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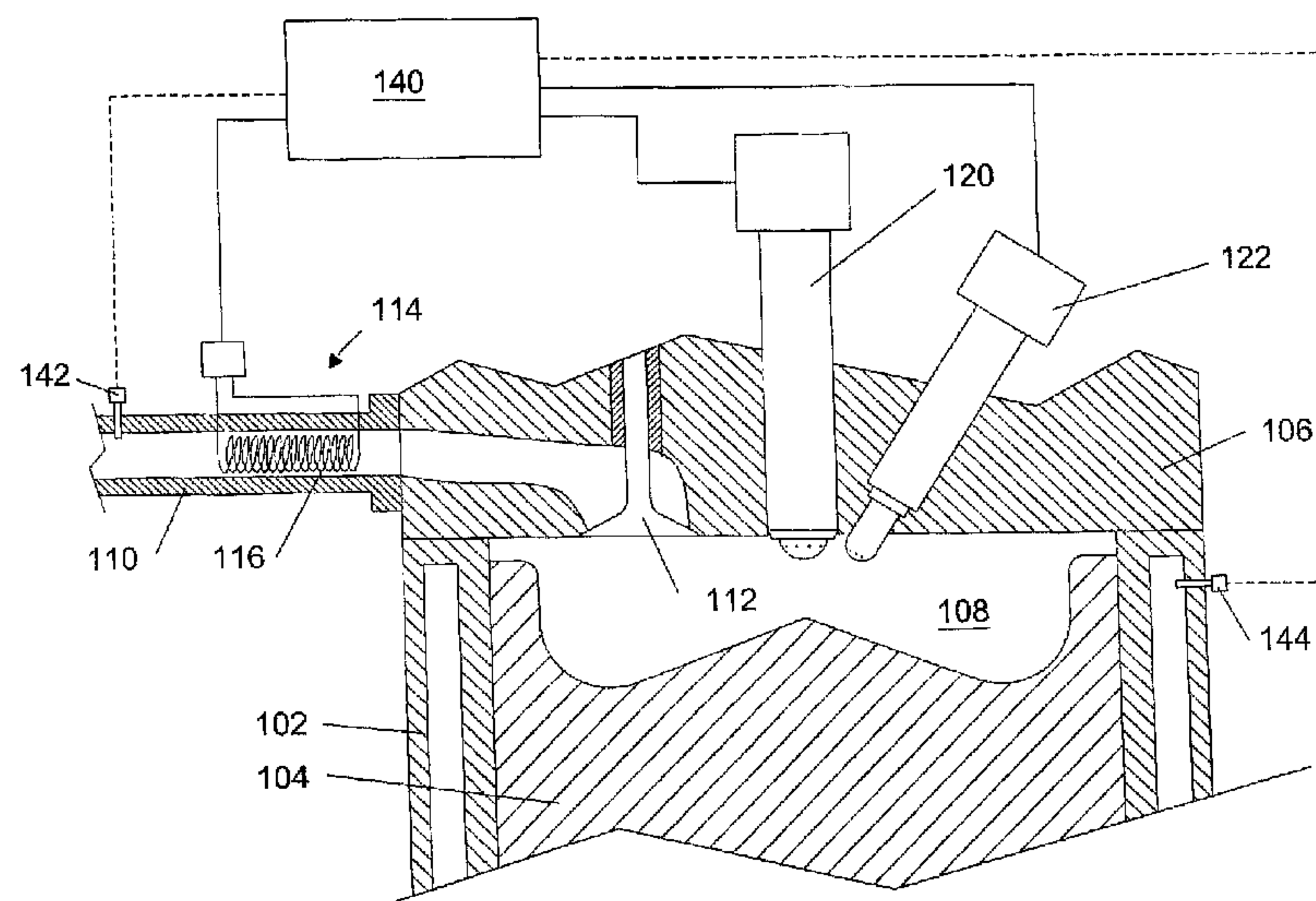
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(54) Titre : MOTEUR A COMBUSTION INTERNE A INJECTION DIRECTE ET METHODE DE FABRICATION ET D'EXPLOITATION

(54) Title: DIRECT INJECTION INTERNAL COMBUSTION ENGINE AND METHOD OF MAKING AND OPERATING SAME



(57) Abrégé/Abstract:

An internal combustion engine is provided that can be fuelled with first fuel alone or a combination of the first fuel and a second fuel or the second fuel alone. The engine comprises two separate fuel injection valves each disposed in the cylinder head for respectively injecting the first and second fuels directly into the combustion chamber. With the disclosed engine, conventional cylinder heads can be employed by utilizing the location normally occupied by a glow plug to mount the second fuel injection valve. To provide ignition assistance in lieu of a glow plug, the disclosed engine employs an ignition-assist apparatus that is operative to pre-condition air within the intake air manifold. An electronic controller is programmable to command operation of the first fuel injection valve, the second fuel injection valve and the ignition-assist apparatus responsive to measured engine operating conditions. The method of operating the disclosed engine comprises pre-conditioning air within the intake air manifold before introducing it into the combustion chamber by operating an ignition-assist apparatus; introducing the first fuel directly into the combustion chamber through a first fuel injection valve; introducing the second fuel directly into the combustion chamber through a second fuel injection valve; and selecting one of a plurality of predetermined operating modes for determining when to pre-condition the air, when to introduce the first fuel, and when to introduce the second fuel, with these determinations being made responsive to measured engine operating conditions and operator inputs.



DIRECT INJECTION INTERNAL COMBUSTION ENGINE AND METHOD OF MAKING AND OPERATING SAME

Abstract

An internal combustion engine is provided that can be fuelled with first fuel alone or a combination of the first fuel and a second fuel or the second fuel alone. The engine comprises two separate fuel injection valves each disposed in the cylinder head for respectively injecting the first and second fuels directly into the combustion chamber. With
5 the disclosed engine, conventional cylinder heads can be employed by utilizing the location normally occupied by a glow plug to mount the second fuel injection valve. To provide ignition assistance in lieu of a glow plug, the disclosed engine employs an ignition-assist apparatus that is operative to pre-condition air within the intake air manifold. An electronic controller is programmable to command operation of the first fuel injection valve, the
10 second fuel injection valve and the ignition-assist apparatus responsive to measured engine operating conditions. The method of operating the disclosed engine comprises pre-conditioning air within the intake air manifold before introducing it into the combustion chamber by operating an ignition-assist apparatus; introducing the first fuel directly into the combustion chamber through a first fuel injection valve; introducing the second fuel directly
15 into the combustion chamber through a second fuel injection valve; and selecting one of a plurality of predetermined operating modes for determining when to pre-condition the air, when to introduce the first fuel, and when to introduce the second fuel, with these determinations being made responsive to measured engine operating conditions and operator inputs.

DIRECT INJECTION INTERNAL COMBUSTION ENGINE AND METHOD OF MAKING AND OPERATING SAME

Field of the Invention

[0001] The present invention relates to a direct injection internal combustion engine, a method of operating same, and a method of converting a conventional diesel-fuelled engine to operate with direct injection of a two different fuels through two
5 separate fuel injection valves so that the engine can be fuelled with one fuel, the other fuel or a combination of both fuels.

Background of the Invention

[0002] So-called compression ignition engines employ compression ratios that are
10 much higher than Otto cycle (spark-ignited) engines. The most common compression ignition engines are diesel engines. Under normal operating conditions in a diesel engine, the heat produced by the mechanical compression of the fuel and air mixture auto-ignites the liquid diesel fuel at or near the end of the piston's compression stroke. In such an engine a glow plug is employed to provide ignition assist during start-up conditions when
15 the engine is cold. The glow plug is normally turned off when the engine achieves normal operating conditions. "Glow plug" is defined in this specification to mean any type of electrically heated hot surface element employed within an engine's combustion chamber to assist with ignition of the fuel.

[0003] Recent developments have been directed to burning gaseous fuels such as
20 natural gas in a compression ignition engine. By substituting gaseous fuels for liquid fuels such as diesel, a compression ignition engine can be operated with much lower emissions of undesirable pollutants such as oxides of nitrogen (NOx) and particulate matter (PM). Governments around the world are introducing ever more stringent regulations aimed at reducing pollution today and in the future by prescribing
25 increasingly lower levels of engine emissions.

[0004] A problem with burning gaseous fuels in a compression ignition engine is that while gaseous fuels are generally cleaner burning, compared to diesel fuels, they

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typically require higher temperatures and pressures to achieve reliable auto-ignition. One approach has been to maintain the same compression ratios found in conventional diesel engines, and provide a means for assisting ignition of the gaseous fuel when the engine is running, such as, for example, a hot surface provided by a continuously operable glow
5 plug or a pilot fuel that is introduced into the combustion chamber. When a pilot fuel is employed, the pilot fuel is a fuel that is more readily auto-ignited compared to the gaseous fuel, which in this example is referred to as the main fuel since it typically represents the majority of the fuel that is consumed by the engine when measured on an energy basis. Since the pilot fuel is more easily ignited, it auto-ignites at a lower
10 temperature than the main fuel and the ignition of the pilot fuel triggers the ignition of the gaseous fuel.

[0005] A challenge associated with using a pilot fuel is that a different fuel from the main fuel is added to the system and apart from requiring two separate fuel systems, such a system is also challenged by physical constraints such as allocating space in the
15 fire deck of the cylinder head above the combustion chamber to accommodate a separate pilot fuel valve in addition to a gaseous (main) fuel valve and a conventional glow plug. This can be especially difficult now that recent trends in engine design have led to the use of more intake and exhaust valves per cylinder. Instead of only one intake valve and one exhaust valve per cylinder, current engine designs employ a total of at least three or four
20 intake and exhaust valves, leaving less space for other components that are mounted in the cylinder head such as the fuel injection valve(s) and a glow plug.

[0006] In converting a conventional diesel-fuelled engine to operate with a main fuel and a pilot fuel, it is preferable to utilize as many of the same parts to reduce development and set up costs and to maintain economies of scale. Accordingly, it is
25 desirable to avoid the need to design and manufacture a new cylinder head to accommodate separate pilot fuel and main fuel injection valves. One solution is to employ a single fuel injection valve that can be mounted in the same opening normally occupied by a conventional diesel fuel injection valve, and that is capable of injecting both the main fuel and the pilot fuel, as taught, for example, by co-owned United States
30 patent numbers 5,996,558, 6,073,862, 6,336,598, 6,439,192, and 6,761,325. In preferred

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embodiments, so-called “dual fuel injectors” allow the separate and independent injection of pilot fuel and main fuel, allowing both fuels to be introduced directly into the combustion chamber, with the dual fuel injector occupying the space normally occupied by a conventional diesel fuel injection valve. The dual fuel injector approach permits the use of conventional cylinder heads without any substantial modifications. This solution can be employed for all engine sizes but is more suited to larger engines, compared to smaller engines, because there is more space in a larger engine to accommodate a dual fuel injector.

[0007] However, there remains a need for other arrangements and approaches for operating a bi-fuel engine with the same power, performance and efficiency of a conventional diesel engine. In this disclosure a bi-fuel engine is defined as an engine that can burn two different fuels, and in preferred embodiments it can burn one of the two fuels or a combination of both fuels. For a bi-fuel engine that employs a pilot fuel that is directly injected into the combustion chamber, there is a need for an arrangement that is suitable for engines of all sizes, including smaller engines. In the example of a gaseous-fuelled engine, by injecting only a pilot quantity of liquid fuel, cleaner burning gaseous fuel can be substituted to satisfy the majority of the energy requirements, thereby reducing emissions. However, emissions can be further reduced in some operating modes if under certain conditions a means other than the introduction of a pilot fuel can be employed to assist with ignition of the gaseous fuel. The present disclosure relates to a novel solution for addressing these needs with an apparatus that allows separate and independent introduction of two different fuels directly into an engine’s combustion chamber without requiring any substantial modification of the cylinder head. The present disclosure also relates to an apparatus and method that allows an engine to be operated in several operating modes responsive to real-time operating conditions, with flexibility to burn two different fuels separately or together.

Summary of the Invention

[0008] An internal combustion engine is provided that can be fuelled with a first fuel alone or a combination of the first fuel and a second fuel or the second fuel alone. The

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engine comprises the following components that cooperate with one another to combust the first fuel and/or the second fuel within a combustion chamber to produce mechanical work without ignition assistance from glow plugs:

5 an engine block defining the combustion chamber in cooperation with a piston reciprocable within the combustion chamber, and a cylinder head covering one end of the combustion chamber opposite the piston;

an intake air manifold through which air can flow into the combustion chamber by operation of an intake valve;

10 a piston rod operatively connecting the piston to a crankshaft, whereby reciprocating movement of the piston is linked to rotation of the crankshaft;

a first fuel injection valve disposed in the cylinder head and operative to inject the first fuel directly into the combustion chamber through a first nozzle;

15 a second fuel injection valve distinct from the first fuel injection valve and disposed in the cylinder head and operative to inject the second fuel directly into the combustion chamber through a second nozzle;

an ignition-assist apparatus associated with the intake air manifold that can be activated to change a property of air inside the intake air manifold to promote ignition of the first or second fuel that is directly injected into the combustion chamber; and

20 an electronic controller programmable to command operation of the first fuel injection valve, the second fuel injection valve and the ignition-assist apparatus responsive to measured engine operating conditions.

