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

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
16 February 2023 (16.02.2023)

WIPO | PCT

(10) **International Publication Number**
WO 2023/016742 A1

(51) **International Patent Classification:**
F02D 19/06 (2006.01) ***F02D 23/00*** (2006.01)
F02D 19/08 (2006.01) ***F02M 21/02*** (2006.01)

(21) **International Application Number:**
PCT/EP2022/069689

(22) **International Filing Date:**
13 July 2022 (13.07.2022)

(25) **Filing Language:** English

(26) **Publication Language:** English

(30) **Priority Data:**
63/231,028 09 August 2021 (09.08.2021) US

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

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH,

(54) Title: MULTI POINT FUEL INJECTION IN BI-FUEL COMBUSTION ENGINES

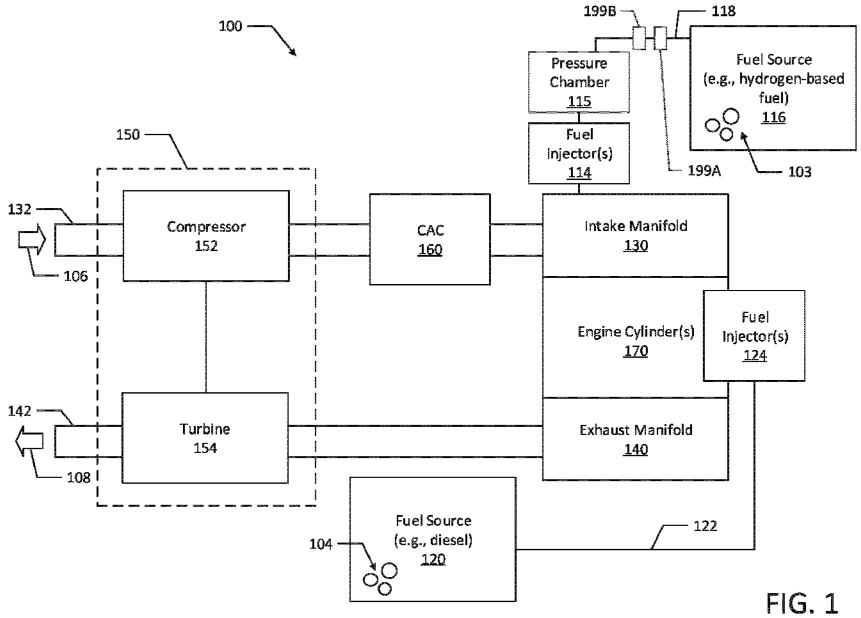

FIG. 1

(57) **Abstract:** A multi-fuel combustion system includes a primary fuel source, a secondary hydrogen fuel source, a turbocharger including a compressor and a turbine, a charged-air- cooler positioned downstream of the compressor, at least one engine cylinder, a primary fuel injector for each of the at least one engine cylinder, and a plurality of other fuel injectors. Each of the primary fuel injectors is configured to directly inject the primary fuel in a corresponding engine cylinder. The plurality of other fuel injectors are configured to inject the hydrogen fuel in an intake manifold downstream of the compressor and charged-air- cooler and upstream of the at least one engine cylinder.

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

Published:
— *with international search report (Art. 21(3))*
— *in black and white; the international application as filed contained color or greyscale and is available for download from PATENTSCOPE*

TITLE

MULTI POINT FUEL INJECTION IN BI-FUEL COMBUSTION ENGINES

BACKGROUND

[0001] Engines may use various forms of fuel delivery to provide a desired amount of fuel for combustion in each cylinder. One type of fuel delivery uses a direct injector for each cylinder. Engines may also use multiple fuel sources, such as a fumigation system that injects fuel upstream of a turbocharger. A typical turbocharged engine system includes a turbocharger with a compressor and turbine and a charged-air-cooler that cools the fuel-air mixture from the compressor before passing the mixture to the engine cylinders.

SUMMARY

[0002] The present disclosure provides new and innovative systems and methods of multi point fuel injection for dual-fuel or bi-fuel combustion engines. In an example, a multi-fuel combustion system includes a primary fuel source, a secondary hydrogen fuel source, a turbocharger including a compressor and a turbine, a charged-air-cooler positioned downstream of the compressor, at least one engine cylinder, a primary fuel injector for each of the at least one engine cylinder, and a plurality of other fuel injectors. Each of the primary fuel injectors is configured to directly inject the primary fuel in a corresponding engine cylinder. The plurality of other fuel injectors are configured to inject the hydrogen fuel into an intake manifold downstream of the compressor and charged-air-cooler and upstream of the at least one engine cylinder. Additionally, the at least one other injector is asymmetrically controlled based on at least one engine parameter.

[0003] In an example, a method for operating a multi-fuel combustion engine includes supplying air to a compressor of a turbocharger of the multi-fuel combustion engine. The multi-fuel combustion engine has at least one engine cylinder. The method also includes passing the air from the compressor to an intake manifold of the engine and injecting a hydrogen fuel into the intake manifold to mix with the air. The hydrogen fuel is injected from a pressure ramp at an injection point at a first time. Additionally, the hydrogen fuel is injected into the intake manifold upstream of the at least one engine cylinder and downstream of the compressor. The hydrogen fuel is asymmetrically injected based on at least one engine parameter to provide asymmetric control. The method also includes directly injecting a primary fuel into the engine cylinder at a second time such that the primary fuel, hydrogen fuel and air mix and combust within a cylinder of the at least one engine cylinder.

[0004] Additional features and advantages of the disclosed method and system are described in, and will be apparent from, the following Detailed Description and the Figures. The features and advantages described herein are not all-inclusive and, in particular, many additional features and advantages will be apparent to one of ordinary skill in the art in view of the figures and description. Moreover, it should be noted that the language used in the specification has been principally selected for readability and instructional purposes, and not to limit the scope of the inventive subject matter.

BRIEF DESCRIPTION OF THE FIGURES

[0005] Fig. 1 illustrates a block diagram of an example bi-fuel combustion engine system according to an example embodiment of the present disclosure.

[0006] Fig. 2 illustrates an example of fluid flow in a bi-fuel combustion engine according to an example embodiment of the present disclosure.

[0007] Fig. 3A illustrates an example injector configuration for a bi-fuel combustion engine system according to an example embodiment of the present disclosure.

[0008] Fig. 3B illustrates an example injector configuration for a bi-fuel combustion engine system according to an example embodiment of the present disclosure.

[0009] Fig. 3C illustrates an example injector configuration for a bi-fuel combustion engine system according to an example embodiment of the present disclosure.

[0010] Fig. 4 illustrates an example graph of the position of a piston within a bi-fuel combustion engine system, and the corresponding valve and injector timing according to an example embodiment of the present disclosure.

[0011] Figs. 5A and 5B illustrate an example injector configuration for a bi-fuel combustion engine system according to an example embodiment of the present disclosure.

[0012] Fig. 6 illustrates a flow chart of an example method of multi-point fuel injection for a bi-fuel combustion engine according to an example embodiment of the present disclosure.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

[0013] Techniques are disclosed for providing multi point fuel injection in multi-fuel (e.g., bi-fuel) combustion engines. As illustrated in Fig. 1, an internal combustion system 100 (e.g., engine) may include a first fuel source 120 (e.g., diesel) and a second fuel source 116 (e.g., hydrogen fuel source 116). As used herein, the multi-fuel combustion engine may be a diesel engine that has been modified to use additional fuel sources (e.g., hydrogen). Therefore, instead of a first fuel and second fuel - the first or diesel fuel source 120 may be referred to as a primary fuel source as the diesel fuel is the original or primary fuel source for the engine that is often directly injected in the cylinder. The second or hydrogen fuel source 116 may be referred to as a secondary fuel source. The fuel source(s) may be a storage tank(s) holding the respective fuels.

[0014] In an example, the first fuel (also referred to as a primary fuel) provided in the first fuel source 120 may be diesel and the second fuel (also referred to as a secondary fuel) provided in the second fuel source 116 may be hydrogen. The fuel sources 116, 120 are connected to fuel injector(s) 114, 124 via fuel lines 118, 122. The hydrogen fuel source 116 is a tank containing compressed hydrogen gas and/or cryogenic or liquid hydrogen. As illustrated in Fig. 1, fuel 103 (e.g., hydrogen-based fuel) from the second fuel source or hydrogen fuel source 116 is injected into a pressure chamber 115. After the hydrogen fuel 103 has been injected into the pressure chamber 115, the hydrogen fuel 103 may then be injected into the intake manifold 130 by fuel injector(s) 114, and fuel 104 (e.g., diesel) from the first fuel source 120 is directly injected into engine cylinder(s) 170 by fuel injector(s) 124. For example, the fuel 104 (e.g., diesel) may be directly injected into the combustion chamber of the engine cylinder(s) 170.

[0015] In an example, air 106 travels through air inlet 132 to a compressor 152 of turbocharger 150, where the air is condensed and pushed to a charged-air-cooler ("CAC") 160. The CAC 160 cools and further condenses the air, which then travels to the intake manifold 130 (also commonly referred to as a suction manifold) where it is mixed with hydrogen fuel 103. The air-fuel mixture travels from the intake manifold 130 to the engine cylinder(s) 170 where it is further mixed with directly injected fuel 104 from the first fuel source 120 and combusted. The combustion process creates exhaust 108, which exits the engine cylinder(s) 170 through the exhaust manifold 140 and to the turbine 154 of the turbocharger 150. The exhaust 108 passing through turbine 154 runs the compressor 152. Then, the exhaust 108 exits through exhaust outlet 142.

[0016] The internal combustion system 100 is an example of a bi-fuel combustion engine (e.g., a modified diesel engine). The bi-fuel combustion engine burns or combusts two different fuels 103 and 104 (e.g., hydrogen-based fuel and diesel) at the same time. For example, the first fuel 104 (e.g., diesel) may be directly injected in the engine cylinder(s) 170 and may be used as the initiator to initiate the combustion of the hydrogen fuel 103. In other examples, other fuels (e.g., hydrogen) may be used as the initiator to initiate combustion of the first fuel (e.g., diesel). It should be appreciated that the system 100 may be configured in various arrangements using predetermined fuel ratios and injection timing techniques such that one or more fuels 103, 104 may serve as the initiator for the other fuel.

