(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
27 October 2016 (27.10.2016)

WIPO | PCT

(10) International Publication Number
WO 2016/172083 A1

(51) International Patent Classification:
F02C 7/232 (2006.01) *F02C 9/26* (2006.01)

(21) International Application Number:
PCT/US2016/028250

(22) International Filing Date:
19 April 2016 (19.04.2016)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/150,017 20 April 2015 (20.04.2015) US

(71) Applicant: **WOODWARD, INC.** [US/US]; 1000 East Drake Road, Fort Collins, Colorado 80525 (US).

(72) Inventors: **WILSON, Kevin Emery**; 629 Dakota Way, Windsor, Colorado 80550 (US). **FARROW, Timothy John**; 2013 Bennington Circle, Fort Collins, Colorado 80526 (US).

(74) Agents: **MUSSELMAN, JR., P. Weston** et al.; Fish & Richardson P.C., P.O. Box 1022, Minneapolis, Minnesota 55440-1022 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

[Continued on next page]

(54) Title: GAS FLOW FUEL METERING

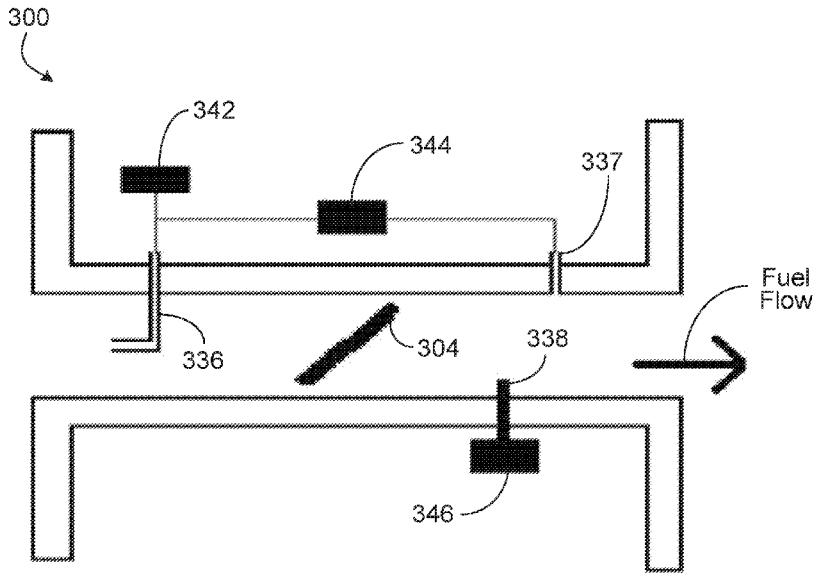


FIG. 3

(57) Abstract: A fuel metering valve includes a valve body housing a valve element in an interior chamber between an inlet port and an outlet port, an actuator coupled to move the valve element relative to the valve body, and a controller configured to regulate the position of the valve body. The valve element regulates a flow of fuel through the valve body. The controller regulates the position of the valve body via an actuator based on a measurement by a pressure sensor to achieve a target mass flow rate of the fuel through the valve body. The pressure sensor is calibrated for accuracy only across a limited scale range based on a predetermined maximum subsonic pressure.

WO 2016/172083 A1

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

Published:

— *with international search report (Art. 21(3))*

GAS FLOW FUEL METERING

CLAIM OF PRIORITY

This application claims priority to U.S. Provisional Application No. 62/150,017, filed on April 20, 2015, the contents of which are hereby incorporated by reference.

TECHNICAL FIELD

This specification relates to fuel metering valves for combustion engines that operate on gaseous fuels.

BACKGROUND

Gas fuel systems are used for a variety of internal combustion engines, such as reciprocating or turbine engines used on vehicles and in industrial settings. These engines may utilize fuel systems that provide natural gas (predominantly methane) from liquid natural gas (LNG) or compressed natural gas (CNG) sources, or other gaseous fuels such as propane or hydrogen. In many systems, a fuel metering valve operates to control the flow of gaseous fuel delivered to the engine. Accuracy and reliability concerns with respect to fuel metering valves are often based on error accumulation when the output from multiple sensors is used as input for fuel mass flow rate calculations.

SUMMARY

In a first aspect of the present disclosure, a fuel metering valve includes: a valve body housing a valve element in an interior chamber between an inlet port and an outlet port, the valve element regulating a flow of fuel through the valve body; an actuator coupled to move the valve element relative to the valve body; a controller configured to regulate the position of the valve body via the actuator based on a pressure measurement to achieve a target mass flow rate of the fuel through the valve body; and a pressure sensor arranged to provide the pressure measurement. The pressure sensor is calibrated for accuracy only across a limited scale range based on a predetermined maximum subsonic pressure.

In some embodiments of the first aspect, the flow of fuel includes a flow of gaseous fluid.

In some embodiments of the first aspect, the controller is configured to identify a sonic or subsonic flow condition on a downstream side of the valve element based on the pressure measurement. In some embodiments of the first aspect, the controller is further configured to: in response to identifying a subsonic flow condition, implement a first set of one or more flow equations to achieve the target mass flow rate; and in response to identifying a sonic flow condition, implement a second set of one or more different flow equations to achieve the target mass flow rate. In some embodiments of the first aspect, only the first set of flow equations include the pressure measurement as an input.

In some embodiments of the first aspect, the pressure sensor is fluidically coupled to an upstream pressure probe and a downstream pressure probe, such that the pressure measurement corresponds to a pressure differential across the valve element. In some embodiments of the first aspect, the upstream pressure probe includes a pitot probe and the downstream pressure probe includes a static pressure probe. In some embodiments of the first aspect, the predetermined maximum subsonic pressure includes a maximum expected subsonic pressure differential determined as the largest magnitude pressure difference that corresponds to a pressure ratio less than or equal to the critical pressure for the fuel over an expected range of system operating conditions.

In some embodiments of the first aspect, the limited scale range defines an upper limit less than or equal to a predetermined maximum inlet pressure of the fuel metering valve. In some embodiments of the first aspect, the limited scale range defines an upper limit less than or equal to the predetermined maximum subsonic pressure.

In a second aspect of the present disclosure, a combustion engine system includes: a fuel source; an engine that generates mechanical power via combustion of fuel provided by the fuel source; and a fuel metering valve located upstream of the engine and downstream of the fuel source, the fuel metering valve regulating the flow of gaseous fuel provided from the fuel source. The fuel metering valve includes: a valve body housing a valve element in an interior chamber between an inlet port and an outlet port, the valve element regulating a flow of fuel through the valve body; an actuator coupled to move the valve element relative to the valve body; a controller configured to regulate the position of the valve body via the actuator based on a pressure measurement to achieve a target mass flow rate of the fuel through the valve

body; and a pressure sensor arranged to provide the pressure measurement. The pressure sensor is calibrated for accuracy only across a limited scale range based on a predetermined maximum subsonic pressure.

