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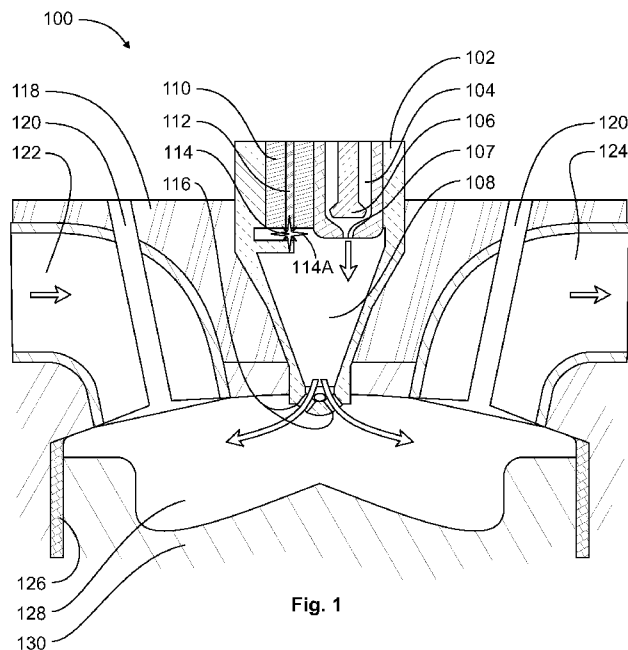


Fig. 1

(57) Abstract: An injector-igniter including a pre-chamber in fluid connection with a combustion chamber of a combustion engine may be embodied as an integrated, bolt-in, singular unit that is suitable to operate heavy duty compression ignition engines in spark-ignited direct injection mode with gaseous and other fuels at dilute or lean ratios. Methods for combustion processes are also disclosed for operating a lean-burn spark ignited direct injected engine. The disclosed apparatuses, systems, and methods describes a device that may be configured to use existing diesel injector hole openings in a cylinder head with minimal or no additional machining to the cylinder head and base engine piston or compression ratio.

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PRE-CHAMBER INJECTOR-IGNITER FOR GASEOUS FUEL
COMBUSTION AND ASSOCIATED SYSTEMS AND METHODS

CROSS-REFERENCE TO RELATED APPLICATION(S)

[0001] This application claims priority to U.S. Provisional Application No. 61/953,528 filed on March 14, 2014.

TECHNICAL FIELD

[0002] This patent document relates to systems, devices and processes that use a combination injector-igniter in an internal combustion engine.

BACKGROUND

[0003] There are difficulties associated with conversion of a heavy duty (HD) compression ignition engine to gaseous fuel at highly dilute or lean (e.g., $\Lambda > 1.3$) air-fuel ratios with a spark-ignited direct injected (SIDi) combustion system. For example, spark ignited combustion of natural gas (NG) conventionally incorporates a throttle in order to maintain a near-stoichiometric and premixed air-fuel mixture in order to initiate combustion. This leads to volumetric inefficiencies at part-load due to throttling or pumping losses in comparison to throttle-less diesel operation. Additionally, premixed air-fuel mixtures when spark-ignited under high compression ratio (e.g., 16:1 to 18:1), found in diesel engines, results in end gas compression leading to excessive engine knock. Excessive knock can lead to severe engine damage. Thus, the engine is calibrated to avoid knock by limiting load, thereby restricting the engine's useful operating range. Compression ratio reduction is common among HD NG SI engines (e.g., 10:1 to 12:1) to prevent knock and extend load limit. However, for HD NG retrofit applications, the stock HD Diesel compression ratio and original cylinder head should be maintained for minimal engine modification.

SUMMARY

[0004] An injector-igniter including a pre-chamber in fluid connection with a combustion chamber of a combustion engine may be embodied as an integrated, bolt-in, singular unit that is suitable to operate heavy duty compression ignition engines in spark-ignited direct injection mode with gaseous and other fuels at dilute or lean ratios. Methods for combustion processes are also disclosed for operating a lean-burn spark ignited direct injected engine. The disclosed apparatuses, systems, and methods describes a device that may be configured to use existing diesel injector hole openings in a cylinder head with minimal or no additional machining to the cylinder head and base engine piston or compression ratio.

[0005] An embodiment may include a method of sequential ignition of a fuel during operation of a combustion engine. The method may inject a fuel into a pre-chamber of a combustion chamber. The pre-chamber may be at least partially physically separated from the combustion chamber. The method may also direct a portion of the fuel into the combustion chamber through one or more nozzles of the pre-chamber and initiate a first ignition event within the pre-chamber. The method may also initiate a second ignition event within the combustion chamber as a result of the first ignition event.

[0006] A further embodiment may include a fuel ignition system for use with a combustion engine. The system may comprise a fuel injector having a valve configured to dispense fuel, and an ignition site adjacent to the valve. Further, the system may include a cover defining a volume encompassing at least part of the valve and at least part of the ignition site. The cover may include one or more nozzles providing a fluid passage between the pre-chamber and a combustion chamber of the combustion engine.

[0007] A still further embodiment may include a fuel injection and ignition apparatus comprising one or more controllers and one or more computer memories communicatively coupled to the one or more controllers. The one or more computer memories may include a fuel control and ignition control module storing tangible computer-executable instructions. When executed by the one or more controllers, the instructions may cause a

single valve to inject a fuel into a pre-chamber of a combustion chamber and into the combustion chamber. The pre-chamber may be at least partially physically separated from the combustion chamber. The instructions may also initiate a first ignition event within the pre-chamber to create a turbulent reacting jet that exits the pre-chamber through one or more nozzles of the pre-chamber and that enters a combustion chamber. There, the turbulent reacting jet may initiate a second ignition event within the combustion chamber as a result of the first ignition event.

[0008] A still further embodiment may include a combustion method. The method may initiate a first combustion event inside a pre-chamber having a first volume consisting of an air-fuel mixture in fluid communication with a combustion chamber having a second volume. The first combustion event may create a turbulent reacting jet that exits the pre-chamber and enters the combustion chamber. The second volume may consist of air, and the turbulent reacting jet may raise both a temperature and a pressure of the combustion chamber to an auto-ignition temperature of the air-fuel mixture. The method may then subsequently inject a quantity of fuel through the pre-chamber and into the combustion chamber wherein the quantity of fuel is auto-ignited and proceeds to burn by diffusion process.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The figures described below depict various aspects of the methods, systems, and devices disclosed herein. It should be understood that each figure depicts an embodiment of a particular aspect of the disclosed methods, systems, and devices, and that each of the figures is intended to accord with a possible embodiment thereof. Further, wherever possible, the following description refers to the reference numerals included in the following figures, in which features depicted in multiple figures are designated with consistent reference numerals.

[0010] Non-limiting and non-exhaustive embodiments of the devices, systems, and methods, including the preferred embodiment, are described with reference to the various figures disclosed.

[0011] Fig. 1 illustrates a cross-sectional view of an embodiment of an injector-ignitor including a pre-chamber;

[0012] Fig. 2 illustrates a fuel system for use with a combustion engine;

[0013] Fig. 3A illustrates a cross-sectional view of an embodiment of an injector-ignitor including a pre-chamber with a single pre-chamber nozzle;

[0014] Fig. 3B illustrates a face view of a reacting jet in an injector-ignitor embodiment including a pre-chamber with a single pre-chamber nozzle;

[0015] Fig. 3C illustrates a cross-sectional view of an embodiment of an injector-ignitor including a pre-chamber with a plurality of pre-chamber nozzles;

[0016] Fig. 3D illustrates a face view of a reacting jet in an embodiment of an injector-ignitor including a pre-chamber with a plurality of pre-chamber nozzles;

[0017] Fig. 3E illustrates a cross-sectional view of an embodiment of an injector-ignitor including a pre-chamber with a single pre-chamber nozzles during a combustion event;

[0018] Fig. 4 illustrates a side view of an embodiment of an injector-ignitor;

[0019] Fig. 5A illustrates a cross-sectional view of one embodiment of an injector-ignitor pre-chamber tip having a single nozzle;

[0020] Fig. 5B illustrates a cross-sectional view of one embodiment of an injector-ignitor pre-chamber tip having a plurality of nozzles;

[0021] Figs. 6A and 6B illustrate a cross-sectional view of an embodiment of an injector-igniter including a single-hole large nozzle with offset inlet valve and high voltage igniter in a pre-chamber;

[0022] Figs. 7A and 7B illustrate a cross-sectional view of an embodiment of an injector-igniter including multi-hole small angle nozzles with offset inlet tube and high voltage igniter in a pre-chamber;

[0023] Figs. 8A and 8B illustrate a cross-sectional view of an embodiment of an injector-igniter including a single-hole large nozzle with center inward opening inlet and offset high voltage igniter in a pre-chamber;

[0024] Figs. 9A and 9B illustrate a cross-sectional view of an embodiment of an injector-igniter including a single-hole large nozzle with center outward opening inlet and offset high voltage igniter in a pre-chamber;

[0025] Figs. 10A and 10B illustrate a cross-sectional view of an embodiment of an injector-igniter including a multi-hole nozzle with center inward opening inlet and offset high voltage igniter in a pre-chamber;

[0026] Figs. 11A and 11B illustrate a cross-sectional view of an embodiment of an injector-igniter including a multi-hole nozzle with center outward opening inlet and offset high voltage igniter in a pre-chamber;

[0027] Figs. 12A and 12B illustrate a cross-sectional view of an embodiment of an injector-igniter including a nozzle with center outward opening inlet and concentric or coaxially configured voltage igniter in a pre-chamber;

[0028] Fig. 13 illustrates a cross-sectional view of an embodiment of an injector-igniter including a channel to draw air into a pre-chamber;

[0029] Fig. 14 illustrates one embodiment of a method for injecting and combusting fuel in an injector-igniter pre-chamber; and

[0030] Figs. 15A-15H illustrate cross-sectional views for various embodiments of pre-chamber internal shape geometries.

DETAILED DESCRIPTION

[0031] The representative embodiments disclosed herein include an injector-igniter as an integrated, bolt-in, singular unit that is suitable to operate heavy duty compression ignition engines in spark-ignited direct injection mode with gaseous fuel at dilute or lean (e.g., $\Lambda > 1.3$) air-fuel ratios. Methods for combustion processes are also disclosed for operating a lean-burn spark ignited direct injected engine on a gaseous fuel. The disclosed technology provides an easy to install device that may be configured to use existing diesel injector hole openings in a cylinder head with minimal or no additional machining to the cylinder head and base engine piston or compression ratio.

[0032] Specific details of several embodiments of the technology are described below with reference to the figures. Many of the details, dimensions, angles, steps, 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, steps, 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 the figures.

[0033] With reference to Fig. 1, an injector-igniter or injector-igniter assembly 100 includes a small volume, defined as a "pre-chamber" 108, that is at least partially physically separate from the main combustion chamber 128. In some embodiments, the pre-chamber is also located within the injector-igniter housing 102, near the point of fuel injection 107. The pre-chamber 108 may include a cover or housing defining a volume that encompasses a valve 106 and an ignition site 114, where the valve 106 may meter fuel 104 into the pre-chamber 108. In some embodiments, the pre-chamber 108 maintains a near-stoichiometric air-fuel mixture, or stratified mixture, at the ignition site 114 by containing the air-fuel mixture in a small volume. In some embodiments, the volume of the pre-chamber 108 may be fixed. In other embodiment, the volume of the pre-chamber 108 may be modifiable or configurable based on conditions within the

combustion chamber or operating conditions (e.g., load, temperature, etc.) of the vehicle. The air-fuel mixture is ignited in the pre-chamber 108 with an ignition initiator or device 112. In some embodiments, the ignition device 112 includes a high-voltage ignition device that has an electrical isolating material or fluid 110. The ignition device 112 may generate an arc, corona discharge, laser, microwave, or other event to ignite the air-fuel mixture. Upon ignition, the high-pressure combustion of primary chamber gases may then be directed via one or more nozzle holes 116 into the main chamber 128 to continue a burn of gaseous fuel and air. Generally, the nozzles 116 provide a passage between the pre-chamber 108 and the combustion chamber 128. In some embodiments, the burn is a lean burn. For example, the main combustion chamber 128 may contain excess air and fuel mixture from previous combustion events or may contain only air. The result is an overall lean burn combustion process. The combustion chamber may be configured for use in a heavy or medium duty diesel engines. The chamber may include intake ports 122 and exhaust ports 124 with valves 120 on both intake and exhaust or scavenging port to control the air flow in and out of the main chamber 128. Additionally, the combustion chamber 128 may include a piston 130, cylinder liner 126, and cylinder head 118.

[0034] With reference to Figs. 1 and 2, existing diesel injectors may be replaced with injector-igniters 100 and a fuel system 200. The fuel system 200 may include an injector-igniter assembly 208, an injector driver 204. The injector driver may meter fuel 218 (e.g., high pressure gaseous fuel) directly into the pre-chamber 108 (Fig. 1), where it is ignited at near stoichiometric conditions by means of a high voltage ignition driver 206. The fuel may be delivered by means of a fuel system comprised of a fuel rail 220, an accumulator 216, a pressure intensifier 214, a regulator 212, a relief valve 222, a fuel tank 210, and engine control unit (ECU) 202.

[0035] Both the injector driver 204 and ignition driver 206 may be controlled using computer-readable instructions that are stored within a tangible memory of the ECU. The ECU 202 may include both a memory 202a for storing instructions and a microcontroller or processor 202b for executing instructions to control the ignition driver 206, the injector

driver 204, and any other computer-controlled functions of the fuel system 200. The controller 202b may include a register set or register space which may be entirely on-chip, or alternatively located entirely or partially off-chip and directly coupled to the controller 202b via dedicated electrical connections and/or via an interconnection bus. The controller 202b may be any suitable processor, processing unit or microprocessor. Although not shown, the fuel system 200 or any system employing various embodiments of the injector-ignitor as herein described may be a multi-processor device and, thus, may include one or more additional processors that are identical or similar to the controller 202b and that are communicatively coupled to an interconnection bus. The controller 202b may also be coupled to a chipset, which includes a memory controller and a peripheral input/output (I/O) controller. As is well known, the chipset typically provides I/O and memory management functions as well as a plurality of general purpose and/or special purpose registers, timers, etc. that are accessible or used by one or more processors coupled to the chipset. The memory controller performs functions that enable the processor controller (or processors if there are multiple processors) to access a system memory and a mass storage memory (not shown).

[0036] The controller 202b may also include one or more memories 202a storing instruction modules to implement fuel control and ignition strategies such as a method 1400 (Fig. 14) for injecting and combusting fuel in the pre-chamber, adaptive control strategies, or other functions as herein described. For example, a fuel control and ignition module 202c may be stored in memory 202a and include tangible computer-executable instructions that are stored in a non-transitory computer-readable storage medium. The instructions of the fuel control and ignition module 202c are executed by the controller 202b or the instructions can be provided from computer program products that are stored in tangible computer-readable storage mediums (e.g. RAM, hard disk, optical/magnetic media, etc.).

[0037] With reference to Fig. 3A, another embodiment of an injector-igniter 300 may include a high-voltage primary ignition device 112 within the injector-igniter 100 that ignites

a portion of the air-fuel mixture that has not exited the pre-chamber 108 into the main combustion chamber 128 (i.e., a remaining portion of an air fuel plume 302) at the ignition site 114 within the injector/igniter 300. The ignited remaining portion of the air-fuel plume 302 may then be directed into one or more nozzles 316 that each generate a turbulent reacting jet 310 that spreads into the main combustion chamber 128. The one or more turbulent reacting jets 310 may also act as spatially-distributed secondary ignition sources for air-fuel mixture previously present in the main chamber. The one or more reacting jets 310 are reactive and can ignite lean air-fuel mixtures. Fig. 3B shows the reacting jet 310 with individual, smaller jets 310a from the perspective of the piston bowl 130 looking toward the nozzle 316. The various injector-igniters described herein may be configurable ("tunable") to optimize various engine applications. For example combustion strategies using different configurations of the injector-igniter described herein may optimize thermal efficiency, emissions and fuel consumption for a combustion engine. In some embodiments of the injector-igniter, the lean flammability limit may extend to a value greater than Lambda of 1.3 for some fuels (e.g., natural gas), where Lambda is defined as the ratio of actual air to fuel ratio divided by stoichiometric air to fuel ratio. In other embodiments of the injector-igniter, the lean flammability limit will extend to a value greater than Lambda 1.6 for some fuels (e.g., natural gas). Although the disclosed embodiments are described with respect to natural gas, other fuels (liquid, gas, or other forms) can be used with the present technology. For example and without limitation, suitable fuels may include methanol, hydrogen, hydrogen-methane mixtures, syngas, dimethyl ether (DME), diethyl ether (DEE), etc.