[0017] As discussed above, and illustrated in more detail in Fig. 2, hydrogen fuel 103 (illustrated as circles) is introduced into the intake manifold 130 upstream of an engine cylinder(s) 170 and downstream of a turbocharger 150 and CAC 160 (also commonly referred to as an intercooler or an aftercooler). The compressor 152 and CAC 160 deliver a compressed charge flow of air 106 (illustrated by squares) to the suction manifold. In an example, an air filter 134 may be positioned along air inlet 132 upstream of the compressor 152 to remove particulate matter from air 106. As illustrated in Fig. 2, the “squares” representing air 106 appear closer together after exiting the compressor 152 and CAC 160 to indicate that the air 106 is a compressed charge flow. In an example, the air 106 exiting the compressor 152 of the turbocharger 150 travels to the CAC 160 where the air is cooled via any suitable heat exchange process, such as an air-to-water or air-to-air heat exchange process.

[0018] After the fuel injector 114 injects hydrogen fuel 103 into the charged flow of air 106, the charged flow of the mixture of air 106 and hydrogen fuel 103 is delivered to the engine cylinder(s) 170. For example, the air-fuel mixture may exit the CAC 160 to the intake manifold 130 of the engine for combustion by one or more cylinders 170 of the engine. The air-fuel mixture may enter one or more engine cylinders 170 through corresponding air intake valves. As the piston 172 is at the bottom of the cylinder 170 during the “induction” phase, the air intake valve opens to allow air or the air-fuel mixture to enter the cylinder 170 from the intake manifold. For example, in a diesel engine, the mixture of air 106 and hydrogen fuel 103 may be introduced into the cylinder 170. Then, the air intake valve is closed (and the exhaust valve remains closed) while the piston rod 174 pushes the piston 172 towards the top of cylinder 170 (during the "compression" phase) and the mixture is compressed.

[0019] Within the cylinder(s) 170, a first fuel 104 (illustrated by diamonds) is directly injected into the cylinder(s) 170, which may act as an initiator to combust the air-fuel mixture. After the first fuel 104 (e.g., diesel) is injected or sprayed into the cylinder 170, the heat from the compression may cause the mixture (e.g., hydrogen fuel 103, first fuel 104 and air 106) to ignite. The expansion of the combustion gases pushes the piston 172 back toward the bottom of the cylinder 170 during the power stroke (e.g., during the "combustion" phase). After the mixture of hydrogen fuel 103, first fuel 104 and air 106 is combusted in the respective cylinder(s) of the engine, an exhaust valve is opened which allows the exhaust gas 108 (illustrated by triangles) to outlet into an exhaust manifold 140 where it is delivered to the turbine 154 of the turbocharger 150 to drive the compressor 152 via a rotatable shaft therebetween. Then, the exhaust gas 108 leaves the turbine 154 to an exhaust outlet 142. In another example, spark ignition may be used to ignite the mixture (e.g., hydrogen fuel 103, first fuel 104 and air 106), causing combustion. Alternatively, as noted above, other fuels or other fuel combinations may serve as an initiator. For example, one or more fuels 103, 104 or fuel combinations may serve as the initiator for the other fuel.

[0020] Additionally, as illustrated in Fig. 2, the system may include shut-off valves to cease the flow of fuel from a fuel source (e.g., fuel source 116). Dual serial valve configurations, such as the configuration illustrated in Fig. 2 by valves 199A, 199B, may be particularly advantageous for use with volatile fuels (e.g., hydrogen-based fuels). In this example arrangement, if one of the shut-off valves 199A, 199B malfunctions, the fuel may still be prohibited from entering the combustion chamber and combusting inadvertently.

[0021] Additionally, as illustrated in Fig. 2, the system may include multiple sensors to monitor flow rates, temperatures, etc. of the system. For example, a boost air temperature sensor 180 may sense and monitor the temperature of the air 106 or air-fuel mixture. Additionally, a knocking sensor 182 may sense variations in the vibrations caused by combustion of a hydrogen fuel 103, first fuel 104, and air 106 in the one or more engine cylinders 170. Upon detecting engine knock, the timing of the injection by injector 114 and/or injectors 124 may be adjusted.

[0022] In another example, the system may include at least one exhaust temperature sensor 184 to monitor the temperature of the exhaust gas 108. The at least one exhaust temperature sensor 184 may monitor the exhaust gas 108 leaving one or more cylinder(s) 170 or at a point later in the exhaust manifold, such as near the turbine 154 of the turbocharger 150.

[0023] In another example, the system may include at least one pressure sensor for sensing the pressure of hydrogen fuel 103. The at least one pressure sensor may be located between the hydrogen fuel source 116 and the pressure chamber 115. Alternatively or additionally, the at least one pressure sensor may be located in the pressure chamber 115. Alternatively or additionally, the at least one pressure sensor may be located in the intake manifold 130.

[0024] The fuel injection or delivery may be based at least partially on outputs from one or more of the sensors. For example, the amount of hydrogen fuel 103 injected into the intake manifold 130 may be based on one or more of the following measured values: intake air manifold temperature, intake air manifold pressure, exhaust gas temperature (e.g., exhaust gas temperature of each cylinder), exhaust gas temperature after the turbocharger, knocking sensor values and a diesel flow sensor. In an example, the amount of fuel 104 injected into the engine cylinder(s) may be adjusted based on the amount of hydrogen fuel 103 injected into the intake manifold 130. For example, the total output energy from the engine may be the energy from hydrogen fuel 103 plus the energy from the first fuel 104 (e.g., diesel). If the total output energy is to remain the same, an increase in the amount of hydrogen fuel 103 injected into the intake manifold 130 may correspond to a decreasing amount of the first fuel 104 (e.g., diesel) directly injected into the engine cylinder(s). Additionally, for high speed engines up to 1800 rotations per minute ("RPM"), an engine speed regulator may regulate the RPM and when hydrogen fuel 103 is injected, the engine speed regulator may automatically decrease the amount of the first fuel 104 (e.g., diesel) injected into the engine cylinder(s) to maintain a constant RPM, otherwise the engine may experience an over-speed or an over frequency condition.

[0025] The injector 125 advantageously injects the hydrogen fuel 103 into a pressure chamber 115, which may be structured and arranged to maintain a constant pressure across the chamber. By injecting the hydrogen fuel 103 into a pressure chamber 115, a consistent pressure may be achieved prior to being injected by injector(s) 114.

[0026] The injector(s) 114 advantageously injects hydrogen fuel 103 downstream of the turbocharger 150 and the CAC 160 thereby eliminating any damage caused by hydrogen fuel 103 within the turbocharger 150 and CAC 160. By injecting hydrogen fuel 103 downstream of both the turbocharger 150 and CAC 160, the system 100 prevents gas from entering the compressor 152 of the turbocharger 150 as well as the CAC 160, which improves the durability, longevity and safety of the system 100. For example, if hydrogen fuel 103 is added upstream of the compressor 152, the molecules of hydrogen fuel 103 may damage the compressor 152. In one example, compressor blades may be damaged due to the impact of hydrogen fuel 103 against the compressor blades rotating at high speeds. Additionally, the corrosive nature of hydrogen fuel 103 may also cause damage to the internal components of both the turbocharger 150 (e.g., compressor 152) and the CAC 160. Mixing hydrogen fuel 103 and air 106 within the compressor 152 also creates a safety concern as fuel-air mixtures are highly combustible and may combust within the compressor 152 of the turbocharger 150.

[0027] A further advantage of injecting hydrogen fuel 103 downstream of the turbocharger 150 and CAC 160 is to prevent build-up of particulate matter (e.g., impurities in hydrogen fuel 103) within the turbocharger 150 and/or CAC 160, which also prevents damage to those components caused by the build-up.

[0028] In an example, the exhaust outlet 142 may include an aftertreatment system to treat the exhaust gas for emissions prior to being outlet to atmosphere. The aftertreatment system may remove particulates, nitrogen-oxide compounds, and other regulated emissions. In another example, a throttle may be positioned within the intake manifold 130 to regulate the charge flow of hydrogen fuel 103 and air 106 to the cylinders 170. However, to improve control of the fuel-air mixture, each of the injectors 114 that inject hydrogen fuel 103 into the intake manifold 130 may include electromagnetic valves associated with the injectors 114. The electromagnetic valves may ensure homogeneity of the fuel-air mixture for different engine arrangements (e.g., engines with one cylinder up to engines with 20 cylinders or engine output power form 20kW up to 1000kW). The electromagnetic valves may advantageously provide more precise and linear control of flow than other technologies. The mass flow of the fuel-air mixture may be precisely controlled by the opening time of the electromagnetic valves. Conversely, other systems such as fumigation systems typically include a butterfly throttle, which is less precise that the system described herein as the flow follows an “S-curve”.

[0029] As illustrated in Figs. 3A, 3B and 3C, the injector(s) 114 may inject hydrogen fuel 103 at a set of points “P” or regions (illustrated by the dashed circles) within the intake manifold 130. By injecting hydrogen fuel 103 at a set of points “P”, less injectors 114 and fuel lines 118 are required. Some multi-fuel systems, such as the system illustrated in Fig. 3A, may include an injector 114 for each engine cylinder to directly inject hydrogen fuel 103 into each engine cylinder 170. The additional components (e.g., injectors 114 and fuel lines 118) results in more control over air-fuel ratio among each cylinder(s) 170. In another example, such as a fumigation system, hydrogen fuel 103 is introduced upstream or before the turbocharger 150, which may cause damage to the compressor 152 of the turbocharger 150 or to the CAC 160.

[0030] As illustrated in Fig. 3A, air 106 (illustrated by clear arrows) passes through the compressor 152 and CAC 160 and into the intake manifold 130 where it is mixed with hydrogen fuel 103. The air 106 and hydrogen fuel 103 mix when hydrogen fuel 103 is injected by injector(s) 114 at a set of points “P” or regions within the intake manifold 130. As illustrated in Fig. 3A, multiple injectors (e.g., injectors 114A-C) may inject hydrogen fuel 103 at a set of points or regions within the intake manifold 130. Then, the air-fuel mixture 107 (illustrated by hatched arrows) flows through the intake manifold 130 to the engine cylinders (e.g., cylinders 170A-D). In the illustrated example, the engine includes four engine cylinders 170A-D, but other cylinder configurations may be used (e.g., 1 cylinder to 20 cylinders). The first fuel 104 (e.g., diesel) may be directly injected into each cylinder 170A-D, where the mixture of hydrogen fuel 103, first fuel 104 and air 106 combust and exit the cylinders 170A-D as exhaust gas 108 (illustrated by solid black arrows). The exhaust gas 108 travels through the exhaust manifold and to the turbine 154 of the turbocharger.