[0009] An important feature of the ignition-assist apparatus is that, unlike a conventional glow plug or spark plug, it is associated with the intake air manifold and not
25 the combustion chamber. This allows more space in the cylinder head above the combustion chamber for installing the first and second fuel injection valves, which require two separate mounting positions since these fuel injection valves are distinct from each other. The ignition-assist apparatus is operable to change a property of the air inside the intake manifold to promote ignition of the first or second fuel that is directly injected
30 into the combustion chamber. For example, the ignition-assist apparatus can be operable

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to increase the temperature of the intake air, or to introduce a fluid into the intake air that helps to promote combustion when the intake charge is compressed and heated in the combustion chamber.

[0010] In a preferred embodiment, the ignition-assist apparatus is a heater that is operative to heat air within the intake air manifold when activated, whereby the property of the air that is changed is its temperature. The heater can comprise, for example, an electrical resistance heating element disposed within the intake air manifold, or a burner that can burn the gaseous fuel in a burner combustion chamber proximate to the air intake manifold. If the heater is a burner, the burner can be operable to emit hot combustion products from the burner combustion chamber directly into the intake air manifold. In another embodiment, the ignition-assist apparatus can be an injection valve for introducing a fuel into the intake air manifold that is more readily ignited within the combustion chamber compared to the first or second fuels. Dimethylether is an example of a fuel that would be suitable for conditioning the intake air to prime the intake charge for ignition. An advantage of the ignition-assist apparatus being a heater is that there is no need to supply a third fuel to the engine. For this reason, while persons skilled in the technology will understand that other embodiments of the ignition-assist apparatus are possible, in the detailed description of the preferred embodiments set out below and in the accompanying figures, the ignition-assist apparatus is described and illustrated as a heater.

[0011] The disclosed engine is a bi-fuel engine since two different fuels may be employed to provide the energy needed to service the load applied to the engine. In a preferred embodiment, one fuel is a liquid fuel and the other fuel is a gaseous fuel, wherein the gaseous fuel is cleaner burning than the liquid fuel, and the liquid fuel has a lower auto-ignition temperature compared to the gaseous fuel. When both fuels are introduced into the combustion chamber, the liquid fuel can act as a pilot fuel to ignite the gaseous fuel. In preferred operating modes the quantity of liquid fuel is limited, allowing the majority of the fuel, on an energy basis, to be the cleaner burning gaseous fuel. In addition to the environmental benefits associated with most of the burned fuel being a cleaner burning gaseous fuel, there can also be economic advantages because in

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many markets, gaseous fuels such as natural gas are less expensive than conventional liquid fuels such as diesel, when fuel costs are calculated on an energy basis.

[0012] The first and second fuel injection valves can be any type of valve suitable for regulating the injection of fuel directly into a combustion chamber, as long as they
5 can be manufactured with dimensions that allow them to be installed in the openings available in the cylinder head. For example, one or both of the fuel injection valves can employ inward opening valve needles if such valves can provide the desired performance characteristics while also meeting the dimensional constraints imposed by the space available for installing the valves in the cylinder head. Modern four-stroke internal
10 combustion engines typically accommodate four intake and exhaust valves, in addition to the two fuel injection valves of the disclosed engine, and in a preferred embodiment, if there is not enough available space in the cylinder head to accommodate a fuel injection valve with an inward opening needle, at least one of the fuel injection valves can be a poppet valve. Poppet valves can be made with smaller outside diameters compared to
15 valves with inward opening needles, and this can be advantageous if one of the fuel injection valves is mounted in an opening that is normally occupied by a glow plug.

[0013] When one of the fuel injection valves is a poppet valve, it can be desirable to break up the fuel spray so that instead of being introduced in a conical sheet, the fuel is introduced in plumes with more contact interfaces with the oxygen in the intake charge.
20 To divide the fuel spray into plumes, a nozzle tip can be disposed over the end of each poppet valve, the nozzle tip comprising orifices whereby fuel spray plumes can be introduced into the combustion chamber through the poppet valve. Such a nozzle tip can be detached from the nozzle tip and attached to the cylinder head, whereby the poppet valve is removable from the cylinder head separately from the nozzle tip. If the nozzle
25 tip is damaged, worn, or clogged, it can be desirable to remove and clean or replace the nozzle tip. In preferred embodiments the nozzle tip is removably attached to the cylinder head. Instead of using a nozzle tip with orifices, a poppet valve can further comprise posts projecting from the end of the poppet valve, whereby the posts extend into the path of a fuel spray introduced into the combustion chamber through the poppet valve, thereby
30 breaking up fuel spray to provide more contact surfaces with the oxygen in the intake

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charge. In yet another embodiment, the poppet valve can comprise a fluted plenum provided between a valve stem and a nozzle body adjacent to a valve seat. The fluted plenum channels the fuel into the plenum openings so that when the valve is opened the fuel flows into the combustion chamber in plumes.

5 **[0014]** In preferred embodiments the electronic controller is programmable to operate the engine in one of a plurality of selectable predetermined operating modes. Each one of the plurality of selectable operating modes determines the commands that the electronic controller sends to operate the first fuel injection valve, the second fuel injection valve, and the ignition-assist apparatus. Under some engine operating conditions it may not
10 be necessary to operate the ignition-assist apparatus to auto-ignite the fuel in the combustion chamber. In some embodiments, the ignition-assist apparatus will only be commanded to operate during special operating conditions such as during a cold start up. In other embodiments, the electronic controller can be programmed to operate the ignition-assist apparatus whenever air temperature within the intake air manifold is less than a
15 predetermined value. In another embodiment, if the ignition-assist apparatus is a heater, the electronic controller can be further programmed to determine heat input from the heater, quantity of the first fuel, quantity of the second fuel, and timing and duration for each injection event with reference to an engine map and data inputs received by the electronic controller, with the data inputs comprising measured engine operating parameters and
20 operator inputs. In the embodiment wherein the ignition-assist apparatus is a heater, in a start-up mode, the electronic controller can be programmed to:

 switch on the heater to heat air in the intake manifold before cranking the engine;

 inject a pilot quantity of the first fuel into the combustion chamber through
25 the first fuel injection valve; and

 inject a main quantity of the second fuel into the combustion chamber through the second fuel injection valve.

[0015] If the heater is an electrical resistance heater, the electronic controller is preferably programmed to switch off the heater before cranking the engine, so that the
30 electrical load during start up is not excessive.

[0016] The predetermined operating modes define for each combustion cycle whether the first fuel is injected alone or in combination with the second fuel or if the second fuel is injected alone. The predetermined operating modes also define whether the ignition-assist apparatus is operated or not. The electronic controller is programmed with at least two operating modes wherein each of the first and second fuels is introduced into the combustion chamber in at least one of the selectable predetermined operating modes. The plurality of selectable predetermined operating modes from which the electronic controller is programmed to select comprise at least two of:

operating mode 1 in which the ignition-assist apparatus is operated and both of the first fuel injection valve and the second fuel injection valve are commanded to open;

operating mode 2 in which the ignition-assist apparatus is not operated and both of the first fuel injection valve and the second fuel injection valve are commanded to open;

operating mode 3 in which the ignition-assist apparatus is operated, the first fuel injection valve is held closed and the second fuel injection valve is commanded to open;

operating mode 4 in which the ignition-assist apparatus is not operated, the first fuel injection valve is held closed and the second fuel injection valve is commanded to open;

operating mode 5 in which the ignition-assist apparatus is operated, the first fuel injection valve is commanded to open and the second fuel injection valve is held closed; and

operating mode 6 in which the ignition-assist apparatus is not operated, the first fuel injection valve is commanded to open and the second fuel injection valve is held closed.

[0017] For example, in one embodiment, when starting up the internal combustion engine, the electronic controller can be programmed to operate the ignition-assist apparatus as part of a predetermined start up sequence. After start up, the electronic controller can be

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programmed to select between operating mode 2 and operating mode 6 responsive to measured engine operating parameters and operator inputs.

- [0018] A method is also disclosed of manufacturing an internal combustion engine that comprises at least one combustion chamber defined by a cylinder bore
- 5 provided within an engine block, a piston reciprocable within the cylinder bore, and a cylinder head covering an end of the cylinder bore opposite to the piston, wherein the cylinder head comprises a first opening suitable for receiving a conventional diesel fuel injection valve and a second opening suitable for receiving a glow plug. The method comprises:
- 10 installing a first fuel injection valve in one of the first and second openings in the cylinder head;
- installing a second fuel injection valve in the one of the first and second openings in the cylinder head that is not occupied by the first fuel injection valve;
- installing an ignition-assist apparatus in an intake air manifold through which
- 15 air is flowable enroute to the combustion chamber; and
- programming an electronic controller to operate the engine in one of a plurality of operating modes wherein in at least one operating mode a first fuel and a second fuel are injectable directly into the combustion chamber, and in another operating mode the first fuel alone is injectable directly into the combustion
- 20 chamber, and in all operating modes the electronic controller is programmed to switch on the ignition-assist apparatus responsive to predetermined operating conditions to assist with promoting combustion in the combustion chamber.

- [0019] If the second fuel is auto-ignitable within the combustion chamber without
- 25 ignition assistance from the first fuel, the method of manufacturing the engine can further comprise programming the electronic controller to detect engine operating conditions in which the second fuel is auto-ignitable without assistance from the first fuel, so that when such engine operating conditions are detected, the electronic controller is programmed to select an operating mode in which the first fuel injection valve is held closed and the
- 30 second fuel injection valve is opened. When the first fuel is diesel fuel and the second

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fuel is a cleaner burning gaseous fuel, in some operating modes this feature enables the engine to run without burning any diesel fuel, thereby reducing engine emissions.

[0020] In a preferred manufacturing method the internal combustion engine is made with many of the same parts that are used to make a conventional diesel engine, such as the engine block, the cylinder head, pistons, and other major components. The first fuel is a liquid fuel and the second fuel is a gaseous fuel, and by practising the method, glow plugs are removed or not installed, and the engine is made to be operable as a gaseous-fuelled engine with liquid pilot fuel ignition assistance.

[0021] A method is disclosed of operating an internal combustion engine that can be fuelled with a first fuel alone or a combination of the first fuel and a second fuel. The method comprises:

pre-conditioning air within an intake air manifold by pre-heating the air or introducing an ignition-assisting fluid to promote auto-ignition of the first or second fuel within the combustion chamber by operating an ignition-assist apparatus associated with the intake air manifold;

introducing the first fuel directly into the combustion chamber through a first fuel injection valve;

introducing the second fuel directly into the combustion chamber through a second fuel injection valve; and

selecting one of a plurality of predetermined operating modes for determining when to pre-condition the air, when to introduce the first fuel, and when to introduce the second fuel, with these determinations being made responsive to measured engine operating conditions and operator inputs.

[0022] In a preferred method, one of the plurality of operating modes is a start-up mode for starting up the engine. In the start-up mode the method can further comprise:

measuring engine temperature;

switching on the ignition-assist apparatus to pre-condition air in the intake manifold before cranking the engine if the engine temperature is below a predetermined value;

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determining a quantity of the first fuel and a quantity of the second fuel, and timing for starting and ending respective injection events, with reference to data inputs received by the electronic controller and an engine map, the data inputs comprising measured engine operating parameters and operator inputs;

5 introducing the first fuel directly into the combustion chamber through the first fuel injection valve; and

 introducing the second fuel directly into the combustion chamber through the second fuel injection valve.

10 **[0023]** In a preferred method the ignition-assist apparatus is a heater and in the start-up mode, the method further comprises switching off the heater before cranking the engine.

[0024] In preferred methods each of the first and second fuels is introduced into the combustion chamber in at least one of the plurality of selectable predetermined operating modes, which comprise at least two of:

15 a first operating mode in which the ignition-assist apparatus is operated and both of the first fuel and the second fuel are introduced directly into the combustion chamber;

 a second operating mode in which the ignition-assist apparatus is not operated and both of the first fuel and the second fuel are introduced directly into the combustion chamber;

20 a third operating mode in which the ignition-assist apparatus is operated, the first fuel injection valve is held closed and the second fuel is introduced directly into the combustion chamber;

 a fourth operating mode in which the ignition-assist apparatus is not operated, the first fuel injection valve is held closed and the second fuel is directly introduced into the combustion chamber;

25 a fifth operating mode in which the ignition-assist apparatus is operated, the first fuel is introduced directly into the combustion chamber and the second fuel injection valve is held closed; and

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a sixth operating mode in which the ignition-assist apparatus is not operated, the first fuel is introduced directly into the combustion chamber and the second fuel injection valve is held closed.

