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(54) **APPARATUS AND METHOD FOR FUELLING A FLEXIBLE-FUEL INTERNAL COMBUSTION ENGINE**

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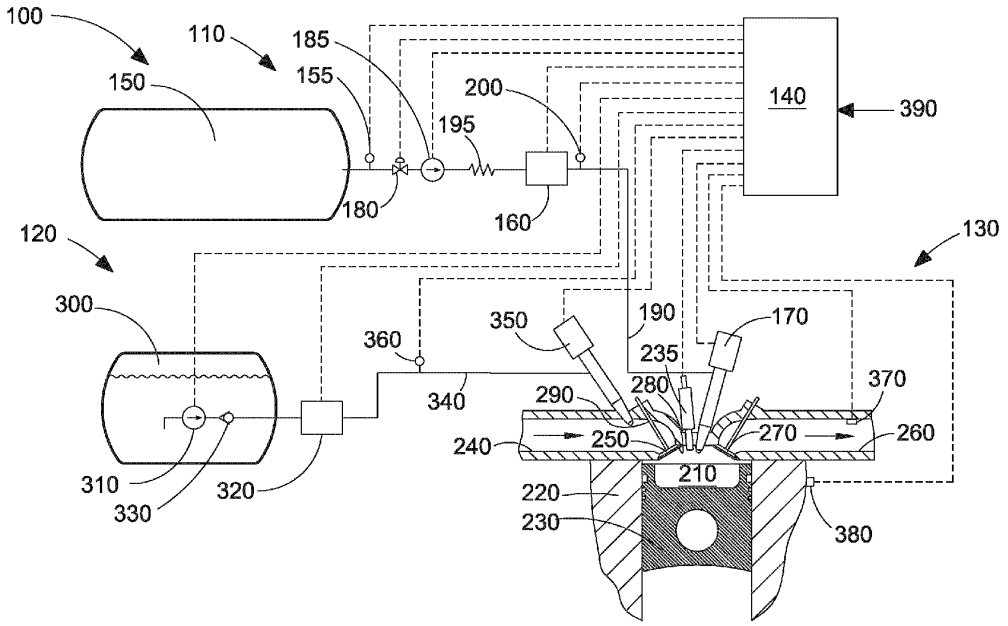
(57) **ABSTRACT**

A flexible-fuel internal combustion engine apparatus comprises a combustion chamber, an intake valve, a first fuel injector, a second fuel injector, and a computer. The intake valve is operable to admit an intake charge into the combustion chamber. The first fuel injector injects a gaseous fuel directly into the combustion chamber. The second fuel injector injects a liquid fuel into the intake charge upstream of the intake valve. The computer is operatively connected with the first fuel injector and the second fuel injector to actuate injection of fuel respectively therefrom. The computer is programmed to command a gaseous-to-liquid fuel ratio as a function of at least one operating parameter from a group comprising gaseous fuel pressure, gaseous fuel mass, engine speed, engine torque, inlet air temperature, inlet air humidity, knock detection, operating history, torque command, and emissions.



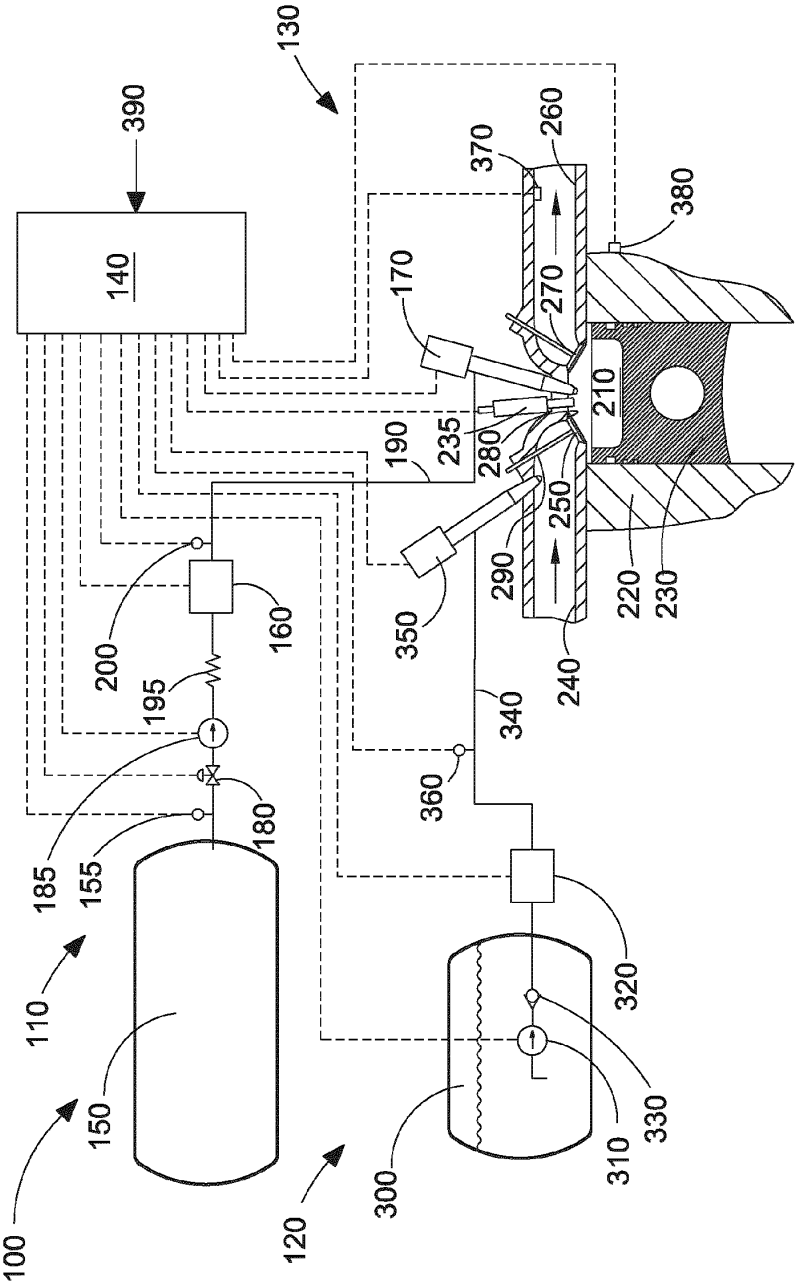

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FIG. 1

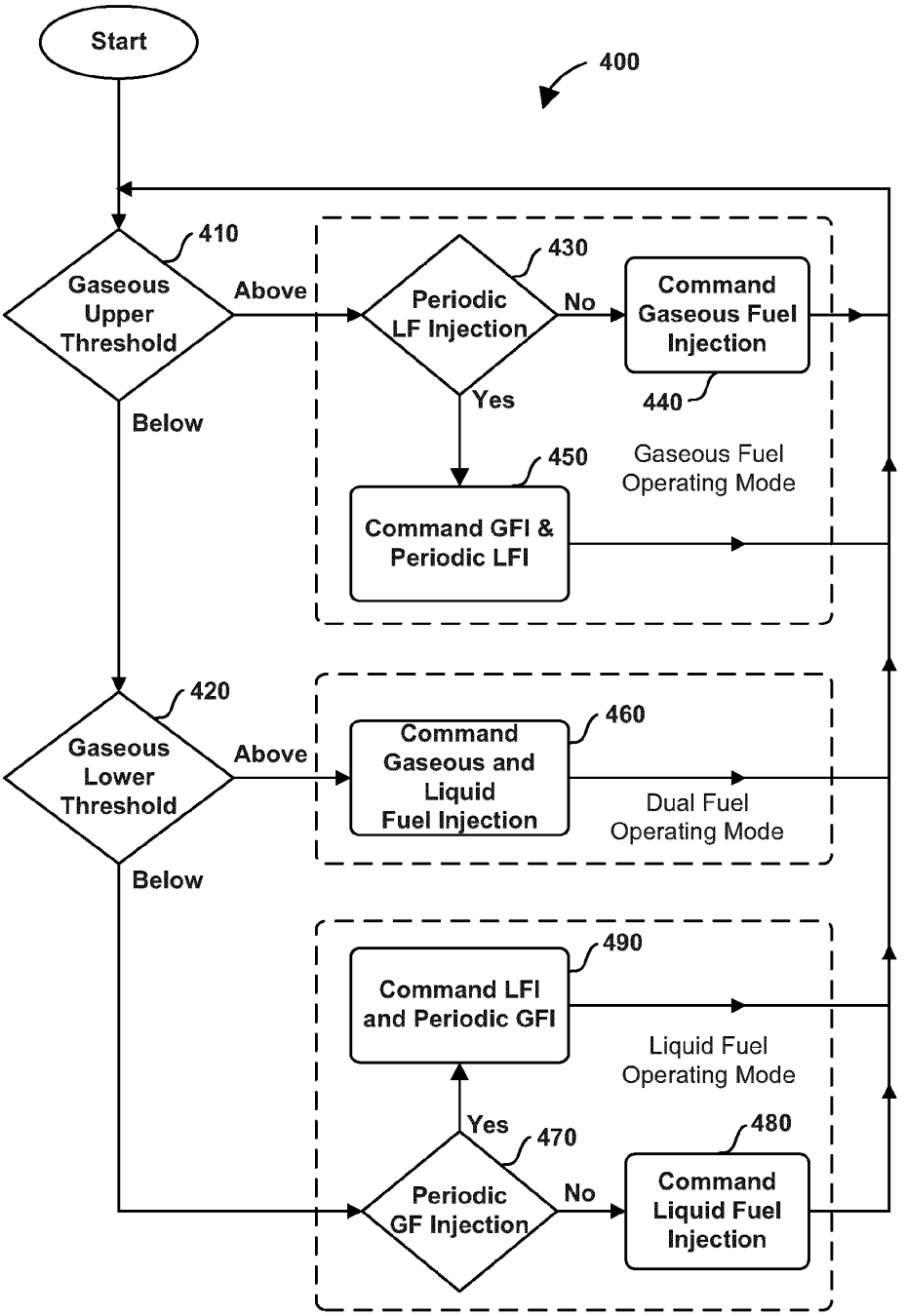
Start
400
410
Gaseous Upper Threshold
Above
Below
430
Periodic LF Injection
No
Yes
Command Gaseous Fuel Injection
440
450
Command GFI & Periodic LFI
Gaseous Fuel Operating Mode
420
Gaseous Lower Threshold
Above
Below
460
Command Gaseous and Liquid Fuel Injection
Dual Fuel Operating Mode
490
Command LFI and Periodic GFI
Liquid Fuel Operating Mode
Yes
470
Periodic GF Injection
No
480
Command Liquid Fuel Injection

