

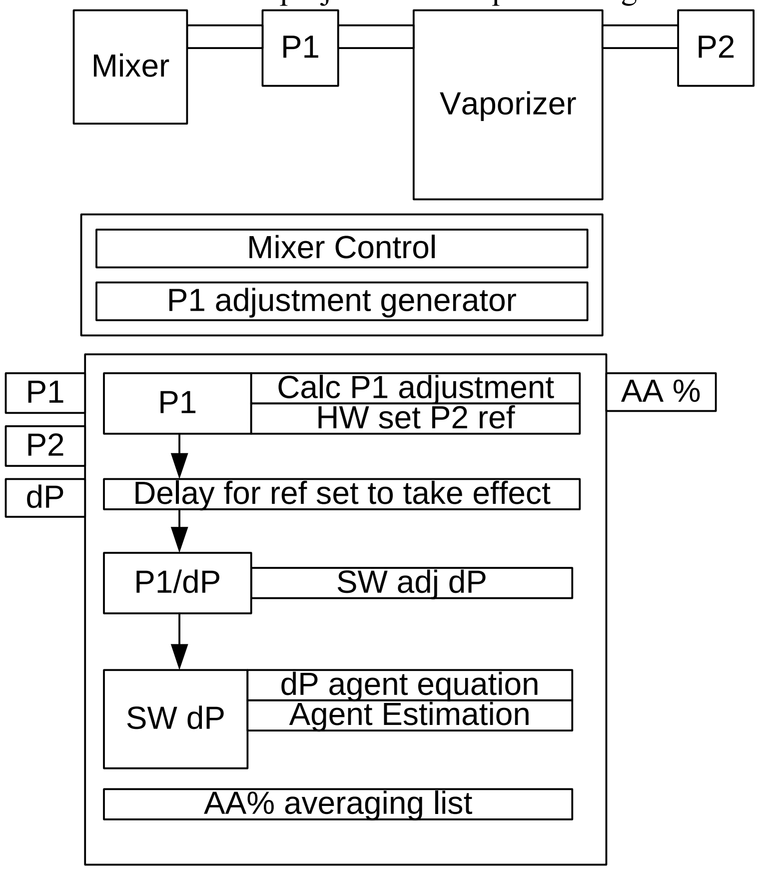


Figure 1 – Initial Algorithm Design Behavior

2.1.1 VI Calibration and Application Sequence Diagrams

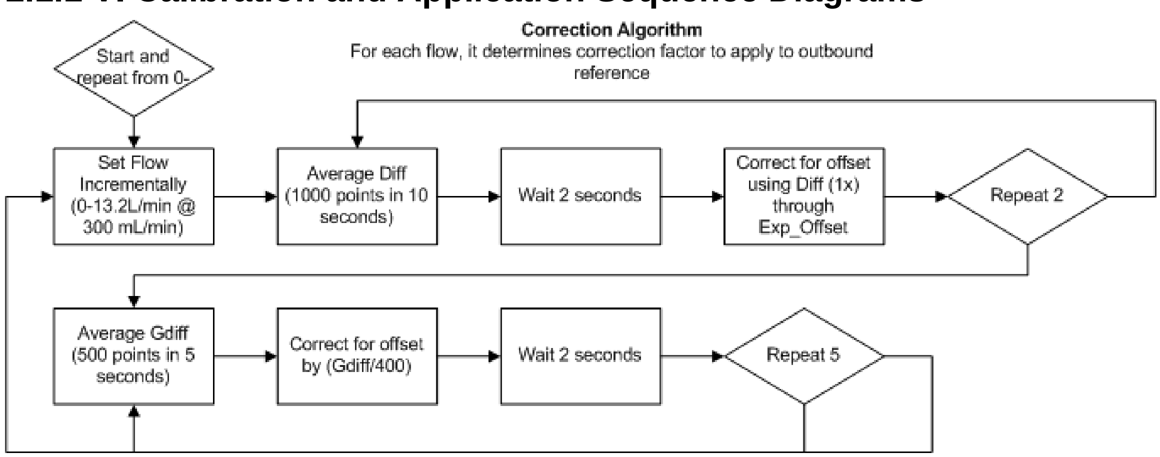


Figure 2: Correction Algorithm

This is the correction algorithm that gets run prior to testing. It tweaks the offset of the outbound voltage reference to get the inbound and outbound amplifiers match. This offset correction table is then interpolated in the application to provide correction for all flows.

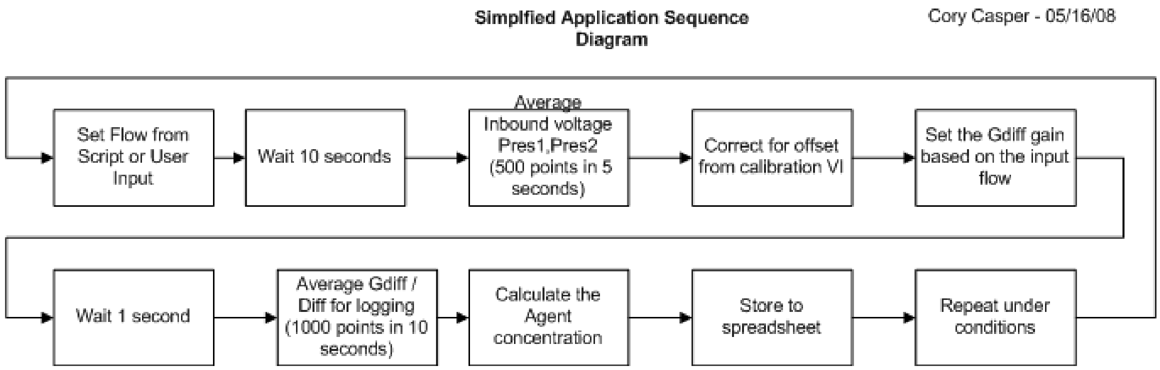


Figure 3: Application Algorithm

Above is a simplified sequence diagram of the application. The basic operation is shown above, however the VI allows for a number of different capabilities like script running, script stepping, and update only. Along side this sequence diagram are threads executing mixer instructions for both mixer 1 and mixer 2, analog and digital I/O processing, and MGas data collection for use in this sequence.

2.1.2 Labview Design

The labview software design is broken into two components, the calibration VI and application VI. The calibration VI is responsible for calibrating and determining correction factors for anything used in the application. The calibration VI and application VI are structured in exactly the same way: an I/O sequence, a mixer sequence, and a user control sequence. The I/O sequence is responsible for all of the input and output from the labview data acquisition card. This consists of number of analog inputs, two analog outputs and digital outputs. The analog inputs gather the analog voltages for the pressure sensors as well as the gain circuit. The analog outputs are used for correction offset, and the digital outputs are used to control the gain factor on the final differential. These are all done using DAQ-mx labview controls.

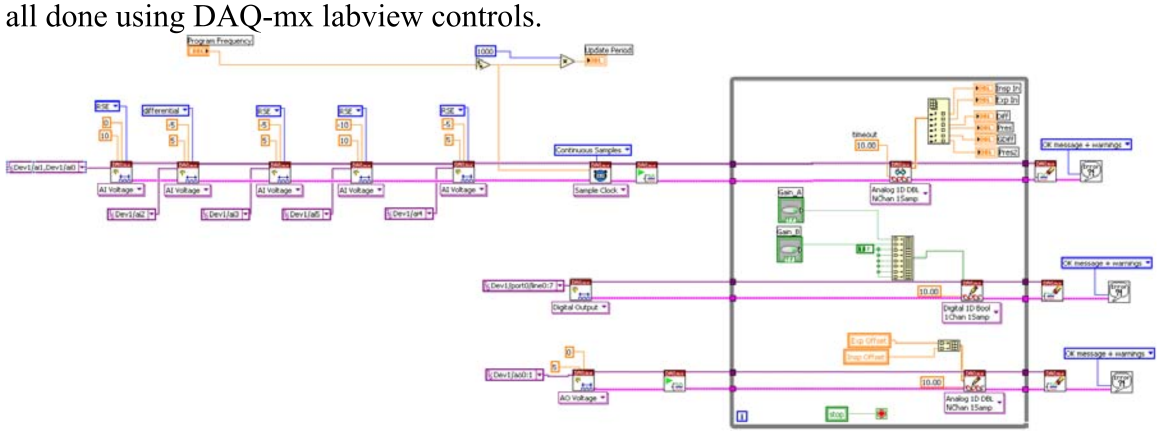


Figure 4: Application I/O Sequence

The second section of the VI is the mixer sequence. Initially the mixer sequence only consisted of one mixer; however, there was a time when two mixers became necessary, one for bypass flow and one for vaporizer flow. This test setup was done in order to try eliminating the pressure effects since both sides of the inbound pressure restrictor had varying pressure. This varying pressure on both sides made it very difficult to measure the flow and difference accurately. Therefore the pressure restrictor was moved upstream of two mixers, therefore one side of the upstream restrictor would be held constant at the regulator pressure. All of the blocks were simply duplicated when adding the second mixer. This is shown in the figure below. The first part of the mixer sequence waits for the mixer communication and initialization. The second part of the sequence diagram sends and receives gas settings and status information. A third part, which has not been added, would close the mixer communication. However, this part was removed to prevent adverse effects on labview and sometimes caused Windows to crash. The mixer blocks are C++ methods used from an IRIS dynamic linked library (dll). The code for this dll is also found in this project.

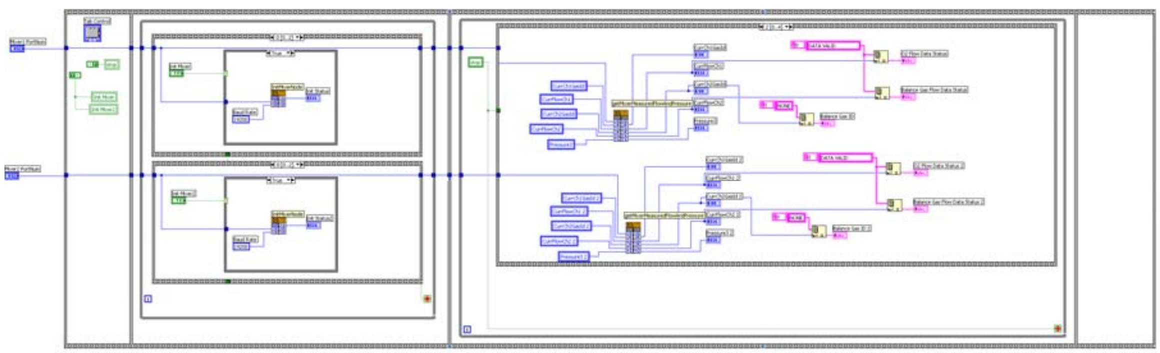


Figure 5: Application Mixer Sequence

Lastly, the user control sequence uses the mixer and I/O data with the VI controls to perform the desired tasks. The application and calibration VI's both contain unique user control sequences. The sequence diagrams are described above, and the user sequence mimics this behavior. The first section is initializing local variables. The second section gets the data from the calibration tables stored from the calibration VI. The rest of the sequence is a loop that can be controlled by the user interface. The loop starts only after the Start/Continue user control switch is turned on. After this, if the Step user control is set, the current loop will turn off Start/Continue and wait for the user to turn this switch on again. Then the loop follows the following sequence:

1) Load the mixer values from the script file.
2) Average the inbound differential measurement (Insp In).
3) Adjust the pressure transducer offset based on an interpolation of the calibration data and set the gain differential resistor setting based on the flow.
4) Average the Gain Differential (Gdiff).
5) Calculate the agent concentration using code nodes
6) write the collected data to file.