[0038] An ignition event 114a (Fig. 1) at the primary ignition site 114 can be supplied by the ignition driver 206. The ignition driver 206 may supply any ignition type that is suitable to ignite the air-fuel mixture within the pre-chamber 108. For example and without limitation, the ignition driver 206 may supply one or more of an arc, corona discharge, plasma spark, Lorentz, spark, glow plug, laser, Radio Frequency (RF), microwave frequency, chemical ignition (e.g., high reactivity fuel such as diesel or DME), catalytic

ignition, and thermally assisted catalytic ignition as an ignition event 114a. For example, the injector-igniter 100 can include catalytic coatings to provide reaction sites for fuel reformation within the pre-chamber and on interface surfaces with the combustion chamber.

[0039] In some embodiments, as shown in Figs. 3A, 3B, 3C, and 3D, for example, the injector-igniter 300 may inject single or multiple quantities of fuel without igniting through the pre-chamber nozzle(s) 316, 318 and into the main combustion chamber 128 to develop a stratified charge in the main combustion chamber 128. Upon the last injection, the remaining portion of the air-fuel plume 302 within the pre-chamber 108 is ignited at primary ignition site 114 causing pressure to increase in the pre-chamber and forcing the contents to exit the pre-chamber 108 via the one or more nozzles 316, 318. Various geometries of the nozzles 316, 318 may create one or more turbulent reacting jets 310a, 312a and can ignite the stratified charge 304 in the main combustion chamber 128. This method may be described but not limited to "Premixed" or "Partially Premixed" or "Partially Stratified" pre-chamber combustion. These embodiments may be best suited (but not limited) to low engine load operating regions, where combustion stability is of concern and knock limitations are not of primary concern.

[0040] In another representative embodiment, shown as Figure 3E, fuel may be injected into the pre-chamber 108 and ignited at the ignition site 114, which causes pressure to build in the pre-chamber and forces a reactive fuel jet 308 now within the pre-chamber 108 to exit the pre-chamber 108 into the main combustion chamber 128, via one or more nozzles 316, where the reactive fuel jet 308 encounters abundant air within the combustion chamber 128, initiating a flame kernel 314 which may or may not increase the temperature and pressure of the main combustion chamber 128. Subsequently, fuel is injected through the pre-chamber 108 but not ignited in the pre-chamber 108, and into the main combustion chamber 128 which leads to auto ignition of the injected fuel due to the previously established flame kernel 314. This method may be described but not limited to "Diffusion" or "Stratified" or "Partially Stratified" or "Hybrid" pre-chamber combustion. This

embodiment may be best suited (but not limited to) high load operating regions where knock limitations and combustion stability are of primary concern, or idle operating regions where lean flammability is of greatest concern in combustion engine operation. Fig. 3D shows another embodiment of a reacting jet 312 with individual jets 312a from the perspective of the piston bowl 130 looking toward the pre-chamber 108.

[0041] It should be appreciated that the present technology directly injects the fuel for both the pre-chamber events and the main combustion chamber events through the single fuel valve 106.* This is in contrast to the conventional systems that employ "premixed combustion" by providing the bulk of the fuel for combustion through the intake port 122. Intake port injection leads to homogeneous or premixed air-fuel mixtures which have been known to cause knock as load is increased with high compression ratios, because highly premixed end gas is unavoidable with premixed combustion.

[0042] Referring to Fig. 4, an injector-igniter assembly 400 may include a pre-chamber assembly 402 and an injector body 404 having connections for a high voltage ignition driver 406, gaseous fuel inlet port 408, and injector actuator control signal 410. The injector-igniter 400 provides a mechanism to precisely meter the amount of gaseous fuel charge. In some embodiments, the amount of gaseous fuel charge may be metered by either an inward opening valve (e.g., Figs. 1, 3A, 3B, 3C, 6A, 6B, 7A, 7B, 8A, 8B, 10A, 10B, and 13A-H) or an outward opening valve (e.g., Fig. 4, 9A, 9B, 11A, 11B, and 12). The motion of fuel valve 106 can be controlled directly or indirectly in the longitudinal direction of the injector-igniter 400 with an actuator 410. In some embodiments, the actuator 410 may include one or more of a piezoelectric stack(s), solenoid coil(s), hydraulic fluid, magneto-restrictive devices, or any combination thereof. The primary ignition site 114 is isolated by a non-conductive material 110 and/or dielectric gaseous fuel to the inside of the body 404 along the length of the injector 412 from the fuel valve 106 to the fuel port 408. The ignition is powered using an ignition driver 206 (Fig. 2) connected to the injector-igniter 400 at the high voltage assembly 406 and may or may not include a standard spark ignition, corona discharge, laser, microwave, or other suitable energy source. The high voltage assembly

may be concentrically, coaxially, or off-set located relative to the fuel valve 106. The primary ignition site 114 can also be located off-set, concentrically or coaxially to the longitudinal axis or in numerous locations within the pre-chamber 108 based on performance optimization. The performance of the ignition can be optimized by combination of computational fluid dynamic (CFD) modeling and engine testing on a single cylinder engine to evaluate ignition kernel growth, pre-chamber pressure build-up, turbulent reactive jet intensity, and main chamber flame propagation and rate of heat release. The injector-igniter assembly 400 consists of a body 404 having a connection 406 for the high voltage ignition driver 206 (Fig. 2), a connection 410 to receive control signals from the injector driver 204, and a fuel inlet port 408, to receive fuel from the tank 210.

[0043] In some embodiments of the injector-igniter, shown in Fig. 5A, the pre-chamber 108 includes a specific volume and shape/geometry as discussed herein with reference to Fig. 15, and can comprise a first embodiment 500 including a single nozzle hole 502 or, as shown in Fig. 5B, a second embodiment 504 including multiple nozzle holes 506 with various diameters and angles relative to a centerline axis of the pre-chamber 108. The internal shape and geometry can be optimized by using (CFD) analysis to obtain an ignitable air-fuel mixture. The nozzle(s) 502, 506 to the pre-chamber 108 may be of a specific geometry optimized by the use of CFD and heat transfer modeling and/or catalytic reactor modeling to maximize performance for each individual application and is constructed of a material capable of withstanding high temperatures. In some embodiments, a target pre-chamber volume range should be within 0.1% to 7% of main chamber volume at top dead center. In further embodiments, a pre-chamber nozzle hole size could range from about 1% to 95 % of an injector bore size in the cylinder head. Likewise, a number of holes could be anywhere from 1 to about 20. Angle of holes with respect to centerline of injector-igniter can be anywhere from 0 to about 120 degrees. Once the engine and the pre-chamber are at operating temperatures, the pre-chamber will heat up significantly, and is then in a condition to transfer heat to the subsequent cycles of fuel injection and will enhance the ignitability of the gaseous fuel injected thus enabling shorter ignition delay

times, leaner mixture ignition, and improved consistency from cycle to cycle. Suitable pre-chamber and nozzle materials include, for example and without limitation, Haynes®, Hastelloy®, and Inconel® alloys, high thermal conductivity alloys such as copper alloys, nickel alloys, graphene/graphite (as liner materials to enhance or impede thermal transfer), thermal and oxidation resistant materials or coatings such as MoSi₂, SiC, AlN, ZrC or ceramic coatings.

[0044] With reference to Figs. 6A-11B, embodiments of the injector ignitor 600, 700, 800, 900, 1000, 1100 may include various combinations, dimensions, and angles of pre-chamber nozzles 612, 712, 812, 912, 1012, and 1122 as well as different configurations of inlet valves 614, 714, 814, 914, 1014, 1114 and igniters 616, 716, 816, 916, 1016, 1116. While the various elements embodiments of Figs. 6A-11B are shown as corresponding to a particular embodiment, any of the elements may be combined or included with any of the other embodiments herein described. As shown in Figs. 6A and 6B, an embodiment of the injector-igniter 600 may include a single-hole centered nozzle 612 with offset inlet valve 614 and offset high voltage igniter 616 in the pre-chamber 108. With reference to Figs. 7A and 7B, another embodiment of the injector-igniter 700 may include multi-hole directed nozzles 712 with offset inlet tube 714 and high voltage igniter 716 in the pre-chamber 108. With reference to Figs. 8A and 8B, another embodiment of the injector-igniter 800 may include a single-hole centered nozzle 812 with center inward opening inlet 814 and offset high voltage igniter 816 in the pre-chamber 108. The igniter 816 may extend from the non-conductive material 110 into the pre-chamber 108. With reference to Figs. 9A and 9B, still another embodiment of the injector-igniter 900 may include a single-hole centered nozzle 912 with center outward opening inlet 914 and offset high voltage igniter 916 in the pre-chamber 108. As with the embodiments of Figs. 8A and 8B, the igniter 916 may extend from the non-conductive material 110 into the pre-chamber 108. With reference to Figs. 10A and 10B, an embodiment of the injector-igniter 1000 may include a multi-hole directed nozzle 1012 with center inward opening inlet 1014 and offset high voltage igniter 1016 in the pre-chamber 108. As with the embodiments of Figs. 8A,

8B, 9A, and 9B, the igniter 1016 may extend from the ceramic material 110 into the pre-chamber 108. With reference to Figs. 11A and 11B, another embodiment of the injector-igniter 1100 may include a multi-hole nozzle 1112 with center outward opening inlet 1114 and offset high voltage igniter 1116 in the pre-chamber 108. As with the embodiments of Figs. 8A, 8B, 9A, 9B, 10A, and 10B, the igniter 1116 may extend from the non-conductive material 110 into the pre-chamber 108.

[0045] With reference to Fig. 12, another embodiment of the injector-igniter 1200 may include a single or multi-hole outlet nozzle or some combination thereof 1212. The injector ignitor 1200 may include a center outward opening fuel inlet 1214 and an igniter 1216 that is configured concentrically or co-axially within the pre-chamber 108. The igniter 1216 may provide ignition sites 608a or 608b.

[0046] In an embodiment 1300 shown and described in Fig. 13, a channel 1302 may extend from the pre-chamber 108 to the main combustion chamber 128. As fuel is injected past the pre-chamber side of the channel 1302, a local low pressure region is created and thus air and/or an air-fuel mixture is drawn into the pre-chamber 108 via the air channel 1302 from the main chamber 128 using the Bernoulli Effect. Thus, passage 1302 provides additional oxygen (e.g., air) from the combustion chamber 128 to the pre-chamber 108 for ignition of gaseous mixtures in the pre-chamber 108 and in the main chamber 128.

[0047] With reference to Figs. 6A, 7A, 8A, 9A, 10A, and 11A, and Fig. 14, embodiments of the injector-ignitor pre-chamber and a method 1400 for injecting and combusting fuel 602 in the pre-chamber 108 may be described. The method 1400 may describe both a sequential ignition of fuel and multiple ignition and/or combustion events to enable operation of a combustion engine. At block 1402 (Fig. 14), the engine control unit 202 (Fig. 2) may include instructions to cause the injector driver 204 to initiate a first fuel injection event. In some embodiments, the block 1402 may include an instruction to inject fuel 602 into the pre-chamber 108 where it mixes with air 604. Single or multiple injection events (i.e., second, third, fourth, etc., injection events) can occur during the

intake and compression stroke in an engine depending upon its engine cycle (e.g., 4 stroke engine cycle or 2 stroke engine cycle). At block 1404, the engine control unit 202 may include further instructions to cause the injector driver 204 to inject fuel so that, within the pre-chamber 108, an air-fuel plume 606 may reach a mixture of air 604 and fuel 602 that is capable of ignition. In some embodiments, the mixture is or approximately a stoichiometric air-fuel mixture, or stratified mixture. At block 1406, in engine combustion cycles including longer opening times for the fuel inlet 614, 714, 814, 914, 1014, 1114, at least a portion of the air-fuel plume 606 may exit the pre-chamber 108 through a single hole nozzle 612, 812, or 912 or one or more of the multi-hole nozzles 712, 1012, 1112. Further, the nozzles may direct the portion of the air-fuel plume 606 from the nozzle(s) toward the center of the main combustion chamber 128 (Fig. 1) resulting in enhanced mixing of the air-fuel plume 606 components. With reference to Figs. 6B, 7B, 8B, 9B, 10B, 11B, and 13, embodiments of the injector-ignitor pre-chamber and the method 1400 may describe a combustion event within the pre-chamber 108. At block 1408, a discharge at an ignition point 608 or other ignition event (e.g., arc, corona discharge, laser, microwave, or other event to ignite the air-fuel mixture) may initiate a first ignition event to ignite a remaining portion of the air-fuel plume 609 that has not exited the pre-chamber 108. In some embodiments, the engine control unit 202, injector driver 204 and ignition driver 206 (Fig. 2) may include instructions and/or be configured to time the discharge to initiate the first ignition event, i.e., the ignition of the remaining portion of the air-fuel plume 609, when the mixture is at local stoichiometric to rich conditions in the pre-chamber 108 within the vicinity of the ignition point 608. The remaining portion of the air-fuel plume 609 may be partially burned or oxidized in the pre-chamber 108 proceeding from the ignition point 608 toward a nozzle of the pre-chamber. At block 1410, this burn may increase pre-chamber pressure as well as produce free-radicals and a turbulent reacting jet 618 (also 310 of Fig. 3A). The increased pressure within the pre-chamber 108 may force the turbulent reacting jet 618 out of the pre-chamber 108 and towards the outer regions of the main combustion chamber 128 (Figs. 1, 3A, 3B, and 3C) towards a piston bowl 130 (Fig. 1) and cylinder liner 126. Excess air and/or air-fuel mixture (i.e., lean) conditions may

exist within the main combustion chamber 128 generally, and within the piston bowl 130, in particular, due to at least a portion of the air-fuel plume 606 exiting the pre-chamber 108 before the first ignition event. At block 1412, the highly reactive, turbulent reacting jet 618 exiting the one or more pre-chamber nozzles may interface with the lean air-fuel mixture condition within the combustion chamber to initiate a further or second ignition event and ignite the lean air-fuel mixtures within the main combustion chamber 128. In the absence of the turbulent reacting jet 618 or other combustion event employing the injector-ignitor as herein described, the lean air-fuel mixtures within the main combustion chamber 128 may be difficult to ignite. Ignition of these lean mixtures in the second ignition event may result in shorter ignition delay, enhanced rate of pressure rise within the combustion chamber, improvement of lean ignitability, increased thermal efficiency, decreased fuel consumption, and clean emission combustion. The method 1400 may then repeat the injection/combustion cycle of the method 1400, or end.

[0048] Several embodiments are presented related to pre-chamber internal shape geometries 1500 in Figs 15A-15H. Any of the injector-igniter embodiments described herein may include one of the geometries illustrated in Figs. 15A-15H or a combination of the geometries illustrated in Figs. 15A-15H. Fig. 15A illustrates a cylindrical geometry. Fig. 15B illustrates a cylindrical geometry with chamfered bottom corners designed to direct the flow towards exit. Fig. 15C illustrates a cylindrical geometry with rounded corners designed to better guide the flow for mixing and towards nozzle exit. Fig. 15D illustrates a spherical geometry designed to enable wall guided mixing of the fuel internal to the pre-chamber towards the ignition site. Fig. 15E illustrates a rounded funnel geometry design to wall guide flow towards exit. Fig. 15F illustrates a sharp funnel geometry. Fig. 15G illustrates a cone shaped geometry designed to better direct flow towards exit. Fig. 15H illustrates a spiral geometry designed to force tangential velocity to the flow creating a spiral as it exits the pre-chamber. All geometries above may be used in conjunction but without limit various types of nozzle holes geometries shown in Fig. 15 and ignition electrode geometries.

