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(54) **Multiple capillary fuel injector for an internal combustion engine**

Mehrfachkapillare Kraftstoffeinspritzdüse für einen Verbrennungsmotor

Injecteur de carburant à capillaires multiples pour moteur à combustion interne

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Description

[0001] The present invention relates to fuel delivery in an internal combustion engine.

[0002] Since the 1970's, port-fuel injected engines have utilized three-way catalysts and closed-loop engine controls in order to seek to minimize NO_x, CO, and unburned hydrocarbon emissions. This strategy has proven to be particularly effective during normal operation in which the engine and exhaust components have reached sufficient temperatures. However, in order to achieve desirable conversion efficiencies of NO_x, CO, and unburned hydrocarbons, the three-way catalyst must be above its inherent catalyst light-off temperature.

[0003] In addition, the engine must be at sufficient temperature to allow for vaporization of liquid fuel as it impinges upon intake components, such as port walls and/or the back of valves. The effectiveness of this process is important in that it provides a proper degree of control over the stoichiometry of the fuel/air mixture and, thus, is coupled to idle quality and the performance of the three-way catalyst, and it ensures that the fuel supplied to the engine is burned during combustion and, thus, eliminates the need for over-fueling to compensate for liquid fuel that does not vaporize sufficiently and/or collects on intake components.

[0004] In order for combustion to be chemically complete, the fuel-air mixture must be vaporized to a stoichiometric gas-phase mixture. A stoichiometric combustible mixture contains the exact quantities of air (oxygen) and fuel required for complete combustion. For gasoline, this air-to-fuel ratio is about 14.7:1 by weight. A fuel-air mixture that is not completely vaporized, and/or contains more than a stoichiometric amount of fuel, results in incomplete combustion and reduced thermal efficiency. The products of an ideal combustion process are water (H_2O) and carbon dioxide (CO_2). If combustion is incomplete, some carbon is not fully oxidized, yielding carbon monoxide (CO) and unburned hydrocarbons (HC).

[0005] Under cold-start and warm-up conditions, the processes used to reduce exhaust emissions and deliver high quality fuel vapor break down due to relatively cool temperatures. In particular, the effectiveness of three-way catalysts is not significant below approximately 250 °C and, consequently, a large fraction of unburned hydrocarbons pass unconverted to the environment. Under these conditions, the increase in hydrocarbon emissions is exacerbated by over-fueling required during cold-start and warm-up. That is, since fuel is not readily vaporized through impingement on cold intake manifold components, over-fueling is necessary to create combustible mixtures for engine starting and acceptable idle quality.

[0006] The mandates to reduce air pollution worldwide have resulted in attempts to compensate for combustion inefficiencies with a multiplicity of fuel system and engine modifications. As evidenced by the prior art relating to fuel preparation and delivery systems, much effort has been directed to reducing liquid fuel droplet size, increasing system turbulence and providing sufficient heat to vaporize fuels to permit more complete combustion.

[0007] However, inefficient fuel preparation at lower engine temperatures remains a problem which results in higher emissions, requiring after-treatment and complex control strategies. Such control strategies can include exhaust gas recirculation, variable valve timing, retarded ignition timing, reduced compression ratios, the use of catalytic converters and air injection to oxidize unburned hydrocarbons and produce an exothermic reaction benefiting catalytic converter light-off.

[0008] As indicated, over-fueling the engine during cold-start and warm-up is a significant source of unburned hydrocarbon emissions in conventional engines. It has been estimated that as much as 80 percent of the total hydrocarbon emissions produced by a typical, modern port fuel injected (PFI) gasoline engine passenger car occurs during the cold-start and warm-up period, in which the engine is over-fueled and the catalytic converter is essentially inactive.

[0009] Given the relatively large proportion of unburned hydrocarbons emitted during startup, this aspect of passenger car engine operation has been the focus of significant technology development efforts. Furthermore, as increasingly stringent emissions standards are enacted into legislation and consumers remain sensitive to pricing and performance, these development efforts will continue to be paramount. Such efforts to reduce start-up emissions from conventional engines generally fall into two categories: 1) reducing the warm-up time for three-way catalyst systems and 2) improving techniques for fuel vaporization. Efforts to reduce the warm-up time for three-way catalysts to date have included: retarding the ignition timing to elevate the exhaust temperature; opening the exhaust valves prematurely; electrically heating the catalyst; burner or flame heating the catalyst; and catalytically heating the catalyst. As a whole, these efforts are costly and do not address HC emissions during and immediately after cold start.

[0010] A variety of techniques have been proposed to address the issue of fuel vaporization. U.S. Patents proposing fuel vaporization techniques include U.S. Patent No. 5,195,477 issued to Hudson, Jr. et al, U.S. Patent No. 5,331,937 issued to Clarke, U.S. Patent No. 4,886,032 issued to Asmus, U.S. Patent No. 4,955,351 issued to Lewis et al., U.S. Patent No. 4,458,655 issued to Oza, U.S. Patent No. 6,189,518 issued to Cooke, U.S. Patent No. 5,482,023 issued to Hunt, U.S. Patent No. 6,109,247 issued to Hunt, U.S. Patent No. 6,067,970 issued to Awarzamani et al., U.S. Patent No. 5,947,091 issued to Krohn et al., U.S. Patent No. 5,758,826 issued to Nines, U.S. Patent No. 5,836,289 issued to Thring, and U.S. Patent No. 5,813,388 issued to Cikanek, Jr. et al.

[0011] Other fuel delivery devices proposed include U.S. Patent No. 3,716,416, which discloses a fuel-metering device for use in a fuel cell system. The fuel cell system is intended to be self-regulating, producing power at a predetermined level. The proposed fuel metering system includes a capillary flow control device for throttling the fuel flow in response to the power output of the fuel cell, rather than to provide improved fuel preparation for subsequent combustion. Instead, the fuel is intended to be fed to a fuel reformer for conversion to H_2 and then fed to a fuel cell. In a preferred embodiment, the capillary tubes are made of metal and the capillary itself is used as a resistor, which is in electrical contact with the power output of the fuel cell. Because the flow resistance of a vapor is greater than that of a liquid, the flow is throttled as the power output increases. The fuels suggested for use include any fluid that is easily transformed from a liquid to a vapor phase by applying heat and flows freely through a capillary. Vaporization appears to be achieved in the manner that vapor lock occurs in automotive engines.

[0012] U.S. Patent No. 6,276,347 proposes a supercritical or near-supercritical atomizer and method for achieving atomization or vaporization of a liquid. The supercritical atomizer of U.S. Patent No. 6,276,347 is said to enable the use of heavy fuels to fire small, light weight, low compression ratio, spark-ignition piston engines that typically burn gasoline. The atomizer is intended to create a spray of fine droplets from liquid, or liquid-like fuels, by moving the fuels toward their supercritical temperature and releasing the fuels into a region of lower pressure on the gas stability field in the phase diagram associated with the fuels, causing a fine atomization or vaporization of the fuel. Utility is disclosed for applications such as combustion engines, scientific equipment, chemical processing, waste disposal control, cleaning, etching, insect control, surface modification, humidification and vaporization.

[0013] To minimize decomposition of the fuel, U.S. Patent No. 6,276,347 proposes keeping the fuel below the supercritical temperature until passing the distal end of a restrictor for atomization. For certain applications, heating just the tip of the restrictor is desired to minimize the potential for chemical reactions or precipitations. This is said to reduce problems associated with impurities, reactants or materials in the fuel stream which otherwise tend to be driven out of solution, clogging lines and filters. Working at or near supercritical pressure suggests that the fuel supply system operate in the range of 21 kg/cm^2 (300 psig) to 56 kg /cm^2 (800 psig). While the use of supercritical pressures and temperatures might reduce clogging of the atomizer, it appears to require the use of a relatively more expensive fuel pump, as well as fuel lines, fittings and the like that are capable of operating at these elevated pressures.

US 2003/178011 A1 and US 2003/178010 A1 disclose a fuel injector comprising a plurality of capillary flow passages, a heat source arranged along each of said plurality of capillary flow passages, and a valve downstream of the capillary flow passages. US-A-3868939 teaches a semi-spherical valve member.

[0014] Despite these and other advances in the art, there exists a need for injector designs capable of delivering improved vaporization while still meeting critical design requirements such as acceptable pressure drop across the injector, acceptable vaporized fuel flow rate at 100 % duty cycle, acceptable liquid fuel flow rate at 100 % duty cycle, exhibit minimal heat-up time, possess minimal power requirement, exhibit a linear relationship between duty cycle and vaporized fuel flow an exhibit a linear relationship between duty cycle and liquid fuel flow. It is the object of the present invention to provide a fuel injector having these capabilities. This object is attained with a fuel injector according to claim 1 and a method according to claim 7.

[0015] The fuel injectors provided are effective in reducing cold-start and warm-up emissions of an internal combustion engine. Efficient combustion can be promoted by forming an aerosol of fine droplet size when the substantially vaporized fuel condenses in air. The substantially vaporized fuel can be supplied directly or indirectly to a combustion chamber of an internal combustion engine during cold-start and warm-up of the engine, or at other periods during the operation of the engine, and reduced emissions can be achieved due to the capacity for improved mixture control during cold-start, warm-up and transient operation.

[0016] The capillary passage can be formed within a capillary tube and the heat source can include a resistance heating element or a section of the tube heated by passing electrical current therethrough. The fuel supply can be arranged to deliver pressurized or non-pressurized liquid fuel to the flow passage. The fuel injectors can provide a stream of vaporized fuel that mixes with air and forms an aerosol having a mean droplet size of 25 μm or less.

[0017] The invention will now be described in more detail with reference to preferred forms of the invention, given only by way of example, and with reference to the accompanying drawings, in which:

[0018] FIG. 1 shows an isometric view of another multiple capillary fuel injector having an electronically heated capillary bundle positioned upstream of a solenoid activated fuel metering valve;

[0019] FIG. 2 is a partial cross-sectional side view of the multiple capillary fuel injector of FIG. 1;

[0020] FIG. 3 is a chart illustrating the trade-off between minimizing the power supplied to the injector and minimizing the warm-up time associated with the injector for different heated masses;

[0021] FIG. 4 is a chart illustrating that maximum emission reduction may be achieved by injecting vapor only during the portion of the engine cycle in which the intake valves are open;

[0022] FIG. 5 is a schematic of a fuel delivery and control system, in accordance with a preferred form;

[0023] FIG. 6 presents the liquid mass flow rate and vapor mass flow rate of fuel through a single 3.8 cm (1.5 in) capillary as a function of the pressure drop over the capillary; and

[0024] FIG. 7 presents fuel droplet size (SMD in microns) as a function of the resistance set-point of a 3.8 cm (1.5 in) thin wall capillary.

