

VOLUMETRIC AND MASS FLOW CONTROL OF FLUIDS UTILIZING A VARIABLE PRESSURE RESTRICTION WITH A MECHANICAL DIFFERENTIAL PRESSURE BALANCING LOOP

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ABSTRACT

Traditional pressure based mass and volumetric flow meters/controllers calculate a flow rate by measuring the upstream pressure, pressure differential, and fluid temperature across some type of flow restriction. A different concept of pressure based mass flow measurement and control, introduced in this paper, can employ single absolute pressure and temperature measurement to control liquids and gases with constant outlet process pressure. An intrinsically safe, all mechanical volumetric flow producer maintains the fluid control while sensors in the device acquire temperature, absolute, and differential pressure for mass flow calculation. The device maintains less than 0.5% stability for output and repeatability, 100 msec time responses, and less than 0.004% change in flow per 1-psi change in inlet pressure.

INTRODUCTION

Flow controllers are used in almost all industries that require the accurate delivery of fluids, either gaseous or liquid, to a chemical or mass transport process. These controllers will control the rate of mass or volumetric flow into a process by utilizing a flow meter coupled with some sort of proportional control valve. The differences in the different type of controllers are mainly differentiated by their respective flow metering technologies. Flow meter technologies can be categorized into several

different technologies: variable-area, thermal mass, Coriolis, differential-pressure, turbine, and oval-gear (1). In all cases, regardless of metering technology, the flow controller is a classic servo-control loop with the flow meter providing the respective feedback signal. The servo-loop is the control of a single control element (i.e. proportional valve) by means of the deviation in value of input (provided by the flow meter and scaling circuitry) (2). See appendix A for graphical representations of the feedback loop(s) in a typical flow controller and that of the controller in this analysis.

The basic flow controller must perform the following basic functions for the device to properly control the amount of mass or volume. These basic functions are:

- 1) The flow sensor must provide an electrical signal to conditioning circuitry that provides linearization and amplification to the output signal.
- 2) The amplified and conditioned sensor output is scaled according to different parameters such as zero offset, maximum scale, and fluid specific calibration multipliers to obtain a calibrated $y=mx+b$ relationship.
- 3) The scaled and calibrated flow sensor output is compared to the user's desired set point or output. If the sensor output differs from the set point, the control circuitry will send an electrical signal to a *prime mover* (i.e. valve) that opens or closes proportionally according to a pre-determined transfer function.

A novel fluid control technology is introduced in this paper, where the controller does not fit the scheme of a classic flow control servo-loop. The flow sensor in this device is used only to set the position of the prime mover. Once set, the controller does not need to constantly slew through the entire servo loop to maintain a constant volumetric flow output. For mass flow, the sensor will be used to move the prime mover in case of a deviation in gas density from that of the initial calibration conditions. In essence, once set at the desired flow, the device will maintain flow through purely intrinsic or mechanical means, without the need for additional pressure conditioning devices. The salient concepts of the flow sensing and controlling technology of this device will be described along with its response to differing inlet and outlet pressures and transients, different fluid or gas types, and gas temperature changes. In addition, the advantages and limitations of this technology will be briefly compared to other fluid controller technologies.

CONTROLLER PRINCIPLES

The fluid control device in this study (FMC series, FlowMatrix Inc.) is essentially an all-mechanical volumetric flow-producing device. An overall schematic of the device layout can be seen in Figure 1 below. The volumetric flow is held constant by maintaining a constant differential pressure across an adjustable flow restriction. The adjustable portion of the restriction assembly allows the device to be fine tuned for a specific value; whereas the majority of the pressure restriction is created by a laminar flow element. The laminar flow element (LFE) reduces any turbulent or transitional flow (Reynolds number = $N_{Re} > 2300$) to a smaller velocity (i.e. $N_{Re} < 2300$), which creates a linear relationship between differential pressure and flow rate.

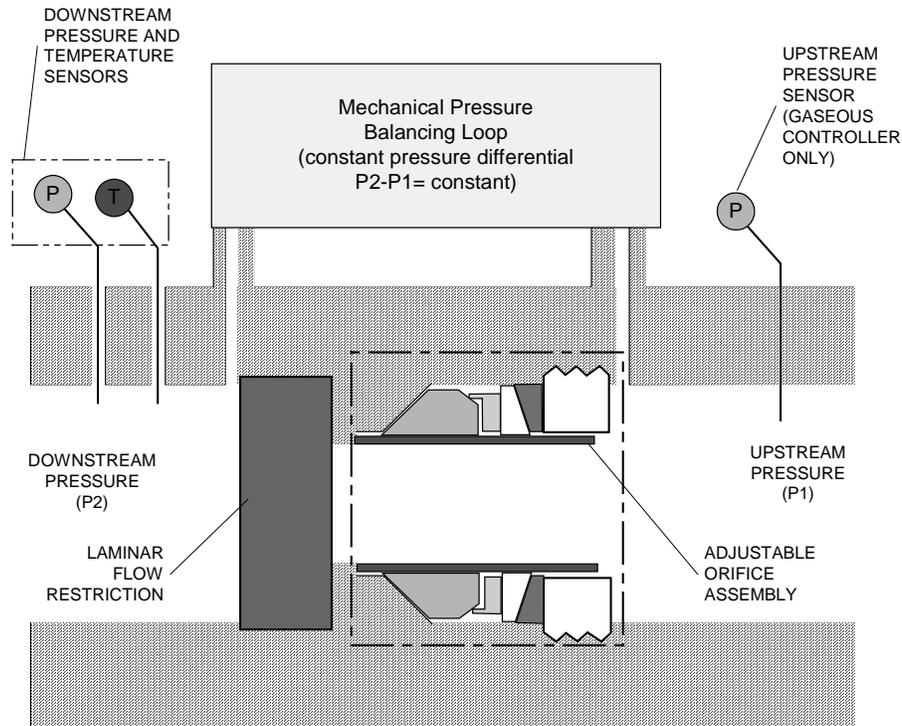


FIG. 1 -BASIC SCHEMATIC OF THE SENSOR/CONTROLLER ASSEMBLY

The following relationship describes the basic volumetric and mass flow across a laminar flow or porous restriction (the standard Darcy Equation) (3,4).