In some embodiments of the second aspect, the combustion engine system further includes an engine control unit communicatively coupled to the fuel metering valve and configured to provide the target mass flow rate via a fuel demand signal.

In some embodiments of the second aspect, the flow of fuel includes a flow of gaseous fluid.

In some embodiments of the second aspect, the controller is configured to identify a sonic or subsonic flow condition on a downstream side of the valve element based on the pressure measurement. In some embodiments of the second aspect, the controller is further configured to: in response to identifying a subsonic flow condition, implement a first set of one or more flow equations to achieve the target mass flow rate; and in response to identifying a sonic flow condition, implement a second set of one or more different flow equations to achieve the target mass flow rate. In some embodiments of the second aspect, only the first set of flow equations include the pressure measurement as an input.

In some embodiments of the second aspect, the pressure sensor is fluidically coupled to an upstream pressure probe and a downstream pressure probe, such that the pressure measurement corresponds to a pressure differential across the valve element. In some embodiments of the second aspect, the upstream pressure probe includes a pitot probe and the downstream pressure probe includes a static pressure probe. In some embodiments of the second aspect, the predetermined maximum subsonic pressure includes a maximum expected subsonic pressure differential determined as the largest magnitude pressure difference that corresponds to a pressure ratio less than or equal to the critical pressure for the fuel over an expected range of system operating conditions.

In some embodiments of the second aspect, the limited scale range defines an upper limit less than or equal to a predetermined maximum inlet pressure of the fuel metering valve. In some embodiments of the second aspect, the limited scale range defines an upper limit less than or equal to the predetermined maximum subsonic pressure.

In a third aspect of the present disclosure, a method of constructing a fuel metering valve includes: identifying a plurality of operating conditions over an expected operating range of a combustion engine system; determining a maximum expected subsonic pressure based on identified operating conditions; and installing a pressure sensor into the fuel metering valve, the pressure sensor being calibrated for accuracy only across a limited scale range based on the determined maximum expected subsonic pressure.

In some embodiments of the third aspect, identifying the plurality of operating conditions includes identifying a plurality of upstream and downstream pressure pairs over the expected operating range of the combustion engine system. In some embodiments of the third aspect, determining the maximum expected subsonic pressure includes determining, based on the plurality of upstream and downstream pressure pairs, the largest magnitude pressure difference that corresponds to a pressure ratio less than or equal to a critical pressure for a predetermined fuel.

In some embodiments of the third aspect, installing the pressure sensor includes fluidically coupling the pressure sensor to an upstream pressure probe and a downstream pressure probe. In some embodiments of the third aspect, the upstream pressure probe includes a pitot probe and the downstream pressure probe includes a static pressure probe. In some embodiments of the third aspect, installing the pressure sensor further includes positioning the pressure sensor within a housing of a sensor module communicatively coupled to a main controller of the fuel metering valve.

In some embodiments of the third aspect, the limited scale range defines an upper limit less than or equal to a predetermined maximum inlet pressure of the fuel metering valve. In some embodiments of the third aspect, the limited scale range defines an upper limit less than or equal to the maximum expected subsonic pressure.

The details of one or more implementations of the subject matter described in this specification are set forth in the accompanying drawings and the description below. Other features, aspects, and advantages of the subject matter will become apparent from the description, the drawings, and the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is schematic diagram of an example combustion engine system.

FIGS. 2A-2D are perspective, top, rear and front views of an example fuel metering valve.

FIG. 3 is a schematic diagram of a portion of an example fuel metering valve.

FIG. 4 is a flow chart of a process for constructing an example fuel metering valve.

Like reference numbers and designations in the various drawings may indicate like elements.

DETAILED DESCRIPTION

Referring first to Fig. 1, a combustion engine system 100 includes a fuel source 102, a fuel metering valve 200, an engine 104, and an engine control unit (ECU) 106. The engine 104 generates mechanical power via combustion of a gaseous fuel provided by the fuel source 102. In some examples, the engine 104 is an industrial or aeroderivative gas turbine engine. The gas turbine engine may include an upstream compressor coupled to a downstream turbine with a combustion chamber located therebetween. The combustion chamber receives air from the compressor and gaseous fuel from the fuel source 102, and the fuel-air mixture is ignited to generate high temperature, high pressure fluid flow to drive the shaft of the turbine. In some examples, the engine 104 is a reciprocating internal combustion engine featuring a movable piston driven by combustion energy from the gaseous fuel mixed with air. The linear motion of the piston is converted to rotational motion of a crankshaft by a suitable mechanical linkage (e.g., a connecting rod).

The fuel source 102 may include a large storage tank, smaller pressure vessels (e.g., compressed gas cylinders), and/or a gas transportation pipeline. The flow of gaseous fuel 108 provided by the fuel source 102 may include any grade or quality of ambient gas-phase fluid suitable for combustion by the engine 104 (e.g., gaseous fuels ranging from methane to landfill gas to coal gas). In some examples, such as described below, the fuel metering valve 200 is an integrated, digitally compensated control valve and actuator system for regulating and metering the flow of gaseous fuel 108 provided from the fuel source 102, such that the engine 104 receives a metered flow of gaseous fuel 108' suitable for providing a required power output. The ECU 106 sends and receives signals 110a, 110b to and from the fuel metering valve 200 and the engine 104 to ensure proper operation of the engine 104 during use. As one

particular example, the fuel metering valve 200 may be designed to receive a fuel rate demand signal 110b from the ECU 106. The fuel rate demand signal 110b may correspond to a physical mass flow rate of fuel required by the engine 104. As described below, the fuel metering valve 200 incorporates feedback sensors which monitor fuel pressure, temperature, and valve pressure differential. Based on these sensor signals, the fuel metering valve 200 modulates a valve opening to produce the physical mass flow rate of fuel 108'.

In the foregoing description of the combustion engine system 100, various items of equipment, such as pipes, valves, pumps, fasteners, fittings, etc., may have been omitted to simplify the description. However, those skilled in the art will realize that such conventional equipment can be employed as desired. Those skilled in the art will further appreciate that various components described are recited as illustrative for contextual purposes and do not limit the scope of this disclosure.

FIGS. 2A-2D depict an example fluid metering valve 200 that can, for example, be incorporated in the combustion engine system 100 described above. As shown, the fuel metering valve 200 includes a valve body 202 housing a valve element 204 (see FIG. 2D), a sensor module 206, an actuator 208, and valve controller 210. The valve body 202 is situated between an inlet pipe 212 and an outlet pipe 214. The inlet pipe 212 includes a tubular body 216a bracketed by an inner flange 218a and an outer flange 220a. Similarly, the outlet pipe 214 includes a tubular body 216b bracketed by an inner flange 218b and an outer flange 220b. The inner flanges 218a, 218b are coupled to mating flanges 222 of the valve body 202 by mechanical fasteners 224. The flanges 222 define an inlet port and an outlet port of the valve body 202. The inlet pipe 212 is couplable to upstream piping leading from the fuel source 102 via the outer flange 220a. The outlet pipe is couplable to downstream piping leading to the engine 104 via the outer flange 220b.