[0025] Reference is now made to the embodiments illustrated in Figs. 1-7 wherein like numerals are used to designate like parts throughout.

[0026] Provided herein is a multiple capillary fuel injector with metering valve and a fuel system employing same that is useful for cold-start, warm-up and normal operation of an internal combustion engine. The fuel system includes a fuel injector having a plurality of capillary flow passages, each capillary flow passage capable of heating liquid fuel so that substantially vaporized fuel is supplied when desired. The substantially vaporized fuel can be combusted with reduced emissions compared to conventional fuel injector systems. The fuel delivery system of the present invention requires less power, and has shorter warm-up times than other vaporization techniques.

[0027] The injector designs provided herein are specifically aimed at meeting several automotive fuel injector design requirements including: provide an acceptable pressure drop across the injector body, provide an acceptable vaporized fuel flow rate at 100% duty cycle, provide an acceptable liquid fuel flow rate at 100% duty cycle, exhibit minimal heat-up time, possess minimal power requirement, exhibit a linear relationship between duty cycle and vaporized fuel flow and exhibit a linear relationship between duty cycle and liquid fuel flow.

[0028] As is well-known, gasoline does not readily vaporize at low temperatures. During the cold start and warm-up period of an automotive engine, relatively little vaporization of the liquid fuel takes place. As such, it is necessary to provide an excess of liquid fuel to each cylinder of the engine in order to achieve an air/fuel mixture that will combust. Upon ignition of the fuel vapor, which is generated from the excess of liquid fuel, combustion gases discharged from the cylinders include unburned fuel and undesirable gaseous emissions. However, upon reaching normal operating temperature, the liquid fuel readily vaporizes, so that less fuel is needed to achieve an air/fuel mixture that will readily combust. Advantageously, upon reaching normal operating temperature, the air/fuel mixture can be controlled at or near stoichiometry, thereby reducing emissions of unburned hydrocarbons and carbon monoxide. Additionally, when fueling is controlled at or near stoichiometry, just enough air is available in the exhaust stream for simultaneous oxidation of unburned hydrocarbons and carbon monoxide and reduction of nitrogen oxides over a three-way catalyst (TWC) system.

[0029] The fuel injector and fuel system disclosed herein injects fuel that has been substantially vaporized into the intake flow passage, or directly into an engine cylinder, thereby eliminating the need for excess fuel during the start-up and warm-up period of an engine. The fuel is preferably delivered to the engine in a stoichiometric or fuel-lean mixture, with air, or air and diluent, so that virtually all of the fuel is burned during the cold start and warm-up period.

[0030] With conventional port-fuel injection, over-fueling is required to ensure robust, quick engine starts. Under fuel-rich conditions, the exhaust stream reaching the three-way catalyst does not contain enough oxygen to oxidize the excess fuel and unburned hydrocarbons as the catalyst warms up. One approach to address this issue is to utilize an air pump to supply additional air to the exhaust stream upstream of the catalytic converter. The objective is to generate a stoichiometric or slightly fuel-lean exhaust stream that can react over the catalyst surface once the catalyst reaches its light-off temperature. In contrast, the system and method of the present invention enables the engine to operate at stoichiometric or even slightly fuel-lean conditions during the cold-start and warm-up period, eliminating both the need for over-fueling and the need for an additional exhaust air pump, reducing the cost and complexity of the exhaust after treatment system.

[0031] As mentioned, during the cold start and warm-up period, the three-way catalyst is initially cold and is not able to reduce a significant amount of the unburned hydrocarbons that pass through the catalyst. Much effort has been devoted to reducing the warm-up time for three-way catalysts, to convert a larger fraction of the unburned hydrocarbons emitted during the cold-start and warm-up period. One such concept is to deliberately operate the engine very fuel-rich during the cold-start and warm-up period. Using an exhaust air pump to supply air in this fuel-rich exhaust stream, a combustible mixture can be generated which is burned either by auto-ignition or by some ignition source upstream of, or in, the catalytic converter. The exotherm produced by this oxidation process significantly heats up the exhaust gas and the heat is largely transferred to the catalytic converter as the exhaust passes through the catalyst. Using the system and method of the present invention, the engine could be controlled to operate alternating cylinders fuel-rich and fuel-lean to achieve the same effect but without the need for an air pump. For example, with a four-cylinder engine, two cylinders could be operated fuel-rich during the cold-start and warm-up period to generate unburned hydrocarbons in the exhaust. The two remaining cylinders would be operated fuel-lean during cold-start and warm-up, to provide oxygen in the exhaust stream.

[0032] The system and method of the present invention may also be utilized with gasoline direct injection engines (GDI). In GDI engines, the fuel is injected directly into the cylinder as a finely atomized spray that evaporates and mixes with air to form a premixed charge of air and vaporized fuel prior to ignition. Contemporary GDI engines require high fuel pressures to atomize the fuel spray. GDI engines operate with stratified charge at part load to reduce the pumping losses inherent in conventional indirect injected engines. A stratified-charge, spark-ignited engine has the potential for burning lean mixtures for improved fuel economy and reduced emissions. Preferably, an overall lean mixture is formed in the combustion chamber, but is controlled to be stoichiometric or slightly fuel-rich in the vicinity of the spark plug at the time of ignition. The stoichiometric portion is thus easily ignited, and this in turn ignites the remaining lean mixture. While pumping losses can be reduced, the operating window currently achievable for stratified charge is limited to low engine speeds and relatively light engine loads. The limiting factors include insufficient time for vaporization and mixing at higher engine speeds and insufficient mixing or poor air utilization at higher loads. By providing vaporized fuel, the system and method of the present invention can widen the operating window for stratified charge operation, solving the problem associated with insufficient time for vaporization and mixing. Advantageously, unlike conventional GDI fuel systems, the fuel pressure employed in the practice of the present invention can be lowered, reducing the overall cost and complexity of the fuel system.

[0033] The invention provides a fuel delivery device for an internal combustion engine which includes a pressurized liquid fuel supply that supplies liquid fuel under pressure, a plurality of capillary flow passages connected to the liquid fuel supply, and a heat source arranged along the plurality of capillary flow passages. The heat source is operable to heat liquid fuel in the at least one capillary flow passage sufficiently to deliver a stream of substantially vaporized fuel. The fuel delivery device is preferably operated to deliver the stream of vaporized fuel to one or more combustion chambers of an internal combustion engine during start-up, warm-up, and other operating conditions of the internal combustion engine. If desired, the plurality of capillary flow passages can be used to deliver liquid fuel to the engine under normal operating conditions.

[0034] The invention also provides a method of delivering fuel to an internal combustion engine, including the steps of supplying the pressurized liquid fuel to a plurality of capillary flow passages, and heating the pressurized liquid fuel in the plurality of capillary flow passages sufficiently to cause a stream of vaporized fuel to be delivered to at least one combustion chamber of an internal combustion engine during start-up, warm-up, and other operating conditions of the internal combustion engine.

[0035] A fuel delivery system according to the invention includes a plurality of capillary-sized flow passage through which pressurized fuel flows before being injected into an engine for combustion. Capillary-sized flow passages can be provided with a hydraulic diameter that is preferably less than 2 mm, more preferably less than 1 mm, and most preferably less than 0.75 mm. Hydraulic diameter is used in calculating fluid flow through a fluid carrying element. Hydraulic radius is defined as the flow area of the fluid-carrying element divided by the perimeter of the solid boundary in contact with the fluid (generally referred to as the "wetted" perimeter). In the case of a fluid carrying element of circular cross section, the hydraulic radius when the element is flowing full is $(\pi D^2/4)/\pi D = D/4$. For the flow of fluids in noncircular fluid carrying elements, the hydraulic diameter is used. From the definition of hydraulic radius, the diameter of a fluid-carrying element having circular cross section is four times its hydraulic radius. Therefore, hydraulic diameter is defined as four times the hydraulic radius.

[0036] When heat is applied along the capillary passageways, at least a portion of the liquid fuel that enters the flow passages is converted to a vapor as it travels along the passageway. The fuel exits the capillary passageways as a vapor, which optionally contains a minor proportion of heated liquid fuel that has not been vaporized. By substantially vaporized, it is meant that at least 50% of the volume of the liquid fuel is vaporized by the heat source, more preferably at least 70%, and most preferably at least 80% of the liquid fuel is vaporized. Although it may be difficult to achieve 100% vaporization due to the complex physical effects that take place, nonetheless complete vaporization would be desirable. These complex physical effects include variations in the boiling point of the fuel since the boiling point is pressure dependent and pressure can vary in the capillary flow passage. Thus, while it is believed that a major portion of the fuel reaches the boiling point during heating in the capillary flow passage, some of the liquid fuel may not be heated enough to be fully vaporized with the result that a portion of the liquid fuel passes through the outlet of the capillary flow passage along with the vaporized fluid.

[0037] Each capillary-sized fluid passage is preferably formed within a capillary body such as a single or multilayer metal, ceramic or glass body. Each passage has an enclosed volume opening to an inlet and an outlet, either of which, or both, may be open to the exterior of the capillary body or may be connected to another passage within the same body or another body or to fittings. The heater can be formed using a portion of the body; for example, a section of a stainless steel or Inconel tube or the heater can be a discrete layer or wire of resistance heating material incorporated in or on the capillary body. Each fluid passage may be any shape comprising an enclosed volume opening to an inlet and an outlet and through which a fluid may pass. Each fluid passage may have any desired cross-section with a preferred cross-section being a circle of uniform diameter. Other capillary fluid passage cross-sections include non-circular shapes such as triangular, square, rectangular, oval or other shape and the cross section of the fluid passage need not be uniform. In the case where the capillary passages are defined by metal capillary tubes, each tube can have an inner diameter of 0.01 to 3 mm, preferably 0.1 to 1 mm, most preferably 0.3 to 0.75 mm. Alternatively, the capillary passages can be defined by transverse cross sectional area of the passage, which can be 8×10^{-5} to 7 mm^2, preferably 8×10^{-3} to 8×10^{-1} mm^2 and more preferably 7×10^{-2} to 4.5×10^{-1} mm^2. Many combinations of multiple capillaries, various pressures, various capillary lengths, amounts of heat applied to the capillary, and different cross-sectional areas will suit a given application.