[0031] Also, as illustrated in Fig. 3A, each injector 114 may be connected to a pressure chamber 115 where hydrogen fuel 103 is injected into via injector 125 prior to being injected into intake manifold 130. Conversely, the intake manifold 130 may serve as the pressure chamber 115. However, in a preferable configuration, hydrogen fuel is injected via a predetermined quantity of injection points that match the quantity of engine cylinders. As illustrated in Fig. 3A, there are four injection points ("P") corresponding to the four engine cylinders 170A-C.

[0032] Fig. 3B illustrates another example configuration with eight cylinders (e.g., cylinders 170A-H) with the intake manifold split into two separate banks 136 (e.g., banks 136A-B). Fig. 3C illustrates a "v-type" engine configuration. In an example, injectors 114 may inject hydrogen fuel 103 in each bank 136 of the intake manifold 130 upstream of the engine cylinders 170. For example, injector 114 or group of injectors (e.g., injectors 114A-D) may inject hydrogen fuel 103 in a first bank 136A of the intake manifold 130 upstream of engine cylinders (170A-D). Similarly, injector 114 or group of injectors (e.g., injectors 114E-H) may inject hydrogen fuel 103 in a second bank 136B of the intake manifold 130 upstream of engine cylinders (170E-H). The injectors 114 may be positioned along various portions of the intake manifold 130 or along a pressure chamber (e.g., pressure chamber 115 of Fig. 3A) to provide multi point injection of a hydrogen fuel. For example, the injectors may be positioned similar to the arrangement in Fig. 3A, such that there are eight injection points ("P") corresponding to the eight engine cylinders 170A-H.

[0033] For "v-type" engine configures, such as the configuration shown in Fig. 3B, multiple injectors (e.g., injectors 114A-C) may inject hydrogen fuel 103 into the intake manifold 130. The number of injectors may depend on the capacity of each injector and the requirements of the engine. For example, higher output engines requiring larger fuel capacities may include several injectors 114 to meet the fuel needs of the engine. The number or size of injectors may depend on the proximity of the injector to the cylinder(s) (e.g., cylinders 170A-H). For example, higher output engines requiring larger fuel capacities may include a larger injector 114 or several injectors (e.g., injectors 114A-C) if far from the cylinder head, while an injector 114 or injectors close to the cylinder may be smaller. Additionally, multiple injectors may be used to prevent overheating of the electromagnetic valves. Depending on the flow capacity of the injectors and frequency of use, multiple injectors 114 may be implemented to provide gas flow based on the engine characteristics (e.g., number of cylinders, power output, size, etc.) and product life considerations. For example, depending on the frequency of injections, multiple injectors 114 may be implemented to provide adequate cool down time between injection cycles. In an illustrative example, a combustion engine system that needs two injectors 114 (e.g., 114A and 114B) to satisfy the flow capacity requirements may include a four-injector configuration to reduce overheating and extend the lifetime of the injector system. While two of the injectors 114 are injecting gas (e.g., hydrogen fuel 103) into the intake manifold 130, the other two injectors 114 are turned off and their associated electromagnetic valves are cooling. Additionally groups of injectors 114 may be used (e.g., three groups of two injectors 114) to further extend the expected life of the system. Alternatively, injectors 114 with higher output may also be used to reduce the injection period or dose period, which may also extend the expected life of the system.

[0034] In the example illustrated in Fig. 3C, an engine such as the Cummins KTA50 may have four CACs 160A-D for cooling air 106 output by one or more turbochargers 150. Each CAC 160A-D cools air 106 that is directed to a different group of engine cylinders (e.g., cylinders 170A-B form a group, cylinders 170C-D form a group, cylinders 170E-F form a group and cylinders 170G-H form a group). Specifically, CAC 160A sends air 106 to cylinders 170A-B, CAC 160B sends air 106 to cylinders 170C-D, CAC 160C sends air 106 to cylinders 170E-F and CAC 160D sends air 106 to cylinders 170G-H. In an example, there may be a corresponding injector 114 or set of injectors 114 for each CAC 160A-D. Specifically injector(s) 114W correspond to CAC 160A and cylinders 170A-B. Similarly, injector(s) 114X-Z correspond to CAC 160B-D and their respective engine cylinders 170C-H. Injections of hydrogen fuel 103 at each of the four injection points “P” may be independently and separately controlled to balance the thermal efficiency of the engine for each bank of cylinders (e.g., cylinders 170A-D for a first bank and cylinders 170E-H for a second bank) and each side of the engine (e.g., cylinders 170A-B and 170E-F for a left side and cylinders 170C-D and 170G-H for a right side).

[0035] For the “v-type” engine configurations illustrated in Figs. 3B and 3C, the injectors 114 may be controlled by a single control signal such that the same amount of hydrogen fuel 103 is injected into each side or bank of the “v-type” engine. For example, referring to Fig. 3B, with a single control signal, the same amount of hydrogen fuel 103 may be injected by injectors 114A-C and 114D-F so that the same amount of hydrogen fuel 103 is injected into each bank 136A and 136B of the intake manifold 130.

[0036] In another example, the control signal may be split such that the injectors for each side or bank of the "v-type" engines are controlled independently and separately. For example, some engine configurations may include multiple turbochargers 150 and air filters 134. In an example, referring to the air manifold and cylinder layout of Fig. 3B, air 106 entering bank 136A may be provided by its own turbocharger 150 and set of air filters 134 while air 106 entering bank 136B may be provided by its own turbocharger 150 and set of air filters 134. However, as discussed above, the air filters 134 may remove particulate matter from air 106. As the particulate matter builds up and dirties the filter 134, the filter 134 may become saturated with particulate matter, which restricts and reduces air flow. If the air filters 134 for bank 136B allow less air 106 to pass to the engine cylinders (e.g., the filters 134 are dirty or more restricted) than the air filters 134 for bank 136A, then there may be less air 106 available for combustion within the engine cylinders (e.g., cylinders 170E-H) associated with bank 136B. The reduced flow or quantity of air 106 in bank 136B may reduce the effectiveness of the burning and ignition process. In this illustrated example, the injectors 114D-F may be controlled such that they inject less hydrogen fuel 103 into bank 136B to corresponded with the reduced air flow to properly balance the fuel/air ratio with bank 136B to prevent the engine from running too rich.

[0037] Reduced air flow from a clogged or saturated air filter 134 is just one illustrative example of how non-symmetrical or asymmetric injection may be used to adjust fuel injection to optimize engine performance and improve engine life. For example, properly balancing the fuel/air ratio may extend the lifetime of several engine components by preventing overheating or corrosion from either excess air 106 or excess hydrogen fuel 103 during the combustion process.

[0038] In other examples, non-symmetrical injection may be used depending on the temperature of engine components or cylinders. For example, the amount of hydrogen fuel 103 injected may be modified to reduce the temperature of certain engine cylinders in one bank of a "v-type" engine. Each of the factors that influences the thermal efficiency of a bank or section of cylinders 170 in the engine may be monitored to determine how to independently and separately control injectors 114. Readings from sensors such as intake air manifold temperature, intake air manifold pressure, exhaust gas temperature (e.g., exhaust gas temperature of each cylinder), exhaust gas temperature after the turbocharger, knocking sensor values and a diesel flow sensor may be used to modify the amount of hydrogen fuel 103 injected at a specific injection point. Other examples for using non-symmetric or asymmetric injection may include thermodynamic air flow characteristics, construction differences of turbochargers 150, CAC efficiency, engine intake manifold 130 design, number of CACs 160, etc. By controlling each set of gas injectors independently or separately, the engine may be balanced for thermal efficiency for dual-fuel operation to improve performance and extend engine life.

[0039] Fig. 4 illustrates a graph of the position of a piston within a cylinder 170 across two rotations of a crankshaft. In a first rotation, the intake valve opens at a first time 410 before the piston reaches top-dead-center (“TDC”). At a second time 420, while the intake valve is still open, the injector 114 may begin injecting the hydrogen fuel 103. At a third time 430, injector 114 may cease injecting hydrogen fuel 103 thereby creating an injection-duration 425 between the second time 420 and the third time 430. At a fourth time 440 after the injector ceases injecting hydrogen fuel 103 and after the piston reaches bottom dead center (“BDC”), the intake valve may close. As shown in Fig. 4, the intake valve is open for an intake-open-duration 415. After the intake valve closes at the fourth time 440, the piston returns to TDC and compresses the air-fuel mixture in the piston cylinder. This concludes the first rotation of the piston, which comprises the first time 410, second time 420, third time 430, and fourth time 440.

[0040] As the air-fuel mixture compresses near TDC, the air-fuel mixture will combust. Combustion marks the beginning of the second rotation of the piston within the cylinder 170. The combustion will drive the piston down towards BDC. At a fifth time 450 while the piston is nearing BDC, the exhaust valve opens. While the exhaust valve is open, the piston will pass BDC and travel upwards, driving the combusted exhaust air out of the piston through the open exhaust valve. Finally, at a sixth time after the piston has passed TDC, the exhaust valve will close. As shown in Fig. 4, the exhaust valve is open for an exhaust-open-duration 455 between the fifth time 450 and the sixth time 460. This concludes the second rotation of the piston, which comprises the fifth time 450 and sixth time 460. These cycles continues as long as the engine is operating.

[0041] The beginning of the first rotation cycle and the end of the second rotation cycle overlap. Before the exhaust valve closes at the sixth time 460, the intake valve opens at time 410. This allows fresh air from the intake valve to enter the cylinder and force the exhaust air out. The fuel injector 114 opens at the second time 420 only after the exhaust valve has closed at the sixth time 460. Injecting the hydrogen fuel 103 after the exhaust valve has closed prevents hydrogen fuel 103 from leaking into the exhaust before it is combusted.

[0042] The time between the second time 420 and third time 430 is the duration that hydrogen fuel 103 is being injected by injector 114 (e.g., injection-duration 425). The injection-duration 425 may depend on one or more of the following: the type of engine, engine size, engine speed, engine temperature, data gathered by a knock sensor, exhaust gas temperature, injector size, injector location, number of injectors, or air flow rate.

