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(54) Title: SYSTEMS AND METHODS FOR PROVIDING MOTION AMPLIFICATION AND COMPENSATION BY FLUID DISPLACEMENT

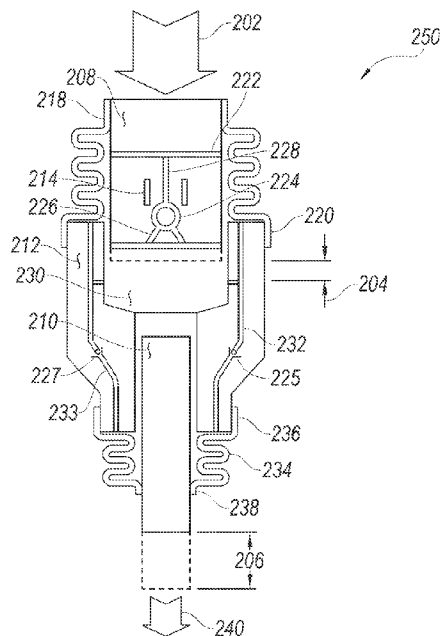


Fig. 2

(57) Abstract: The present technology relates generally systems and methods for providing motion amplification and compensation by fluid displacement in gaseous fuel injector systems. For example, some embodiments of gaseous fuel injectors include a piezoelectric actuator and a motion transfer system coupled to the piezoelectric actuator. The motion transfer system includes a housing, a first piston having a first effective area disposed in the housing, and a second piston having a second effective area disposed in the housing. The second effective area is less than the first effective area and the first and second pistons define a fluid chamber therebetween. The motion transfer system can amplify actuation of a gaseous fuel injector valve.

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SYSTEMS AND METHODS FOR PROVIDING MOTION AMPLIFICATION  
AND COMPENSATION BY FLUID DISPLACEMENT

CROSS-REFERENCE TO RELATED APPLICATION

**[0001]** The present application claims priority to and the benefit of U.S. Patent Application No. 13/842,636 filed March 15, 2013, which is incorporated herein by reference in its entirety.

TECHNICAL FIELD

**[0002]** The present technology relates generally to systems and methods for providing motion amplification and compensation by fluid displacement. Particular embodiments are directed to motion transfer systems for use in gaseous fuel injectors.

BACKGROUND

**[0003]** Fuel injection systems are typically used to inject a fuel spray into an inlet manifold or a combustion chamber of an engine. Fuel injection systems have become the primary fuel delivery system used in automotive engines, having almost completely replaced carburetors since the late 1980s. The gaseous fuel injectors used in these fuel injection systems are generally capable of two basic functions. First, they deliver a metered amount of fuel for each inlet stroke of the engine so that a suitable air-fuel ratio can be maintained for fuel combustion. Second, they disperse fuel to improve the efficiency of the combustion process. Conventional gaseous fuel injection systems are typically connected to a pressurized fuel supply, and the fuel can be metered into the combustion chamber by varying the time for which the injectors are open. The fuel can also be dispersed into the combustion chamber by forcing the fuel through a small orifice in the injectors.

BRIEF DESCRIPTION OF THE DRAWINGS

**[0004]** Figure 1 is a schematic cross-sectional side view of an injector configured in accordance with embodiments of the technology.

**[0005]** Figure 2 is a cross-sectional side view of a motion transfer system for use in the injector of Figure 1 and configured in accordance with embodiments of the technology.

**[0006]** Figure 3 a cross-sectional side view of a motion transfer system configured in accordance with embodiments of the technology.

**[0007]** Figure 4 a cross-sectional side view of a motion transfer system configured in accordance with embodiments of the technology.

**[0008]** Figure 5 a cross-sectional side view of a motion transfer system configured in accordance with embodiments of the technology.

#### DETAILED DESCRIPTION

**[0009]** The present technology relates generally to systems and methods for providing motion amplification and compensation by fluid displacement in fuel injector systems. For example, some embodiments of gaseous fuel injectors include a piezoelectric actuator and a motion transfer system coupled to the piezoelectric actuator. The motion transfer system includes a housing, a first piston having a first effective area disposed in the housing, and a second piston having a second effective area disposed in the housing. The second effective area is smaller than the first effective area, and the first and second pistons define a fluid chamber therebetween. The motion transfer system can amplify actuation of a gaseous fuel injector valve.

**[0010]** Specific details of several embodiments of the technology are described below with reference to Figures 1-5. Other details describing well-known structures and systems often associated with motion transfer systems, fuel injection systems, and ignition systems have not been set forth in the following disclosure to avoid unnecessarily obscuring the description of the various embodiments of the technology. Many of the details, dimensions, angles, and other features shown in the Figures are merely illustrative of particular embodiments of the technology. Accordingly, other embodiments can have other details, dimensions, angles, and features without departing from the spirit or scope of the present technology. A person of ordinary skill in the art, therefore, will accordingly understand that the technology may have other embodiments with additional elements, or the technology may have other embodiments without several of the features shown and described below with reference to Figures 1-5.

