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FLOW RATIO CONTROLLERS AND GAS DISTRIBUTION SYSTEMS UTILIZING FLOW RATIO CONTROLLERS

Abstract

Disclosed example flow ratio controllers include: an inlet configured to receive a input process gas flow; an inlet pressure sensor configured to measure an inlet pressure; first and second outlets configured to output first and second portions of the input process gas flow; first and second flow valves configured to control a flow of the input process gas to the first and second outlets; first and second position sensors configured to measure valve positions of the first and second flow valves; first and second outlet pressure sensors configured to measure outlet pressures of the first and second outlets; and control circuitry configured to control the first flow valve and the second flow valve using a valve flow model and based on a predetermined flow ratio for the first outlet and the second outlet, the inlet pressure, the first and second valve positions, and the first and second outlet pressures.

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Background/Summary

RELATED APPLICATIONS [0001] The present application claims the benefit of U.S. Provisional Patent Application Ser. No. 63/553,958, filed Feb. 15, 2024, entitled “FLOW RATIO CONTROLLERS AND GAS DISTRIBUTION SYSTEMS UTILIZING FLOW RATIO CONTROLLERS.” The entirety of U.S. Provisional Patent Application Ser. No. 63/553,958 is expressly incorporated herein by reference.

FIELD OF THE DISCLOSURE
[0002] This disclosure is directed generally to flow control and, more particularly, to flow ratio controllers and gas distribution systems utilizing flow ratio controllers.
BACKGROUND
[0003] Flow ratio controllers receive a flow of one or more gases, and distribute the flow among multiple outputs according to defined ratios.
SUMMARY
[0004] Flow ratio controllers and gas distribution systems utilizing flow ratio controllers are disclosed, substantially as illustrated by and described in connection with at least one of the figures, as set forth more completely in the claims.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
[0005] These and other features, aspects, and advantages of the present disclosure will become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:
[0006] FIG. **1** is a block diagram of an example gas distribution system including multiple sources of gases and a flow ratio controller for controlled distribution of the gases, in accordance with aspects of this disclosure.
[0007] FIG. **2** is a schematic diagram of an example flow valve which may be used to implement each of the flow valves in the flow ratio controller of FIG. **1**.
[0008] FIG. **3** depicts the elements of a flow model which may be used by the control circuitry of FIG. **1** to control the flow valve of FIG. **2** and/or determine flow through the flow valve without the use of a dedicated flow meter.
[0009] FIGS. **4**A and **4**B are graphs of example valve flow models that may be used by the control circuitry of FIG. **1** to control the flow valve of FIG. **2** and/or determine flow through the flow valve without the use of a dedicated flow meter.
[0010] FIG. **5** is a flowchart representative of example machine readable instructions which may be executed to implement the control circuitry of FIG. **1** to provide controlled distribution of gases.
[0011] The figures are not necessarily to scale. Wherever appropriate, similar or identical reference numerals are used to refer to similar or identical components.
DETAILED DESCRIPTION
[0012] For the purpose of promoting an understanding of the principles of the claimed technology and presenting its currently understood, best mode of operation, reference will be now made to the embodiments illustrated in the drawings and specific language will be used to describe the same. It will nevertheless be understood that no limitation of the scope of the claimed technology is thereby

intended, with such alterations and further modifications in the illustrated device and such further applications of the principles of the claimed technology as illustrated therein being contemplated as would typically occur to one skilled in the art to which the claimed technology relates.

[0013] Flow ratio controllers are used in applications such as semiconductor manufacturing to deliver precise ratios of gases to different regions of a wafer. Such semiconductor manufacturing applications benefit from faster response times, repeatability of results, and consistency of results, in addition to cost-effectiveness. Conventional flow ratio controllers include inlet pressure sensors and outlet pressure sensors for each channel, as well as mass flow meters and control valves which can result in errors in the flow ratio distribution due to differences between the sensors.

[0014] Disclosed example flow ratio controllers provide improved stability and accuracy compared with conventional flow ratio controllers, as well as improved response times to changing flow rates. Disclosed example flow ratio controllers use piezoelectric valves and an inlet pressure sensor that is shared between all of the outlet channels of the flow ratio controller to provide accurate, repeatable gas distribution to multiple channels without the use of flow sensors for flow detection. Instead, disclosed examples use valve flow models, inlet and outlet pressure sensors, and valve position sensors to determine the flow through each channel.