$$\dot{Q} = \frac{dV}{dt} = -\kappa \frac{\pi d^2 \Delta P}{4\eta L} \quad \text{(Volumetric Flow)} \quad \text{(Equation 1)}$$

$$\dot{m} = \frac{dm}{dt} = -\kappa \frac{\pi d^2 M_w \Delta P P_i}{4\eta L R T Z(P, T)} \quad \text{(Mass flow for Gas)} \quad \text{(Equation 2)}$$

Where:

- d = Hydraulic diameter or flow passage diameter
- P_i = Pressure upstream of restriction
- P_o = Pressure downstream of restriction
- ΔP = Pressure differential across restriction
- R = Universal Gas Constant
- T = Gas Temperature
- M_w = Molecular weight of the gas
- L = Length over which the pressure drop occurs
- η = Fluid absolute viscosity
- κ = Material permeability (for porous media)
- $Z(P, T)$ = Non-ideal gas compressibility (function of pressure and temp.)

Due to small inconsistencies in geometry or LFE permeability, it is very difficult to manufacture LFE's or porous restrictions with a precise pressure drop vs. flow characteristic; therefore, the adjustable secondary restriction upstream of the primary restriction allows for custom tailored pressure drops with given flow rates in a manufacturing environment.

The pressure sensors used in the metering system shown in figure 2 are both thin film piezo-restrictive strain gauges. They have a typical linear accuracy/hysteresis of $\pm 0.1\%$ full-scale (F.S.) and a temperature coefficient of less than $\pm 0.02\%/^{\circ}\text{C}$. The temperature measurement device used is an integrated circuit temperature transducer with a temperature coefficient of $1\mu\text{A}/\text{K}$ and an accuracy of $2.5\pm 0.8\text{ K}$. The total measurement uncertainty for the meter will be directly dependent on the accuracy of the pressure and temperature transducers as well as the accuracy of the flow standard used to ascertain the flow controller's calibration constant.

EXPERIMENTAL PROCEDURE AND SETUP

Appendix B outlines the overall schematic and specifications of the test apparatus and equipment used in this analysis. The controller in this study is referenced against two different flow meter standards: a characterized thermal mass flow meter and a primary volumetric piston prover that is compensated for pressure and temperature. The thermal flow meter is used for high time resolution data and the piston prover is used for high accuracy data. The thermal flow standard is pre-characterized by a high-accuracy, pressure based secondary standard prior to the analysis to ensure the highest accuracy measurements possible.

To limit the scope of this study, only gaseous flows are analyzed to simulate the worst-case conditions of variable fluid density or compressibility (i.e. pressure, volume, and temperature interdependence). In addition, only a maximum flow range of $250\text{ cm}^3/\text{min}$ is analyzed. For this analysis, the raw sensor values and their respective correlation to equations 1 and 2 are compared directly to the measured flow standard outputs in order to test the DUT's flow measurement validity. The different prime mover mechanisms (stepper motors, solenoid valves, pneumatic & piezoelectric actuators) were not analyzed in this study and will be mentioned later in the discussion.

The following tests were performed to simulate various real world process conditions (In all cases, the flow output signal of the DUT is compared to the flow standard output). The gas used throughout this analysis was clean dry air (with the exception of Test #5).

- 1) Flow Output vs. Set Point and Temperature: The flow output is measured with different set points and temperatures to validate controllers adherence to the laminar flow relationship in equations 1 & 2.
- 2) Varying and Transient Input Pressure: The inlet pressure is stepped up and down in random increments while measuring the flow output. In addition, fast and severe pressure transients are introduced upstream while measuring the flow output.
- 3) Increasing Backpressure: The backpressure or outlet pressure is varied while measuring the flow output.
- 4) Set Point Stability, Repeatability, and Time Constant: The controller is given a set point and its output is measured over time utilizing a reference flow standard. For repeatability, the gas

input to the controller is shut off and all of the pressure in the test system is allowed to vent to atmospheric pressure. The gas supply valve is then opened and the output is measured. During this test, the time to attain a stable set point is measured.

- 5) Multiple Gas Data: The mass flow output vs. backpressure for different gases were analyzed to measure the mass output characteristics of the controller with various gas properties (molecular weight and viscosity).

TEST RESULTS

Flow Output vs. Set Point and Temperature

Figures 2 and 3 show the correlation between mass flow output, pressure differential, and temperature for the control apparatus. When compared to the relationships shown in equations 1 and 2, the controller shows an increasing linear flow output (both mass and volumetric) with increasing pressure differential.

Figure 3 shows the proportionality between mass flow and temperature. The figure also shows that the pressure differential stays constant with temperature, which indicates a constant volumetric flow regardless of temperature. This correlates to equation #1.