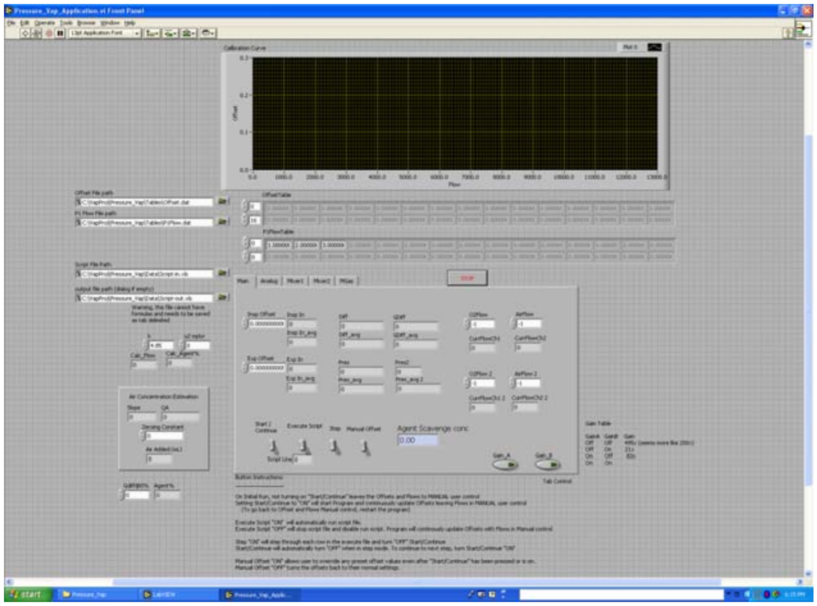


Figure 6: Snapshot of the Application User Control VI

On both the Application and Calibration User Control VI, there are a number of tabs. The Main tab is the one most often used, however the others are available for diagnostic status information and COM port configuration. The graph at the top of both of the VI shows the calibration equation. If the calibration equation has points close to or less than zero, then they will not be correctable. This happens if the instrumentation amplifiers span adjustment is not close enough. To fix this, try a range of flows and compare the Insp and Exp values. These should go up together linearly. If they are not, then use a small flathead screwdriver and adjust the Insp and Exp spans on the VIB board to bring them closer together. The correction algorithm can fix up most of the span and offset errors if the spans are closely aligned. Note, when moving the upstream pressure restrictor from or to wall pressure, this adjustment is required. See the section on “Transducer span behavior upstream of mixer” for more information on this topic. Another important thing to know is the reference voltage offset is adjustable. If the span won’t align, changing the set point in labview can be done, however the higher the value is set, the less range is available on the upper end. Currently the set point is 0.1 V (100 mV) but if this is changed to 0.2 V, then the calibration algorithm can correct up to 200 mV of difference, instead of only 100 mV. This value is set in the first stage of the Application User Control Sequence.

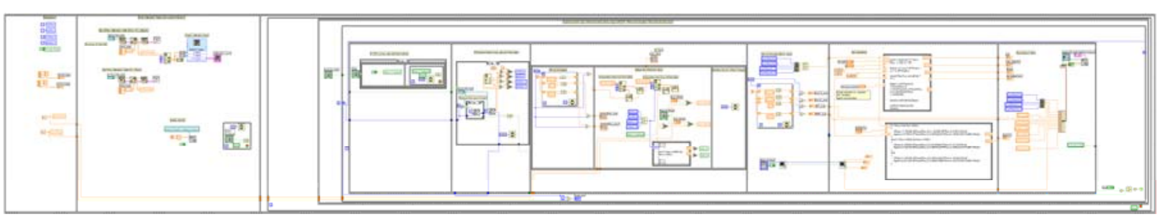


Figure 7: Application User Control Sequence

The calibration user interface loops through a set of flows while tweaking the Instrumentation Amplifier outbound reference voltage (correction factor) to align the inbound and outbound transducer outputs for a constant paired flow. When these two are matched, the common mode noise will be close to zero allowing for high gains between the two for detecting added gas. This is what is referred to as the gain differential (Gdiff).

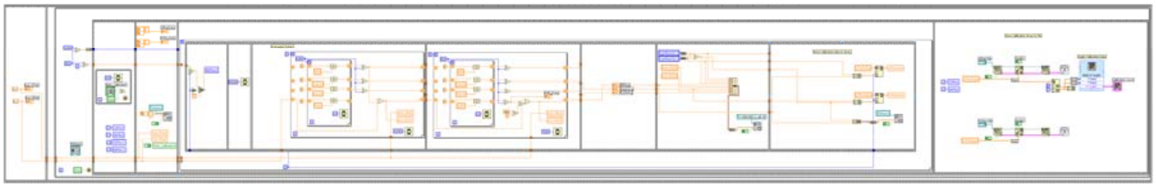


Figure 8: Calibration User Control Sequence

2.1.3 Pressure Transducer Circuit Design

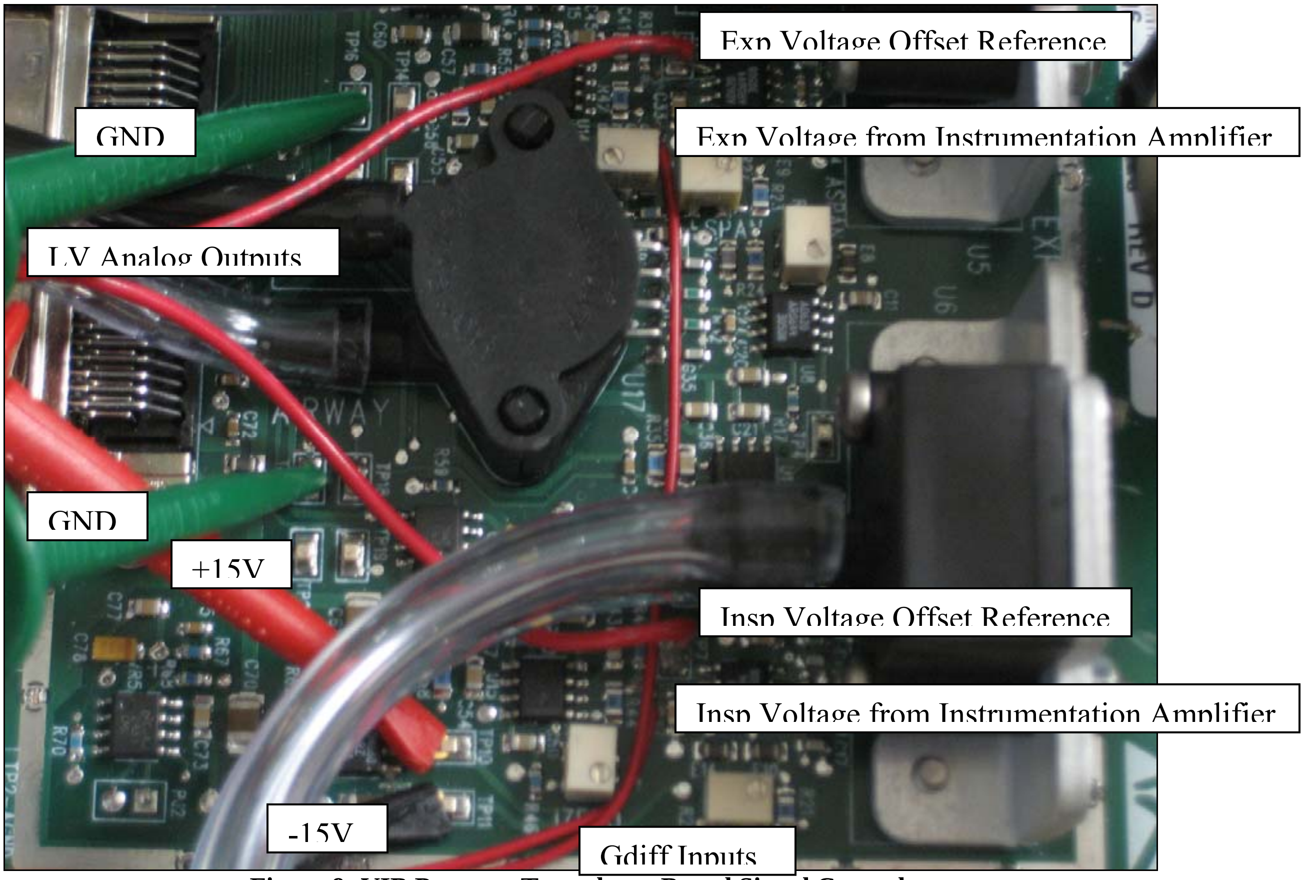


Figure 9: VIB Pressure Transducer Board Signal Controls

In software, VIB Insp refers to the outbound differential measurement, and VIB Exp refers to the inbound differential measurement. Also note to the left of the +15V, -15V test pins, there is a chip. This chip normally generates the –6V that is used on the board; however, this chip cannot handle +15V, therefore the connection between this chip and –15V needed to be broken. The +15V, -15V and Ground signals are coming from the Gain Differential prototyping board. Also note LV stands for LabView.

2.1.4 Gain Differential (Gdiff) Circuit Design

The circuit below is the Gain Differential circuit that takes the Insp Instrumentation Amplifier output and the Exp Instrumentation Amplifier output and amplifies this difference. The digital outputs from labview control which gain resistor is used based on the current gas flow. Lower flow selects the higher gain resistor, medium flow selects a smaller gain resistor, and high flow selects the lowest gain resistor. The analog multiplexor is capable of switching between 8 different inputs, so more resistors could be added. However, three seems to be sufficient.