[0015] Disclosed example flow ratio controllers include: an inlet configured to receive an input process gas flow; an inlet pressure sensor configured to measure an inlet pressure of the input process gas flow; a first outlet configured to output a first portion of the input process gas flow; a second outlet configured output a second portion of the input process gas flow; a first flow valve configured to control a flow of the input process gas to the first outlet; a second flow valve configured to control a flow of the input process gas to the second outlet; a first position sensor configured to measure a first valve position of the first flow valve; a first outlet pressure sensor configured to measure a first outlet pressure of the first outlet; a second position sensor configured to measure a second valve position of the second flow valve; a second outlet pressure sensor configured to measure a second outlet pressure of the second outlet; and control circuitry configured to control the first flow valve and the second flow valve using a valve flow model and based on a predetermined flow ratio for the first outlet and the second outlet, the inlet pressure, the first valve position, the second valve position, the first outlet pressure, and the second outlet pressure.

[0016] In some example flow ratio controllers, the control circuitry is configured to: determine, without a flow meter, a first flow rate at the first outlet based on the inlet pressure, the first outlet pressure, and the first valve position; determine, without a flow meter, a second flow rate at the second outlet based on the inlet pressure, the second outlet pressure, and the second valve position; and control at least one of the first flow valve and the second flow valve based on the first flow rate, the second flow rate, and the predetermined flow ratio. In some example flow ratio controllers, the control circuitry is configured to: control the first flow valve to create a sonic flow condition through the first flow valve while the first flow valve is open; and control the second flow valve to create a sonic flow condition through the second flow valve while the second flow valve is open.

[0017] In some example flow ratio controllers, the first flow valve comprises a first loss region in series with a second loss region, wherein the control circuitry is configured to control the first flow valve based on calculating a first laminar flow through the first loss region and calculating a first sonic flow through the second loss region. In some example flow ratio controllers, the second flow valve comprises a third loss region in series with a fourth loss region, and the control circuitry is configured to control the second flow valve based on calculating a second laminar flow through the third loss region and calculating a second sonic flow through the fourth loss region.

[0018] In some examples, the flow ratio controller includes three or more flow valves including the first flow valve and the second flow valve, each of the three or more flow valves having an orifice, a position sensor, and an outlet pressure sensor, wherein the control circuitry is configured to calculate flow through each of the three or more flow valves and control each of the three or more flow valves to satisfy a pre-determined split ratio.

[0019] In some example flow ratio controllers, the first flow valve and the second flow valve each include a piezoelectric valve. In some example flow ratio controllers, each of the first position sensor and the second position sensor includes at least one of a capacitive position sensor, a strain gauge position sensor, a Hall effect position sensor, or an optical position sensor. In some example flow ratio controllers, the valve flow model is a predetermined model relating valve position, flow, input pressure, and output pressure for each of the first and second flow valves.

[0020] Some example flow ratio controllers further include a manifold configured to distribute the input process gas flow to the first flow valve and the second flow valve, in which the inlet pressure sensor is configured to measure the inlet pressure in the manifold. In some example flow ratio controllers, the control circuitry is configured to: determine a rate of change of the inlet pressure based on measurements from the inlet pressure sensor; and based on the inlet pressure and the rate of change of the inlet pressure, control the first flow valve and the second flow valve to maintain the inlet pressure within a predetermined range of a predetermined inlet pressure.

[0021] Disclosed example precision gas distribution systems include: a plurality of mass flow controllers configured to control flow of respective gases to respective outlets; and a flow ratio controller configured to: receive the gases from the mass flow controllers via an inlet; and control delivery of respective portions of the gases to a plurality of outlets of the flow ratio controller according to a predetermined flow ratio for the plurality of outlets by controlling a plurality of flow valves using a valve flow model and based on an inlet pressure at the inlet, valve positions of the plurality of flow valves, and outlet pressures of the plurality of outlets.

[0022] In some example precision gas distribution systems, the flow ratio controller includes: an inlet pressure sensor configured to measure an inlet pressure of an input process gas flow including the gases at the inlet, in which the plurality of outlets include a first outlet configured to output a first portion of the input process gas flow and a second outlet configured output a second portion of the input process gas flow, and the plurality of flow valves include a first flow valve configured to control a flow of the input process gas to the first outlet and a second flow valve configured to control a flow of the input process gas to the second outlet. The flow ratio controller further includes: a first position sensor configured to measure a first valve position of the first flow valve; a first outlet pressure sensor configured to measure a first outlet pressure of the first outlet; a second position sensor configured to measure a second valve position of the second flow valve; a second outlet pressure sensor configured to measure a second outlet pressure of the second outlet; and control circuitry configured to control the first flow valve and the second flow valve using a valve flow model and based on a predetermined flow ratio for the first outlet and the second outlet, the inlet pressure, the first valve position, the second valve position, the first outlet pressure, and the second outlet pressure.

[0023] In some example precision gas distribution systems, the control circuitry is configured to: control the first flow valve to create a sonic flow condition through the first flow valve while the first flow valve is open; and control the second flow valve to create a sonic flow condition through the second flow valve while the second flow valve is open. In some example precision gas distribution systems, the first flow valve includes a first loss region in series with a second loss region, wherein the control circuitry is configured to control the first flow valve based on calculating a first laminar flow through the first loss region and calculating a first sonic flow through the second loss region.