FIG. 2

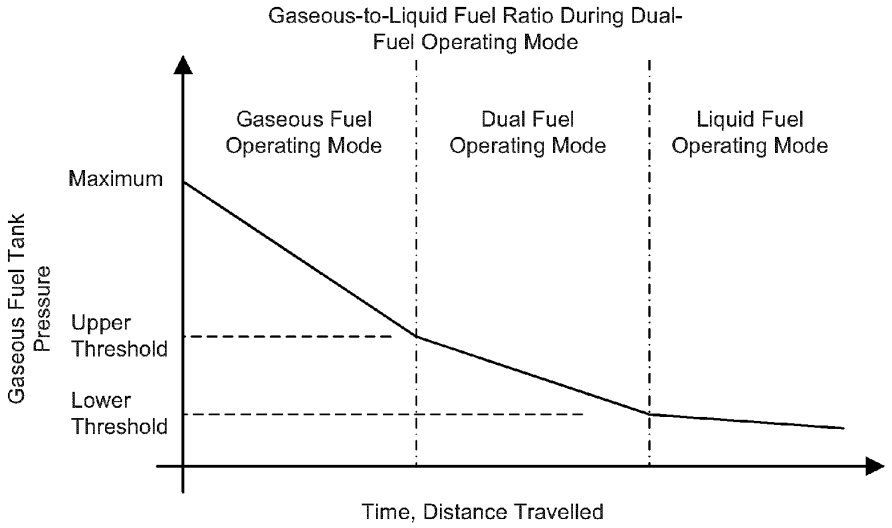
Gaseous-to-Liquid Fuel Ratio During Dual-Fuel Operating Mode
Gaseous Fuel Operating Mode
Dual Fuel Operating Mode
Liquid Fuel Operating Mode
Maximum
Upper Threshold
Lower Threshold
Gaseous Fuel Tank Pressure
Time, Distance Travelled

FIG. 3

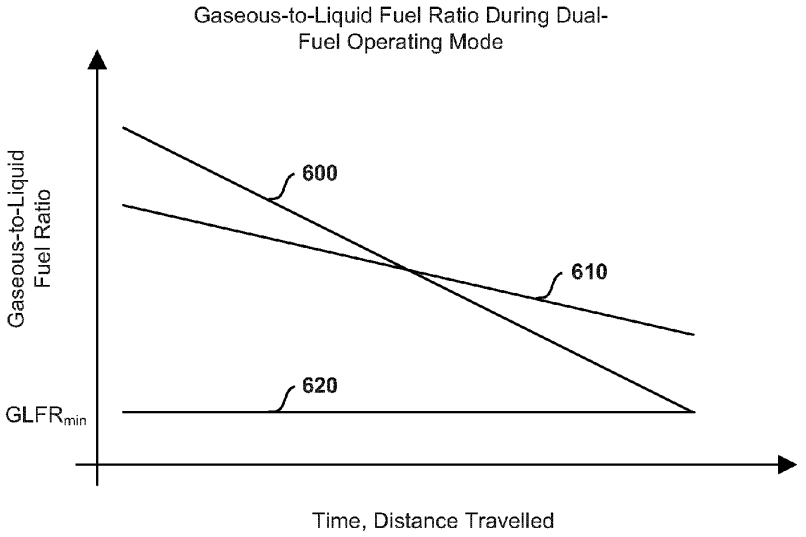
Gaseous-to-Liquid Fuel Ratio During Dual-Fuel Operating Mode
600
610
620
Gaseous-to-Liquid Fuel Ratio
GLFR$_{min}$
Time, Distance Travelled

FIG. 4

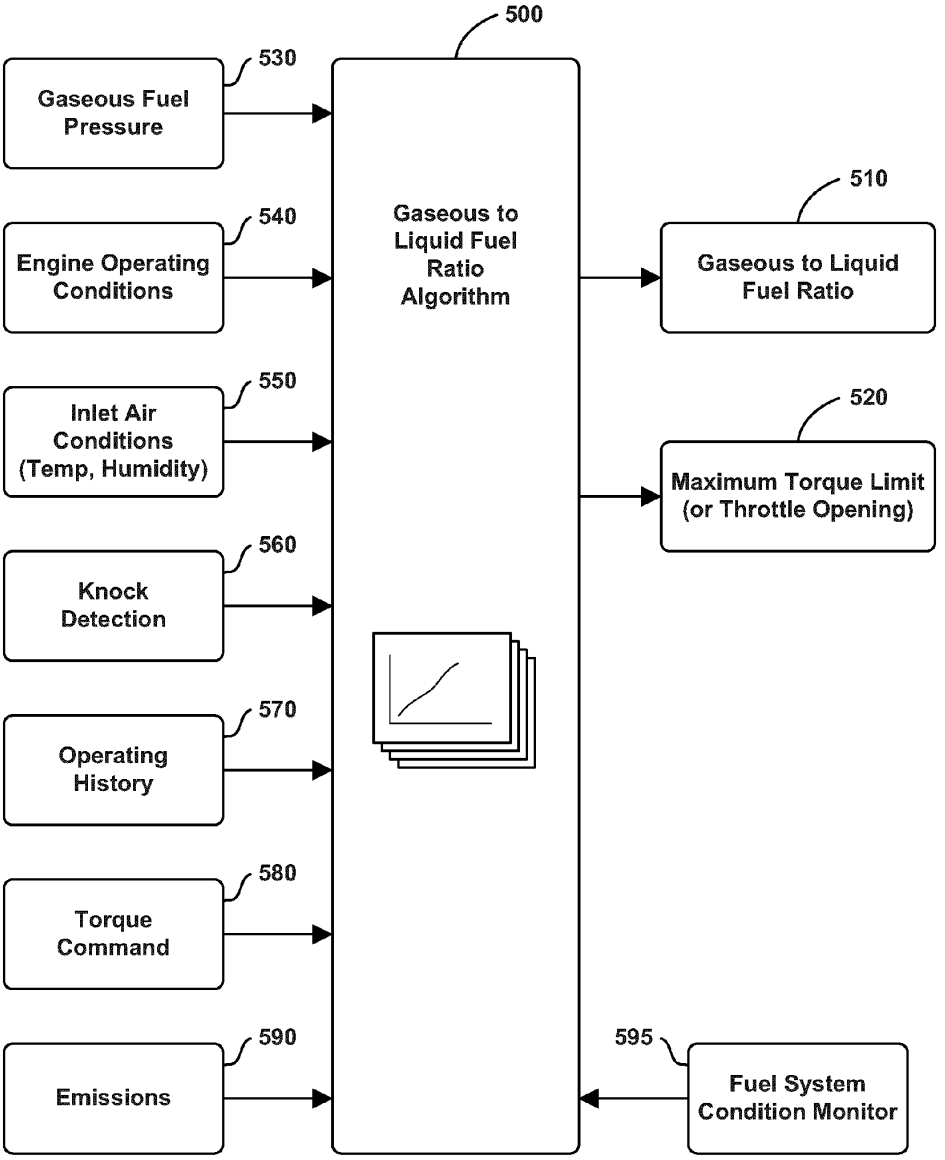
500
530
Gaseous Fuel Pressure
540
Engine Operating Conditions
550
Inlet Air Conditions (Temp, Humidity)
560
Knock Detection
570
Operating History
580
Torque Command
590
Emissions
Gaseous to Liquid Fuel Ratio Algorithm
510
Gaseous to Liquid Fuel Ratio
520
Maximum Torque Limit (or Throttle Opening)
595
Fuel System Condition Monitor

FIG. 5

APPARATUS AND METHOD FOR FUELLING A FLEXIBLE-FUEL INTERNAL COMBUSTION ENGINE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of International Application No. PCT/CA2012/050830 having an international filing date of Nov. 20, 2012 entitled "Method And Apparatus For Pumping Fuel To A Fuel Injection System". The '830 international application claimed priority benefits, in turn, from U.S. Provisional Patent Application Ser. No. 61/562,754 filed on Nov. 22, 2011. The '830 international application is hereby incorporated by reference herein in its entirety.

FIELD OF THE INVENTION

[0002] The present application relates to internal combustion engines and, in particular, to an apparatus and method for fuelling a flexible-fuel engine.

BACKGROUND OF THE INVENTION

[0003] Bi-fuel vehicles fuelled with a liquid fuel, such as gasoline or ethanol, as one fuel, and alternatively with a gaseous fuel, such as compressed natural gas (CNG) or liquefied petroleum gas (LPG), historically have had limited penetration into the consumer automobile market. More recently, growing market demand has led automobile original equipment manufacturers (OEMs) to invest more in developing bi-fuel vehicles as a product. Two major reasons influencing this trend include commodity prices and emissions standards.

[0004] Decisions for automobile purchases are directly affected by the relationship between the prices of crude oil versus natural gas. Manufacturers of automobiles are responsive to these decisions and accordingly are indirectly influenced by this relationship. That is, fuel costs influence how consumers will invest in automobiles that consume natural gas or fuels derived from crude oil, such as gasoline and diesel. Historically, the prices of crude oil and natural gas generally maintained a 10-to-1 relationship, so that one barrel of crude oil was priced at roughly 10 times one million British thermal units of natural gas. Energy parity is approximately a 6-to-1 ratio, implying that other barriers, such as infrastructure logistics, must be factored into the equation even though energy derived from crude is more expensive than natural gas. More recently, this relationship has increased by about 100% to a 20-to-1 ratio. Suddenly, consumers are more willing to consider alternative fuel vehicles, for example so called bi-fuel, dual fuel or multi-fuel type vehicles, in large part because of the much higher fuel costs associated with gasoline or diesel.

[0005] A dual fuel engine is defined herein to be an engine that can be fuelled with two different fuels at the same time, whereas a bi-fuel engine is defined herein to be an engine that can be fuelled with either one fuel or another fuel, and a flexible-fuel engine is defined herein to be an engine that operates either as a bi-fuel or a dual fuel engine. There is a need for a new and improved apparatus and method for delivering fuel to a combustion chamber of a flexible-fuel engine.