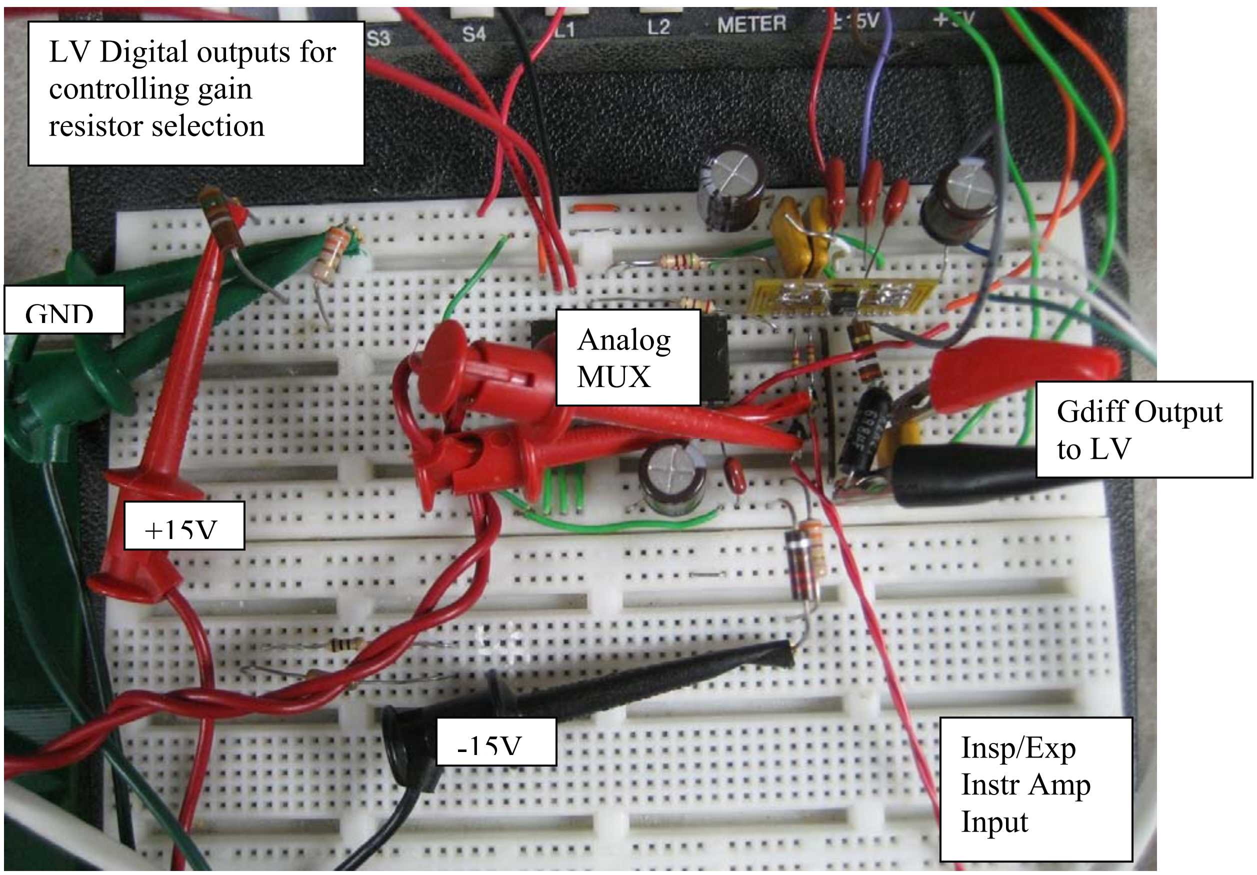


Figure 10: Gain Differential Circuit

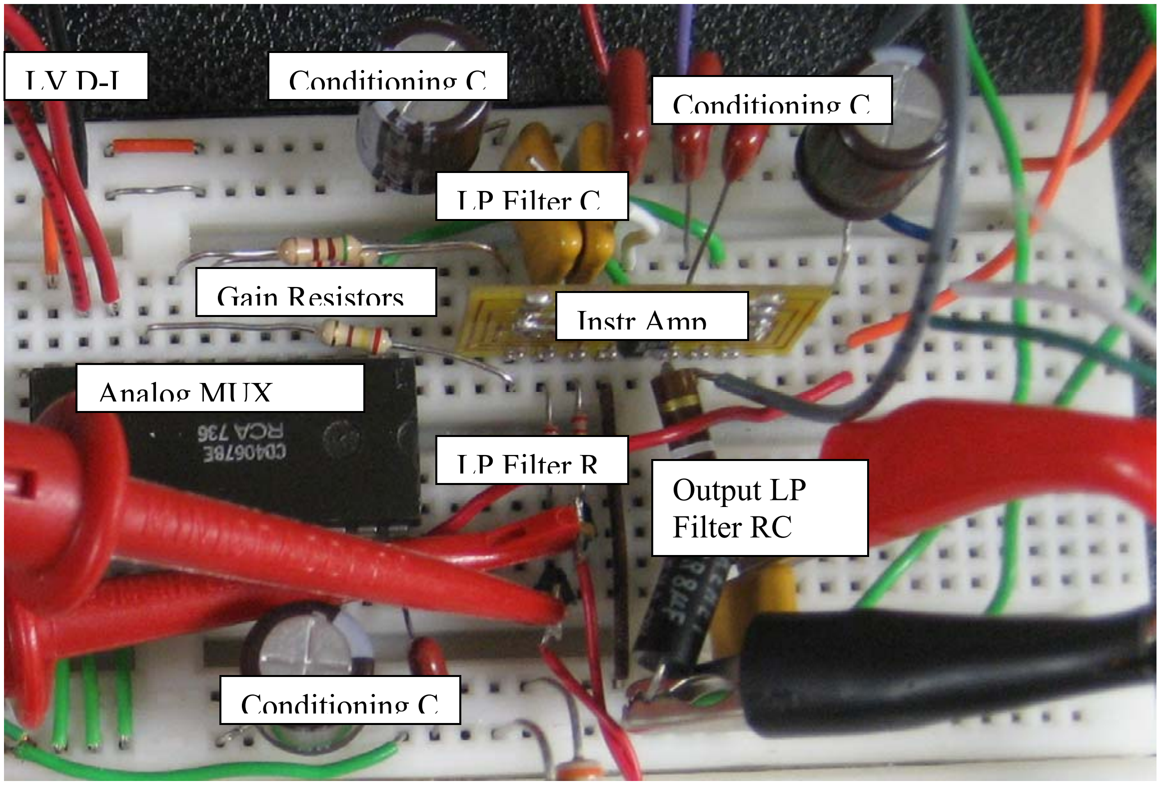


Figure 11: Close up of Gain Differential circuit

Figure 12: Restrictor Assembly attached to Differential Pressure Transducer

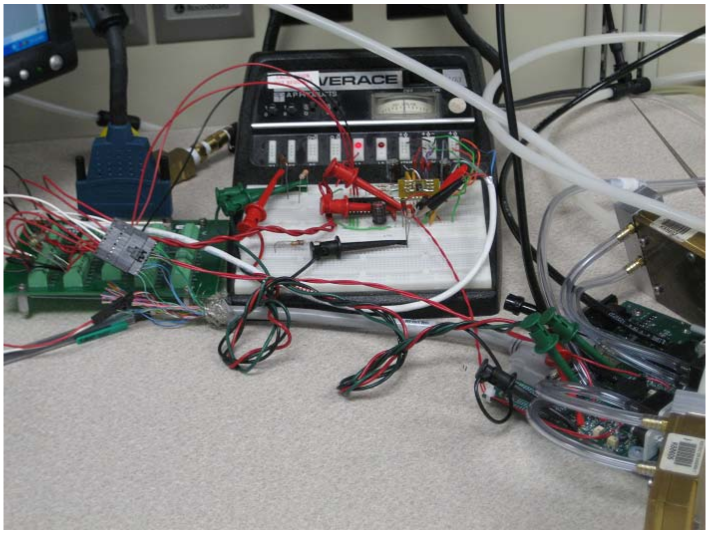


Figure 13: Complete Circuit Setup

2.1.5 Testing Configurations.

Over the course of the project, a number of different configurations were tested to try and find correlation to the behaviors observed. These observations can be found at the end of the report, with descriptions and what was learned.

2.2 Basic Agent Calculation

The agent calculation began with the following equation:

$$\Delta\Delta p = [Q_2(\mu_2 - \mu_1) + Q_A\mu_1]k$$

(<u>Fluid Mechanics, 5th ed.</u> by Frank White)

Q = Volumetric flow rate
μ = Viscocity
$\Delta\Delta p$ = The difference between the pressure drops across the two flow meters ($\Delta p_2 - \Delta p_1$)
k = constant in terms of length of laminar flow meter and inner radius of laminar flow meter

Solving for Q_A comes up with an equation ignoring the effects of temperature and absolute pressure. This formula was used for measurement when adding air or O2 between the pressure restrictors, however with a sump and agent, this equation has not been proven usable. In the case of agent, equations for each specific flow rate are calculated and used on the data through spreadsheet formulas until all the challenges of this setup are completely known. The absolute pressure effect on the transducers seems to have a drastic effect on the agent measurement.

2.3 Tec 7 Vaporizer resistance properties

2.3.1 Vaporizer Data

The mixer delivers a nearly constant flow under all pressure conditions. Therefore, as the vaporizer cassette is opened or closed, the pressure varies as well causing both sides of the inbound differential pressure restrictor to vary.

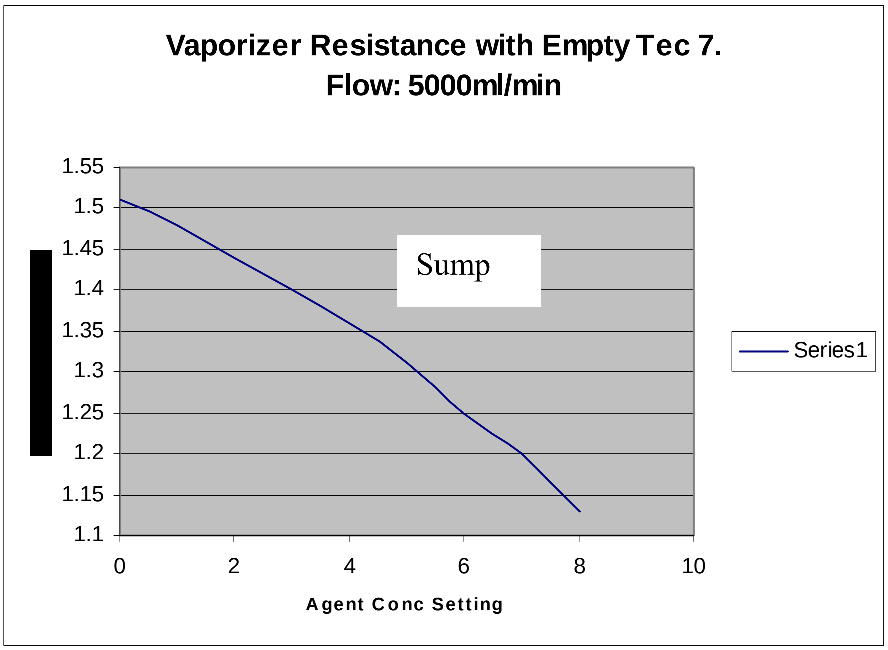


Figure 14: Pressure Differential across vaporizer due to Vaporizer Resistance

2.3.2 Findings

As the Vaporizer closes, the resistance increases causing the pressure on the right side of the restrictor to increase. This increase also causes the Mixer output pressure to rise generating a smaller pressure differential across the restrictor

2.3.3 Method of getting around properties

In order to get around these properties, resistances under all settings of flow diversion need to be constant. The vaporizer adds additional resistance when the flow is fully diverted in this direction, however when a small flow is directed through the vaporizer, the parallel paths create a reduction in the overall resistance. The second option would be to compensate for the absolute pressure change. This could involve additional absolute pressure measurements with correction either in software, hardware, or a mix of both.

