United States Patent

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[54] FUEL INJECTION APPARATUS

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[52] **U.S. Cl.** ..... **123/119 R**, 261/DIG. 69, 123/DIG. 10, 123/97 B, 123/103

[51] **Int. Cl.** **F02m 7/00**, F02d 31/00

[58] **Field of Search** ..... 123/119 R, DIG. 10, 103; 137/81.5, 82; 261/DIG. 69, 39, 69

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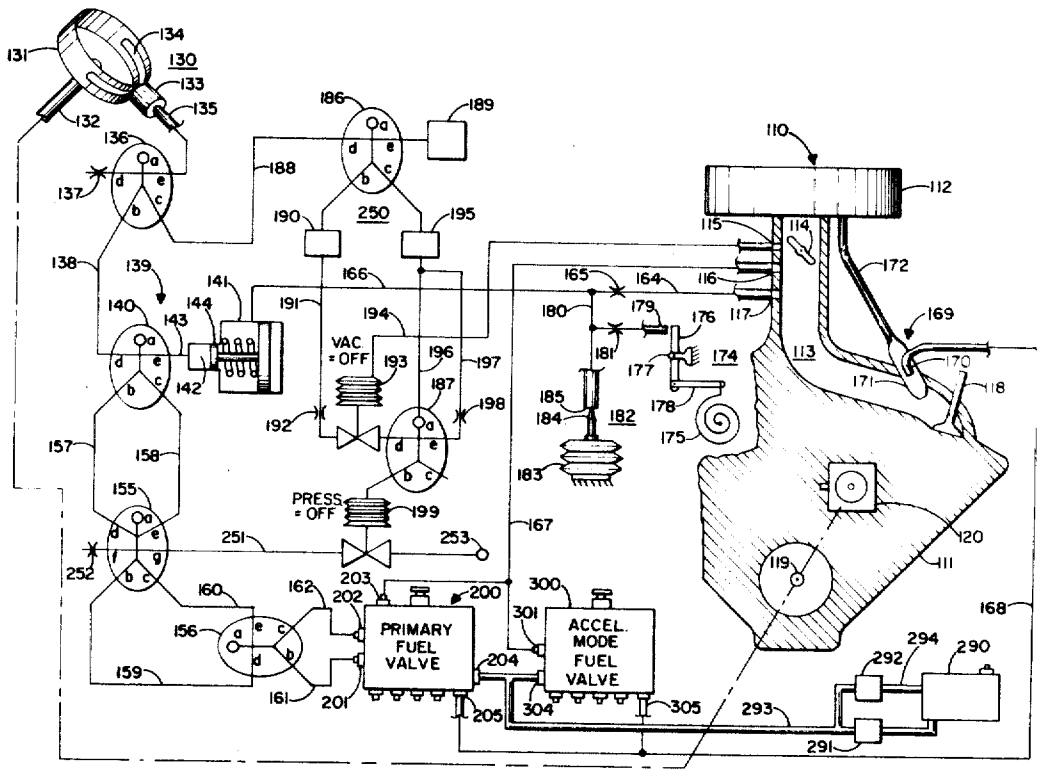
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[57] **ABSTRACT**

A fluidically controlled fuel injection system wherein fuel is delivered to the engine in pulses, the repetition rate of the pulses corresponding to engine speed, and the duration of the pulses being determined primarily by engine manifold vacuum. Pneumatic means may be provided to compensate the fuel injection system for variations in air temperature, engine temperature, and atmospheric pressure.