[0024] In some example precision gas distribution systems, the first flow valve and the second flow valve each include a piezoelectric valve. In some example precision gas distribution systems, each of the first position sensor and the second position sensor includes at least one of a capacitive position sensor, a strain gauge position sensor, a Hall effect position sensor, or an optical position sensor. In some example precision gas distribution systems, the valve flow model is a predetermined model relating valve position, flow, input pressure, and output pressure for each of the first and second flow valves.

[0025] Some example precision gas distribution systems further include a manifold configured to distribute the input process gas flow to the first flow valve and the second flow valve, wherein the inlet pressure sensor is configured to measure the inlet pressure in the manifold. In some example precision gas distribution systems, the control circuitry is configured to: determine a rate of change of the inlet pressure based on measurements from the inlet pressure sensor; and based on the inlet pressure and the rate of change of the inlet pressure, control the first flow valve and the second flow valve to maintain the inlet pressure within a predetermined range of a predetermined inlet pressure.

[0026] Some example precision gas distribution systems further include a temperature sensor configured to measure a temperature of the input process gas flow, the control circuitry configured to control the first and second flow valves based on the temperature.

[0027] FIG. **1** is a block diagram of an example gas distribution system **100** including multiple sources of gases **102***a*-**102***n*, and a flow ratio controller **104** for controlled distribution of the gases **102***a*-**102***n*, such as a predetermined mixture of two or more of the gases **102***a*-**102***n*. The gases **102***a*-**102***n* may be different types of process gases, such as process gases for semiconductor manufacturing.

[0028] The example gas distribution system **100** includes a set of mass flow controllers **106***a*-**106***n*, which control respective flow rates for each of the gases **102***a*-**102***n*. The mass flow controllers **106***a*-**106***n* output the respective gases **102***a*-**102***n* to a manifold **108**, or other mixing volume, and fed into an inlet **110** of the flow ratio controller **104**.

[0029] The example flow ratio controller **104** of FIG. **1** receives respective portions of an inlet process gas flow (e.g., the gases **102***a*-**102***n*) via the inlet **110** (e.g., as a mixture), and controls delivery of the input process gas flow to a set of outlets **112***a*-**112***m*. As disclosed in more detail below, the flow ratio controller **104** controls delivery of the input process gas flow according to a predetermined flow ratio for the set of outlets **112***a*-**112***m* by controlling a set of flow valves using a valve flow model and based on an inlet pressure at the inlet **110**, valve positions of the plurality of flow valves, and outlet pressures of the plurality of outlets **112***a*-**112***m*. The inlet **110** and the outlets **112***a*-**112***m* may be any single type or combination of types of disconnectable or permanent gas connection, such as a threaded connection, quick-connect connection, welded or soldered connection, and/or any other appropriate type(s) of connection(s). The outlets **112***a*-**112***m* may be coupled (e.g., via hoses, pipes, ducts, and/or any other rigid, semi-rigid, and/or flexible lines) to corresponding outlet locations **114***a*-**114***m* to which the input process gas flow is to be output.

[0030] The example flow ratio controller **104** includes a set of flow valves **116***a*-**116***m*, each of which controls flow from the shared inlet **110** to a corresponding outlet **112***a*-**112***m*. The inlet pressure at the inlet **110**, which is also the inlet pressure at the inlets to the flow valves **116***a*-**116***m*, is measured via an inlet pressure sensor **118**. As discussed in more detail below with reference to FIG. **2**, each of the flow valves **116***a*-**116***m* includes a position sensor **120***a*-**120***m* to measure a valve position of the corresponding flow valve **116***a*-**116***m*.

[0031] In some examples, the flow ratio controller **104** includes a manifold to distribute the input process gas flow to the first flow valve and the second flow valve, wherein the inlet pressure sensor is configured to measure the inlet pressure in the manifold.

[0032] Each of the gas paths from the inlet **110** to one of the outlets **112***a*-**112***m* is referred to herein as an "outlet channel." Each outlet channel **126***a*-**126***m* includes the corresponding flow valve **116***a*-**116***m* (having the corresponding position sensor **120***a*-**120***m*), the corresponding outlet **112***a*-**112***m*, and a corresponding outlet pressure sensor **122***a*-**122***m*. The outlet pressure sensor **122***a*-**122***m* measures an outlet pressure of the corresponding outlet **112***a*-**112***m* (e.g., between an outlet of the flow valve **116***a*-**116***m* and the outlet **112***a*-**112***m*).