2.4 Leak Discovery

When leaks occur while delivering agent, the concentration calculation will typically be negative. The inbound flow restrictor sees more gas than the outbound flow restrictor causing this negative value. This is a clear sign that there is a leak in the system.

It could be possible however that the leak is not detected. Under this condition, the agent would be compensating for the lost gas. This circumstance needs another method of detection. This could be done through the absolute pressure, knowledge of the relative position of the diverter valve, or another means of checking the system behavior. All of these options would require additional data with typical behavior expectations to compare to. For example, if the valve is directing 90% of the flow into the vaporizer, it would not be reasonable for the differential measurement to see an agent concentration of only 1%. The method of detecting reasonable error for warnings or fail conditions will need to be determined during productization, and is disregarded at this time.

2.5 Inbound Transducer Placement

2.5.1 Transducer span behavior downstream of mixer

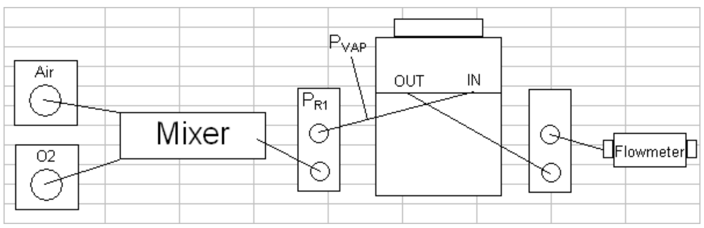


Figure 15: System with differential flow meter downstream mixer

The bypass flow of the vaporizer using the agent setting control on the Tec 7 vaporizer has an increased resistance over the vaporizer resistance. This was designed in this way to help redirect flow into the vaporizer sump. The system however is experiencing absolute pressure effects at the pressure differential measurement directly downstream of the mixer. The mixer automatically compensates for the absolute pressure, however the pressure transducer is susceptible to absolute pressure changes.

Two options are being considered to remove this challenge. Either the vaporizer resistance to flow needs to be reduced, or the transducer downstream of the mixer needs to be less dependent on the absolute pressure shifts.

Moving the inbound restrictor before the mixer would keep one side of the transducer at wall pressure which helps eliminate this behavior. To reduce the vaporizer resistance, a diverter valve would need to be added before the vaporizer. This diverter would pass the flow either through the fully open Tec 7 sump, or a bypass that would route the flow around the vaporizer. This helps reduce the effect on the upstream mixer, however when small proportions of the flow are redirected though the vaporizer, the outbound pressure restriction becomes sensitive to the decreased absolute pressure that is believed to be caused by the parallel resistance paths. An option to decrease this outbound pressure sensitivity could be to drop the pressure transducer restrictor resistance to help minimize this effect.

2.5.2 Transducer span behavior upstream of mixer

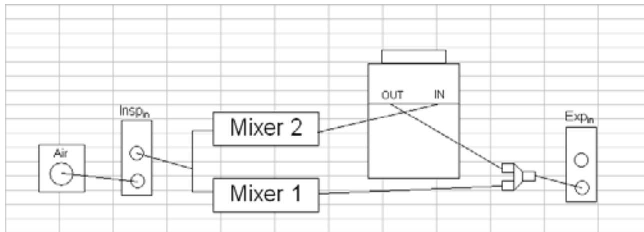


Figure 16: System with differential flow meter upstream of mixer

The new placement of the inbound transducer before the dual mixers caused variations with the inbound transducer span range relative to the outbound span range. This variation will pose design challenges if the wall pressure, or the source of the gas is not constant. The span will in fact change under these conditions making it necessary to adjust the span potentiometer. A regulator could also be used to keep the mixer inbound pressure constant to eliminate this design challenge.

When the inbound transducer was placed after the mixer, the mixer pressure output would vary in order to keep a constant flow. This pressure difference was due to the vaporizer resistance from 0% setting to 5% setting on the isoflurance Tec 6 vaporizer. At 0% setting, all the flow must travel through the bypass restriction, while at full 5%, the flow passes through both the sump and bypass restriction in parallel reducing the overall inbound resistance.

When the inbound transistor was placed before the mixer, the absolute pressure was raised to 15 psi. This change was done for two reasons: to keep one side of the transducer at a constant pressure, and to allow use of two mixers. Two mixers made it possible to set the vaporizer at full open to reduce the resistance drop. This however caused the spans to shift as shown below.

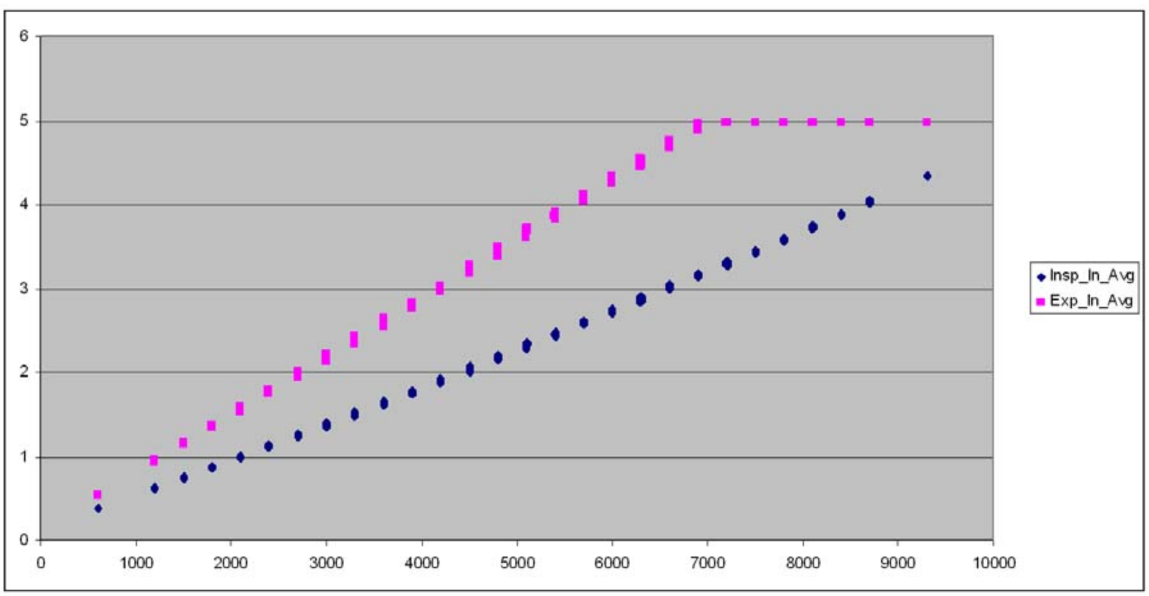


Figure 17: Inbound and Output differential measurement with inbound at wall pressure

Absolute Pressure effect when moving inbound flow restrictor to wall pressure

Vaporizer at 0% flowing wide combination of flows with mixer1 and mixer2 with the total flow plotted on x-axis. The variation of each point is caused either by vaporizer resistance, position sensitivity of the transducer, noise of the circuit, or the flow delivering precision between the mixers. Also note 5V was the maximum circuit output therefore the Exp (outbound) Avg saturated.

This determines that higher absolute pressures at the transducer causes the pressure differential across the orifice to lessen under the same flow.

2.5.3 Inbound Transducer Placement span correction

In order to balance out the Insp(Inbound) and Exp(Outbound) transducers, the span on the circuit board was modified. The span potentiometer on the VIB(Vent interface board) has a 100 Ohm resistor in series with a 100 Ohm potentiometer. To correct for this span offset, the Inbound and Outbound AD620 gains were adjusted in the following way.
AD620 Gain = 49.4 kOhm / Resistor value + 1
Inbound Gain Resistor set to: ~115 Ohms
Outbound Gain Resistor set to: ~184 Ohms

Which results in an Inbound gain from the transducer of 428x and an outbound gain from the transducer of 268x. Below is a circuit schematic of the DCXL10DS transducer with AD620 gain. The label ((2)) on the schematic shows the potentiometer used to make the needed gain adjustments.

2.6 Circuit Design Revision 2

In order to improve the low voltage differential measurement, an additional instrumentation amplifier was added to the design.

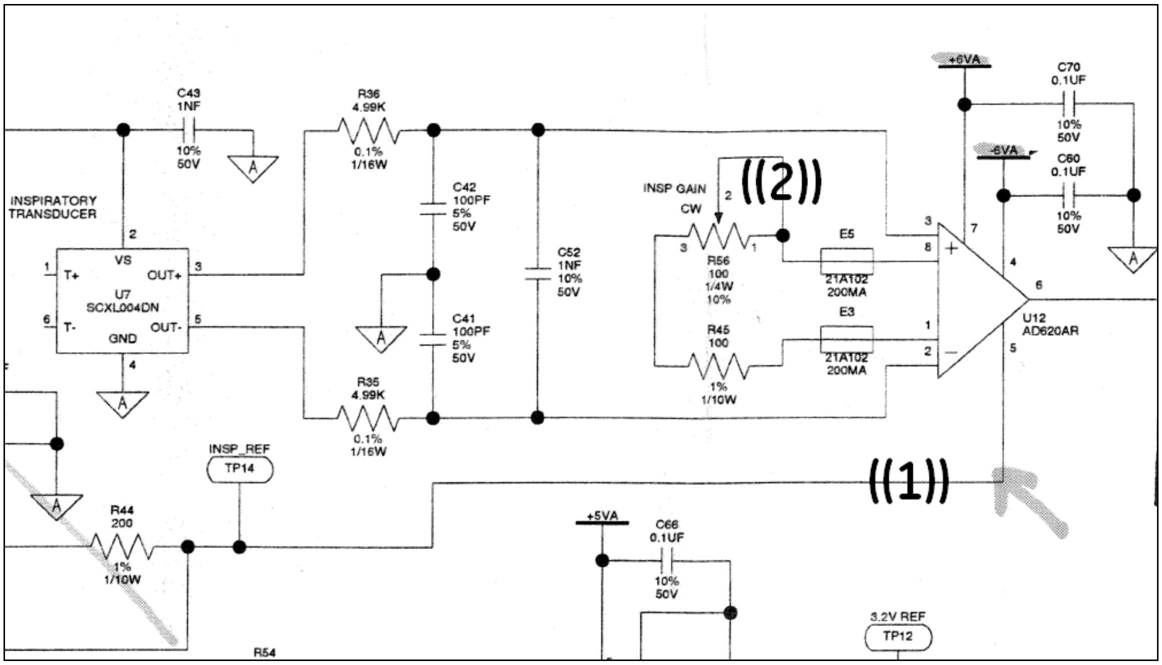


Figure 18: Circuit Design Revision 2

The wire at location ((1)) in the above schematic is voltage signal controlled by a software correction algorithm. This signal corrects the difference between the inbound and outbound tranducer measurements. The voltage signal is controlled from labview through a calibration script that incrementally sets the flows and stores the delta difference between both the inbound transducer and outbound transducer.

((2)) is the span/gain correction.