**[0011]** Figure 1 is a schematic cross-sectional side view of an injector 101 configured in accordance with an embodiment of the technology. The injector 101 is configured to inject fuel into

a combustion chamber 105 and utilize a motion transfer system to transfer force and linear motion to a reduced, equal or greater motion magnitude. The motion transfer system 150 is schematically illustrated in Figure 1 and can be positioned at any location on the injector 101 and coupled to any of the features described in detail below. Moreover, in certain embodiments the motion transfer system 150 can be integral with one or more of the valve actuating components described in detail below. Furthermore, although several of the additional features of the illustrated injector 101 described below are shown schematically for purposes of illustration, several of these schematically-illustrated features are described in detail below with reference to various features of embodiments of the disclosure. Accordingly, the relative location, position, size, orientation, etc. of the schematically-illustrated components of the Figures are not intended to limit the present disclosure.

**[0012]** In the illustrated embodiment, the injector 101 includes a casing or body 113 having a middle portion 117 extending between a base portion 115 and a nozzle portion 119. The nozzle portion 119 extends at least partially through a port in an engine head 107 to position the nozzle portion 119 at the interface with the combustion chamber 105. The injector 101 further includes a fuel passage or channel 141 extending through the body 113 from the base portion 115 to the nozzle portion 119. The channel 141 is configured to allow fuel to flow through the body 113. The channel 141 is also configured to allow other components, such as a valve operator assembly 131, an actuator 123, instrumentation components, and/or energy source components of the injector 101 to pass through the body 113. According to additional features of the illustrated embodiment, the nozzle portion 119 can include one or more ignition features for generating an ignition event for igniting the fuel in the combustion chamber 105. For example, the injector 101 can include any of the ignition features disclosed in U.S. Patent Application No. 12/841,170 entitled "INTEGRATED FUEL INJECTORS AND IGNITERS AND ASSOCIATED METHODS OF USE AND MANUFACTURE," filed July 21, 2010, which is incorporated herein by reference in its entirety.

**[0013]** In certain embodiments, the actuator 123 can be a cable, stiffened cable, or rod that has a first end portion that is operatively coupled to a flow control device or valve 121 carried by the nozzle portion 119. The actuator 123 can be integral with the flow valve 121 or a separate component from the flow valve 121. As such, the flow valve 121 is positioned proximate to, and

in communication with, the combustion chamber 105. Although not shown in Figure 1, in certain embodiments the injector 101 can include more than one flow valve 121, as well as one or more one-way check valves positioned proximate to the combustion chamber 105, as well as at other locations on the body 113. For example, the injector 101 can include any of the valves and associated valve actuation assemblies as disclosed in the patent applications incorporated by reference above.

**[0014]** The position of the flow valve 121 can be controlled by the valve operator assembly 131. For example, the valve operator assembly 131 can include a plunger, prime mover, or driver 125 that is operatively coupled to the actuator 123. The actuator 123 and/or driver 125 can further be coupled to a processor or controller 129. As explained in detail below with reference to various embodiments of the disclosure, the driver 125 and/or actuator 123 can be responsive to the controller 129. The controller 129 can be positioned on the injector 101 or remotely from the injector 101. The controller 129 and/or the driver 125 are configured to rapidly and precisely actuate the actuator 123 to inject fuel into the combustion chamber 105 by moving the flow valve 121 via the actuator 123. For example, in certain embodiments, the flow valve 121 can move outwardly (e.g., toward the combustion chamber 105) and, in other embodiments, inwardly (e.g., away from the combustion chamber 105) to meter and control injection of the fuel. Moreover, the driver 125 can add tension to the actuator 123 to keep the flow valve 121 in a closed or seated position, and the driver 125 can relax or relieve the tension in the actuator 123 to allow the flow valve 121 to inject fuel. In other embodiments, the flow valve 121 may be opened and closed depending on the pressure of the fuel in the body 113, without the use of an actuator cable or rod. Additionally, although only a single flow valve 121 is shown at the interface of the combustion chamber 105, in other embodiments the flow valve 121 can be positioned at other locations on the injector 101 and can be actuated in combination with one or more other flow valves or one-way check valves.

**[0015]** The injector 101 can further include a sensor and/or transmitting component 127 for detecting and relaying combustion chamber properties, such as temperatures and pressure, and providing feedback to the controller 129. The sensor 127 can be integral to the valve 121, the actuator 123, and/or the nozzle portion 119 or a separate component that is carried by any of these

portions of the injector 101. In one embodiment, the actuator 123 can be formed from fiber optic cables or insulated transducers integrated within a rod or cable, or can include other sensors to detect and communicate combustion chamber data. Although not shown in Figure 1, in other embodiments, the injector 101 can include other sensors or monitoring instrumentation located at various positions on the injector 101. For example, the body 113 can include optical fibers integrated into the material of the body 113. In addition, the flow valve 121 can be configured to sense or carry sensors to transmit combustion data to one or more controllers 129 associated with the injector 101. This data can be transmitted via wireless, wired, optical or other transmission mediums to the controller 129 or other components. Such feedback enables extremely rapid and adaptive adjustments for desired fuel injection factors and characteristics including, for example, fuel delivery pressure, fuel injection initiation timing, fuel injection durations for production of multi-layered or stratified charges, combustion chamber pressure and/or temperature, the timing of one, multiple or continuous plasma ignitions or capacitive discharges, etc. For example, the sensor 127 can provide feedback to the controller 129 as to whether the measurable conditions within the combustion chamber 105, such as temperature or pressure, fall within ranges that have been predetermined to provide desired combustion efficiency. Based on this feedback, the controller 129 in turn can direct the motion transfer system 150 to manipulate the frequency and/or degree of flow valve 121 actuation.