- 5 **[0025]** When the engine is operating in a mode in which the ignition-assist apparatus is not operated, the method can further comprise changing operating modes and operating the ignition-assist apparatus when air temperature within the intake air manifold is less than a predetermined fixed value. Instead of a predetermined fixed value, the method can comprise changing operating modes and operating the ignition-
- 10 assist apparatus when air temperature within the intake air manifold is less than a predetermined value that is determined from an engine map. That is, the threshold temperature for triggering operation of the ignition-assist apparatus can be different depending upon the selected operating mode and/or the current operating point on the engine map.
- 15 **[0026]** If the ignition-assist apparatus is a heater, the method can further comprise regulating air temperature inside the intake air manifold by controlling heat output from the heater. For example, if the heater comprises an electrical resistance element disposed in the intake air manifold, and the method can further comprise controlling the electrical current delivered to the resistance element to control heat output from the heater. If the
- 20 heater comprises a burner that is fuelled with the gaseous fuel, the method can further comprise regulating the flow of gaseous fuel to the burner to control heat output from the heater.
- [0027]** If the ignition-assist apparatus is a burner the method can further comprise releasing hot combustion products from the burner directly into the intake air manifold.
- 25 **[0028]** In preferred methods, one of the fuels is a gaseous fuel selected from the group consisting of natural gas, methane, ethane, liquefied petroleum gas, lighter flammable hydrocarbon derivatives, hydrogen, and blends thereof. A “gaseous” fuel is defined herein to mean a fuel that is combustible in an internal combustion engine and that is in the gaseous phase when it enters the combustion chamber.

[0029] Normally one of the two fuels has a lower auto-ignition temperature than the other fuel. If it is the first fuel that has a lower auto-ignition temperature than the second fuel, the first fuel can be a liquid fuel selected from the group consisting of diesel fuel, dimethylether, bio-diesel, kerosene, and mixtures thereof. In preferred embodiments, the first fuel is a liquid fuel that has a cetane number greater than or equal to 40.

[0030] The method can further comprise recirculating exhaust gas produced by combustion inside the combustion chamber, back into the combustion chamber.

Brief Description of the Drawing(s)

10 [0031] Figure 1 is a schematic view of an engine's intake air manifold and combustion chamber, showing a heater disposed in the intake air manifold, and mounted separately in the cylinder head above the combustion chamber: a first fuel injection valve and a second fuel injection valve.

15 [0032] Figure 2 shows the cylinder head above the combustion chamber, viewed looking up from within the combustion chamber.

[0033] Figure 3 is an axial view of a cross section of a fuel injection valve with a fluted valve stem, which provides channels for dividing the fuel into separate spray jets.

[0034] Figure 4 is a side view of a nozzle tip for a poppet-style fuel injection valve with posts extending from the tip to break up the fuel spray into plumes.

20 [0035] Figure 5 is a side view of a domed nozzle tip for a poppet-style fuel injection valve with orifices for introducing the fuel into the combustion chamber in plumes.

25 [0036] Figure 6 is a flow diagram illustrating a control strategy for starting up an internal combustion engine with direct injection of liquid and gaseous fuels into the combustion chamber with a heater for pre-heating the intake air.

[0037] Figures 7 through 9 are flow diagrams that each illustrates a different embodiment of a control strategy for selecting an operating mode for an internal combustion engine with direct injection of liquid and gaseous fuels into the combustion chamber with a heater for pre-heating the intake air.

Detailed Description of Preferred Embodiment(s)

[0038] In the figures illustrating the physical embodiments of the disclosed engine, like-named features in different illustrated embodiments are referred to with like reference numbers increased by increments of 100.

5 [0039] The schematic view of Figure 1 shows part of the intake air manifold and a combustion chamber for an internal combustion engine. The disclosed engine can be fuelled with liquid fuel alone or a combination of gaseous fuel and liquid fuel or gaseous fuel alone. Like a conventional engine, the engine components cooperate with one another to combust fuel within a combustion chamber to produce mechanical work, but
10 the presently disclosed engine operates without glow plugs. Instead of glow plugs an ignition-assist apparatus is associated with the intake air manifold, whereby the ignition-assist apparatus can be activated to promote conditions in the combustion chamber that result in the ignition of the directly injected fuel.

[0040] Figure 1 is illustrative of the disclosed system but the components are not
15 drawn to scale. Engine block 102, piston 104 and cylinder head 106 collectively define the boundaries of combustion chamber 108. Like a conventional internal combustion engine, a piston rod (not shown) is operatively connected to piston 104 and a crankshaft, whereby reciprocating movement of piston 104 is linked to rotation of the crankshaft. Intake air is directed to combustion chamber 108 through intake manifold 110 and intake
20 valve 112.

[0041] In the embodiment illustrated by Figure 1, the ignition-assist apparatus is heater 114. Heater 114 is operative to heat air within intake manifold 110. As illustrated in Figure 1, heater 114 can comprise, for example, electrical resistance heating element 116 disposed within intake manifold 110 for direct contact with the intake air. In another
25 embodiment (not shown) heater 114 can comprise a burner fueled with the same gaseous fuel that is burned by the engine. In such an arrangement, the burner can comprise a burner combustion chamber proximate to intake manifold 110 but not within the intake manifold, and a burner exhaust port for releasing hot combustion products into intake manifold 110. An advantage of a burner is that it reduces the electrical load on the
30 battery at start up.

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[0042] For a number of reasons, heater 114 is not as efficient as glow plugs that are installed in each cylinder. For example, there is some heat dissipation between heater 114 and combustion chamber 108, more energy is required to heat air in intake manifold 110 to a temperature that will promote ignition, compared to the energy required to heat a glow plug to provide a hot surface inside combustion chamber 108 towards which fuel can be directed to promote ignition. Also, by heating the air inside intake manifold 110, the hot air expands and less air can be inducted into combustion chamber 108. Accordingly, in a conventional diesel engine, these are some of the reasons why glow plugs are employed instead of an intake manifold heater to assist with ignition at start up when the diesel fuel may not auto-ignite. All of these disadvantages remain disadvantages associated with the use of an intake manifold heater in the presently disclosed invention. However, unlike a conventional engine, with the presently disclosed engine, these disadvantages are offset by the advantages gained by the presently disclosed engine, which is capable of burning a first fuel alone, a combination of the first fuel and a second fuel, or the second fuel alone without ignition assistance from a glow plug. Removing the glow plugs provides space for the installation of a second fuel injection valve, so that two fuel injection valves can be installed in cylinder head 106 for each combustion chamber without requiring a custom-designed cylinder head or major modifications to a conventional cylinder head. Even though heater 114 is less efficient than glow plugs, heater 114 need only be used when the engine is in a start-up operating mode or when the intake air temperature is below a predetermined value. Normally, once the engine is running and the engine block is heated to normal operating temperatures, heater 114 can be turned off since the retained heat of combustion and the normal in-cylinder operating temperature near top dead center can be hot enough to auto-ignite at least one of the two directly injected fuels, which can in turn cause the ignition of the other fuel.

[0043] In addition, since heater 114 need only be normally employed when the engine is starting up and optionally under specific predefined conditions such as idle or low load conditions, the reduced air mass flow caused by the lower density of heated air is not a detriment. Higher air mass flow rates are needed when the engine is running

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under high load operating conditions, but under such conditions, the heat generated in the combustion chamber is normally sufficient to make pre-heating the intake air unnecessary. Under low load and idle conditions, with the smaller amounts of fuel being combusted, the heat of combustion may be relatively low and with the disclosed engine it is possible to activate the heater to increase the temperature in the combustion chamber for improved combustion and lower emissions. Accordingly, the performance of the disclosed engine is not affected by the effect of pre-heating the intake air on the air mass flow rate into the combustion chamber.

[0044] Therefore, while heater 114 may not be a desirable substitute for glow plugs in a conventional diesel engine, it is an advantageous solution for the presently disclosed engine since it allows two separate fuel injection valves to each be installed in the cylinder head that was originally designed to accommodate only one fuel injection valve and a glow plug. The disclosed engine arrangement is also advantageous for new engines designed from the outset as bi-fuel engines because the disclosed engine arrangement simplifies the design of the cylinder head, which might otherwise be required to accommodate two fuel injection valves in addition to a glow plug or spark plug.

[0045] A first fuel can be injected directly into combustion chamber 108 through first fuel injection valve 122. A second fuel can be injected directly into combustion chamber 108 through second fuel injection valve 120. Both fuel injection valves are mounted in cylinder head 106. As noted above in the discussion relating to heater 114, the installation of two fuel injection valves associated with each combustion chamber and using a conventional cylinder head designed for a diesel engine, is made possible by removing the glow plugs, and substituting an ignition-assist apparatus such as heater 114 to assist with ignition during start-up by preheating air in intake manifold 110.

[0046] Compared to a single dual fuel injector that is capable of injecting both gaseous fuel and liquid fuel, an advantage of having two separate fuel injection valves is that the fuel supply systems can be completely segregated. With a dual fuel injector, because there are moving parts, and two types of fuel, dynamic seals, such as fluid seals, are needed to keep the gaseous and liquid fuels separate. To reduce leakage in a dual fuel

injection valve, it is desirable to substantially balance the pressures of the gaseous fuel and the liquid fuel. With the presently disclosed arrangement there can be separate gaseous and liquid fuel injection valves, allowing gaseous and liquid fuel pressures to be selected based on operational requirements. In the case of the liquid fuel, operational requirements can include, for example, the pressure required to atomize the fuel. In the case of the gaseous fuel, operational requirements can include, for example, the pressure that is needed to introduce the desired amount of fuel with the desired mass flow rate, and fuel spray velocity since this may be controlled to promote fuel penetration into combustion chamber 108 as well as turbulence and mixing therein.

10 [0047] In addition, the design of two separate fuel injection valves is less complex than the design of a single fuel injection valve that separately and independently injects a gaseous fuel and a liquid fuel. Depending upon an engine's fuel requirements fuel injection valves that are currently mass-produced can be employed with minor modifications, or without any modifications at all. Accordingly, the presently disclosed engine can be less expensive to manufacture compared to an engine that employs a single custom-designed dual fuel injection valve.

[0048] In one embodiment, at least one of first fuel injection valve 122 and second fuel injection valve 120 is a poppet valve (also known as an outward opening pintle valve). Such poppet valves can be made with dimensions suitable for fitting in the cylinder head opening normally provided for accommodating a glow plug.

20 [0049] In the simplified illustration of Figure 1, the exhaust system is not shown, but like a conventional engine, combustion products are exhausted through exhaust valves and an exhaust manifold. The disclosed engine can employ an exhaust gas recirculation system, such as the system disclosed by co-owned published Patent Cooperation Treaty Application serial number PCT/CA03/01466, entitled, "Exhaust Gas Recirculation Methods and Apparatus for Reducing NOx Emissions from Internal Combustion Engines".

25 [0050] As is known by persons skilled in the technology, an electronic control unit (ECU) can be programmed to control the operation of the engine. With the presently disclosed engine, the ECU also controls activation of heater 114, and operation of second

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fuel injection valve 120 and first fuel injection valve 122. In Figure 1, solid lines are drawn from ECU 140 to heater 114 and second fuel injection valve 120 and first fuel injection valve 122 to indicate that they can be controlled responsive to signals transmitted from ECU 140. ECU 140 receives measured data representative of engine
5 operating parameters which can comprise, for example, one or more of the following: engine speed, actual engine load, commanded engine load, boost pressure, and oil temperature, ambient air temperature, air temperature inside intake manifold 110, engine block temperature, pilot fuel rail pressure, gaseous fuel rail pressure, and start of combustion. Dashed lines are shown to indicate data inputs that ECU 140 can receive
10 that can be of particular relevance to embodiments of the presently disclosed engine. The dashed line from temperature sensor 142 indicates that in the illustrated embodiment ECU 140 can receive data representative of the air temperature measured in intake manifold 110 by temperature sensor 142. Similarly, the dashed line from temperature sensor 144 shows that ECU 140 can receive data representative of the temperature of
15 engine block 102 measured by sensor 144. For example, one or both of these temperature measurements can be processed by ECU 140 to determine when to activate heater 114.

[0051] With the disclosed engine, ECU 140 can be programmed to choose from at least two different predetermined operating modes, depending upon measured
20 operating parameters. With the understanding that the disclosed engine enables operation with two different fuels that can both be liquid or both gaseous or one liquid and one gaseous, by way of example, six operating modes are set out in Table 1 below for an engine that burns a liquid fuel and a gaseous fuel and that uses a heater associated with the intake air manifold as the ignition-assist apparatus. That is, in Table 1, "LIQUID
25 FUEL" could be replaced with "FIRST FUEL" and "GASEOUS FUEL" could be replaced with "SECOND FUEL".