An interior chamber is provided between the flanges 222 of the valve body 202 to house the valve element 204 (see FIG. 2D). The central bores of the inlet and outlet pipes 212, 214 are aligned with the inlet and outlet ports of the valve body 202, and therefore in fluid communication with the interior chamber to form a continuous flow path through the fluid metering valve 200. The valve element 204 is movable relative to the valve body 202 to regulate the flow of gaseous fuel 108 passing therethrough by altering the size of the flow path through the valve ("the valve area"). Movement of

the valve element 204 to constrict the valve area will decrease the mass flow rate of the fuel, and movement to open the valve area will increase the fuel mass flow rate. In this example, the valve element 204 is a rotating butterfly valve mounted on a rotatable valve shaft 228. The valve shaft 228 is coupled to the rotating drive stem (not shown) of the actuator 208. The actuator 208 acts as a rotary positioner to rotate the valve shaft 228, and therefore, the valve element 204, to a specified angular position. In this example, the actuator 208 includes an electromagnetic servo drive system including a displacement sensor and an integral controller. However, other suitable drive systems, such as an electrohydraulic servo drive or a stepper motor, may be used without departing from the scope of the present disclosure.

The valve element 204 is depicted in FIGS. 2C and 2D at a fully-closed position, having the face of its butterfly disk fully aligned with the inlet port of the valve body 202 to block fluid flow. Progressive rotation of the valve element 204 along the central axis of the valve shaft 228 turns the butterfly disk out of alignment with the inlet port of the valve body 202 to gradually open the flow path and increase the valve area, which increases the mass flow rate of gaseous fuel delivered to the engine 104. The valve element 204 can be rotated by the actuator 208 via the valve shaft 228 through numerous positions between the fully-closed position and a fully-opened position, where the butterfly disk is turned away from (e.g., orthogonal to) the inlet port of the valve body 202.

The valve controller 210 of the example fluid metering valve 200 is communicatively coupled to the actuator 208. The circuitry of the valve controller 210 can include one or more microprocessors configured to execute computer-readable instructions stored on one or more memory devices so as to achieve any of the control operations described herein. In some examples, during use, the valve controller 210 provides a position command signal that is received by the integral controller of the actuator 208 and executed by the drive system to alter the angular position of the valve element 204 within the valve body 202, as described above. The valve controller 210 derives the position command signal based on a fuel rate demand signal 110b (see FIG. 1) received from the ECU 106 (see FIG. 1) via a data port 230. That is, the valve controller 210 determines the angular position of the valve element 204 that corresponds to the valve area needed to physically achieve the mass flow rate indicated by the fuel rate demand signal 110b. In this example, the valve controller 210 is

configured (e.g., appropriately equipped and programmed) to calculate the valve area and derive the corresponding position command signal under both subsonic and sonic flow regimes. Further, in some examples, the valve controller 210 may be fully integrated with the actuator 208, such that the valve controller 210 directly operates the drive system of the actuator 208.

In the exemplary embodiment, the sensor module 206 is communicatively coupled to the valve controller 210 via a data transmission cable 232. The sensor module 206 includes a housing 234 mounted to the outlet pipe 214, and a collection of sensors enclosed within an internal space of the housing 234 that continually provide output to the valve controller 210 via the data transmission cable 232 at a predetermined sampling rate. The valve controller 210 receives the sensory output signal and calculates the requisite valve area based on the data contained therein. In this example, the sensor module 206 includes an inlet pressure sensor, a differential pressure sensor, and a temperature sensor (see FIG. 3). However, other suitable sensor configurations are also contemplated within the scope of the present disclosure. As shown in FIGS. 2C and 2D, the fuel metering valve 200 includes a stagnation (total) pressure probe 236 (e.g., a pitot probe) mounted on the inlet pipe 212, as well as a static pressure probe (not shown) and a temperature probe 238 mounted on the outlet pipe 214. A fluid line 240 fluidically couples the stagnation pressure probe 236 to the sensor module 206.

FIG. 3 illustrates an example sensor configuration suitable for use with an example fuel metering valve 300. In this example, the fuel metering valve 300 includes an inlet pressure sensor 342 fluidically coupled to a stagnation pressure probe 336 located on the inlet (upstream) side of the valve element 304, a differential pressure sensor 344 fluidically coupled to the stagnation pressure probe 336 and a static pressure probe 337 located on the outlet (downstream) side of the valve element 304, and a temperature sensor 346 coupled to a temperature probe 338 (e.g., a thermocouple or a thermistor) located on the outlet side of the valve element 304. The inlet pressure sensor 342 is appropriately configured to measure the absolute total pressure of the incoming flow of gaseous fuel 108 provided by the fuel source 102 (see FIG. 1). The differential pressure sensor 344 is appropriately configured to measure the stagnation-to-static pressure difference across the valve element 304. In some

examples, the differential pressure sensor is a dual-port resistive or capacitive pressure transducer.

Referring back to FIGS. 2A-2D, the valve controller 210 is configured to facilitate control of the valve element 204 via the actuator 208 by implementing appropriate flow equations (which may be stored in computer memory) that use the sensory output provided by the sensor module 206 (e.g., upstream total pressure (absolute), pressure differential across the valve element 204, and downstream temperature) as input variables in order to meet the physical mass fuel rate indicated by the fuel rate demand signal 110b from the ECU 106. In some implementations, various operating conditions of the engine 104 may cause the fuel metering valve 200 to experience either subsonic or sonic flow at the outlet side of the valve element 204. Sonic flow occurs when the velocity of the gaseous fuel flow reaches a Mach number of 1. For a given gas flowing through the fuel metering valve 200 at a given temperature, there is a critical pressure ratio (P_{cr}) of the outlet (downstream) pressure to the inlet (upstream) pressure (P_o/P_i) at which sonic flow occurs. The critical pressure ratio is not the same for all gases, for instance it is about 0.53 for air, about 0.54 for natural gas, and about 0.58 for propane. When sonic flow occurs at the outlet side of the valve element 204, downstream pressure (e.g., pressure differential) no longer has an effect on the velocity, and therefore mass flow rate, of the gaseous fuel. However, during subsonic flow conditions, the fuel mass flow rate is highly dependent on pressure differential. Accordingly, the valve controller 210 may be appropriately configured to implement a first set of one or more flow equations upon a detection of subsonic flow conditions, and a second set of one or more different flow equations upon a detection of sonic flow conditions. In some examples, the valve controller 210 may monitor the ratio of downstream to upstream pressure based on the sensory output of the inlet pressure sensor and the differential pressure sensor to detect when sonic flow occurs.