[0043] Fig. 5A illustrates a pressure chamber 115 used to achieve constant pressure of hydrogen fuel 103. Hydrogen fuel 103 may be injected from the pressure chamber or directly from the hydrogen fuel source 116 into the intake manifold 130 upstream of the at least one engine cylinder 170 and downstream of the compressor 152 and/or CAC 160. The pressure chamber 115 may be any suitable chamber that can hold hydrogen fuel 103. The size of the pressure chamber may depend on one or more engine parameters such as: engine displacement, number of cylinders, number of injectors, turbocharger size, and type of fuel used. Similarly, the pressure of the gas inside the pressure chamber 115 may depend on one or more engine parameters such as: engine displacement, number of cylinders, number of injectors, turbocharger size, and type of fuel used.

[0044] The hydrogen fuel source 116 may be connected to the pressure chamber 115 via fuel lines 118 connected to injectors 125. Alternatively, fuel pumps may be used to pump hydrogen fuel 103 into the pressure chamber 115.

[0045] The pressure chamber 115 may be connected to the intake manifold 130 by a single injector 114 or group of injectors 114a-f. Each of the at least one fuel mixture injector(s) 114a-f may be configured to inject hydrogen fuel 103 into the intake manifold 130 upstream of the at least one engine cylinder 170 and downstream of the compressor 152 and/or CAC 160. For each of the at least one injector(s) 114a-f, an injection valve 113a-f controls the injector 114. The injector(s) 114 may be configured to inject a hydrogen fuel 103 into the intake manifold 130 when the injection valve 113 opens.

[0046] In an example embodiment, there may be more than one pressure chamber 115. For example, in the configuration of Fig. 3C, each bank of cylinders (e.g., cylinders 170A-D for a first bank and cylinders 170E-H for a second bank) or each side of the engine (e.g., cylinders 170A-B and 170E-F for a left side and cylinders 170C-D and 170G-H for a right side) may have their own pressure chamber 115.

[0047] Fig. 5B illustrates an example embodiment of a portion of the pressure chamber 115 and an injector 114 corresponding to each cylinder 170. For example, Fig. 5B may correspond to injection valve 113a, injector 114a and cylinder 170A of Fig. 5A. In the illustrated example, hydrogen fuel 103 is injected by fuel injector 114 near the cylinder head. In this example embodiment, each cylinder 170 would have a corresponding injector 114. By locating the injector(s) 114 proximate to the cylinder 170, the injector 114 may be smaller than if the injector 114 was located further upstream. Alternatively, the injector 114 may be activated for a shorter amount of time than if the injector 114 was located further upstream, thereby reducing the heat generated by the injector 114 and improving its longevity.

[0048] Fig. 6 illustrates a flowchart of an example method 600 of multi-point fuel injection according to an example embodiment of the present disclosure. Although the example method 600 is described with reference to the flowchart illustrated in Fig. 6, it will be appreciated that many other methods of performing the acts associated with the method 600 may be used. For example, the order of some of the blocks may be changed, certain blocks may be combined with other blocks, blocks may be repeated, and some of the blocks described are optional. The method 600 may be performed by processing logic that may comprise hardware (circuitry, dedicated logic, etc.), software, or a combination of both.

[0049] The example method 600 includes supplying air to a compressor of a turbocharger (block 602). In an example, the turbocharger 150 may be a component of a multi-fuel combustion engine system (e.g., system 100) that has at least one engine cylinder 170. The air 106 may be supplied through an air inlet 132, which flows to the compressor 152. The method also includes passing the air from the compressor to an intake manifold of the engine (block 604). For example, the air 106 may be compressed and condensed within compressor 152 and then may flow to an intake manifold 130 of the engine. In another example, the air 106 may be further cooled and condensed by flowing through a CAC 160 prior to entering the intake manifold 130.

[0050] The method 600 also includes injecting a hydrogen fuel from a pressure ramp or pressure chamber proximate to corresponding intake valves (block 606). For example, hydrogen fuel 103 may be injected into a pressure chamber. Next, the hydrogen fuel 103 is injected into the intake manifold to mix with the air. For example, after air 106 enters the intake manifold 130, hydrogen fuel 103 may be injected into the intake manifold 130 to mix with the air 106 to form an air-fuel mixture. In an example, hydrogen fuel 103 is injected at an injection point that is upstream of the at least one engine cylinder 170 and downstream of the compressor 152 and/or CAC 160. Hydrogen fuel 103 may be injected non-symmetrically or asymmetrically for different cylinder banks or different sides of the engine by independently and separately controlling fuel injectors 114. For example, fuel injectors 114 may be independently controlled to ensure each cylinder 170 has the proper fuel/air ratio. Injection of hydrogen fuel 103 may be controlled by at least one other control valve corresponding to each respective fuel injector associated with hydrogen fuel 103 or pressure ramp 115.

[0051] By injecting hydrogen fuel 103 downstream of both the turbocharger 150 and CAC 160, the method 600 advantageously prevents hydrogen fuel 103 from entering the compressor 152 of the turbocharger 150 as well as the CAC 160, which improves the durability, longevity and safety of the multi-fuel combustion engine.

[0052] Next, method 600 includes directly injecting a first fuel into the engine cylinder(s) (block 608). For example, after the air-fuel mixture passes into a cylinder 170 of the at least one engine cylinder 170, a first fuel 104 may be directly injected into the cylinder 170 such that the air-fuel mixture (e.g., hydrogen fuel 103 and air 106) mix with the first fuel 104 and combust within the cylinder 170. In an example, the hydrogen fuel 103 may be a hydrogen-based fuel and the first fuel may be diesel, which may act as a combustion initiator for the air-fuel mixture within the engine cylinder. Injection of the first fuel 104 is controlled by at least one primary control valve corresponding to each respective primary fuel injector. Each of the respective primary control valves and the respective other control valves may be configured to immediately shut-off injection of first fuel 104 (e.g., diesel) or hydrogen fuel 103 injected from pressure ramp 115 at a respective control instance. The other control valves may be configured to shut off immediately by a dual serial valve 199A, 199B, such as two shut-off valves placed between the fuel source (e.g., fuel source

116, or pressure chamber 115) and the respective injector (e.g., injector 125, injector 114). Dual serial valve configurations, such as the configuration illustrated in Fig. 1 by valves 199A, 199B, may be particularly advantageous for use with volatile fuels (e.g., hydrogen fuels). In this example arrangement, if one of the shut-off valves 199A, 199B malfunctions, the fuel may still be prohibited from entering the combustion chamber and combusting inadvertently.

[0053] The various examples described herein provide improved efficiency compared to traditional fumigation systems. For example, efficiency may be improved between 1 percent and 3 percent depending on the engine size, operating conditions, load and RPM of the engine.

[0054] In addition to the improved efficiency, the present disclosure also provides improved emissions. By using a mixture of fuels that includes a hydrogen-based fuel, the engine produces water as a by-product of emissions. Specifically, the hydrogen molecules (H_2) in the hydrogen-based fuel oxidises with oxygen (O) in the air to form H_2O. This chemical process reduces the carbon by-products in emissions, such as carbon monoxide (CO), carbon dioxide (CO_2) and hydrocarbon (HC).

[0055] Aspects of the subject matter described herein may be useful alone or in combination with one or more other aspects described herein. In a 1st exemplary aspect of the present disclosure, a multi-fuel combustion system includes a primary fuel source, a secondary hydrogen fuel source, a turbocharger including a compressor and a turbine, a charged-air-cooler positioned downstream of the compressor, at least one engine cylinder, a primary fuel injector for each of the at least one engine cylinders, and at least two other fuel injectors arranged along a pressure ramp. Additionally, the at least one primary injector is asymmetrically controlled based on at least one engine parameter. Each of the primary fuel injectors is configured to directly inject the primary fuel in a corresponding engine cylinder. The at least two other fuel injectors are configured to inject the hydrogen fuel into an intake manifold downstream of the compressor and charged-air-cooler and upstream of the at least one engine cylinder.

[0056] In a 2nd exemplary aspect of the present disclosure, which may be used in combination with any one or more of the preceding aspects (e.g., the 1st aspect), the multi-fuel combustion system further includes at least one primary control valve. Each of the primary fuel injectors is controlled by a corresponding primary control valve.

[0057] In a 3rd exemplary aspect of the present disclosure, which may be used in combination with any one or more of the preceding aspects (e.g., the 1st or 2nd aspects), the multi-fuel combustion system further includes at least one other control valve. Each of the at least two other fuel injectors is controlled by a corresponding control valve of the at least one other control valve.

[0058] In a 4th exemplary aspect of the present disclosure, which may be used in combination with any one or more of the preceding aspects (e.g., the 1st to 3rd aspect), the at least one primary control valve and the at least one other control valve are configured to immediately shut-off injection of the primary fuel and the hydrogen fuel at a respective control instance.

[0059] In a 5th exemplary aspect of the present disclosure, which may be used in combination with any one or more of the preceding aspects (e.g., the 1st to 4th aspects), the at least one other control valve is configured to open its corresponding other fuel injector based on a fuel-air mixture flow rate.

[0060] In a 6th exemplary aspect of the present disclosure, which may be used in combination with any one or more of the preceding aspects (e.g., the 1st to 5th aspects), the at least one primary control valve is configured to open its corresponding primary fuel injector based on a fuel-air mixture flow rate.

[0061] In a 7th exemplary aspect of the present disclosure, which may be used in combination with any one or more of the preceding aspects (e.g., the 1st to 6th aspects), the fuel-air mixture flow rate is a function of engine RPM, number of engine cylinders, engine power output or a combination thereof.

[0062] In an 8th exemplary aspect of the present disclosure, which may be used in combination with any one or more of the preceding aspects (e.g., the 1st to 7th aspects), the primary control valve is an electromagnetic valve.

[0063] In a 9th exemplary aspect of the present disclosure, which may be used in combination with any one or more of the preceding aspects (e.g., the 1st to 8th aspects), at least one of the primary fuel and the hydrogen fuel is configured to initiate combustion of the other respective fuel within the at least one engine cylinder.

[0064] In a 10th exemplary aspect of the present disclosure, which may be used in combination with any one or more of the preceding aspects (e.g., the 1st to 9th aspects), the primary fuel source is diesel fuel.