[0049] Some aspects of the technology described herein may take the form of or make use of computer-executable instructions, including routines executed by a programmable computer or controller. Those skilled in the relevant art will appreciate that aspects of the technology can be practiced on computer systems other than those described herein. Aspects of the technology can be embodied in one or more special-purpose computers or data processors, such as an engine control unit 202 (ECU), engine control module (ECM), injector driver 204, fuel system controller, ignition driver 206, or the like, that is specifically programmed, configured, or constructed to perform one or more computer-executable instructions consistent with the technology described herein. Accordingly, the term "computer," "processor," or "controller" as may be used herein refers to any data processor and can include ECUs, ECMs, and modules, as well as Internet appliances and hand-held devices (including diagnostic devices, palm-top computers, wearable computers, cellular or mobile phones, multi-processor systems, processor-based or programmable consumer electronics, network computers, mini computers and the like). Information handled by these computers can be presented at any suitable display medium, including a CRT display, LCD, or dedicated display device or mechanism (e.g., a gauge).

[0050] The technology can also be practiced in distributed environments, where tasks or modules are performed by remote processing devices that are linked through a communications network. In a distributed computing environment, program modules or subroutines may be located in local and remote memory storage devices. Aspects of the technology described herein may be stored or distributed on computer-readable media, including magnetic or optically readable or removable computer disks, as well as distributed electronically over networks. Such networks may include, for example and without limitation, Controller Area Networks (CAN), Local Interconnect Networks (LIN), and the like. In particular embodiments, data structures and transmissions of data particular to aspects of the technology are also encompassed within the scope of the technology.

[0051] 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. Also contemplated herein are methods which may include any procedural step inherent in the structures and systems described. Accordingly, the disclosure and associated technology can encompass other embodiments not expressly shown or described herein.

CLAIMS

1. A method of sequential ignition of a fuel during operation of a combustion engine, the method comprising:
 - injecting a fuel into a pre-chamber of a combustion chamber, the pre-chamber at least partially physically separated from the combustion chamber;
 - directing a portion of the fuel into the combustion chamber through one or more nozzles of the pre-chamber;
 - initiating a first ignition event within the pre-chamber; and
 - initiating a second ignition event within the combustion chamber as a result of the first ignition event.
2. The method of claim 1, wherein injecting the fuel into a pre-chamber of a combustion chamber includes creating an air-fuel mixture within the pre-chamber.
3. The method of claim 1, wherein a single fuel valve injects both the fuel into the pre-chamber and the portion of the fuel into the combustion chamber.
4. The method of claim 1, wherein initiating the first ignition event within the pre-chamber includes initiating the first ignition event when air-fuel mixture is at a local stoichiometric to rich condition in the pre-chamber using an ignition device positioned within the pre-chamber.
5. The method of claim 4, wherein the local stoichiometric to rich condition in the pre-chamber is located at an ignition point within the pre-chamber.
6. The method of claim 1, wherein the first ignition event increases a pressure within the pre-chamber to produce a turbulent reacting jet and the first ignition event

causes the turbulent reacting jet to exit the pre-chamber through the one or more nozzles of the pre-chamber.

7. The method of claim 6, wherein directing the portion of the fuel into the combustion chamber through one or more nozzles of the pre-chamber creates a lean air-fuel mixture condition within the combustion chamber.

8. The method of claim 7, wherein an interface between the turbulent reacting jet and the lean air-fuel mixture condition within the combustion chamber initiates the second ignition event.

9. The method of claim 1, wherein the fuel includes one or more of hydrogen, a hydrogen and natural gas mixture, a Syngas mixture which may contain one or more of CH₄, CO, CO₂, H₂ and H₂O, methanol, a hydrogen-methane mixture, dimethyl ether, and diethyl ether.

10. The method of claim 1, wherein the first ignition event includes one or more of a corona discharge, a spark discharge, and a chemical ignition fluid.

11. The method of claim 1, further comprising isolating an ignition initiator from the pre-chamber using a gas as a dielectric.

12. A fuel ignition system for use with a combustion engine, the system comprising:

a fuel injector having a valve configured to dispense fuel;

an ignition site adjacent to the valve; and

a cover defining a volume encompassing at least part of the valve and at least part of the ignition site;

wherein the cover includes one or more nozzles providing a fluid passage between the pre-chamber and a combustion chamber of the combustion engine.

13. The fuel ignition system of claim 12, wherein the volume is positioned adjacent to the combustion chamber.

14. The fuel ignition system of claim 12, wherein the pre-chamber is at least partially physically separated from the combustion chamber.

15. The fuel system of claim 12, wherein the valve is configured to dispense fuel based on the volume to produce a local stoichiometric to rich condition of an air-fuel mixture in the pre-chamber and a lean air-fuel mixture in the combustion chamber.

16. The fuel system of claim 12, wherein the valve is configured to dispense fuel into both the pre-chamber and the combustion chamber.

17. The fuel system of claim 12, wherein a first ignition event at the ignition site proceeds through the one or more nozzles to produce a further ignition event outside the pre-chamber and within the combustion chamber as a result of the ignition event.

18. The fuel system of claim 12, wherein the fuel includes one or more of hydrogen, a hydrogen and natural gas mixture, a Syngas mixture which may contain one or more of CH₄, CO, CO₂, H₂ and H₂O, methanol, a hydrogen-methane mixture, dimethyl ether, and diethyl ether.

19. The fuel ignition system of claim 12, wherein the ignition site is configured to produce one or more of a corona discharge, a spark discharge, and a chemical ignition fluid.

20. The fuel ignition system of claim 12, wherein the ignition site includes an ignition device.

21. The fuel ignition system of claim 20, further comprising a dielectric positioned to isolate the ignition device from the cover.

22. A fuel injection and ignition apparatus comprising:
one or more controllers; and
one or more computer memories communicatively coupled to the one or more controllers, the one or more computer memories including a fuel control and ignition control module storing tangible computer-executable instructions to, when executed by the one or more controllers:

cause a single valve to inject a fuel into a pre-chamber of a combustion chamber and into the combustion chamber, the pre-chamber at least partially physically separated from the combustion chamber; and

initiate a first ignition event within the pre-chamber to create a turbulent reacting jet that exits the pre-chamber through one or more nozzles of the pre-chamber and that enters a combustion chamber;

wherein the turbulent reacting jet initiates a second ignition event within the combustion chamber as a result of the first ignition event.

23. The apparatus of claim 22, wherein the instruction to initiate the first ignition event within the pre-chamber includes an instruction to initiate the first ignition event when an air-fuel mixture is at a local stoichiometric to rich condition in the pre-chamber using an ignition device positioned within the pre-chamber.

24. The apparatus of claim 23, wherein the local stoichiometric to rich condition in the pre-chamber is located at an ignition point within the pre-chamber.

25. The apparatus of claim 22, wherein the first ignition event increases a pressure within the pre-chamber to produce a turbulent reacting jet and the first ignition event causes the turbulent reacting jet to exit the pre-chamber through the one or more nozzles of the pre-chamber.

26. The apparatus of claim 25, wherein an interface between the turbulent reacting jet and a lean air-fuel mixture condition within the combustion chamber initiates the second ignition event.

27. The apparatus of claim 22, wherein the fuel includes one or more of hydrogen, a hydrogen and natural gas mixture, a Syngas mixture which may contain one or more of CH₄, CO, CO₂, H₂ and H₂O, methanol, a hydrogen-methane mixture, dimethyl ether, and diethyl ether and the first ignition event includes one or more of a corona discharge, a spark discharge, and a chemical ignition fluid.

28. A combustion method, comprising:

initiating a first combustion event inside a pre-chamber having a first volume consisting of an air-fuel mixture in fluid communication with a combustion chamber having a second volume, the first combustion event creating a turbulent reacting jet that exits the pre-chamber and enters the combustion chamber, the second volume consisting of air, the turbulent reacting jet raising both a temperature and a pressure of the combustion chamber to an auto-ignition temperature of the air-fuel mixture; and

subsequently injecting a quantity of fuel from a valve through the pre-chamber and into the combustion chamber wherein the quantity of fuel is auto-ignited and proceeds to burn by diffusion process.

29. The combustion method of claim 26, wherein the quantity of fuel proceeds to burn with or without the use of an ignition device internal to the pre-chamber.