Generally, fuel mass flow is a function of the valve area, fuel pressure and fuel temperature, along with one or more properties of the gaseous fuel (e.g., gas constants). Likewise, the error associated with the fuel mass flow is a function of the errors associated with each individual input. As suggested above, a significant difference between subsonic mass flow equations and the sonic mass flow equations is the downstream or differential pressure measurement, which is only used as an input

with subsonic flow. Thus, reducing the error in the downstream or differential pressure measurement directly reduces the subsonic mass flow error, but not the sonic mass flow error. Accordingly, one or more embodiments of the present disclosure are based on a realization that the percent-of-point accuracy of the fuel metering valve 200 may be directly improved by utilizing a differential pressure sensor (or a downstream pressure sensor) that is calibrated for less than the entire operating range of pressures which the fuel metering valve 200 is designed to accommodate. In some examples, the percent-of-point accuracy of the fuel metering valve 200 can be improved by utilizing a differential pressure that is calibrated over a range that does not exceed the maximum expected subsonic pressure differential (within an appropriate error margin). With this technique, the percent-of-point accuracy for the fuel metering valve 200 is directly improved without incorporating a more accurate, and therefore more expensive, pressure differential sensor. In this context, the "maximum expected subsonic pressure differential" refers to the largest magnitude pressure difference (P_i-P_o) that corresponds to a pressure ratio (P_o/P_i) less than or equal to the critical pressure (P_{cr}) for a given gaseous fuel over the expected range of operating conditions of the combustion engine system 100.

The added benefit of the above-described technique is demonstrated by the following non-limiting example. In this example, the fuel metering valve is designed to operate within a combustion engine system having an inlet pressure range between 0 and 100 psia. The maximum expected subsonic pressure differential is 45 psid. The accuracy of the pressure differential sensor is set at 1% of the full scale of the sensor. A first differential pressure sensor is calibrated over a scale range limited from 0 to 100 psid (i.e., the full range of the fuel metering valve), and therefore produces a total error of 1 psid over the total scale. A second differential pressure sensor is calibrated over a scale range from 0 to 45 psid (i.e., a limited range corresponding to the maximum expected subsonic pressure differential), and therefore produces a total error of 0.45 psid over the total scale. In this example, in order to have the same percent-of-point accuracy for the fuel metering valve, the first differential pressure sensor would have required an accuracy of 0.45% of the full scale of the sensor, which is considerably less than the 1% accuracy specification for the second differential pressure sensor.

FIG. 4 illustrates a process 400 for constructing a fuel metering valve (e.g., the fuel metering valve 200). The process 400 can be implemented, for example, in connection with one or more components of the combustion engine system 100. Further, the operations of the processes do not require the any particular order to achieve desirable results. In addition, other operations may be provided, or operations may be eliminated, from the described processes without departing from the scope of the present disclosure.

According to the process 400, a plurality of operating conditions over the expected operating range of the combustion engine system 100 are identified (402). In some examples, each of the plurality of operating conditions can be expressed in terms of the respective upstream and downstream pressures on either side of the fuel metering valve. The upstream pressure may correspond to the supply pressure between the fuel source and the fuel metering valve. The downstream pressure may correspond to the fuel chamber pressure or the cylinder pressure of the engine. In some examples, the plurality of operating conditions may be identified via simulation (e.g., via suitable computational modeling software) or empirical testing. The maximum expected subsonic pressure is determined (404) based on the identified (402) plurality of operating conditions. In some examples, the maximum expected subsonic pressure may be determined in terms of a pressure differential between the upstream and downstream sides of the valve element. In such examples, the maximum expected subsonic pressure differential may be determined as the largest magnitude pressure difference that corresponds to a pressure ratio less than or equal to the critical pressure for a given gaseous fuel over the identified (402) plurality of operating conditions. A pressure sensor calibrated over a limited scale range selected based on the maximum expected subsonic pressure is installed (406) in the fuel metering valve. In some examples, the limited scale range defines an upper limit less than or equal to a predetermined maximum upstream pressure of the fuel metering valve. In some examples, the limited scale range defines an upper limit less than or equal to the maximum expected subsonic pressure. In some embodiments, the pressure sensor is installed to directly measure a differential pressure across the valve element. In some examples, the pressure sensor may be installed within the housing of a sensor module communicatively coupled to the main controller of the fuel metering valve.

A number of embodiments of the invention have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the inventions. For example, various other types of valve elements and assemblies (e.g., flapper valves, single-port ball valves, globe valves, etc.) may be used in conjunction with one or more devices, systems and methods descried above. As another example, various other types of pressure probes and sensors may be utilized. For instance, the differential pressure sensor described above may be replaced with a pressure sensor arranged to measure the absolute pressure on the downstream side of the valve element. In this case, the pressure differential may be calculated by the valve controller, as opposed to being directly measured. A maximum expected subsonic downstream pressure is determined from the expected operating conditions, and the downstream pressure sensor is calibrated over a limited scale range within the determined pressure. As yet another example, the combustion engine system described above may include two or more fuel metering valves, such as may be used in conjunction with a multi-stage gas turbine.

What is claimed is:

CLAIMS

1. A fuel metering valve, comprising:

a valve body housing a valve element in an interior chamber between an inlet port and an outlet port, the valve element regulating a flow of fuel through the valve body;

an actuator coupled to move the valve element relative to the valve body;

a controller configured to regulate the position of the valve body via the actuator based on a pressure measurement to achieve a target mass flow rate of the fuel through the valve body; and

a pressure sensor arranged to provide the pressure measurement,

wherein the pressure sensor is calibrated for accuracy only across a limited scale range based on a predetermined maximum subsonic pressure.

2. The fuel metering valve of claim 1, wherein the flow of fuel comprises a flow of gaseous fluid.

3. The fuel metering valve of claim 1 or claim 2, wherein the controller is configured to identify a sonic or subsonic flow condition on a downstream side of the valve element based on the pressure measurement.

4. The fuel metering valve of claim 3, wherein the controller is further configured to:

in response to identifying a subsonic flow condition, implement a first set of one or more flow equations to achieve the target mass flow rate; and

in response to identifying a sonic flow condition, implement a second set of one or more different flow equations to achieve the target mass flow rate.

5. The fuel metering valve of claim 4, wherein only the first set of flow equations include the pressure measurement as an input.

6. The fuel metering valve of any of the above claims, wherein the pressure sensor is fluidically coupled to an upstream pressure probe and a downstream pressure probe,

such that the pressure measurement corresponds to a pressure differential across the valve element.

7. The fuel metering valve of claim 6, wherein the upstream pressure probe comprises a pitot probe and the downstream pressure probe comprises a static pressure probe.

8. The fuel metering valve of claim 6 or claim 7, wherein the predetermined maximum subsonic pressure comprises a maximum expected subsonic pressure differential determined as the largest magnitude pressure difference that corresponds to a pressure ratio less than or equal to the critical pressure for the fuel over an expected range of system operating conditions.