[0033] The example flow ratio controller **104** further includes control circuitry **124** to control the flow valves **116***a*-**116***m* to output the gases to two or more of the outlet channels **126***a*-**126***m*. The example control circuitry **124** may be an integrated processing system, a programmable logic controller, a general-purpose computer, a laptop computer, a tablet computer, and/or any other type of processing system configured to communicate with the sensors **120***a*-**120***m*, **122***a*-**122***m* and flow valves **116***a*-**116***m* of the flow ratio controller **104**. For example, the control circuitry **124** includes a processor **128**, memory **130**, and a storage device **132**. The example processor **128** may be any general purpose central processing unit (CPU) from any manufacturer. In some other examples, the processor **128** may include one or more specialized processing units, such as RISC processors with an ARM core, graphic processing units, digital signal processors, and/or system-on-chips (SoC). The processor **128** executes machine readable instructions **134** that may be stored locally at the processor (e.g., in an included cache or SoC), in the memory (e.g., a random access memory or other volatile memory, a read only memory or other non-volatile memory such as FLASH memory, and/or in the storage device **132**. The example storage device **132** may be a hard drive, a solid state storage drive, a hybrid drive, a RAID array, and/or any other mass data storage device.

[0034] In the example of FIG. **1**, the control circuitry **124** uses a predetermined (e.g., stored, received) flow ratio to control the flow valves **116***a*-**116***m*. The predetermined flow ratio may be stored in the memory **130** and/or the storage device **132**, and/or received at the processor from an external control system (e.g., via communication circuitry).

[0035] In the example of FIG. **1**, the flow ratio controller **104** does not have flow sensors to directly measure the outlet flow through the outlet channels **126***a*-**126***m*. Instead, the example control circuitry **124** controls the flow valves **116***a*-**116***m* according to one or more valve flow models. The valve flow model(s) may be stored in a memory or other storage device of the control circuitry **124**. An example valve flow model that may be used by the control circuitry **124** relates valve position, inlet pressure, outlet pressure, and flow for each example flow valve **116***a*-**116***m*. The control circuitry **124** may use different valve flow models for different flow valves **116***a*-**116***m* due to, for example, the different flow valves **116***a*-**116***m* having different configurations.

[0036] The example flow ratio controller **104** further includes a temperature sensor **136** to measure a temperature of the gas received via the inlet **110**, and/or multiple temperature sensors configured to measure the temperatures of the gases distributed through the flow valves **116***a*-**116***m*. While in many cases the temperatures of the gases distributed to the different outlet channels **126***a*-**126***m* are substantially equal, the control circuitry **124** may use the measured temperature(s) to compensate or correct the flow rates and/or pressure changes.

[0037] FIG. **2** is a schematic diagram of an example flow valve **200** which may be used to implement each of the flow valves **116***a*-**116***m* in the flow ratio controller **104** of FIG. **1**. The example flow valve **200** of FIG. **2** is a piezoelectric-type of valve, which includes a stacked piezoelectric actuator **202** coupled to a control plate **204** to control a size of a gas pathway between a valve inlet **206** (e.g., coupled to the inlet **110** of FIG. **1**) and a valve outlet **208** (e.g., coupled to the outlet **112**) in a base **210**. The valve inlet **206** and valve outlet **208** are selectively coupled via a flow channel **212** within a housing **214** of the flow valve **200**.

[0038] The example piezoelectric flow valve **200** is a normally-opened valve which, in the event of a power loss, allows the gases to be vented into the desired location instead of being trapped within the gas distribution system **100**. In other examples, the flow valve **200** is a normally-closed valve.

[0039] The flow channel **212** is adjustable by controlling the piezoelectric actuator **202** to move the control plate **204**. For example, the control plate **204** may be moved away from the base **210** to increase a size of the flow channel **212** and moved toward the base **210** to decrease the size of the flow channel **212** and/or close the flow channel **212**.

[0040] The piezoelectric actuator **202** is coupled to the control plate **204** via a stem **216**, a rod, or other rigid coupling. To detect a position of the flow valve **200**, the example position sensor **120** detects a distance between the position sensor **120** and a target **218** coupled to the stem **216**. As the stem **216** is actuated to move by the piezoelectric actuator **202**, the target **218** moves toward and away from the position sensor **120**. The position sensor **120** may be a capacitive position sensor, a strain gauge position sensor, an optical position sensor, a Hall effect sensor, and/or any other type of position sensor, and the target **218** may be a type of target that is suitable for the type of position sensor **120**.

[0041] The example control circuitry **124** may include multiple elements in the flow model for the valve **200**. For example, the flow model may represent multiple sources of flow constraint, such as a first pressure loss region (e.g., a viscous flow region) and a second loss region (e.g., an inviscid flow region). FIG. **3** depicts the elements of a flow model which may be used by the control circuitry **124** of FIG. **1** to control the flow valve **200** of FIG. **2** and/or determine flow through the flow valve without the use of a dedicated flow meter.