7 Claims, 6 Drawing Figures



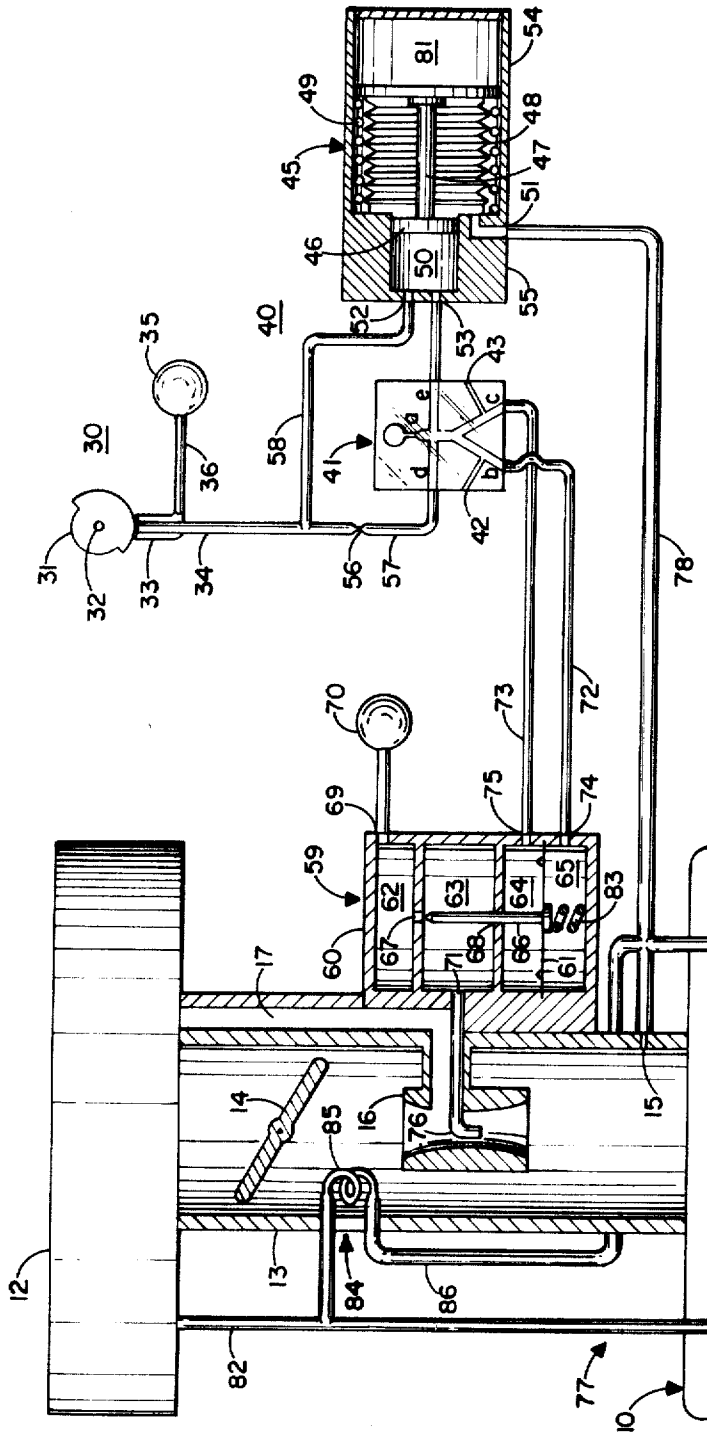


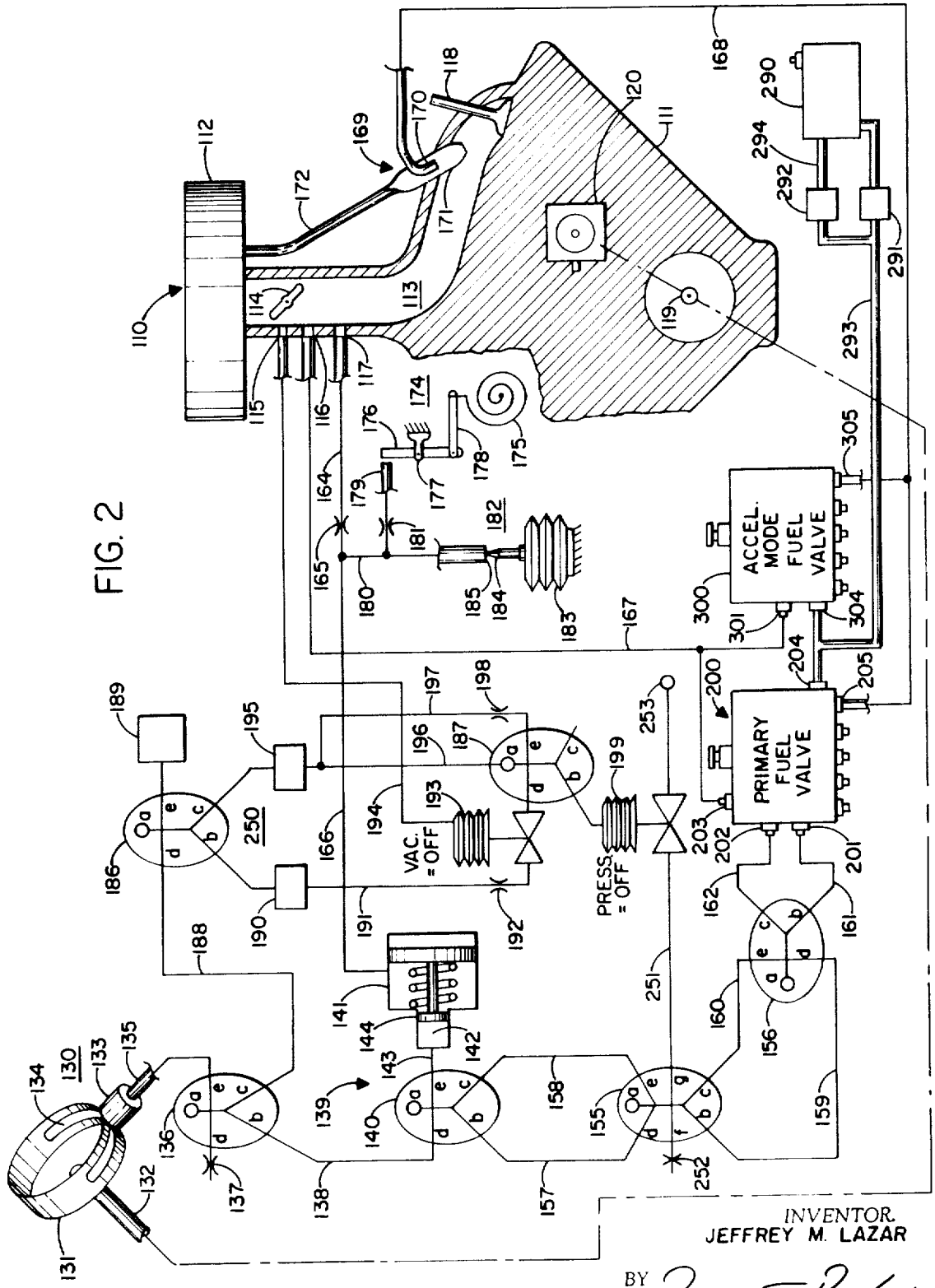
FIG. 1

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FIG. 2



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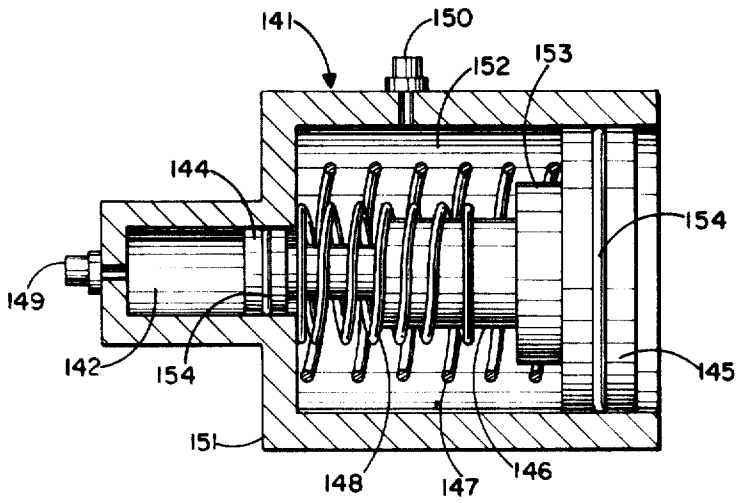


FIG. 3

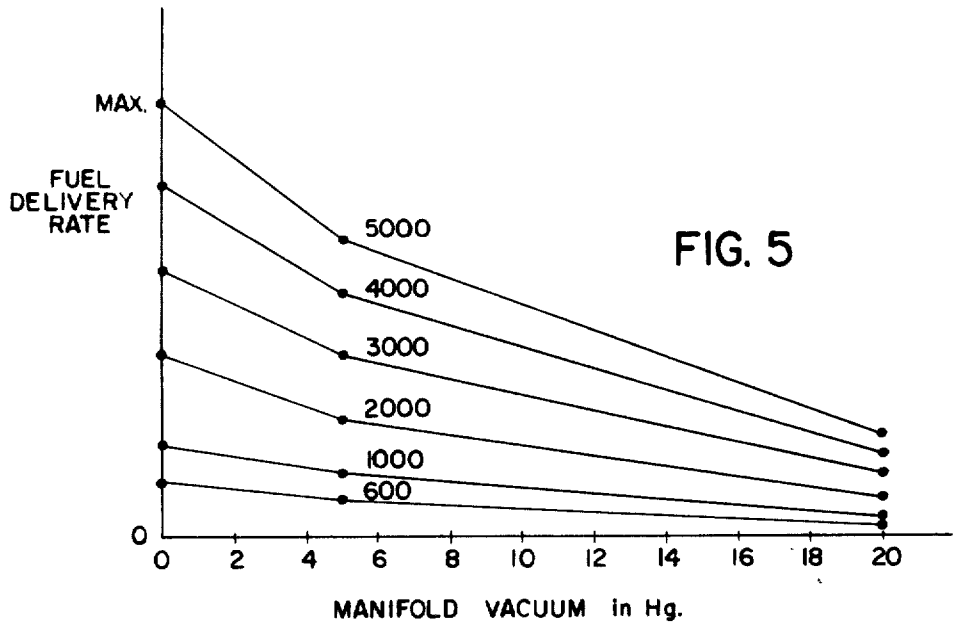


FIG. 5

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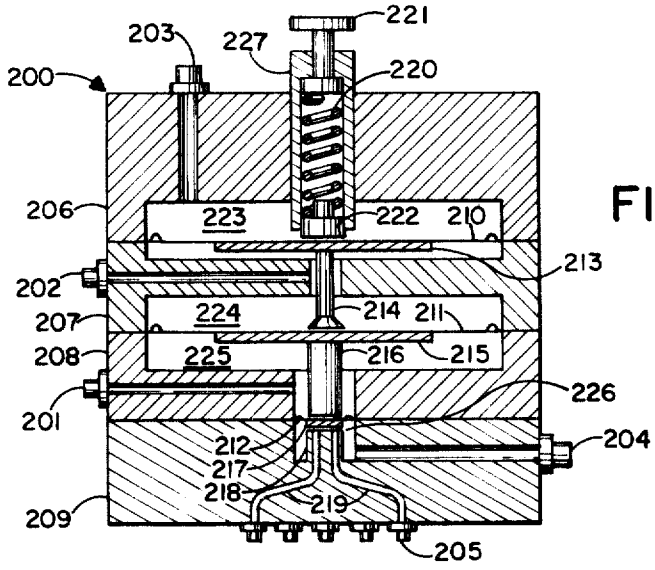