[0038] The liquid fuel can be supplied to the capillary flow passage under a pressure of at least 0.7 kg/cm^2 (10 psig), preferably at least 1.4 kg/cm^2 (20 psig). In the case where each capillary flow passage is defined by the interior of a stainless steel or Inconel tube having an internal diameter of approximately 0.051 cm (0.020 in) to 0.076 cm (0.030 in) and a length of approximately 2.54 cm (1 in) to 7.62 cm (3 in), the fuel is preferably supplied to the capillary passageway at a pressure of 7 kg/cm^2 (100 psig) or less to achieve mass flow rates required for stoichiometric start of a typical size automotive engine cylinder (on the order of 100-200 mg/s). With two to four capillary passageways of the type described herein, a sufficient flow of substantially vaporized fuel can be provided to ensure a stoichiometric or nearly stoichiometric mixture of fuel and air. It is important that each capillary tube be characterized as having a low thermal inertia, so that each capillary passageway can be brought up to the desired temperature for vaporizing fuel very quickly, preferably within 2.0 seconds, more preferably within 0.5 second, and most preferably within 0.1 second, which is beneficial in applications involving cold starting an engine. The low thermal inertia also could provide advantages during normal operation of the engine, such as by improving the responsiveness of the fuel delivery to sudden changes in engine power demands.

[0039] In order to meter fuel through the low thermal inertia capillary passages described herein, a valve arrangement effective to regulate vapor flow from the distal end of a fuel injector is required. Because of the small thermal mass of capillary flow passages contemplated herein, the valve arrangement used to regulate vapor flow must be designed to add minimal thermal mass to the heated system so that warm-up time and effectiveness is not degraded. Likewise, the surface area wetted by the fuel must be minimized so that the vaporized fuel does not re-condense on contact and jeopardize performance.

[0040] The preferred forms described below each allow for the pulsed delivery of fuel vapor and provide the capacity to switch over to liquid fuel injection. In each of the forms herein described, the vapor flow path through the capillary flow passages is actively heated such that the working fluid is in the vapor phase upon coming into contact with the valve. It is preferred that the valve itself not be actively heated.

[0041] Referring now to FIGS. 1 and 2, an embodiment of a fuel injector 100 for vaporizing liquid fuel is presented. Fuel injector 100 has an inlet 190 and outlet 192, which may advantageously be designed in a manner similar to conventional port fuel injectors, so as to be substantially interchangeable therewith. As is particularly preferred, this embodiment possesses a ball-in-cone valve assembly 144. A capillary bundle 115 is positionable within central bore 170.

[0042] Capillary bundle 115 is shown having a plurality of capillary flow passages 112, each having an inlet end 114 and an outlet end 116, with the inlet end 114 in fluid communication with a liquid fuel source F. A heat source 120 is arranged along each capillary flow passage 112. Each heat source 120 is provided by forming capillary flow passage 112 from a tube of electrically resistive material, a portion of each capillary flow passage 112 forming a heater element when a source of electrical current is connected to the tube at electrical connections 122 and 124 for delivering current therethrough. Each heat source 120, as may be appreciated, is then operable to heat the liquid fuel in each capillary flow passage 112 to a level sufficient to change at least a portion thereof from a liquid state to a vapor state and deliver a stream of substantially vaporized fuel from outlet end 116 of each capillary flow passage 112. Once again, this method of vapor delivery into the body of the injector minimizes the surface area of the material that comes into contact with the vaporized fuel and, therefore, also minimizes the thermal mass that must be heated in order to prevent premature condensation of the vapor.

[0043] Capillary bundle 115 may consist of from 2 to 4 thin-walled capillary flow passages 112 (0.081 cm (0.032 in) outer diameter (OD) and 0.071-0.074 cm (0.028-0.029 in) inner diameter (ID)). Capillary flow passages 112 may be constructed from stainless steel or annealed Inconel 600 tubes, each having a heated length 20 of from about 3.18 cm (1.25 in) to about 6.25 cm (2.50 in). When current is supplied to capillary bundle 115, the heated source 120 of each capillary passage 112 becomes hot and subsequently vaporizes fuel as the fuel flows through the capillary passages 112.

[0044] One method having utility in the attaching of the capillary bundle 115 in the region of the ball-in-cone valve assembly 144 is through the use of laser welding. Specifically, the capillary passages 112 are laser welded onto a securing disk, where the capillary passages 112 extend through the thickness of the disk. This securing disk is then welded to the inner diameter of the central bore 170 that extends down the centerline of the injector 100. As may be appreciated, the capillary passages 112 are secured in position through this welding process. Once again, although this method of attachment does not result in thermal isolation of the capillaries from the metal portion of the injector 100, the resultant increase in thermal mass is not considered to be significant since the flow path is relatively small (i.e., the point of connection between the securing disk and the centerline passage is small). However, it should be recognized that a thermally insulating material could also be used to hold the securing disk in place.

[0045] A brazing technique may be used to attach the capillary bundle 115 in the region of the ball-in-cone valve assembly 144. Through this technique, a cup-and-disk apparatus is used to secure the outlet ends 16 of the capillary passages 112 in place. The cup portion of this assembly consists of a short cylindrical piece of metal, into which the outlet ends 116 of the capillary passages 112 are fit. The ends of the capillary passages are then brazed to the inner diameter of the cup. The end of the cup closest to the ball-in-cone valve assembly 144 is flared out such that it is perpendicular to the axis of the cylinder. This cup portion is then brazed to the inner diameter of a separate disk. A separate method is used to ensure that there is no fluid flow path between the disk and the fuel injector housing 180. Some examples of such methods include the use of a soft weld to create a physical connection between the disk and the fuel injector housing 180 or the use of an O-ring. It should be noted that the non-magnetic property of the braze, the magnetic properties of the cup and the disk, and the orientation and thickness of each piece in this assembly are designed to act as part of the magnetic circuit of the fuel injector 100.

[0046] Referring to FIG. 2, a low-mass ball valve assembly 144 is operated by solenoid 128. Solenoid 128 has coil windings 132 connected to electrical connectors 176. When the coil windings 132 are energized, a magnetic field is directed through plate 146, which is connected to ball 140, thereby causing it to lift from conical sealing surface 142, exposing an orifice 152, and allowing fuel to flow. When electricity is cut off from the coil windings 132, a spring (not shown) returns the plate 146 and attached ball 140 to their original position.

[0047] In an alternate embodiment, a solenoid element (not shown) could be drawn into the center of coil windings 132 to lift ball 140, which could be connected to the solenoid element. Movement of the solenoid element, caused by applying electricity to the coil windings 132, would cause the ball 40 to be drawn away from conical sealing surface 142, exposing an orifice 152, and allowing fuel to flow. Again, when electricity is cut off from the coil windings 132, a spring (not shown) returns the ball 140 to its original position.

[0048] The spring is dimensioned such that the force of the spring pushing the ball against the conical section of the injector exit is sufficient to block the flow of the pressurized liquid fuel in the injector.

[0049] Referring still to FIG. 2, upon exiting the outlet ends 116 of capillary passages 112, fuel flow is directed toward ball-in-valve assembly 144 of fuel injector 100. As with conventional fuel injectors, the metering section 150 consists of a solenoid operated ball-in-cone metering valve assembly 144. The act of actuating the solenoid 128 to move the plate 146 and ball 140 assembly between the open and closed position serves to meter the flow of fuel exiting the injector 100. Upon exiting the orifice 152, the fuel flows through a conical chimney section 160 to create the desired spray atomization and spray angle. The angle of the cone can span a wide range of values provided that the ball forms a seal with the surface of the cone. Chimney section 160 also serves to allow the injector 100 to satisfy overall length requirements of conventional port fuel injectors. As may be appreciated, proper operation of injector 100 is possible without the inclusion of the chimney section 160.

[0050] As may be appreciated, the ball-in-cone valve assembly 144 allows vaporized fuel flow to be metered through a metering section 150 having low thermal inertia and minimal wetted area. These features are useful for ensuring that vaporized fuel delivery is achieved with a minimal temporal delay after initial power-up. These features have been found to also mitigate against premature recondensation of fuel vapor as it exits the injector 100. This ensures that minimal droplet sizes are achieved during steady-state operation of the injector 100 when operated in the fuel vaporizer mode. Nevertheless, it should be readily recognized that the ball-in-cone valve assembly 140 depicted in FIG. 1 represents one of several valve designs that can be used in the design of the injectors of the present invention. The critical features of a suitable valve design used to meter fuel vapor are the combination of low thermal inertia and minimal wetted area. Other suitable valve designs possessing these critical features are disclosed in U.S. Application Serial Number 10/342,267, filed on January 15, 2003, the contents of which are hereby incorporated by reference for all that is disclosed.

[0051] Still referring to FIG 2, the electric circuit used to supply heat to the capillary passages 112 consists of a power supply (not shown) and a controller 2050 (see FIG. 5), capillary bundle 115, and spades 174 attached to the capillary bundle 115 to allow resistance heating of heated section 120 of the capillary passages 112. In the preferred embodiment, the capillary bundle 115 is formed through the use of a bus proximate to the inlet ends 114 of the capillary passages 112 and another bus proximate to the outlet ends 116 of the capillary passages 112 such that the entire capillary bundle 115 forms a single conductive unit. Electrical connections are made such that four spade connections 174 and 176 are molded into the bobbin 130. Two of the connections at the feed end of the bobbin 130 serve to power the solenoid 128. An additional connection at the inlet end of the bobbin 130 is attached to the inlet end of the capillary bundle 115. A fourth electrical connection is embedded through the bobbin 130 and terminates at the distal end of the bobbin 130 such that an electrical connection is made with the outlet ends 116 of the capillary bundle 115.

[0052] To achieve vaporization in a cold engine environment, there exists a tradeoff between minimizing the power supplied to the injector for heating and minimizing the associated warm-up time, as shown in FIG. 3. As may be appreciated, the power available to heat the injector is limited to the available battery power, while the injector warm-up time is limited by consumer performance requirements.

[0053] In addition to the design and performance requirements outlined above, it is also necessary to have some degree of control over the fuel/air ratio as necessitated by the exhaust after-treatment scheme and/or the start-up control strategy. At a minimum, the fuel injector must have the capacity to accommodate the requisite turndown ratio, from cranking to idle to other engine operating conditions. However, in some forms, maximum emission reduction is achieved by injecting vapor only during the portion of the engine cycle in which the intake valves are open. Such an injection profile is illustrated in FIG. 4, together with the approximate times associated with each portion of a four-stroke cycle. As indicated, at 1500 rpm, open valve injection is achieved through control of the vapor flow rate such that injection occurs for 20 ms followed by a 60 ms period in which little to no vapor is delivered to the engine.