**[0016]** The motion transfer system 150 can take on numerous forms according to different embodiments of the disclosure and can transfer or modify motion of the driver 125, the actuator 123, the flow valve 121, and/or to other components of the gaseous fuel injector 101. In some embodiments, the motion transfer system 150 transfers motion directly to the actuator 123 by any of the means described above. The actuator 123 in turn opens the flow valve 121 in a stroke responsive to the motion transfer, thereby altering the fuel distribution rate and/or pressure. In some embodiments, the motion transfer system 150 transfers motion to the flow valve 121 directly.

**[0017]** Figure 2 a cross-sectional side view of a motion transfer system 250 configured in accordance with embodiments of the technology. The system 250 can be used to transfer a force or linear motion to a reduced, equal, or greater magnitude. The system 250 can include a first piston 208 and second piston 210 that move within respective bores within a housing 212 in response to an

initial force 202 applied directly or indirectly to the first piston 208. In some embodiments, one or both pistons 208, 210 move unidirectionally within the housing 212. A working fluid in a displacement zone 230 serves as a deformable medium and linkage to transfer the initial force 202 exerted through the first piston 208 to the second piston 210. In several embodiments, the displacement zone 230 comprises a fluid chamber or working volume reservoir at least partially positioned between the first piston 208 and the second piston 210. In some embodiments, the fluid comprises silicone or fluorosilicone hydraulic oil. In other embodiments, the working fluid can be diesel fuel, gasoline, jet fuels, or other liquid fuels such as alcohols.

**[0018]** In an illustrative embodiment of operation, the initial force 202 on the first piston 208 produces pressure in the fluid in the displacement zone 230 that is approximately equivalent to the magnitude of the initial force 202 divided by a cross-sectional area  $A_1$  (i.e., “effective area”) of the first piston 208. The first piston 208 is moved by an initial displacement 204 by the initial force 202. The initial displacement 204 is amplified by the pressurized fluid in the displacement zone 230 to produce a greater magnitude of resulting displacement 206 in the second piston 210. The second piston 210 transfers this resulting displacement 206 via an output force 240.

**[0019]** The resulting displacement 206 is greater than the initial displacement 204 according to the ratio of the cross-sectional area  $A_1$  of the first piston 208 divided by a cross-sectional area  $A_2$  of the second piston 210. More specifically, the initial force 202 makes the first piston 208 move, causing displacement of a volume  $V_1$  equaling the first piston’s cross-sectional area  $A_1$  multiplied by the initial displacement 204 of the first piston 208, to produce the resulting linear displacement 206 of the second piston 210. The resulting displacement 206 multiplied by the cross-sectional area  $A_2$  of the second piston 210 is also equivalent to  $V_1$ , so the subsequent displacement 206 is larger than the initial displacement 204 of the first piston 208 according to the ratio of piston areas  $A_1/A_2$ . The resulting displacement 206 is approximately equal to the initial force 202 multiplied by the ratio of the piston’s cross-sectional areas  $A_2/A_1$ , or the pressure in the fluid in the displacement zone 230 multiplied by the cross-sectional area of the second piston 210.

**[0020]** Referring to Figures 1 and 2 together, in some embodiments, the motion transfer system 250 can be used to modify an initial displacement of the actuator 123 to a different resulting displacement 206 of the flow valve 121. This enables a relatively small initial displacement 204 of

the actuator 123 (such as motion generated by a prime mover, such as a piezoelectric, magnetostrictive, electromagnetic, electromechanical, pneumatic, or hydraulic force generator) to be amplified by the motion transfer system 250 as needed for actuation of the flow valve 121 (i.e., the inward or outward opening of the flow valve 121). The motion transfer system 250 can also serve as a thermal expansion compensation linkage for assemblies such as the injector 101.

**[0021]** Leakage of fluid past the first piston 208 and/or the second piston 210 can be contained within one or more suitable reservoirs such as hermetically sealed upper bellows 228 and/or lower bellows 234. Each bellows 228, 234 can comprise a reservoir chamber. In some embodiments, the term “bellows” as used herein may include bellows that are spiral formed and that may perform spring actions where needed to improve desired operations. In some embodiments, an annular portion of the upper bellows 228 is welded, brazed, or otherwise sealingly attached to the first piston 208 at a first attachment point 218 and to the housing 212 at a second attachment point 220. Similarly, the lower bellows 234 can be sealingly attached to the housing 212 at a third attachment point 236 and to the second piston 210 at a fourth attachment point 238. Hermetically sealing the motion transfer system 250 can provide assurance that the fluid is provided continuously in the correct amount needed for motion transfer operations, and can greatly improve the internal protection of other components from contamination by the fluid that might otherwise eventually leak into potentially sensitive zones.

**[0022]** The upper and lower bellows 228, 234 may be connected via passageways 232, 233. Reloading the fluid from storage within the upper bellows 228 to the working fluid inventory in the displacement zone 230 can be done by pumping the first piston 208 to provide passage through a conduit 222 to the upper bellows 228 and past a one-way check valve 224, which may be urged into a closed position by the action of the first piston 208 and/or by a suitable spring such as a magnet 214. Transferring the fluid that has accumulated within the lower bellows 234, by pumping the second piston 210, through passageways 232, 233 may be unidirectional as provided by one-way check valves 225, 227. Thus, the fluid will be delivered from the lower bellows 234 to the upper bellows 228 for reloading the inventory of fluid in the displacement zone 230 as shown.