FIG. 4

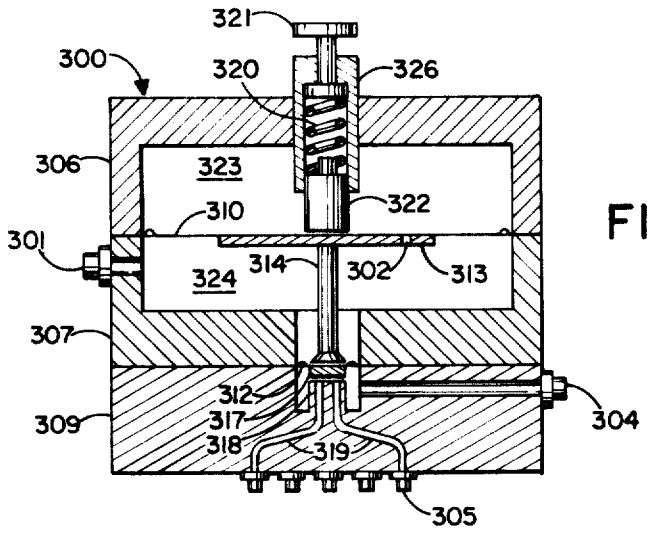


FIG. 6

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FUEL INJECTION APPARATUS

BACKGROUND OF THE INVENTION

This invention relates generally to fuel injection apparatus, and more specifically to fluidically controlled fuel injection systems for internal combustion engines.

It has long been recognized that fuel injection of spark ignition internal combustion engines offers significant advantages over conventional carburetion. These advantages include higher volumetric efficiency, more uniform distribution of mixture among the cylinders, improved fuel economy, better cooling of inlet valves, and lack of need for preheating air to provide vaporization, which in turn permits the use of higher compression ratios and the development of higher output power. Fuel injection systems have been successfully in automobile racing engines and in aircraft engines, where they offer the additional advantage of freedom from icing. Although fuel injection systems have also been used in certain high performance, limited production sports cars, with a few exceptions they have not seen general use in standard production car engines.

The greater complexity and higher cost of a fuel injection system over a comparable carburetor have been the principle reasons why fuel injection systems have not received more general use. Over the years, many different fuel injection systems have been proposed, but these systems have in general required additional fuel pumps, fuel metering devices, valves, injectors, and associated pipes, tubes and wiring. Some systems have employed electrically operated injectors which require solenoids, timing switches, and even electronic computers for their operation. The inclusion of these devices has contributed to higher costs and lower reliability. Additionally, in order to realize the potential benefits of any fuel injector system, it must be capable of accurately metering the proper quantity of fuel to the cylinders. To meet this requirement, many of the components of the prior art fuel injection systems have had to be specially machined to very close tolerances, which leads to high costs. In addition to the high cost of manufacture, many of these systems have required elaborate and precise adjustment and calibration for proper operation.

Because of growing concern over controlling exhaust gas emissions of automobile engines, there has been renewed interest in fuel injection systems. It is felt that the more accurate fuel metering possible with fuel injection allows better control over the combustion in the individual cylinders, and it is therefore possible to keep production of pollutants at a minimum.

SUMMARY OF THE INVENTION

In the present invention the applicant has provided a fuel injection system that overcomes the main disadvantages heretofore associated with fuel injection systems. The applicant has provided a system wherein the fuel metering functions are performed accurately and reliably by fluidic components, with a minimum of moving mechanical parts. Critically close manufacturing tolerances are not required, and complicated and frequent calibrations and adjustments are not needed.

Applicant's invention comprises means for generating a train of fluid pulses having frequency indicative of engine speed, means for varying the duration of the fluid pulses primarily according to the pressure in the engine air intake passage, fuel valve means for energization by the fluid pulses, and injector means for supplying fuel to the engine upon energization of the fuel valve means.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic representation of one embodiment of applicant's invention;

FIG. 2 is a schematic representation of a second embodiment of applicant's invention;

FIG. 3 is a cross sectional view of a variable fluidic capacitor which may be used in applicant's invention;

FIG. 4 is a cross sectional view of a fuel valve used in one embodiment of applicant's invention;

FIG. 5 is a graph showing the operation of applicant's invention; and

FIG. 6 is a cross sectional view of another fuel valve which may be used in applicant's invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 1, reference numeral 10 designates an internal combustion engine incorporating a fuel injection system according to the present invention. Engine 10 includes an engine block 11, an air intake passage 13, and an air cleaner 12. Positioned inside air intake passage 13 is a conventional throttle butterfly valve 14, and a venturi tube 16. An air intake passage 17 provides air for engine idling.

Fluid pulses for the operation of the fuel injector system are provided by pulse generating means 30, which comprises a wheel 31 attached to a shaft 32, and a pair of coaxial conduits 33 and 34. In this embodiment, shaft 32 is geared (not shown) to run at one half engine crank shaft speed. For convenience, wheel 31 may be attached to the ignition distributor shaft (not shown). Wheel 31 has a first portion having a first radius extending through 180° of arc, and a second portion having a second larger radius extending through the remaining 180° of arc. Coaxial conduits 33 and 34 are mounted in close proximity to the circumference of the larger portion of wheel 31. Air at a working pressure from an air supply 35 is supplied to conduit 33 by conduit 36. When wheel 31 is in the position shown, air escaping from conduit 33 is reflected back by the circumference of wheel 31, and enters conduit 34. When shaft 32 has rotated through an angle so that the smaller portion of wheel 31 is nearest conduit 33, the pressurized air therein is free to escape, and does not reflect back into conduit 34. Pulse generator 30 therefore produces a square wave or a series of pressure pulses in conduit 34, whose amplitude is determined primarily by the pressure of the air from supply 35, and whose frequency is equal to the rotational speed of shaft 32 which is proportional to engine speed.

The fluid pulses thus generated are supplied to pulse modifying means 40, for pulse duration modulation according to engine fuel requirements. Pulse modifying means 40 comprises a fluid amplifier 41 and a variable capacitor 45. Fluid amplifier 41 is a bistable, or wall attachment type amplifier, the operating principles and construction of which are well known to those skilled in the art. Amplifier 41 comprises a power nozzle *a*, a pair of outlet passages *b* and *c*, a pair of control ports *d* and *e*, and a pair of vents 42 and 43. Air at a working pressure is applied to power nozzle *a*, causing a power stream to pass through the amplifier and out either outlet passage *b* or outlet passage *c*. The air for energizing power nozzle *a* may be supplied from a suitable source of pressure, not shown. For convenience, air supply 35 may be used to energize fluid amplifier 41. A fluid signal or pulse applied to control port *d* of fluid amplifier 41 causes the power stream to switch to outlet passage *c*, or to remain there if the power stream was flowing through outlet passage c prior to the pulse. Likewise, a fluid signal or pulse applied to control port *e* causes the power stream to switch to outlet passage *b*.

The basic elements of variable capacitor 45 include a base 55 having a cylindrical chamber 50, and a piston 46 slideably positioned therein. Attached to base 55 is a bellows 48 which connects to piston 46 through a shaft 47. A vacuum signal is applied to the interior of bellows 48 through a port 51, as will hereinafter be explained. A spring 49 opposes the inward movement of bellows 48. The bellows assembly is covered by a pressure case 54, which is attached to base 55. A pair of ports 52 and 53 in base 55 communicate with chamber 50, which is the capacitance chamber.