[0054] Prior valve designs used to regulate the flow of vapor fuel injectors have been known to produce an undesirable increase in the thermal mass, which is the mass that must be heated in order to achieve sufficient temperature to vaporize the liquid. This increase in thermal mass is undesirable because it increases the warm-up time of the injector (see FIG. 3) and, as such, compromises the vapor quality issued from the injector during startup and/or transient operation.

[0055] Referring now to FIG. 5, an exemplary schematic of a control system 2000 is shown. Control system 2000 is used to operate an internal combustion engine 2110 incorporating a liquid fuel supply valve 2220 in fluid communication with a liquid fuel supply 2010 and a liquid fuel injection path 2260, a vaporized fuel supply valve 2210 in fluid communication with a liquid fuel supply 2010 and capillary flow passages 2080, and an oxidizing gas supply valve 2020 in fluid communication with an oxidizing gas supply 2070 and capillary flow passages 2080. The control system includes a controller 2050, which typically receives a plurality of input signals from a variety of engine sensors such as engine speed sensor 2060, intake manifold air thermocouple and intake pressure sensor 2062, coolant temperature sensor 2064, exhaust air-fuel ratio sensor 2150, fuel supply pressure 2012, etc. In operation, the controller 2050 executes a control algorithm based on one or more input signals and subsequently generates an output signal 2024 to the oxidizer supply valve 2020 for cleaning clogged capillary passages in accordance with the invention, an output signal 2014 to the liquid fuel supply valve 2220, an output signal 2034 to the fuel supply valve 2210, and a heating power command 2044 to a power supply which delivers power to heat to the capillaries 2080.

[0056] In operation, the system herein proposed can also be configured to feed back heat produced during combustion through the use of exhaust gas recycle heating, such that the liquid fuel is heated sufficiently to substantially vaporize the liquid fuel as it passes through the capillary flow passages 2080 reducing or eliminating or supplementing the need to electrically or otherwise heat the capillary flow passages 2080.

[0057] As will be appreciated, the preferred forms of fuel injectors depicted in FIGS. 1 and 2 may also be used in connection with another embodiment of the present invention. The injector may also include means for cleaning deposits formed during operation of injector. As envisioned, the means for cleaning deposits includes placing each capillary flow passage in fluid communication with a solvent, enabling the in-situ cleaning of each capillary flow passage when the solvent is introduced into each capillary flow passage. While a wide variety of solvents have utility, the solvent may comprise liquid fuel from the liquid fuel source. In operation, the heat source should be phased-out over time or deactivated during the cleaning of capillary flow passage. As will be appreciated by those skilled in the art, the injector design depicted in FIGS. 1 and 2 can be easily adapted to employ in-situ solvent cleaning.

[0058] Referring again to FIG. 2, the heated capillary flow passages 112 of fuel injector 100 can produce vaporized streams of fuel, which condense in air to form an aerosol. Compared to conventional automotive port-fuel injectors that deliver a fuel spray comprised of droplets in the range of 150 to 200 μm Sauter Mean Diameter (SMD), the aerosol has an average droplet size of less than 25 μm SMD, preferably less than 15 μm SMD. Thus, the majority of the fuel droplets produced by the heated capillary injectors according to the invention can be carried by an air stream, regardless of the flow path, into the combustion chamber.

[0059] The difference between the droplet size distributions of a conventional injector and the fuel injectors disclosed herein is particularly critical during cold-start and warm-up conditions. Specifically, using a conventional port-fuel injector, relatively cold intake manifold components necessitate over-fueling such that a sufficient fraction of the large fuel droplets, impinging on the intake components, are vaporized to produce an ignitable fuel/air mixture. Conversely, the vaporized fuel and fine droplets produced by the fuel injectors disclosed herein are essentially unaffected by the temperature of engine components upon start-up and, as such, eliminate the need for over-fueling during engine start-up conditions. The elimination of over-fueling combined with more precise control over the fuel/air ratio to the engine afforded through the use of the fuel injectors disclosed herein results in greatly reduced cold start emissions compared to those produced by engines employing conventional fuel injector systems. In addition to a reduction in over-fueling, it should also be noted that the heated capillary injectors disclosed herein further enable fuel-lean operation during cold-start and warm-up, which results in a greater reduction in tailpipe emissions while the catalytic converter warms up.

[0060] Fuel can be supplied to the injectors disclosed herein at a pressure of less than 7 kg/cm^2 (100 psig), preferably less than 4.9 kg/cm^2 (70 psig), more preferably less than 4.2 kg/cm^2 (60 psig) and even more preferably less than 3.2 kg/cm^2 (45 psig). It has been shown that this embodiment produces vaporized fuel that forms a distribution of aerosol droplets that mostly range in size from 2 to 30 μm SMD with an average droplet size of about 5 to 15 μm SMD, when the vaporized fuel is condensed in air at ambient temperature. The preferred size of fuel droplets to achieve rapid and nearly complete vaporization at cold-starting temperatures is less than about 25 μm. This result can be achieved by applying approximately 10.2 to 40.8 kg/sec (100 to 400W), e.g., 20.4 kg/sec (200W) of electrical power, which corresponds to 2-3% of the energy content of the vaporized fuel to the capillary bundle. Alternatives for heating the tube along its length could include inductive heating, such as by an electrical coil positioned around the flow passage, or other sources of heat positioned relative to the flow passage to heat the length of the flow passage through one or a combination of conductive, convective or radiative heat transfer. After cold-start and warm-up, it is not necessary to heat the capillary bundle and the unheated capillaries can be used to supply adequate volumes of liquid fuel to an engine operating at normal temperature. After approximately 20 seconds (or preferably less) from starting the engine, the power used to heat the capillaries can be turned off and liquid injection initiated, for normal engine operation. Normal engine operation can be performed by liquid fuel injection via continuous injection or pulsed injection, as those skilled in the art will readily recognize.

[0061] The fuel injectors disclosed herein can be positioned in an engine intake manifold at the same location as existing port-fuel injectors or at another location along the intake manifold. The fuel injectors disclosed herein provide advantages over systems that produce larger droplets of fuel that must be injected against the back side of a closed intake valve while starting the engine. Preferably, the outlet of the capillary tube is positioned flush with the intake manifold wall similar to the arrangement of the outlets of conventional fuel injectors.

<u>Example</u>

[0062] Laboratory bench tests were performed using gasoline supplied at constant pressure with a micro-diaphragm pump system for the capillaries described below. Peak droplet sizes and droplet size distributions were measured using a Spray-Tech laser diffraction system manufactured by Malvern. Droplet sizes are given in Sauter Mean Diameter (SMD). SMD is the diameter of a droplet whose surface-to-volume ratio is equal to that of the entire spray and relates to the spray's mass transfer characteristics.

[0063] FIG. 6 presents the liquid mass flow rate and vapor mass flow rate of fuel through a single 1.5" capillary as a function of the pressure drop over the capillary. In FIG. 6, flow through a "regular wall" (0.081 cm (0.032 in) OD, 0.051 cm (0.020 in) ID) capillary is compared to flow through a "thin wall" (0.081 cm (0.032 in) OD, 0.071-0.074 cm (0.028-0.029 in) ID) capillary. For the results shown in Fig. 6, each capillary was constructed of 304 stainless steel, although it should be readily recognized that similar results are achievable with Inconel 600. A critical difference between the use of stainless steel 304 and Inconel 600 in this application is the electrical resistivity of each material. Specifically, Inconel 600 has a higher resistivity than stainless steel 304 and, therefore, is better suited to the present application where higher resistivity is essential for compatibility with the electrical circuit used to supply heat to the capillaries.

[0064] As indicated in FIG. 6, the increased flow area of the "thin wall" capillary results in significant increases in both liquid and vapor mass flow rate compared to the "regular wall" capillary. The solid vertical line on the graph represents a design point based on a total fuel injector pressure of 3.5 kg/cm^2 (50 psig) and a requirement of less than 10% pressure drop over the capillary. At this design point, the results in FIG. 6 indicate that the liquid and vapor flow rate requirements for most automotive port fuel injection applications can be met with 2-4 thin-walled, 3.8 cm (1.5 in) capillaries.

[0065] FIG. 7 presents fuel droplet size (SMD in microns) as a function of the resistance set-point of a 3.8 cm (1.5 in) thin wall capillary. The results indicate that the droplet sizes vary significantly with the temperature set-point of the capillary expressed as the ratio of the heated capillary resistance (R) to the cold capillary resistance (R_o). However, the preferred range for the temperature set-point of the stainless steel capillary is around an R/R_o value of 1.12 to 1.2. For stainless steel, this range corresponds to a bulk capillary temperature on the order of 140 °C to 220°C.

Claims

1. A fuel injector (100) for vaporizing and metering a liquid fuel to an internal combustion engine (2110), comprising:

(a) a plurality of capillary flow passages (112), each of said plurality of capillary flow passages (112) having an inlet end (114) and an outlet end (116);

(b) a heat source (120) arranged along each of said plurality of capillary flow passages (112), each heat source (120) is provided by forming a capillary flow passage (112) from a tube of electrically resistive material, a portion of each capillary flow passage (112) forming a heater element when a source of electrical current is connected to the tube, said heat source (120) operable to heat the liquid fuel in each of said plurality of capillary flow passages (112) to a level sufficient to change at least a portion thereof from the liquid state to a vapor state and deliver a stream of substantially vaporized fuel from each said outlet end (116) of said plurality of capillary flow passages (112); and

(c) a valve for metering substantially vaporized fuel to the internal combustion engine (2110), said valve located downstream of each said outlet end (116) of said plurality of capillary flow passages (112),

wherein said valve for metering fuel to the internal combustion engine (2110) is a low-mass ball valve assembly (144) operated by a solenoid (128).

2. The fuel injector of claim 1, wherein said low-mass ball valve assembly (144) comprises a ball (140) connected to said solenoid (128), a conical sealing surface (142) and a spring dimensioned to provide a spring force operable to push said ball (140) against said conical section and block fluid flow from the injector (100).

3. The fuel injector of claim 1 or 2, wherein said low-mass ball valve assembly (144) further comprises an exit orifice (152), wherein movement of said solenoid (128) caused by applying electricity to said solenoid (128) causes said ball (140) to be drawn away from said conical sealing surface (142), allowing fuel to flow through said exit orifice (152).

4. The fuel injector of any preceding claim, wherein each of said plurality of capillary flow passages (112) are formed within a tube selected from the group consisting of stainless steel and Inconel and have an internal diameter from about 0,508 mm to about 0,762 mm (about 0,020 to about 0,030 inches) and a length of from about 2,54 cm to about 7,62 cm (about 1 to about 3 inches).