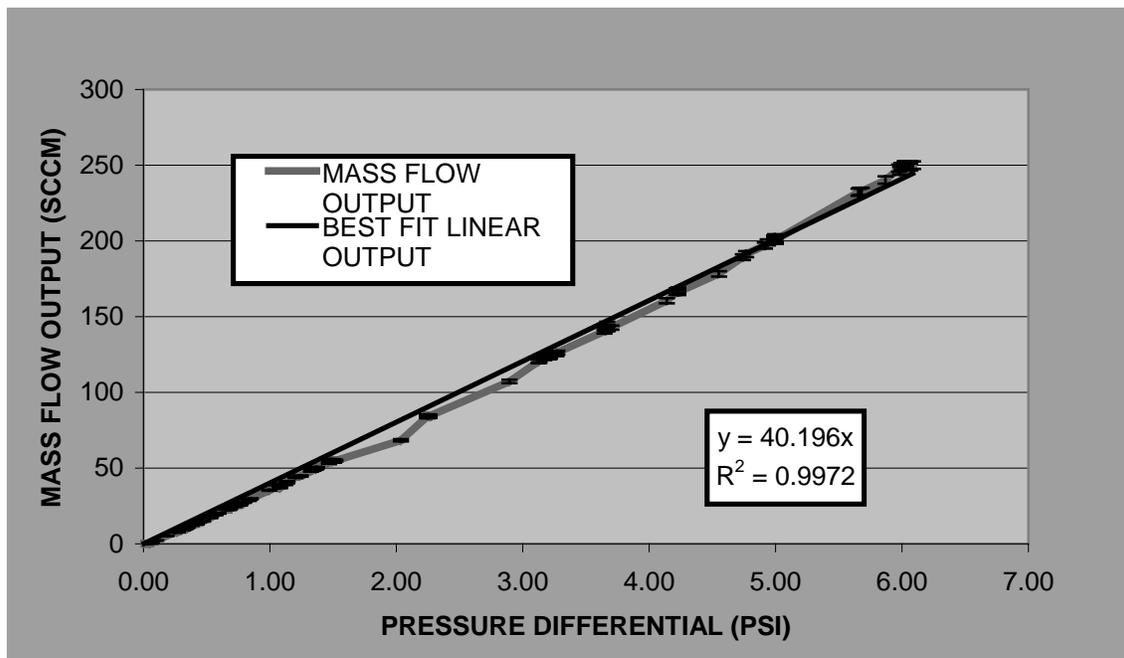


FIG. 2 -MASS FLOW OUTPUT VS. PRESSURE DIFFERENTIAL ACROSS LFE

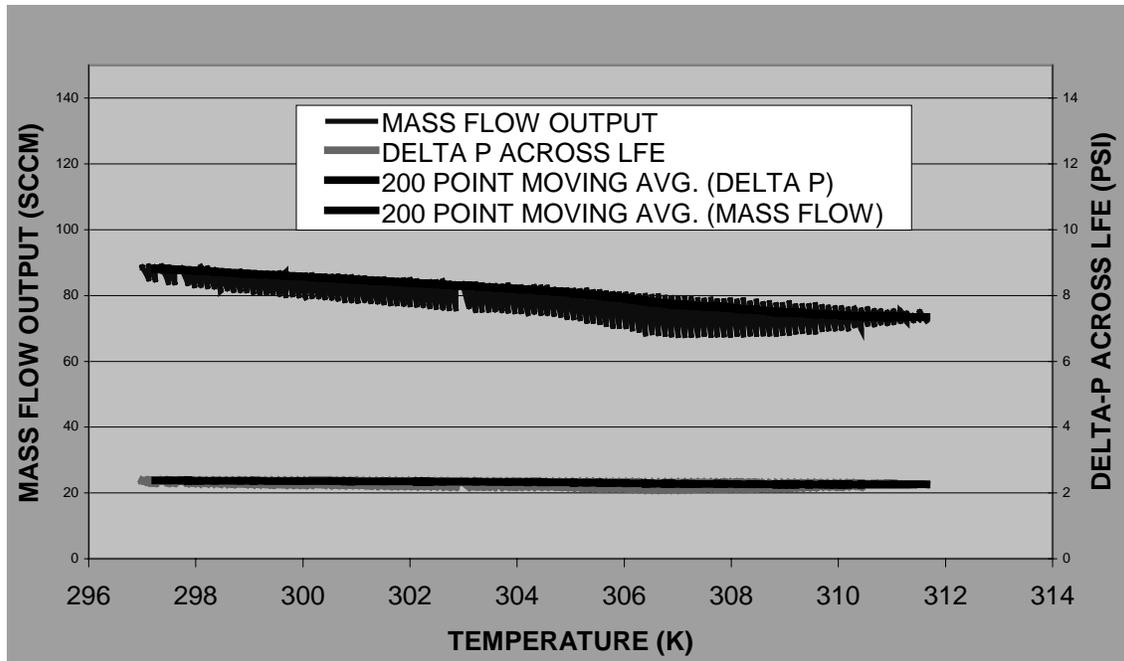


FIG. 3 -MASS FLOW OUTPUT AND PRESSURE DIFFERENTIAL ACROSS LFE WITH INCREASING TEMPERATURE

Varying and Transient Input Pressures

Figure 4 shows a plot of the flow output of the controller measured with the thermal mass flow standard with inlet pressure step functions as well as very fast random, upstream pressure transients. Further analysis of this data shows an average deviation from set point of $0.31 \pm 0.013\%$ with a 99.7% confidence over an overall pressure deviation of 87.1 psig. This results in an inlet pressure coefficient of 0.004% of set point flow output change per 1-psi change in inlet pressure.