[0006] Emissions standards are regulatory requirements that set specific limits to the amount of pollutants that can be released into the environment from the operation of a motor vehicle. These standards specifically restrict emissions of carbon monoxide (CO), oxides of nitrogen (NO_X), particulate matter (PM), formaldehyde (HCHO), and non-methane organic gases (NMOG) or non-methane hydrocarbons (NMHC). The limits are typically defined in grams per kilometer (g/km). Since the introduction of catalytic converters and the corresponding phase-out of leaded gasoline in most of the world, great improvements have been made towards reducing pollution derived from automobiles. Over time, and with technology advances, emissions standards become increasingly more stringent. For example, in the United States an automobile manufacturer's combined fuel economy for their entire fleet must now meet average targets, and more recently these targets include greenhouse gas emissions. In order to meet new regulatory requirements improvements were sought in engine control system technologies and in the catalytic converters that reduce harmful by-products from combustion of liquid fuels. However, as standards for emissions are continually becoming more stringent, manufacturers are finding it more difficult to meet these standards with catalytic converters alone, or with changes to well established engine control systems.

[0007] Natural gas is the cleanest of all the broadly available fossil fuels. The main products of the combustion of natural gas are carbon dioxide and water vapor. Gasoline is composed of more complex molecules, with a higher carbon ratio and higher nitrogen and sulfur contents. As gasoline is combusted there are higher levels of carbon emissions, nitrogen oxides (NO_X), sulfur dioxide (SO_2) and particulate matter (soot) compared to the by-products of natural gas combustion.

[0008] Improvements in emissions are obtained if a vehicle is fuelled at least some of the time with natural gas. Automobile manufacturers are now considering alternative fuel vehicles, and especially bi-fuel vehicles fuelled with natural gas as one fuel or gasoline as another fuel, as a means for meeting current and future emissions standards, as emission reductions achieved by catalytic converters are approaching the current paradigm limit and further improvements in such converters are more difficult to obtain. The present-day fuelling infrastructure for natural gas is not as well developed as that for gasoline and diesel, so bi-fuel vehicles allow operation in areas where an operator might be at risk of running out of fuel if natural gas were the only fuel the vehicle could use.

[0009] After-market bi-fuel vehicles have been in use for some time. Conventionally, standard gasoline vehicles are retrofitted in specialized shops, which involve installing compressed natural gas (CNG) cylinders in the trunk to serve as fuel tanks and the installation of an injection system and electronics on the engine. The performance and emissions of these vehicles are less than optimal due to a limited cooperation between the original engine system and the aftermarket system. Gasoline vehicles converted to run on natural gas suffer a performance penalty due to the low compression ratio of the gasoline engines, resulting in a reduction of delivered power (10%-15%) while running on natural gas. Such bi-fuel vehicles are optimized to operate with gasoline and are typically less efficient when fuelled with natural gas.

[0010] After market dual-fuel vehicles conventionally employed a fumigation conversion kit or an injection conversion kit. Prior to on board vehicle computers, for example on-board diagnostics (OBD) systems, fumigation conversion kits were used with a mixer and a regulator for non-injection systems. With the introduction of fuel injection and on board

diagnostics into standard vehicles, conversion kits evolved into port injection techniques that interoperate, though in a limited fashion, with the original vehicle manufacturers' fuelling strategy and sensor system checks. Again, both conversion techniques were sub-optimal solutions due to limited cooperation between the original engine system and the conversion kit, the compression ratios employed, and due to performance limitations inherent in low pressure natural gas introduction through the intake valve.

[0011] The introduction of gasoline into cylinders for combustion has progressed due to advances in technology from being blended with air in a carburetor to being port injected into intake ports, both methods by which gasoline is introduced into the combustion chambers as part of the intake charge. The latest development has been injecting gasoline directly into the cylinders. Direct injection pressures are very high, for example 30,000 pounds per square inch (psi) (206,842.7 kilopascals (kPa)), in order to overcome in-cylinder pressure and to atomize the gasoline as it is injected to improve combustion efficiency. Gasoline being a liquid fuel is an incompressible fluid and is easily and quickly pressurized to the required pressure for direct injection. Because of the relatively high pressure differential between fuel rail pressure and in-cylinder pressure, the fuel flow rate is controllable and predictable. By controlling the amount of fuel delivered to the cylinder the amount of power created from combustion can also be controlled. Higher compression ratios are allowed in direct injection engines with less danger of knocking, defined as the premature ignition of fuel in the combustion chamber. Direct injection also means that the fuel does not displace air from the intake charge drawn into the combustion chamber through the intake ports.

[0012] Since gaseous fuels like natural gas are compressible fluids it is more difficult to manage higher injection pressures and there is an energy penalty associated with compressing gaseous fuels to higher pressures. Accordingly, conventional gaseous fuel systems have favored relatively low pressure injection systems. For example, an injection pressure in the range of 30 to 300 psi (206.8 to 2,068.4 kPa) involves fewer technical challenges than injection at high pressure and is adequate for injection into the intake air stream. After market systems typically employ low pressure port injection strategies for natural gas in dual-fuel and bi-fuel vehicles. However, because the fuel is pre-mixed with the intake air, natural gas spark ignition engines operate at modest compression ratios in the range of 9:1 to 12:1, in order to prevent engine knock, which can cause serious engine damage. Compared to engines with higher compression ratios, these engines operate at lower brake mean effective pressure (BMEP) and peak pressure levels.

[0013] High pressure direct injection of natural gas, that is, injection beginning late in the compression stroke, for example 20° before and after top dead center, involves greater technical challenges in the fuelling system. For engines operating with this architecture, the natural gas fuel rail pressure is on the order of 3,000 psi (20,684.3 kPa). This pressure is not as high as liquid fuels because there is no need to atomize a gaseous fuel, but the pressure still needs to be high enough to overcome the in-cylinder pressure and to allow fuel flow rates high enough to inject the required amount of fuel in the time available. However, even at this relatively low injection pressure, compared to liquid fuels, there is still a significant energy penalty for pressurizing the fuel and there is a significant capital cost associated with equipment needed to raise the gaseous fuel pressure. The high pressure equipment includes fuel compressors and fuel injectors. Designing high pressure, natural gas fuel injectors that inject a precise quantity of fuel into the combustion chamber has technical challenges not associated with low pressure, natural gas injection. The high pressure injection window for natural gas is typically smaller than in low pressure injection. It is known that as the on-time of the injector is decreased ballistic mode effects in the injector can decrease the accuracy of the quantity of fuel delivered. These factors are no deterrent for large heavy duty vehicles that use a lot of fuel and that require higher efficiency and higher torque. However, these same factors can deter the acceptance of this technology for light duty vehicles which consume less fuel and have lower power requirements.

[0014] Bi-fuel vehicles have traditionally been gasoline fuelled vehicles adapted to be capable of being fuelled with a different fuel. This has resulted in the most current gasoline fuel systems being combined with a gaseous fuel system. Now that the latest designs for gasoline engines use injectors to inject gasoline directly into the combustion chamber the problem to be solved has been designing a complementary fuel system for operation using another fuel, like natural gas. A typical solution would be to add the natural gas upstream of the combustion chamber, for example using port injectors. However, when combining conventional direct-injection gasoline injectors and either port or direct injectors of natural gas in bi-fuel vehicles, under normal operating conditions, the gasoline injectors are subjected to intense heat. When operating with gasoline, the gasoline fuel injectors are cooled, in part, by liquid fuel running through them. This cooling does not happen when operating in CNG mode for extended periods of time. Then, the uncooled gasoline injectors heat up and can become damaged. Additionally, liquid fuel held inside the charged injectors begins to form deposits which tend to restrict the flow of fuel, with this adversely affecting injector behavior. The longer CNG mode continues with dormant gasoline injectors the greater the risk for accumulation and hardening of deposits inside the gasoline injector.

[0015] U.S. Pat. No. 7,832,381, issued Nov. 16, 2010 to Pott et al., discloses a method of operating an internal combustion engine of a motor vehicle, that selectively uses gasoline or ethanol by direct injection into combustion chambers, and optionally instead of or in addition to injection of gasoline or ethanol the internal combustion engine is operated with a gaseous fuel, for example compressed natural gas (CNG) or liquefied petroleum gas (LPG) which is introduced with the intake air. Pott et al. teach that fouling of direct-injection gasoline injectors in CNG gas mode is monitored by this method and damage to the gasoline injectors is avoided by means of periodic changeovers to gasoline mode of operation, so that the flow of gasoline through the injectors acts to keep them cool. This method results in greater use of gasoline in order to maintain the integrity of the gasoline injectors, which increases emissions of pollutants from combustion and which can lead to greater fuel costs and more frequent trips to fuelling stations in order to maintain the fuel available in multiple fuel tanks.

[0016] European Patent Publication No. EP 2,009,277A1, published on Dec. 31, 2008 for Mats Morén, discloses an engine system with injection of a liquid fuel directly into the combustion chamber through liquid fuel injectors, and gaseous fuel injectors arranged to inject gaseous fuel into the intake port of the engine. Further, the engine system com-

prises means to selectively inhibit supply of the liquid fuel to the liquid fuel injectors. The gaseous fuel supply system is arranged to communicate with the liquid fuel injectors through inter-fuel system conduits, fuel pressure sensors and fuel conduit shut-off valves so that the gaseous fuel can be temporarily directed to the liquid fuel injectors in order to purge remaining liquid fuel therefrom during switchover to a gaseous fuel mode of operation.

[0017] The present apparatus and method provide improved delivery of fuel to a flexible-fuel internal combustion engine.

SUMMARY OF THE INVENTION

[0018] An improved apparatus delivers two fuels to a combustion chamber of an internal combustion engine. The apparatus comprises a first fuel system, a second fuel system, a first fuel injector, a second fuel injector and a computer. The first fuel system comprises a first fuel supply and a first fuel pressure regulator operatively connected with the first fuel supply. The first fuel supply is a source of gaseous fuel. The first fuel injector is disposed to directly inject the gaseous fuel into the combustion chamber and is operatively connected with the first fuel pressure regulator. The second fuel system comprises a second fuel supply, a fuel pump operatively connected with the second fuel supply and a second fuel pressure regulator operatively connected with the fuel pump. The second fuel supply is a source of a liquid fuel. The second fuel injector is disposed to inject the liquid fuel upstream of an intake valve operative to admit an intake charge into the combustion chamber. The second fuel injector is operatively connected with the second fuel pressure regulator. The computer is operatively connected with the first fuel injector and the second fuel injector to actuate injection of fuel therefrom. The computer is programmed to command a gaseous-to-liquid fuel ratio as a function of inputs comprising at least one of gaseous fuel storage pressure, gaseous fuel injection pressure, gaseous fuel mass, engine speed, engine torque, inlet air temperature, inlet air humidity, intake air manifold pressure, intake air mass, knock detection, operating history, torque command, and emissions.