9. The fuel metering valve of any of the above claims, wherein the limited scale range defines an upper limit less than or equal to a predetermined maximum inlet pressure of the fuel metering valve.

10. The fuel metering valve of claim 9, wherein the limited scale range defines an upper limit less than or equal to the predetermined maximum subsonic pressure.

11. A combustion engine system, comprising:

a fuel source;

an engine that generates mechanical power via combustion of fuel provided by the fuel source; and

a fuel metering valve located upstream of the engine and downstream of the fuel source, the fuel metering valve regulating the flow of gaseous fuel provided from the fuel source, and wherein the fuel metering valve comprises:

a valve body housing a valve element in an interior chamber between an inlet port and an outlet port, the valve element regulating a flow of fuel through the valve body;

an actuator coupled to move the valve element relative to the valve body;

a controller configured to regulate the position of the valve body via the actuator based on a pressure measurement to achieve a target mass flow rate of the fuel through the valve body; and

a pressure sensor arranged to provide the pressure measurement,

wherein the pressure sensor is calibrated for accuracy only across a limited scale range based on a predetermined maximum subsonic pressure.

12. The combustion engine system of claim 11, further comprising an engine control unit communicatively coupled to the fuel metering valve and configured to provide the target mass flow rate via a fuel demand signal.

13. The combustion engine system of claim 11 or claim 12, wherein the flow of fuel comprises a flow of gaseous fluid.

14. The combustion engine system of any of claims 11-13, wherein the controller is configured to identify a sonic or subsonic flow condition on a downstream side of the valve element based on the pressure measurement.

15. The combustion engine system of claim 14, wherein the controller is further configured to:

in response to identifying a subsonic flow condition, implement a first set of one or more flow equations to achieve the target mass flow rate; and

in response to identifying a sonic flow condition, implement a second set of one or more different flow equations to achieve the target mass flow rate.

16. The combustion engine system of claim 15, wherein only the first set of flow equations include the pressure measurement as an input.

17. The combustion engine system of any of claims 11-16, wherein the pressure sensor is fluidically coupled to an upstream pressure probe and a downstream pressure probe, such that the pressure measurement corresponds to a pressure differential across the valve element.

18. The combustion engine system of claim 17, wherein the upstream pressure probe comprises a pitot probe and the downstream pressure probe comprises a static pressure probe.

19. The combustion engine system of claim 17 or claim 18, wherein the predetermined maximum subsonic pressure comprises a maximum expected subsonic pressure differential determined as the largest magnitude pressure difference that corresponds to a pressure ratio less than or equal to the critical pressure for the fuel over an expected range of system operating conditions.

20. The combustion engine system of any of claims 11-19, wherein the limited scale range defines an upper limit less than or equal to a predetermined maximum inlet pressure of the fuel metering valve.

21. The combustion engine system of claim 20, wherein the limited scale range defines an upper limit less than or equal to the predetermined maximum subsonic pressure.

22. A method of constructing a fuel metering valve, the method comprising:

identifying a plurality of operating conditions over an expected operating range of a combustion engine system;

determining a maximum expected subsonic pressure based on identified operating conditions; and

installing a pressure sensor into the fuel metering valve, the pressure sensor being calibrated for accuracy only across a limited scale range based on the determined maximum expected subsonic pressure.

23. The method of claim 22, wherein identifying the plurality of operating conditions comprises identifying a plurality of upstream and downstream pressure pairs over the expected operating range of the combustion engine system.

24. The method of claim 23, wherein determining the maximum expected subsonic pressure comprises determining, based on the plurality of upstream and downstream

pressure pairs, the largest magnitude pressure difference that corresponds to a pressure ratio less than or equal to a critical pressure for a predetermined fuel.

25. The method of any of claims 22-24, wherein installing the pressure sensor comprises fluidically coupling the pressure sensor to an upstream pressure probe and a downstream pressure probe.

26. The method of claim 25, wherein the upstream pressure probe comprises a pitot probe and the downstream pressure probe comprises a static pressure probe.

27. The method of claim 25 or claim 26, wherein installing the pressure sensor further comprises positioning the pressure sensor within a housing of a sensor module communicatively coupled to a main controller of the fuel metering valve.

28. The method of any of claims 22-27, wherein the limited scale range defines an upper limit less than or equal to a predetermined maximum inlet pressure of the fuel metering valve.

29. The method of claim 29, wherein the limited scale range defines an upper limit less than or equal to the maximum expected subsonic pressure.

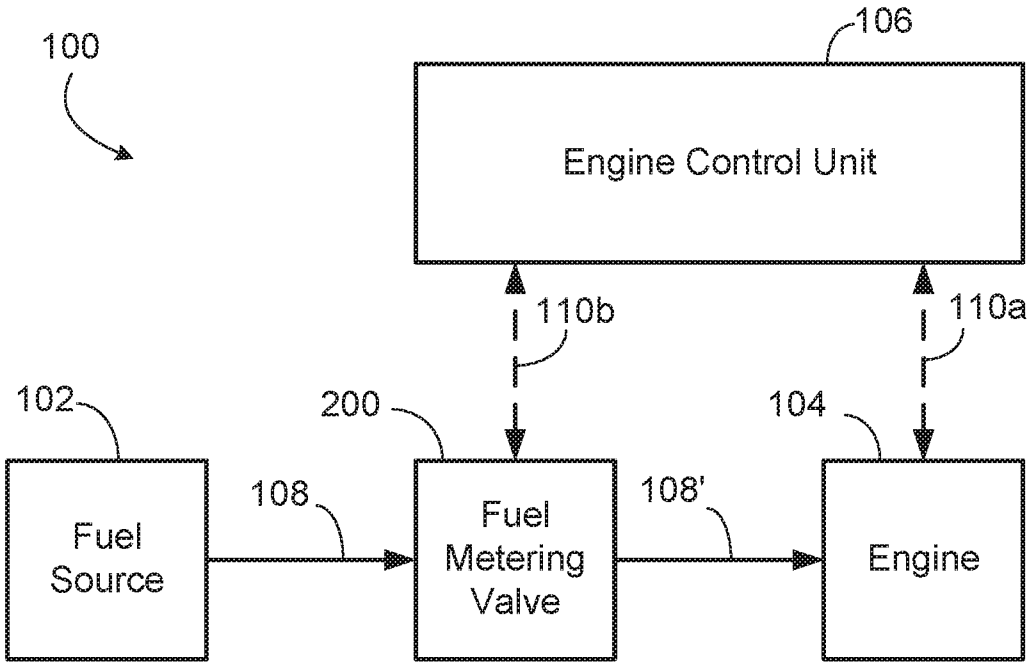

100
106
Engine Control Unit
110b
110a
102
200
104
108
108'
Fuel Source
Fuel Metering Valve
Engine