**[0023]** In certain embodiments, the upper and lower bellows 228, 234 are operated with preferred transfer rates that minimize the transfer of fluid past the first piston 208 compared to the

allowed fluid transfer rate past the second piston 210. This provides for considerable heat transfer to and through the higher surface-to-volume passageways 232, 233 and through the housing 212. Heat can be generated in the motion transfer system 250 by friction and/or viscous losses as fluid inventory in the displacement zone 230 is rapidly moved and reshaped to translate the initial displacement 204 to the resulting displacement 206. The motion of the fluid within the passageways 232, 233 and the motion of the bellows 228, 234 provide assured heat transfers and remove excess heat. Ultimately such heat is removed from the fuel and/or other fluids that are circulated through the injector 101.

**[0024]** Figure 3 a cross-sectional side view of a motion transfer system 350 configured in accordance with embodiments of the technology. The motion transfer system 350 includes several features generally similar to the motion transfer system 250 described above. For example, the system 350 can include a larger piston 304 and smaller piston 306 that move within respective bores within a body 332 in response to an initial force 330 applied directly or indirectly to the larger piston 304. A working fluid in a displacement zone 302 serves as a deformable medium and linkage to transfer the initial force 330 exerted through the larger piston 304 to the smaller piston 306. In several embodiments, the displacement zone 302 comprises a fluid chamber or working volume reservoir at least partially positioned between the larger piston 304 and the smaller piston 306. In operation, the larger piston 304 is moved by an initial displacement 308 by the initial force 330. The initial displacement 308 is amplified by the pressurized fluid in the displacement zone 302 to produce a greater magnitude of resulting displacement 310 in the smaller piston 306.

**[0025]** Fluid that leaks past the larger piston 304 and/or the smaller piston 306 can be contained within one or more suitable reservoirs such as hermetically sealed upper bellows 324 and/or lower bellows 314. In some embodiments, the bellows 314, 324 are spiral bellows. The bellows 314, 324 may be utilized to keep fuel constituents and/or particles and debris out of the clearances between the respective cylinder bores in the body 332. This can help ensure the smooth relative motion between components such as the larger piston 304 and the smaller piston 306.

**[0026]** The upper and lower bellows 324, 314 may be connected via passageways 316, 320, 322. Reloading the fluid from storage within the upper bellows 324 to the working fluid inventory in the displacement zone 302 in the manner described above can restart the operating cycle.

Transferring the fluid that has accumulated within the lower bellows 314, by pumping the smaller piston 306, through passageway 316 may be unidirectional as provided by one-way check valves 318.

**[0027]** Deformable substances in the displacement zone 302 can include water and ethylene or propylene glycol solutions, thixotropic fluids that produce low viscosity molecular movements upon application of deforming force, and rubber-like compositions that are readily reshaped to conform to space geometry changes. Thixotropic fluids can provide higher viscosity resistance to leakage along with greatly reduced viscosity when the shape of the occupied space is rapidly varied.

**[0028]** One exemplary embodiment of a thixotropic fluid is a solution of mostly water and a relatively small amount of an antifreeze agent that enables various live tissue cells to survive temperatures that ordinarily cause freeze rupture as water freezes. In some embodiments, agents such as a beta-mannopyranosyl-(1-->4), a beta-xylopyranose backbone, and a fatty acid component may be utilized as an internal lubricant to provide desirable thixotropic viscosity and body. The lipid inventory may include types and portions that are covalently linked to the saccharide. Similarly, protein-like polymeric components may be utilized to further customize the internal lubrication and/or thixotropic performance.

**[0029]** Figure 4 a cross-sectional side view of a motion transfer system 450 configured in accordance with embodiments of the technology. The motion transfer system 450 includes several features generally similar to the motion transfer system 250 described above. For example, the system 450 includes a first piston 408 and second piston 410 that move within respective bores within a body 412 in response to an initial force 402 applied directly or indirectly to the first piston 408. A working fluid in a displacement zone 430 serves as a deformable medium and linkage to transfer the initial force 402 exerted through the first piston 408 to the second piston 410. In several embodiments, the displacement zone 430 comprises a fluid chamber or working volume reservoir at least partially positioned between the first piston 408 and the second piston 410. In operation, the first piston 408 is moved by an initial displacement 404 by the initial force 402. The initial displacement 404 is amplified by the pressurized fluid in the displacement zone 430 to produce a greater magnitude of resulting displacement 406 in the second piston 410.

**[0030]** Fluid leaking past the first piston 408 and/or the second piston 410 can be contained within one or more suitable reservoirs such as hermetically sealed upper bellows 428 and/or lower bellows 434. The upper bellows 428 can be hermetically sealed to the first piston 408 by a suitable annular braze, weld, or adhesive 418 and sealed to the body 412 by an annular seal 420. The lower bellows 434 can be sealed to the case 412 at a first annular seam 436 and sealed to the second piston 410 along a second annular seam 438.

**[0031]** The upper and lower bellows 428, 434 may be connected via passageways 432, 433. Reloading the fluid from storage within the upper bellows 428 to the working fluid inventory in the displacement zone 430 can be done by pumping the first piston 408 to provide passage through a conduit 422 to the upper bellows 428. This provides assured retention of the total requirement of fluid within the hermetically sealed system and transfer of fluid for maintenance of the inventory in the displacement zone 430 to assure adequate and sustained output force 440 in response to the initial displacement 404. Transferring the fluid that has accumulated within the lower bellows 434 by pumping the second piston 410 through passageway 433 may be unidirectional as provided by one-way check valves 425, 427.