[0019] In preferred embodiments, the gaseous fuel is natural gas or methane, and the liquid fuel is gasoline or ethanol gasoline blends. The first fuel pressure regulator can be a single-step regulator, a continuously variable regulator or a multi-step regulator. The first fuel pressure regulator regulates the gaseous-fuel injection pressure between 10 bar and 300 bar, and preferably between 10 bar and 40 bar and more preferably between 10 bar and 20 bar. The second fuel pressure regulator regulates the liquid-fuel injection pressure between 2 bar and 10 bar, and preferably between 2 bar and 6 bar. In some embodiments the internal combustion engine can be shut-off after idling for a predetermined idle-time threshold. The first fuel injector can be actuated to introduce a stratified fuel charge in the combustion chamber during cold-start of the internal combustion engine such that emissions are reduced and stability is improved.

[0020] In preferred embodiments, the computer is programmed to select one of a gaseous-fuel operating mode or a liquid-fuel operating mode, to selectively actuate the first fuel injector to inject the gaseous fuel during the gaseous-fuel operating mode, and to selectively actuate the second fuel injector to inject the liquid fuel during the liquid-fuel operating mode. The gaseous fuel is injected no less than 40°, and preferably no less than 60°, before top dead center during a compression stroke associated with the combustion chamber during the gaseous fuel operating mode. The gaseous-to-liquid fuel ratio is mathematically undefined during the gaseous-fuel operating mode and is zero during the liquid-fuel operating mode. The gaseous-fuel operating mode or the liquid-fuel operating mode can be selected as a function of inputs comprising at least one of gaseous-fuel storage pressure, gaseous-fuel mass, liquefied gaseous-fuel level, liquefied gaseous-fuel volume, liquefied gaseous-fuel mass and gaseous-fuel injection pressure. During high load conditions the first fuel injector is actuated after the intake valve closes during a compression stroke associated with the combustion chamber. During partial load and high speed operation the first fuel injector can be selectively actuated to start injecting gaseous fuel while the intake valve is open. When a predetermined condition is detected during the gaseous-fuel operating mode the computer is further programmed to define the gaseous-to-liquid fuel ratio and to selectively actuate the second fuel injector. The predetermined condition is at least one of a lubricate-time threshold, a cool-time threshold, a clean-time threshold or a liquid-fuel-cycle-time threshold, and the predetermined condition is detected when at least one of the claimed thresholds is met or exceeded. The computer is further programmed to selectively actuate the second fuel injector during the gaseous-fuel operating mode as a function of inputs comprising at least one of average crank rotational speed, gaseous fuel consumed, average torque, inlet temperature, mass air flow, engine temperature, coolant temperature and time since the second fuel supply was filled. When a predetermined condition is detected during the liquid-fuel operating mode the computer is further programmed to command a gaseous-to-liquid fuel ratio greater than zero and to selectively actuate the first fuel injector. When the predetermined condition is a threshold level of engine knock, the apparatus further comprises an engine knock sensor. The computer is responsive to an output of the engine knock sensor to selectively actuate the first fuel injector during the liquid-fuel operating mode when the output meets or exceeds the threshold level of engine knock.

[0021] When the predetermined condition is a threshold level of emissions, the apparatus further comprises an emissions sensor. The computer is programmed responsive to an output of the emissions sensor to selectively actuate the first fuel injector during the liquid-fuel operating mode when the output meets or exceeds the threshold level of emissions. In preferred embodiments, the computer can select a dual-fuel operating mode and selectively actuate the first and second fuel injectors during the dual-fuel operating mode. The gaseous-to-liquid fuel ratio is mathematically defined and greater than zero during the dual-fuel operating mode.

[0022] An improved internal combustion engine apparatus comprises a combustion chamber; an intake valve operable to admit an intake charge into the combustion chamber; a first fuel injector disposed to inject a gaseous fuel directly into the combustion chamber; a second fuel injector disposed to inject a liquid fuel into the intake charge upstream of the intake valve; and a computer operatively connected with the first fuel injector and the second fuel injector to actuate injection of fuel respectively therefrom. The computer is programmed to command a gaseous to liquid fuel ratio as a function of inputs comprising at least one of gaseous fuel storage pressure, gaseous fuel injection pressure, gaseous fuel mass,

engine speed, engine torque, inlet air temperature, inlet air humidity, knock detection, operating history, torque command, and emissions.

[0023] An improved method of delivering two fuels to a combustion chamber of an internal combustion engine comprises:

[0024] commanding a gaseous-to-liquid fuel ratio as a function of inputs comprising at least one of gaseous fuel storage pressure, gaseous fuel injection pressure, gaseous fuel mass, engine speed, engine torque, inlet air temperature, inlet air humidity, knock detection, operating history, torque command, and emissions;

[0025] injecting a gaseous fuel directly into the combustion chamber as a function of the gaseous-to-liquid fuel ratio; and

[0026] injecting a liquid fuel upstream of an intake valve as a function of the gaseous-to-liquid fuel ratio.

[0027] In preferred embodiments, the method further comprises selecting one of a gaseous-fuel operating mode or a liquid-fuel operating mode; injecting the gaseous fuel directly into the combustion chamber during the gaseous-fuel operating mode; and injecting the liquid fuel upstream of an intake valve into an intake charge during the liquid-fuel operating mode. The gaseous-to-liquid fuel ratio is mathematically undefined during the gaseous-fuel operating mode and is zero during the liquid-fuel operating mode. The gaseous fuel is injected not less than 40°, and preferably not less than 60°, before top dead center during a compression stroke associated with the combustion chamber. In still further preferred embodiments the method further comprises selecting a dual-fuel operating mode, the gaseous-to-liquid fuel ratio is mathematically defined and greater than zero during the dual-fuel operating mode; injecting the gaseous fuel directly into the combustion chamber during the dual-fuel operating mode; and injecting the liquid fuel upstream of an intake valve into an intake charge during the dual-fuel operating mode. The gaseous-to-liquid fuel ratio can decrease during the dual-fuel operating mode as a pressure of the gaseous-fuel decreases such that operation on gaseous-fuel is extended. During the dual-fuel operating mode the gaseous-to-liquid fuel ratio is preferably selected to maintain emissions below an acceptable level.

BRIEF DESCRIPTION OF THE DRAWINGS

[0028] FIG. **1** is a schematic view of a gaseous fuel direct injection and liquid fuel port injection engine.

[0029] FIG. **2** is a flow chart of an operating mode selection algorithm for the engine of FIG. **1**.

[0030] FIG. **3** is a chart of gaseous fuel tank pressure versus time or distance travelled for the engine of FIG. **1**.

[0031] FIG. **4** is a chart of gaseous-to-liquid fuel ratio versus time or distance travelled.

[0032] FIG. **5** is a schematic view of a gaseous-to-liquid fuel ratio algorithm comprising measured parameter inputs and control outputs for the engine of FIG. **1**.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENT(S)

[0033] Referring to the schematic view of FIG. **1**, there is shown an apparatus **100** for fuelling an internal combustion engine with a gaseous fuel and/or a liquid fuel, the manner by which will now be described. Apparatus **100** includes a direct-injection fuel system **110**, a port-injection fuel system **120**, an engine **130** and an electronic controller **140**. Only a cross-section showing the combustion chamber of one engine cylinder is shown but those familiar with the technology involved here will understand that the engine comprises other components and typically a plurality of cylinders. Engine **130** can be for a vehicle, and can also be employed in marine, locomotive, mine haul, power generation or stationary applications. Electronic controller **140** communicates with and commands both direct-injection fuel system **110** and port-injection fuel system **120** to deliver fuel for combustion in engine **130**. In the present example, electronic controller **140** is a computer comprising a processor and memories, including a permanent memory, such as FLASH or EEPROM, and a temporary memory, such as SRAM or DRAM, for storing and executing a program. In a preferred embodiment electronic controller **140** is an engine control unit (ECU) of engine **130**.

[0034] Direct-injection fuel system **110** comprises storage vessel **150**, which is made to store the gaseous fuel. The gaseous fuel can be compressed natural gas, methane, hydrogen or other fuels that are in a gaseous phase at room temperature and atmospheric pressure. In the illustrated embodiment, the gaseous fuel can be stored in storage vessel **150**, which is rated to store the gaseous fuel at a predetermined storage pressure, and in the present example the gaseous fuel can be stored up to a pressure of 700 bar. Pressure sensor **155** measures the pressure of the gaseous fuel in vessel **150**, which decreases as the gaseous fuel therein is consumed by engine **130**. Storage vessel **150** is designed to comply with local regulations which can specify safety factors for ensuring containment of the gaseous fuel even in the event of impact, for example if storage vessel **150** is a vehicular fuel tank that could be involved in a vehicle collision. In addition to safety factors and design strength requirements, local regulations typically impose a maximum storage pressure. In other embodiments, storage vessel **150** can be a cryogenic storage vessel holding a multiphase fluid at cryogenic temperatures including a liquefied gaseous fuel, such as liquefied natural gas (LNG) or liquefied propane gas, and vapor such as natural gas vapor or propane gas vapor. In this situation, fuel system **110** can comprise a liquid pump and an accumulator. In a stationary application, storage vessel **150** can be replaced by a gaseous-fuel supply conduit connected with a commercial gaseous-fuel supply line.

[0035] Gaseous-fuel pressure regulator **160** is operable to regulate the gaseous-fuel pressure from storage vessel **150** to between 10 and 300 bar, and preferably to between 10 and 40 bar in gaseous-fuel supply rail **190**, and more preferably to between 10 and 20 bar to increase or maximize useable mass in storage vessel **150**. Regulator **160** supplies gaseous fuel at a regulated pressure to gaseous-fuel direct injector **170**. Optional pressure increasing device **185**, for example a gas compressor, can increase the pressure of the gaseous fuel from vessel **150** when the pressure drops below the lower limit of 10 bar in the ranges above, or below an intermediate pressure depending upon operating requirements. Optional heat exchanger **195** operates to reduce the temperature of the gaseous fuel which is elevated due to pressure increasing device **185**. In a preferred embodiment, direct-injection fuel system **110** is a common rail system, meaning that the gaseous fuel is delivered to gaseous-fuel direct injector **170** at injection pressure. In such a common rail system, pressure sensor **200** can be employed to measure the fuel pressure in gaseous-fuel supply rail **190** so that gaseous-fuel pressure

regulator **160** can be operated to maintain gaseous fuel injection pressure between a predetermined low and high set point. Gaseous-fuel pressure regulator **160** is preferably a single-step type pressure regulator; however in other embodiments, pressure regulator **160** can be a continuously-variable type or a multi-step type pressure regulator. The advantage of a continuously variable type or multi-step type pressure regulator is the ability to adjust the pressure in the gaseous-fuel supply rail **190** according to the operating conditions of engine **130**, thereby improving the efficiency of engine **130** and lowering emissions accordingly. Control valve **180** is operable under command of electronic controller **140** to enable and disable communication of the gaseous fuel between storage vessel **150** and gaseous-fuel pressure regulator **160**.