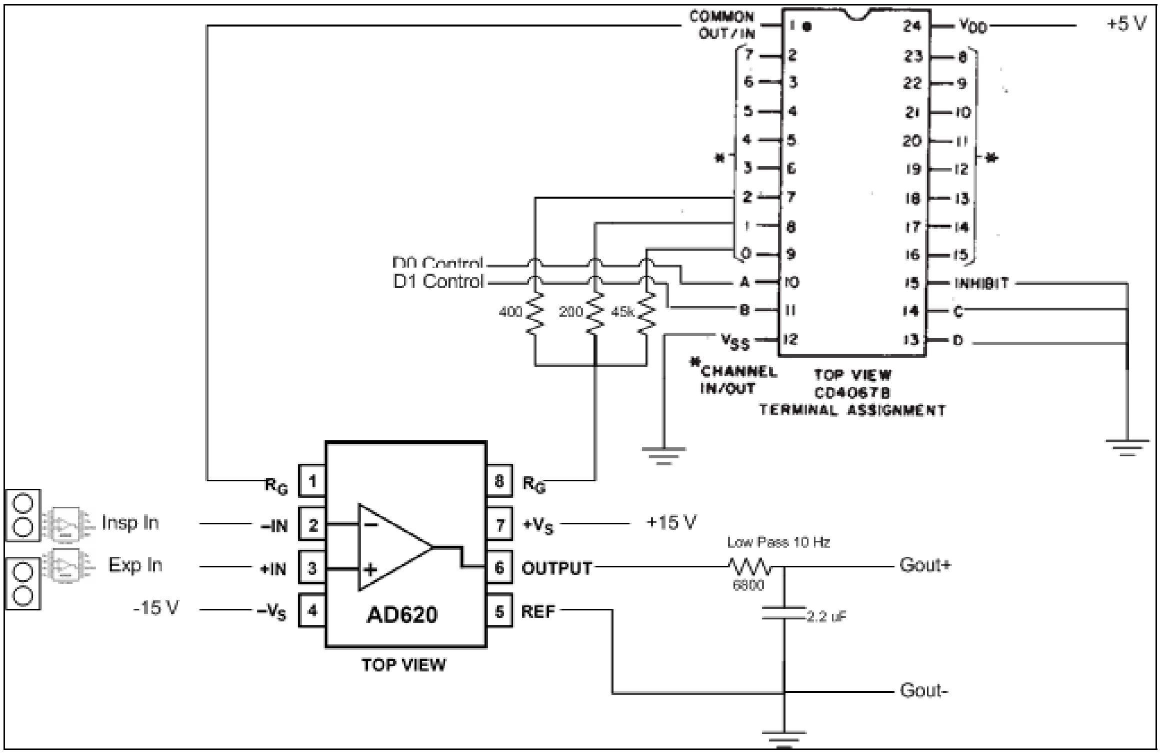


Figure 19: Circuit GDiff (Gain Differential) amplifier

2.7 Low Flow Transducer Characteristics

When low flow is directed through the vaporizer, a strange behavior is always observed. This behavior can be seen in the data below. The behavior seems to happen when small flows are diverted through the vaporizer and also at low flows. It is believed the resistance of the parallel resistance paths, the vaporizer, or the diverter valve causes this characteristic.