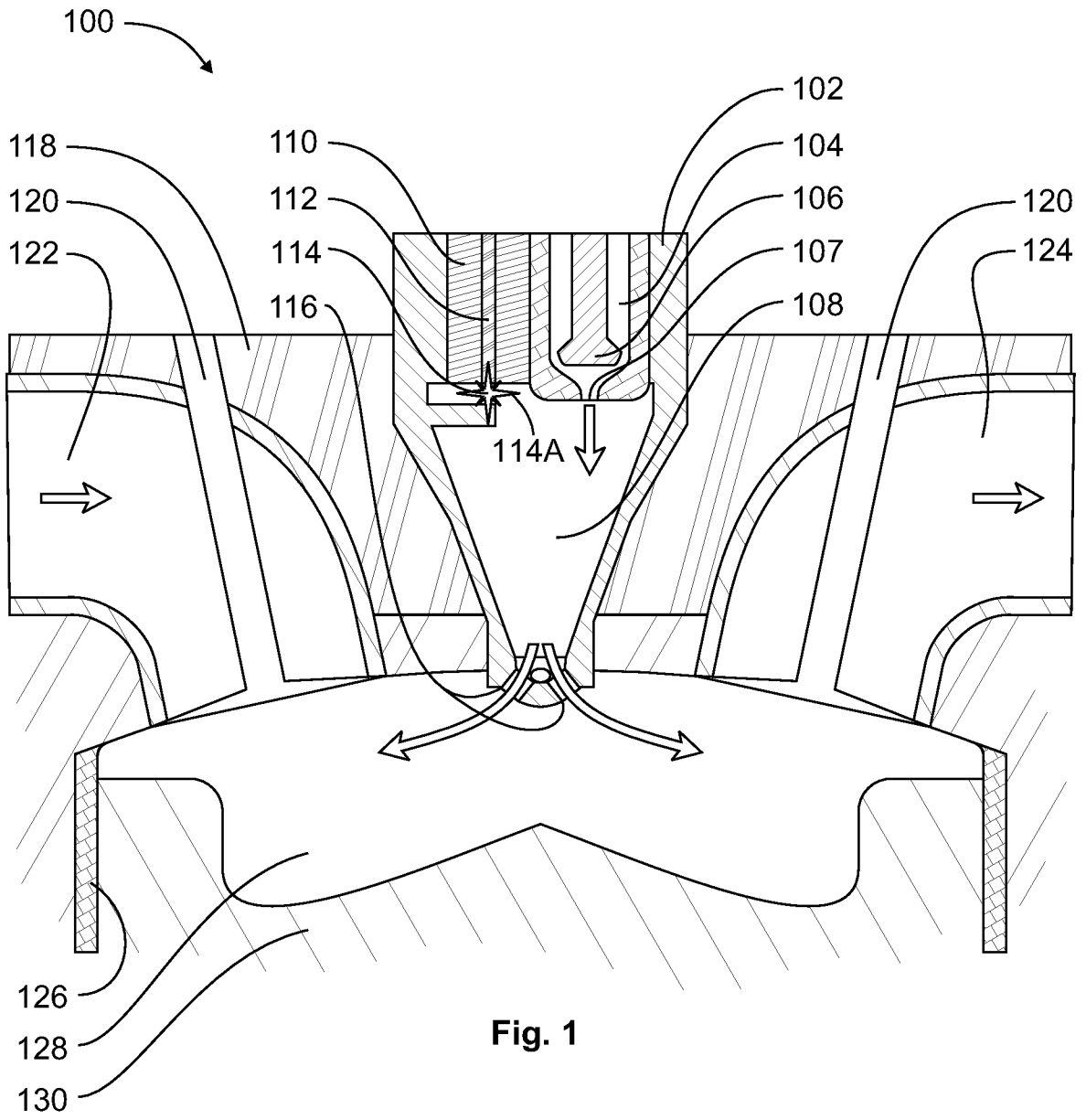


Fig. 1

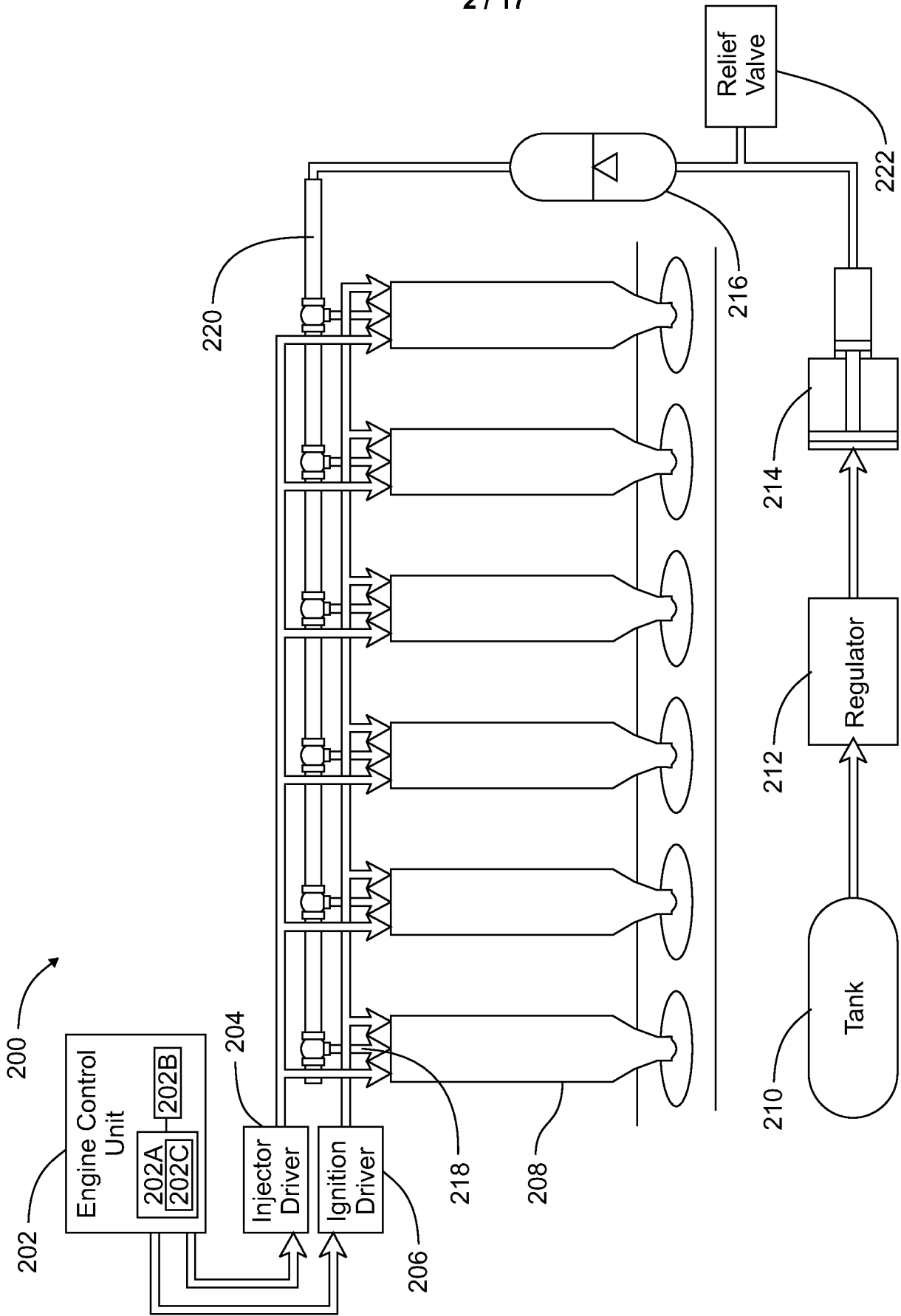


Fig. 2

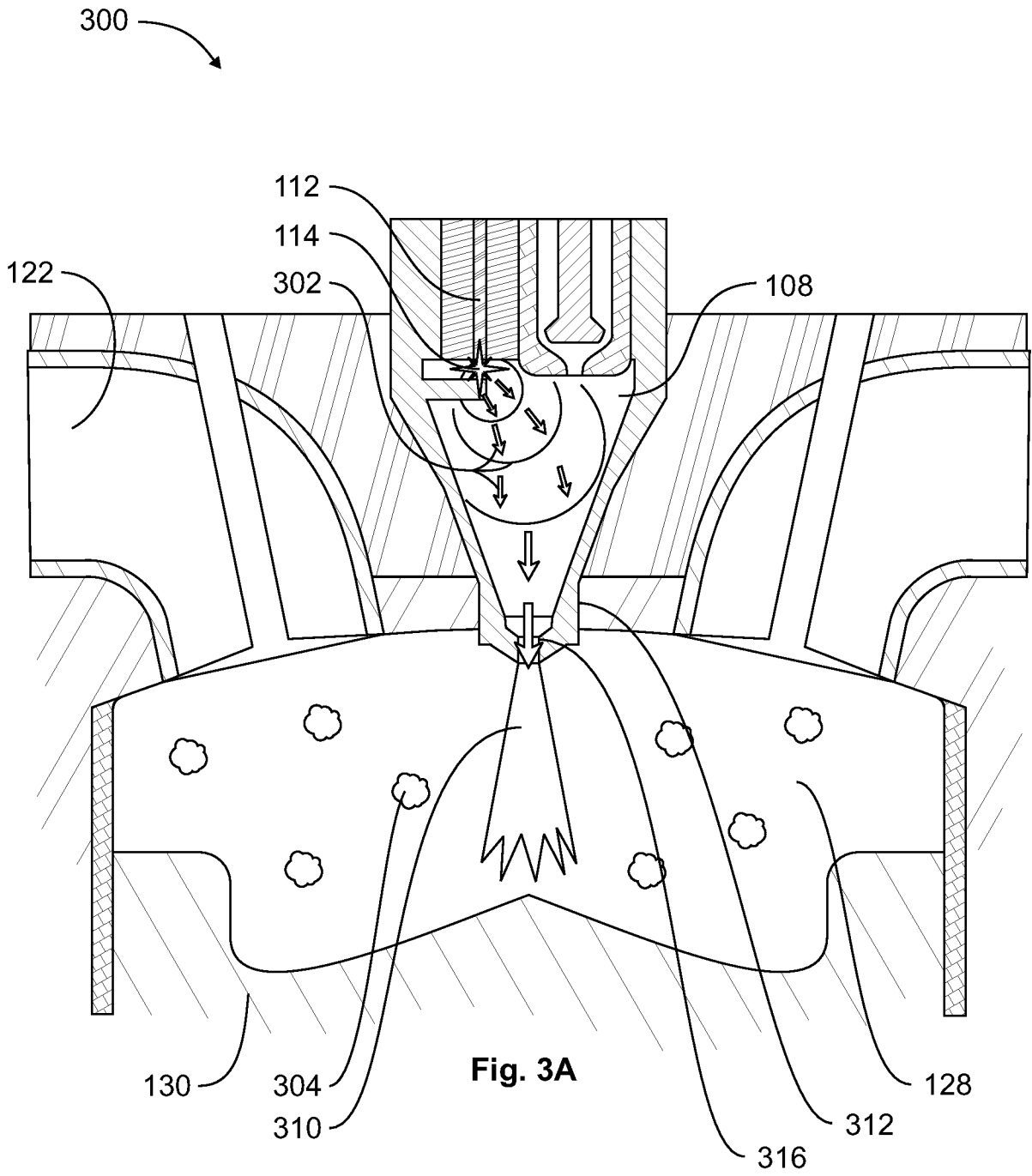


Fig. 3A

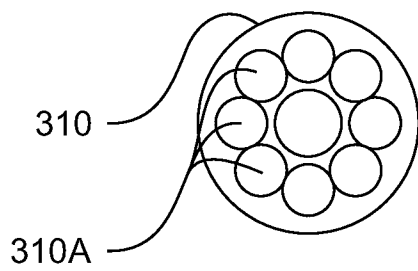
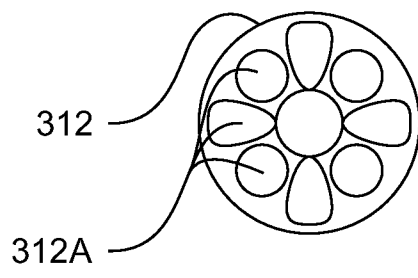
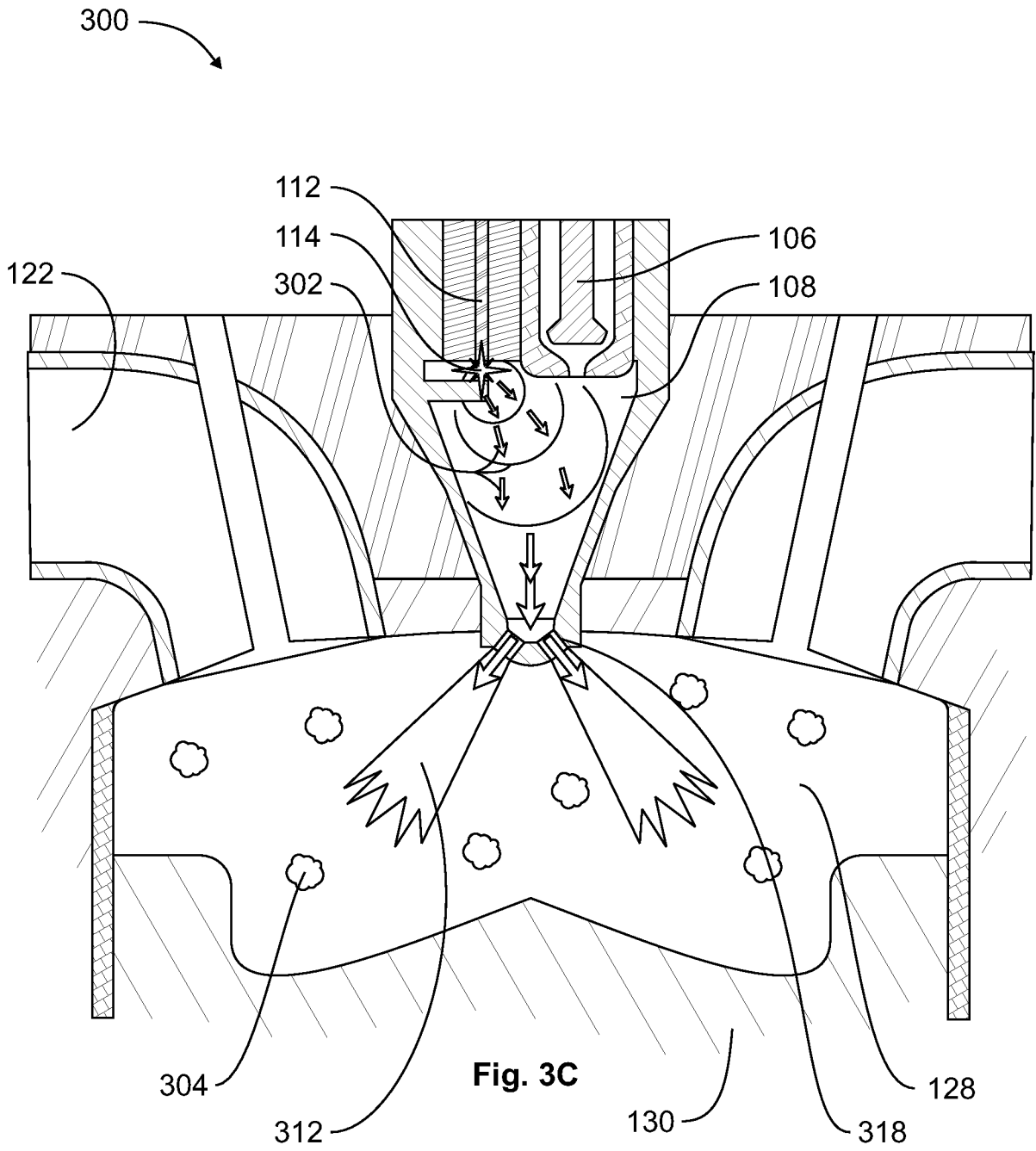
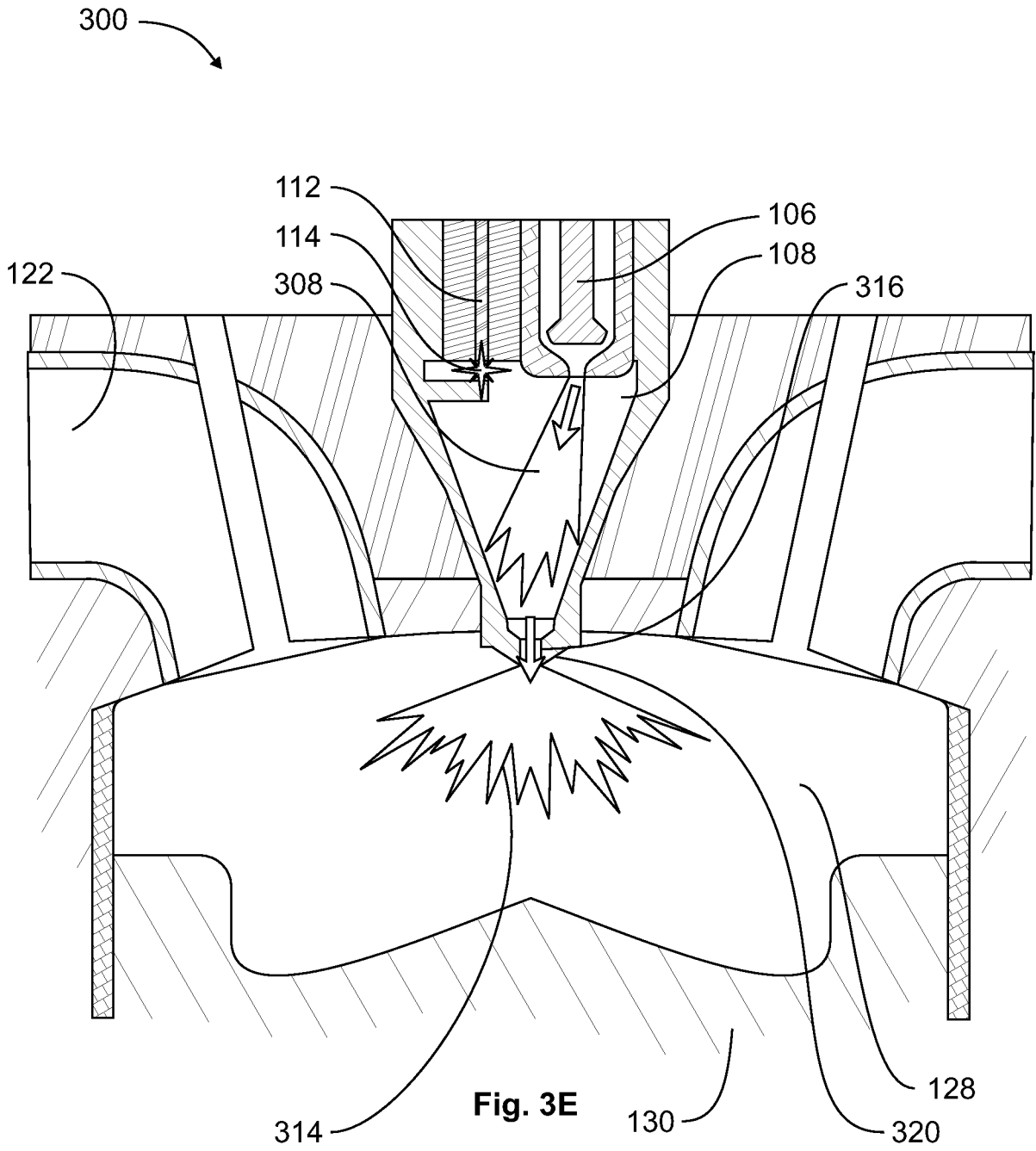


Fig. 3B





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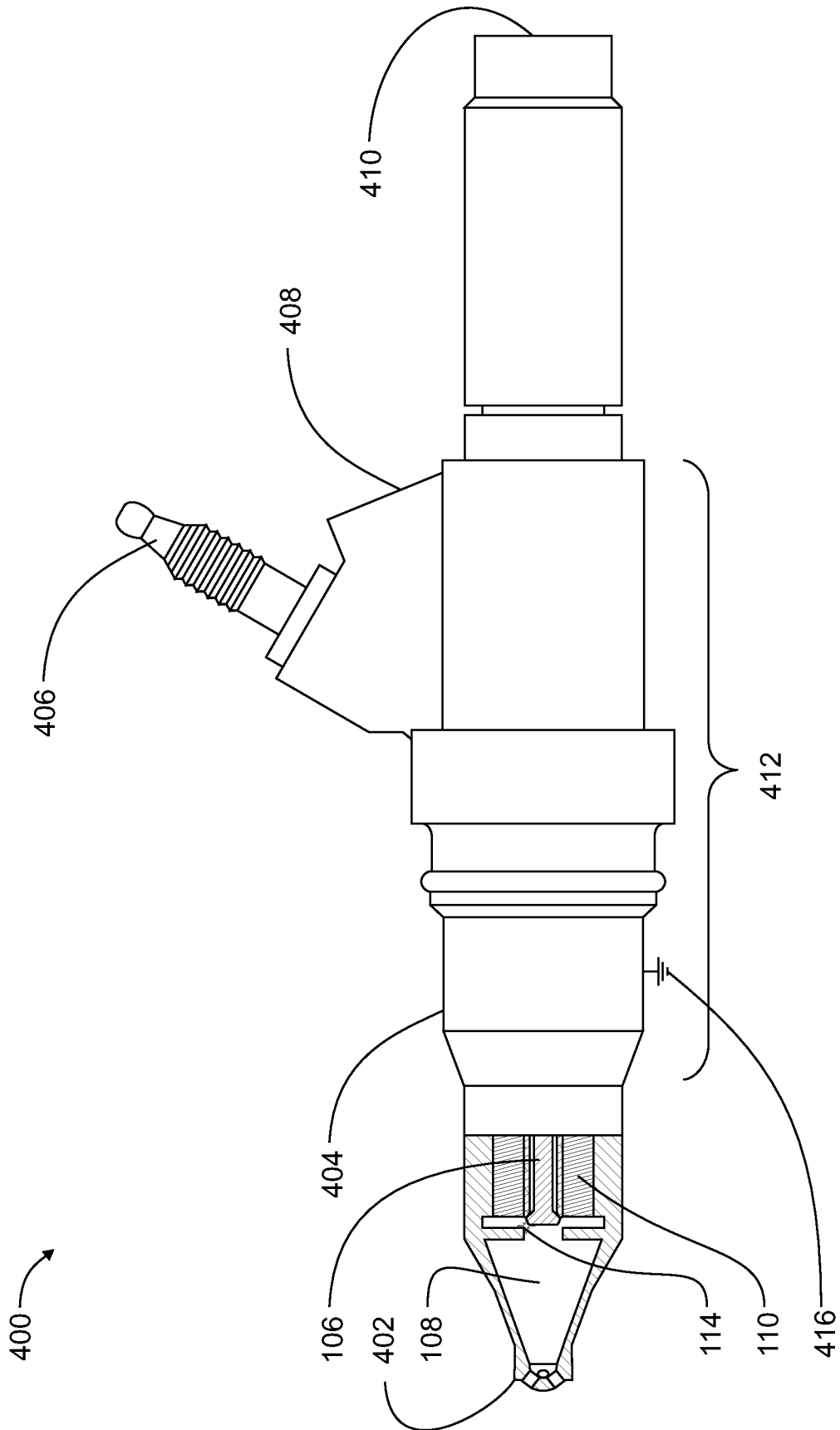