[0036] The flow of air into combustion chamber **210** from intake air manifold **240** is controlled by intake valve **250**, which can be opened during intake strokes of piston **230**. Like conventional gasoline engines, the disclosed engine can employ a turbocharger (not shown) to pressurize the intake air or the engine can be naturally aspirated. Gaseous-fuel direct injector **170** introduces the gaseous fuel directly into combustion chamber **210**, which is generally defined by a bore provided in cylinder block **220**, the cylinder head, and piston **230**, which is movable up and down within the bore. Gaseous-fuel direct injector **170** is shown centrally located in the cylinder head, but can be located in cylinder block **220** in a side mounted orientation in alternative embodiments. Generally, the centrally located injector has better efficiency, whereas the side mounted injector has better performance due to increased cooling effect. The gaseous-fuel/air mixture is ignited with ignition device **235** in combustion chamber **210**. In a preferred embodiment ignition device **235** is a spark plug, but in other embodiments can be an ignition plug, a glow plug, a laser ignition device or a pilot diesel injection. The glow plug when employed is typically part of a torch ignition system. Combustion products are expelled from combustion chamber **210** into exhaust manifold **260** through exhaust valve **270**, which is opened during exhaust strokes of piston **230**. Sensor **370** in exhaust manifold **260** is operable to detect emissions, and in particular O_2 and/or NO_X concentrations in the combustion products in order to influence the fuelling of engine **130**. Sensor **380**, such as an accelerometer, is disposed adjacent a wall of cylinder **220** in the present example, however other locations are possible such as the bearing cap, and is operable to detect vibrations from combustion chamber **210** characteristic of engine knock. Electronic controller **140** is responsive to outputs of sensors **370** and **380**. The operation of sensors **370** and **380** will be described in more detail below.

[0037] Electronic controller **140** is programmable to control the operation of gaseous-fuel pressure regulator **160**, pressure increasing device **185** (when required) and control valve **180** to control the pressure of the gaseous fuel in gaseous-fuel supply rail **190**. For example, electronic controller **140** can command gaseous-fuel pressure regulator **160** to decrease fuel pressure in gaseous-fuel supply rail **190** when engine **130** is operating in idle mode, and to increase fuel pressure when engine **130** is operating in full-load mode.

[0038] Electronic controller **140** is also programmable to selectively command the timing for opening and closing of a valve member in gaseous-fuel direct injector **170** that respectively controls the injection of the gaseous fuel into combustion chamber **210**. For example, electronic controller **140** can be programmed for early-cycle injection timing to control gaseous-fuel direct injector **170** so that the gaseous fuel is introduced into combustion chamber **210** starting before intake **250** closes for partial load and after intake valve **250** closes for high load and ending no later than 40° before top dead center (BTDC) during the compression stroke of piston **230**, and preferably no later than 60° BTDC. Partial load is defined herein to mean between 0 to 90% of the full load capacity of engine **130**, and high load is defined herein to mean between 90% and 100%. Injecting before intake valve **250** closes under partial load, that is, when engine **130** is partially throttled, reduces pumping losses and results in a premixed, homogenous gaseous-fuel/air mixture in combustion chamber **210**.

[0039] As the load on engine **130** increases from 0% to 100%, the start of injection timing is delayed further into the intake stroke during partial loading, and further into the compression stroke during high loading. For the compression ratio used for engine **130**, injecting no later than 60° BTDC results in a gaseous-fuel jet having good speed, and for a substantial portion of the gaseous-fuel injection pressure the speed is sonic, that is the ratio of gaseous fuel injection pressure and cylinder pressure is greater than 2. Typically, intake valve **250** closes around 150° before top dead center during the compression stroke of piston **230**. Compared to fuel injection later in the compression cycle, fuel injection within this range of the compression cycle generally does not require a high pressure compressor and a subsequent after-cooler between storage vessel **150** and gaseous-fuel pressure regulator **160**. In contrast, the present illustrative example employs a relatively simple gaseous-fuel pressure regulator **160** to regulate pressure in gaseous-fuel supply rail **190**. This allows for rapid re-starting in a stop-start system where engine **130** is turned off by electronic controller **140** after idling for a predetermined idle-time threshold, for example, while waiting at a traffic light, or while excessively idling in congested traffic and when being employed as part of a hybrid electric power train. In this situation, engine **130** can be started instantly since target fuel pressure in gaseous-fuel supply rail **190** is lower than fuel pressure in storage vessel **150** when engine **130** is started, requiring only a minor pressure drop that is quickly achieved by gaseous-fuel pressure regulator **160**. That is, there is no need to pressurize the gaseous fuel delivery system using a pump or compressor.

[0040] When gaseous-fuel injection occurs later in the compression cycle, for example starting at 20° before top dead center in the compression stroke, a high pressure compressor is required to raise the fuel pressure in gaseous-fuel supply rail **190** in order to overcome higher in-cylinder injection pressures, and this introduces a parasitic load that is required to build-up the pressure before injection can occur and this can delay starting of the vehicle. By using stratification techniques to introduce a stratified fuel charge during the compression cycle and additional injections during the combustion cycle, other advantages of gaseous-fuel injection timing no later than 40° BTDC during the compression stroke is reduction of cold start emissions and improved stability. Cold start emissions are emissions during start-up of apparatus **100** after being shut-off for a predetermined cold-start-time threshold or after engine temperature in apparatus **100** is below a predetermined cold-start-temperature threshold. And yet another advantage for some operating embodiments, at high engine speeds electronic controller **140** can command gaseous-fuel direct injector **170** to begin injecting gaseous fuel into combustion chamber **210** before intake valve **250** is closed to obtain a better gaseous-fuel/air mixture by allowing

more time for mixing. In this situation, good mixing comes at the expense of volumetric efficiency due to displacement of air by the gaseous fuel, leading to a loss of up to 10% of BMEP at a given manifold pressure. This reduction in BMEP can be offset by turbo-charging. Good mixing of fuel and air results in fuel that is combusted with lower overall emissions, and poor mixing leads to higher hydrocarbons and carbon monoxide emissions and lower overall efficiency. And still a further advantage for operating modes that fuel primarily with the gaseous fuel is higher output potential when directly injecting the gaseous fuel after intake valve **250** is closed, compared to previous engines that port inject the gaseous fuel. This is especially true for a naturally aspirated engine or for a turbocharged engine at low speeds.

[0041] The gaseous-fuel injection timing can be predetermined responsive to engine operating conditions determined from measured parameters that are inputted into electronic controller **140**, and the input of such parameters among others is represented by arrow **390**.

[0042] Port-injection fuel system **120** comprises storage vessel **300**, which is made to store the liquid fuel, which in the present embodiment is gasoline (petrol), and in other embodiments can be ethanol, blends of ethanol, or liquefied propane gas (LPG). Liquid fuel pump **310** is operable to deliver the liquid fuel from storage vessel **300** to liquid-fuel pressure regulator **320**. Check valve **330** allows the liquid fuel to flow towards liquid-fuel pressure regulator **320**, and prevents the liquid fuel from the pressure regulator flowing back towards liquid fuel pump **310**. There are alternative liquid-fuel supply systems used in port injection systems which are also included in the scope of the present disclosure. For example, in alternative embodiments, liquid-fuel pressure regulator **320** can further comprise a return outlet that communicates with a conduit connected with storage vessel **300** to return fuel thereto in order to regulate liquid-fuel pressure. Liquid-fuel pressure regulator **320** is operable to deliver liquid fuel under pressure from storage vessel **300** to liquid-fuel port injector **350** via liquid-fuel supply rail **340**. In the present example liquid-fuel pressure maintained by pressure regulator **320** is within the range of 2 bar to 10 bar, and preferably within the range of 2 bar to 6 bar; however in other examples this range can vary. In a preferred embodiment, port-injection fuel system **120** is a common rail system, meaning that the liquid fuel is delivered to liquid-fuel port injector **350** at injection pressure. In such a common rail system, pressure sensor **360** can be employed to measure the liquid-fuel pressure in liquid-fuel supply rail **340** so that liquid-fuel pressure regulator **320** can be operated to maintain liquid-fuel injection pressure between a predetermined low and high set point.

[0043] Under selective command of electronic controller **140**, liquid-fuel port injector **350** introduces the liquid fuel upstream of intake valve **250**. In a preferred embodiment injector **350** is employed in a multi-point injection system in which there is a fuel injector for each intake port. In alternative embodiments, injector **350** can be a single point injector, a continuous injector or a central port injector. Depending upon engine operating conditions it is possible that liquid-fuel port injector **350** is injecting the liquid fuel for up to 90% of the 720 degree crank angle for engine **130**. Typically, injector **350** is aimed to spray at a back side of intake valve **250** such that the liquid fuel is vaporized due to heat from valve **250**, and when valve **250** opens for the intake stroke of piston **230** the liquid fuel enters as a mist. The injected liquid fuel and the charge of air in the intake manifold **240** enter the combustion chamber **210** where the liquid-fuel/air mixture is compressed and ignited by ignition device **235**. Electronic controller **140** is programmable to control the operation of liquid-fuel pump **310** and liquid-fuel pressure regulator **320** to control the pressure of the liquid fuel in liquid-fuel supply rail **340**. Electronic controller **140** is also programmable to command the timing for opening and closing of a valve member in liquid-fuel port injector **350** that respectively controls the injection of the liquid fuel. The liquid-fuel injection timing can be predetermined responsive to engine operating conditions determined from measured parameters that are inputted into electronic controller **140**, and the input of such parameters among others is represented by arrow **390**.