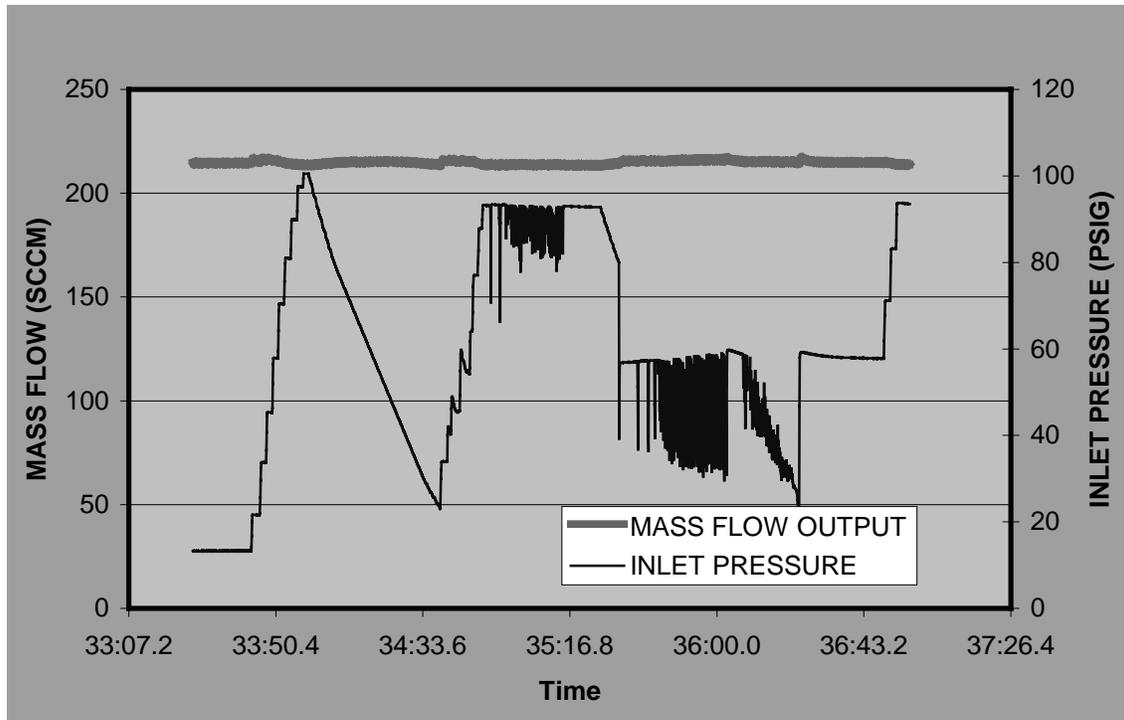


FIG. 4 -FLOW OUTPUT WITH INLET PRESSURE STEP INCREASES AND FAST PRESSURE TRANSIENTS

Increasing Backpressure

Figure 6 shows the controllers intrinsic ability to compensate for an increase in absolute backpressure. The pressure differential across the LFE remains constant, hence a constant volumetric flow, and the mass flow increases in direct proportion to absolute pressure as predicted in equation #2.

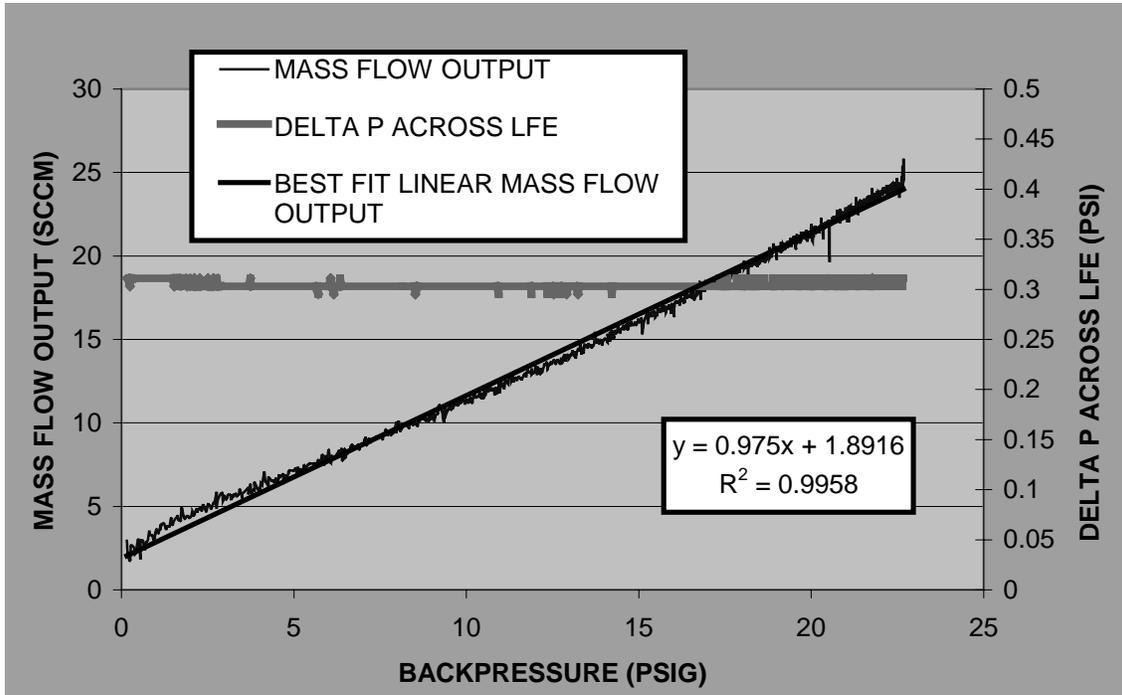


FIG. 5 -MASS FLOW AND PRESSURE DIFFERENTIAL ACROSS LFE WITH INCREASING BACKPRESSURE

Set Point Stability, Repeatability, and Time Constant

Table 1 summarized the data from the stability, repeatability, and time constant tests (time constant is defined as the time to achieve set point from zero flow condition). Their respective data plots are shown in Appendix C for further reference.