Pulses from pulse generating means 30 are applied through conduit 34, a fluid resistor 56, and a conduit 57 to control port d of fluid amplifier 41. Pulses are also applied to port 52 of variable capacitor 45 through conduit 34 and a conduit 58. Port 53 of variable capacitor 45 is connected to control port *e* of the amplifier. A positive pulse from pulse generating means

30 travels through conduit 34, resistor 56, and conduit 57 to control port *d* of amplifier 41, causing the power stream to switch to outlet passage *c*. The same pulse also travels through conduit 58 to capacitance chamber 50, initiating a pressure rise therein. The rate of pressure increase within chamber 50 is controlled by the volume of capacitance chamber 50 and the effective resistance of the charging path described in the preceding sentence. When piston 46 is in the position shown, the volume is large, the charging time of the capacitor is relatively long, and the pressure rise relatively is slow. When piston 46 is moved to the left, the charging time of the capacitor decreases, and the rate of pressure rise increases. When the pressure in chamber 50, acting upon control port *e*, reaches sufficient magnitude, the power stream of amplifier 41 switches to outlet passage *b*. From the foregoing it will be appreciated that the length of time during which the power stream flows through outlet passage *c* depends upon the position of piston 46 within chamber 50.

Fuel valve means 59 is provided for controlling the flow of fuel to the engine, according to signals received from pulse modifying means 40. Fuel valve means 59 comprises the following element. A housing 60 is mounted close to air intake passage 13. Inside housing 60, a diaphragm 61 and two partitions of the housing define four chambers 62–65. A needle 66 is attached to diaphragm 61. Needle 66 passes through seal 68 and operates to open or close aperture 67, according to its vertical position which is controlled by the flexure of diaphragm 61. A spring 83 is provided in chamber 65 to normally hold diaphragm 61 and needle 66 upward to close aperture 67 in the absence of fluid signals. Fuel at a working pressure is supplied to chamber 62 through a port 69 from a fuel supply 70. Chamber 63 communicates through a port 71 to injector means 76, which is positioned within air intake passage 13.

Fuel valve means 59 is operated by fluid pulses from pulse modifying means 40 as follows. Pulses from outlet passages *b* and *c* of amplifier 41 are applied to chambers 65 and 64 of fuel valve means 59 by conduits 72 and 73, and ports 74 and 75, respectively. An ON pulse from outlet passage c of the amplifier increases the pressure in chamber 64, thereby causing diaphragm 61 and needle 66 to move downward. This opens aperture 67, allowing fuel at a pressure from chamber 62 to flow through chamber 63 to injector means 76. Fuel exiting from injector means 76 is broken up to a fine spray for mixture with the air passing through air intake passage 13. A venturi tube 16 positioned within air intake passage 13 increases the velocity of the air in the locality of the injector means to aid in the mixture process. At the end of an ON pulse, the power stream of amplifier 41 is switched to pass through outlet passage *b* to pressurize chamber 65. This pushes diaphragm 61 and needle 66 upward to block aperture 67, thereby cutting off the flow of fuel to injector means 76.

Engine manifold pressure is sensed at a manifold pressure tap 15, and is applied to port 51 of variable capacitor 45 by a conduit 78. Also connected to conduit 78 is a conduit 79 and a capillary tube 80, and a conduit 86 and a capillary tube 85, the operation of which is explained hereinafter.

When the engine is at idle, very little fuel is required. Under this condition throttle butterfly valve 14 is closed, the small air flow required enters air intake passage 13 through idle air passage 17, and manifold pressure is low, or, stated another way, manifold vacuum is high. This high manifold vacuum is supplied to the interior of bellows 48 of variable capacitor 45 through conduit 78 and port 51. Volume 81 is filled with a gas at normal sea level atmospheric pressure, and sealed by case 54. The force generated on the end of bellows 48 by the atmospheric pressure within case 54 and the high engine manifold vacuum inside bellows 48 causes the bellows to contract against spring 49, moving piston 46 to the left, greatly reducing the volume of chamber 50. With the volume of chamber 50 thus reduced, the duration of pulses passing through outlet passage *c* of amplifier 41 to the fuel valve is also decreased, so that the duration of the fuel pulses injected by injector means 76 is at a minimum. It will be appreciated that the diameter of chamber 50 the length of shaft 47, and the stiffness of spring 49 are so chosen that the proper amount of fuel is supplied to the engine under idle, as well as other operating conditions.

When engine 10 is under heavy load, such as might be encountered during acceleration, throttle butterfly valve 14 is opened, allowing a great quantity of air to enter air intake passage 13. Accordingly, manifold pressure rises i.e., manifold vacuum decreases. With the decrease in manifold vacuum, the pressure force generated on the end of bellows 48 is no longer sufficient to overcome the force exerted by spring 49. Therefore bellows 47 expands, pulling shaft 47 and piston 46 to the right. This movement increases the volume of chamber 50, which in turn increases the duration of the fuel pulses applied to injector means 76.

For intermediate settings of throttle butterfly valve 14, manifold vacuum assumes an intermediate value, as does the position of piston 46. The quantity of fuel supplied per pulse is determined solely by the duration of the pulse, since fuel is supplied to the valve at a constant supply pressure. Thus, it will be appreciated that the fuel metering system of FIG. 1 is effective to automatically supply the proper amount of fuel to engine 10 through all ranges of engine speed and engine loading.

It is well known that in addition to metering fuel according to engine speed and load, it is desirable to adjust the quantity of fuel delivered according to engine temperature, ambient air temperature, and ambient air pressure. To effect these adjustments, compensation devices are provided in the fuel injection system of FIG. 1.

For example, when engine 10 is cold, such as during start-up and warm-up phases of operation, it is desirable to supply a fuel-air mixture that is richer than normal. Accordingly, temperature sensing means or means responsive to engine temperature 77 is provided. Temperature sensing means 77 includes capillary tube 80 which is a very small diameter tube which is mounted on or near engine block 11. In another embodiment, capillary tube 80 is placed in a small well adjacent the exhaust manifold of the engine. Capillary tube 80 uses the dependence of the viscosity of air upon its temperature to provide a variable impedance to the flow of air therethrough. A conduit 82 connects from air cleaner 12 to capillary tube 80, and a conduit 79 connects from capillary tube 79 to conduit 78. Engine manifold vacuum in air intake passage 13 draws air through air cleaner 12, conduit 82, capillary 80 and conduit 79. Manifold pressure tap 15 acts as a pressure dropping resistance, since its diameter is smaller than the diameter of conduit 78. During normal running of the engine, the high temperature of engine block 11 heats the air in capillary tube 80 thereby increasing its viscosity to the point that very little air can flow through the series path of conduit 82, capillary tube 80, conduit 79, and manifold pressure tap 15. Consequently, air flow rate through manifold pressure tap 15 is negligible (There is no steady state air flow in conduit 78 since bellows 48 represents a closed volume.) Therefore, the pressure in conduit 78 is substantially the same as the pressure in air intake passage 13, and the fuel metering system operates substantially as described in the foregoing paragraphs.

However, when engine block 11 is cold, the lower viscosity of cool air permits some flow of air through capillary tube 80, conduit 79, and manifold pressure tap 15 into air intake passage 13. This air flow through manifold pressure tap 15 causes a pressure drop insuring that the pressure in conduit 78 will be somewhat higher than the pressure in intake passage 13, (i.e., the vacuum in conduit 78 will be somewhat lower than the vacuum in intake passage 13) no matter what position throttle butterfly valve 14 assumes, so long as engine block 11 is cold. A somewhat higher pressure in conduit 78 causes bellows 48 to expand, increasing the volume of chamber 50. This leads to the increase in the duration of the fuel pulses supplied, thereby providing an enriched mixture to the engine.