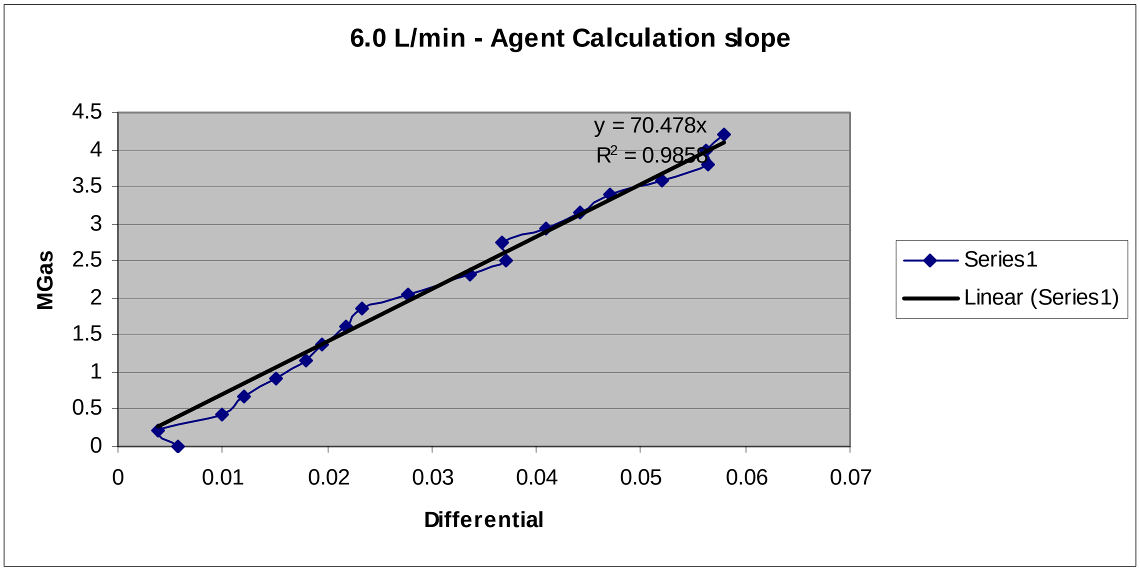


Figure 20: System behavior at 6 L/min

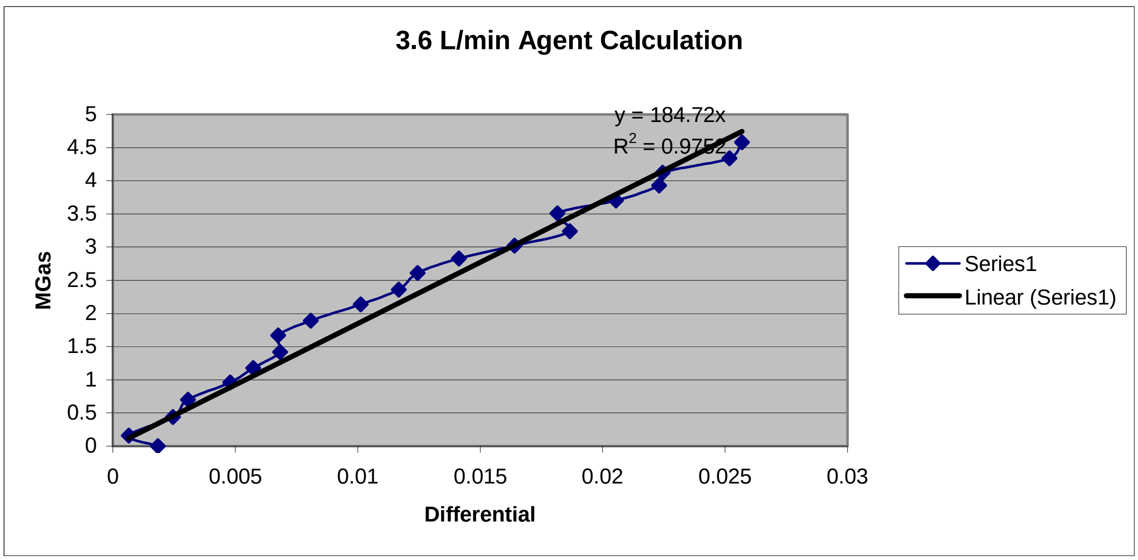


Figure 21: System behavior at 3.6 L/min

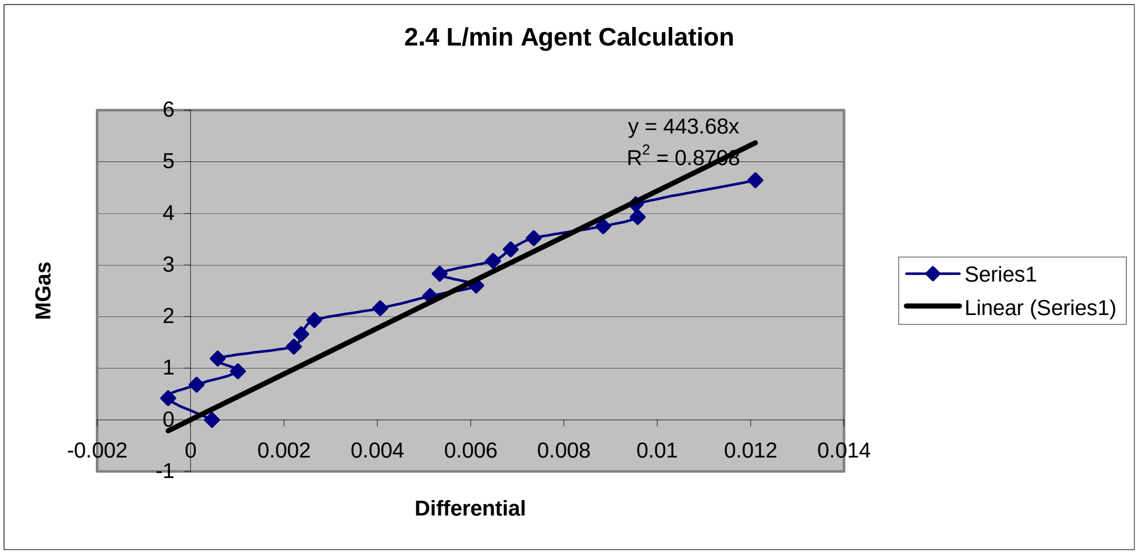


Figure 22: System behavior at 2.4 L/min

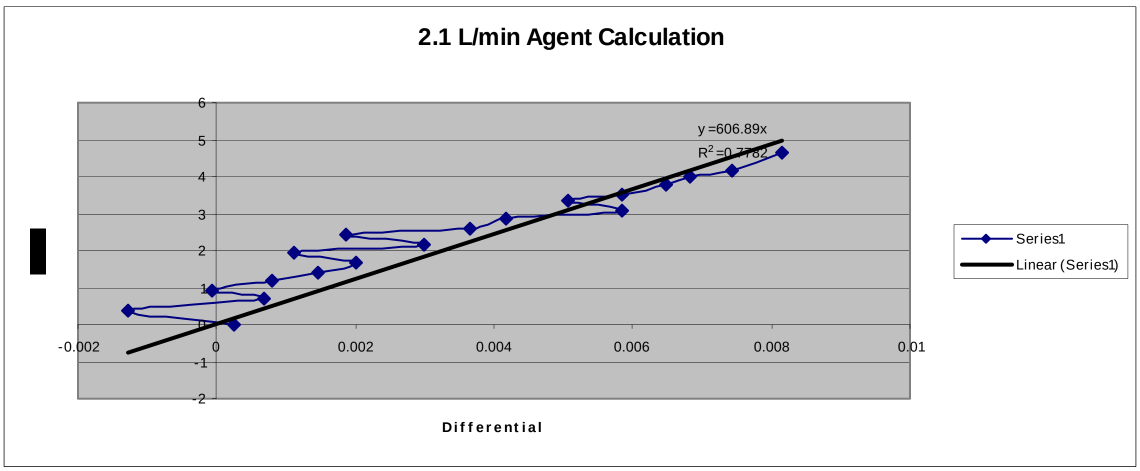


Figure 23: System behavior at 2.1 L/min

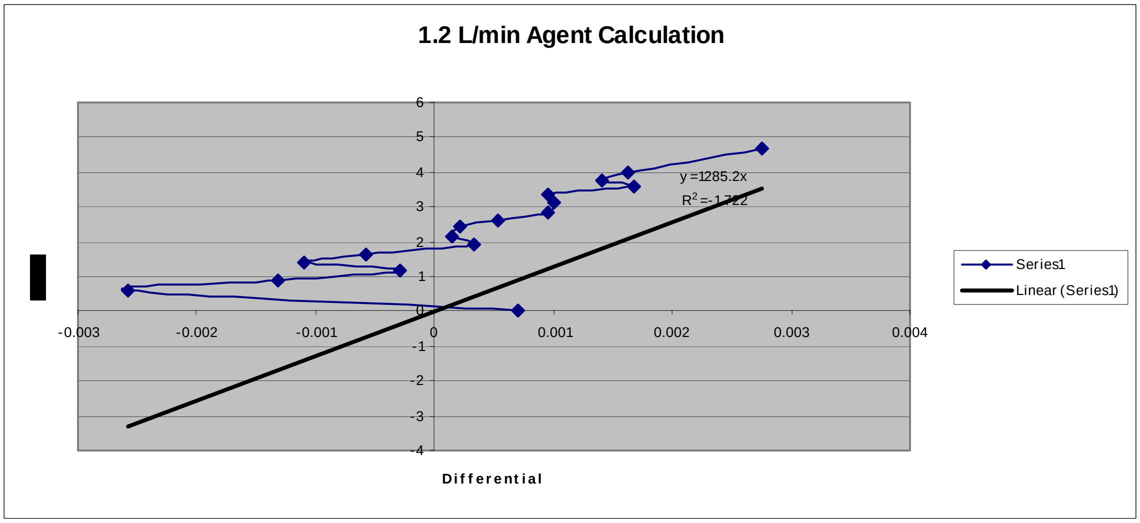


Figure 24: System behavior at 1.2 L/min

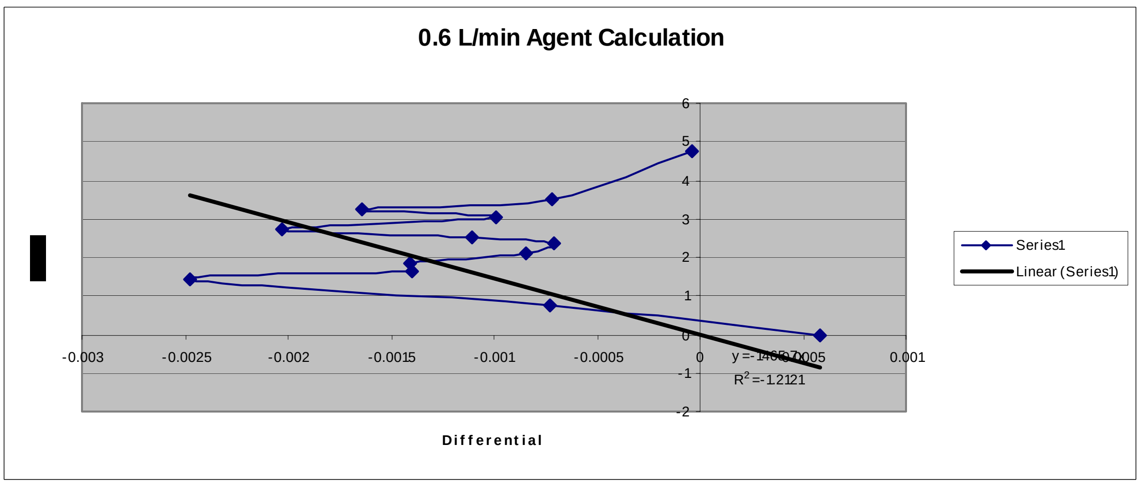


Figure 25: System behavior at 600 mL/min

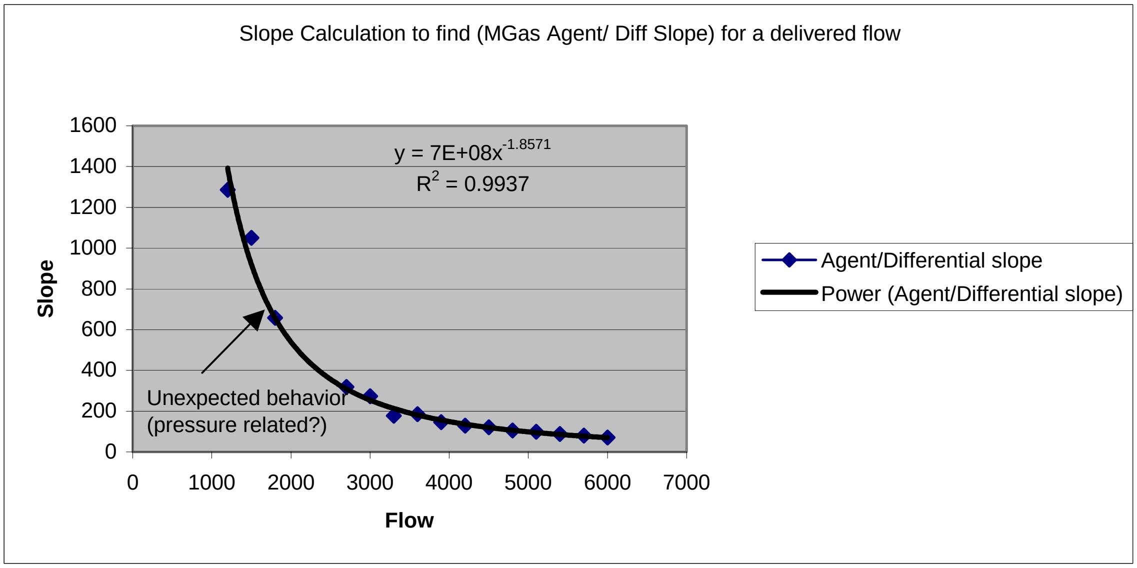


Figure 26: Slope of MGas to Differential to show slope behavior for agent calculation

2.8 Circuit Design Revision 3 (signal conditioning)

To condition the signal from the noise of the circuit, filtering was added. Below is a schematic of the new circuit which cleans up the signals substantially. Also the wires that connect between the VIB, LabView, and Gdiff circuit all became twisted pair. Shielding was also added between the Gdiff circuit and LabView.

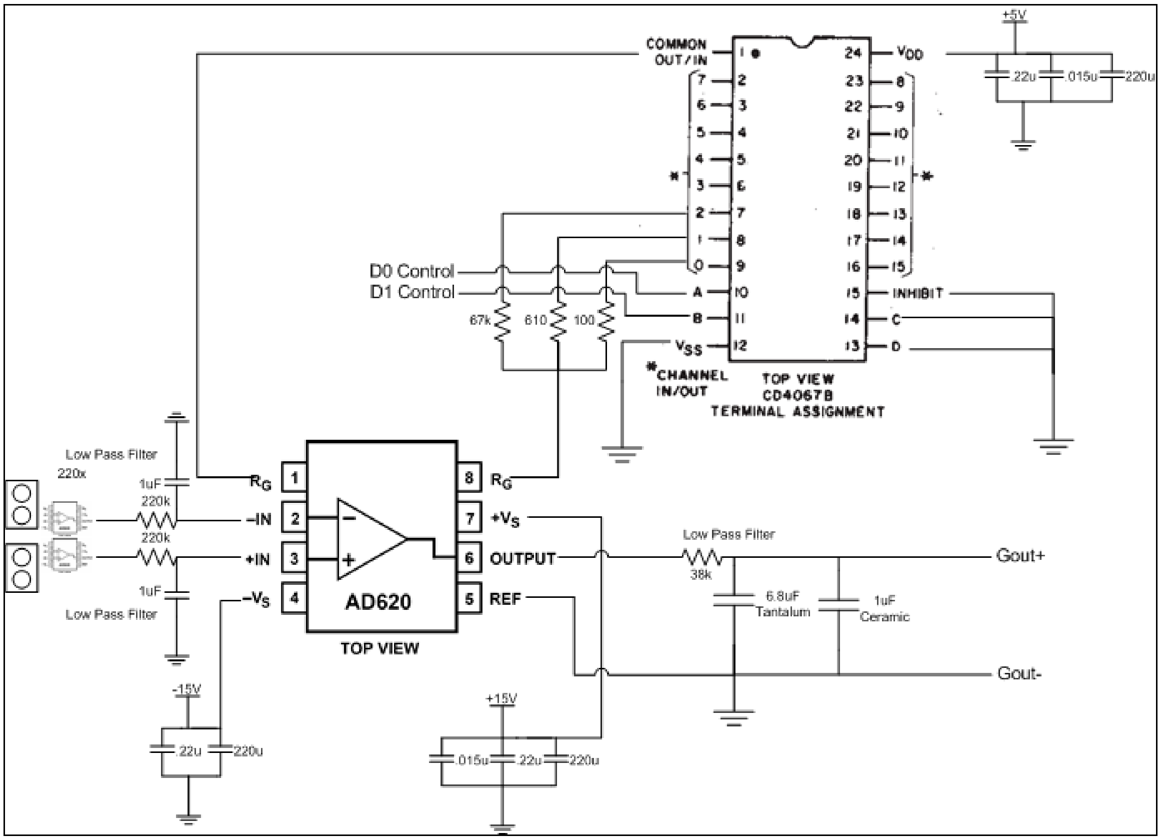


Figure 27: Circuit Schematic Revision 3

2.8.1 Status before signal conditioning

The signal conditioning was not sufficient for low flow measurements. The signal noise was overpowering the actual flow changes with an output peak-to-peak signal drift of around 125 mV.

The drift and noise measurements were done with a Techtronic 2420 oscilloscope. With the probe signal and ground terminals connected, the drift was peak-to-peak 2 mV.

The LabView analog output signal being fed to the instrumentation amplifier reference pin was 174 mV, while the signal drift from the VIB output was 8mV, and the output drift from the final gain differential was 125 mV. An output noise of 125 mV is too substantial to achieve clean agent calculation at low flows.

2.8.2 Power Rail Conditioning

To maintain strong signals across the power rails, conditioning capacitors were added to regulate the voltage rails under current switching conditions. The capacitors used between all the rails were 220 uF electrolytic capacitors. Additionally, 1uF bypass capacitors were added to the integrated circuits to ensure better current switching voltage stability.

2.8.3 Labview Analog Output capacitors

The signals from the Labview analog outputs were excessively noisy with the peak to peak drift being around 174 mV. These signals are fed to the instrumentation amplifier for both of the restrictor instrumentation amplifiers reference inputs for correction before the final gain differential. To reduce this noise, 1.7uF capacitors were connected across the output to ground.