[0042] The flow valve **200** and the elements **302-308** of FIGS. **2** and **3** may be duplicated for each of the example flow valves **116*a*-116*m*** of FIG. **1**.

[0043] As illustrated in FIG. **3**, the distance between the control plate **204** and a valve seat **302** controls a size of a viscous flow region **304** and a size of an inviscid flow region **306**. The example inviscid flow region **306** may include an orifice **308** which can be different between different ones of the flow valves **116*a*-116*m*** of FIG. **1**.

[0044] The control circuitry **124** determines a flow rate through the valve **200** by determining a flow rate through the viscous flow region **304** and the inviscid flow region **306** based on the position of the valve **200** (e.g., the position of the control plate **204** as measured by the position sensor **120**), based on the inlet pressure (e.g., measured by the inlet pressure sensor **118** of FIG. **1**), the outlet pressure (e.g., measured by the outlet pressure sensor **122** coupled to the valve outlet **208**), a size of the orifice **308**, and the qualities of the gas being transmitted (e.g., viscosity of the gas, temperature, gas density).

[0045] The control circuitry **124** determines a first pressure drop across the viscous flow region **304** using Equation 1 to determine an intermediate pressure P.sub.x and a corresponding flow rate Q.sub.vis.

[00001] $$Q_{\text{vis}} = \frac{(P_1^2 - P_x^2)\text{wH}^3}{12\ \text{.Math.}\quad \text{LRT}} \quad \text{(Equation1)}$$

[0046] In Equation 1, Q.sub.vis is the mass flow rate through the viscous flow region **304**, P.sub.1 is the inlet pressure (as measured by the inlet pressure sensor **118**), P.sub.x is the intermediate pressure between the viscous flow region **304** and the inviscid flow region **306**, H is the distance between the control plate **204** and the valve seat **302**, μ is the dynamic viscosity of the gas, w is the breadth of the viscous flow region **304**, and L is the length of the flow path of the viscous flow region **304**, and R is the gas constant.

[0047] The control circuitry **124** further determines a second pressure drop across the inviscid flow region **306** using Equation 2 (for a sonic flow condition) or Equation 3 (for sub-sonic flow conditions).

[00002] $$Q_{\text{inv}} = C_d \frac{T_{\text{ref}}}{P_{\text{ref}}} * \text{Dia} * h * P_x \sqrt{\frac{2R_u}{MWT_{\text{act}}} \left(\frac{k}{k-1}\right)\left[\left(\frac{P_2}{P_x}\right)^{\frac{2}{k}} - \left(\frac{P_2}{P_x}\right)^{\frac{k+1}{k}}\right]} \quad \text{(Equation2)}$$

$$Q_{\text{inv}} = C_d \frac{T_{\text{ref}}}{P_{\text{ref}}} * \text{Dia} * h * P_x \sqrt{\frac{2R_u}{MWT_{\text{act}}}} \left(\frac{k}{k-1}\right)^{\frac{k+1}{k-1}} \quad \text{(Equation3)}$$

[0048] In Equations 2 and 3, C.sub.d is the discharge coefficient, k is a gas-specific heat ratio, M is the gas molecular weight, T is the gas temperature, Dia is the diameter **308** of the orifice, T.sub.ref is a reference temperature, P.sub.ref is a reference pressure, Ru is a universal gas constant and h is the distance between the control plate **204** and the valve seat **302**.

[0049] Sonic flow occurs when the condition expressed in Equation 4 is true.

[00003] $$\frac{P_2}{P_1} \leq \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \quad \text{(Equation4)}$$

[0050] During sonic flow, a standing shock wave is formed which limits the flow rate through an orifice despite further increases in the upstream pressure relative to downstream pressure. By operating the flow valve **200** in the sonic flow condition, the control circuitry **124** can more reliably determine the flow rate through the flow valve **200**.

[0051] Using Equations 1-4, the control circuitry **124** determines an intermediate pressure value P.sub.x for which Q.sub.vis and Q.sub.inv are equal based on the measured values of P.sub.1 (the inlet pressure) and P.sub.2 (the outlet pressure for that channel **126**). The flow rate at which Q.sub.vis and Q.sub.inv are equal for the same value of the intermediate pressure P.sub.x is the flow rate through the valve **200** and, therefore, through the corresponding outlet channel.

[0052] In some examples, the control circuitry **124** controls the flow valves **116***a*-**116***m* to operate consistently in the sonic flow condition when the flow valve **116***a*-**116***m* is open, such as by controlling the pressure drop across the flow valve **200** to satisfy Equation 4. In some other examples, the control circuitry **124** may control the flow valves **116***a*-**116***m* to operate in a sub-sonic flow condition. However, operation in the sub-sonic flow condition may require additional computational effort by the control circuitry **124**.