[0052] Table 1: Operating Modes

MODE	HEATER	LIQUID FUEL	GASEOUS FUEL
1	ON	INJECTED	INJECTED
2	OFF	INJECTED	INJECTED
3	ON	NOT INJECTED	INJECTED
4	OFF	NOT INJECTED	INJECTED
5	ON	INJECTED	NOT INJECTED
6	OFF	INJECTED	NOT INJECTED

[0053] Referring to Table 1, ECU 140 can select operating mode 1, for example, when the engine is cold or when the engine is operating in a cold climate, and when the heat of compression alone is not sufficient to ensure auto-ignition of the liquid fuel. Such conditions can be detected by data inputs from engine block temperature sensor 144 and intake manifold temperature sensor 142, respectively. When operating mode 1 is selected, ECU 140 commands heater 114 to pre-heat the intake air, and both first fuel injection valve 122 and second fuel injection valve 120 are commanded to respectively inject liquid and gaseous fuel into the combustion chamber with the liquid fuel acting as a pilot fuel to initiate combustion of the gaseous fuel.

[0054] Operating mode 2 is selectable, for example, if ECU 140 determines that combustion chamber 108 is at a temperature that is consistently above a predetermined value at which pre-heating the intake air is unnecessary to ensure combustion of at least one of the fuels (normally it is the liquid fuel that has the lower auto-ignition temperature). ECU 140 can determine when this condition is met from data input from engine block temperature sensor 144. For example, if ECU 140 determines that the engine block temperature is above a predetermined threshold value when the piston is at top dead center at the end of a compression stroke, ECU 140 can command heater 114 to turn off. In operating mode 2, ECU 140 commands both first fuel injection valve 122 and second fuel injection valve 120 to respectively inject liquid and gaseous fuels directly into the combustion chamber with the fuel with the lower auto-ignition temperature acting as a pilot fuel to assist with combustion of the other fuel. That is, in this example the gaseous fuel is the main fuel that is metered to satisfy the energy needs demanded by

the engine load while the quantity of liquid fuel is limited to only that amount which is needed to ignite the gaseous fuel.

[0055] The disclosed engine can be controlled by employing only operating modes 1 and 2, but under certain operating conditions operating modes 3 through 6 can be advantageously employed for improved performance, reduced emissions and/or improved operational flexibility. Operating modes 3 and 4 can only be used with gaseous fuels that can auto-ignite without ignition assistance from a pilot fuel, and these operating modes allow the disclosed engine to operate using gaseous fuel alone. Operating modes 5 and 6 provide operational flexibility by allowing the disclosed engine to operate using liquid fuel alone.

[0056] ECU 140 can be programmed to select operating mode 3, for example, if the temperature inside the combustion chamber at the end of the compression stroke is above a predetermined temperature such that the gaseous fuel will auto-ignite with ignition assistance from pre-heated intake air, but without requiring ignition assistance from the liquid pilot fuel. ECU 140 can determine when combustion chamber temperatures at the desired ignition timing are above this predetermined temperature from data received from engine block temperature sensor 144. This operating mode is desirable for reducing emissions since gaseous fuels are generally cleaner burning compared to liquid fuels. In this operating mode ECU 140 commands heater 114 to switch on, while no command signal is sent to actuate first fuel injection valve 122 so that it remains closed. ECU 140 commands second fuel injection valve 120 to open to inject the desired amount of gaseous fuel into the combustion chamber. With the ignition assistance provided by the pre-heated intake air, the gaseous fuel auto-ignites.

[0057] ECU 140 can be programmed to select operating mode 4, for example, if ECU 140 determines that the projected temperature of engine block 102 at the desired ignition time is already above a predetermined temperature at which the gaseous fuel is known to auto-ignite without ignition assistance from the liquid pilot fuel and without the need to pre-heat the intake air. The auto-ignition temperature of the gaseous fuel depends upon the properties of the gaseous fuel. When operating mode 4 is selected, ECU 140 commands heater 114 to switch off and an actuating command is not sent to first fuel

injector 122 so that it remains closed, while ECU 140 sends an actuating command to second fuel injector 120 so that gaseous fuel is injected into combustion chamber 108.

5 [0058] Operating modes 5 and 6 both define operating modes where only liquid fuel is injected. For example, if a vehicle runs out of gaseous fuel before it reaches a re-fueling station or if the engine is idling and requires only a very small amount of fuel and it is not practical to inject two different fuels and gaseous fuel will not auto-ignite on its own. In operating mode 5 the heater is switched on and in operating mode 6 the heater is switched off. In these operating modes, heater 114 is switched on when ECU 140 determines that pre-heating the intake air is necessary to assist with ignition of the liquid
10 fuel.

[0059] In operating modes 1, 3, and 5, heater 114 is switched on, and ECU 140 can determine from the measured operating parameters whether to regulate the heater to increase or decrease the level of heating provided by heater 114. For example, if the heater is an electrical resistance heater, the amount of electrical current directed to the
15 heating coil can be adjusted to raise or lower the temperature of the intake air. If the heater is a burner, a flow regulator can be adjusted to control the amount of fuel that is sent to the burner to raise or lower the temperature of the intake air. An open or closed loop control system can be employed to control intake air temperature.

[0060] Using the operating modes set out in Table 1 that are described above,
20 many different control strategies are possible. Figures 6 through 9 are control diagrams that provide examples of a few control strategies made possible by the disclosed engine with references to the "operating modes" being the operating modes of Table 1. As with Table 1, these descriptions relate to a preferred embodiment in which the ignition-assist apparatus is a heater, and the first fuel is a liquid fuel and the second fuel is a gaseous
25 fuel.

[0061] Figure 6 illustrates a start-up control strategy. In the first step, the ECU determines the engine block temperature and if the temperature is higher than a predetermined temperature T_i , the ECU proceeds with cranking the engine. If the engine block temperature is less than T_i , then the ECU commands the heater to turn on. When
30 the intake air temperature is greater than a predetermined temperature T_s , if the heater is

an electric heater, the ECU can turn off the heater to reduce the load on the electrical system while the engine is being cranked. If the heater is a burner it can be left on during the cranking step. While the engine is being cranked, the ECU commands pilot fuel to be injected, followed by gaseous fuel. If fuel ignition is not detected, then the start up
5 process can be repeated. Once fuel ignition is detected, the ECU can proceed with selecting the desired operating mode.

[0062] Figure 7 shows a control strategy for selecting one of operating modes 1, 2, 5, or 6 as described in Table 1. With this control strategy, the first query is to determine if the engine block temperature is greater than predetermined temperature T_A .
10 For example, temperature T_A can be an engine block temperature that correlates to when the conditions in the combustion chamber ensure auto-ignition of the liquid fuel at a desired ignition time at or near the beginning of the power stroke. As with all of the described control strategies, the engine block temperature is preferably measured with the same timing in each combustion cycle, for example, at a fixed time in the engine cycle
15 defined by the position of the crankshaft measured in degrees before the piston is at top dead center. From the measured engine block temperature and other measured operating parameters such as engine speed, engine load, and intake air temperature, the ECU can predict the temperature in the combustion chamber at the desired ignition time, for example by referring to an engine map or by computation. Accordingly, it is anticipated
20 that when the engine block temperature from the preceding combustion cycle is greater than T_A , the liquid fuel that is injected directly into the combustion chamber in the next combustion cycle auto-ignites at the desired time, at or near the beginning of the power stroke. If the engine block temperature is less than T_A then the ECU turns the heater on, or leaves it on if already on. Conversely, if the ECU determines that the engine block
25 temperature is greater than T_A then the ECU turns the heater off or leaves it off if already off.

[0063] After determining whether to turn the heater on or off, the next step is to determine if gaseous fuel is available. If gaseous fuel is available, then the ECU commands the injection of a pilot quantity of liquid fuel followed by the injection of
30 gaseous fuel to supply the energy needed for the current engine load. If gaseous fuel is

not available, the ECU commands the liquid fuel injection valve to inject enough liquid fuel to supply the energy needed for the current engine load, up to the maximum flowrate that can be injected through the liquid fuel injection valve. If the operator decides to shut down the engine, then the heater is turned off and the process stops. If the operator
5 wishes to continue running the engine the control strategy can be repeated when a change is detected in the engine operating conditions, or periodically after a fixed number of engine cycles or a fixed time interval, or the control strategy for selecting the operating mode can be repeated for each combustion cycle.

[0064] In the control strategy illustrated in Figure 7, liquid fuel is injected in
10 every operating mode. In operating modes 1 and 2 the amount of liquid fuel is limited to pilot quantities for ignition assistance. In operating modes 5 and 6 the liquid fuel represents the entire quantity of fuel is that injected into the combustion chamber. Accordingly, because there is liquid fuel introduced into the combustion chamber in every operating mode, and the liquid fuel is more readily ignited compared to the gaseous
15 fuel, the engine block temperature that correlates to the combustion chamber conditions that promote auto-ignition of the liquid fuel is the predetermined temperature T_A which is employed by this control strategy to determine whether to turn the heater on or off.

[0065] Figure 8 shows a control strategy that can be used when under some conditions the gaseous fuel is auto-ignitable without ignition assistance from the injection
20 of a liquid pilot fuel. For example, the operating conditions in the combustion chamber can promote auto-ignition of the gaseous fuel with the help of residual heat of combustion, heat returned to the combustion chamber by exhaust gas recirculation and heat provided from the intake air manifold heater. Under other operating conditions, the engine can be fuelled with a combination of a pilot quantity of liquid fuel and a main
25 quantity of gaseous fuel. In still other situations, such as when gaseous fuel is not available, the engine can be fuelled with only liquid fuel. With reference to Figure 8, if gaseous fuel is not available, the ECU considers the engine block temperature to determine if the intake air heater is required to assist with ignition of the liquid fuel. In this embodiment, like in the embodiment of Figure 7, temperature T_A correlates to
30 conditions in the combustion chamber that promote auto-ignition of the liquid fuel. If the

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engine block temperature is greater than T_A then the ECU selects operating mode 6 and the heater is turned off or left off if already off. Liquid fuel is injected and auto-ignites without any ignition assistance from the heater. If the engine block temperature is not greater than T_A then the ECU selects operating mode 5 and the heater is turned on, or left
5 on if already on to pre-heat the intake air to assist with ignition of the liquid fuel.

[0066] If gaseous fuel is available, then according to the control strategy of Figure 8, the ECU computes the average engine block temperature for the last "n" number of cycles, where n is a predetermined number programmed into the ECU. The heater is turned off (or left off) if the average engine block temperature is greater than
10 threshold temperature T_B , which in this embodiment is the temperature of the engine block that correlates to when the temperature in the combustion chamber at the desired timing for ignition is the auto-ignition temperature for the gaseous fuel. According to the strategy diagramed in Figure 8, the ECU selects operating mode 1 if the average engine block temperature is not greater than T_B and the engine block temperature from the
15 immediately preceding engine cycle is also not greater than T_B . The ECU selects operating mode 2 if the average engine block temperature is greater than T_B but the engine block temperature from the immediately preceding engine cycle is not greater than T_B . The ECU selects operating mode 3 if the average engine block temperature is not greater than T_B and the engine block temperature from the immediately preceding
20 cycle is greater than T_B . The ECU selects operating mode 4 if the average engine block temperature and the engine block temperature from the immediately preceding engine cycle are both greater than T_B .

[0067] The control strategy shown in Figure 9 is the same as the control strategy shown in Figure 8 but with one additional feature. If the required quantity of fuel on an
25 energy basis is less than a predetermined value e_f , then the ECU commands only the liquid fuel injection valve to inject fuel into the combustion chamber. Under these operating conditions, because of the small quantity of fuel required, it can be difficult to inject both a pilot quantity of liquid fuel and gaseous fuel, so under these conditions according to the strategy of Figure 9, the ECU determines that only liquid fuel will be
30 injected.

[0068] Returning now to the description of the physical embodiments, Figure 2 is a view of cylinder head 206 viewed from inside the combustion chamber. The circular outlines of two intake valves 212 and two exhaust valves 250 are shown. Second fuel injection valve 220 is shown centrally located with first fuel injection valve 222 positioned nearby. A conventional diesel engine can be converted to operate according to the disclosed method by installing second fuel injection valve 220 in the opening that would normally be occupied by a diesel fuel injection valve and installing first fuel injection valve 222 in the opening that would normally be occupied by a glow plug. First fuel injection valve 222 can be employed to inject a liquid fuel and second fuel injection valve 220 can be employed to inject a gaseous fuel. With a conventional diesel engine, the central opening typically has a larger diameter than that of the opening for the glow plug, and with the presently disclosed engine, since gaseous fuel has a lower density than liquid fuel, and in preferred operating modes, the large majority of the fuel that is injected is gaseous fuel, in preferred embodiments second fuel injection valve 220 is installed in the central opening that has the larger diameter, and first fuel injection valve 222 is installed in the opening with the smaller diameter that is normally occupied by a glow plug in a conventional diesel engine. In another embodiment, the positions of the two valves can be exchanged so that first fuel injection valve 222 can be a conventional diesel fuel injection valve that is designed to fit in the central opening normally occupied by a diesel injection valve.