[0044] Port-injection fuel system **120** for liquid fuel has several advantages over liquid-fuel direct injection systems. Port injecting liquid fuel lubricates intake valve **250** and reduces the likelihood of valve seat recession from occurring. As liquid fuel is introduced into combustion chamber **210** with the charge of air flowing in intake air manifold **240** it coats intake valve **250** with a thin layer of liquid fuel that lubricates the surface boundary between intake valve **250** and valve seat **280** and provides a low viscosity, liquid damping cushion. This lubrication results in less wear on valve seat **280** and intake valve **250** as the valve is continuously opened and closed. Port injecting liquid fuel also cleans intake valve **250**. Trace lubricating oil seeping down stem **290** of intake valve **250** due to low intake manifold pressure carbonizes along intake valve **250** due to heat of combustion leaving carbon deposits. When these carbon deposits build up significantly the air flow is reduced which tends to choke engine **130** at higher speeds and also disrupts the air flow pattern. Port injected liquid fuel, which can comprise additives that further reduce the formation of carbon deposits, helps to keep the valve clean preventing carbon deposit build-up on stem **290** and the back of intake valve **250**. Port injecting liquid fuel also helps to cool intake valve **250**. It has been observed that peak pressure rise and possibly heat transfer coefficient from combustion of natural gas, especially with aggressive spark advance, can be greater than that from combustion of gasoline (petrol) causing increased heat transfer to and flexure in the face of intake valve **250** leading to valve seat fretting and recession. Running relatively cool liquid fuel over intake valve **250** helps to manage the temperature of the valve and improves material durability. When the liquid fuel is gasoline, port injection of gasoline can reduce the mass and number of particulate emissions compared to direct injection of gasoline.

[0045] Referring now to FIGS. **2** and **3** the operation of engine **130** will now be described. Electronic controller **140** is programmed with fuel mode selection algorithm **400**. Generally, engine **130** operates in a gaseous-fuel operating mode where engine **130** is fuelled primarily from gaseous fuel, but can have periodic injections of liquid fuel. In a liquid-fuel operating mode engine **130** is primarily fuelled with liquid fuel, but can have periodic injections of gaseous fuel. In a dual-fuel operating mode engine **130** is fuelled simultaneously from both gaseous fuel and liquid fuel. The dual-fuel operating mode intends injections of both gaseous fuel and liquid fuel primarily to extend the gaseous fuelling range of engine **130** while keeping average emissions below a predetermined level which in preferred embodiments, is less than or equal to levels attainable by the liquid fuel operating mode. Normally, the operating mode of engine **130** is determined by a quantity of gaseous fuel in storage vessel **150**, which can be

ascertained by a measurement of mass of gaseous fuel or a measurement of pressure of gaseous fuel in storage vessel **150** using sensor **155**. In step **410** electronic controller **140** determines whether the quantity of the gaseous fuel in storage vessel **150** is above or below an upper threshold. Engine **130** is preferably in the gaseous-fuel operating mode when the quantity of the gaseous fuel is above the upper threshold, and is in either the dual-fuel or liquid fuel operating modes when it is below the upper threshold. Electronic controller **140** determines whether the quantity of the gaseous fuel in storage vessel **150** is above or below a lower threshold in step **420**. Engine **130** is in the dual-fuel operating mode when the quantity of the gaseous fuel is above the lower threshold, and is in the liquid-fuel operating mode when it is below the lower threshold.

[0046] In each of the operating modes there can be gaseous fuel and liquid fuel injections during a single cycle of engine **130**. With reference to FIG. **5**, fuel ratio algorithm **500**, which is programmed in electronic controller **140**, can be used to determine gaseous-to-liquid fuel ratio **510** that can be used to command gaseous-fuel direct injector **170** and liquid-fuel port injector **350** to inject respective amounts of gaseous fuel and liquid fuel to obtain ratio **510**. Algorithm **500** is responsive to measured parameters of engine **130** to generate ratio **510** and maximum torque limit **520**. The measured parameters comprise, but are not limited to, gaseous fuel pressure **530** and temperature in storage vessel **150**, which is representative of a quantity of gaseous fuel, engine operating conditions **540**, inlet air conditions **550**, knock detection **560**, operating history **570**, torque command **580**, emissions **590** and fuel system condition monitor **595**. Gaseous fuel pressure **530** includes storage pressure from sensor **155** and injection pressure from sensor **200**. Engine operating conditions **540** comprise, but are not limited to, measured parameters such as vehicle speed, torque, engine coolant temperature, engine temperature, engine speed (RPM). Inlet air conditions can comprise air temperature and humidity, intake air manifold pressure and intake air mass. Operating history **570** comprises time since key-on, time and distance since last fill-up, time operating in the gaseous-fuel operating mode, the dual-fuel operating mode and the liquid-fuel operating mode, in addition to other parameters. Fuel system condition monitor **595** comprises respective models of tips of fuel injectors **170** and **350** for monitoring the performance and behavior of the tips based on other measured parameters input into algorithm **500**. In alternative operating embodiments, when storage vessel **150** is a cryogenic storage vessel holding a multiphase fluid at cryogenic temperatures comprising a liquefied gaseous fuel and a vapor, such as LNG and natural gas vapor or LPG and propane vapor, measured parameters can further include a level of the liquefied gaseous fuel, a volume of the liquefied gaseous fuel, a mass of the liquefied gaseous fuel, a pressure of the vapor, a volume of the vapor and a mass of the vapor. Normally, in the gaseous-fuel operating mode ratio **510** is mathematically undefined since no liquid fuel is normally injected. That is, gaseous-to-liquid fuel ratio **510** is defined as the quantity of gaseous fuel to be injected divided by the quantity of liquid fuel to be injected. When no liquid fuel is to be injected ratio **510** is mathematically undefined due to division by zero. However, ratio **510** is mathematically defined when there are periodic injections of liquid fuel in the gaseous-fuel operating mode. In the liquid-fuel operating mode ratio **510** is normally zero since no gaseous fuel is normally injected, however ratio **510** is greater than zero when there are periodic injections of gaseous fuel. In the dual-fuel operating mode ratio **510** is mathematically defined and greater than zero.

[0047] Referring back to FIG. **2**, in the gaseous-fuel operating mode electronic controller **140** determines whether a periodic injection of liquid fuel is required in step **430**. Electronic controller **140** commands a gaseous fuel injection in step **440** if a periodic injection of liquid fuel is not required, which is normally the case in this mode. It has been found that during the gaseous-fuel operating mode there are advantages to periodic injections of liquid fuel. In step **450** electronic controller **140** commands a gaseous fuel injection from gaseous-fuel direct injector **170**, in addition to a liquid fuel injection from liquid-fuel port injector **350** if a periodic injection of liquid fuel is required. The periodic liquid fuel injection lubricates, cleans and cools intake valve **250**, as discussed in detail above, and prevents carbon deposit build-up in liquid-fuel injector **350**. Liquid-fuel port injector **350** heats up after engine **130** is shut-off and heat gets conducted from the engine into intake manifold **240** after coolant in engine **130** stops circulating. Operating in the gaseous-fuel operating mode for successive engine starts and stops can cause liquid fuel remaining in liquid-fuel port injector **350** to deteriorate over time and form carbon deposits. As these carbon deposits build-up over time they can affect the flow rate and spray pattern of the liquid fuel in liquid-fuel port injector **350**. For these reasons periodic operation of liquid-fuel port injector **350** is beneficial. The frequency of such periodic operation of liquid-fuel port injector **350** would be less than that required for idle liquid-fuel direct injectors that directly inject liquid fuel into combustion chamber **210**, since such direct injectors are exposed to hot combustion gases and the deterioration of liquid fuel is greatly accelerated. To achieve the benefits described above, electronic controller **140** can command injections from both gaseous-fuel direct injector **170** and liquid-fuel port injector **350** during a single engine cycle, or complete fuel substitution injections from liquid-fuel port injector **350**. In either situation, the total energy content of the total fuel injected into combustion chamber **210** would be consistent with the fuelling requirement according to the current operating condition of engine **130**. Electronic controller **140** can be programmed to selectively actuate liquid-fuel port injector **350** during the gaseous-fuel operating mode after a predetermined lubricate-time threshold, a predetermined cool-time threshold, a predetermined clean-time threshold, or a predetermined liquid-fuel-cycle-time threshold, or a combination of these thresholds, has been reached. The liquid-fuel-cycle-time threshold is defined herein to mean an amount of time in which the liquid fuel has been stored in tank **300** and not injected into combustion chamber **210**; after the liquid-fuel-cycle-time threshold is reached a portion of the liquid fuel can be injected in order to periodically consume the liquid fuel. Alternatively, operating history **570** of engine **130**, as seen in FIG. **5**, can be used to determine whether a periodic injection of liquid fuel is required. Operating history **570** includes statistical information comprising, for example, the last time tank **300** was filled, hours of operation on gaseous fuel only and operating conditions while running on gaseous fuel only, such as average crank rotational speed, fuel consumed, average torque, inlet temperature, engine temperature, coolant temperature and mass air flow. It is advantageous to have periodic injections of the liquid fuel based on the last time tank **300** was filled such that the liquid fuel is consumed regularly and problems associated with

reduced volatility due to vaporization, that is, degraded combustion performance, and water and oxidation contamination are reduced or minimized. This information along with other measured parameters of apparatus **100** can be used to select gaseous-to-liquid fuel ratio **510** that can be used when commanding fuel injection in step **450** shown in FIG. **2**.

[0048] In the dual-fuel operating mode electronic controller **140** commands gaseous fuel and liquid fuel injections in step **460**. Algorithm **500** determines gaseous-to-liquid fuel ratio **510** that is used when commanding fuel injection in step **460**. As gaseous-fuel pressure drops below the upper threshold in FIG. **3** algorithm **500** begins commanding a large gaseous-to-liquid fuel ratio in order to start introducing liquid fuel, initially at high speed operation than gradually further down the speed range as gaseous-fuel pressure continues to decrease. As gaseous-fuel pressure further continues to decrease gaseous-to-liquid fuel ratio **510** is gradually decreased in value in order to increase or maximize gaseous-fuel operation of engine **130**. It is preferable not to deplete gaseous-fuel storage vessel **150** completely in order to protect nozzles of gaseous-fuel direct injectors **170** against over heating due to peak combustion loads when there is no gaseous-fuel pressure or flow, and to protect against engine knock due to the lower octane number for liquid fuel. The dual-fuel operating mode can be alternatively entered depending on operating history **570** and driver command, even though gaseous-fuel pressure is above the upper threshold, such that gaseous-to-liquid fuel ratio **510** can be adjusted to consume both gaseous fuel and liquid fuel. The driver of the vehicle can select the dual-fuel operating mode in order to increase or maximize liquid fuel consumption with the aim of depleting liquid-fuel tank **300** at the same time as gaseous-fuel storage vessel **150**, or to even allow enough gaseous-fuel in reserve to get an extra refill of liquid fuel tank **300**. For example, gaseous-fuel storage vessel **150** can provide a fuelling range of 300 km in the gaseous-fuel operating mode, and liquid-fuel tank **300** can provide a fuelling range of 150 km in the liquid-fuel operating mode. In the dual-fuel operating mode, also called a gaseous-fuel extended range mode, storage vessel **150** and tank **300** can be depleted completely providing a range of 450 km, that is a 150 km extended range for gaseous fuel operation. It is especially advantageous to allow the driver to command the dual-fuel operating mode in regions where there are only liquid-fuel refilling stations and no gaseous-fuel refilling stations within the fuelling range of the vehicle. Depending upon the gaseous-to-liquid fuel ratio **510** employed during the dual-fuel operating mode, it is possible to provide multiple refills of liquid-fuel tank **300** while still consuming gaseous fuel from storage vessel **150**. For example, FIG. **4** illustrates three plots of gaseous-to-liquid fuel ratio **510** versus time or distance travelled. Plots **600** and **610** show that gaseous-to-liquid fuel ratio **510** decreases, that is more liquid fuel and less gaseous fuel is consumed, as engine **130** operates in the dual-fuel operating mode. Plot **600** has a greater magnitude slope than plot **610** meaning that the rate of switchover to liquid fuel is greater in plot **600**. Plot **620** is representative of a minimum value for gaseous-to-liquid fuel ratio **510** needed to meet emissions standards that cannot be met with liquid fuel alone. When starting with a full gaseous-fuel storage vessel **150** and meeting minimum emission standards, the greatest number of refills of liquid-fuel tank **300** while in dual-fuel operating mode would occur when engine **130** operates with gaseous-to-liquid fuel ratio **510** equal to plot **620**.