TABLE 1 –RESPECTIVE VALUES FOR FLOW OUTPUT STABILITY, REPEATABILITY, AND TIME CONSTANT

TEST	RESULT	UNCERTAINTY	TEST DURATION
STABILITY	± 0.025% /HOUR	± 0.003%	12 HOURS
REPEATABILITY	±0.33%	±0.063%	7 COMPLETE ON/OFF CYCLES
TIME CONSTANT	<100 msec	±1 msec	N/A

Multiple Gas Data

Figure 7 shows the mass flow output vs. backpressure for the different gas types. At approximately 42 psia of backpressure, the total pressure drop from the inlet of the controller to the outlet becomes too small for the controller to operate efficiently. At this point, the controller fails to maintain a constant flow output. This data will be commented on in further detail later in the discussion.

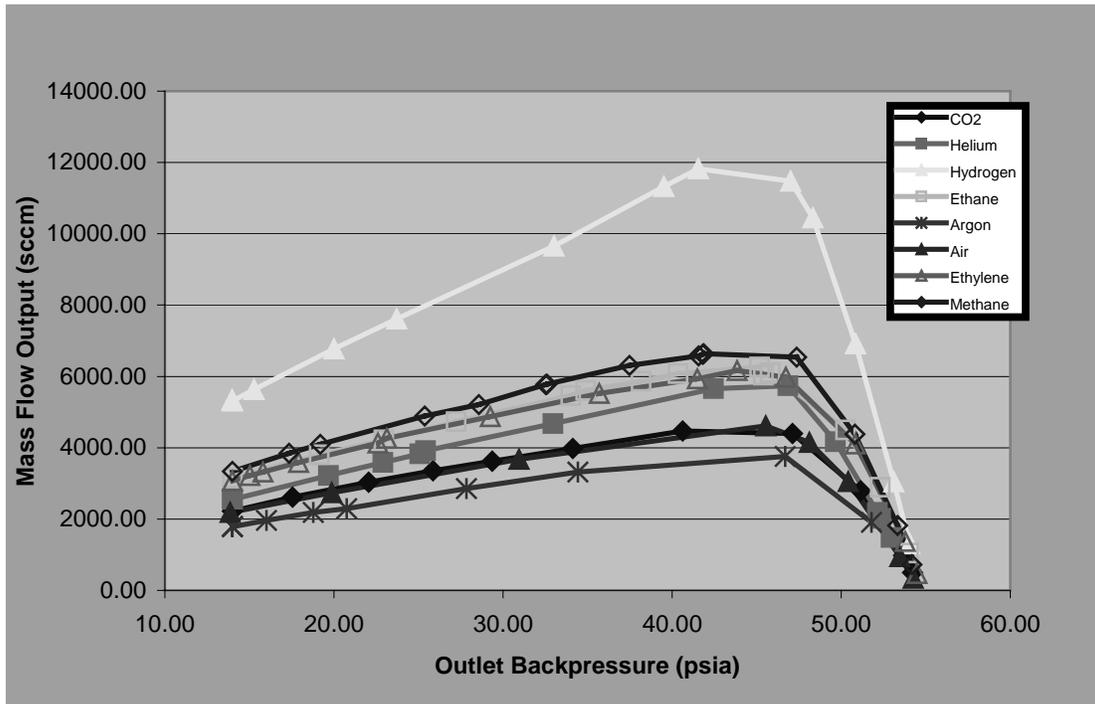


FIG. 6 -MASS FLOW VS. BACKPRESSURE FOR MULTIPLE GAS TYPES (2 LITER/MIN CONTROLLER USING PISTON PRIMARY MEASUREMENT STANDARD)

DISCUSSION OF RESULTS

Overall the results show a very good correlation to the parameters outlined in the standard Darcy Equation. The controller exhibits a linear relationship with pressure drop across the LFE, temperature changes, and changes in gas type, which allows a user to calibrate the controller with high precision. In addition, the linear slope of the mass flow curves shown in figure 6 allows one to generate a mathematical relationship that will be very similar to the standard Darcy Equation. Once corroborated with experimental data, the controller can be calibrated for any hazardous gas use with a reasonable accuracy using only inert gases in production. In addition, since the pressure differential across the LFE is constant regardless of various system conditions, a single absolute pressure measurement can be used for constant density fluids, such as liquids, and for gases venting to a constant outlet pressure.

The main differentiating feature of the controller in this study is its ability to maintain constant volumetric flow output by purely mechanical means. This allows the user to incorporate intrinsically safe flow control into hazardous or explosive environments. Most, if not all, current flow controlling devices use solenoid-type proportioning valves as the prime mover, these devices require significant

power and by definition do not meet the classification of intrinsically safe (5). Some other advantages, in comparison to classic flow control devices, include:

- 1) This device can provide flow control, calibrated mass or volumetric output, pressure regulation and measurement in one single footprint. Almost all flow other flow control devices need a stable, regulated pressure input to function properly, due to pressure limitations in their valves.
- 2) No need for constant power to a prime mover (when using a stepper motor/encoder as a prime mover). Once the position is set, the device can be left alone, unless there is a change in gas absolute pressure or temperature.
- 3) The maximum flow range or span is scaled mechanically therefore it is impervious to drift or manipulation by means of electrical adjustments such as potentiometers.
- 4) The mechanical device has a near infinite resolution as opposed to finite or discrete resolution, such as a digital thermal mass flow controller.