[0069] For example, a poppet valve for injecting a quantity of liquid pilot fuel can be made with the requisite diameter to be installed in the opening normally filled by a glow plug. The desired quantity of liquid pilot fuel is less than ten percent and more preferably less than five percent of the total fuel burned on an energy basis when the engine is operating at full load. Poppet valves open when the outward opening valve member moves away from the valve seat allowing the fuel to be sprayed into the combustion chamber. A simple poppet valve disperses the fuel in a conical sheet, but it can be desirable to break up this fuel spray sheet to provide more surfaces between the fuel spray and the air inside the combustion chamber. Fuel flow can be divided into separate streams by using a poppet valve with a fluted plenum like the one shown in

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Figure 3. Figure 3 is an axial cross section view of a poppet valve with a fluted valve stem. Fuel can flow parallel to the axis of valve stem 330 in channels defined between valve body 326 and grooves 332. Grooves 332 are shown as having a circular profile, but it would be understood by persons skilled in this technology that other shapes would function in substantially the same manner. In another embodiment, it is also possible to provide a fluted plenum by providing the grooves in the valve body near the valve seat, with the raised areas between the grooves acting as guides for the valve stem.

5 [0070] In other embodiments, the nozzle tip of the fuel injection valve downstream from the valve seat can comprise features that break up the fuel spray into separate spray plumes. With reference to Figure 4, to break up the fuel spray and provide more fuel/air interfaces, features can be added to poppet valve 422 achieve this, such as posts 428. Posts 428 extend from valve body 426 and into the path of the fuel spray thereby breaking up the fuel spray sheet that is introduced through valve 422 into the combustion chamber.

10 [0071] With reference to Figure 5, poppet valve 522 can be provided with domed nozzle tip 528, which comprises orifices 529 so that fuel is introduced into the combustion chamber in the form of spray plumes emerging from orifices 529. Domed nozzle tip 528 can be integral to the nozzle tip as shown in Figure 5 or a dome-shaped cover with orifices can be attached to the cylinder head. If a dome-shaped cover is attached to the cylinder head, poppet valve 522 can be removed without removing the dome-shaped cover. In such an embodiment, the dome-shaped cover is preferably removably attached to the cylinder head so that it can be replaced if damaged or fouled.

20 [0072] Also disclosed is a method of manufacturing the disclosed engine by converting a conventional internal combustion engine which has a cylinder head with a first opening suitable for receiving a conventional diesel fuel injection valve and a second opening suitable for receiving a conventional glow plug. The manufacturing method comprises the steps of:

installing a first fuel injection valve in one of the first and second openings in the cylinder head;

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installing a second fuel injection valve in the other one of said first and second openings that is not occupied by the first fuel injection valve;

installing a heater that is operative to heat air in an intake air manifold through which air is flowable enroute to the combustion chamber; and

5 programming an electronic controller to operate the engine in one of a plurality of operating modes wherein in at least one operating mode the second fuel and a pilot fuel quantity of the first fuel are injected directly into the combustion chamber through the respective fuel injection valves, and in another operating mode the first fuel alone is injected directly into the combustion
10 chamber, and in all operating modes the electronic controller is programmed to switch on the heater responsive to predetermined operating conditions to assist with promoting combustion in the combustion chamber when the piston is at or near top dead center.

[0073] In operating modes in which gaseous fuel is introduced into the
15 combustion chamber, responsive to engine operating conditions the electronic controller can determine whether to assist with ignition of the gaseous fuel by: (a) heating intake air by switching on the heater; and/or (b) introducing a quantity of liquid fuel through the liquid-fuel injection valve, whereby the liquid fuel auto-ignites to in turn ignite the gaseous fuel.

20 [0074] For embodiments in which the liquid fuel is normally only used as a pilot fuel, the conversion method can further comprise replacing the diesel fuel storage tank with a smaller liquid fuel storage tank, and/or replacing the conventional fuel pump with a smaller fuel pump.

[0075] The disclosed engine provides operational flexibility since it is capable of
25 being fuelled with only liquid fuel, only gaseous fuel, or a combination of liquid pilot fuel and gaseous fuel. However, since engine emissions are higher when fuelling the engine with only liquid fuel, in locations where government regulations mandate that pollutant emissions must be lower than prescribed levels, the liquid fuel injection valve can be designed to restrict fuel flow so that full power cannot be achieved when fuelling
30 the engine with only liquid fuel. This would make a vehicle impractical to operate

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normally using only liquid fuel. However, if the vehicle runs out of gaseous fuel, even when a liquid fuel injection valve has limited flow capacity, it is still possible for the vehicle to "limp" home, or to a re-fueling station, or move to a safe location where it can be parked out of harms way.

- 5 **[0076]** While particular elements, embodiments and applications of the present invention have been shown and described, it will be understood, of course, that modifications may be made by those skilled in the art without departing from the scope of the present disclosure, particularly in light of the foregoing teachings.

What is claimed is:

1. An internal combustion engine is provided that can be fuelled with a first fuel alone or a combination of said first fuel and a second fuel or said second fuel alone, said engine comprising the following components that cooperate with one another to combust said first fuel and/or said second fuel within a combustion chamber to produce mechanical work
5 without ignition assistance from glow plugs:
 - (a) an engine block defining said combustion chamber in cooperation with a piston reciprocable within said combustion chamber, and a cylinder head covering one end of said combustion chamber opposite said piston;
 - (b) an intake air manifold through which air can flow into said combustion chamber by
10 operation of an intake valve;
 - (c) a piston rod operatively connecting said piston to a crankshaft, whereby reciprocating movement of said piston is linked to rotation of said crankshaft;
 - (d) a first fuel injection valve disposed in said cylinder head and operative to inject said first fuel directly into said combustion chamber through a first nozzle;
 - 15 (e) a second fuel injection valve distinct from said first fuel injection valve and disposed in said cylinder head and operative to inject said second fuel directly into said combustion chamber through a second nozzle;
 - (f) an ignition-assist apparatus associated with said intake air manifold that can be activated to change a property of air inside said intake air manifold to promote
20 ignition of said first or second fuel that is directly injected into said combustion chamber; and
 - (g) an electronic controller programmable to command operation of said first fuel injection valve, said second fuel injection valve and said ignition-assist apparatus responsive to measured engine operating conditions.
2. The internal combustion engine of claim 1 wherein said ignition-assist apparatus is a heater that is operative to heat air within said intake air manifold when activated, whereby the property of said air that is changed is its temperature.

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3. The internal combustion engine of claim 2, wherein said heater comprises an electrical resistance heating element disposed within said intake air manifold.
4. The internal combustion engine of claim 2, wherein said heater comprises a burner that can burn said gaseous fuel in a burner combustion chamber proximate to said air intake manifold.
5. The internal combustion engine of claim 4 wherein said burner is operable to emit hot combustion products from said burner combustion chamber directly into said intake air manifold.
6. The internal combustion engine of claim 1 wherein said ignition-assist apparatus is an injection valve for introducing a fuel into said intake air manifold that is more readily ignited within said combustion chamber compared to said first or second fuels.
7. The internal combustion engine of claim 1 wherein said first fuel is a gaseous fuel and said second fuel is a liquid fuel.
8. The internal combustion engine of claim 1 wherein at least one of said first fuel injection valve and said second fuel injection valve is a poppet valve.
9. The internal combustion engine of claim 8 further comprising a nozzle tip disposed over the end of said poppet valve, said nozzle tip comprising orifices whereby fuel spray plumes can be introduced into said combustion chamber through said poppet valve.
10. The internal combustion engine of claim 9 wherein said nozzle tip is detached from said nozzle tip and attached to said cylinder head, whereby said poppet valve is removable from said cylinder head separately from said nozzle tip.

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11. The internal combustion engine of claim 9 wherein said nozzle tip is removably attached to said cylinder head.
12. The internal combustion engine of claim 8 further comprising posts projecting from the end of said poppet valve, whereby said posts extend into the path of a fuel spray introduced into said combustion chamber through said poppet valve.
13. The internal combustion engine of claim 8 wherein said poppet valve comprises a fluted plenum provided between a valve stem and a nozzle body adjacent to a valve seat.
14. The internal combustion engine of claim 1 wherein said electronic controller is programmable to operate said engine in one of a plurality of selectable predetermined operating modes, wherein each one of said plurality of selectable operating modes determines the commands that said electronic controller sends to operate said first fuel
5 injection valve, said second fuel injection valve, and said ignition-assist apparatus.
15. The internal combustion engine of claim 14 wherein said electronic controller is programmed to operate said ignition-assist apparatus when air temperature within said intake air manifold is less than a predetermined value.
16. The internal combustion engine of claim 14 wherein said ignition-assist apparatus is a heater and said electronic controller is further programmed to determine heat input from said heater, quantity of said first fuel, quantity of said second fuel, and timing and duration for each injection event with reference to an engine map and data inputs received by said
5 electronic controller, said data inputs comprising measured engine operating parameters and operator inputs.
17. The internal combustion engine of claim 16 wherein in a start-up mode, said electronic controller is programmed to:
switch on said heater to heat air in said intake manifold before cranking said engine;

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inject a pilot quantity of said first fuel into said combustion chamber through said
5 first fuel injection valve; and

inject a main quantity of said second fuel into said combustion chamber through said
second fuel injection valve.

18. The internal combustion engine of claim 17 wherein said electronic controller is
programmed to switch off said heater before cranking said engine.

19. The internal combustion engine of claim 14 wherein each of said first and second
fuels is introduced into said combustion chamber in at least one of said plurality of
selectable predetermined operating modes, which comprise at least two of:

operating mode 1 in which said ignition-assist apparatus is operated and both of said
5 first fuel injection valve and said second fuel injection valve are commanded to open;

operating mode 2 in which said ignition-assist apparatus is not operated and both of
said first fuel injection valve and said second fuel injection valve are commanded to open;

operating mode 3 in which said ignition-assist apparatus is operated, said first fuel
injection valve is held closed and said second fuel injection valve is commanded to open;

10 operating mode 4 in which said ignition-assist apparatus is not operated, said first
fuel injection valve is held closed and said second fuel injection valve is commanded to
open;

operating mode 5 in which said ignition-assist apparatus is operated, said first fuel
injection valve is commanded to open and said second fuel injection valve is held closed;
15 and

operating mode 6 in which said ignition-assist apparatus is not operated, said first
fuel injection valve is commanded to open and said second fuel injection valve is held
closed.

20. The internal combustion engine of claim 19 wherein when starting up said internal
combustion engine, said electronic controller is programmable to operate said ignition-assist
apparatus as part of a predetermined start up sequence, and after start up, said electronic

controller is programmable to select between said operating mode 2 and said operating
5 mode 6 responsive to measured engine operating parameters and operator inputs.

21. A method of manufacturing an internal combustion engine, said engine comprising
at least one combustion chamber defined by a cylinder bore provided within an engine
block, a piston reciprocable within said cylinder bore, and a cylinder head covering an end
of said cylinder bore opposite to said piston, wherein said cylinder head comprises a first
5 opening suitable for receiving a conventional diesel fuel injection valve and a second
opening suitable for receiving a glow plug, said method comprising:

installing a first fuel injection valve in one of said first and second openings in said
cylinder head;

installing a second fuel injection valve in the one of said first and second openings in
10 said cylinder head that is not occupied by said first fuel injection valve; and

installing an ignition-assist apparatus in an intake air manifold through which air is
flowable enroute to said combustion chamber;

programming an electronic controller to operate said engine in one of a plurality of
operating modes wherein in at least one operating mode a first fuel and a second fuel are
15 injectable directly into said combustion chamber, and in another operating mode said first
fuel alone is injectable directly into said combustion chamber, and in all operating modes
said electronic controller is programmed to switch on said ignition-assist apparatus
responsive to predetermined operating conditions to assist with promoting combustion in
said combustion chamber.

22. The method of claim 21, wherein said second fuel is auto-ignitable within said
combustion chamber without ignition assistance from said first fuel, said method further
comprising programming said electronic controller to detect engine operating conditions in
which said second fuel is auto-ignitable without assistance from said first fuel, and when
5 such engine operating conditions are detected, selecting an operating mode in which said
first fuel injection valve is held closed and said second fuel injection valve is opened.

23. The method of claim 21 further comprising programming said electronic controller to operate said ignition-assist apparatus when air temperature within said intake air manifold is less than a predetermined value.
24. The method of claim 23 wherein said predetermined value for air temperature that determines when to operate said ignition-assist apparatus, can be a different temperature for each predefined operating mode.
25. The method of claim 21 wherein said internal combustion engine is made with many of the same parts that can be used to make a conventional diesel engine, including said engine block, said cylinder head, and said piston, wherein said first fuel is a liquid fuel and said second fuel is a gaseous fuel, and by practising said method glow plugs are removed or
5 not installed, and said engine is made to be operable as a gaseous-fuelled engine with liquid pilot fuel ignition assistance.
26. A method of operating an internal combustion engine that can be fuelled with a first fuel alone or a combination of said first fuel and a second fuel, said method comprising:
pre-conditioning air within an intake air manifold by pre-heating said air or
introducing an ignition-assisting fluid to promote auto-ignition of said first or second fuel
5 within said combustion chamber by operating an ignition-assist apparatus associated with said intake air manifold;
introducing said first fuel directly into said combustion chamber through a first fuel injection valve;
introducing said second fuel directly into said combustion chamber through a second
10 fuel injection valve; and
selecting one of a plurality of predetermined operating modes for determining when to pre-condition said air, when to introduce said first fuel, and when to introduce said second fuel, with these determinations being made responsive to measured engine operating conditions and operator inputs.