[0053] FIGS. **4**A and **4**B are graphs of example valve flow models **400**, **402** that may be used by the control circuitry **124** of FIG. **1** to control the flow valve **200** of FIG. **2** and/or determine flow through the flow valve **200** without the use of a dedicated flow meter. For example, the valve flow models **400**, **402** may be stored in a database in the memory **130** and/or the storage device **132** of FIG. **1**. The example valve flow model **400** relates valve position (e.g., the distance between the control plate **204** and the valve seat **302**) to the flow through the valve **200** for a given orifice size, inlet pressure, and outlet pressure. Similarly, the valve flow model **400** relates valve position to the flow through the valve **200** for a larger orifice size, inlet pressure, and outlet pressure. The example memory **130** and/or storage device **132** of FIG. **1** may include additional sets of inlet pressures and outlet pressures for each orifice size, and/or sets of flow rates for different combinations of valve position, inlet pressures, and outlet pressures for each orifice size present in the set of flow valves **116***a*-**116***m*.

[0054] Returning to FIG. **1**, in some examples, the control circuitry **124** is further configured to compensate for inlet pressure changes caused by changes in the inlet flow from the gases **102***a*-**102***n* (e.g., via the MFCs **106***a*-**106***n*). In conventional flow control systems, changes in flow result in corresponding changes in inlet pressure as gas mass accumulates in the pipes, ducts, manifolds, and/or other gas carriers. Conventional systems, which respond to stable pressures, may be required to wait a significant time before responding to perform any necessary flow control adjustments, thereby reducing the response time of the entire gas distribution system.

[0055] The example control circuitry **124** improves the response time when changes in flow rates occur at the inlet **110** by monitoring both the inlet pressure (measured by the inlet pressure sensor **118**) and determining the rate of change of the inlet pressure based on the measurements by the inlet pressure sensor **118**. If the rate of change of the inlet pressure increases above a predetermined threshold, the control circuitry **124** responds to maintain the inlet pressure within a predetermined range of a predetermined inlet pressure. The predetermined inlet pressure may be a pressure determined by the control circuitry **124** to maintain a sonic flow condition through the flow valves **116***a*-**116***m* (e.g., using Equation 4) and/or any other target pressure determined by the control circuitry **124** to obtain the desired flow ratio. In some examples, the predetermined range of the rate of change of the inlet pressure is selected to avoid changes due to noise but to retain sufficient sensitivity to pressure changes caused by changes in flow rate.

[0056] For example, if the MFCs **106***a*-**106***n* increase the flow rate (e.g., due to a change in process or recipe), the resulting increase in flow will cause a corresponding increase in pressure measured by the inlet pressure sensor **118**. The control circuitry **124** detects that the rate of change of the inlet pressure is increasing, and determines a corresponding change to the position of each of the flow valves **116***a*-**116***m* to maintain both the predetermined flow ratio and the target pressure. For example, for a higher rate of change of the pressure, the control circuitry **124** may determine a larger change in valve position. Conversely, for a lower rate of change of the pressure, the control circuitry may determine a smaller change in valve position.

[0057] FIG. **5** is a flowchart representative of example machine readable instructions **500** which may be executed to implement the control circuitry **124** of FIG. **1** to provide controlled distribution of gases from the outlet channels **126***a*-**126***m*. The example instructions **500** will be described below with reference to the gas distribution system **100** of FIG. **1** and the valve **200** of FIG. **2**.

[0058] At block **502**, the control circuitry **124** determines a flow ratio for the outlet channels **126***a*-**126***m*. The flow ratio may be stored in the memory **130** or storage device **132**, and/or received via an I/O interface and/or communications circuitry.

[0059] At block **504**, the control circuitry **124** determines whether to begin gas distribution. For example, the control circuitry **124** may detect that an input process gas flow is being received from the MFCs **106***a*-**106***n* based on changes in the inlet pressure (e.g., measured by the inlet pressure sensor **118**). If gas distribution is not yet to begin (block **504**), control returns to block **502**.

[0060] When gas distribution begins (block **504**), at block **506** the control circuitry **124** determines target flow valve positions for each of the flow valves **116***a*-**116***m*, based on the flow valve orifice size(s), the inlet pressure, and the target outlet pressures, to output the target flow rates for each of the outlet channels **126***a*-**126***m* matching the flow ratio. For example, the control circuitry **124** may reference the valve flow models **400**, **402** and/or the Equations 1-4 to set the desired flow rates for each outlet channel specified in the flow ratios, such that the total flow through the outlet channels **126***a*-**126***m* is equal to the flow at the inlet **110**. In some examples, the control circuitry **124** may control the flow valves **116***a*-**116***m* to set a sonic flow condition to reduce the complexity of calculations of the target valve positions.