5. The fuel injector of any preceding claim, further comprising:

(d) means for cleaning deposits formed during operation of the injector wherein said means for cleaning deposits employs a solvent comprising liquid fuel from the liquid fuel source and wherein the heat source (120) is phased-out during cleaning of said capillary flow passage (112).

6. The fuel injector of any preceding claim, wherein said heat source includes a resistance heater.

7. A method of delivering vaporized fuel to an internal combustion engine (2110), comprising the steps of:

(a) supplying liquid fuel to a plurality of capillary flow passages (112) of a fuel injector (100),
(b) heating the liquid fuel within the plurality of capillary flow passages (112) of the fuel injector (100) by a heat source (120) arranged along each of said plurality of capillary flow passages (112), each heat source (120) forming a capillary flow passage (112) from a tube of electrically resistive material, a portion of each capillary flow passage (112) forming a heater element when a source of electrical current is connected to the tube, and causing vaporized fuel to pass through each outlet of the plurality of capillary flow passages (112), and
(c) metering the vaporized fuel to a combustion chamber of the internal combustion engine (2110) through a valve located downstream of each outlet of the plurality of capillary flow passages (112),

wherein in step (c) the valve for metering fuel to the internal combustion engine (2110) is a low-mass valve assembly (144) operated by a solenoid (128).

8. The method of claim 7, wherein said step of metering vaporized fuel to the combustion chamber of the internal combustion engine (2110) is limited to start-up and warm-up of the internal combustion engine (2110).

9. The method of claim 7 or 8, further comprising delivering liquid fuel to the combustion chamber of the internal combustion engine (2110) when the internal combustion engine (2110) is at a fully warmed condition.

10. The method of claims 7, 8 or 9, further comprising cleaning periodically the plurality of capillary flow passages (112) said step of periodic cleaning comprising (i) phasing-out said heating of the plurality of capillary flow passages (112), (ii) supplying a solvent to the plurality of capillary flow passages (112), whereby deposits formed in the plurality of capillary flow passages (112) are substantially removed, wherein the solvent includes liquid fuel from the liquid fuel source.

11. The method of claim 7, wherein the low-mass ball valve assembly (144) comprises a ball (140) connected to the solenoid (128), a conical sealing surface (142) and a spring dimensioned to provide a spring force operable to push the ball (140) against the conical section and block fluid flow from the injector (100).

12. The method of claim 11, wherein movement of the solenoid (128) caused by applying electricity to the solenoid causes the ball (140) to be drawn away from the conical sealing surface (142), allowing fuel to flow through an exit orifice (152).

Patentansprüche

1. Kraftstoffeinspritzeinrichtung (100) zum Verdampfen und Dosieren eines flüssigen Kraftstoffs für eine Brennkraftmaschine (2110), die umfasst:

(a) mehrere Kapillarströmungsdurchlässe (112), wobei jeder der mehreren Kapillarströmungsdurchlässe (112) ein Einlassende (114) und ein Auslassende (116) besitzt;
(b) eine Wärmequelle (120), die längs jedes der

mehreren Kapillarströmungsdurchlässe (112) angeordnet ist, wobei jede Wärmequelle (120) durch Bilden eines Kapillarströmungsdurchlasses (112) aus einem Rohr aus einem elektrisch resistiven Material geschaffen ist, wobei ein Abschnitt jedes Kapillarströmungsdurchlasses (112) ein Heizelement bildet, wenn mit dem Rohr eine Quelle für elektrischen Strom verbunden ist, wobei die Wärmequelle (120) betreibbar ist, um den flüssigen Kraftstoff in jedem der mehreren Kapillarströmungsdurchlässe (112) auf ein Niveau zu erwärmen, das ausreicht, um wenigstens einen Teil hiervon vom flüssigen Zustand in einen dampfförmigen Zustand zu verwandeln und um einen Strom von im Wesentlichen verdampftem Kraftstoff von jedem Auslassende (116) der mehreren Kapillarströmungsdurchlässe (112) auszugeben;
(c) ein Ventil zum Dosieren von im Wesentlichen verdampftem Kraftstoff für die Brennkraftmaschine (2110), wobei sich das Ventil stromabseitig jedes Auslassendes (116) der mehreren Kapillarströmungsdurchlässe (112) befindet,

wobei das Ventil zum Dosieren von Kraftstoff für die Brennkraftmaschine (2110) eine Kugelventilanordnung (144) mit geringer Masse ist, die durch ein Solenoid (128) betätigt wird.

2. Kraftstoffeinspritzeinrichtung nach Anspruch 1, wobei die Kugelventilanordnung (144) mit geringer Masse eine Kugel (140), die mit dem Solenoid (128) verbunden ist, eine konische Dichtungsoberfläche (142) und eine Feder, die so bemessen ist, dass sie eine Federkraft bereitstellt, um die Kugel (140) gegen den konischen Abschnitt zu drängen und um eine Fluidströmung von der Einspritzeinrichtung (100) zu blockieren, umfasst.

3. Kraftstoffeinspritzeinrichtung nach Anspruch 1 oder 2, wobei die Kugelventilanordnung (144) mit geringer Masse ferner eine Austrittsöffnung (152) umfasst, wobei die Bewegung des Solenoids (128), die durch Anlegen einer elektrischen Spannung an das Solenoid (128) hervorgerufen wird, veranlasst, dass die Kugel (140) von der konischen Dichtungsoberfläche (142) weggezogen wird, um zu ermöglichen, dass Kraftstoff durch die Austrittsöffnung (152) strömt.

4. Kraftstoffeinspritzeinrichtung nach einem vorhergehenden Anspruch, wobei jeder der mehreren Kapillarströmungsdurchlässe (112) in einem Rohr ausgebildet ist, das aus der Gruppe gewählt ist, die aus Edelstahl und Inconel besteht, und einen Innendurchmesser im Bereich von etwa 0,508 mm bis etwa 0,762 mm (etwa 0,020 bis 0,030 Zoll) sowie eine Länge im Bereich von etwa 2,54 cm bis etwa 7,62 cm (etwa 1 bis etwa 3 Zoll) besitzt.

5. Kraftstoffeinspritzeinrichtung nach einem vorhergehenden Anspruch, die ferner umfasst:

(d) Mittel, um Ablagerungen, die während des Betriebs der Einspritzeinrichtung gebildet werden, zu entfernen, wobei die Mittel zum Reinigen von Ablagerungen ein Lösungsmittel verwenden, das flüssigen Kraftstoff von der Flüssigkraftstoffquelle enthält, und wobei die Wärmequelle (120) während des Reinigens des Kapillarströmungsdurchlasses (112) außer Betrieb genommen wird.

6. Kraftstoffeinspritzeinrichtung nach einem vorhergehenden Anspruch, wobei die Wärmequelle eine Widerstandsheizeinrichtung enthält.

7. Verfahren zum Ausgeben von verdampftem Kraftstoff an eine Brennkraftmaschine (2110), das die folgenden Schritte umfasst:

(a) Zuführen von flüssigem Kraftstoff zu mehreren Kapillarströmungsdurchlässen (112) einer Kraftstoffeinspritzeinrichtung (100)
(b) Erwärmen des flüssigen Kraftstoffs in den mehreren Kapillarströmungsdurchlässen (112) der Kraftstoffeinspritzeinrichtung (100) mittels einer Wärmequelle (120), die längs jedes der mehreren der Kapillarströmungsdurchlässe (112) angeordnet ist, wobei jede Wärmequelle (120) einen Kapillarströmungsdurchlass (112) aus einem Rohr aus einem elektrisch resistiven Material bildet, wobei ein Abschnitt jedes Kapillarströmungsdurchlasses (112) ein Heizelement bildet, wenn eine Quelle für elektrischen Strom mit dem Rohr verbunden ist, und wobei veranlasst wird, dass sich verdampfter Kraftstoff durch jeden Auslass der mehreren Kapillarströmungsdurchlässe (112) bewegt, und
(c) Dosieren des verdampften Kraftstoffs für eine Brennkammer der Brennkraftmaschine (2110) mittels eines Ventils, das sich stromabseitig jedes Auslasses der mehreren Kapillarströmungsdurchlässe (112) befindet, wobei im Schritt (c) das Ventil zum Dosieren von Kraftstoff für die Brennkraftmaschine (2110) eine Ventilanordnung (144) mit geringer Masse ist, die durch ein Solenoid (128) betätigt wird.

8. Verfahren nach Anspruch 7, wobei der Schritt des Dosierens von verdampftem Kraftstoff für die Brennkammer der Brennkraftmaschine (2110) auf ein Anlassen und Aufwärmen der Brennkraftmaschine (2110) eingeschränkt ist.

9. Verfahren nach Anspruch 7 oder 8, das ferner das

Ausgeben von flüssigem Kraftstoff zu der Brennkammer der Brennkraftmaschine (2110), wenn die Brennkraftmaschine (2110) in einem vollständig erwärmten Zustand ist, umfasst.

10. Verfahren nach den Ansprüchen 7, 8 oder 9, das ferner das periodische Reinigen der mehreren Kapillarströmungsdurchlässe (112) umfasst, wobei der Schritt des periodischen Reinigens umfasst: (i) Unterbrechen des Heizens der mehreren Kapillarströmungsdurchlässe (112), (ii) Zuführen eines Lösungsmitteln zu den mehreren Kapillarströmungsdurchlässen (112), wobei Ablagerungen, die in den mehreren Kapillarströmungsdurchlässen (112) gebildet sind, im Wesentlichen entfernt werden, wobei das Lösungsmittel flüssigen Kraftstoff von der Flüssigkraftstoffquelle enthält.

11. Verfahren nach Anspruch 7, wobei die Kugelventilanordnung (144) mit geringer Masse eine Kugel (140), die mit dem Solenoid (128) verbunden ist, eine konische Dichtungsoberfläche (142) und eine Feder, die so bemessen ist, dass sie eine Federkraft bereitstellt, um die Kugel (140) gegen den konischen Abschnitt zu drängen und um eine Fluidströmung aus der Einspritzeinrichtung (100) zu blockieren, umfasst.

12. Verfahren nach Anspruch 11, wobei die Bewegung des Solenoids (128), die durch Anliegen einer elektrischen Spannung an das Solenoid hervorgerufen wird, veranlasst, dass die Kugel (140) von der konischen Dichtungsoberfläche (142) weggezogen wird, um zu ermöglichen, dass Kraftstoff durch eine Auslassöffnung (152) strömt.