Similarly, means responsive to air temperature **84**, which comprises capillary tube **85** and conduit **86** is provided for compensating for changes in ambient air temperature. Air is drawn through conduit **82**, capillary tube **85**, and conduit **86** (which passes behind air intake passage **13**) to join conduit **78**. Capillary tube **85** is placed inside air intake passage **13** where it is exposed to the air drawn therethrough. Capillary tube **85** is effective to vary the duration of fuel pulses supplied to the engine in the same manner as capillary tube **80** previously described.

It is known that a 10 percent reduction in fuel flow is needed at 10,000 feet altitude compared with the fuel flow required at sea level for a standard day. This reduction is required to reflect the lesser density of air at higher altitudes. In addition, there is a 30 percent loss in engine vacuum at 10,000 feet. A volume **81** which is hermetically sealed by case **54** and which is applied to the backside of bellows **48** will compensate for the engine vacuum loss and will automatically shorten the pulses when changing from sea level to 10,000 feet. Additionally, by proper selection of the composition of gas sealed within volume **81**, changes in ambient air temperature may also be accounted for. If volume **81** is also used for air temperature compensation, means responsive to air temperature **84** may be deleted.

In FIG. **2** there is shown an alternate embodiment of applicant's invention which features the use of alternate types of pulse generating means, pulse modifying means, and engine temperature and barometric pressure compensating means illustrated in FIG. **1**. It also features the use of multipoint fuel injectors, and separate acceleration and deceleration circuits. In FIG. **2**, internal combustion engine **110** comprises an engine block **111**, a crank shaft **119**, an air intake passage **113**, and an air cleaner **112**. A throttle butterfly valve **114** is positioned inside air intake passage **113**.

Pulse generating means **130** is provided for generating a train of fluid pulses. Pulse generating means **130** comprises a commutator **131** which is attached to a shaft **132**. Shaft **132** is rotatably driven by crankshaft **119** via suitable gearing (not shown). For convenience, shaft **132** may be coextensive with the ignition distributor shaft of the engine. Commutator **131** has a slot **134** which extends through 180° of arc. A brush **133** is held in contact with commutator **131** by springs or other means (not shown). Brush **133** holds a conduit **135** in alignment with slot **134**. Rotation of shaft **132** alternately opens and closes the end of conduit **135**. This action, together with the operation of fluid amplifier **136**, described below, produces the train of fluid pulses.

A bistable fluid amplifier **136**, which is shown schematically, has a power nozzle *a*, a pair of outlet passages *b* and *c*, and a pair of control ports *d* and *e*. Conduit **135** connects to control port *e*, while control port *d* is vented to the atmosphere through fluid resistor **137**. Fluid amplifier **136** along with the other fluid amplifiers of FIG. **2** are supplied with air at working pressure from air pump **120** which is driven by crank shaft **119**. For clearity, the air conduits from pump **120** to the various fluid amplifiers have been omitted from the drawing. As the power stream flows through fluid amplifier **136** to outlet passage *b* or *c* it entrains a certain amount of air from control ports *d* and *e*, pulling the entrained air on through the amplifier. If the air entrained from the control ports is not replaced by air-flow into the control ports from outside the amplifier, a low pressure condition can develop which may be sufficient to pull the power stream from one outlet passage to the other. For example, when commutator **131** is in the position shown, air is able to enter control port *e* from the atmosphere through slot **134** and conduit **135** to replace the air depleted from control port *e* by entrainment. However, the influx of air to control port *d* is impeded by fluid resistance **137**, and a low pressure condition is therefore maintained in control port *d*. The pressure differential thus produced by ambient air pressure at control port *e* and reduced air pressure at control port *d* causes the power stream to switch to outlet passage *b*. When shaft **132** and commutator **131** have rotated so that slot **134** is not aligned with conduit **135**, the influx of air to control port *e* is prevented, thus putting the pressure therein to a lower value than the pressure existing in control port *d*. This pressure differential causes the power stream to switch to outlet passage *c*. Thus, there appears at outlet passage *b* of fluid amplifier **136**, a train of fluid pulses having a frequency proportional to the speed of the engine.

Pulse modifying means **139** is provided for performing the same pulse duration modulation function performed by amplifier **41** and variable capacitor **45** of FIG. **1**, but by means of a different method of operation. Pulse modifying means **139** includes a fluid amplifier **140** and a variable capacitor **141**. Fluid amplifier **140** is of the bistable or wall attachment type, and includes a power nozzle *a*, a pair of outlet passages *b* and *c* and a pair of control ports *d* and *e*. Control port *e* communicates with capacitance chamber **142** of variable capacitor **141** via a conduit **143**. The various components of variable capacitor **141** are shown more clearly in FIG. **3**.

In FIG. **3**, variable capacitor **141** comprises a housing **151** which defines two cylindrical chambers **142** and **152**. A piston **144** in chamber **142** and a piston **145** in chamber **152** are connected by a shaft **146**. A first spring **147** in chamber **152** positioned between housing **151** and piston **145** opposes the leftward movement thereof. A second, smaller spring **148** is also located in chamber **152** coaxial with shaft **146**. The left end of spring **148** abuts against housing **151**, and the right end of spring **148** engages a flange **153** of shaft **146** when piston **145** has moved a sufficient distance to the left. A pair of ports **149** and **150** communicate with chambers **142** and **152**, respectively. Seals **154** on pistons **144** and **145** give the pistons air tight fits in their respective chambers.

Referring again to FIG. **2**, in the absence of a signal at control port *d*, the power stream of fluid amplifier **140** will be biased to pass through outlet passage *c* because control port *e* communicates only with the closed volume of chamber **142**. As explained above with reference to fluid amplifier **136**, entrainment causes depletion of air from control port *e* resulting in a low pressure condition therein which is sufficient to switch the flow to outlet passage *c*. This condition represents the normally biased, no signal condition of fluid amplifier **140**. Pulses from pulse generating means **130** are applied to control port *d* of fluid amplifier **140** by conduit **138**.

The operation of the modulator circuit comprising fluid amplifier **140** and variable capacitor **141** will now be described. A more detailed description may be found in patent application Ser. No. 851,238, now abandoned, by M. P. Miller filed Aug. 19, 1969 and assigned to the same assignee as the present application. A positive pressure pulse arriving at control port *d* of amplifier **140** causes fluid to pass through control port *e* to charge capacitance chamber **142** to a relatively high pressure condition. The arrival of such a pulse at control port *d* does not cause a change in the output of the amplifier; the power stream continues to pass through outlet passage *c*. Upon termination of the positive pressure pulse at control port *d*, the following instantaneous conditions exist. The pressure in control port *d* is returned to a near ambient condition, the pressure in control port *e* and capacitance chamber **142** remains at the higher charged pressure. The pressure differential thus existing causes the power stream to switch to outlet passage *b* of fluid amplifier **140**, and the high pressure fluid in capacitance chamber **142** begins to discharge through control port *e*, merging with the power stream, and passing through outlet passage *b*. This condition continues until capacitance chamber **142** has completely discharged and the pressure therein begins to go below ambient due to entrainment through control port *e*. The low pressure thus created biases the power stream, causing it to switch back to outlet passage *c*. The length of time during which the power stream passes through outlet passage *b* is equal to the time required for capacitance chamber **142** to discharge. It will be appreciated that this discharge time is a function of the RC time constant of the discharge circuit, wherein the capacitance is determined by the volume of capacitance chamber **142**, and

the resistance is the inherent resistance presented by control port *e*, determined principally by its diameter. In summary, pulse modifying means **139** functions as follows: the output of amplifier **140** is initially in outlet passage *c;* initiation of a pressure pulse at control port *d* causes no change in the output of amplifier **140**; upon termination of the pulse applied to control port *d*, output flow of amplifier **140** switches to outlet passage *b*, and remains therein for a length of time determined by the volume of capacitance chamber **142**; at the end of this time period, output flow of amplifier **140** returns to outlet passage *c*. The circuit is then ready for receipt of the next pulse, and the cycle is repeated. It will be appreciated that the circuit just described functions as a pulse width modulator.