CONCLUSIONS

The mechanical volumetric flow device coupled with a positional and mass calculating feedback control loop provides a stable means of controlling the flow of fluids. The device maintains flow outputs that are stable, repeatable, and linear with differential pressure, temperature, and absolute pressure. The volumetric output is also immune to variations in inlet and outlet pressure. These performance specifications coupled with the inherent intrinsic safety of the device make this a desirable alternative to classic electrical servo-control loop technology for all clean gas and liquid delivery applications.

ACKNOWLEDGEMENTS

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APPENDIX A: COMPARISON OF A GENERAL FLOW CONTROL FEEDBACK SERVO-LOOP AND THE FMC CONTROLLER CONTROL LOOP

FIGURE A1 –GENERAL FLOW CONTROL LOOP

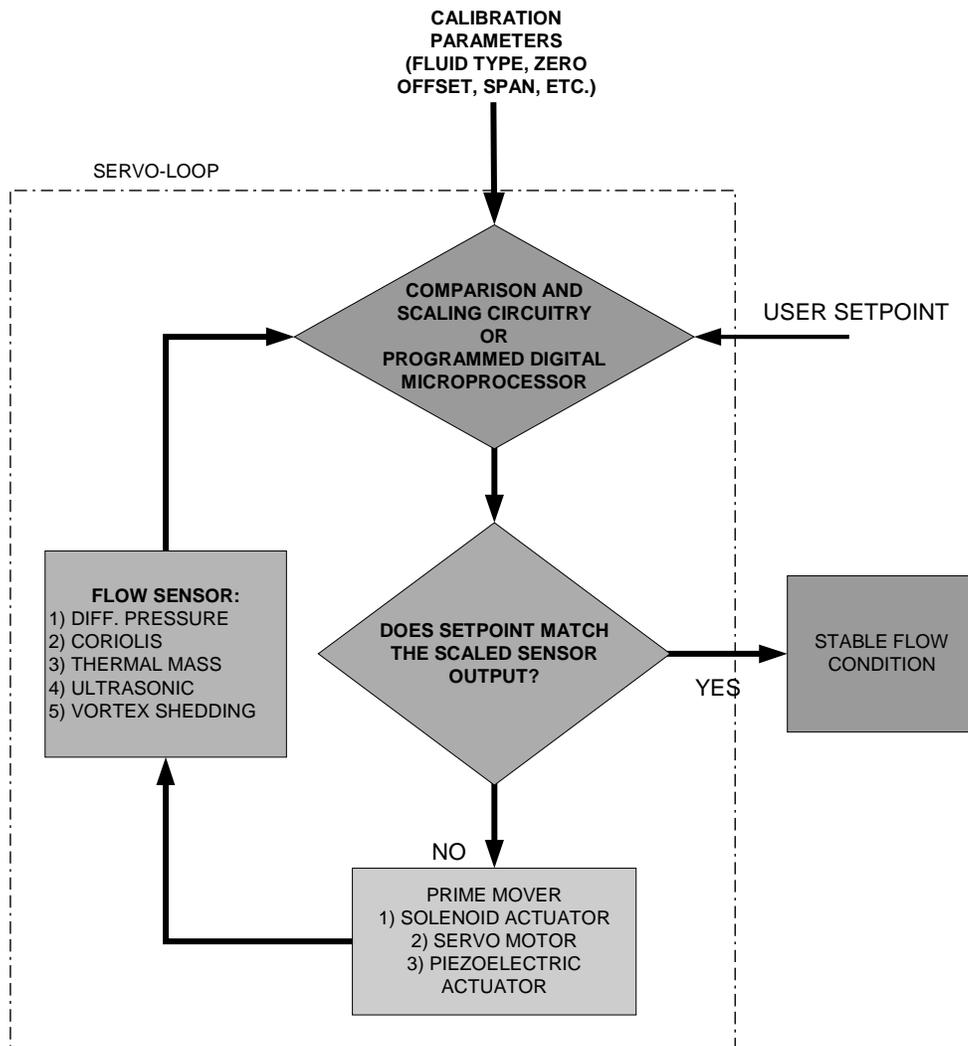
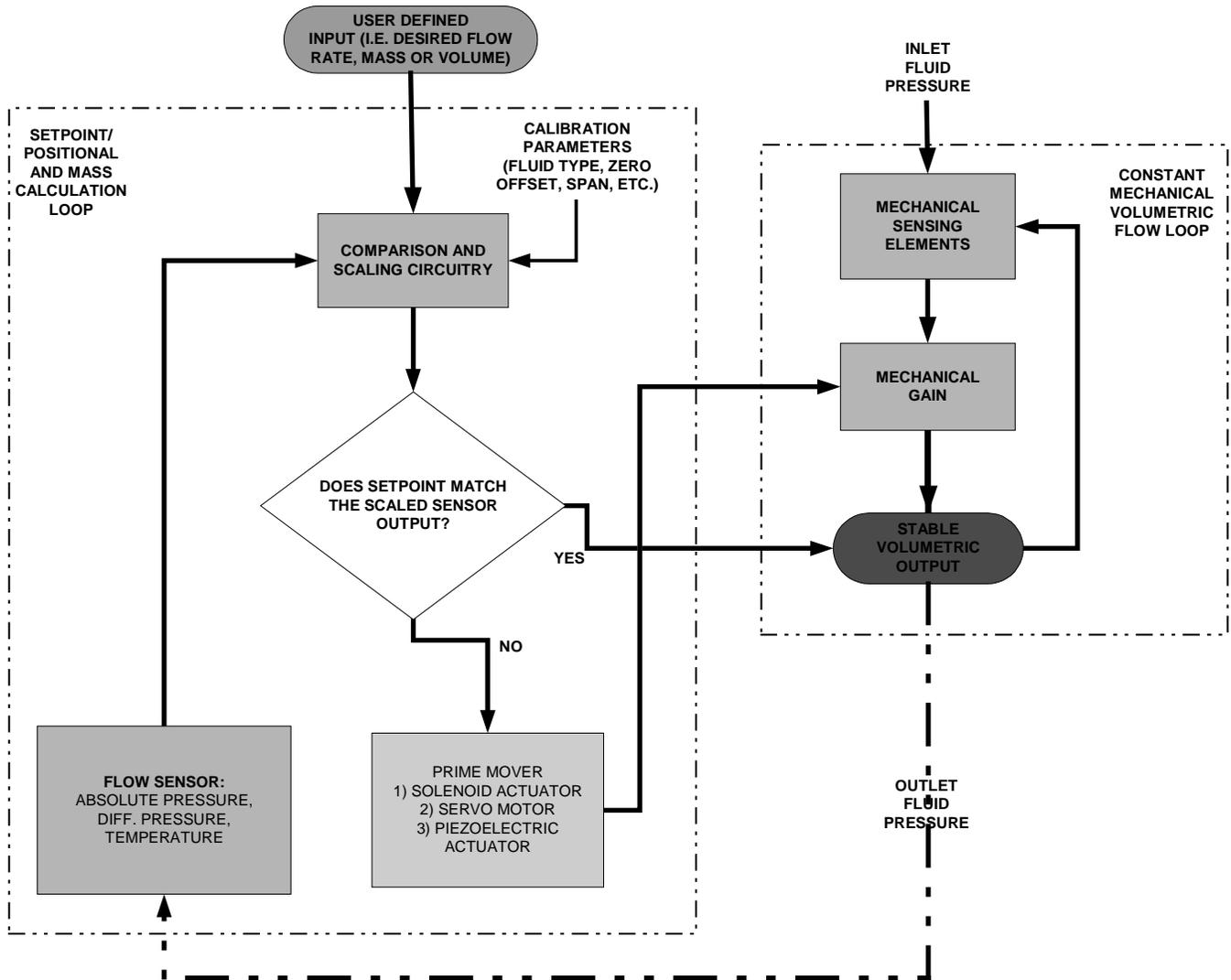