[0049] Referring back to FIG. **2**, in the liquid-fuel operating mode electronic controller **140** determines whether periodic injections of gaseous fuel are required in step **470**. Electronic controller **140** commands only liquid fuel injections in step **480** if periodic injections are not required, which is normally the case when operating in this mode. However, it has been found that during the liquid-fuel operating mode there can be certain operating conditions when there are advantages to periodic injections of gaseous fuel. When electronic controller **140** detects in step **470** an operating condition that warrants a gaseous fuel injection, in step **490** it commands a liquid fuel injection from liquid-fuel port injector **350**, in addition to a gaseous fuel injection from gaseous-fuel direct injector **170**. Knock detection **560** and emissions **590** measurements of engine **130**, as seen in FIG. **5**, can be used to determine whether a periodic injection of gaseous fuel is required. This information along with other measured parameters of apparatus **100** can be used to select gaseous-to-liquid fuel ratio **510** that can be used when commanding fuel injection in step **490**. By injecting both liquid fuel and gaseous fuel during a single cycle of engine **130** the overall emissions of NO_X, particulate matter and hydrocarbons can be reduced compared to liquid fuel only injections. Also, gaseous fuel injections can help suppress engine knock, particularly when the gaseous fuel comprises methane, compared to when gasoline (petrol) alone is used during the liquid-fuel operating mode. Methane, the primary constituent of natural gas, has a higher octane number than petrol. A partial reduction in knock tendency occurs as methane fraction of total injected fuel increases. Methane injections can also enable an increased effective compression ratio during the liquid-fuel operating mode, improving efficiency and emissions by use of variable intake/exhaust valve activation or variable compression volume devices. Residual methane in combustion chamber **210** can be used to increase or maximize effective energy contribution from methane. The liquid-fuel operating mode is intended as a secondary operating mode and can operate with reduced torque due to the need to reduce compression ratio or limit intake manifold pressure, for example using the intake throttle or boost pressure control. It is preferable that storage vessel **150** not be completely depleted of gaseous-fuel. However it is possible that it does get depleted during operation of engine **130**. In this situation, engine **130** can operate with reduced power output in order to protect nozzles of gaseous-fuel direct injectors **170** against overheating due to peak combustion loads when there is no gaseous-fuel pressure or flow.

[0050] While particular elements, embodiments and applications of the present invention have been shown and described, it will be understood, that the invention is not limited thereto since modifications can 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 apparatus for delivering two fuels to a combustion chamber of an internal combustion engine, the apparatus comprising:

(a) a first fuel system comprising a first fuel supply and a first fuel pressure regulator operatively connected with said first fuel supply, said first fuel supply comprising a source of a gaseous fuel;

(b) a first fuel injector for directly injecting said gaseous fuel into said combustion chamber, said first fuel injector operatively connected with said first fuel pressure regulator;

(c) a second fuel system comprising a second fuel supply, a fuel pump operatively connected with said second fuel supply and a second fuel pressure regulator operatively connected with said fuel pump, said second fuel supply comprising a source of a liquid fuel;

(d) a second fuel injector for injecting said liquid fuel upstream of an intake valve operative to admit an intake charge into said combustion chamber, said second fuel injector operatively connected with said second fuel pressure regulator; and

(e) a computer operatively connected with said first fuel injector and said second fuel injector to actuate injection of fuel respectively therefrom, said computer programmed to:

(i) command a gaseous-to-liquid fuel ratio as a function of inputs comprising at least one of gaseous fuel storage pressure, gaseous fuel injection pressure, gaseous fuel mass, engine speed, engine torque, inlet air temperature, inlet air humidity, intake air manifold pressure, intake air mass, knock detection, operating history, torque command, and emissions;

(ii) select a gaseous-fuel operating mode when a quantity of gaseous fuel is above an upper threshold and a liquid-fuel operating mode when the quantity of gaseous fuel is below the upper threshold;

(iii) selectively actuate the first fuel injector to inject the gaseous fuel during the gaseous-fuel operating mode, the gaseous-to-liquid fuel ratio being mathematically undefined during the gaseous-fuel operating mode; and

(iv) selectively actuate the second fuel injector to inject the liquid fuel during the liquid-fuel operating mode, the gaseous-to-liquid fuel ratio being zero during the liquid-fuel operating mode.

2. The apparatus of claim **1**, wherein said gaseous fuel is selected from the group consisting of natural gas and methane.

3. The apparatus of claim **1**, wherein said liquid fuel is selected from the group consisting of gasoline and ethanol/gasoline blends.

4. The apparatus of claim **1**, wherein said first fuel pressure regulator is a single-step regulator.

5. The apparatus of claim **1**, wherein said first fuel pressure regulator is one of a continuously variable pressure regulator and a multi-step regulator.

6. The apparatus of claim **1**, wherein said first fuel pressure regulator regulates said gaseous-fuel injection pressure between 10 bar and 300 bar.

7. The apparatus of claim **1**, wherein said first fuel pressure regulator regulates said gaseous-fuel injection pressure between 10 bar and 40 bar.

8. The apparatus of claim **1**, wherein said first fuel pressure regulator regulates said gaseous-fuel injection pressure between 10 bar and 20 bar.

9. The apparatus of claim **1**, wherein said second fuel pressure regulator regulates said liquid-fuel injection pressure between 2 bar and 10 bar.

10. The apparatus of claim **1**, wherein said second fuel pressure regulator regulates said liquid-fuel injection pressure between 2 bar and 6 bar.

11. The apparatus of claim **1**, wherein said computer is further programmed to shut-off said internal combustion engine after idling for a predetermined idle-time threshold.

12. The apparatus of claim I, wherein said computer is further programmed to actuate said first fuel injector to introduce a stratified fuel charge in said combustion chamber during cold-start of said internal combustion engine resulting in at least one of reduced emissions and improved stability.

13. The apparatus of claim **1**, wherein said gaseous fuel is injected no less than 40° before top dead center during a compression stroke associated with said combustion chamber during said gaseous-fuel operating mode.

14. The apparatus of claim **1**, wherein said gaseous fuel is injected no less than 60° before top dead center during a compression stroke associated with said combustion chamber during said gaseous-fuel operating mode.

15. The apparatus of claim **1**, wherein said computer is further programmed to select one of said gaseous-fuel operating mode and said liquid-fuel operating mode as a function of inputs comprising at least one of gaseous-fuel storage pressure, gaseous-fuel mass, liquefied gaseous-fuel level, liquefied gaseous-fuel volume, liquefied gaseous-fuel mass, and gaseous fuel injection pressure.

16. The apparatus of claim **1**, wherein said computer is further programmed to selectively actuate said first fuel injector after said intake valve closes.

17. The apparatus of claim **1**, wherein said computer is further programmed to selectively actuate said first fuel injector to start injecting gaseous fuel while said intake valve is open.

18. The apparatus of claim **1**, wherein when a predetermined condition is detected during said gaseous-fuel operating mode, said computer is further programmed to mathematically define said gaseous-to-liquid fuel ratio and to selectively actuate said second fuel injector.

19. The apparatus of claim **18**, wherein said predetermined condition is at least one of a lubricate-time threshold, a cool-time threshold, a clean-time threshold, and a liquid-fuel-cycle-time threshold, and said predetermined condition is detected when at least one of said thresholds is met or exceeded.

20. The apparatus of claim **18**, wherein said computer is further programmed to selectively actuate said second fuel injector during said gaseous-fuel operating mode as a function of inputs comprising at least one of average crank rotational speed, gaseous fuel consumed, average torque, inlet temperature, mass air flow, engine temperature, coolant temperature, and time since said second fuel supply was filled.

21. The apparatus of claim **1**, wherein when a predetermined condition is detected during said liquid-fuel operating mode said computer is further programmed to command a gaseous-to-liquid fuel ratio greater than zero and to selectively actuate said first fuel injector.

22. The apparatus of claim **21**, wherein said predetermined condition is a threshold level of engine knock, and said apparatus further comprises an engine knock sensor, said computer programmed responsive to an output of said engine knock sensor to selectively actuate said first fuel injector during said liquid-fuel operating mode when said output meets or exceeds said threshold level of engine knock.

23. The apparatus of claim **21**, wherein said predetermined condition is a threshold level of emissions, and said apparatus further comprises an emissions sensor, said computer programmed responsive to an output of said emissions sensor to

selectively actuate said first fuel injector during said liquid-fuel operating mode when said output meets or exceeds said threshold level of emissions.

24. The apparatus of claim **1**, wherein said computer is further programmed to select a dual-fuel operating mode when the quantity of gaseous fuel is below the upper threshold and above a lower threshold and to select the liquid fuel operating mode when the quantity of gaseous fuel is below the lower threshold, and to selectively actuate said first and second fuel injectors during said dual-fuel operating mode, said gaseous-to-liquid fuel ratio being mathematically defined and having a value greater than zero during said dual-fuel operating mode.