[0061] At block **508**, the control circuitry **124** controls the flow valves **116***a*-**116***m* according to the respective determined valve positions. For outlet channels **126***a*-**126***m* which are not used, the control circuitry **124** controls the corresponding flow valve **116***a*-**116***m* to be closed. The control circuitry **124** may use closed-loop control of the piezoelectric actuators **202** based on position feedback from the position sensors **120***a*-**120***m* to control the flow valves **116***a*-**116***m* to the correct valve positions.

[0062] At block **510**, the control circuitry **124** determines an inlet pressure and a rate of change of the inlet pressure. For example, the control circuitry **124** may receive inlet pressure data from the inlet pressure sensor **118**, and calculate the rate of change of the inlet pressure. At block **512**, the control circuitry **124** determines whether the inlet pressure and/or the rate of change are more than a threshold. If the rate of change of the inlet pressure is more than the threshold (block **512**), at block **514** the control circuitry **124** adjusts the flow valve positions of all of the open flow valves **116***a*-**116***m* to limit the rate of change of the inlet pressure. For example, the flow valve positions are adjusted to maintain the predetermined flow ratio at each of the outlet channels **126***a*-**126***m* and to reduce the settling time for a change in flow rate.

[0063] After adjusting the flow valve positions (block **514**), or if the rate of change of the inlet pressure is not greater than the threshold (block **512**), at block **516** the control circuitry **124** determines whether the flow ratio has changed. If the flow ratio has changed (block **516**), control returns to block **506** to determine new target flow valve positions.

[0064] If the flow ratio has changed (block **516**), at block **518** the control circuitry **124** determines whether gas distribution is to end. If gas distribution is to continue (block **518**), control returns to block **508** to continue controlling the flow valves **116***a*-**116***m*. When gas distribution is to end (block **518**), the example instructions **500** end.

[0065] As utilized herein, “and/or” means any one or more of the items in the list joined by “and/or”. As an example, “x and/or y” means any element of the three-element set {(x), (y), (x, y)}. In other words, “x and/or y” means “one or both of x and y”. As another example, “x, y, and/or z” means any element of the seven-element set {(x), (y), (z), (x, y), (x, z), (y, z), (x, y, z)}. In other words, “x, y and/or z” means “one or more of x, y and z”. As utilized herein, the term “exemplary” means serving as a non-limiting example, instance, or illustration. As utilized herein, the terms

“e.g.,” and “for example” set off lists of one or more non-limiting examples, instances, or illustrations.
[0066] While the present method and/or system has been described with reference to certain implementations, it will be understood by those skilled in the art that various changes may be made, and equivalents may be substituted without departing from the scope of the present method and/or system. For example, block and/or components of disclosed examples may be combined, divided, re-arranged, and/or otherwise modified. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the present disclosure without departing from its scope. Therefore, the present method and/or system are not limited to the particular implementations disclosed. Instead, the present method and/or system will include all implementations falling within the scope of the appended claims, both literally and under the doctrine of equivalents.

Claims

1. A flow ratio controller, comprising: an inlet configured to receive an input process gas flow; an inlet pressure sensor configured to measure an inlet pressure of the input process gas flow; a first outlet configured to output a first portion of the input process gas flow; a second outlet configured output a second portion of the input process gas flow; a first flow valve configured to control a flow of the input process gas to the first outlet; a second flow valve configured to control a flow of the input process gas to the second outlet; a first position sensor configured to measure a first valve position of the first flow valve; a first outlet pressure sensor configured to measure a first outlet pressure of the first outlet; a second position sensor configured to measure a second valve position of the second flow valve; a second outlet pressure sensor configured to measure a second outlet pressure of the second outlet; and control circuitry configured to control the first flow valve and the second flow valve using a valve flow model and based on a predetermined flow ratio for the first outlet and the second outlet, the inlet pressure, the first valve position, the second valve position, the first outlet pressure, and the second outlet pressure.
2. The flow ratio controller as defined in claim 1, wherein the control circuitry is configured to: determine, without a flow meter, a first flow rate at the first outlet based on the inlet pressure, the first outlet pressure, and the first valve position; determine, without a flow meter, a second flow rate at the second outlet based on the inlet pressure, the second outlet pressure, and the second valve position; and control at least one of the first flow valve and the second flow valve based on the first flow rate, the second flow rate, and the predetermined flow ratio.
3. The flow ratio controller as defined in claim 1, wherein the control circuitry is configured to: control the first flow valve to create a sonic flow condition through the first flow valve while the first flow valve is open; and control the second flow valve to create a sonic flow condition through the second flow valve while the second flow valve is open.
4. The flow ratio controller as defined in claim 1, wherein the first flow valve comprises a first loss region in series with a second loss region, wherein the control circuitry is configured to control the first flow valve based on calculating a first laminar flow through the first loss region and calculating a first choked flow through the second loss region.
5. The flow ratio controller as defined in claim 1, wherein the flow ratio controller comprises three or more flow valves including the first flow valve and the second flow valve, each of the three or more flow valves having an orifice, a position sensor, and an outlet pressure sensor, wherein the control circuitry is configured to calculate flow through each of the three or more flow valves and control each of the three or more flow valves to satisfy a pre-determined split ratio.
6. The flow ratio controller as defined in claim 1, wherein the first flow valve and the second flow valve each comprise a piezoelectric valve.
7. The flow ratio controller as defined in claim 1, wherein each of the first position sensor and the