FIGURE A2 –FMC CONTROLLER FLOW CONTROL LOOP



APPENDIX B: TEST SYSTEM SCHEMATIC AND EQUIPMENT SPECIFICATIONS

FIGURE B1 –TEST SETUP SCHEMATIC

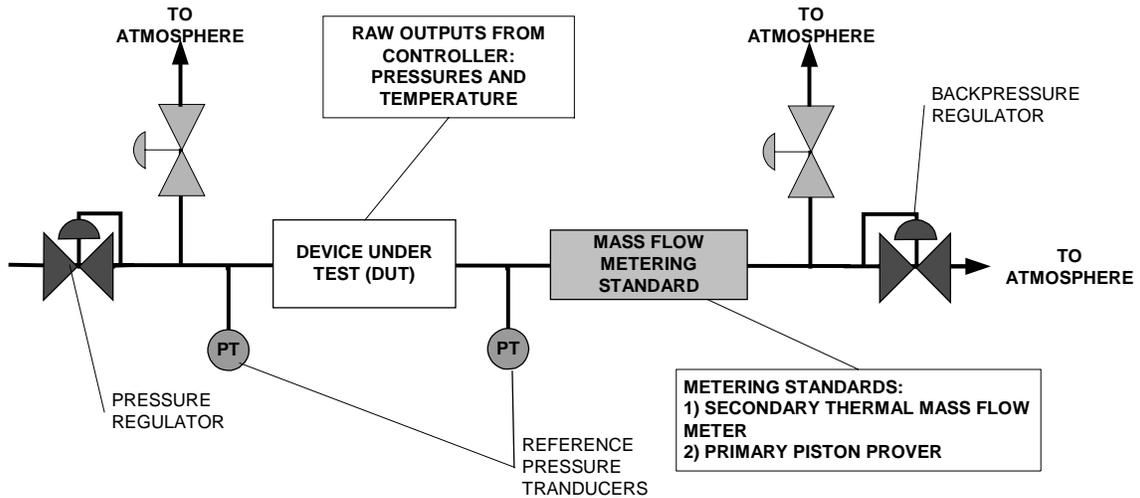


TABLE B1 –EQUIPMENT/SPECIFICATION LIST

EQUIPMENT DESCRIPTION	SUPPLIER/MANUFACTURER	STATED ACCURACY
THERMAL MASS FLOW METER	SIERRA INSTRUMENTS	±1.5% OF FULL-SCALE (±3.75 SCCM)
LAMINAR, PRESSURE-BASED SECONDARY STANDARD FLOW METER	DH INSTRUMENTS	±0.25% OF READING
VOLUMETRIC, AUTOMATED PRIMARY PISTON PROVER	FLOW DYNAMICS INC.	±0.25% ABSOLUTE (TRACEABLE TO NIST)
REFERENCE PRESSURE TRANSDUCERS	MYKROLIS	±0.25% OF FULL-SCALE (±0.25 PSIG)
REFERENCE PRESSURE TRANSDUCERS	DH INSTRUMENTS	±0.01% OF FULL-SCALE (±0.15 PSIG MAXIMUM)