2.8.4 Gain Difference Input Filtering

The signal being passed from both instrumentation amplifiers to the gain differential stage needed noise filtering. The follower circuit was originally doing this filtering, however the drift and noise from this follower circuit was substantial while the voltage limiting aspect was minimizing the usable range. Therefore, passive low pass filters were added to both inputs of the gain differential amplifier. The values for this filter were R=220k and C=1.0uF, creating a 0.72 Hz cut-off frequency.

2.8.5 Gain Difference Output Filtering

In order to maintain a strong signal to labview to reduce noise effects, a single order low pass filter with a low resistance and high capacitance was used. This required larger capacitors to maintain a low cut-off frequency. The resistance was set to 39 kOhm, with a capacitance of 6.8 uF tantalum in parallel with 1.0uF ceramic capacitor. The cut-off frequency of this low pass filter is 0.265 Hz.

2.8.6 Increasing the measurable flow range

To improve the flow range, the VIB board had to be modified. The instrumentation amplifiers are capable of withstanding 15 V sources, however the VIB board only feeds +- 6 V to the instrumentation amplifiers. There is also a buffer stage that follows after the instrumentation amplifier that regulates the output voltage to 4.97 V. This was sufficient for measuring flows up to 6500 mL/min, however in order to achieve the full range goal of 500 mL/min to 15 L/min, this had to be modified. The VIB board has a voltage inverter that can only withstand a maximum source voltage of 7 volts, to this voltage inverter had to be removed and a new inverted voltage used. Since the prototyping board that is being used for the Gdiff amplification stage has a +15 V and –15 V power supply, these voltages would be sufficient for powering the instrumentation amplifiers. The follower circuit also had to be bypassed. Therefore, the output from the instrumentation amplifier was connected directly to the Gdiff amplification stage to get the full output range. In doing this change, the signal noise from GDiff decreased significantly.

The AD620 requires a negative voltage supply. Since this instrumentation amplifier is not rail-to-rail, a negative voltage is required. However, there are other instrumentation amplifiers such as the AD8221 that are designed to be rail-to-rail and can be substituted on the board to eliminate the unnecessary components.

2.9 Transducer pressure effects

2.9.1 Common mode pressure effect

The common mode rejection ratio is ideal with a constant voltage output over the span of pressures from 0 to 50. This test was done by connecting a regulator to both ports of the transducer.

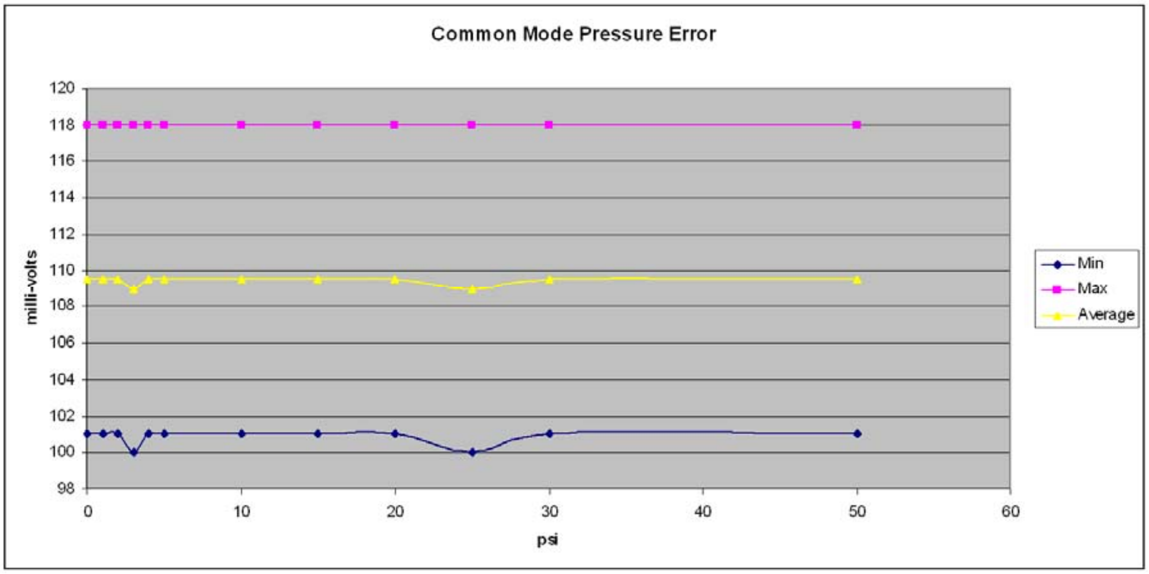


Figure 28: Common mode pressure rejection ratio (Data from 05/15/2008)

As the flow is diverted into the vaporizer, the restriction increase affects the absolute pressure across the inbound restrictor. This absolute pressure increase causes the differential measurement to decrease. Although the agent increases as more flow is diverted to the vaporizer, the inspiratory differential measurement decreases hiding the added agent especially at low flows.

2.9.2 Absolute Pressure variations with constant flows effect

In order to test the absolute pressure effect on the pressure transducers, a constant flow was put through the restrictor, and after the restrictor, a regulator and valve was used to monitor and increase the absolute pressure of the restrictor. The mixer by design drives a constant flow under any absolute output pressure. Below is the data collected from an oscilloscope monitoring the output voltage that enters the gain differential circuit. It can be seen that the absolute pressure effect has great bearing on the voltage output. In fact at low flows (500 mL/min) the output voltage would shift by 7.63 mV per PSI, or 0.108 mV per cmH2O. This voltage deviation is large enough at low flows to cause dips and cause flow calculation errors. This effect will need to be corrected; however this requires an absolute pressure measurement before the outbound flow restriction.

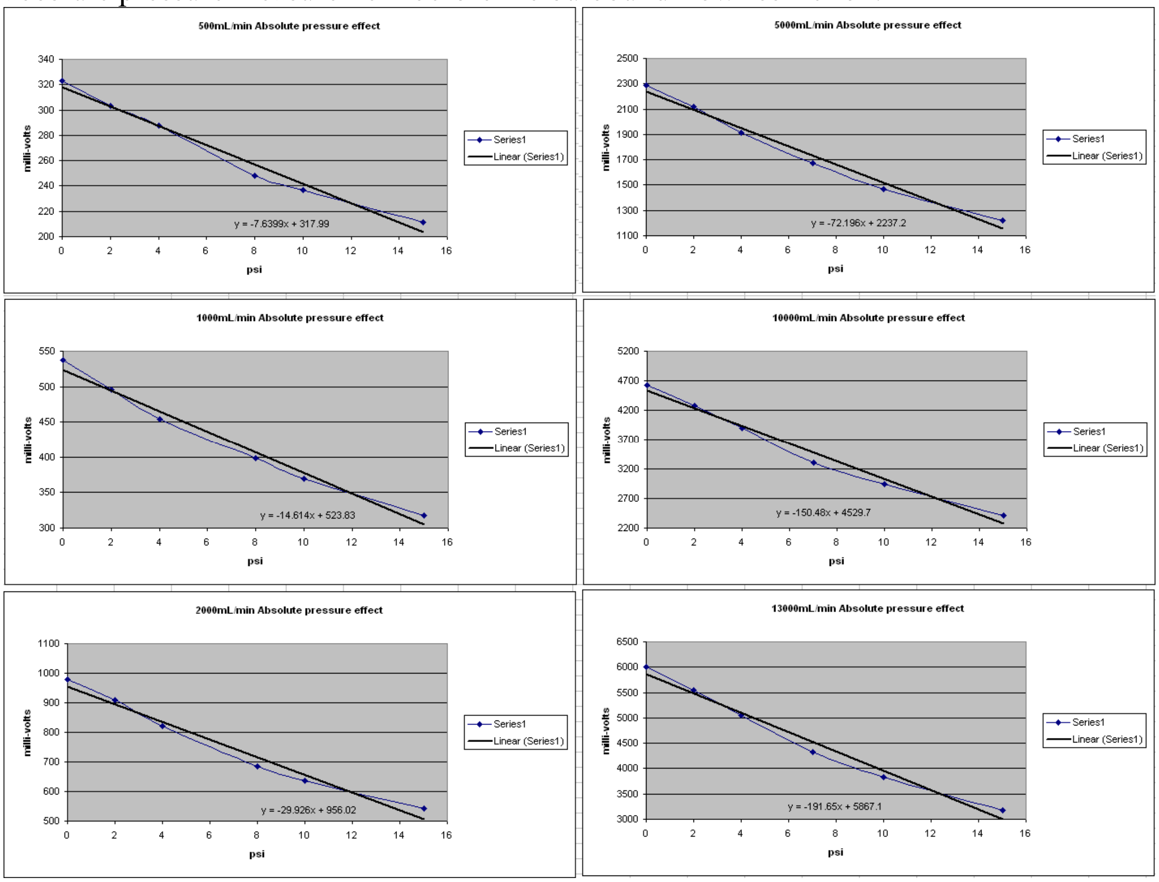


Figure 29: Effect of varying pressure with constant flow

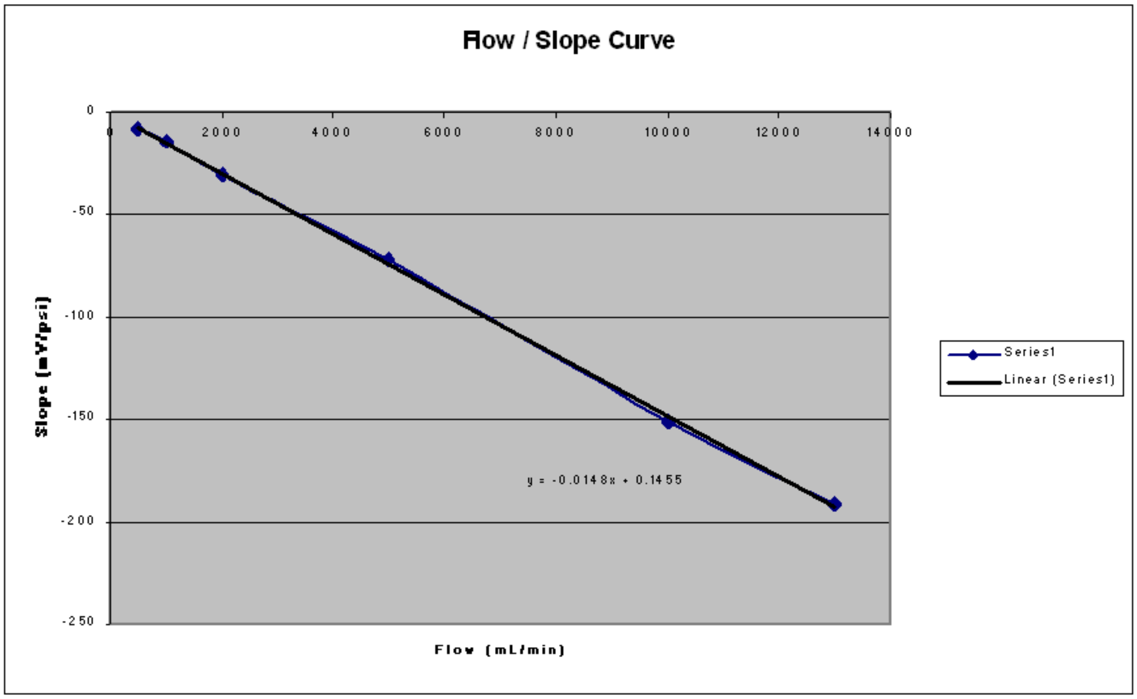


Figure 30: Flow vs slope of pressure effect line.