Fig. 4

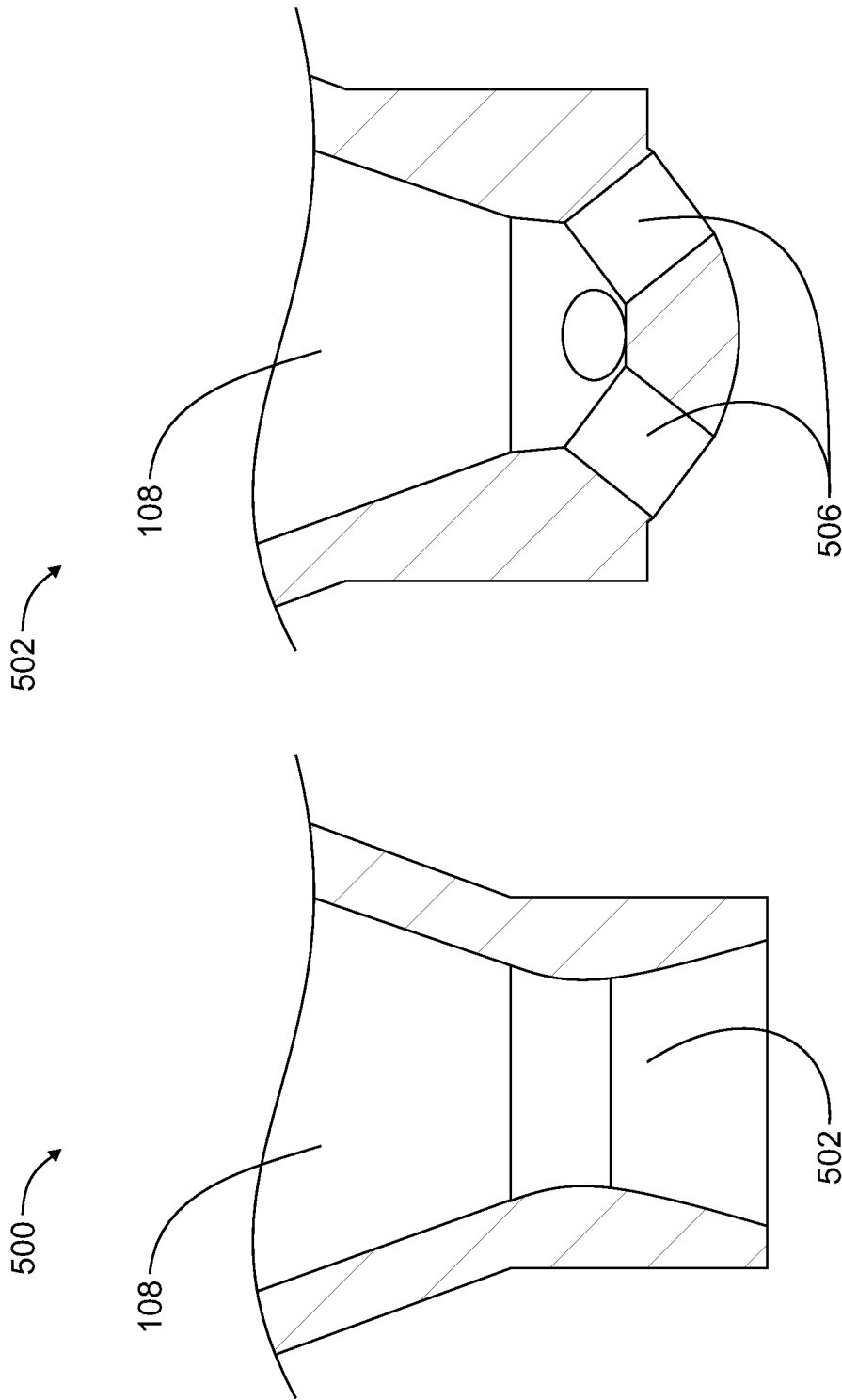


Fig. 5B

Fig. 5A

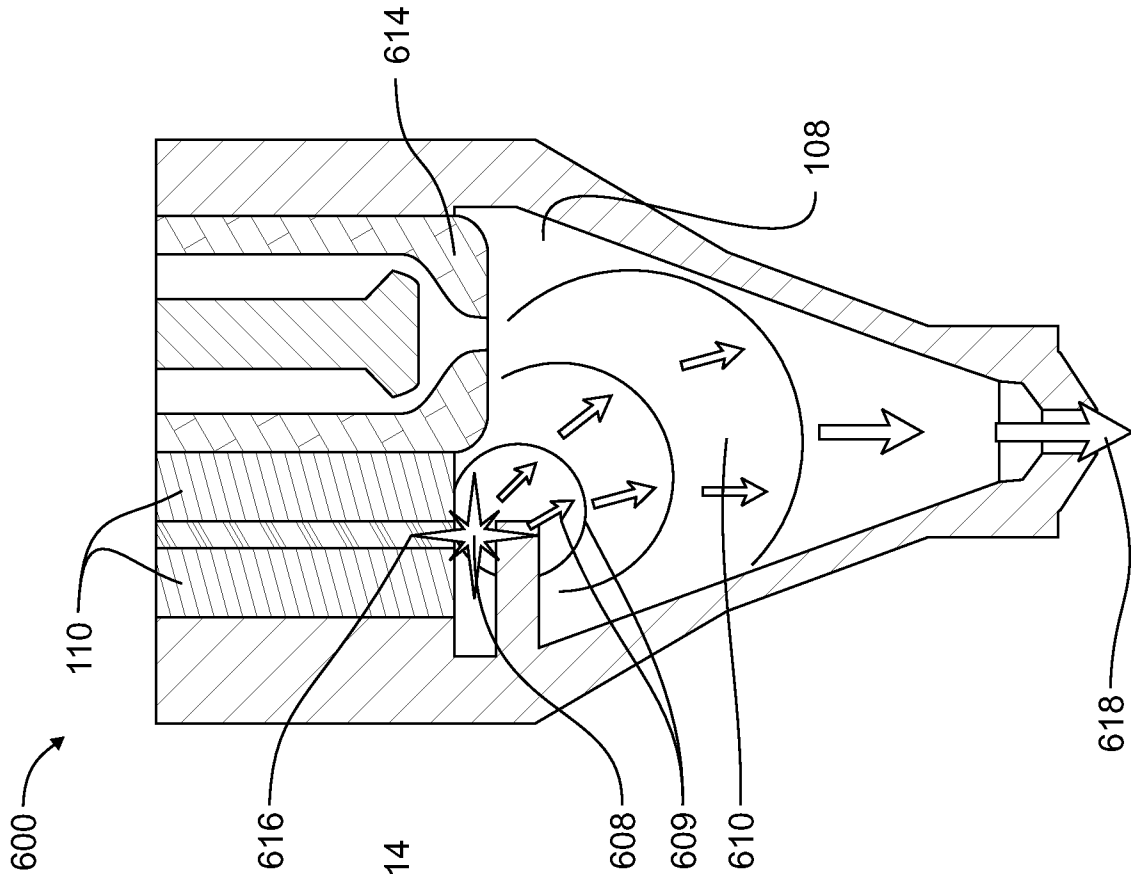


Fig. 6A

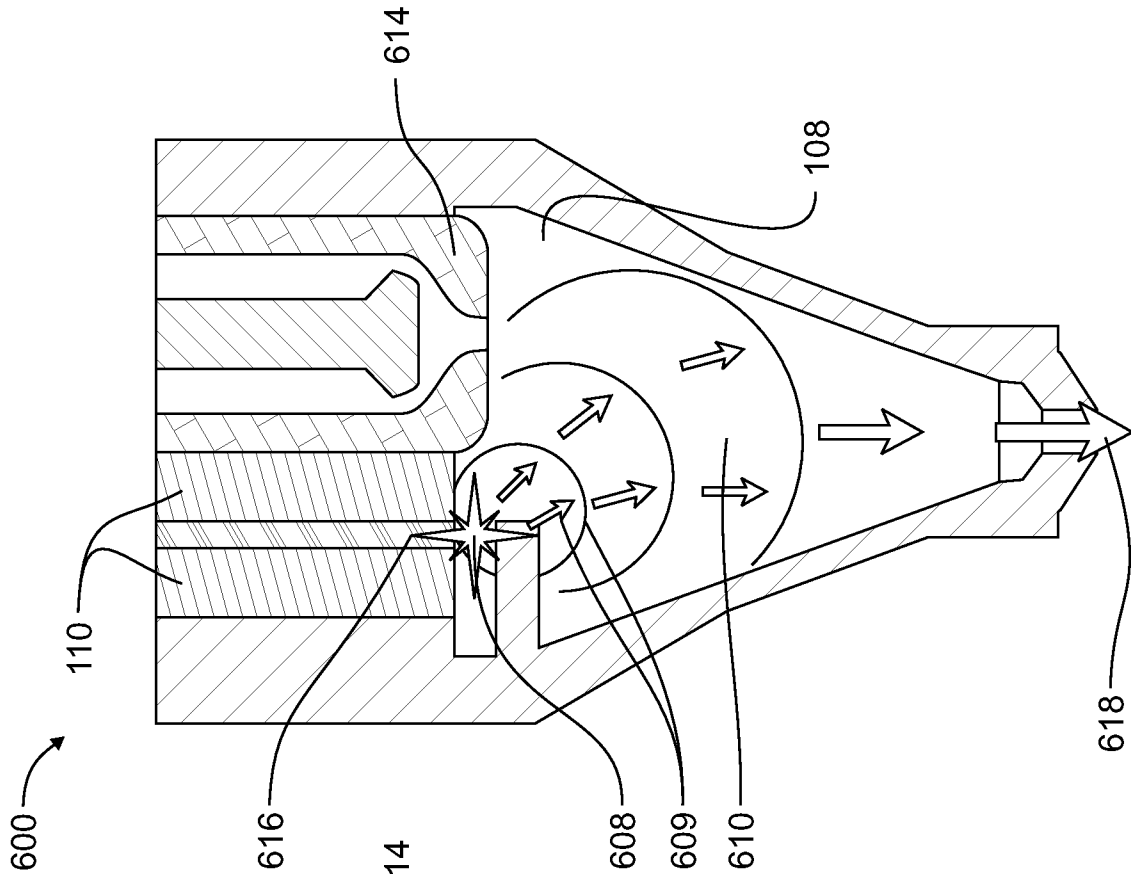


Fig. 6B

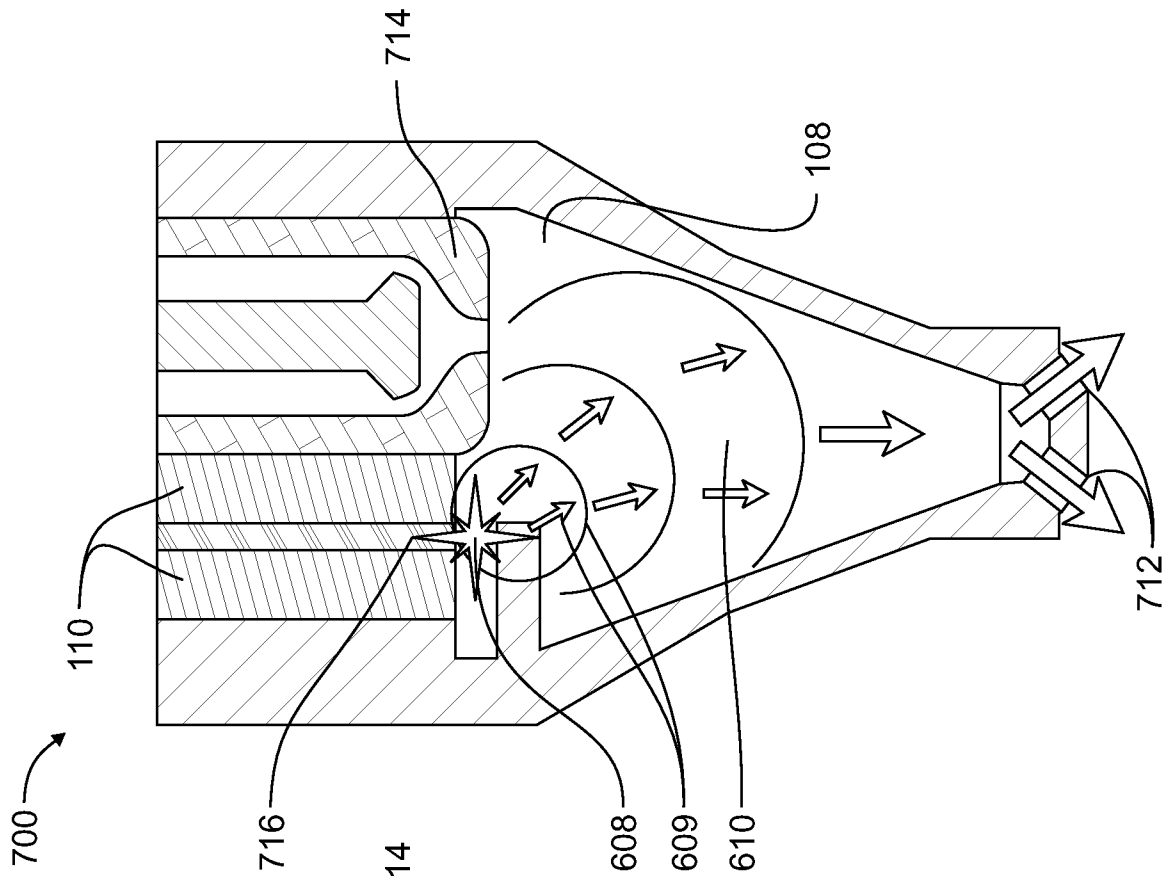


Fig. 7A

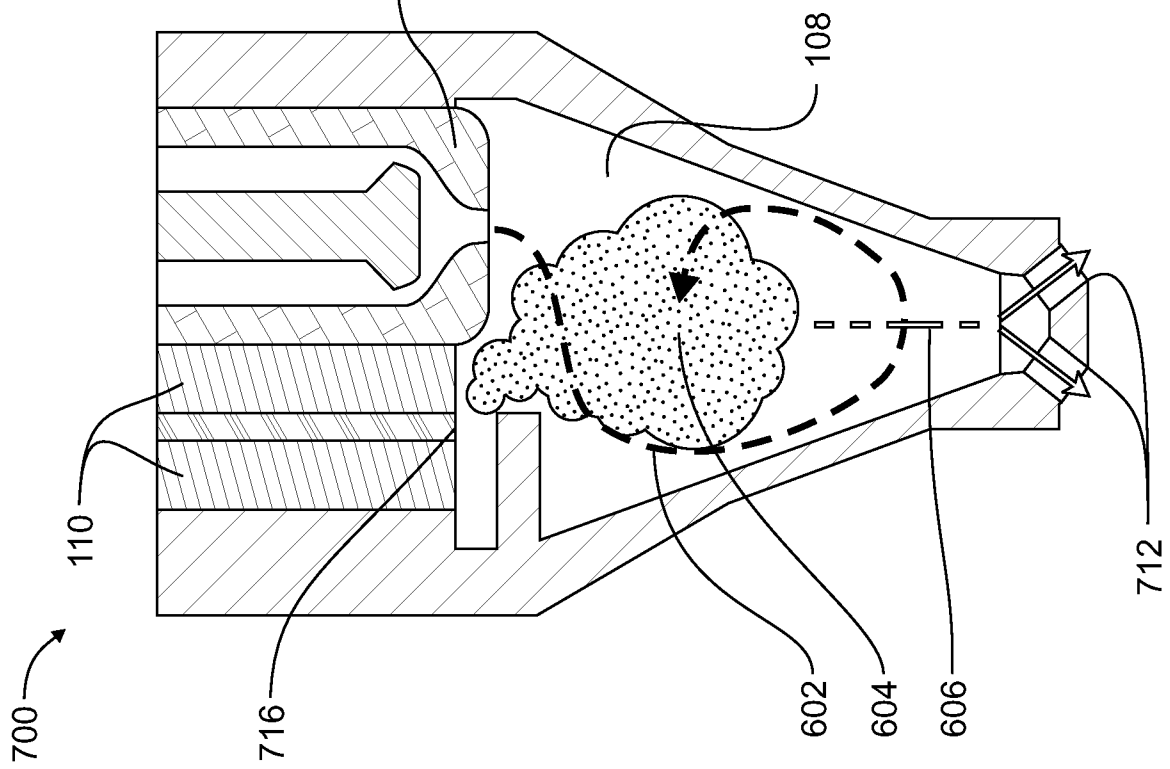


Fig. 7B

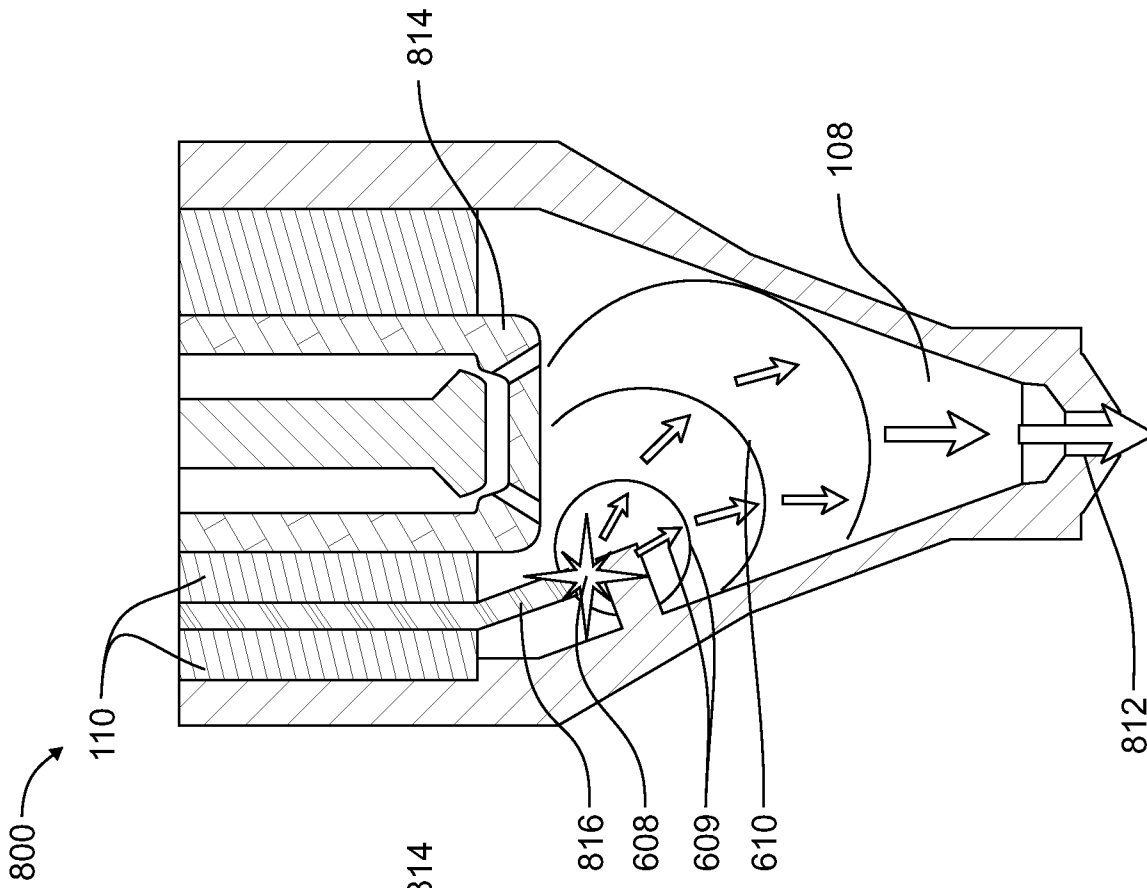


Fig. 8A

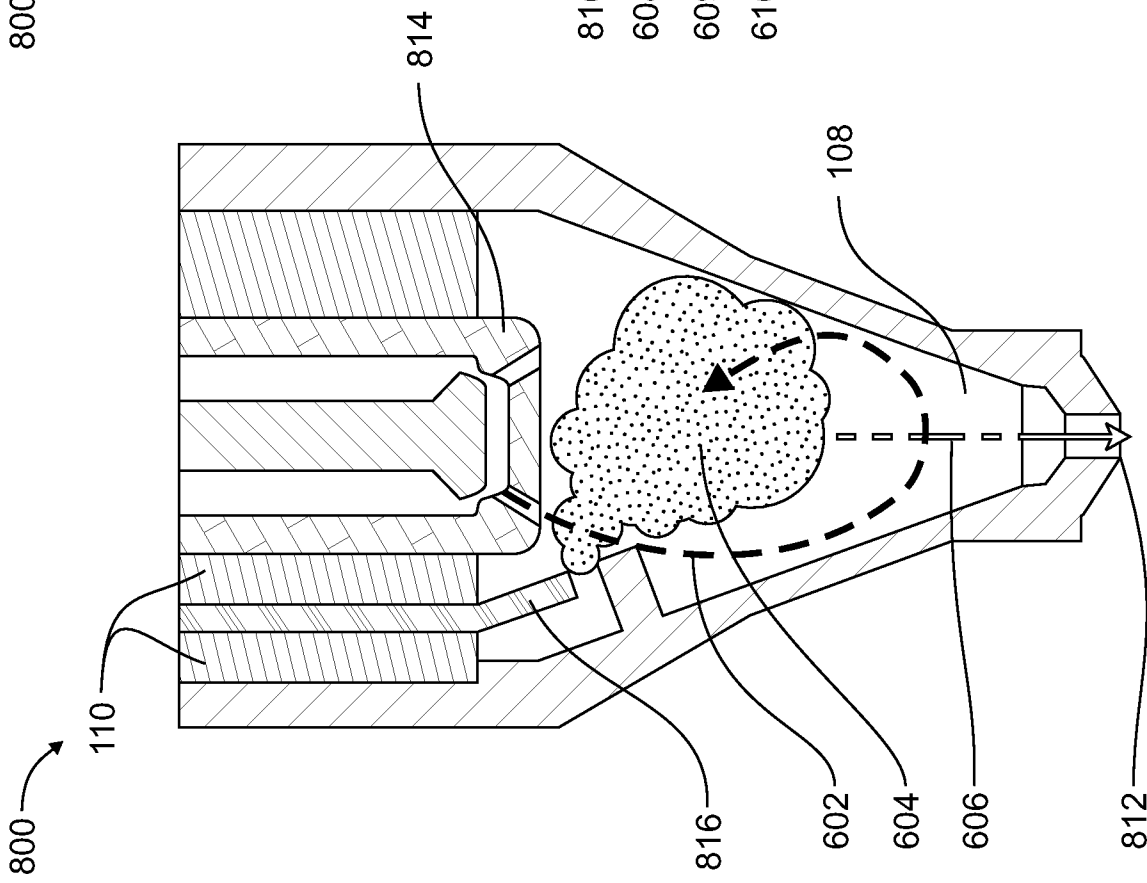


Fig. 8B

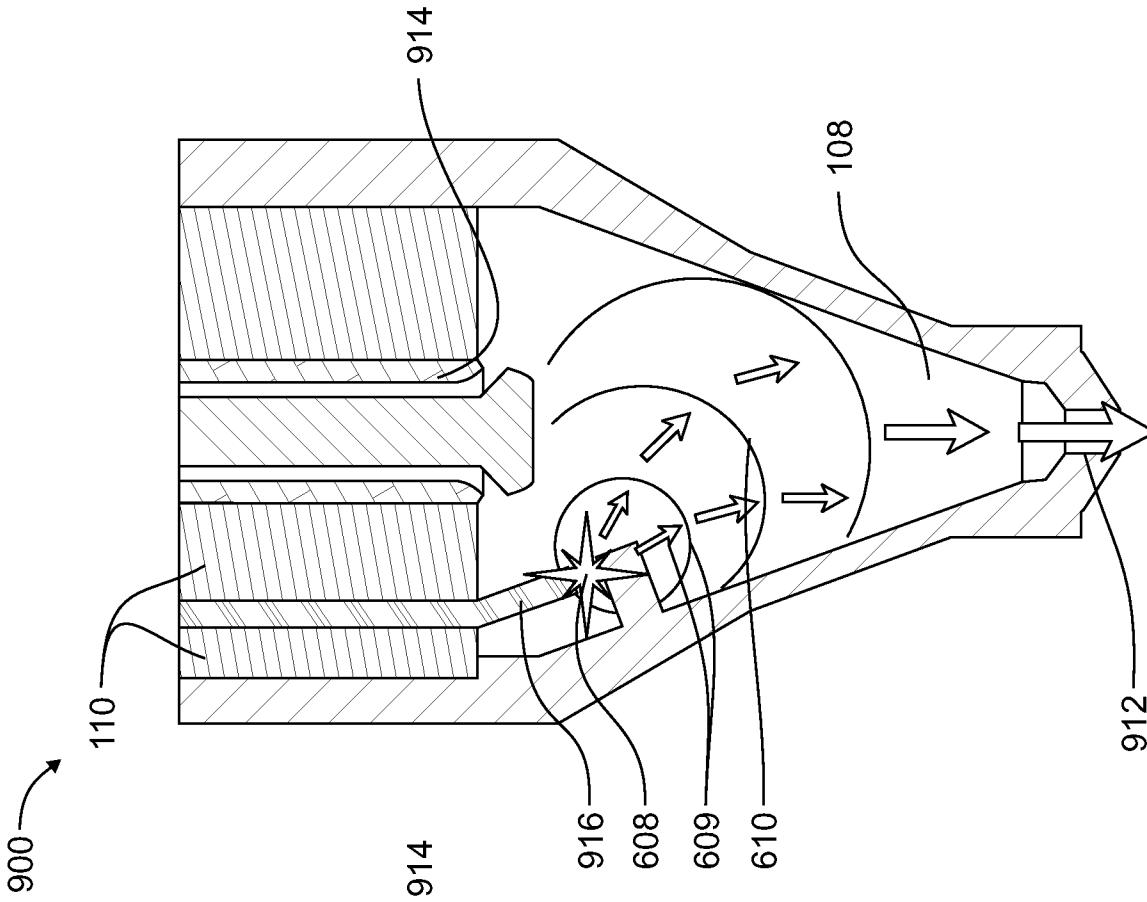


Fig. 9A

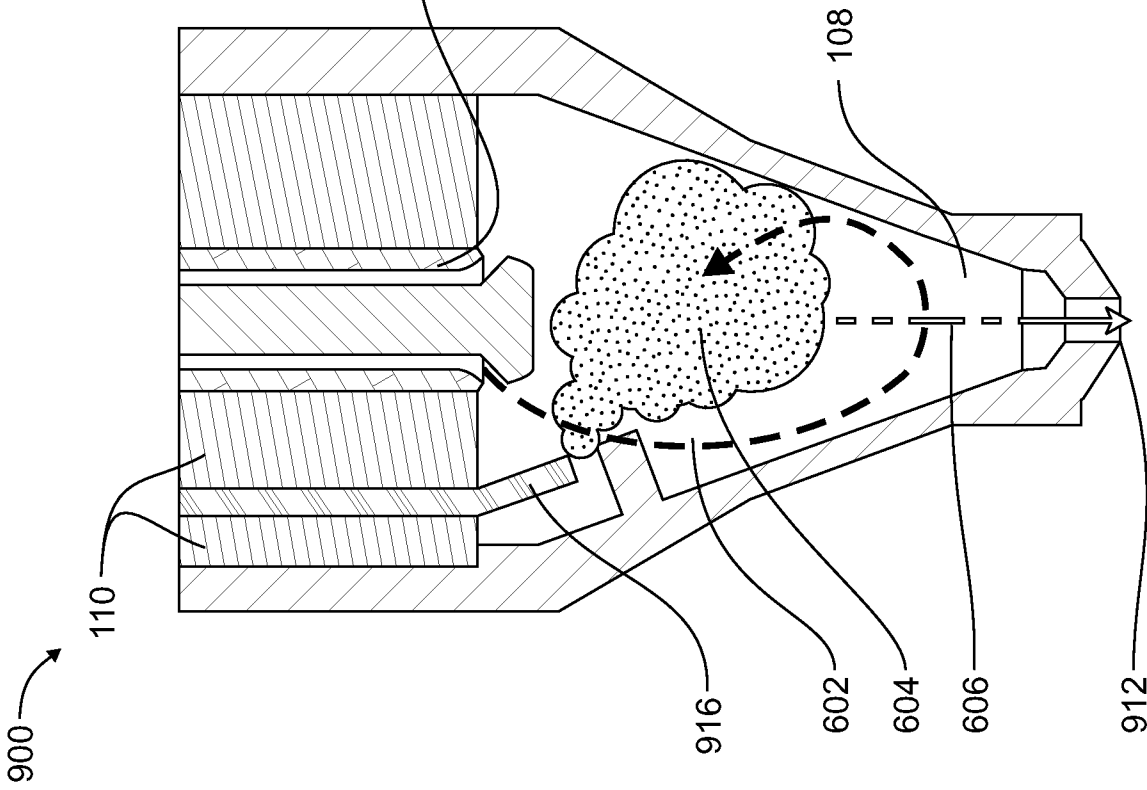


Fig. 9B

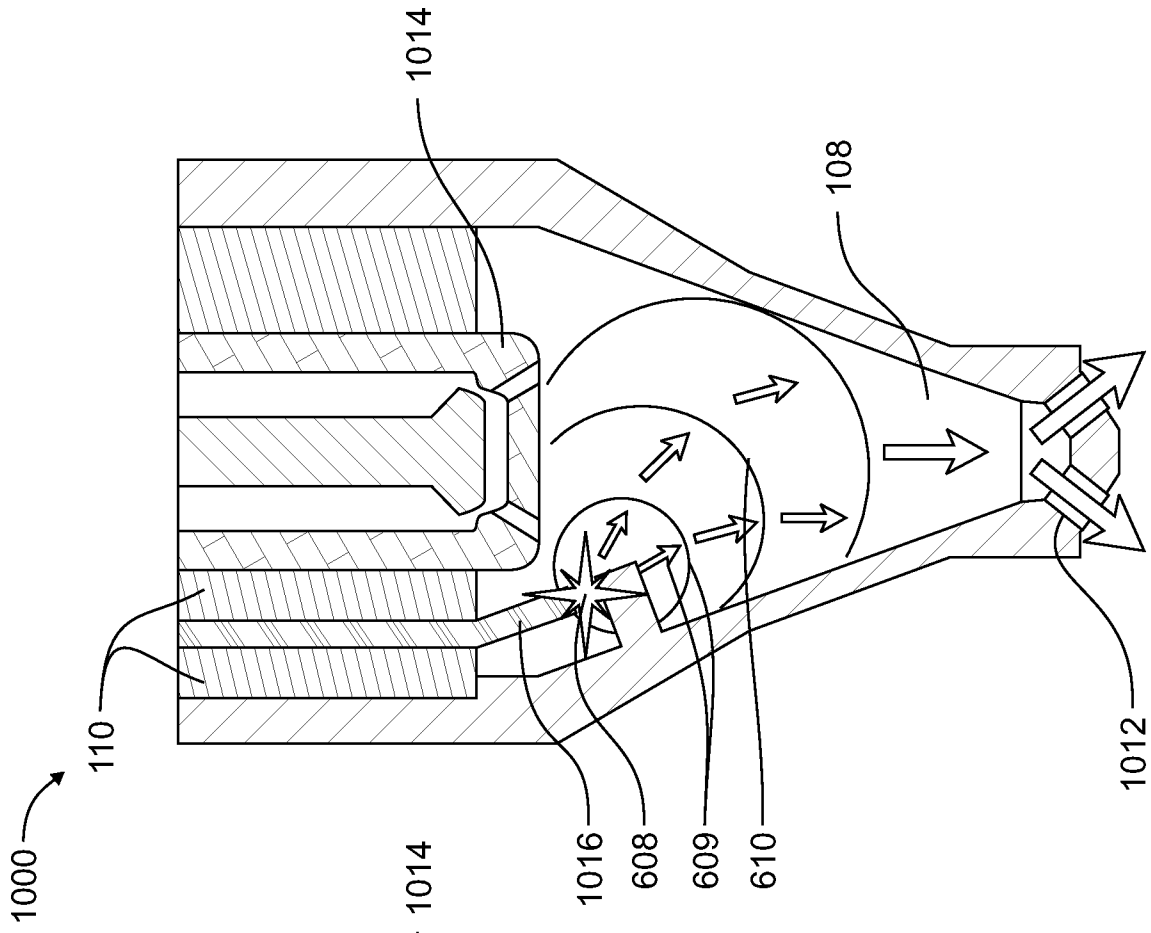


Fig. 10A

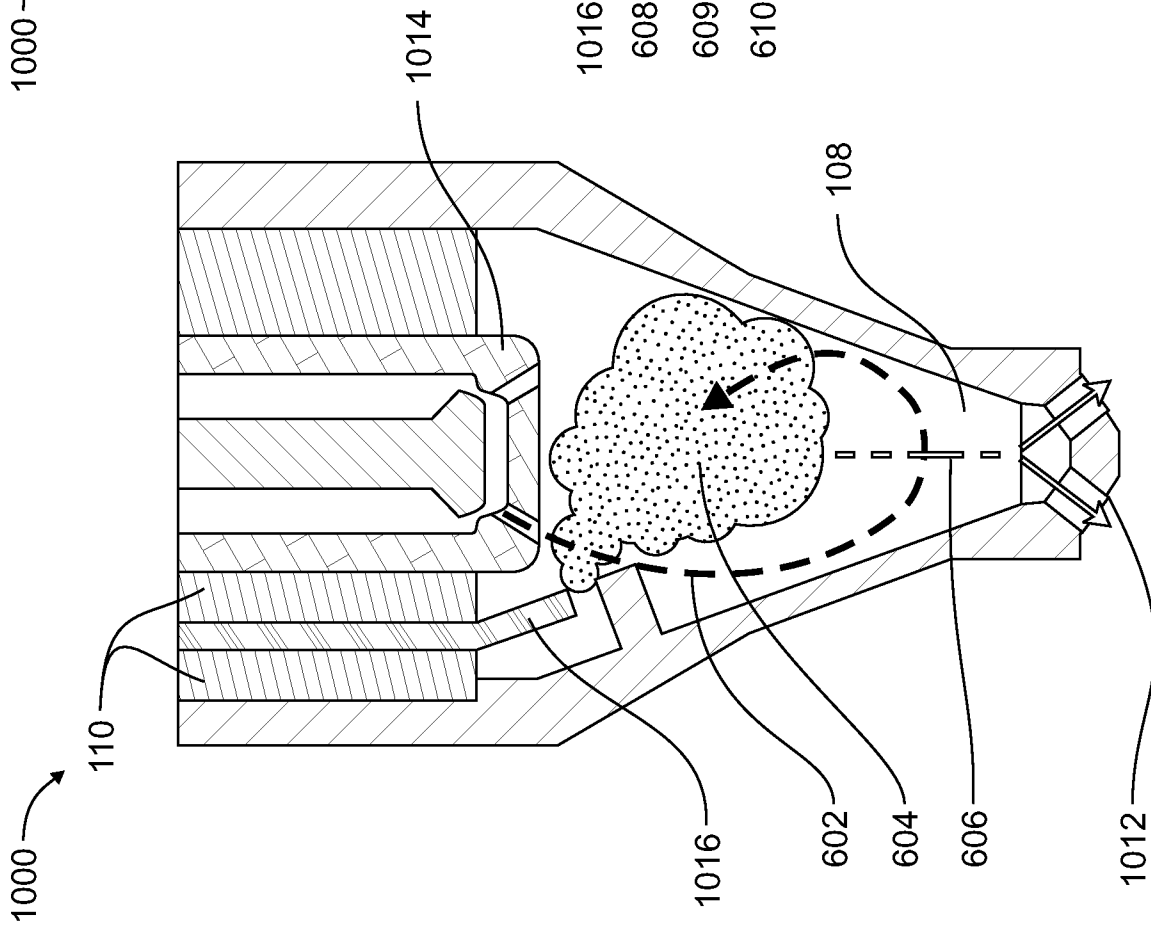


Fig. 10B

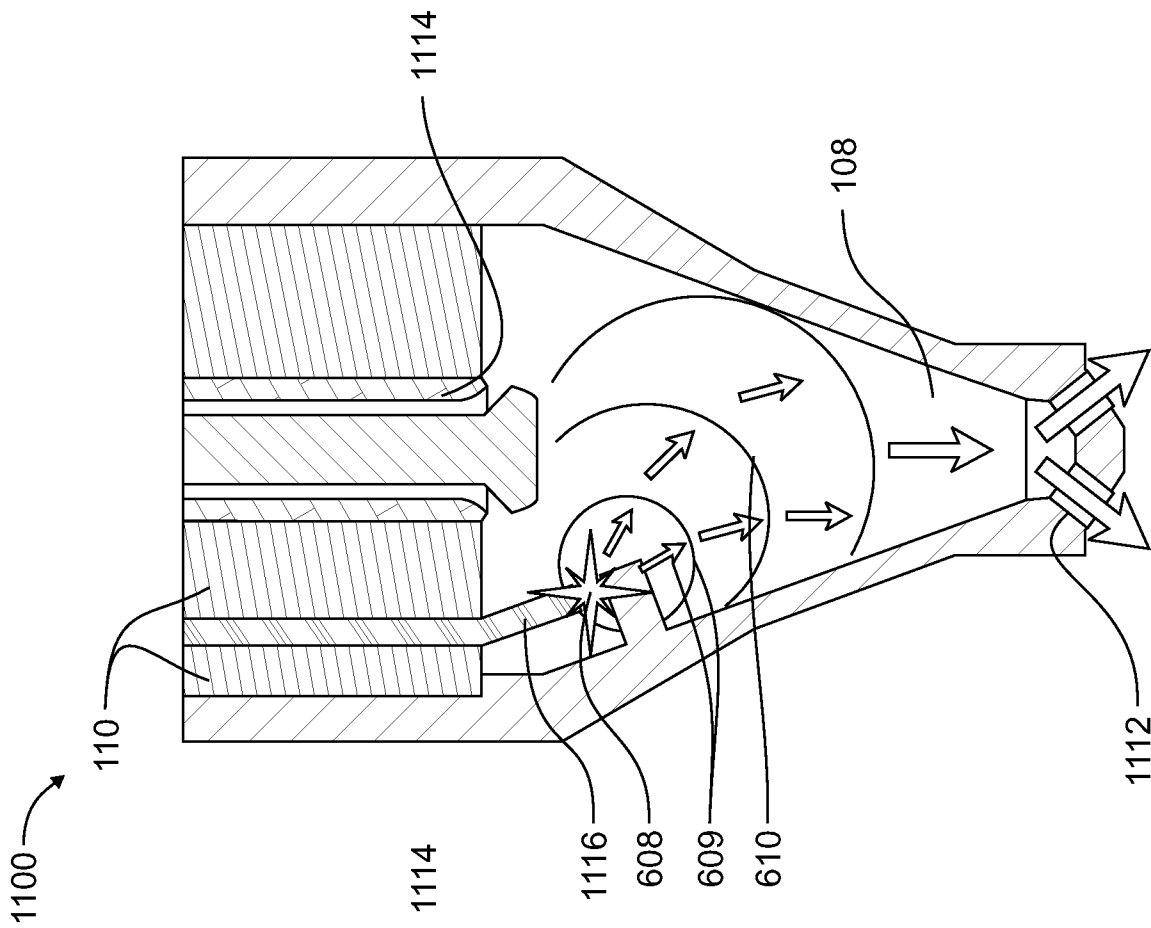


Fig. 11A

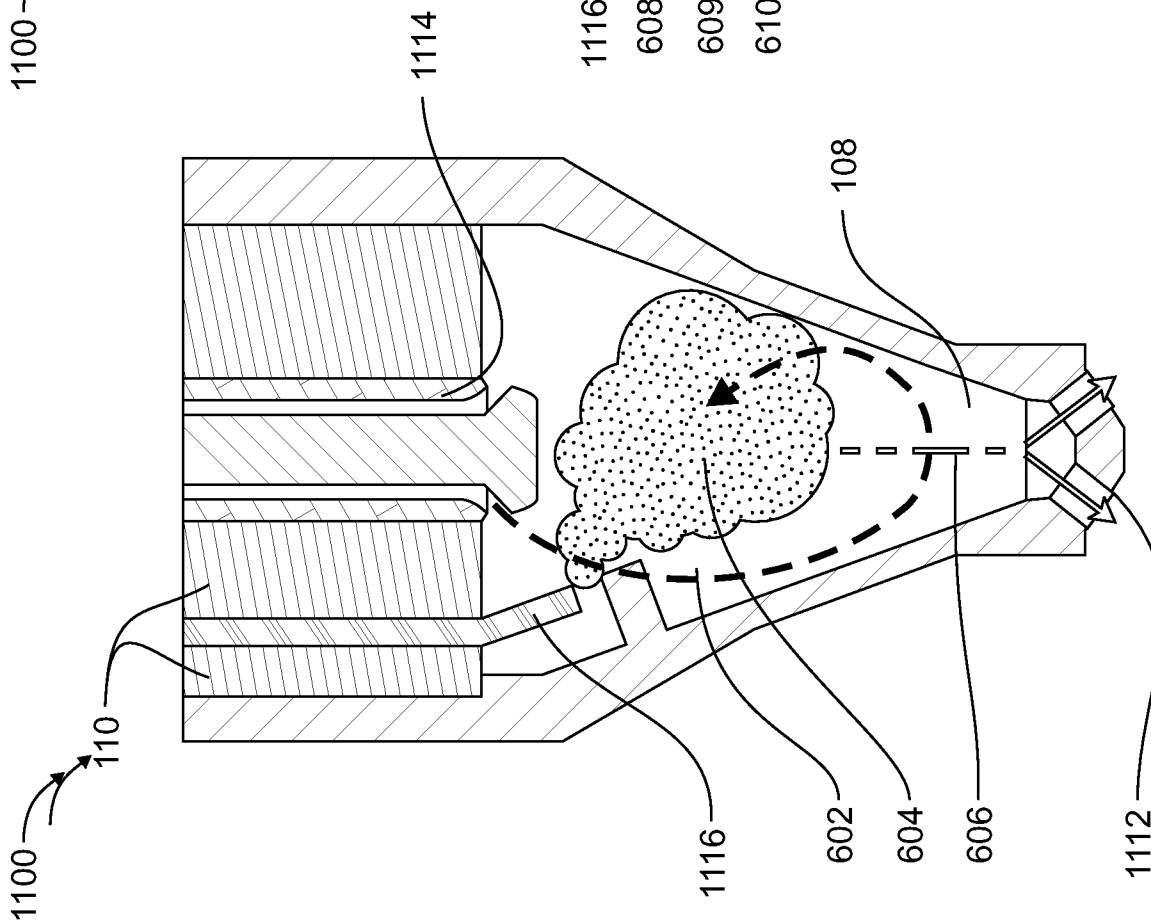


Fig. 11B

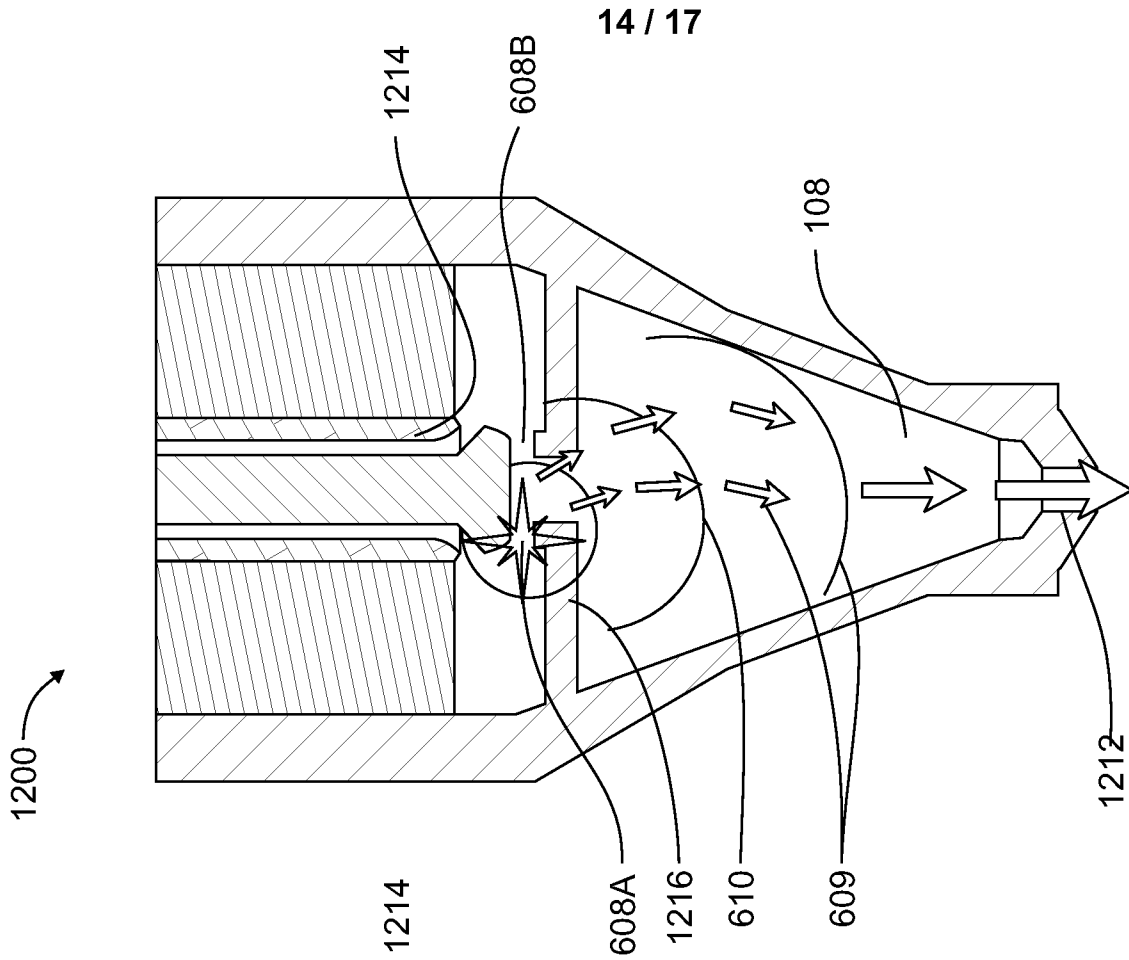


Fig. 12B

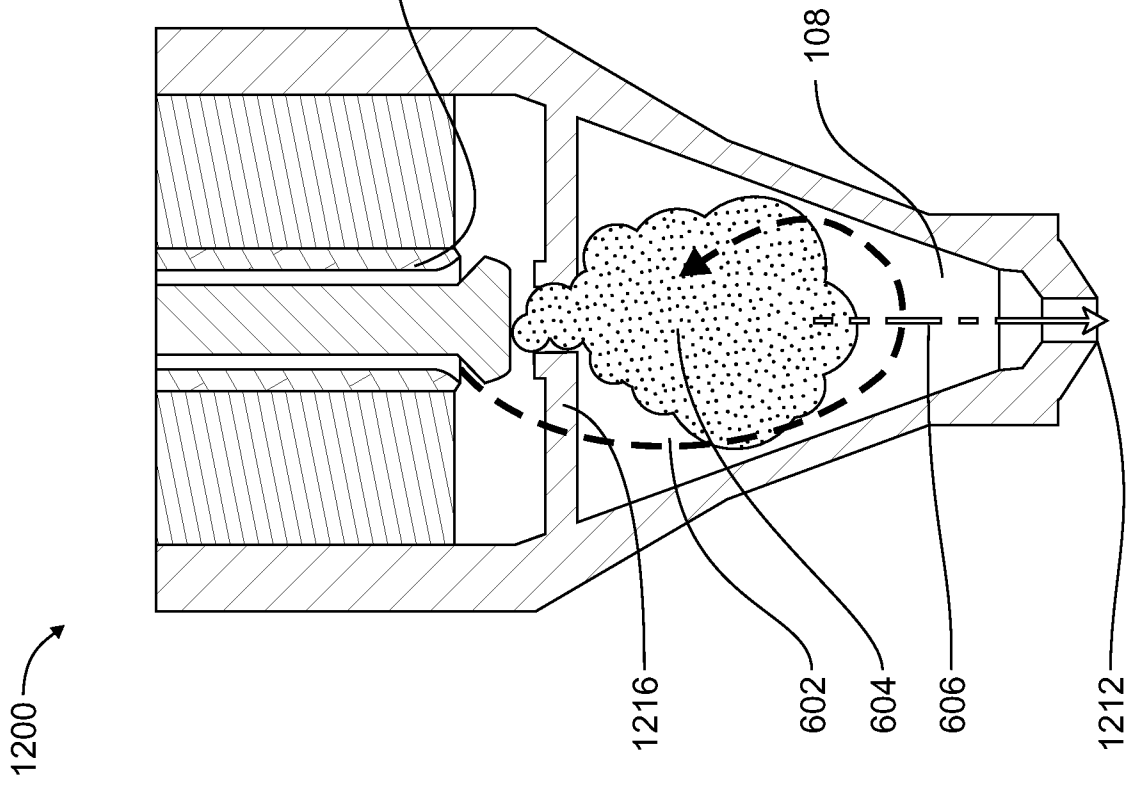


Fig. 12A