**[0032]** In certain embodiments, the upper and lower bellows 428, 434 are operated with preferred transfer rates that minimize the transfer of fluid past the first piston 408 compared to the allowed fluid transfer rate past the second piston 410. This provides for considerable heat transfer to and through the higher surface-to-volume passageways 432, 433 and through the housing 412. Heat can be generated in the motion transfer system 450 by friction and/or viscous losses as fluid inventory in the displacement zone 430 is rapidly moved and reshaped to translate the initial displacement 404 to the resulting displacement 406. The motion of the fluid within the passageways 432, 433 and the motion of the bellows 428, 434 provide assured heat transfers and removal of excess heat. Ultimately, such heat is removed from the fuel and/or other fluids that are circulated through the system 450.

**[0033]** Depending upon the spring rates of the upper bellows 428 compared to the lower bellows 434, the system 450 may provide considerable closing force of valves such as the flow valve 121 shown in Figure 1. Further embodiments show the upper bellows 428 and/or the lower

bellows 434 as helical spiral embodiments to minimize the volumes of fluid inventories that are deformed as a result of axial travel.

**[0034]** Figure 5 a cross-sectional side view of a motion transfer system 550 configured in accordance with embodiments of the technology. The motion transfer system 550 includes several features generally similar to the motion transfer system 250 described above. For example, the system 550 includes a first piston 508 and a second piston 510 on bores in a body 512. Fluid in a displacement zone 530 is displaced by axial motion of the first piston 508 and can transfer an input force 502 applied on the first piston 508 that moves an initial displacement 504. This causes a resulting amplified displacement 506 of the second piston 510 during an output force 511.

**[0035]** Spiral bellows 528, 534 can minimize the inventory of fluid that is displaced to enable faster operation and provide a greater surface-to-volume ratio for dissipation of heat generated by viscous and flexure losses. The spiral bellows 528 can be adhered and sealed to the first piston 508 by a first seal ring 518 and adhered and sealed to the body 512 by a second seal ring 520. Similarly, the spiral bellows 534 can be adhered and sealed to the second piston 510 at a third seal ring 538 and adhered and sealed to the body 512 by a fourth seal ring 536. These spiral bellows 528, 534 can provide reduced internal volumes compared to other bellows designs and enable greater cooling of fluid that is pumped by bellows actions through passageways 532, 533, one-way check valves 525, 527, and passageway 522 to restore the inventory of working fluid to the displacement zone 530.

**[0036]** U.S. Patent Application entitled “MECHANICAL MOTION AMPLIFICATION FOR NEW THERMODYNAMIC CYCLES,” Attorney Docket No.69545-8333.US01, and filed on or before March 15, 2013, and U.S. Patent Application entitled “HYDRAULIC DISPLACEMENT AMPLIFIERS FOR FUEL INJECTORS,” Attorney Docket No.69545-8334.US01, and filed on or before March 15, 2013, are incorporated by reference herein in their entireties.

**[0037]** From the foregoing it will be appreciated that, although specific embodiments of the technology have been described herein for purposes of illustration, various modifications may be made without deviating from the spirit and scope of the technology. Further, certain aspects of the new technology described in the context of particular embodiments may be combined or eliminated in other embodiments. Moreover, while advantages associated with certain embodiments of the

technology have been described in the context of those embodiments, other embodiments may also exhibit such advantages, and not all embodiments need necessarily exhibit such advantages to fall within the scope of the technology. Accordingly, the disclosure and associated technology can encompass other embodiments not expressly shown or described herein. Thus, the disclosure is not limited except as by the appended claims.

## CLAIMS

I/We claim:

1. A gaseous fuel injector, comprising:  
a piezoelectric actuator; and  
a motion transfer system coupled to the piezoelectric actuator, including:  
a housing;  
a first piston having a first effective area disposed in the housing;  
a second piston having a second effective area disposed in the housing, wherein the second effective area is less than the first effective area and wherein the first and second pistons define a fluid chamber therebetween.
2. A gaseous fuel injector according to claim 1 wherein the actuator is coupled to and acts on the first piston.
3. A gaseous fuel injector according to claim 1 wherein the first and second pistons are sealed to the housing with first and second bellows, respectively.
4. A gaseous fuel injector according to claim 3 wherein the first bellows defines a first reservoir chamber and the second bellows defines a second reservoir chamber.
5. A gaseous fuel injector according to claim 4, further comprising a first passageway connecting the first reservoir chamber and second reservoir chamber.
6. A gaseous fuel injector according to claim 5, further comprising a first one-way check valve disposed along the first passageway and operative to allow fluid flow from the second reservoir chamber to the first reservoir chamber.

7. A gaseous fuel injector according to claim 6 wherein the first piston includes a second passageway connecting the fluid chamber to the first reservoir chamber.

8. A gaseous fuel injector according to claim 7, further comprising a second one-way check valve disposed along the second passageway and operative to allow fluid flow from the first reservoir chamber to the fluid chamber.