Revendications

1. Injecteur de carburant (100) servant à vaporiser et doser un carburant liquide acheminé à un moteur à combustion interne (2110), comprenant :

(a) une pluralité de passages d'écoulement capillaire (112), chacun de ladite pluralité de passages d'écoulement capillaire (112) ayant une extrémité d'entrée (114) et une extrémité de sortie (116) ;
(b) une source de chaleur (120) aménagée le long de chacun de ladite pluralité de passages d'écoulement capillaire (112), chaque source de chaleur (120) étant constituée en formant un passage d'écoulement capillaire (112) à partir d'un tube de matériau électriquement résistant, une partie de chaque passage d'écoulement capillaire (112) formant un élément chauffant lorsqu'une source de courant électrique est connectée au tube, ladite source de chaleur (120) pouvant être exploitée pour chauffer le carburant liquide dans chacun de ladite pluralité de passages d'écoulement capillaire (112) à un niveau suffisant pour modifier au moins une partie de celui-ci, de l'état liquide à un état de vapeur et délivrer un courant de carburant sensiblement vaporisé par chaque dite extrémité de sortie (116) de ladite pluralité de passages d'écoulement capillaire (112) ; et
(c) une soupape servant à doser le carburant sensiblement vaporisé acheminé au moteur à combustion interne (2110), ladite soupape étant placée en aval de chaque dite extrémité de sortie (116) de ladite pluralité de passages d'écoulement capillaire (112),

dans lequel ladite soupape servant à doser le carburant acheminé au moteur à combustion interne (2110) est un assemblage (144) de robinet à bille de faible masse activé par un solénoïde (128).

2. Injecteur de carburant selon la revendication 1, dans lequel ledit assemblage (144) de robinet à bille de faible masse comprend une bille (140) raccordée audit solénoïde (128), une surface d'étanchéité conique (142) et un ressort dimensionné pour fournir une force élastique qui est à même de pousser ladite bille (140) contre ladite section conique et de bloquer l'écoulement de fluide venant de l'injecteur (100).

3. Injecteur de carburant selon la revendication 1 ou 2, dans lequel l'assemblage (144) de robinet à bille de faible masse comprend en outre un orifice de sortie (152), dans lequel le mouvement dudit solénoïde (128) provoqué par l'application d'électricité audit solénoïde (128) amène ladite bille (140) à être reculée de ladite surface d'étanchéité conique (142), permettant au carburant de s'écouler à travers ledit orifice de sortie (152).

4. Injecteur de carburant selon l'une quelconque des revendications précédentes, dans lequel chaque passage de ladite pluralité de passages d'écoulement capillaire (112) est formé à l'intérieur d'un tube sélectionné dans le groupe constitué de l'acier inoxydable et de l'Inconel et a un diamètre interne d'environ 0,508 mm à environ 0,762 mm (environ 0,020 à environ 0,030 pouce) et une longueur d'environ 2,54 cm à environ 7,62 cm (environ 1 à environ 3 pouces).

5. Injecteur de carburant selon l'une quelconque de la revendication précédente, comprenant en outre : (d) des moyens servant à nettoyer les dépôts formés pendant le fonctionnement de l'injecteur, dans lequel lesdits moyens servant à nettoyer les dépôts emploient un solvant comprenant du carburant liquide issu de la source de carburant liquide et dans lequel la source de chaleur (120) est interrompue pendant le nettoyage dudit passage d'écoulement capillaire (112).

6. Injecteur de carburant selon l'une quelconque des revendications précédentes, dans lequel ladite source de chaleur comprend un dispositif de chauffage à résistance.

7. Procédé d'acheminement de carburant vaporisé à un moteur de combustion interne (2110), comprenant les étapes consistant à :

   (a) alimenter en carburant liquide une pluralité de passages d'écoulement capillaire (112) d'un injecteur de carburant (100),
   (b) chauffer le carburant liquide à l'intérieur de la pluralité de passages d'écoulement capillaire (112) de l'injecteur de carburant (100) par une source de chaleur (120) aménagée le long de chaque passage de ladite pluralité de passages d'écoulement capillaire (112), chaque source de chaleur (120) formant un passage d'écoulement capillaire (112) et étant constituée à partir d'un tube de matériau électriquement résistant, une partie de chaque passage d'écoulement capillaire (112) formant un élément chauffant lorsqu'une source de courant électrique est connectée au tube, et amener le carburant vaporisé à passer à travers chaque sortie de la pluralité de passages d'écoulement capillaire (112), et
   (c) doser le carburant vaporisé acheminé à une chambre de combustion du moteur à combustion interne (2110) via une soupape placée en aval de chaque sortie de la pluralité de passages d'écoulement capillaire (112), dans lequel, à l'étape (c), la soupape servant à doser le carburant acheminé au moteur de combustion interne (2110) est un assemblage (144) de robinet à bille de faible masse activé par un solénoïde (128).

8. Procédé selon la revendication 7, dans lequel ladite étape de dose du carburant vaporisé acheminé à la chambre de combustion du moteur à combustion interne (2110) est limitée au démarrage et au chauffage du moteur à combustion interne (2110).

9. Procédé selon la revendication 7 ou 8, comprenant en outre l'acheminement de carburant liquide à la chambre de combustion du moteur à combustion interne (2110) lorsque le moteur à combustion interne (2110) est dans un état entièrement chauffé.

10. Procédé selon la revendication 7, 8 ou 9, comprenant en outre le nettoyage périodique de la pluralité de passages d'écoulement capillaire (112), ladite étape de nettoyage périodique comprenant les étapes consistant à (i) interrompre le chauffage de la pluralité de passages d'écoulement capillaire (112), (ii) alimenter en solvant la pluralité de passages d'écoulement capillaire (112), de sorte que les dépôts formés dans la pluralité de passages d'écoulement capillaire (112) soient sensiblement éliminés, dans lequel le solvant comprend du carburant liquide issu de la source de carburant liquide.

11. Procédé selon la revendication 7, dans lequel l'assemblage (144) de robinet à bille de faible masse comprend une bille (140) raccordée au solénoïde (128), une surface étanche conique (142) et un ressort dimensionné pour fournir une force élastique qui est à même de pousser la bille (140) contre la section conique et de bloquer l'écoulement de fluide issu de l'injecteur (100).

12. Procédé selon la revendication 11, dans lequel le mouvement du solénoïde (128) provoqué par l'application d'électricité au solénoïde amène la bille (140) à se retirer de la surface d'étanchéité conique (142), permettant au carburant de s'écouler à travers un orifice de sortie (152).