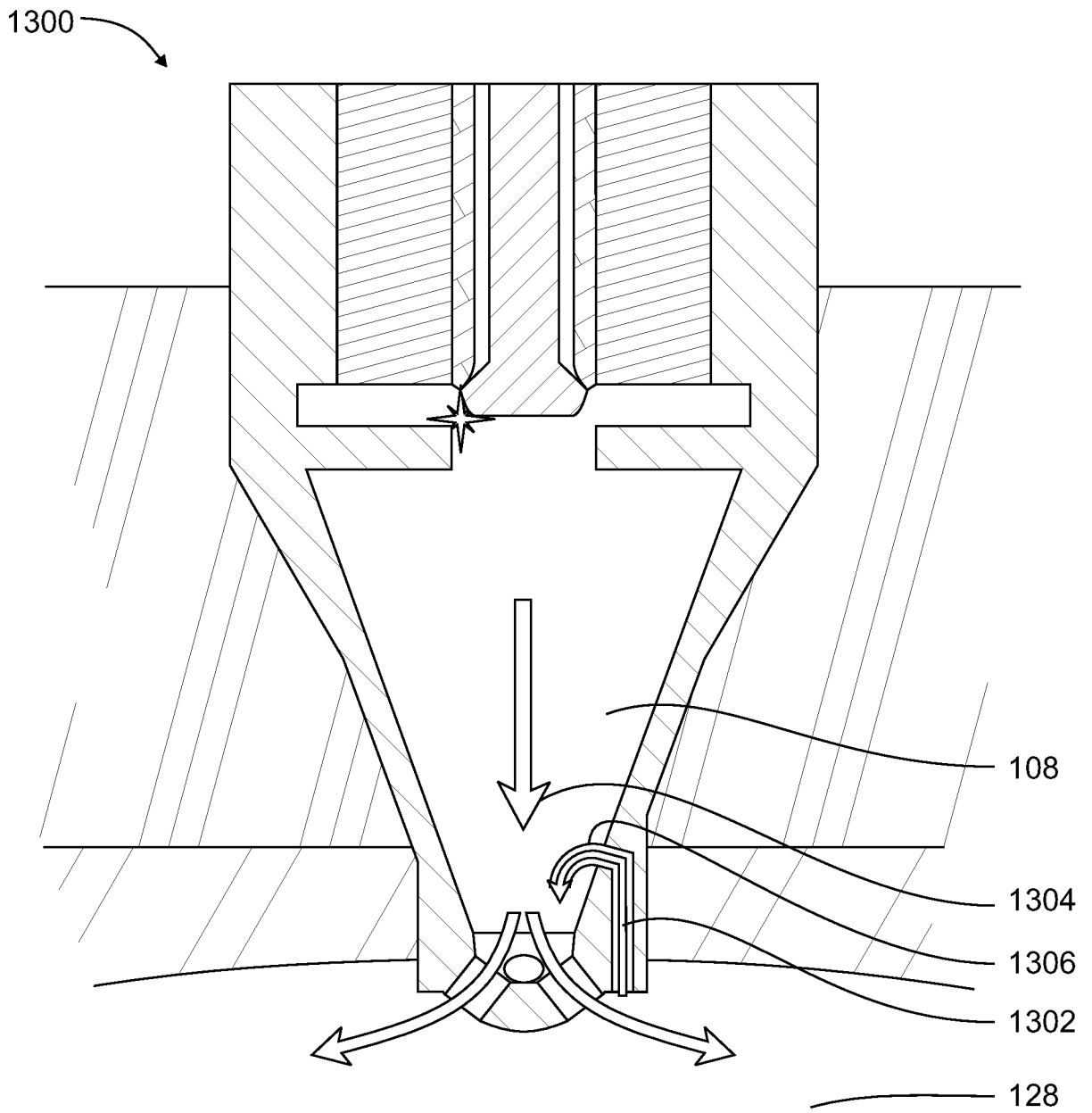


Fig. 13

1400 ↗

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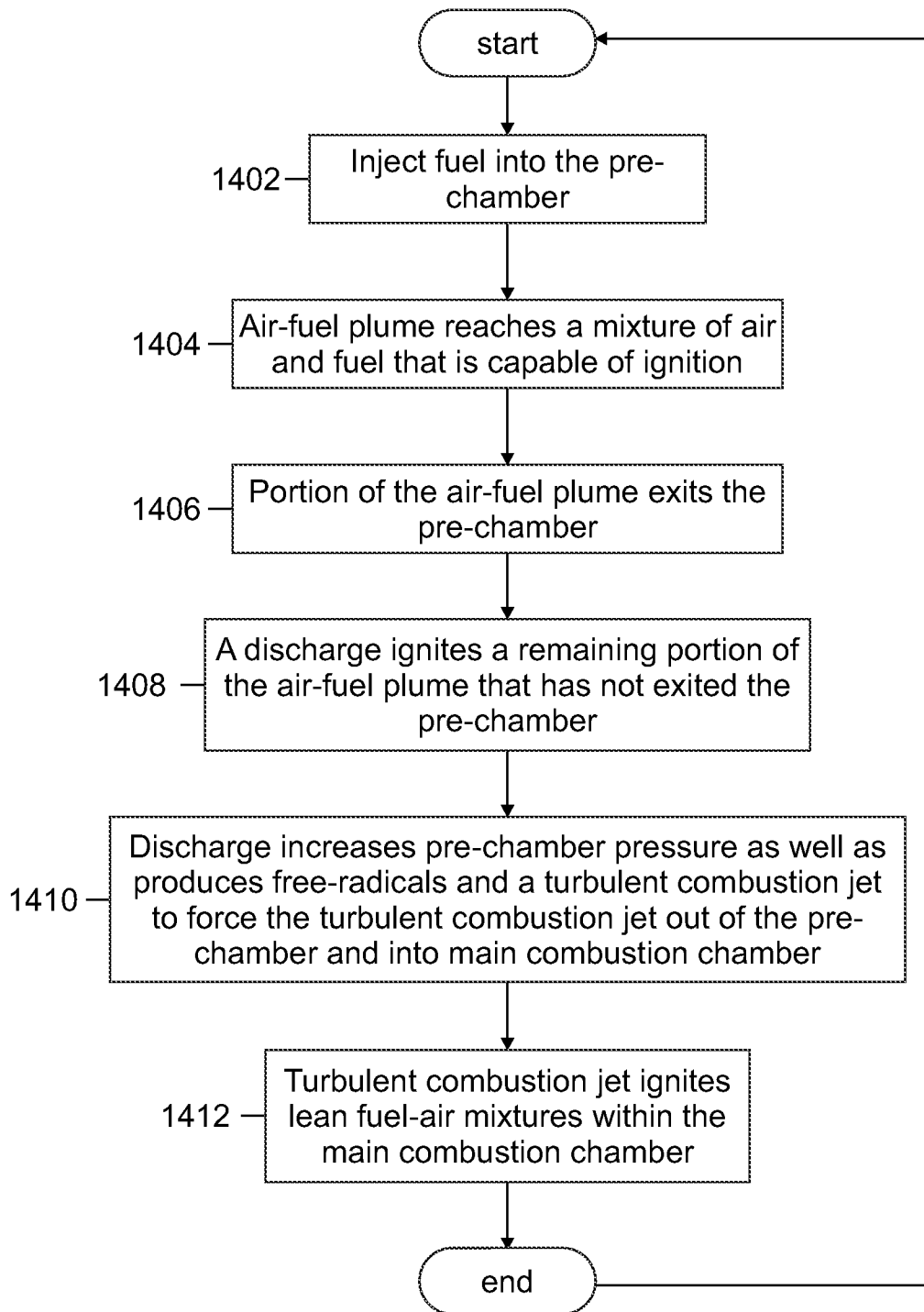


Fig. 14

1500 →

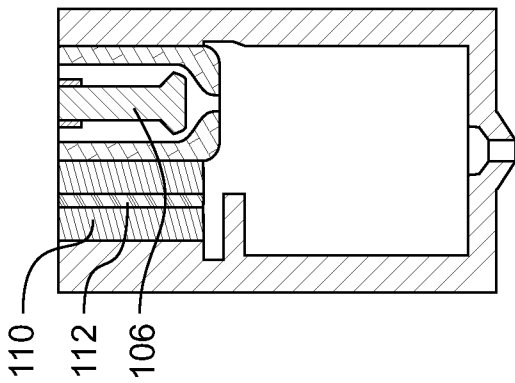


Fig. 15A

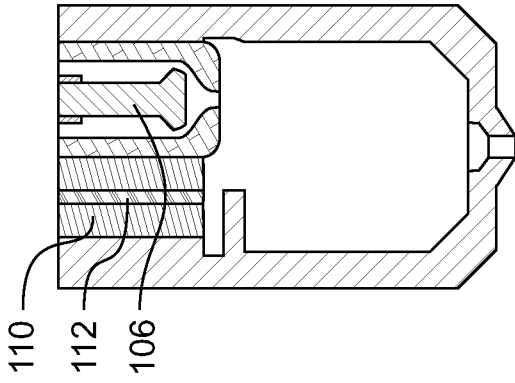


Fig. 15B

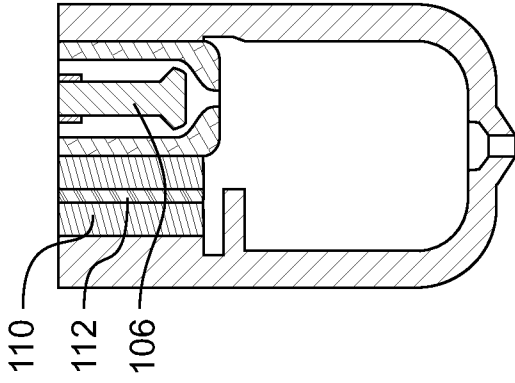


Fig. 15C

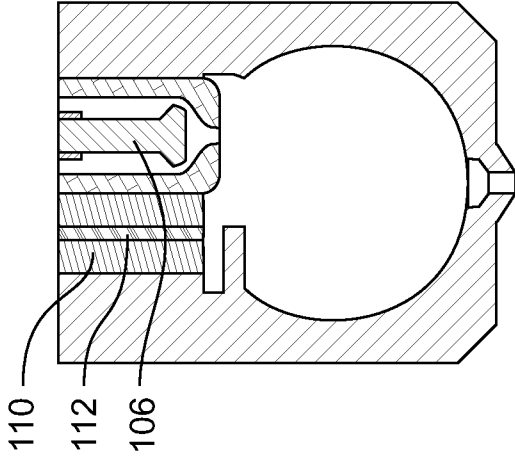


Fig. 15D

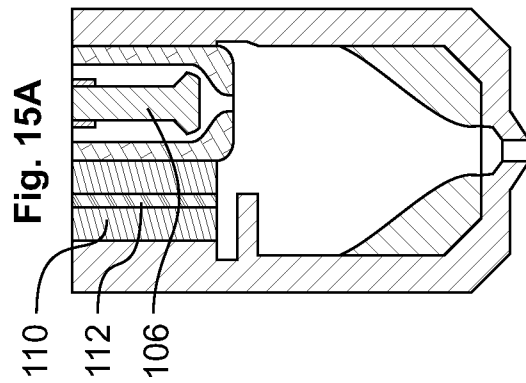


Fig. 15E

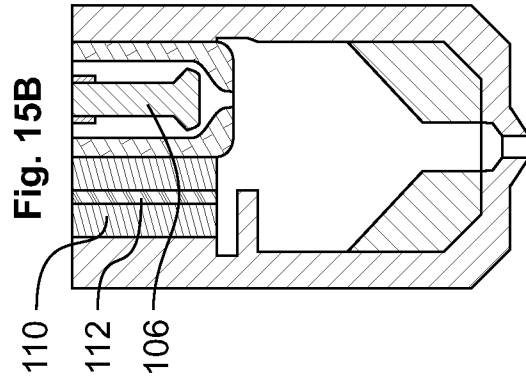


Fig. 15F

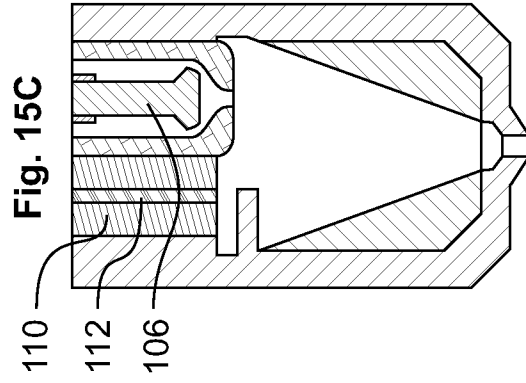


Fig. 15G

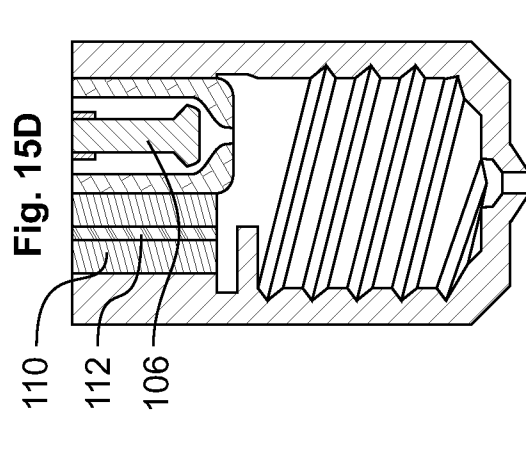


Fig. 15H

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/020583**A. CLASSIFICATION OF SUBJECT MATTER****F02M 57/06(2006.01)i, F02M 61/16(2006.01)i, F02M 61/08(2006.01)i, F02M 61/10(2006.01)i, F02M 29/02(2006.01)i, F02M 