The pulse width modulated fluid pulses from amplifier **140** are amplified by amplifiers **155** and **156**. Fluid amplifier **155** is a bistable summing amplifier comprising a power nozzle *a*, a pair of outlet passages *b* and *c*, a first control port pair *d* and *e*, and a second control port pair *f* and *g*. Control port *f* is sealed by a plug **252**, and signals are applied to control port *g* only during engine deceleration, as is described in a subsequent paragraph. Therefore, in normal operation, the output state of amplifier **155** is determined solely by the inputs applied to control ports *d* and *e*. Outlet passage *b* of amplifier **140** connects to control port *d* of amplifier **155** through a conduit **157**. Similarly, outlet passage *c* of amplifier **140** connects to control port *e* of amplifier **155** through a conduit **158**. Outlet passage *b* of amplifier **155** connects to control port *d* of amplifier **156** through conduit **159**, and outlet passage *c* of amplifier **155** connects to control port *e* of amplifier **156** through a conduit **160**. In normal operation, the output of amplifier **140** is amplified by amplifier **155**. Likewise, the output of amplifier **155** is amplified by amplifier **156**, which is also a bistable fluid amplifier. The output of amplifier **156** is used to operate a primary fuel valve **200**. Outlet passage *b* of amplifier **156** connects through a conduit **161** to a port **201** of primary fuel valve **200**. Similarly, outlet passage *c* of amplifier **156** connects through a conduit **162** to a port **202** of the primary fuel valve.

In addition to the fluid pulses applied to ports **201** and **202** by fluid amplifier **156**, two other inputs are applied to primary fuel valve **200**. They are: fuel supplied to port **204**, and engine manifold vacuum applied to port **203**. Fuel from a fuel tank **290** is delivered to a port **204** of primary fuel valve **200** by an electric fuel pump **291**, and a conduit **293**. The fuel pressure in conduit **293** is held constant by a pressure regulator **292**, which allows excess fuel to return to tank **290** through a bypass conduit **294**. Manifold vacuum is applied to port **203** of primary fuel valve **200** by a conduit, **167** which connects to a tap **116** in air intake passage **113**.

Primary fuel valve **200** is shown in cross sectional view in FIG. **4**. The housing for primary fuel valve **200** comprises four sections, **206** through **209**, which are fastened together by means, not shown. A diaphragm **210** is positioned between section **206** and section **207**. Similarly, a diaphragm **211** is positioned between sections **207** and **208**, and a diaphragm **212** is positioned between sections **208** and **209**. A chamber **223** is formed with sections **206**, and is bounded on the lower side by diaphragm **210**. A port **203** communicates with chamber **223**. A chamber **224** is formed within section **207**, and is bounded on the top by diaphragm **210** and on the bottom by diaphragm **211**. A port **202** communicates with chamber **224**. In a similar manner, a chamber **225** is formed within section **208**. Chamber **225** is bounded on the top by diaphragm **211**, and on the bottom by diaphragm **212**. A port **201** communicates with chamber **225**. A chamber **226** is formed with sections **209**, and is bounded on the top by diaphragm **212**. A port **204** communicates with chamber **226**.

A button **217** is attached to the bottom of diaphragm **212** for movement therewith. Protruding upward from the floor of chamber **226**, and aligned with button **217**, is pedestal **218**. Inside pedestal **218** is a plurality of passages **219**, which connect to ports **205**. In general, primary fuel valve **200** should have one passage **219** and one port **205** per engine cylinder. Fuel at a working pressure supplied to port **204** enters chamber **226**. In the absence of a downward force acting upon diaphragm **212**, the fuel pressure within chamber **226** forces diaphragm **212** and button **217** upward, allowing fuel to pass through passages **219** to ports **205**. When a downward force is applied to diaphragm **212**, as is explained below, button **217** is held against pedestal **218**, and fuel is prevented from passing into passages **219** to ports **205**. Thus it will be appreciated that the flexure of diaphragm **212** is effective to control the flow of fuel to ports **205**.

A pair of discs, **213** and **215**, is attached to the bottom sides of diaphragms **210** and **211**, respectively. A pair of spools, **214** and **216** is attached to discs **213** and **215**, respectively, in alignment with button **217** and pedestal **218**. A sleeve **227** is provided in section **206**. A spring **220** and a slug **222** are provided within sleeve **227**. Spring **220** urges slug **222** downward onto diaphragm **210**. This force is transmitted through spool **217** and **216** to diaphragm **212**. The amount of force exerted by spring **220** may be controlled by a thumb screw **221**, and is normally set so that in the absence of control signals, the force exerted by spring **220** is sufficient to overcome the fuel pressure within chamber **226**, so as to hold button **217** against pedestal **218**. In this condition, primary fuel valve **200** is said to be OFF.

Primary fuel valve **200** operates as follows. When engine **110** in FIG. **2** is OFF, spring **220** keeps primary fuel valve **200** in an OFF condition. When engine **110** is runing, manifold vacuum applied via port **203** to chamber **223** draws diaphragm **210** upward, overcoming the force exerted by spring **220**. The flow of fuel through the valve is then controlled by diaphragm **211** which may move spool **216** up and down against diaphragm **212**, according to the pressures in chambers **224** and **225**. The pulse width modulated fluid pulses from pulse modifying means **139** are applied to ports **201** and **202** of primary fuel valve **200**, as previously described. During an ON pulse, the power stream of fluid amplifier **156** flows through outlet passage *b*, conduit **161**, and port **201** to pressurize chamber **225**. At the same time, a relatively low pressure condition exists in outlet passage *c* at amplifier **156** and chamber **224** of primary fuel valve **200**. This pressure differential causes diaphragm **211** to move upward, allowing the fuel pressure within chamber **226** to push diaphragm **212** upward, which permits fuel to pass through passages **219** to ports **205**. At the end of an ON pulse, the power stream of fluid amplifier **156** switches to outlet passage *c*, thereby pressurizing chamber **224**. The high pressure in chamber **224** pushes diaphragm **211** downward, thereby turning OFF the fuel valve.

Fuel pulses are thus delivered to ports **205** of primary fuel valve **200** and are transmitted through a conduit **168** to injector means **169**. In this embodiment, injector means **169** comprises an inner nozzle **170**, and a larger coaxial nozzle **171**. The two nozzles are mounted in air intake passage **113** near engine intake valve **118**. Fuel pulses are supplied to the inner nozzle **170**, where they are broken up into a fine spray for mixture with the air in intake passage **113**. Air from air cleaner **112** is supplied through a conduit **172** to the larger nozzle **171**. Manifold vacuum in air intake passage **113** draws air inward through conduit **172** and nozzle **171**. This flow of air past nozzle **170** helps atomize the fuel pulse to form a uniform mixture. Also, the air passing through nozzle **171** maintains the pressure surrounding nozzle **170** at near ambient, thus insuring uniform performance of fuel injector **170** regardless of engine manifold pressure. The embodiment of applicant's invention shown in FIG. **2** will also work, of course, with conventional spring check valve fuel injectors.