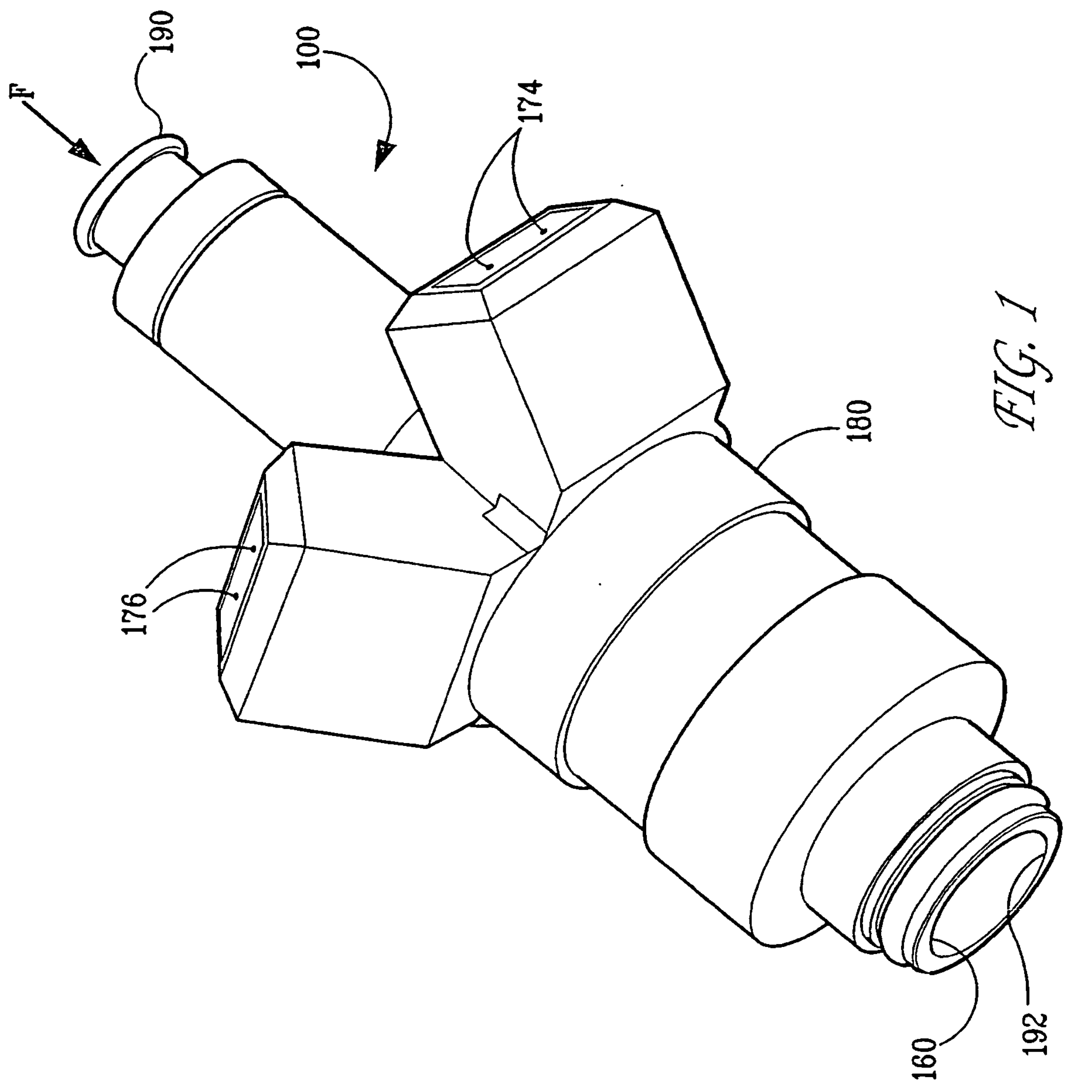


FIG. 1

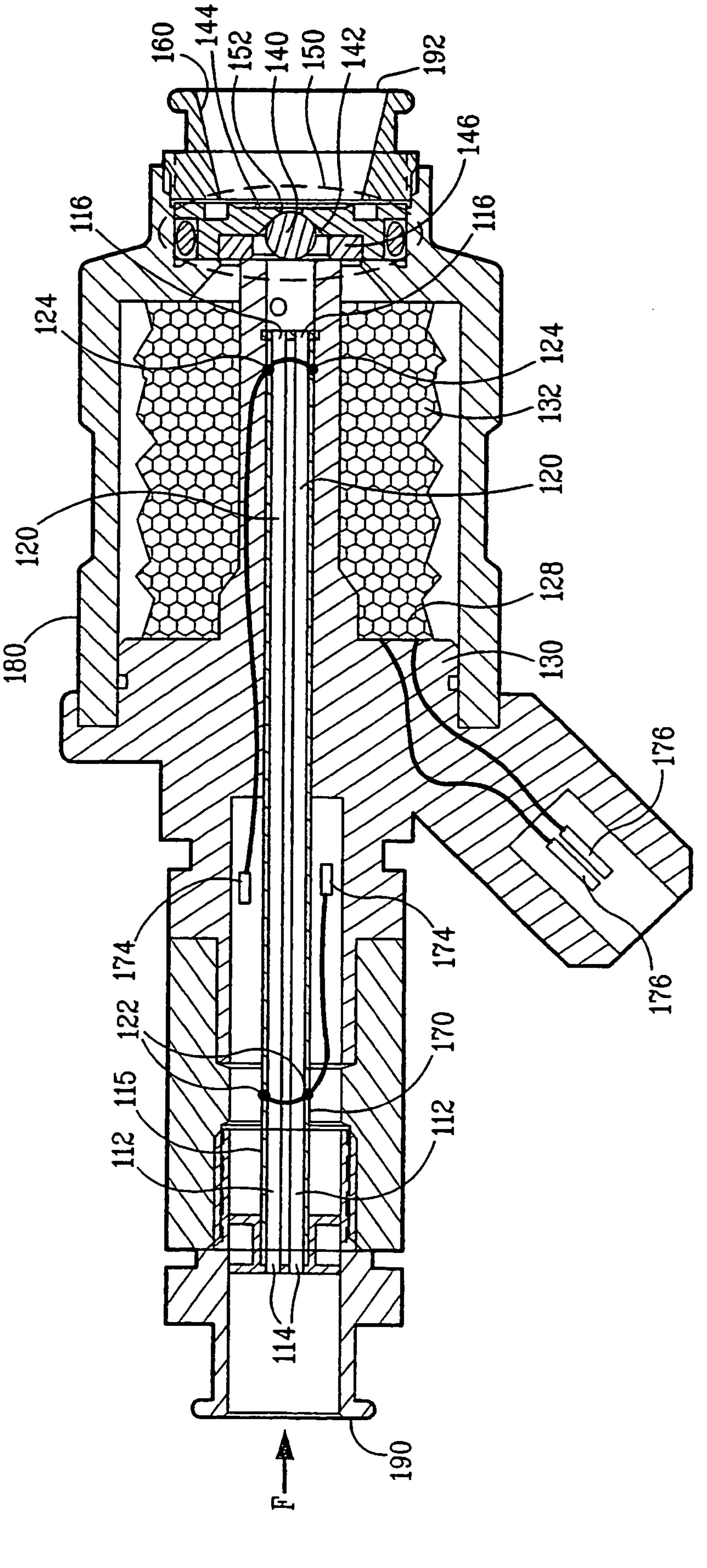

160
144
152
140
150
142
192
146
116
116
124
124
132
120
120
128
180
130
176
176
174
174
122
170
115
112
112
114
190
F

FIG. 2

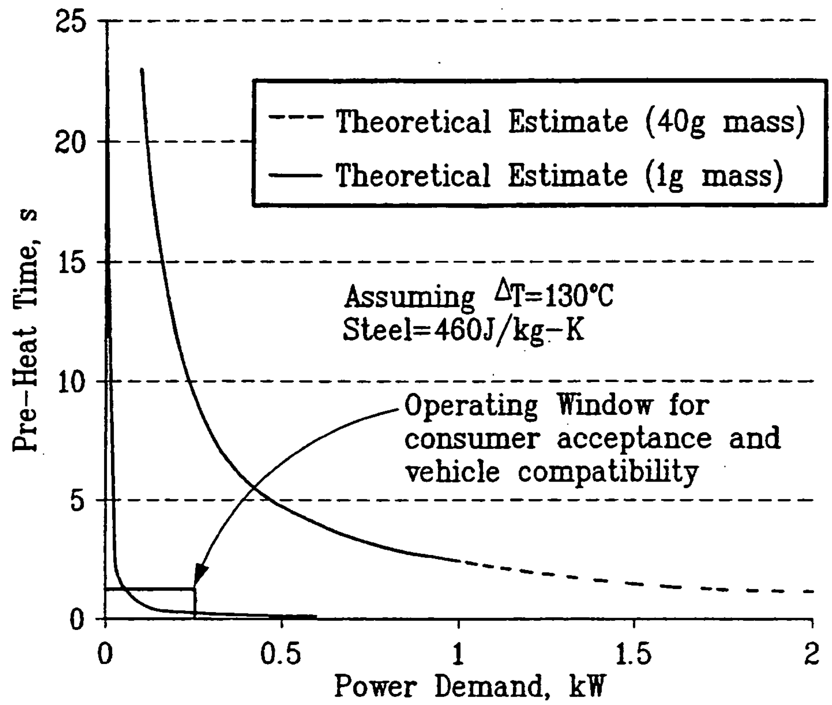

25
20
15
10
5
0
Pre-Heat Time, s
0
0.5
1
1.5
2
Power Demand, kW
--- Theoretical Estimate (40g mass)
— Theoretical Estimate (1g mass)
Assuming ΔT=130°C
Steel=460J/kg-K
Operating Window for consumer acceptance and vehicle compatibility

FIG. 3

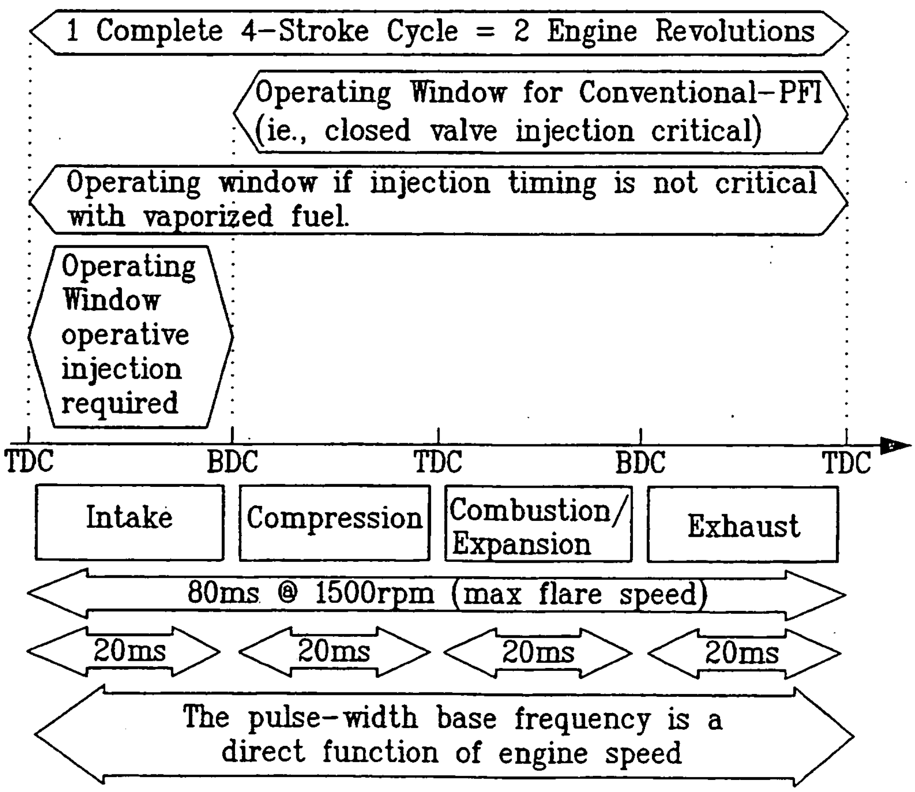
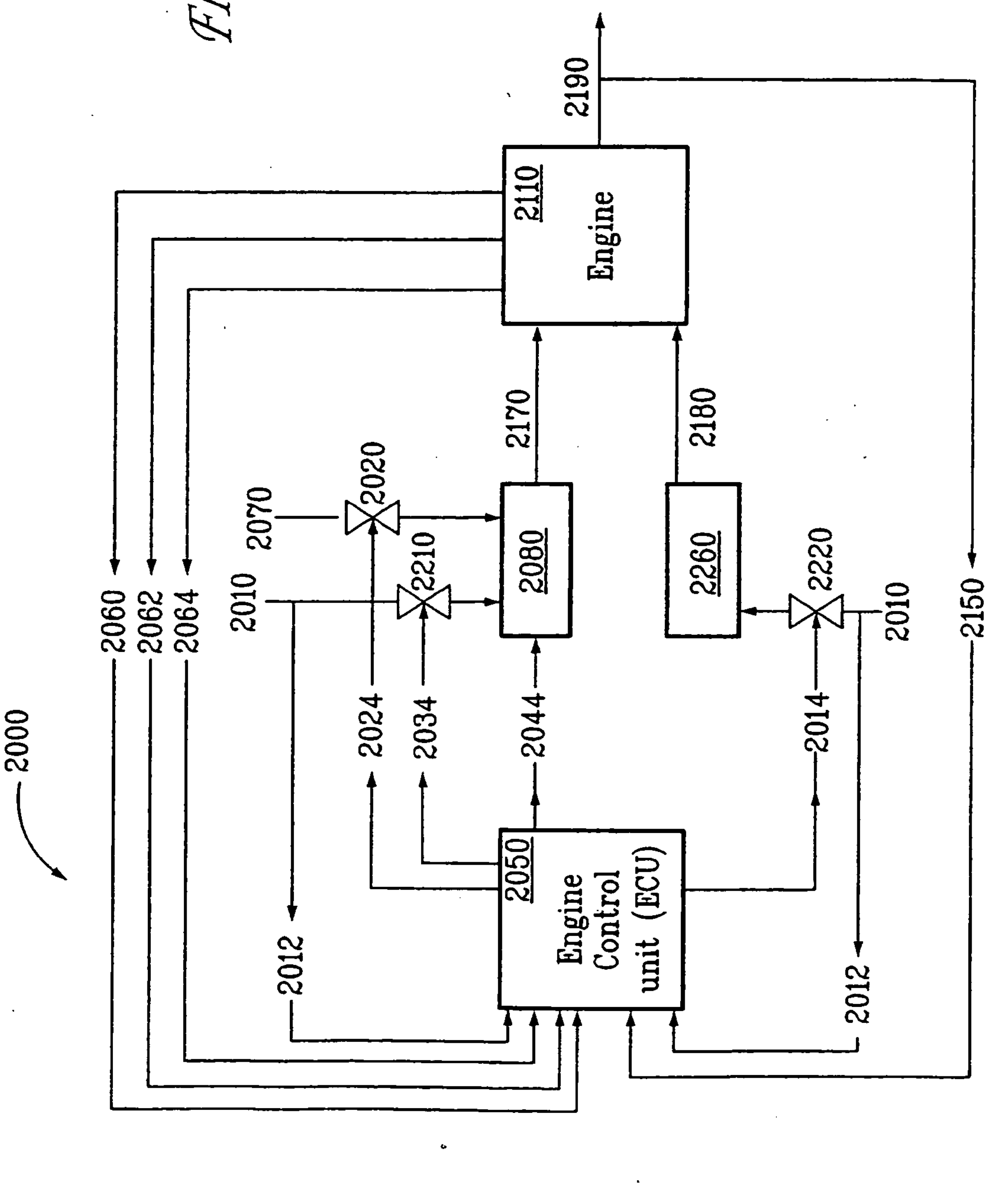