FIG. 1

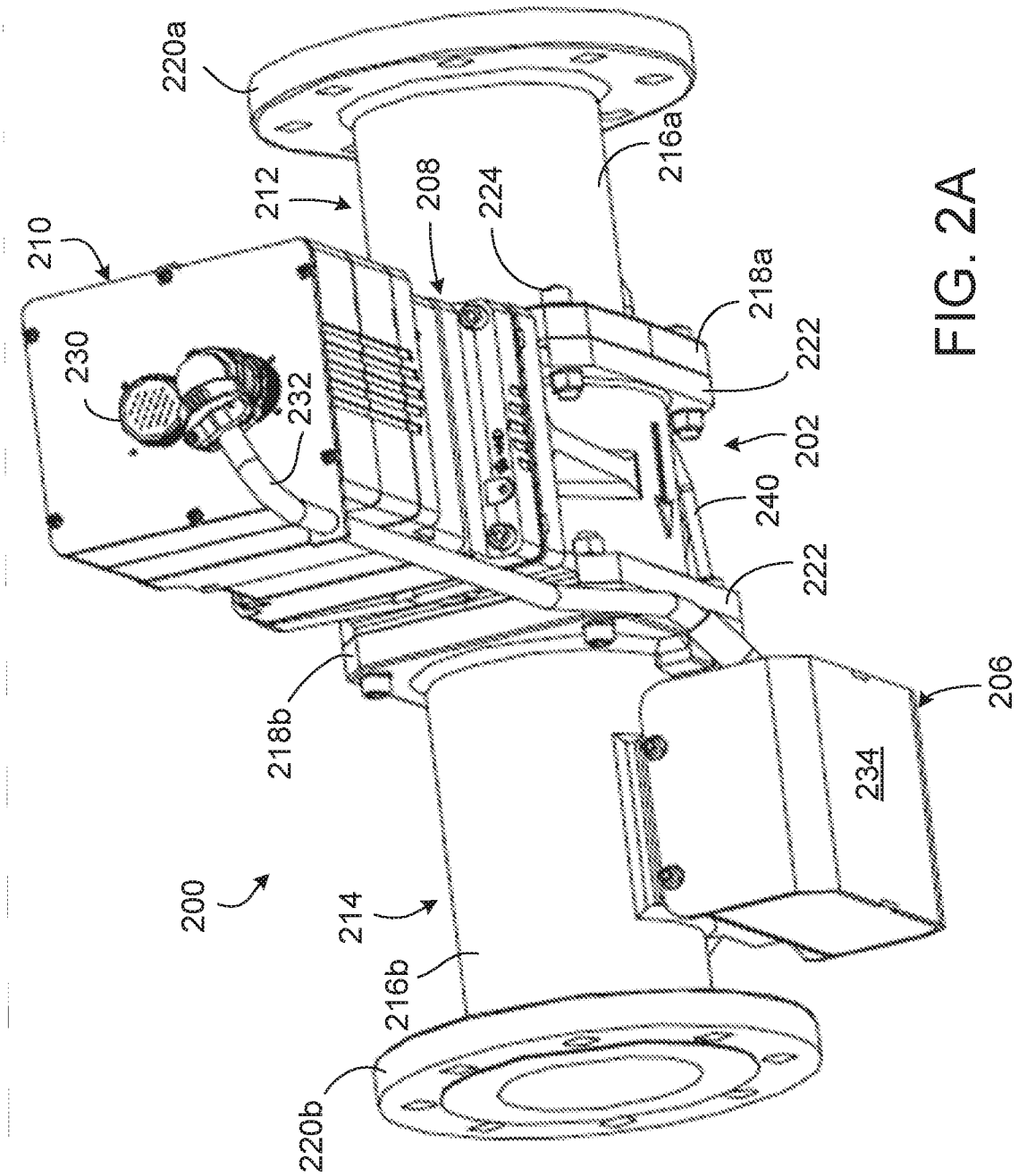

220a
212
208
224
216a
210
218a
230
222
232
202
240
222
218b
206
234
200
214
216b
220b

FIG. 2A

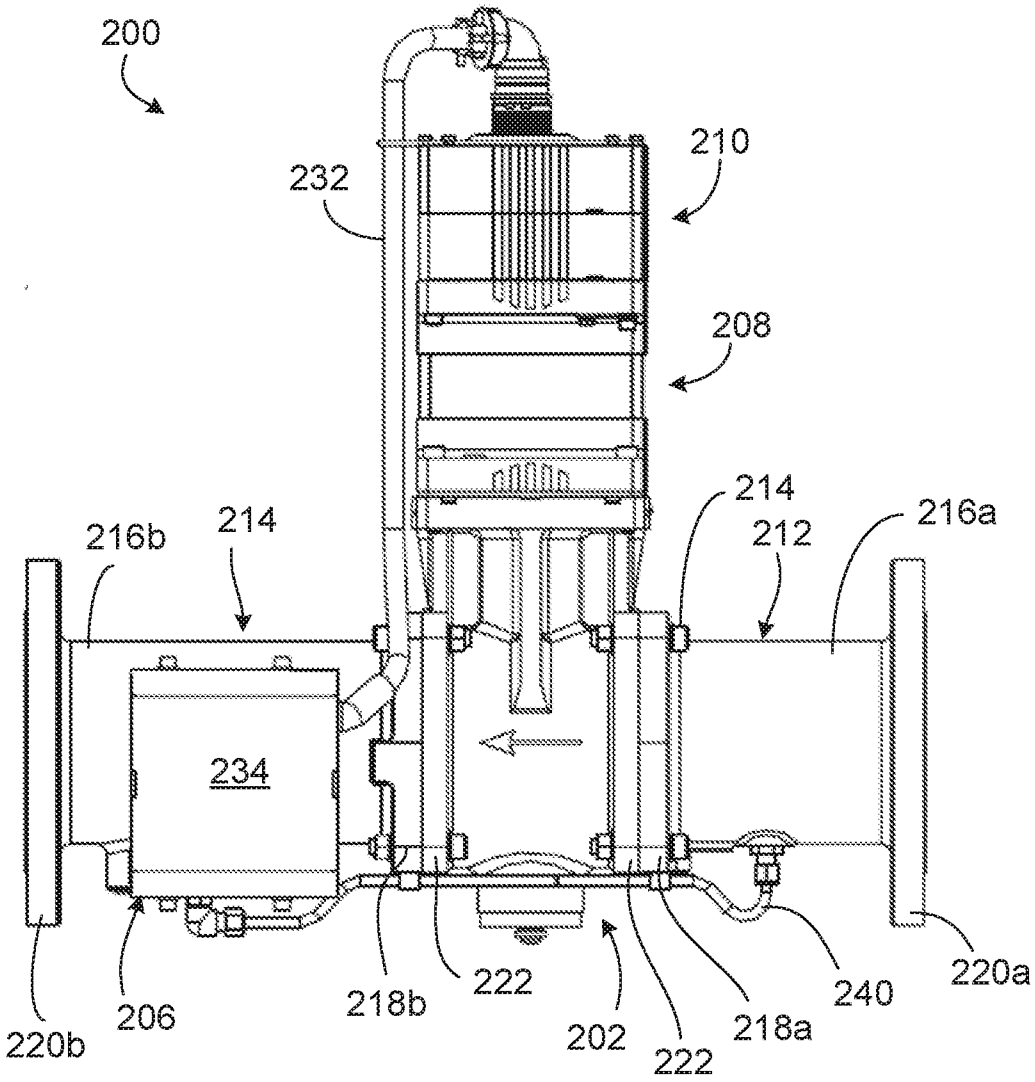

200
210
232
208
214
216b
214
212
216a
234
220b
206
218b
222
202
222
218a
240
220a