Likewise, it is possible, and in some cases might be advantageous, to use conventional electrical solenoid injectors with applicant's invention. For example, the embodiment shown in FIG. **2** could easily be so adapted by replacing injector means **169** and primary fuel valve **200** by a conventional electrical solenoid injector, which includes both valve means and injector means. The fluid signals at conduits **161** and **162** could be used to energize the solenoid by means of a conven-

tional fluidic-to-electrical interface. Fuel from conduit **293** would be supplied directly to the electrical solenoid injectors.

Referring now to FIG. **5**, the overall performance of the fuel system of FIG. **2** is shown for different steady state operating conditions. The vertical scale of the graph of FIG. **5** represents the rate of fuel delivery to the engine, with higher fuel rates towards the tope of the graph. The horizontal scale represents manifold vacuum, with increasing vacuum towards the right of the graph. In the graph there is shown a family of fuel flow curves for different engine speeds at standard sea level conditions. The lower curve shows fuel flow rate versus manifold pressure for a constant engine speed of 600 RPM. The next curve shows the fuel metering characteristics of this system for an engine speed of 1,000 RPM, and so on up to the top curve which represents characteristics at an engine speed of 5,000 RPM. It will be noted that, for a given manifold vacuum, fuel delivery rate increases with engine speed. This result follows from the fact that for a given manifold vacuum, pulse duration (determined by the position of piston **144** in variable capacitor **141**) remains constant, and the frequency or repetition rate of pulses from pulse generating means **130** varies according to engine speed. It should be noted also that for a given engine speed, lower manifold vacuum, which corresponds to a wider open throttle setting, results in an increased fuel delivery rate.

For each of the curves of FIG. **5**, there is a change of slope at a break point which corresponds to a certain value of manifold vacuum. This change of slope provides for "economizer" fuel delivery, wherein a somewhat leaner mixture is provided at low throttle settings (high manifold vacuum) for better economy during cruising and a somewhat richer mixture is provided at high throttle settings for better power during acceleration or high speed operation. One model of the system of FIG. **2** which was tested on a particular engine was found to give best results when the break point was set at a manifold vacuum of 5 inches of mercury. The change in slope at the break point is provided by spring **148** (FIG. **3**). As piston **145** of variable capacitor **141** moves to the left under the influence of increasing manifold vacuum, it is opposed by spring **147** having a given stiffness. But after piston **145** has moved far enough for spring **148** to engage flange **153**, further leftward movement is then opposed by the combined stiffness of springs **147** and **148**. The result is that before spring **148** is engaged, a given increment of manifold vacuum applied to port **150** produces a relatively greater decrease in the volume of chamber **142** and the same increment would after spring **148** is engaged.

In addition to the steady state operation of the fuel injection system of FIG. **2**, explained in the preceding paragraphs, additional modes of operation are provided for use during acceleration, deceleration, cold engine operation, and change of altitude.

Referring again to FIG. **2**, a temperature sensing means or means responsive to engine temperature **174** is provided for applying compensations to conduit **166**, which delivers the controlling vacuum signal to variable capacitor **141**. A thermostat **175** is mounted on or near engine block **111** for response according to the temperature of the engine. Thermostat **175** acts through a link **178** to operate a lever **176**, which is pivoted at a fulcrum **177**. A nozzle **179**, which is positioned near the end of lever **176**, communicates with conduit **166** through a conduit **180** and a resistor **181**. When the engine is at normal operating temperature, the end of lever **176** is held against nozzle **179**, effectively closing it. In this condition, temperature sensing means **174** has no effect, and the operation of the fuel injector systems is as previously described. When the engine is at low temperature, thermostat **175** swings lever **176** away from nozzle **179**, allowing air to bleed into nozzle **179**, through resistor **181**, through conduit **180**, resistor **165**, conduit **164**, and tap **117** to air intake passage **113**. The difference in pressure between ambient and the pressure within intake passage **113** is dropped across resistors **181** and **165**. Conduits **180** and **166** are held at an intermediate pressure which is slightly higher than manifold pressure, thereby causing piston **144** of variable capacitor **141** to move towards the right. This movement gives a wider pulse output, and hence a richer mixture. After engine **110** has warmed up, thermostat **175** closes nozzle **179**, and temperature sensing means **174** exerts no further influence on the operation of the fuel system. Temperature sensing means **174** thus acts as a variable impedance, and allows a quantity of air to enter conduit **180** according to engine temperature.

Altitude compensating means or means responsive to engine temperature, **182** is also provided for applying compensations to conduit **166**. In the embodiment shown in FIG. **2**, altitude compensating means **182** comprises a bellows control valve which comprises a bellows **183**, a needle **184**, and an orifice **185**. Bellows **183** is an aneroid type element, sealed at a certain pressure so as to expand at higher altitudes and contract at lower altitudes. Needle **184** is tapered to fit into orifice **185** to provide a variable impedance to the flow of fluid therethrough. Altitude compensating means **182** is calibrated so that orifice **185** is completely blocked at an ambient air pressure corresponding to 10,000 feet altitude, and fully open at sea level. As previously described, piston **145** of variable capacitor **141** assumes a position according to the balance of forces exerted upon it by spring **147**, the vacuum signal applied through port **150**, and ambient air pressure on the back side of piston **145**. As an automobile travels from sea level to 10,000 feet altitude, the manifold vacuum, i.e., the difference between air intake passage pressure and ambient air pressure, decreases. However, since the spring force in the variable capacitor does not change with altitude, were it not for altitude compensating means **182**, the effect of the reduced manifold vacuum would be for piston **145** to move to the right, thereby increasing pulse duration and enrichening the mixture. It is therefore necessary to compensate the circuit to prevent enrichment of mixture at high altitudes. Further, it is desirable to over compensate the circuit so as to provide a 10 percent reduction in fuel delivered because of the reduced air density at higher altitudes. These compensations are provided by altitude compensating means **182** as follows. At sea level, air enters orifice **185**, flows through conduit **180**, resistor **165**, conduit **164** and tap **117** to air intake passage **113**. The pressure drop of air flowing through resistor **165** insures that the pressure in conduit **180** and **166** will be somewhat higher than the pressure in conduit **164**. Stated another way, the vacuum signal applied to the variable capacitor **141** is less than actual manifold vacuum in conduit **164**. The entire fuel system is then calibrated to give proper fuel delivery at sea level with this reduced vacuum in conduit **166**. As ambient air pressure gradually decreases until a pressure equivalent to 10,000 feet is reached, needle **184** moves progressively into orifice **185**, completely blocking it at an altitude of 10,000 feet. Correspondingly, the amount of air flow through the circuit of orifice **185**, conduit **180**, resistor **165** and eventually into air intake passage **113** is progressively reduced, so that the pressure drop across resistor **165** diminishes to zero at 10,000 feet (not counting any pressure drop due to the engine temperature compensation circuit, which operates in addition, but independently of the altitude compensation circuit). With orifice **185** closed, the pressure in conduit **166** is the same as the pressure in conduit **164**, which is the same as the pressure in air intake passage **113**. It is seen therefore, that although engine manifold vacuum tends to decrease at higher altitudes, this effect is compensated for, and the control vacuum actually delivered to the pulse width modulator through conduit **166** is adjusted, so as to compensate for this decrease in manifold pressure, and to provide for the desired 10 percent decrease in engine fuel requirements at 10,000 feet altitude.