1 Complete 4-Stroke Cycle = 2 Engine Revolutions
Operating Window for Conventional-PFI (ie., closed valve injection critical)
Operating window if injection timing is not critical with vaporized fuel.
Operating Window operative injection required
TDC
BDC
TDC
BDC
TDC
Intake
Compression
Combustion/ Expansion
Exhaust
80ms @ 1500rpm (max flare speed)
20ms
20ms
20ms
20ms
The pulse-width base frequency is a direct function of engine speed

FIG. 4

FIG. 5


2000
2110
Engine
2050
Engine Control unit (ECU)
2080
2260
2190
2170
2180
2020
2210
2220
2070
2010
2060
2062
2064
2024
2034
2044
2014
2012
2150

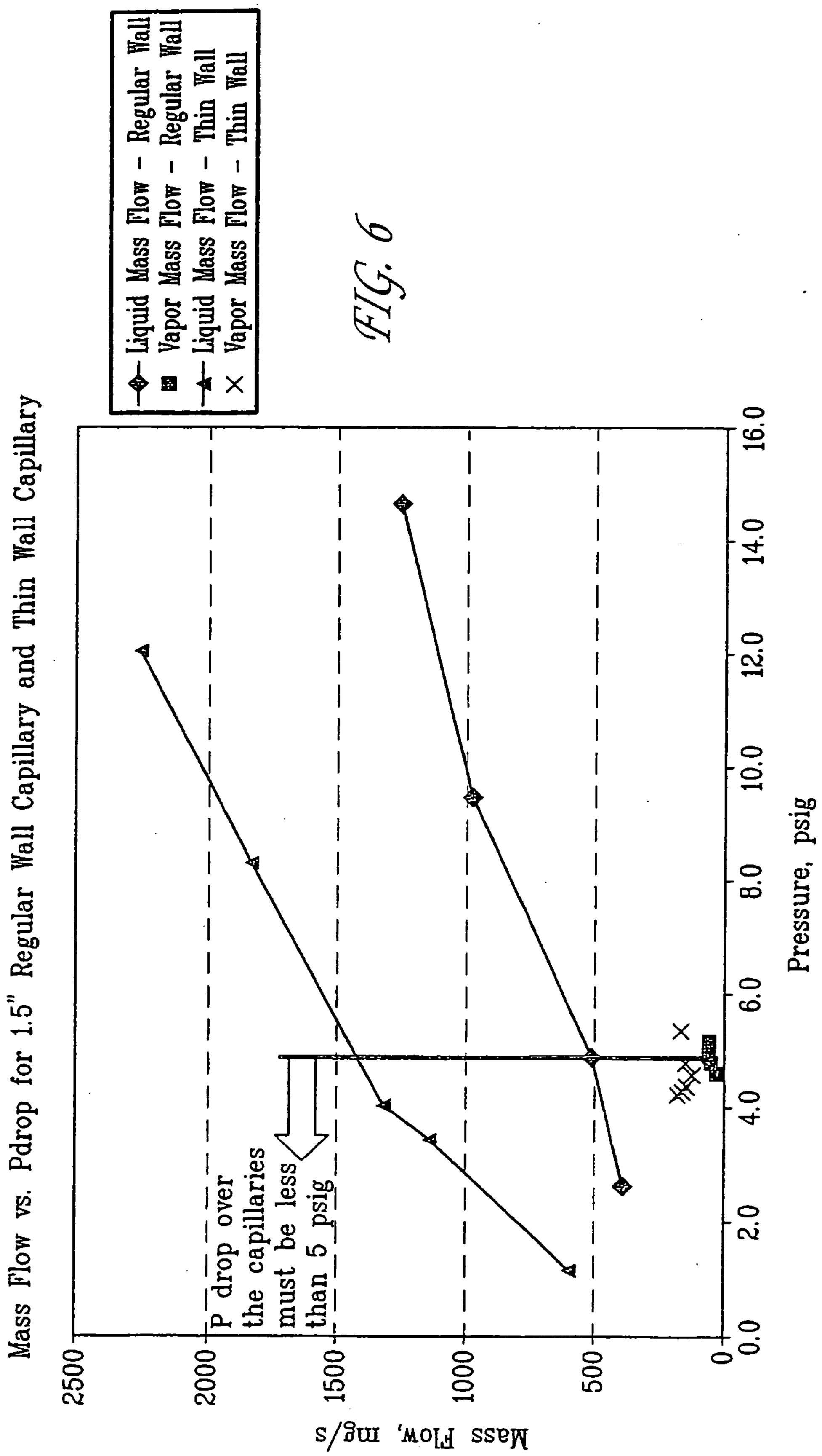

Mass Flow vs. Pdrop for 1.5" Regular Wall Capillary and Thin Wall Capillary
Liquid Mass Flow - Regular Wall
Vapor Mass Flow - Regular Wall
Liquid Mass Flow - Thin Wall
Vapor Mass Flow - Thin Wall
P drop over the capillaries must be less than 5 psig
Mass Flow, mg/s
Pressure, psig
2500
2000
1500
1000
500
0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0

FIG. 6

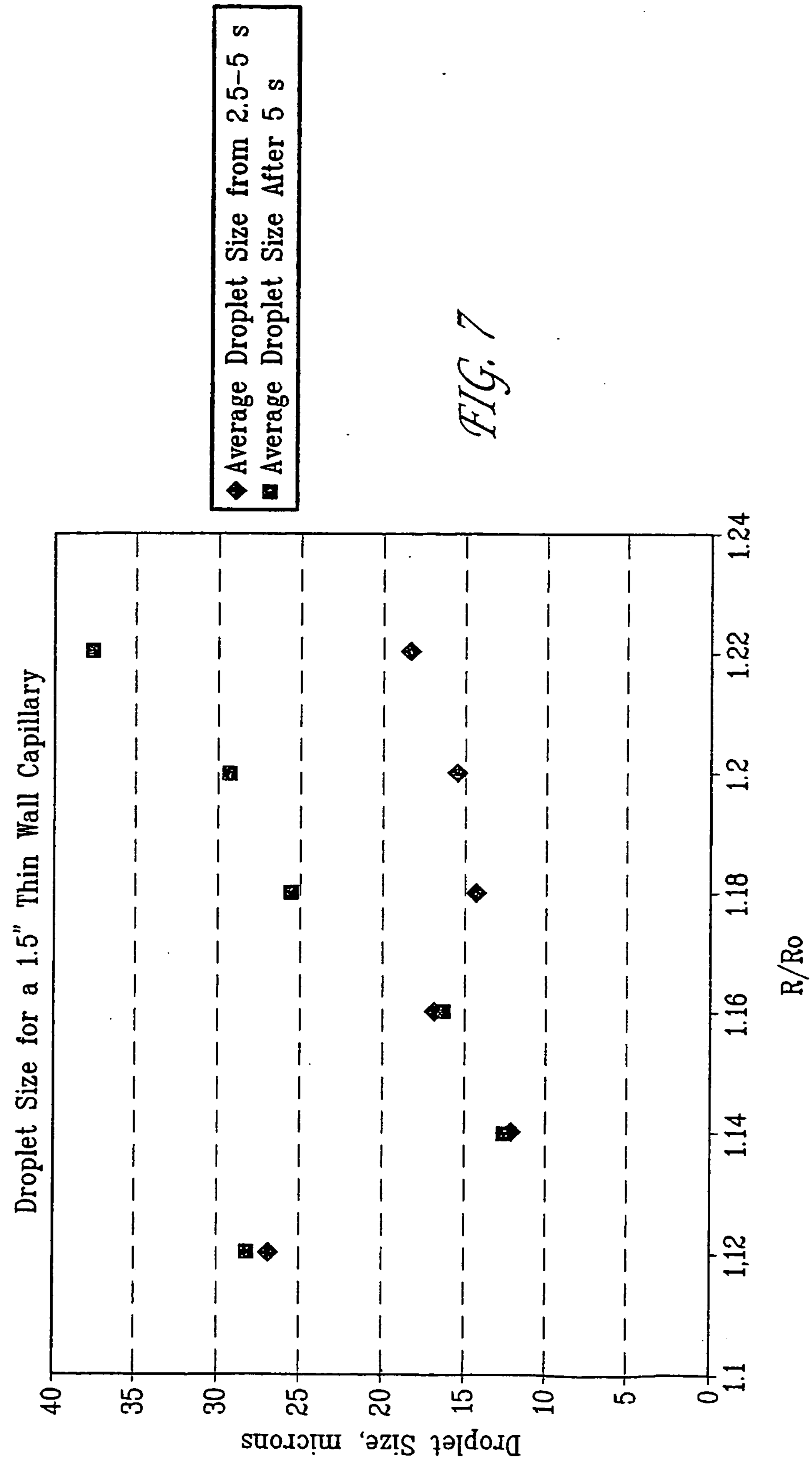

Droplet Size for a 1.5" Thin Wall Capillary
Average Droplet Size from 2.5–5 s
Average Droplet Size After 5 s
Droplet Size, microns
R/Ro
0
5
10
15
20
25
30
35
40
1.1
1.12
1.14
1.16
1.18
1.2
1.22
1.24

FIG. 7

REFERENCES CITED IN THE DESCRIPTION

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