FIG. 2B

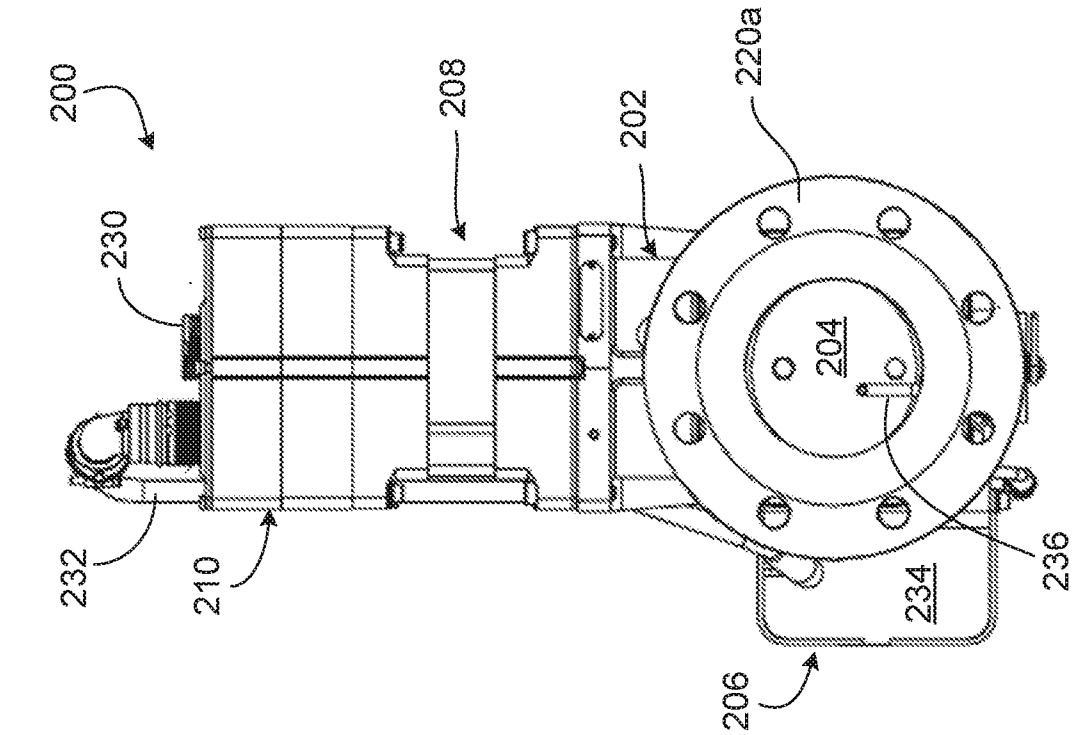

200
208
202
220a
230
204
232
210
236
234
206

FIG. 2D

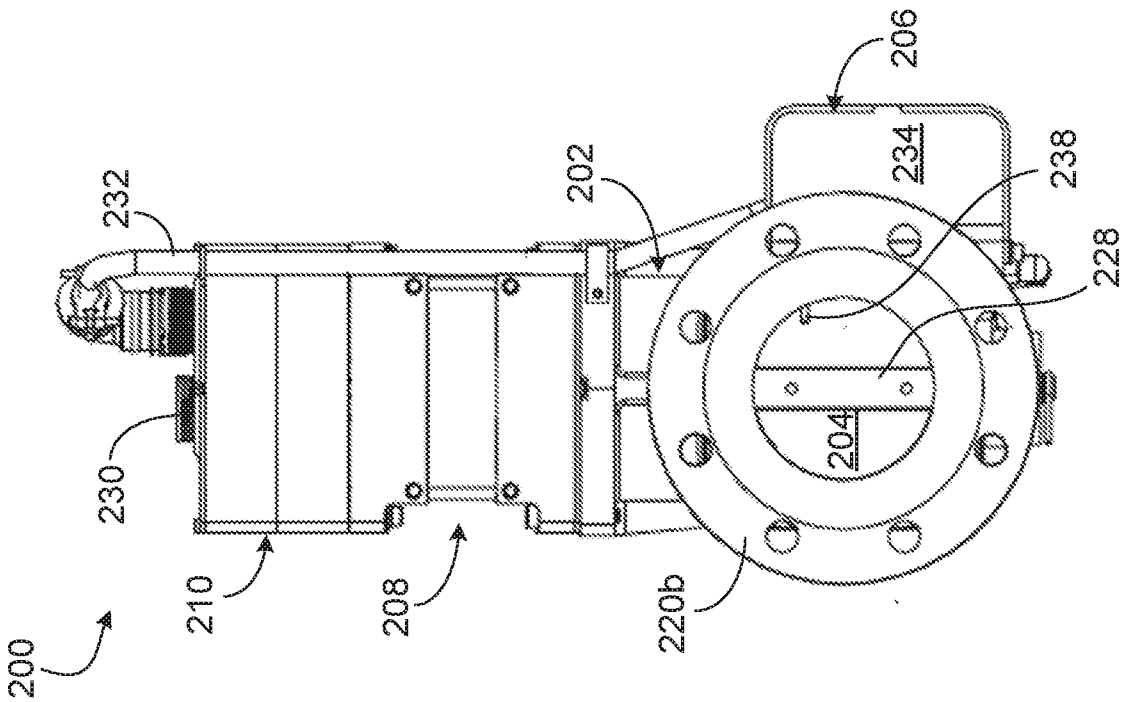

206
234
238
202
232
228
230
204
210
208
220b
200

FIG. 2C

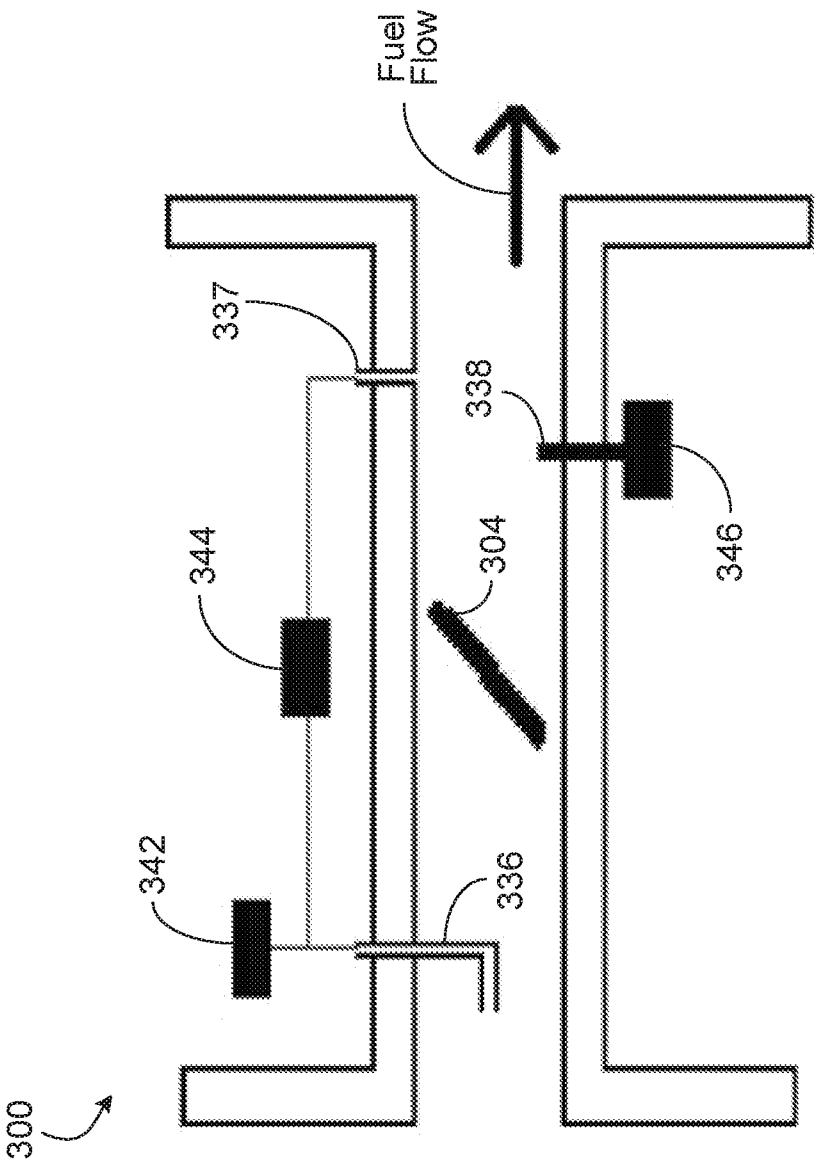


FIG. 3

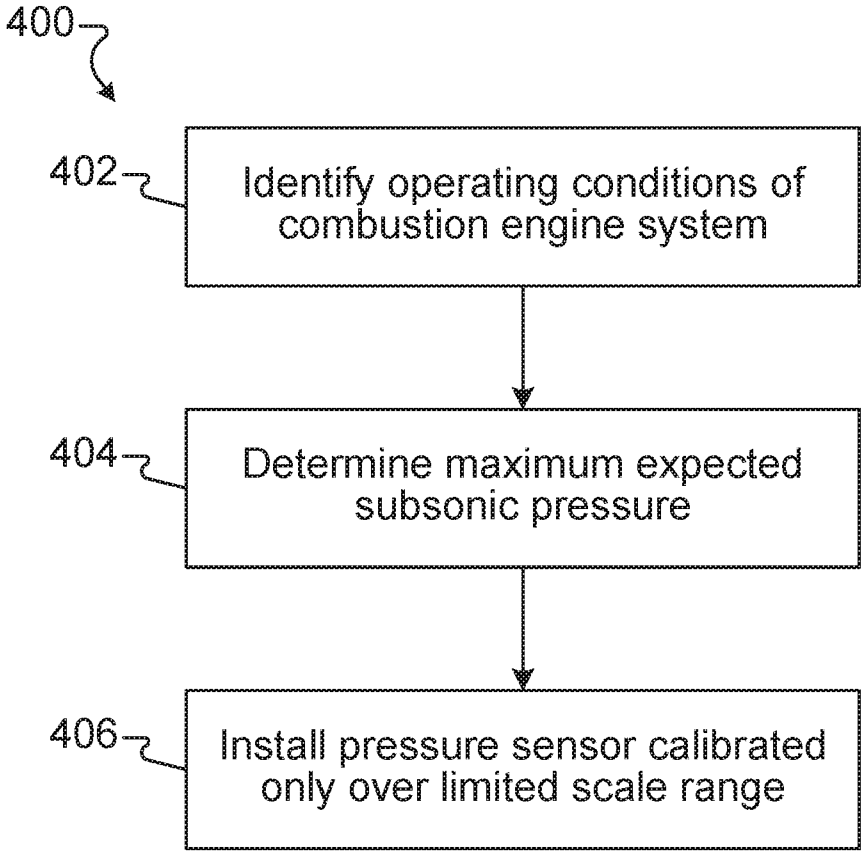

400
402
Identify operating conditions of combustion engine system
404
Determine maximum expected subsonic pressure
406
Install pressure sensor calibrated only over limited scale range

FIG. 4

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2016/028250

A. CLASSIFICATION OF SUBJECT MATTER
INV. F02C7/232 F02C9/26
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F02C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6 016 832 A (VARS CURTIS C [US] ET AL) 25 January 2000 (2000-01-25) column 1, line 5 - column 3, line 5 figures 1-4	1-29
A	US 5 090 390 A (FELDINGER MARTIN [DE]) 25 February 1992 (1992-02-25) column 1, line 45 - column 5, line 2 figures 1-4	1-29
A	US 2003/192595 A1 (BENSON DWAYNE M [US]) 16 October 2003 (2003-10-16) paragraphs [0014] - [0017] figure 1	1-29
A	US 5 388 607 A (RAMAKER ANTONIUS E T J [NL] ET AL) 14 February 1995 (1995-02-14) column 2, line 36 - column 5, line 40 figures 1-4	1-29

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
15 July 2016	21/07/2016

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Gebker, Ulrich

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2016/028250

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 6016832 A	25-01-2000	NONE	
US 5090390 A	25-02-1992	DE 4013849 A1	31-10-1991
		JP H0626382 A	01-02-1994
		US 5090390 A	25-02-1992
US 2003192595 A1	16-10-2003	AU 2003224889 A1	27-10-2003
		EP 1492973 A1	05-01-2005
		US 2003192595 A1	16-10-2003
		WO 03087642 A1	23-10-2003
US 5388607 A	14-02-1995	AT 145449 T	15-12-1996
		AU 4432393 A	03-02-1994
		CA 2101711 A1	01-02-1994
		DE 69306056 D1	02-01-1997
		DE 69306056 T2	13-03-1997
		DK 0581391 T3	09-12-1996
		EP 0581391 A1	02-02-1994
		ES 2096848 T3	16-03-1997
		JP H06173725 A	21-06-1994
		NL 9201391 A	16-02-1994
		US 5388607 A	14-02-1995