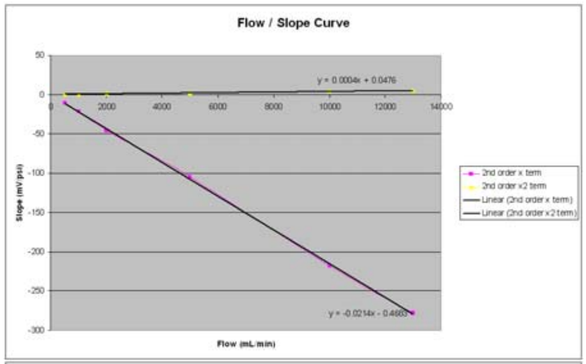
The above figure shows that the flow compared to the slope of mV/psi is linear. This is shows that the relationship is linear and easier to correct for if necessary.

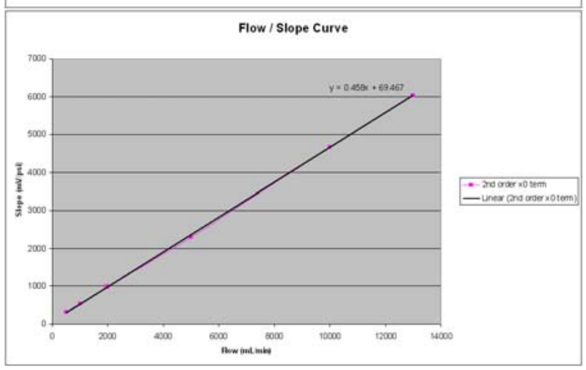
However, since the curves above are not perfectly linear, a second order polynomial was used as well. Below is the graph of the first order flow/slope curve. These curves also show linearity among all three terms, the x^2, x^1, and x^0.

In order to implement this into the Labview VI currently in use, a separate calibration curve will be necessary for the absolute pressure in terms of flow. Then either the software will need to make a dynamic voltage zero reference shift in terms of pressure difference from original calibration, or both a dynamic voltage zero reference shift and dynamic span shift. Both of these solutions will have challenges associated with them. Since it is unknown where on the second order curve the device will start, the first order linear correction will be a good starting point for correcting out a majority of this error. If the second order system is used, the calibration zero will need more complex logic and hardware to determine where the starting point is on the curve through resistance variations.

A device that could be used for dynamic span shifts would be the AD8403. This chip has 4 256 positions over the resistor values of 1k. Using one AD8403 channel per transducer would make each position 3.9 Ohms apart from 0 Ohm to 1 kOhm. However, using two channels per transducer would enable 1.95 Ohm divisions from 0 to 500 Ohms. This would be reasonable for correcting for the absolute pressure span behavior.

The absolute pressure fluctuation could also be corrected by using a system that does not depend on the absolute pressure, or already corrects for the absolute pressure. TSI sensors compensate for both temperature and pressure and other devices may minimize or even eliminate the absolute pressure effects.

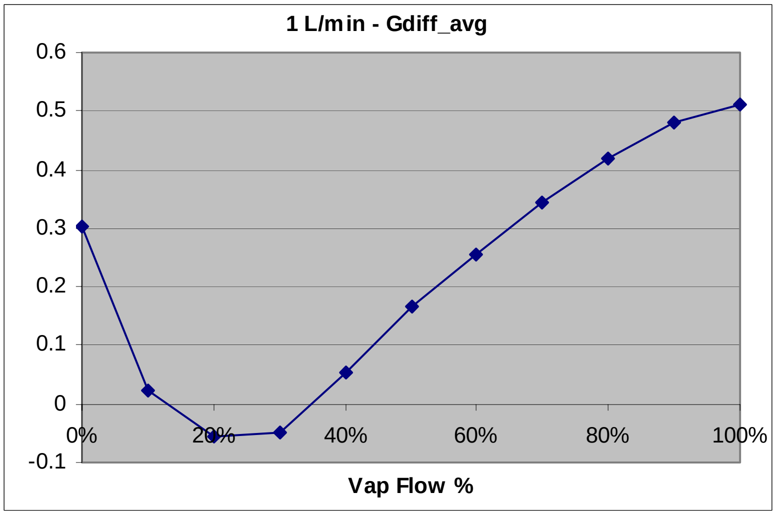


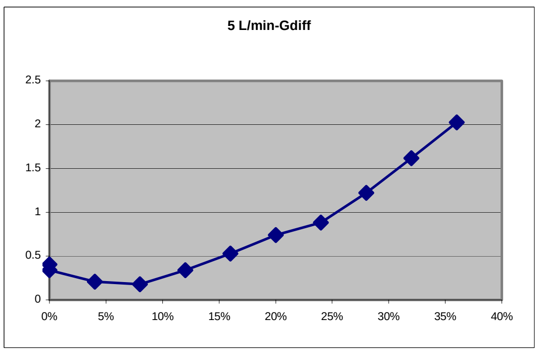


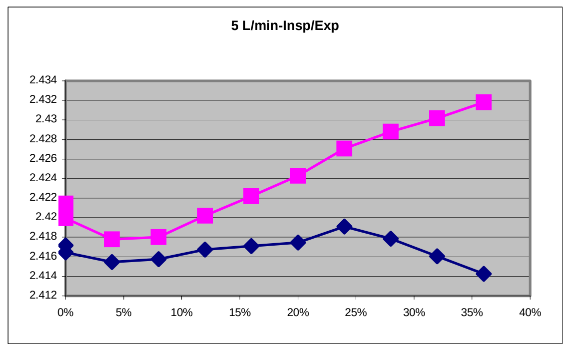
2.10 Future Project Direction

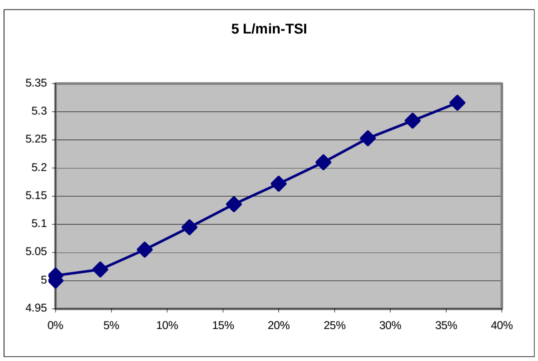
2.10.1 Low flow behavior through vaporizer.

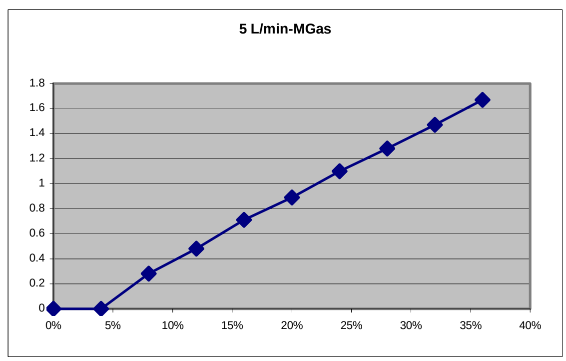
Under low flow conditions through the vaporizer, an uncharacterized phenomenon is occurring. The pressure gradient across the external restriction decreases causing the flow differential to see negative addition. However, this behavior does not occur with the TSI flow sensors. Also the MGas reading at the output shows a more linear curve to agent concentration in the output stream. It is believed that a drop in absolute pressure at the output restriction causes this decreased flow. The problem becomes even more noticeable at lower flows. Below is a snapshot of a test showing this unexplained behavior. The desired behavior would be the 5 L/min-Gdiff graph would mimic the 5 L/min-MGas and TSI curve.



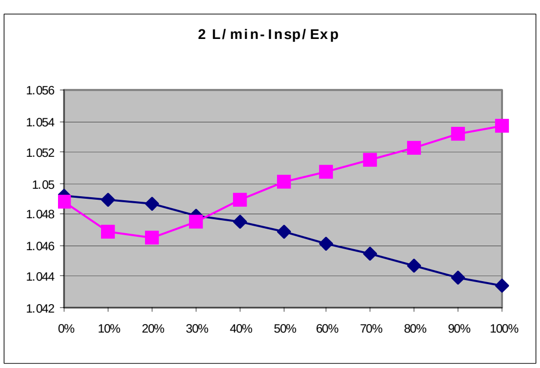


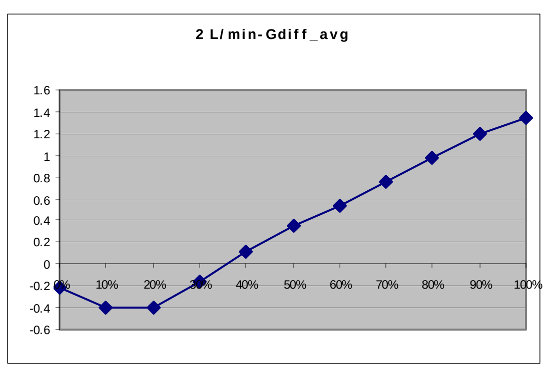






Data collected (2008-05-07 DiverterValve_WithFiltering.xls)





Purple is outbound differential, Blue is inbound differential.
Although the outbound has a dip formation, the Gdiff output is linear and can be used for calculating agent concentrations over 1 percent at 2 L/min.

The cause of this error is due to the absolute pressure dynamically changing. A differential pressure flowmeter is designed to work at a constant pressure, however with the resistance changes, this is affecting this value. Below is the %error calculation that shows the effect of a pressure difference.

$$\% \text{ error } (\varepsilon) = \left(\frac{\sqrt{\text{Specified } \rho}}{\sqrt{\text{Actual } \rho}} - 1 \right) \times 100$$

(http://www.spiraxsarco.com/resources/steam-engineering-tutorials/flowmetering/instrumentation.asp)

2.10.2 Offset shifts

Over time, the starting offset shifts between tests. This implies a need for run-time dynamic calibration of the zero offset. The cause for this is believed to be the pressure sensor. Enhancements continue being added to the labview circuit to improve the correction as well. These changes have included longer delays before averaging, longer averaging times, and using the actual Gdiff for correction along with the small signal difference between the inbound and outbound transducers.

3.0 Conclusion

The project work as tested many system configurations to try and find the causes or find solutions to the pressure behaviors that have been observed. In addition to these different system configurations, circuit and software changes have continued enhancing this research project. It is now possible to calculate the agent concentration under a controlled range of flows with some degree of accuracy.

The pressure sensitivity of the system has been the most challenging aspect to understanding the behavior of the system. It is clear how sensitive the system is when lightly blowing towards one open end of the transducer 10 feet away and seeing the differential gain react by 20-40 mV. The final challenge to hurdle at low flows is the absolute pressure compensation at the outbound pressure transducer restrictor. Either the absolute pressure will need to be compensated by correction, or through changes in the system configuration to get the resistance constant across all flow diversions.