9. A gaseous fuel injector, comprising:

an actuator;

a working volume reservoir adjustable between a first volume and a second volume smaller than the first volume;

a flow valve in communication with the working volume reservoir and movable between a closed configuration when the working volume reservoir comprises the first volume and an open configuration when the working volume reservoir comprises the second volume; and

a motion transfer system in operable connection with the actuator, the motion transfer system including:

a plurality of pistons in communication with the working volume reservoir and configured to adjust the working volume reservoir from the first volume to the second volume; and

a system of bellows and fluid passageways in connection with the working volume and configured to restore the working volume reservoir from the second volume to the first volume.

10. The gaseous fuel injector of claim 9 wherein the plurality of pistons includes a first piston and a second piston, and wherein the first piston has a different cross-sectional area than the second piston.

11. The gaseous fuel injector of claim 10 wherein the actuator acts on the first piston.

12. The gaseous fuel injector of claim 9 wherein the motion transfer system comprises a hermetically sealed system.

13. The gaseous fuel injector of claim 9, further comprising a one-way check valve disposed within the system of bellows and fluid passageways, and operative to allow fluid flow to the working volume reservoir.

14. The gaseous fuel injector of claim 9, further comprising a prime mover coupled to the actuator and configured to supply an initial motion to the actuator.

15. The gaseous fuel injector of claim 14 wherein the prime mover comprises at least one of a piezoelectric, magnetostrictive, electromagnetic, electromechanical, pneumatic, or hydraulic force generator.

16. A method of operating a gaseous fuel injector to inject fuel into a combustion chamber, the method comprising:

introducing fuel into a body portion of the gaseous fuel injector, the body portion including a motion transfer system and a flow valve adjacent to the combustion chamber, the flow valve being moveable between an open position and a closed position;

imparting a motion to the motion transfer system;

hydraulically amplifying a magnitude of the motion by adjusting the motion transfer system from a first position to a second position;

actuating the flow valve to move between the closed position and the open position;

introducing the fuel through the flow valve from the body portion into the combustion chamber; and

restoring the motion transfer system to the first position via a system of bellows and fluid passageways.

17. The method of claim 16 wherein hydraulically amplifying the magnitude of the motion comprises modifying the motion with a plurality of operably connected pistons.

18. The method of claim 16 wherein hydraulically amplifying the magnitude of the motion comprises reducing a working volume in the motion transfer system.

19. The method of claim 18 wherein restoring the motion transfer system comprises increasing the working volume in the motion transfer system.

20. The method of claim 16 wherein restoring the motion transfer system comprises transferring working fluid through a one-way check valve disposed within the system of bellows and passageways.

21. A gaseous fuel injector, comprising:  
a piezoelectric actuator; and  
a motion transfer system operatively coupled to the piezoelectric actuator, including:  
a housing;  
a fluid chamber;  
a first bellows coupled to the housing and defining a first reservoir chamber;  
a second bellows coupled to the housing and defining a second reservoir chamber;  
at least one passageway connecting the first reservoir chamber and second reservoir chamber;  
a one-way check valve disposed along the at least one passageway and operative to allow fluid flow from the second reservoir chamber to the first reservoir chamber.

22. A gaseous fuel injector, comprising:  
an actuator;  
a working volume reservoir;  
a flow valve in communication with the working volume reservoir and movable between a closed configuration and an open configuration; and  
a motion transfer system in operative connection with the actuator and the flow valve, the motion transfer system including:

a housing;  
a first bellows coupled to the housing and defining a first reservoir chamber;  
a second bellows coupled to the housing and defining a second reservoir chamber;  
at least one passageway connecting the first reservoir chamber and second reservoir chamber;  
a one-way check valve disposed along the at least one passageway and operative to allow fluid flow from the second reservoir chamber to the first reservoir chamber.

23. The gaseous fuel injector of claim 22 wherein the first reservoir and second reservoir are in fluid communication with the working volume reservoir.