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27. The method of claim 26 wherein one of said plurality of operating modes is a start-up mode for starting up said engine, and in said start-up mode said method further comprises:

measuring engine temperature;

5 switching on said ignition-assist apparatus to pre-condition air in said intake manifold before cranking said engine if said engine temperature is below a predetermined value;

determining a quantity of said first fuel and a quantity of said second fuel, and timing for starting and ending respective injection events, with reference to data inputs
10 received by said electronic controller and an engine map, said data inputs comprising measured engine operating parameters and operator inputs;

introducing said first fuel directly into said combustion chamber through said first fuel injection valve; and

introducing said second fuel directly into said combustion chamber through said
15 second fuel injection valve.

28. The method of claim 27 wherein said ignition-assist apparatus is a heater and in said start-up mode, said method further comprises switching off said heater before cranking said engine.

29. The method of claim 26 wherein each of said first and second fuels is introduced into said combustion chamber in at least one of said plurality of selectable predetermined operating modes, which comprise at least two of:

a first operating mode in which said ignition-assist apparatus is operated and both of
5 said first fuel and said second fuel are introduced directly into said combustion chamber;

a second operating mode in which said ignition-assist apparatus is not operated and both of said first fuel and said second fuel are introduced directly into said combustion chamber;

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10 a third operating mode in which said ignition-assist apparatus is operated, said first fuel injection valve is held closed and said second fuel is introduced directly into said combustion chamber;

a fourth operating mode in which said ignition-assist apparatus is not operated, said first fuel injection valve is held closed and said second fuel is directly introduced into said combustion chamber;

15 a fifth operating mode in which said ignition-assist apparatus is operated, said first fuel is introduced directly into said combustion chamber and said second fuel injection valve is held closed; and

a sixth operating mode in which said ignition-assist apparatus is not operated, said first fuel is introduced directly into said combustion chamber and said second fuel injection
20 valve is held closed.

30. The method of claim 26 wherein when said engine is operating in a mode in which said ignition-assist apparatus is not operated, said method further comprises changing operating modes and operating said ignition-assist apparatus when air temperature within said intake air manifold is less than a predetermined fixed value.

31. The method of claim 26 wherein when said engine is operating in a mode in which said ignition-assist apparatus is not operated, said method further comprises changing operating modes and operating said ignition-assist apparatus when air temperature within said intake air manifold is less than a predetermined value determined from an engine map.

32. The method of claim 26 wherein said ignition-assist apparatus is a heater and said method further comprises regulating air temperature inside said intake air manifold by controlling heat output from said heater.

33. The method of claim 32 wherein said heater comprises an electrical resistance element disposed in said intake air manifold, and said method further comprises controlling

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the electrical current delivered to said resistance element to control heat output from said heater.

34. The method of claim 32 wherein said heater comprises a burner that is fuelled with said gaseous fuel, and said method further comprises regulating the flow of gaseous fuel to said burner to control heat output from said heater.
35. The method of claim 34 wherein said method comprises releasing hot combustion products from said burner directly into said intake air manifold.
36. The method of claim 26 wherein said second fuel is a gaseous fuel selected from the group consisting of natural gas, methane, ethane, liquefied petroleum gas, lighter flammable hydrocarbon derivatives, hydrogen, and blends thereof.
37. The method of claim 26 wherein said second fuel is a gaseous fuel that is defined as a fuel that is in the gaseous phase when it enters said combustion chamber .
38. The method of claim 26 wherein said first fuel auto-ignites at a lower temperature than said second fuel.
39. The method of claim 38 wherein said first fuel is a liquid fuel selected from the group consisting of diesel fuel, dimethylether, bio-diesel, kerosene, and mixtures thereof .
40. The method of claim 38 wherein said first fuel is a liquid fuel that has a cetane number greater than or equal to 40.
41. The method of claim 26 further comprising recirculating exhaust gas produced by combustion inside said combustion chamber, back into said combustion chamber.