APPENDIX C: SETPOINT STABILITY, REPEATABILITY, AND TIME CONSTANT SUPPORT DATA

FIGURE C1- REPEATABILITY OF SETPOINT DATA

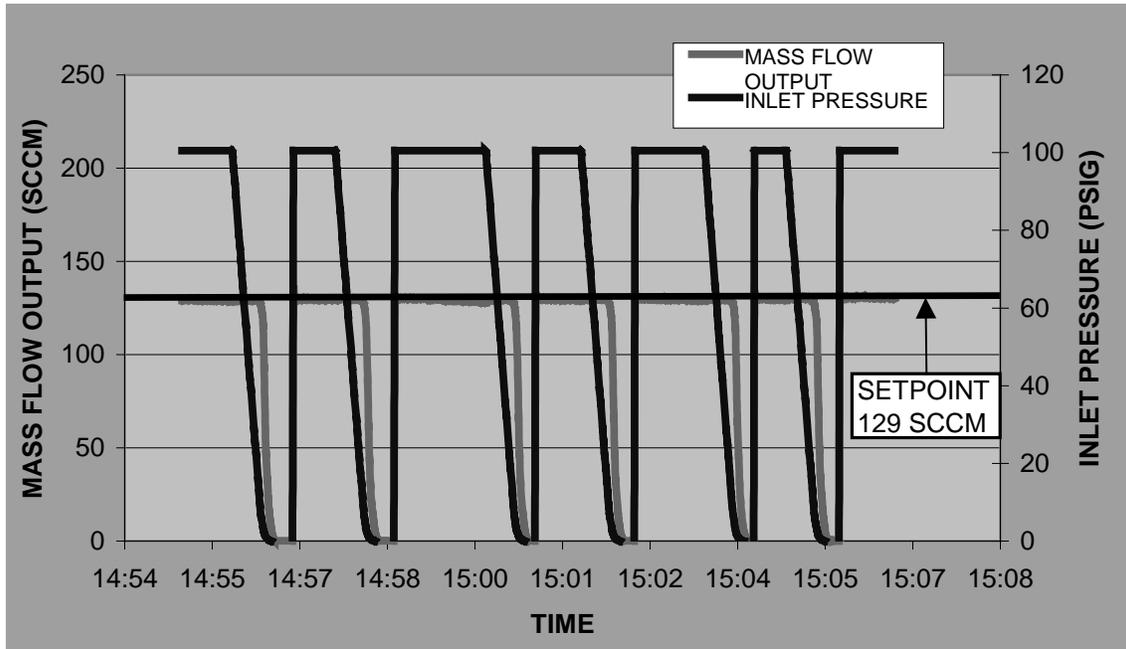


FIGURE C2- STABILITY OF SETPOINT DATA

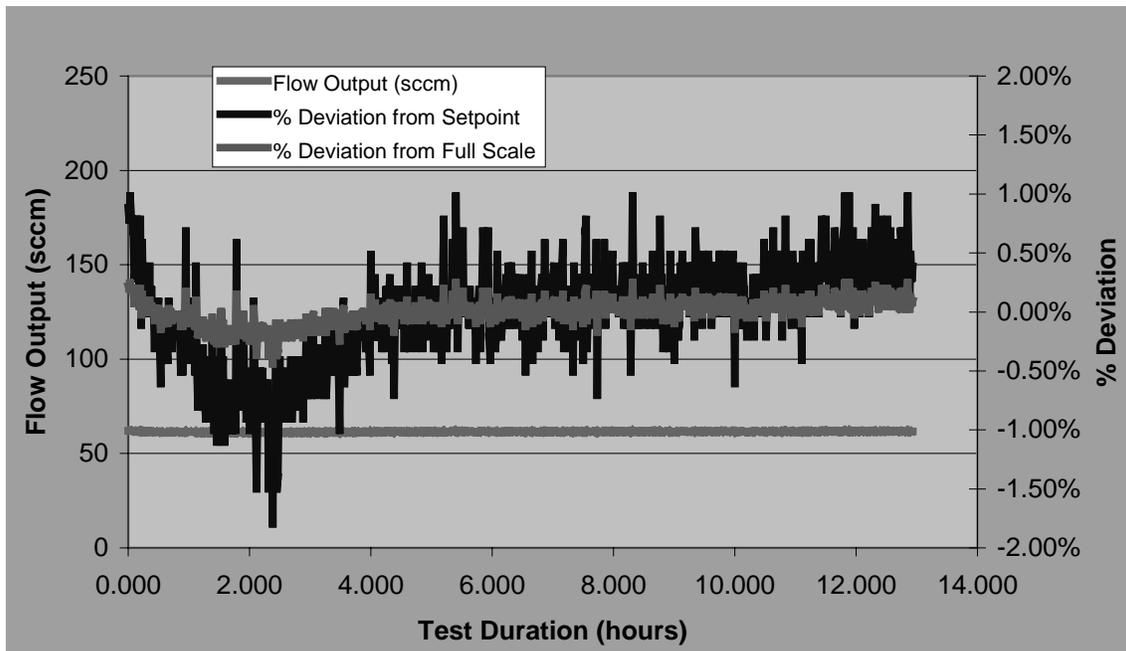


FIGURE C3- TIME RESPONSE DATA