[0065] In an 11th exemplary aspect of the present disclosure, which may be used in combination with any one or more of the preceding aspects (e.g., the 1st to 10th aspects), the pressure ramp includes a first bank and a second bank.

[0066] In a 12th exemplary aspect of the present disclosure, which may be used in combination with any one or more of the preceding aspects (e.g., the 1st to 11th aspects), the at least one cylinder is a group of cylinders ranging between three cylinders and ten cylinders.

[0067] In a 13th exemplary aspect of the present disclosure, which may be used in combination with any one or more of the preceding aspects (e.g., the 1st to 12th aspects), the secondary fuel source is connected to the pressure ramp via a fuel line that contains at least two shut-off valves connected in series.

[0068] Aspects of the subject matter described herein may be useful alone or in combination with one or more other aspects described herein. In a 14th exemplary aspect of the present disclosure, a method for operating a multi-fuel combustion engine includes supplying air to a compressor of a turbocharger of the multi-fuel combustion engine. The multi-fuel combustion engine has at least one engine cylinder. The method also includes passing the air from the compressor to an intake manifold of the engine and injecting a hydrogen fuel at predetermined locations proximate to the corresponding intake valves of the at least one engine cylinder to mix with air. The hydrogen fuel may be injected from a pressure ramp or pressure chamber at an injection point at a first time. Additionally, the hydrogen fuel is injected into the intake manifold upstream of the at least one engine cylinder and downstream of the compressor. Injection of the hydrogen fuel is controlled by at least one other control valve corresponding to each respective fuel injector. The hydrogen fuel is asymmetrically injected based on at least one engine parameter to provide asymmetric control. The method also includes directly injecting a primary fuel into the engine cylinder at a second time such that the primary fuel, hydrogen fuel and air mix and combust within a cylinder of the at least one engine cylinder. Injection of the primary fuel is controlled by at least one primary control valve corresponding to each respective primary fuel injector. Furthermore, each of the respective primary control valves and the respective other control valves are configured to immediately shut-off injection of the primary fuel and the hydrogen fuel at a respective control instance.

[0069] In a 15th exemplary aspect of the present disclosure, which may be used in combination with any one or more of the preceding aspects (e.g., the 14th aspect), the primary fuel is diesel fuel.

[0070] In a 16th exemplary aspect of the present disclosure, which may be used in combination with any one or more of the preceding aspects (e.g., the 14th or 15th aspects), the secondary fuel source is connected to the pressure ramp via a fuel line that contains at least two shut-off valves connected in series.

[0071] It will be appreciated that all of the disclosed methods and procedures described herein can be implemented using one or more computer programs or components. These components may be provided as a series of computer instructions on any conventional computer readable medium or machine-readable medium, including volatile or non-volatile memory, such as RAM, ROM, flash memory, magnetic or optical disks, optical memory, or other storage media. The instructions may be provided as software or firmware, and/or may be implemented in whole or in part in hardware components such as application specific integrated circuits (ASICs), field programmable gate arrays (FPGAs), digital signal processors (DSPs) or any other similar devices. The instructions may be configured to be executed by one or more processors, which when executing the series of computer instructions, performs or facilitates the performance of all or part of the disclosed methods and procedures.

[0072] It should be understood that various changes and modifications to the example embodiments described herein will be apparent to those skilled in the art. Such changes and modifications can be made without departing from the spirit and scope of the present subject matter and without diminishing its intended advantages. It is therefore intended that such changes and modifications be covered by the appended claims.

CLAIMS

The invention is claimed as follows:

1. A multi-fuel combustion system comprising:

a primary fuel source;

a secondary hydrogen fuel source;

a turbocharger including a compressor and a turbine;

a charged-air-cooler positioned downstream of the compressor;

at least one engine cylinder with a corresponding intake valve positioned adjacent to a respective cylinder head of the at least one engine cylinder;

a primary fuel injector for each of the at least one engine cylinder, wherein each of the primary fuel injectors is configured to directly inject the primary fuel in a corresponding engine cylinder; and

a plurality of other fuel injectors arranged along a pressure ramp, downstream of the compressor and charged-air-cooler and upstream of the at least one engine cylinder, wherein the plurality of other fuel injectors are configured to inject a hydrogen fuel from the hydrogen fuel source at predetermined locations proximate to the corresponding intake valves of the at least one engine cylinder.

2. The multi-fuel combustion system of claim 1, further comprising a plurality of primary control valves adapted to control each of the respective primary fuel injectors.

3. The multi-fuel combustion system of claim 2, further comprising a plurality of other control valves adapted to control each of the plurality of other fuel injectors.

4. The multi-fuel combustion system of claim 3, wherein the plurality of primary control valves and the plurality of other control valves are configured to immediately shut-off injection of the primary fuel and the hydrogen fuel at a respective control instance.

5. The multi-fuel combustion system of claim 4, wherein each of the respective other control valves is configured to open its corresponding other fuel injector based on a fuel-air mixture flow rate.

6. The multi-fuel combustion system of claim 4, wherein each of the respective primary control valves is configured to open its corresponding primary fuel injector based on a fuel-air mixture flow rate.

7. The multi-fuel combustion system of claims 5 or 6, wherein the fuel-air mixture flow rate is a function of at least one of engine RPM, a quantity of engine cylinders, and an engine power output.

8. The multi-fuel combustion system of claim 1, wherein the primary control valve is an electromagnetic valve.

9. The multi-fuel combustion system of claim 1, wherein at least one of the primary fuel and the hydrogen fuel is configured to initiate combustion of the other respective fuel within the at least one engine cylinder.

10. The multi-fuel combustion system of claim 1, wherein the primary fuel source is diesel fuel.

11. The multi-fuel combustion system of claim 1, further comprising an anti-knocking unit, wherein each of the plurality of other fuel injectors is controlled by a corresponding secondary control valve according to an injection timing sequence governed by the anti-knocking unit.

12. The multi-fuel combustion system of any of claims 1 to 11, wherein the pressure ramp includes a first bank and a second bank.

13. The multi-fuel combustion system of any of claims 1 to 12, wherein the at least one cylinder is a group of cylinders ranging between three cylinders and ten cylinders.

14. The multi-fuel combustion system of any of claims 1 to 13, wherein the secondary fuel source is connected to the pressure ramp via a fuel line that contains at least two shut-off valves connected in series.

15. A method for operating a multi-fuel combustion engine, comprising:

supplying air to a compressor of a turbocharger of the multi-fuel combustion engine, wherein the multi-fuel combustion engine has at least one engine cylinder;

passing the air from the compressor to an intake manifold of the engine;

injecting a hydrogen fuel from a pressure ramp at predetermined locations proximate to corresponding intake valves of the at least one engine cylinder to mix with the air, wherein

the hydrogen fuel is injected at a first time,

the hydrogen fuel is injected at the predetermined locations upstream of the at least one engine cylinder and downstream of the compressor, and

injection of the hydrogen fuel is controlled by at least one other control valve corresponding to each respective fuel injector associated with the pressure ramp; and

directly injecting a primary fuel into the at least one engine cylinder at a second time such that the hydrogen fuel, primary fuel and air mix and combust within a respective cylinder of the at least one engine cylinder, wherein

injection of the primary fuel is controlled by at least one primary control valve corresponding to each respective primary fuel injector, and

each of the respective primary control valves and the respective other control valves are configured to immediately shut-off injection of the primary fuel and the hydrogen fuel at a respective control instance.

16. The method of claim 15, wherein the primary fuel is diesel fuel.

17. The multi-fuel combustion system of any of claims 15 to 16, wherein the secondary fuel source is connected to the pressure ramp via a fuel line that contains at least two shut-off valves connected in series.

18. A non-transitory machine readable medium storing code, which when executed by a processor of an engine control system is configure to:

supply air to a compressor of a turbocharger of the multi-fuel combustion engine, wherein the multi-fuel combustion engine has at least one engine cylinder;

pass the air from the compressor to an intake manifold of the engine;

inject a hydrogen fuel from a pressure ramp at predetermined locations proximate to corresponding intake valves of the at least one engine cylinder to mix with the air, wherein

the hydrogen fuel is injected at a first time,

the hydrogen fuel is injected at the predetermined locations upstream of the at least one engine cylinder and downstream of the compressor, and

injection of the hydrogen fuel is controlled by at least one other control valve corresponding to each respective fuel injector associated with the pressure ramp; and

directly inject a primary fuel into the at least one engine cylinder at a second time such that the hydrogen fuel, primary fuel and air mix and combust within a respective cylinder of the at least one engine cylinder, wherein

injection of the primary fuel is controlled by at least one primary control valve corresponding to each respective primary fuel injector, and

each of the respective primary control valves and the respective other control valves are configured to immediately shut-off injection of the primary fuel and the hydrogen fuel at a respective control instance.

19. The non-transitory machine-readable medium of claim 18, wherein the primary fuel is diesel fuel.

20. The multi-fuel combustion system of any of claims 18 to 19, wherein the secondary fuel source is connected to the pressure ramp via a fuel line that contains at least two shut-off valves connected in series.