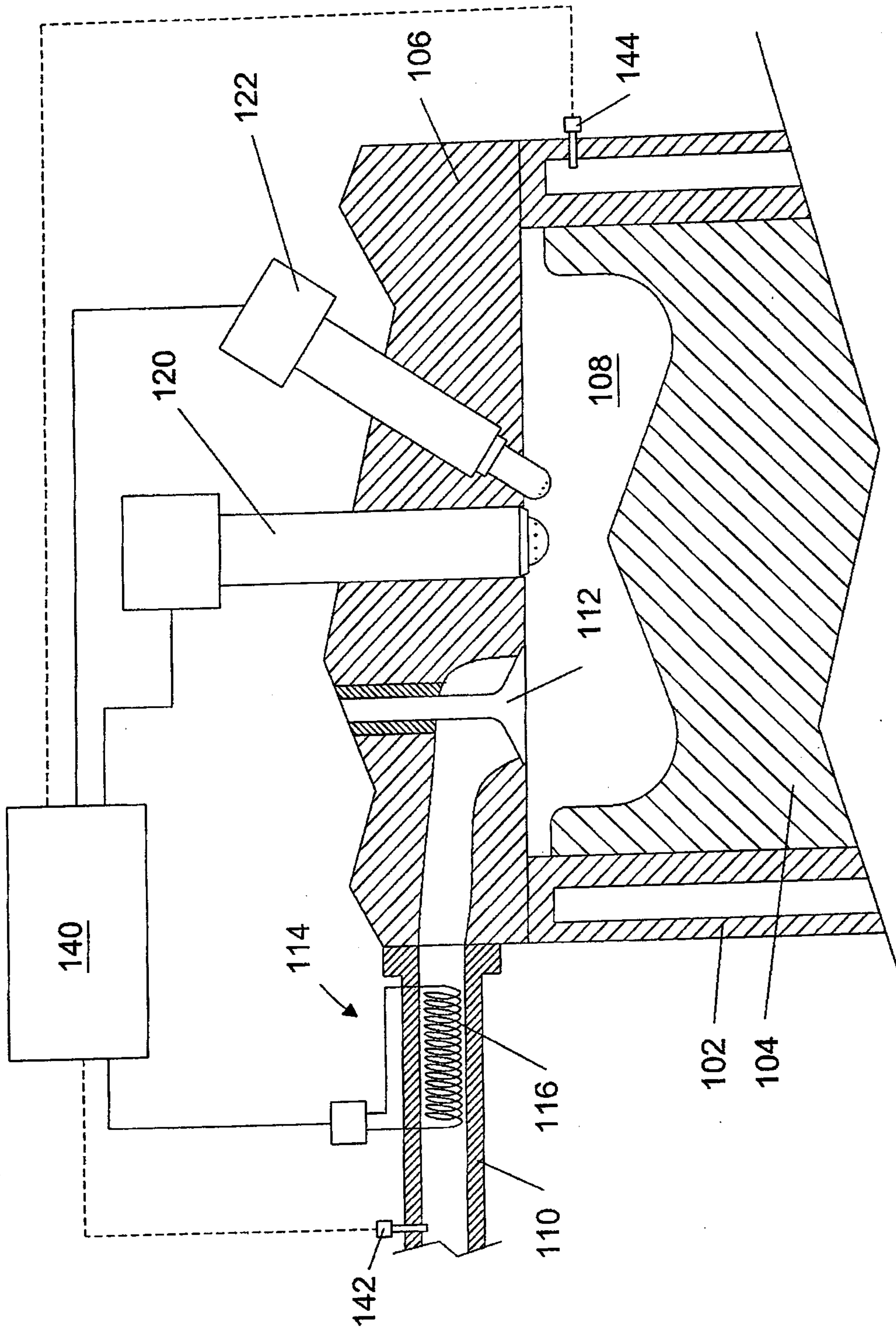


Fig. 1

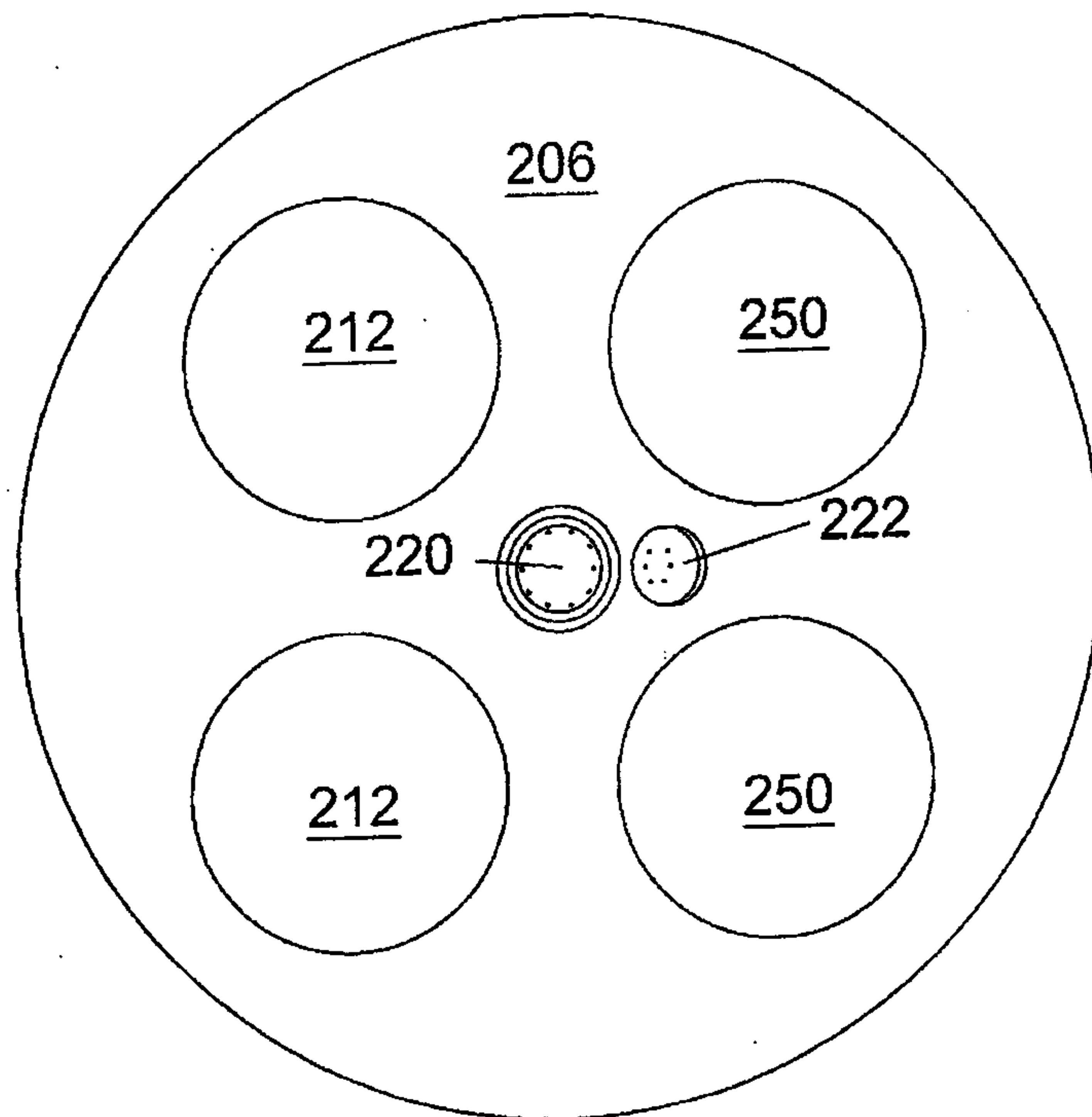


Fig. 2

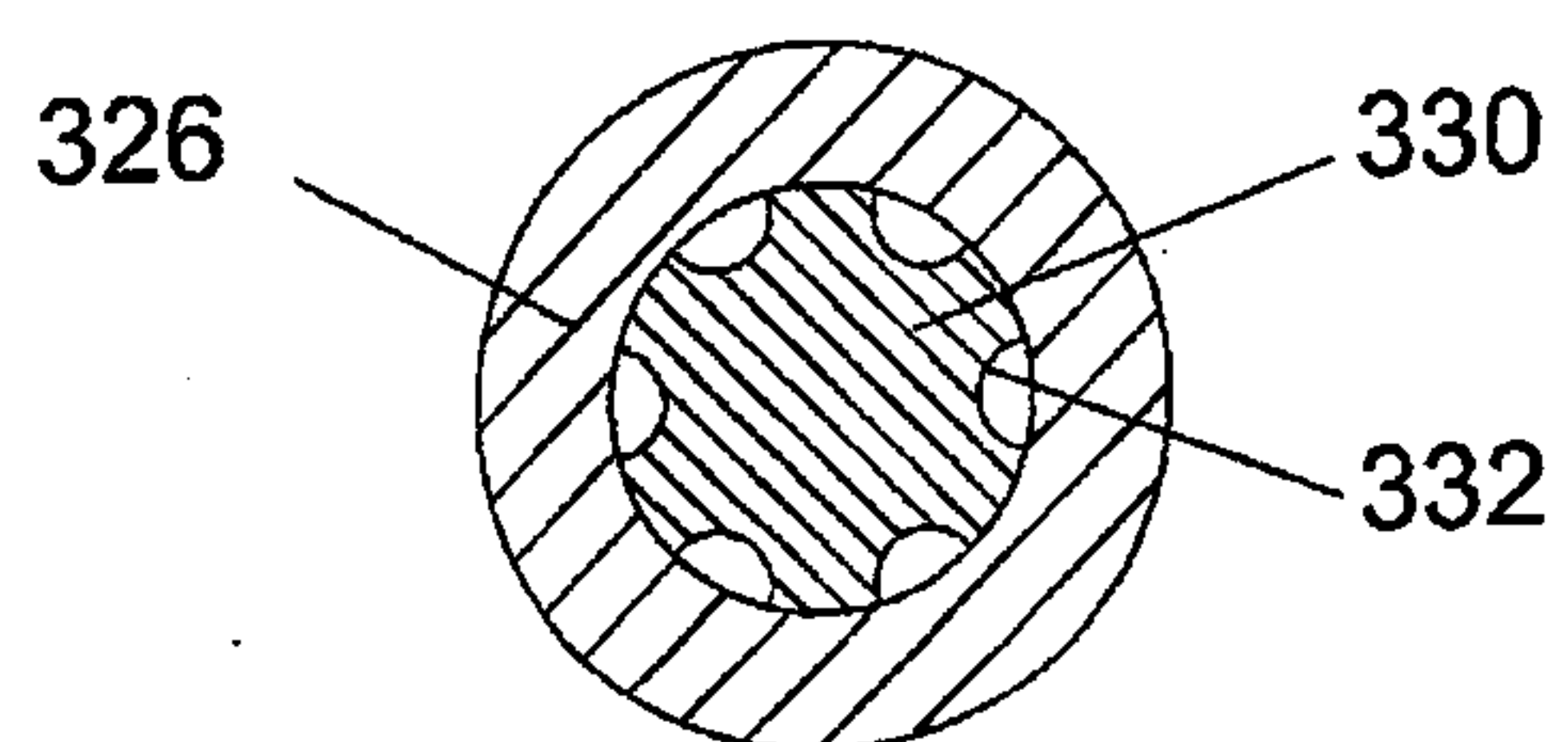


Fig. 3

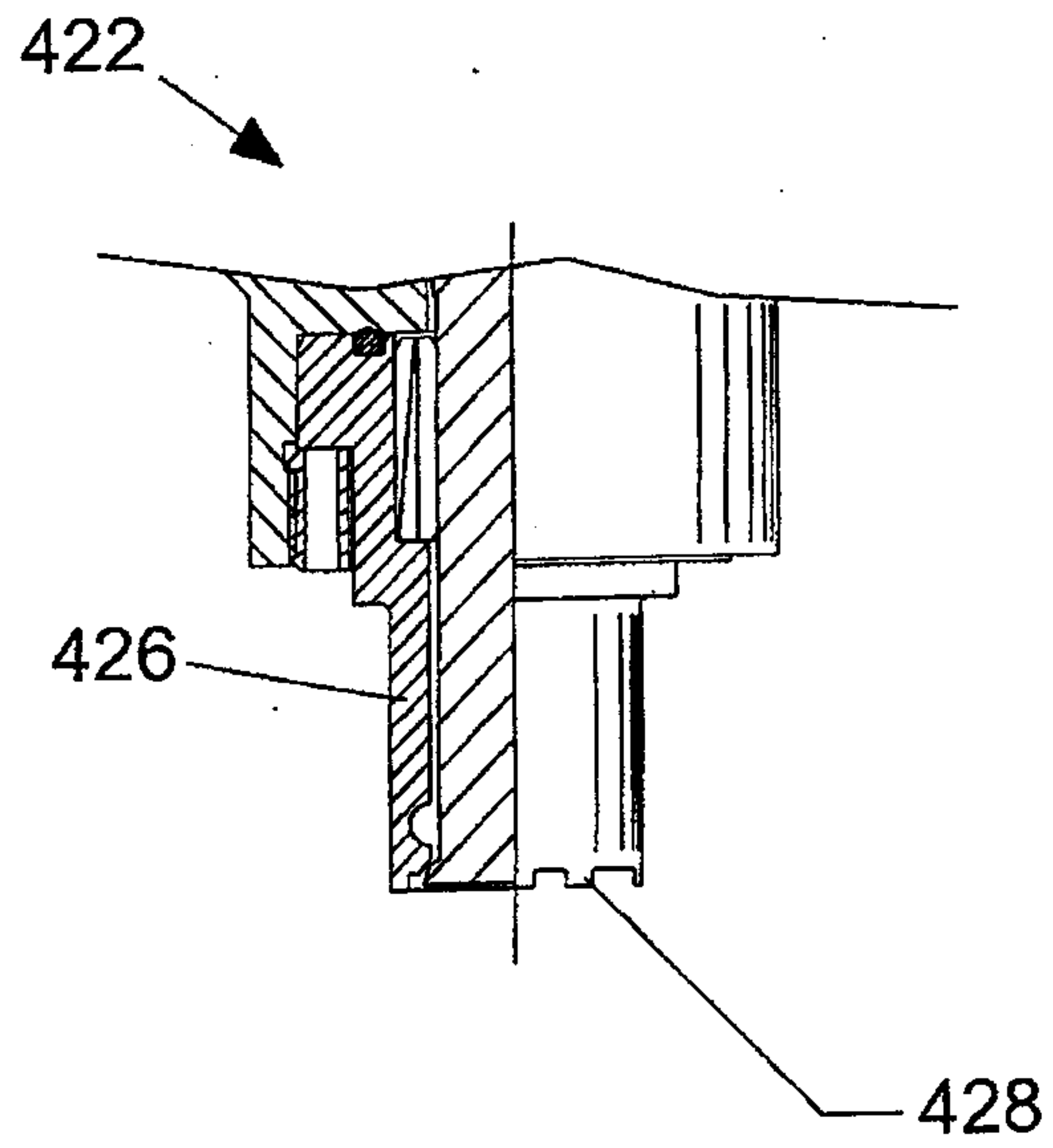


FIG. 4

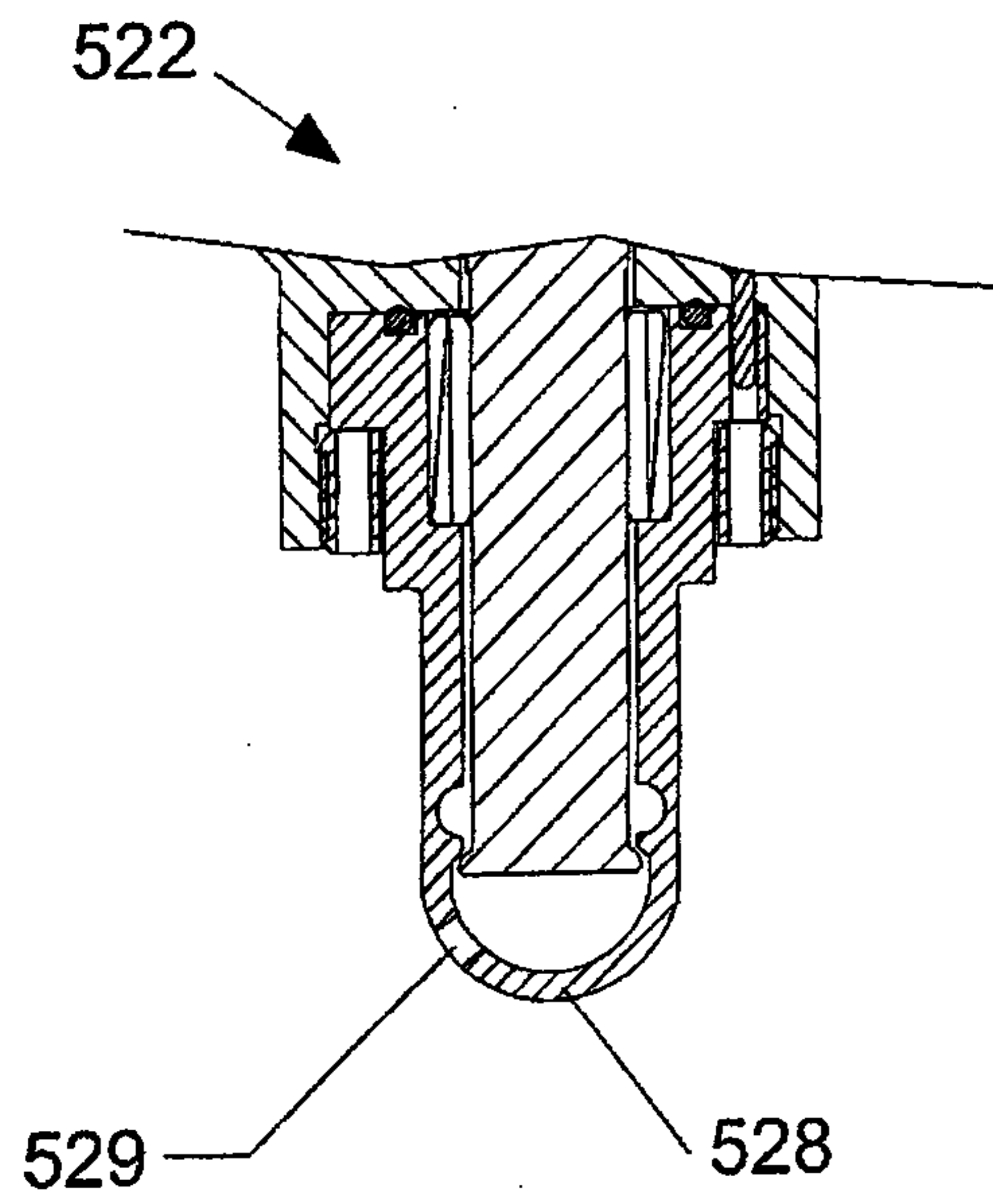