25. An internal combustion engine apparatus comprising;

(a) a combustion chamber;

(b) an intake valve for admitting an intake charge into said combustion chamber;

(c) a first fuel injector for injecting a gaseous fuel directly into said combustion chamber;

(d) a second fuel injector for injecting a liquid fuel into said intake charge upstream of said intake valve; and

(e) a computer operatively connected with said first fuel injector and said second fuel injector to actuate injection of fuel respectively therefrom, said computer programmed to:

(i) command a gaseous to liquid fuel ratio as a function of inputs comprising at least one of gaseous fuel storage pressure, gaseous fuel injection pressure, gaseous fuel mass, engine speed, engine torque, inlet air temperature, inlet air humidity, intake air manifold pressure, intake air mass, knock detection, operating history, torque command, and emissions;

(ii) select a gaseous-fuel operating mode when a quantity of gaseous fuel is above an upper threshold and a liquid-fuel operating mode when the quantity of gaseous fuel is below the upper threshold;

(iii) selectively actuate the first fuel injector to inject the gaseous fuel during the gaseous-fuel operating mode, the gaseous-to-liquid fuel ratio being mathematically undefined during the gaseous-fuel operating mode; and

(iv) selectively actuate the second fuel injector to inject the liquid fuel during the liquid-fuel operating mode, the gaseous-to-liquid fuel ratio being zero during the liquid-fuel operating mode.

26. The apparatus of claim **25**, wherein said gaseous fuel is selected from the group consisting of natural gas and methane.

27. The apparatus of claim **25**, wherein said liquid fuel is selected from the group consisting of gasoline and ethanol/gasoline blends,

28. The apparatus of claim **25**, wherein said computer is further programmed to selectively actuate said first fuel injector after said intake valve closes during a compression stroke associated with said combustion chamber,

29. The apparatus of claim **25**, wherein said computer is further programmed to actuate said first fuel injector to start injecting gaseous fuel while said intake valve is open.

30. The apparatus of claim **25**, wherein said computer is further programmed to shut-oil said internal combustion engine after idling for a predetermined idle-time threshold.

31. The apparatus of claim **25**, wherein said computer is further programmed to actuate said first fuel injector to introduce a stratified fuel charge in said combustion chamber during cold-start of said internal combustion engine resulting in at least one of reduced emissions and improved stability.

32. The apparatus of claim **25**, wherein said first fuel injector has a gaseous fuel injection pressure between 10 bar and 40 bar.

33. The apparatus of claim **25**, wherein said second fuel injector has a liquid fuel injection pressure between 2 bar and 6 bar.

34. The apparatus of claim **25**, wherein said gaseous fuel is injected no less than 40° before top dead center during a compression stroke associated with said combustion chamber during said gaseous-fuel operating mode.

35. The apparatus of claim **25**, wherein said gaseous fuel is injected no less than 60 s before top dead center during a compression stroke associated with said combustion chamber during said gaseous-fuel operating mode.

36. The apparatus of claim **25**, wherein said computer is further programmed to select one of said gaseous-fuel operating mode and said liquid fuel operating mode as a function of inputs comprising at least one of gaseous fuel storage pressure, gaseous fuel mass, liquefied gaseous fuel level, liquefied gaseous fuel volume, liquefied gaseous fuel mass, and gaseous fuel injection pressure.

37. The apparatus of claim **25**, wherein when a predetermined condition is detected during said gaseous-fuel operating mode said computer is further programmed to define said gaseous-to-liquid fuel ratio and to selectively actuate said second fuel injector.

38. The apparatus of claim **37**, wherein said predetermined condition is at least one of a lubricate-time threshold, a cool-time threshold, a clean-time threshold, and a liquid-fuel-cycle-time threshold, and said predetermined condition is detected when at least one of said thresholds is met or exceeded.

39. The apparatus of claim **37**, wherein said computer is further programmed to selectively actuate said second fuel injector during said gaseous-fuel operating mode as a function of inputs comprising at least one of average crank rotational speed, gaseous fuel consumed, average torque, inlet temperature, mass air flow, engine temperature, coolant temperature and time since said second fuel supply was filled,

40. The apparatus of claim **25**, wherein when a predetermined condition is detected during said liquid-fuel operating mode said computer is further programmed to command said gaseous-to-liquid fuel ratio to have a value greater than zero and to selectively actuate said first fuel injector.

41. The apparatus of claim **40**, wherein said predetermined condition is a threshold level of engine knock, and said apparatus further comprises an engine knock sensor, said computer programmed responsive to an output of said engine knock sensor to selectively actuate said first fuel injector during said liquid-fuel operating mode when said output meets or exceeds said threshold level of engine knock.

42. The apparatus of claim **40**, wherein said predetermined condition is a threshold level of emissions, and said apparatus further comprises an emissions sensor, said computer programmed responsive to an output of said emissions sensor to selectively actuate said first fuel injector during said liquid-fuel operating mode when said output meets or exceeds said threshold level of emissions.

43. The apparatus of claim **25**, wherein said computer is further programmed to select a dual-fuel operating mode when the quantity of gaseous fuel is below the upper threshold and above a lower threshold and to select the liquid fuel

operating mode when the quantity of gaseous fuel is below the lower threshold, and to selectively actuate said first and second fuel injectors during dual-fuel operating mode, said gaseous-to-liquid fuel ratio being mathematically defined and having a value greater than zero during said dual-fuel operating mode,

44. A method of delivering a gaseous fuel and a liquid fuel to a combustion chamber of an internal combustion engine, the method comprising:

(a) commanding a gaseous-to-liquid fuel ratio as a function of inputs comprising at least one of gaseous fuel storage pressure, gaseous fuel injection pressure, gaseous fuel mass, engine speed, engine torque, inlet air temperature, inlet air humidity, intake air manifold pressure, intake air mass, knock detection, operating history, torque command, and emissions;

(b) selecting a gaseous-fuel operating mode when a quantity of gaseous fuel is above an upper threshold and a liquid-fuel operating mode when the quantity of gaseous fuel is below the upper threshold;

(c) injecting the gaseous fuel directly into the combustion chamber during the gaseous-fuel operating mode, the gaseous-to-liquid fuel ratio being mathematically undefined during the gaseous-fuel operating mode; and

(d) injecting the liquid fuel upstream of an intake valve during the liquid-fuel operating mode, the gaseous-to-liquid fuel ratio being zero during the liquid-fuel operating mode.

45. The method of claim **44**, wherein said gaseous fuel is selected from the group consisting of natural gas and methane.

46. The method of claim **44**, wherein said liquid fuel is selected from the group consisting of gasoline and ethanol/gasoline blends.

47. The method of claim **44**, further comprising regulating said gaseous fuel injection pressure between 10 bar and 300 bar.

48. The method of claim **44**, further comprising regulating said injection pressure of said gaseous fuel between 10 bar and 40 bar.

49. The method of claim **44**, further comprising regulating said injection pressure of said gaseous fuel between 10 bar and 20 bar.

50. The method of claim **44**, further comprising regulating said injection pressure of said liquid fuel between 2 bar and 10 bar.

51. The method of claim **44**, further comprising regulating said injection pressure of said liquid fuel between 2 bar and 6 bar.

52. The method of claim **44**, further comprising shutting off said internal combustion engine after idling for a predetermined idle-time threshold.

53. The method of claim **44**, further comprising introducing a stratified fuel charge in said combustion chamber during cold-start of said internal combustion engine resulting in at least one of reduced emissions and improved stability.

54. The method of claim **44**, further comprising injecting said gaseous fuel not less than 40° before top dead center during a compression stroke associated with said combustion chamber.

55. The method of claim **44**, further comprising injecting said gaseous fuel not less than 60° before top dead center during a compression stroke associated with said combustion chamber.

56. The method of claim **44**, wherein one of said gaseous-fuel operating mode and said liquid-fuel operating mode is selected as a function of inputs comprising at least one of gaseous fuel storage pressure, gaseous fuel mass, liquefied gaseous fuel level, liquefied gaseous fuel volume, liquefied gaseous fuel mass, and gaseous fuel injection pressure.

57. The method of claim **44**, further comprising injecting said gaseous fuel after said intake valve closes.

58. The method of claim **44**, further comprising starting injection of said gaseous fuel before said intake valve closes.

59. The method of claim **44**, wherein injecting said gaseous fuel further comprises:

(i) detecting a predetermined condition during said gaseous-fuel operating mode;

(ii) mathematically defining said gaseous-to-liquid fuel ratio; and

(iii) selectively injecting said liquid fuel during said gaseous-fuel operating mode.

60. The method of claim **59**, wherein said predetermined condition is at least one of a lubricate-time threshold, a cool-time threshold, a clean-time threshold, and a liquid-fuel-cycle-time threshold, and said predetermined condition is detected when at least one of said thresholds is met or exceeded.

61. The method of claim **59**, wherein selectively injecting said liquid fuel during said gaseous-fuel operating mode further comprises:

measuring at least one of average crank rotational speed, gaseous fuel consumed, average torque, inlet temperature, mass air flow, engine temperature, coolant temperature, and time since said second fuel supply was filled;

whereby said predetermined condition is met when said measurement reaches or exceeds a threshold.

62. The method of claim **44**, wherein injecting said liquid fuel further comprises:

(i) detecting a predetermined condition during said liquid-fuel operating mode;

(ii) commanding said gaseous-to-liquid fuel ratio to have a value greater than zero in response to said predetermined condition; and

(iii) selectively injecting said gaseous fuel during said liquid-fuel operating mode.

63. The method of claim **62**, wherein said predetermined condition is a threshold level of engine knock.

64. The method of claim **62**, wherein said predetermined condition is a threshold level of emissions.

65. The method of claim **44**, further comprising;

(e) selecting a dual-fuel operating mode when the quantity of gaseous fuel is below the upper threshold and above a lower threshold and the liquid fuel operating mode when the quantity of gaseous fuel is below the lower threshold, said gaseous-to-liquid fuel ratio being mathematically defined and having a value greater than zero during said dual-fuel operating mode;

(f) injecting said gaseous fuel directly into said combustion chamber during said dual-fuel operating mode; and

(g) injecting said liquid fuel upstream of an intake valve during said dual-fuel operating mode, said liquid fuel injected into an intake charge.

66. The method of claim **65**, wherein said dual-fuel operating mode is selected as a function of inputs comprising at least one of a gaseous-fuel storage pressure, a gaseous-fuel

injection pressure, a gaseous-fuel storage temperature, a gaseous-fuel mass, a liquefied gaseous-fuel level, and a liquefied gaseous-fuel mass.

67. The method of claim **65**, further comprising decreasing said gaseous-to-liquid fuel ratio during said dual-fuel operating mode based on a decrease in at least one of said gaseous-fuel storage pressure and said gaseous fuel injection pressure.

68. The method of claim **65**, further comprising selecting said gaseous-to-liquid fuel ratio during said dual-fuel operating mode to maintain emissions below a threshold level.

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