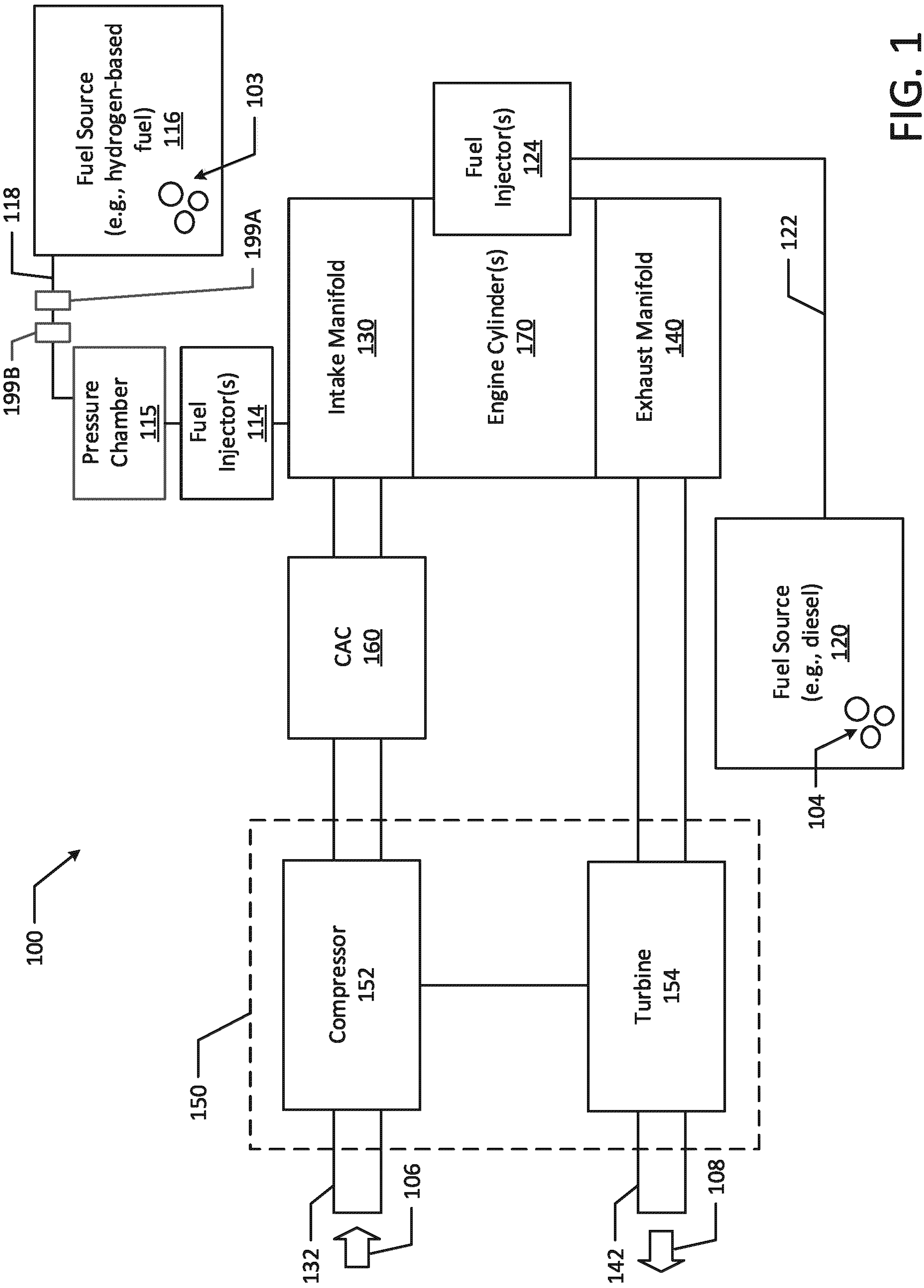

Fuel Source
(e.g., hydrogen-based fuel)
116
103
118
199A
199B
Pressure Chamber
115
Fuel Injector(s)
114
Intake Manifold
130
Engine Cylinder(s)
170
Exhaust Manifold
140
Fuel Injector(s)
124
122
CAC
160
Fuel Source
(e.g., diesel)
120
104
100
Compressor
152
Turbine
154
150
132
106
142
108

FIG. 1

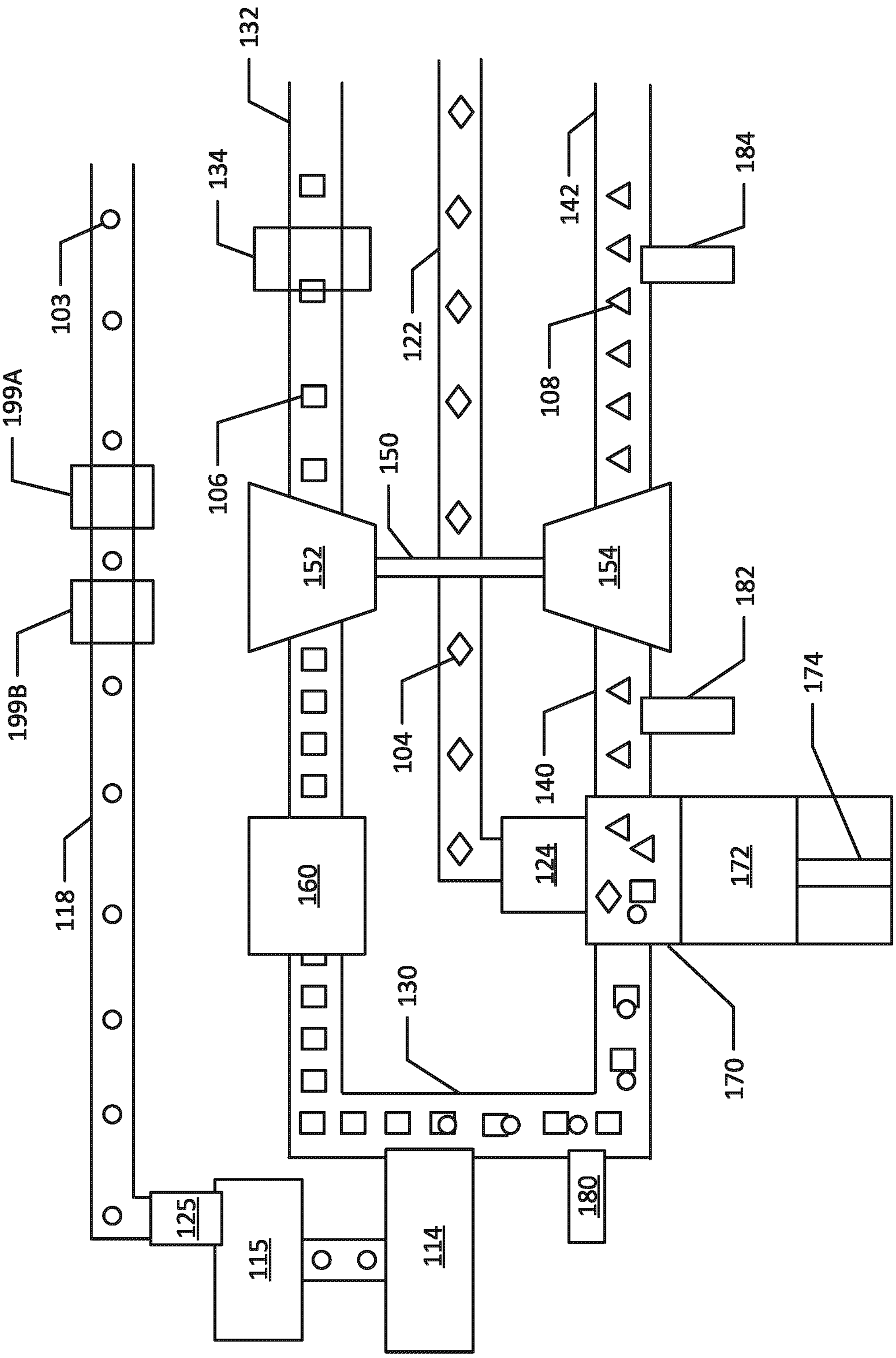

132
134
103
199A
106
150
122
142
184
108
152
154
199B
118
104
182
140
174
124
172
160
130
170
125
115
114
180

FIG. 2

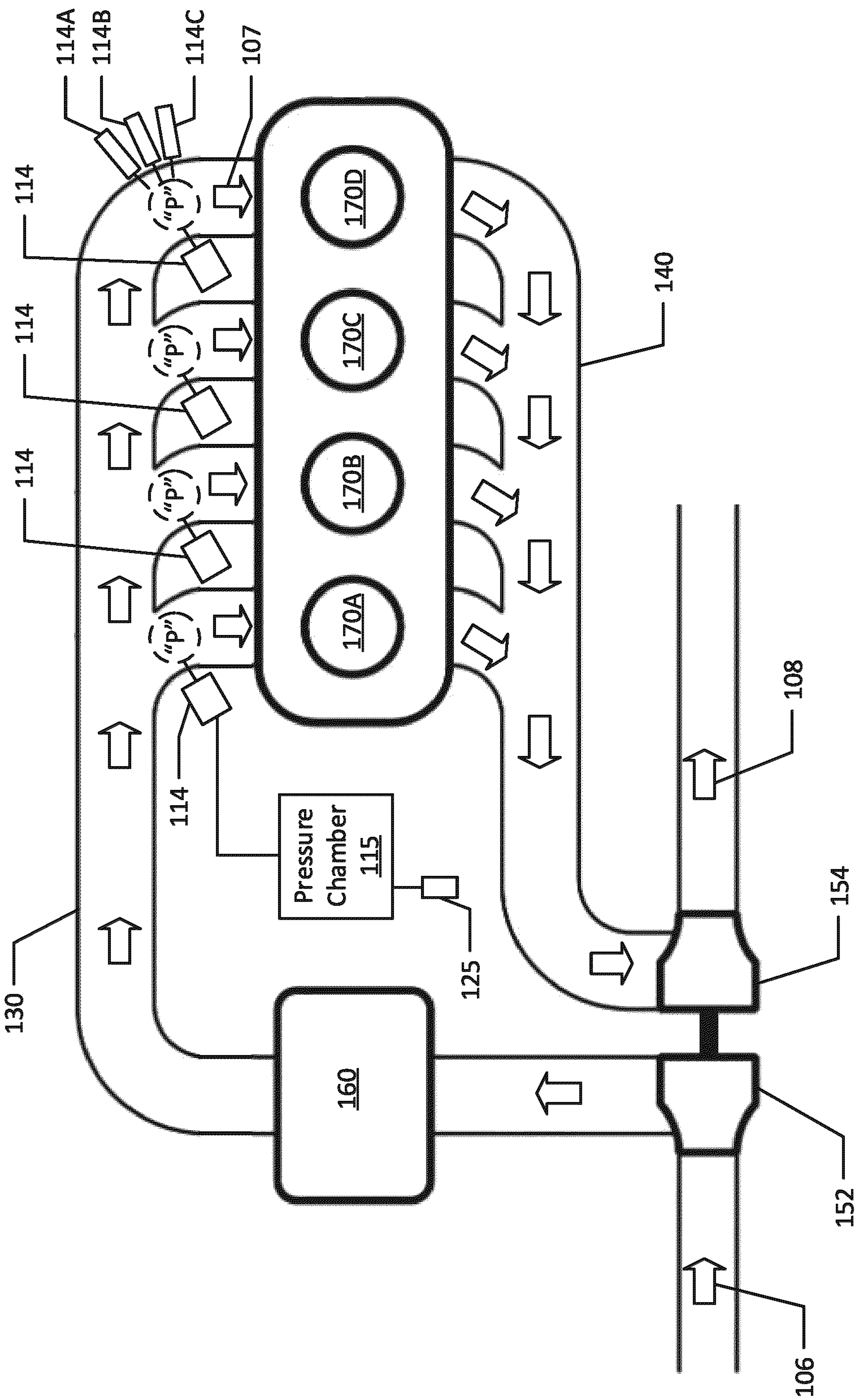

114A
114B
114C
107
114
114
114
114
114
"P"
"P"
"P"
"P"
170D
170C
170B
170A
140
108
Pressure Chamber 115
125
154
130
160
152
106