29/06(2006.01)i, F02P 15/00(2006.01)i, F02B 5/00(2006.01)i, F02B 19/12(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 57/06; F02B 19/12; F02M 27/06; F02P 23/04; H01S 3/11; F02B 19/10; F02B 23/00; F02B 19/08; F02M 61/16; F02M 61/08; F02M 61/10; F02M 29/02; F02M 29/06; F02P 15/00; F02B 5/00

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) & Keywords: ignition, pre-chamber, fuel, combustion, isolate, valve, nozzles, controller, stoichiometric, and inject

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2012-0103302 A1 (ATTARD, WILLIAM) 03 May 2012 See abstract; paragraphs [0009], [0032]-[0050] and figures 2-3.	1-10, 12-20, 22-29
Y		11, 21
Y	US 2013-0047954 A1 (MCALISTER, ROY E.) 28 February 2013 See abstract; paragraph [0050] and figure 5A.	11, 21
A	JP 2006-329116 A (NISSAN MOTOR CO., LTD.) 07 December 2006 See paragraphs [0004]-[0005], [0013] and figures 1-2.	1-29
A	US 2010-0000485 A1 (VOGEL et al.) 07 January 2010 See abstract and paragraphs [0003]-[0011].	1-29
A	US 4892070 A (KUHNER, DIETER) 09 January 1990 See abstract; column 1, line 63 - column 3, line 43 and figure 1.	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

17 June 2015 (17.06.2015)

Date of mailing of the international search report

18 June 2015 (18.06.2015)

Name and mailing address of the ISA/KR

International Application Division
Korean Intellectual Property Office
189 Cheongsa-ro, Seo-gu, Daejeon Metropolitan City, 302-701,
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HWANG, Chan Yoon

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2015/020583

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