second position sensor comprises at least one of a capacitive position sensor, a strain gauge position sensor, a Hall effect position sensor, or an optical position sensor.

8. The flow ratio controller as defined in claim 1, wherein the valve flow model is a predetermined model relating valve position, flow, input pressure, and output pressure for each of the first and second flow valves.

9. The flow ratio controller as defined in claim 1, further comprising a manifold configured to distribute the input process gas flow to the first flow valve and the second flow valve, wherein the inlet pressure sensor is configured to measure the inlet pressure in the manifold.

10. The flow ratio controller as defined in claim 1, wherein the control circuitry is configured to: determine a rate of change of the inlet pressure based on measurements from the inlet pressure sensor; and based on the inlet pressure and the rate of change of the inlet pressure, control the first flow valve and the second flow valve to maintain the inlet pressure within a predetermined range of a predetermined inlet pressure.

11. A precision gas distribution system, comprising: a plurality of mass flow controllers configured to control flow of respective gases to respective outlets; and a flow ratio controller configured to: receive the gases from the mass flow controllers via an inlet; and control delivery of respective portions of the gases to a plurality of outlets of the flow ratio controller according to a predetermined flow ratio for the plurality of outlets by controlling a plurality of flow valves using a valve flow model and based on an inlet pressure at the inlet, valve positions of the plurality of flow valves, and outlet pressures of the plurality of outlets.

12. The precision gas distribution system of claim 11, wherein the flow ratio controller comprises: an inlet pressure sensor configured to measure an inlet pressure of an input process gas flow comprising the gases at the inlet; wherein the plurality of outlets comprise a first outlet configured to output a first portion of the input process gas flow and a second outlet configured output a second portion of the input process gas flow; wherein the plurality of flow valves comprise a first flow valve configured to control a flow of the input process gas to the first outlet and a second flow valve configured to control a flow of the input process gas to the second outlet, the flow ratio controller further comprising: a first position sensor configured to measure a first valve position of the first flow valve; a first outlet pressure sensor configured to measure a first outlet pressure of the first outlet; a second position sensor configured to measure a second valve position of the second flow valve; a second outlet pressure sensor configured to measure a second outlet pressure of the second outlet; and control circuitry configured to control the first flow valve and the second flow valve using a valve flow model and based on a predetermined flow ratio for the first outlet and the second outlet, the inlet pressure, the first valve position, the second valve position, the first outlet pressure, and the second outlet pressure.

13. The precision gas distribution system of claim 12, wherein the control circuitry is configured to: control the first flow valve to create a sonic flow condition through the first flow valve while the first flow valve is open; and control the second flow valve to create a sonic flow condition through the second flow valve while the second flow valve is open.

14. The precision gas distribution system of claim 12, wherein the first flow valve comprises a first loss region in series with a second loss region, wherein the control circuitry is configured to control the first flow valve based on calculating a first laminar flow through the first loss region and calculating a first sonic flow through the second loss region.

15. The precision gas distribution system of claim 12, wherein the first flow valve and the second flow valve each comprise a piezoelectric valve.

16. The precision gas distribution system of claim 12, wherein each of the first position sensor and the second position sensor comprises at least one of a capacitive position sensor, a strain gauge position sensor, a Hall effect position sensor, or an optical position sensor.

17. The precision gas distribution system of claim 12, wherein the valve flow model is a predetermined model relating valve position, flow, input pressure, and output pressure for each of the first and second flow valves.

18. The precision gas distribution system of claim 12, further comprising a manifold configured to distribute the input process gas flow to the first flow valve and the second flow valve, wherein the inlet pressure sensor is configured to measure the inlet pressure in the manifold.

19. The precision gas distribution system of claim 12, wherein the control circuitry is configured to: determine a rate of change of the inlet pressure based on measurements from the inlet pressure sensor; and based on the inlet pressure and the rate of change of the inlet pressure, control the first flow valve and the second flow valve to maintain the inlet pressure within a predetermined range of a predetermined inlet pressure.

20. The precision gas distribution system of claim 12, further comprising a temperature sensor configured to measure a temperature of the input process gas flow, the control circuitry configured to control the first and second flow valves based on the temperature.