FIG. 3A

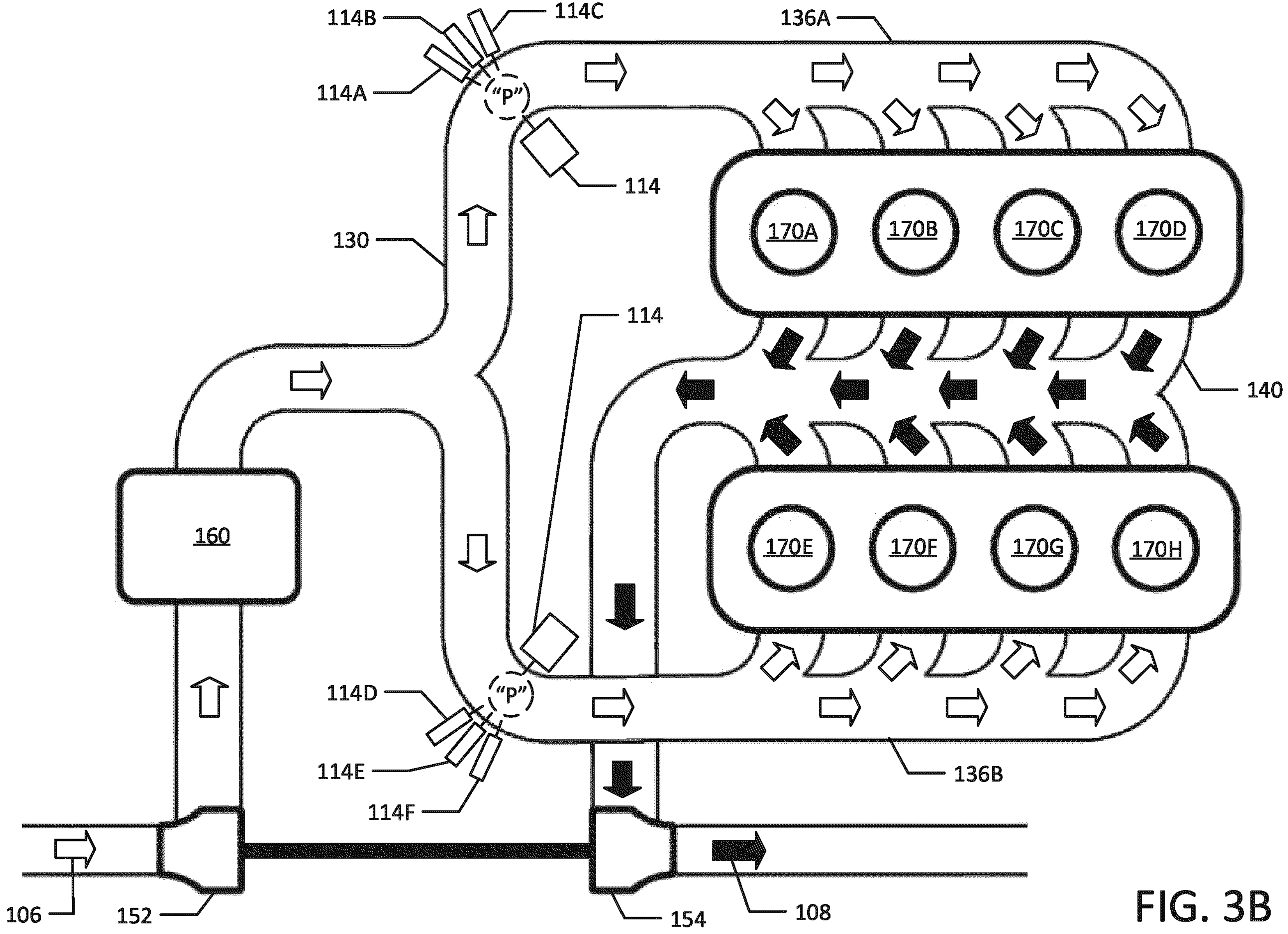

114B
114C
114A
136A
114
130
170A
170B
170C
170D
114
140
160
170E
170F
170G
170H
"P"
"P"
114D
114E
114F
136B
106
152
154
108

FIG. 3B

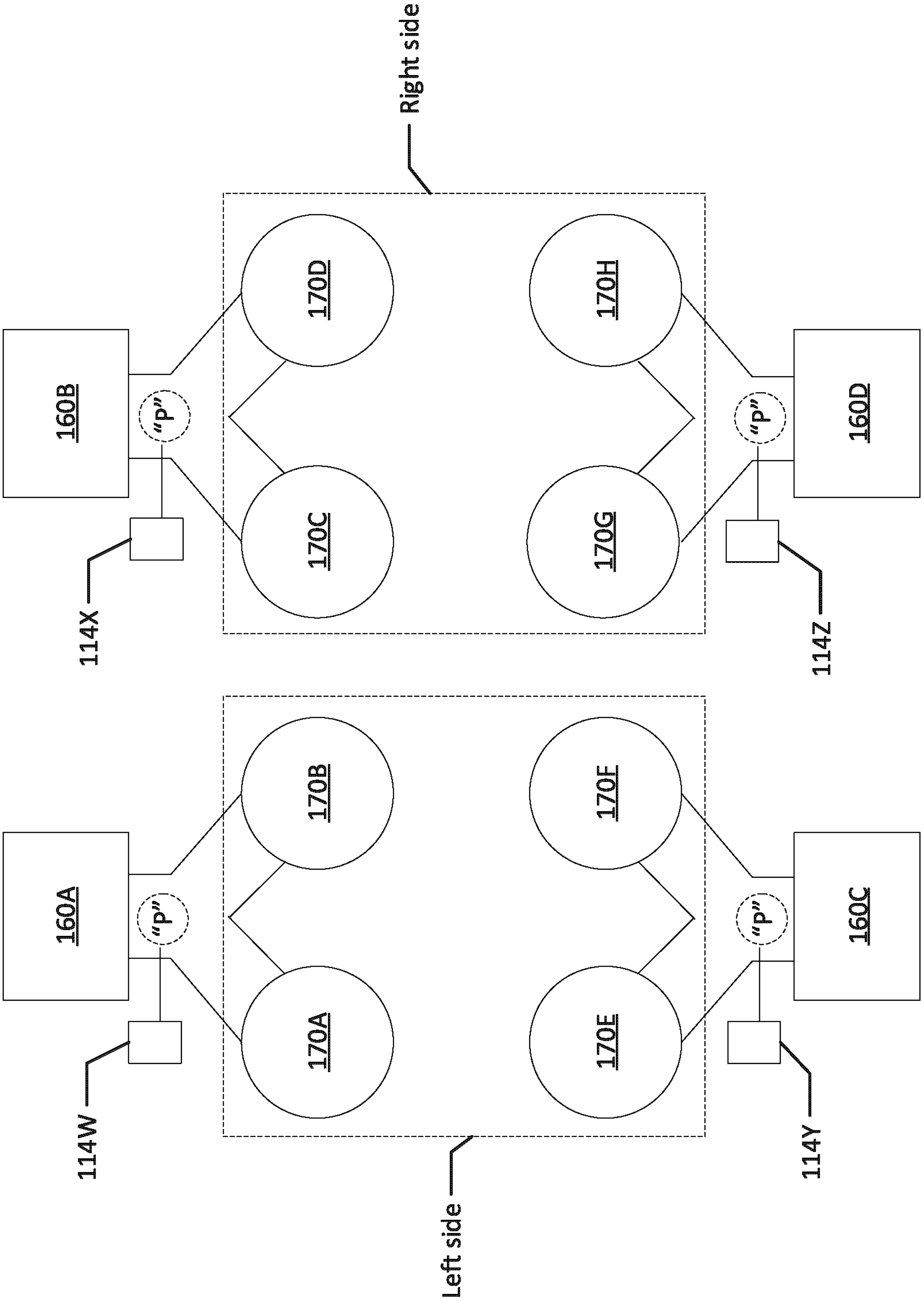

Right side
160B
"P"
170D
170C
114X
170H
170G
"P"
160D
114Z
160A
"P"
170B
170A
114W
170F
170E
"P"
160C
114Y
Left side