FIG. 5

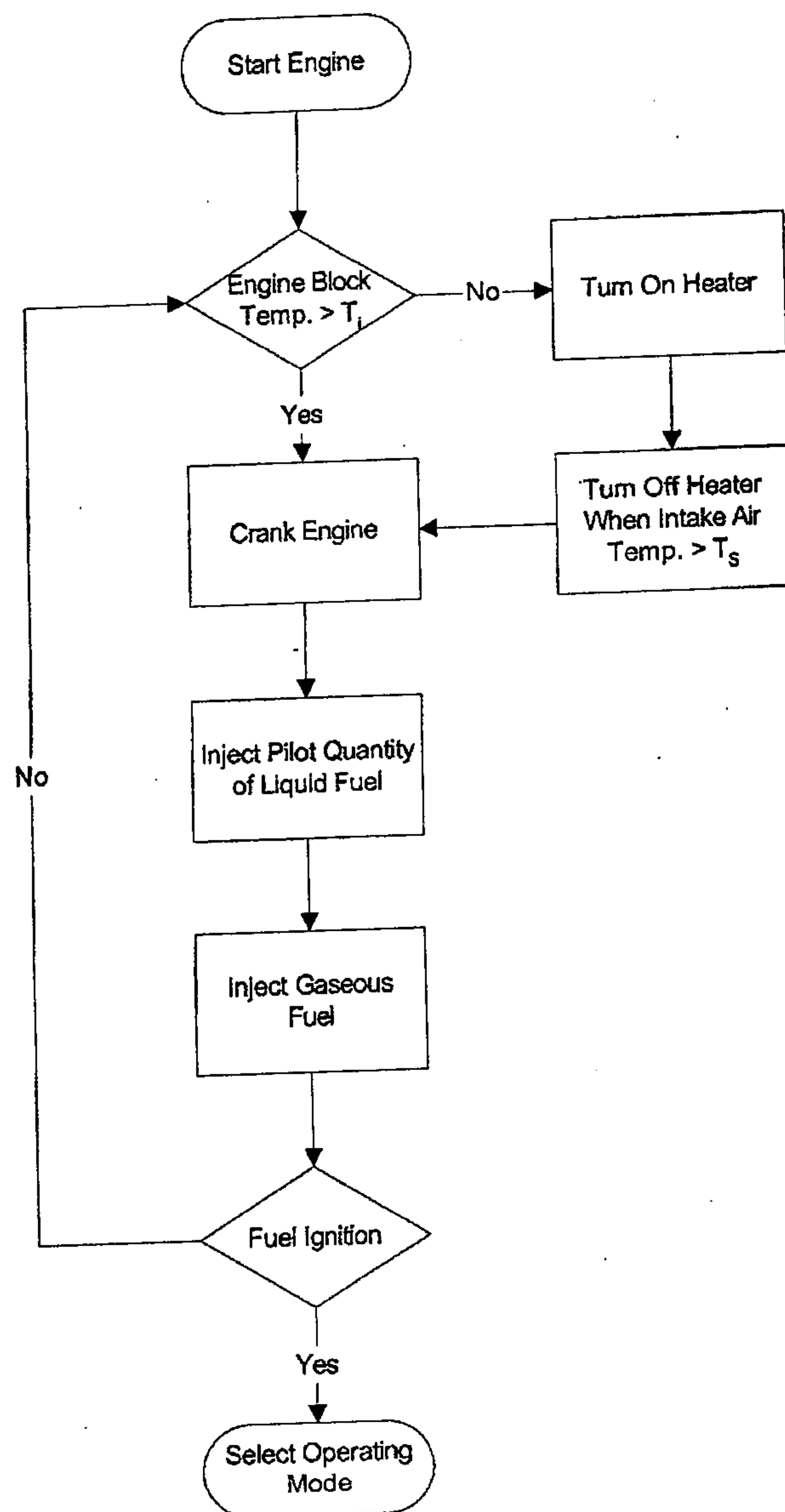


Figure 6

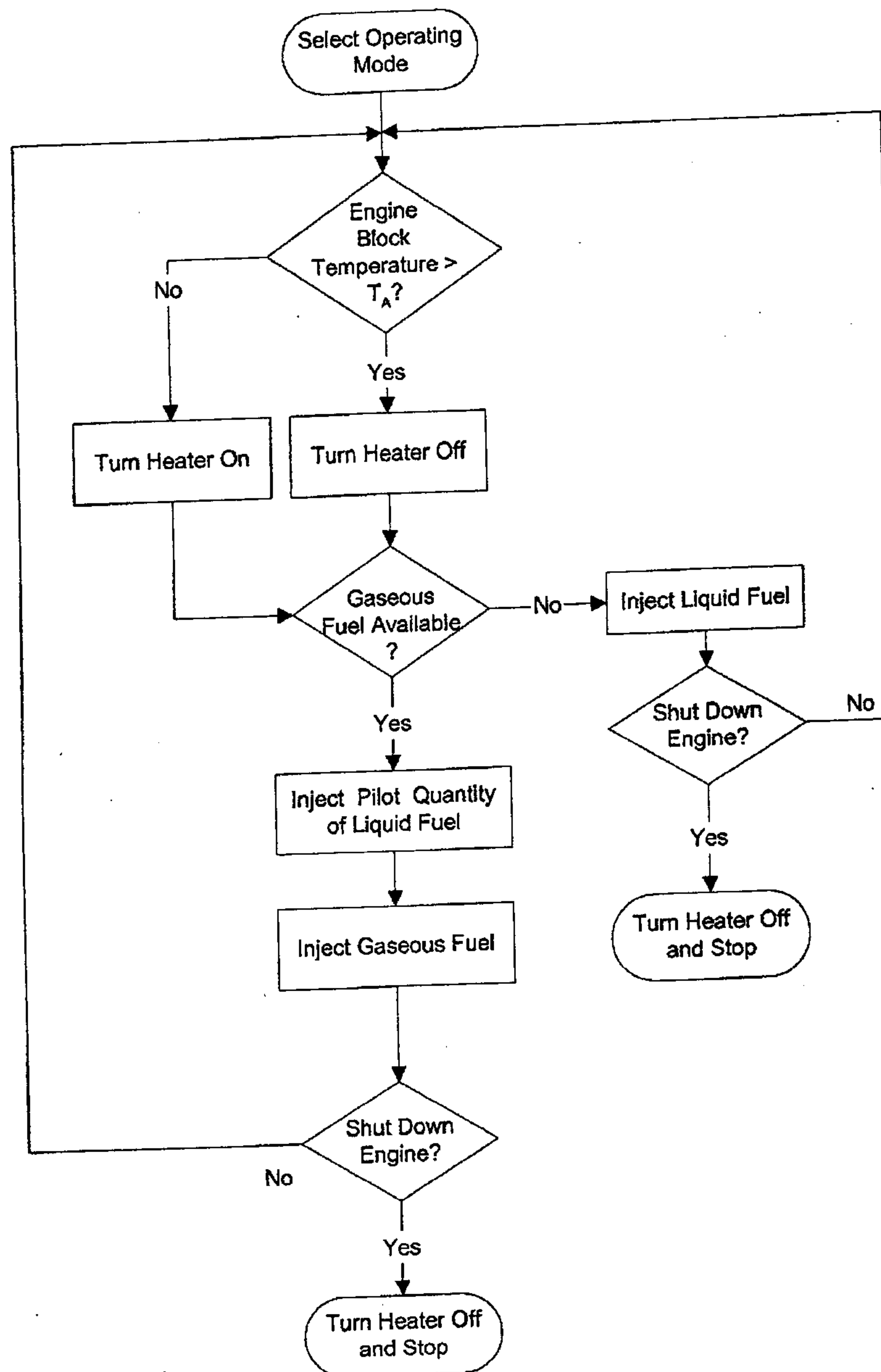


Figure 7

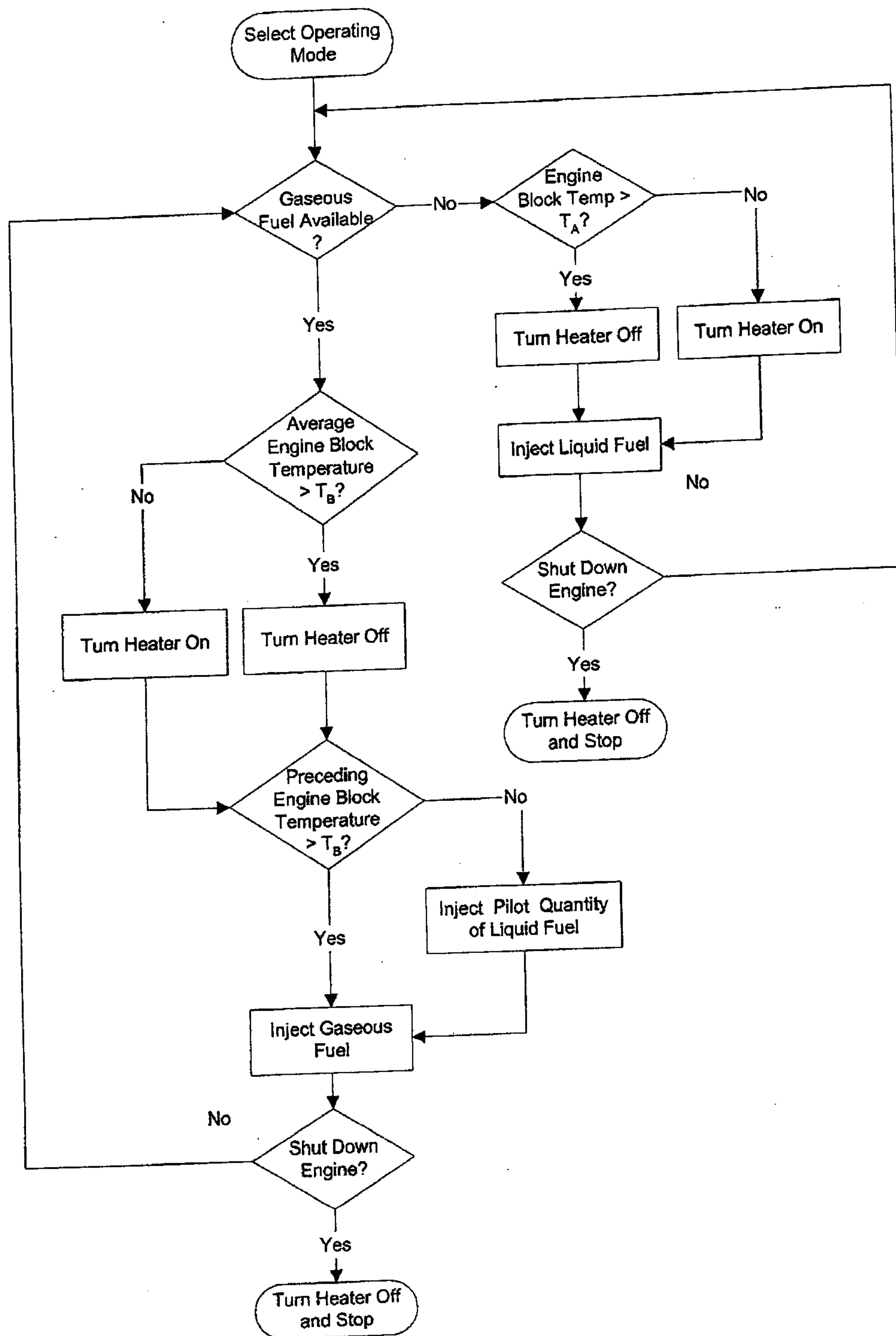


Figure 8

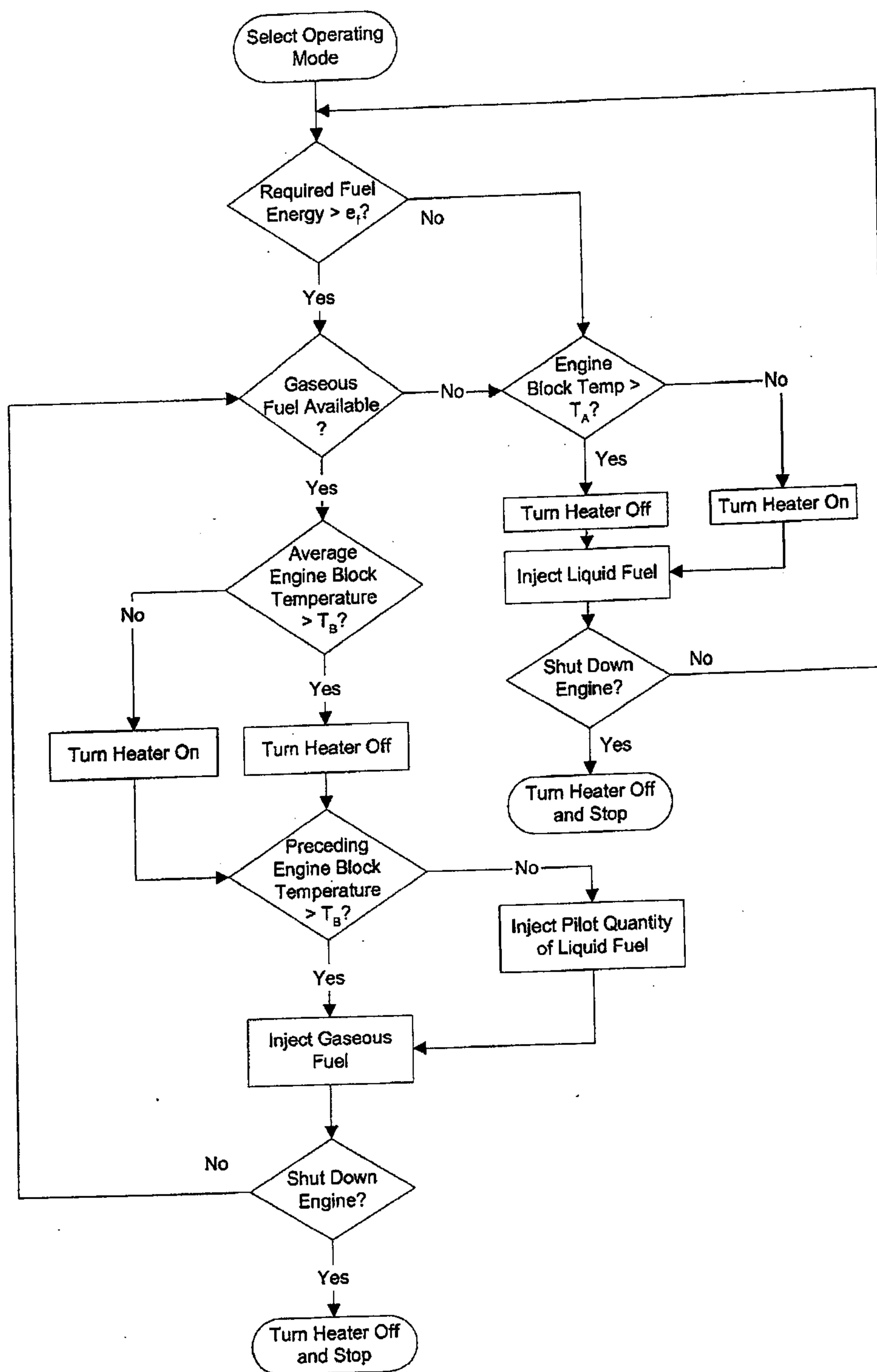


Figure 9