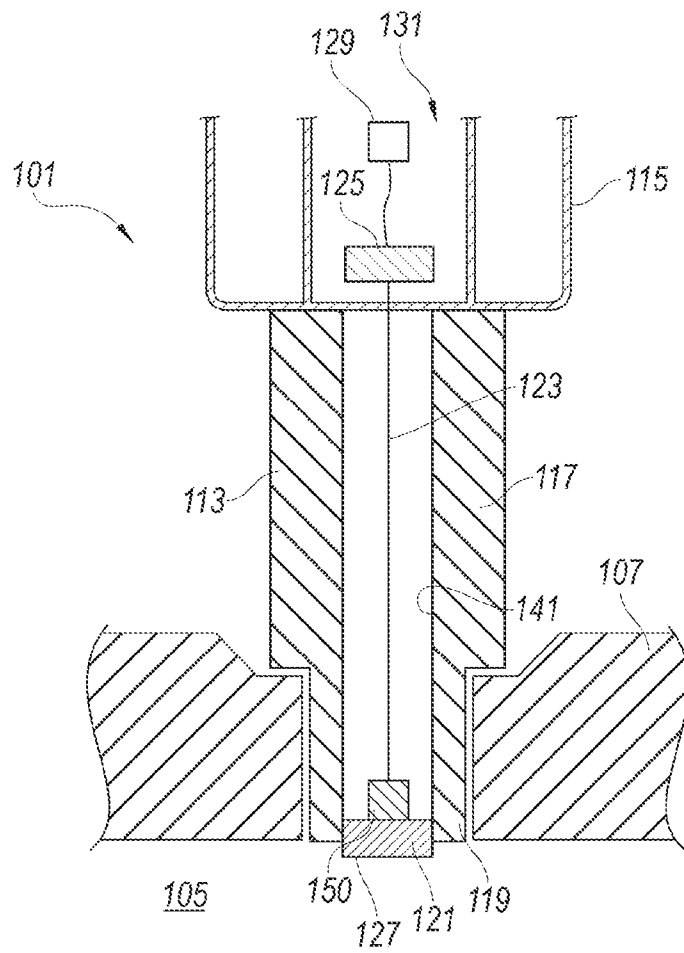


Fig. 1

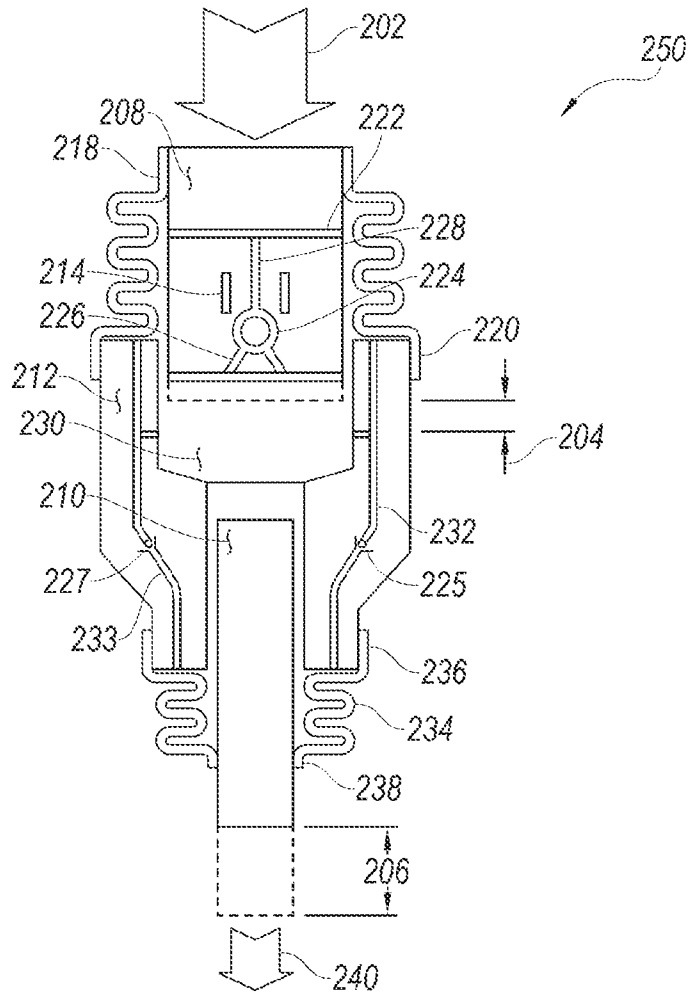


Fig. 2

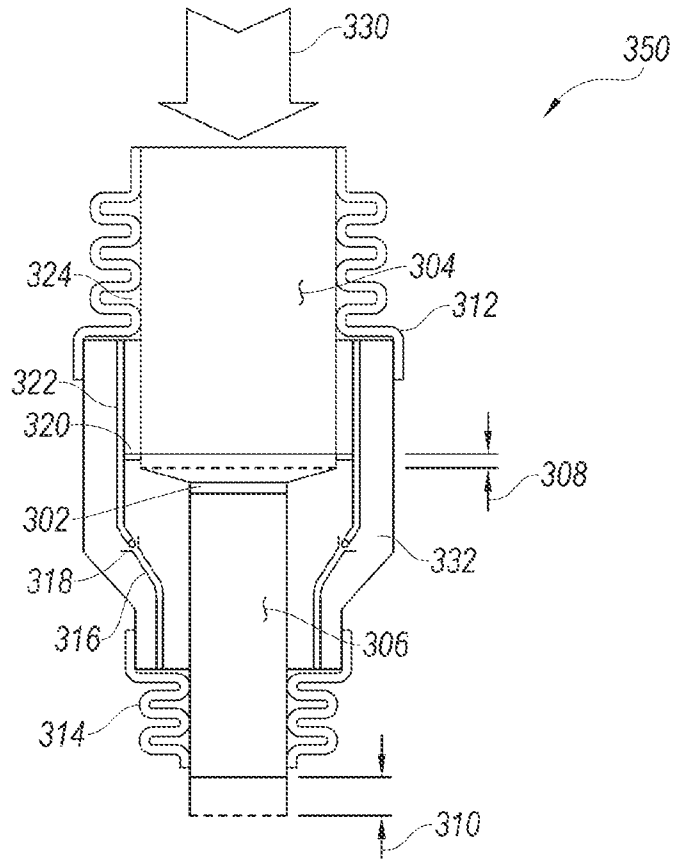


Fig. 3

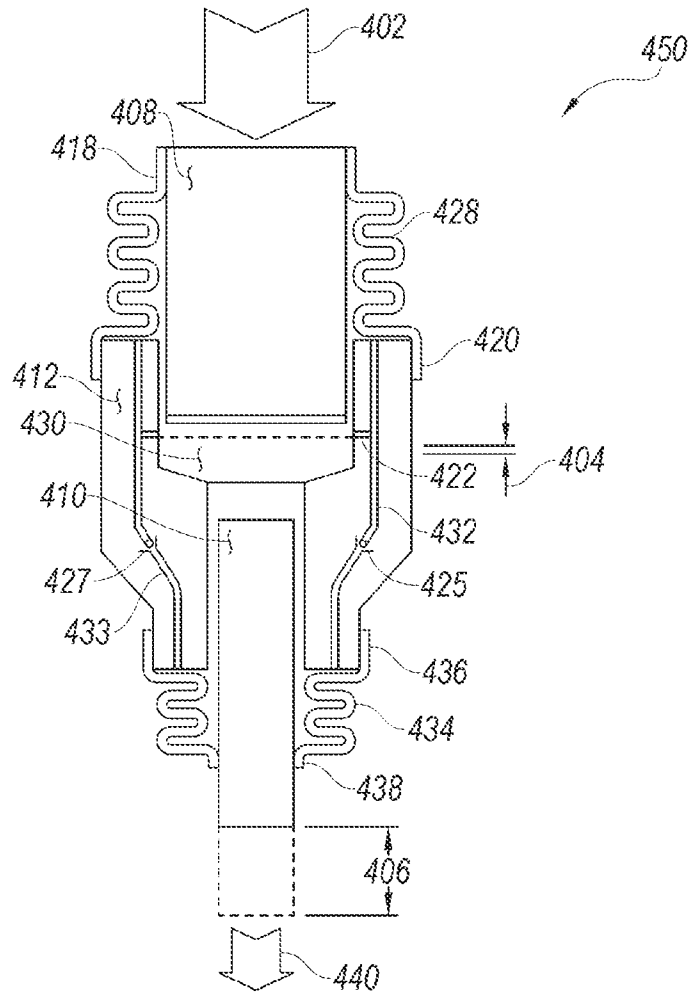


Fig. 4

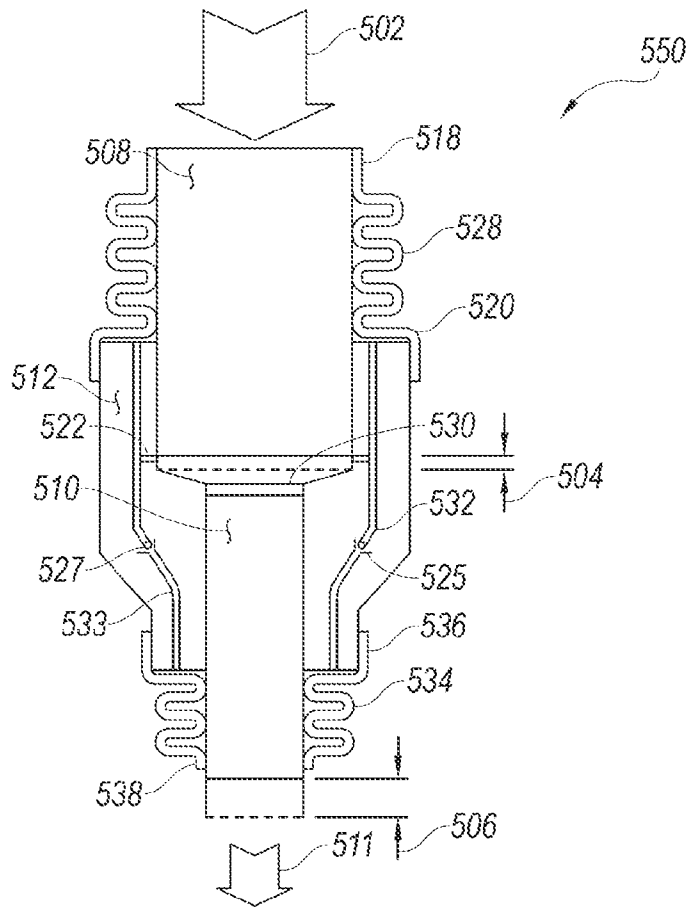


Fig. 5

**A. CLASSIFICATION OF SUBJECT MATTER****F02M 21/02(2006.01)i, F02M 43/04(2006.01)i, F02M 61/16(2006.01)i**

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)

F02M 21/02; B05B 1/30; F02M 47/02; F02M 63/00; F02M 51/00; F02M 51/06; F02D 35/00; F02M 43/04; F02M 61/16

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

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) &amp; Keywords: actuator, piston, pressure, chamber, fuel, valve, and injector

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6752324 B1 (MATTESS, PATRICK) 22 June 2004 See column 1, line 42 - column 4, line 5, claim 1 and the sole figure.	1-5, 9-12, 14-19
A		6-8, 13, 20-23
A	US 2006-0169802 A1 (PAUER, THOMAS) 03 August 2006 See paragraphs [0012]-[0020] and figure 1.	1-23
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A	US 7309032 B2 (FISCHER et al.) 18 December 2007 See column 5 line 56 - column 8 line 47 and figures 1A-2.	1-23
A	EP 2402587 B1 (DENSO CORPORATION et al.) 19 December 2012 See paragraphs [0063]-[0212] and figures 1-8.	1-23

 Further documents are listed in the continuation of Box C. See patent family annex.

\* Special categories of cited documents:

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"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

"&amp;" document member of the same patent family


Date of the actual completion of the international search

27 August 2014 (27.08.2014)

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**INTERNATIONAL SEARCH REPORT**

Information on patent family members

International application No.

**PCT/US2014/029369**

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