FIG. 3C

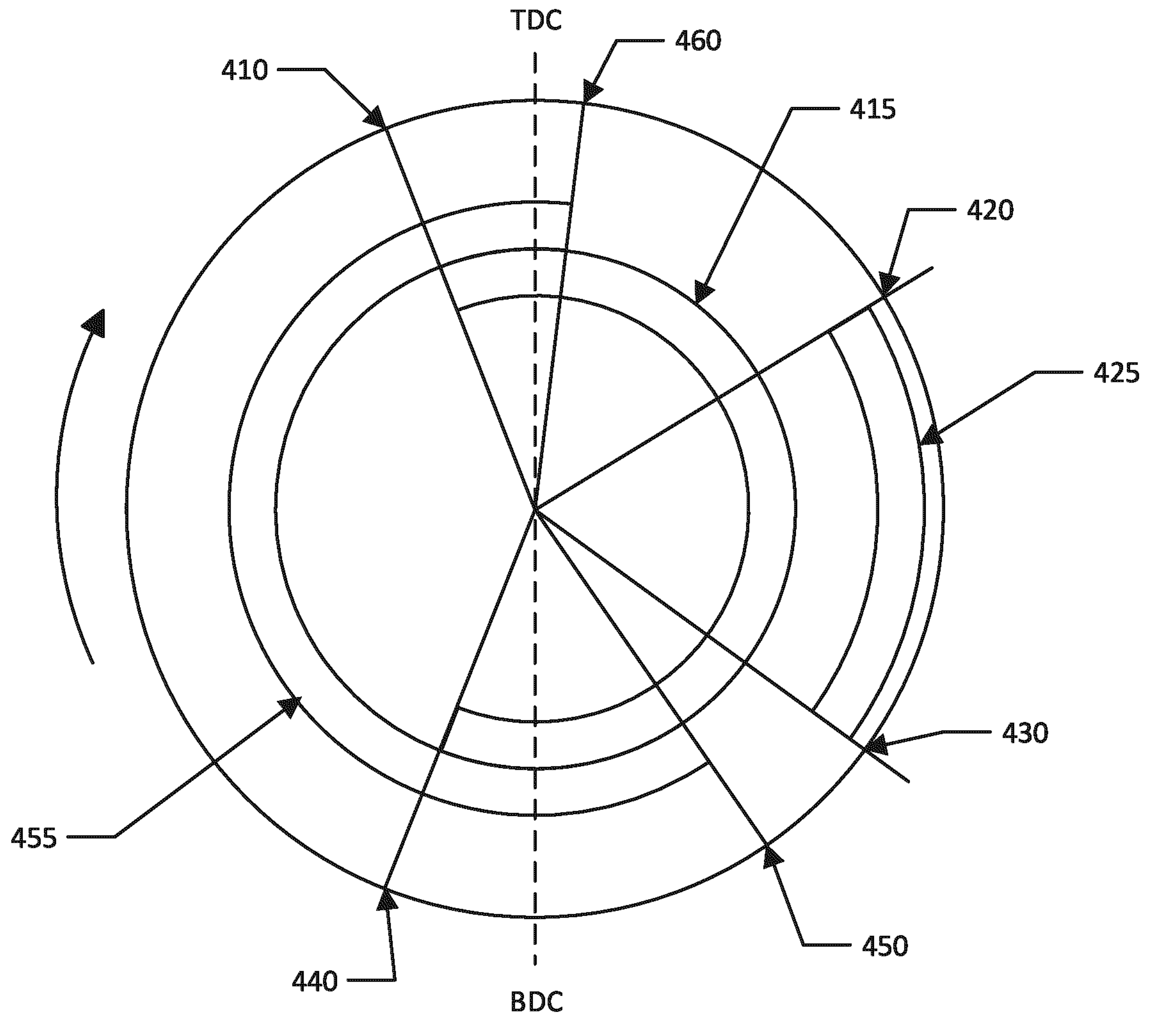


FIG. 4

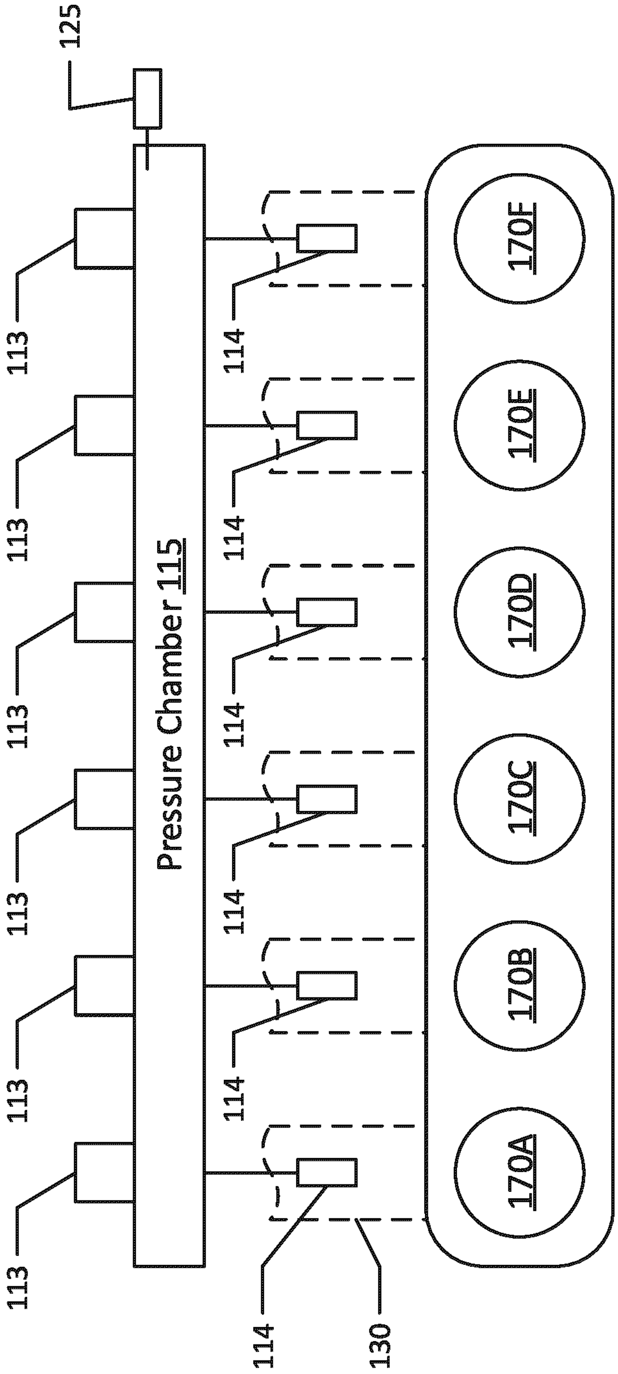
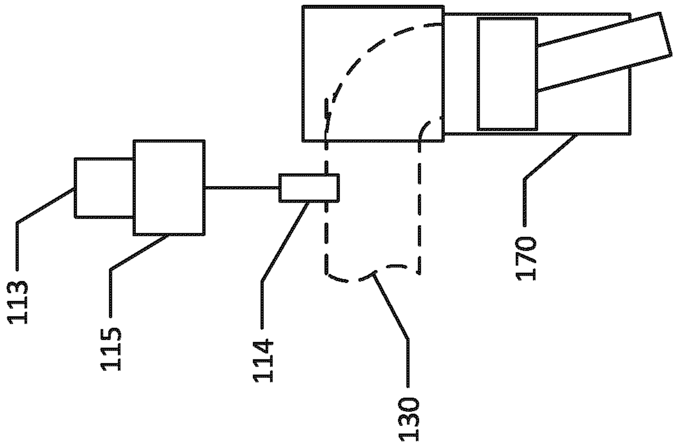

125
Pressure Chamber 115
113
113
113
113
113
113
114
114
114
114
114
114
130
170A
170B
170C
170D
170E
170F

FIG. 5A

FIG. 5B



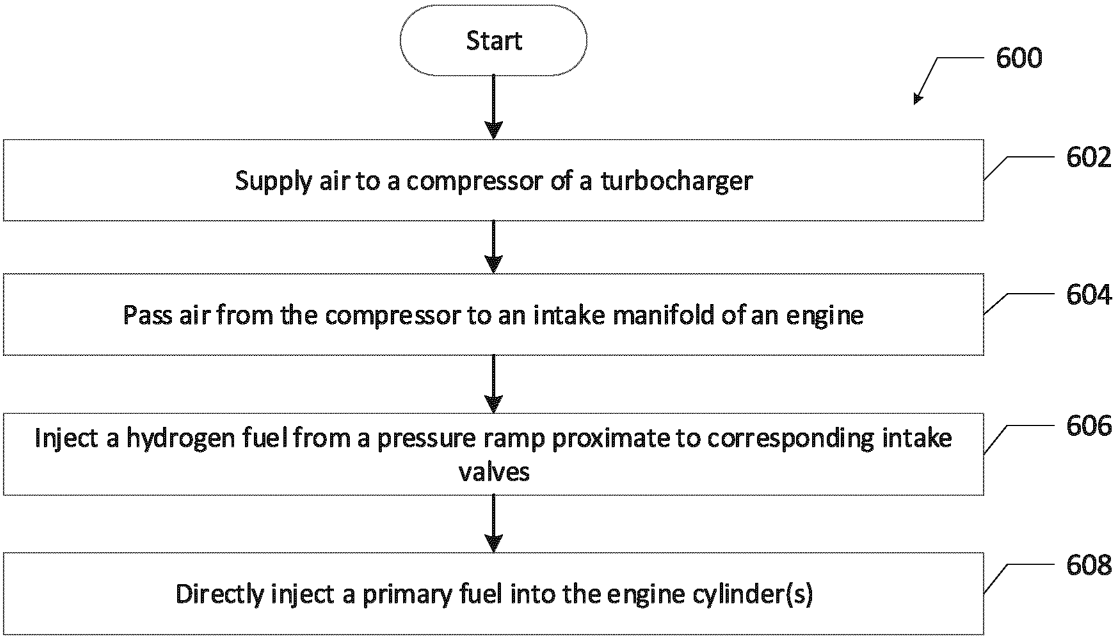

Start
600
Supply air to a compressor of a turbocharger
602
Pass air from the compressor to an intake manifold of an engine
604
Inject a hydrogen fuel from a pressure ramp proximate to corresponding intake valves
606
Directly inject a primary fuel into the engine cylinder(s)
608

FIG. 6

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2022/069689

A. CLASSIFICATION OF SUBJECT MATTER
INV. F02D19/06 F02D19/08 F02D23/00 F02M21/02
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F02M F02D

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

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

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2020/200486 A1 (COMAP A S [CZ]) 8 October 2020 (2020-10-08)	1-13,15, 16,18,19
Y	claims 1-20 -----	14,17,20
X	US 2016/169142 A1 (KLINGBEIL ADAM EDGAR [US] ET AL) 16 June 2016 (2016-06-16) abstract; figure 1 paragraphs [0015] - [0018] -----	1-10,12, 13,15, 16,18,19
X	DE 10 2017 108367 A1 (GEN ELECTRIC [US]) 16 November 2017 (2017-11-16) abstract; figure 1 paragraph [0040] ----- -/--	1-10,12, 13,15, 16,18,19

☒ 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
19 October 2022

Date of mailing of the international search report
27/10/2022

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

Authorized officer
Röttger, Klaus

International application No
PCT/EP2022/069689

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2008/119588 A1 (BOSCH GMBH ROBERT [DE]; FOERSTER JUERGEN [DE]; LANGER WINFRIED [DE]) 9 October 2008 (2008-10-09) abstract; figure 1 pages 3-4 -----	14,17,20
A	US 2011/166769 A1 (BUECHLER JEFFREY DOUGLAS [CA] ET AL) 7 July 2011 (2011-07-07) abstract; figure 1 -----	1-20

2

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2022/069689

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