It will be appreciated that the altitude and temperature corrections and compensations applied to the vacuum signal which operates the pulse width modulator operate in addition to but substantially independent of one another and the engine manifold vacuum. For given engine temperature and altitude conditioning, the fuel injection system of FIG. **2** continues to

operate primarily according to manifold vacuum, as previously described.

Air temperature compensating means may be connnected to conduit **166**, as in the embodiment of FIG. 1, if, for a particular engine, it is found desirable to do so.

Acceleration performance of internal combustion engines may be improved by supplying to the engine during acceleration a greater quantity of fuel than is normally required. Accordingly, acceleration mode fuel valve **300** is provided, the details of which are shown in FIG. 6. Housing for fuel valve **300** comprises sections **306**, **307** and **309**. Inside the housing are chambers **323** and **324**, which are separated by a diaphragm **310**. A disc **313** is attached to the bottom of diaphragm **310**, and a spool **314** is attached to the bottom of disc **313**. Section **309** of fuel valve **300** is substantially identical to section **209** of fuel **200**, in FIG. **4**. The important elements of the bottom section of fuel valve **300** are a diaphragm **312**, a button **317**, a pedestal **318**, passages **319**, ports **305** and port **304**. Button **317** is normally held down on pedestal **318** by a spring **320**, which urges a slug **322** downward on diaphragm **310**.

Referring agin to FIG. **2**, fuel is supplied to port **304** of acceleration mode fuel valve **300** from conduit **293**, which carries fuel at the working pressure. Manifold vacuum is applied to port **301** by tap **116** and conduit **167**. During steady state operation of the engine, manifold pressure is constant at some value, and the pressures in chambers **323** and **324** equalize through a port **302**, in diaphragm **310**. With no pressure differential acting on diaphragm **310**, spring **320** holds button **317** against pedestal **318**, preventing the delivery of fuel to ports **305**. During heavy accelerations, throttle butterfly **114** is opened quickly, and there is a sudden increase in manifold pressure. This sudden rise in manifold pressure creates a momentary pressure differential across diaphragm **310**, flexing it upward thereby allowing fuel to pass through passages **319** to ports **305**. As this is taking place, the pressure in chambers **323** and **324** is being equalized by flow through port **302**. When the pressure difference becomes small enough, spring **320** once again forces button **317** downward, cutting off the flow of fuel. The length of time during which acceleration fuel flows depends upon the volume of chambers **323** and **324**, the diameter of port **302**, and the force exerted by spring **320**, which may be adjusted by a thumb screw **321**. Fuel from port **305** is delivered to conduit **169** and thence to injector means **169**. It will be appreciated from the foregoing that acceleration mode fuel valve **300** delivers fuel to the engine during accelerations, in amounts according to the suddenness and degree of the acceleration, independently of the normal fuel delivery.

It is desirable in automobile engines to provide means for cutting off the fuel during decelerations, so as to improve the braking effect on the engine. Accordingly, the fuel injection system of FIG. **2** is provided with fuel cutoff means **250** which is operable to cut off the fuel whenever the engine throttle is closed and engine speed exceeds a predetermined value. Pressure pulses from outlet passage *c* of amplifier **136** are conducted by a conduit **188** to control port *d* of a bistable fluid amplifier **186**. These pressure pulses are identical to the pressure pulses conveyed by conduit **138** (except for a 180° phase reversal). A fluidic capacitor **189** is connected to control port *e* of amplifier **186**. This circuit arrangement is identical to the circuit of fluid amplifier **140** and variable capacitor **141**, except for the fact that fluid capacitor **189** is fixed in value, so that pulses passing out outlet passage *b* of amplifier **186** are all of uniform width. These pulses are filtered by a capacitor **190**, to form an analog pressure level therein. The magnitude of pressure existing in capacitor **190** depends solely upon the frequency of the received pulses, and hence upon engine speed, since the widths of pulses delivered to capacitor **190** are fixed. The pressure in capacitor **190** is delivered to control port *d* of a bistable fluid amplifier **187** through a conduit **191**, a resistor **192** and a valve **193**. Valve **193** is a conventional bellows activated valve operable to open or close the fluid path from resistor **192** to control port *d* of fluid amplifier **187** according to signals applied to the bellows via a conduit **194**. Valve **193** is so configured that application of vacuum to conduit **194** closes the fluid path through the valve, while ambient pressure in conduit **194** allows valve **193** to open.

The vacuum signal applied to conduit **194** originates at a tap **115**, and is indicative of the position of throttle butterfly valve **114**. When throttle butterfly valve **114** is open anywhere from a slight amount to full open, port **115** is in effect downstream from the throttle, and is subject to manifold pressure, which is always less than ambient pressure. When throttle butterfly **114** is closed, tap **115** is effectively upstream thereof, and as such is subject to near ambient pressure. Thus the pressure at tap **115** and conduit **194** undergoes a sharp transition from near ambient pressure to relatively large manifold vacuum upon opening of the engine throttle.

Fluid passing through outlet passage *c* of amplifier **186** is received and filtered by a capacitor **195**. This flow of fluid represents the remaining output of amplifier **186** other than the uniform pulses, which are supplied to capacitor **190**. Preferably, the volume of capacitor **189** is adjusted so that capacitor **195** receives more than half and capacitor **190** receives less than half of the time averaged output of amplifier **186**, when the engine is operating at maximum speed. This insures that sufficient pressure will be maintained in capacitor **195** to operate a fluid amplifier **187**. Fluid from capacitor **195** is supplied to power nozzle a of amplifier **187** from conduit **196**, and to control port *e* of amplifier **187** through a conduit **197** and a resistor **198**. Outlet passage *c* of amplifier **187** is vented to the atmosphere, an outlet passage *b* is connected to the control bellows of a valve **199**, which is similar to valve **193** except that valve **189** is closed when its bellows is pressurized, and opened when its bellows is subject to ambient air pressure. Air at a working pressure is supplied to a port **253** from air pump **120**, by conduit means not shown. Valve **199** functions to control the flow of air from port **253** through a conduit **251** to control port e of amplifier **155**. Control port f of amplifier **155** is sealed by plug **252**.

In normal engine operation, pressure applied to control port *e* of amplifier **187** biases the power stream to flow through outlet passage *b* to valve **199**, holding it closed. In that condition, both control ports *f* and *g* of amplifier **155** are blocked, and have no effect on the operation of the amplifier. When throttle butterfly valve **114** is closed, ambient pressure at tap **115** and conduit **194** allow valve **193** to open, thereby allowing fluid from capacitor **190** to flow into control port *b* of amplifier **187**. However, unless the engine is operating at a speed above a predetermined value, the pressure delivered to control port *d* through resistor **192** from capacitor **190** is insufficient to overcome the bias applied to control port d to resistor **198**. This prevents fuel from being cut off during engine idling condition. However, if the throttle is closed and engine speed is above a certain value such as occurs during deceleration, valve **193** is open, and the pressure in control port *d* causes the power stream of amplifier **187** to switch to outlet passage *c*. The removal of pressure to the bellows of valve **199** allows the valve to open, and pressure from port **250** is applied to control port *g* amplifier **155**. This signal at control port *g* is of sufficient magnitude to override the normal fuel pulse signals in control port *d*, and the fuel is effectively cut off, until the throttle is reopened, or until engine speed drops below the predetermined value.

I claim as my invention:

1. A fuel system for an internal combustion engine having an air intake passage, comprising:

pulse generating means for generating a train of fluid pulses whose frequency is indicative of engine speed;

conduit means in communication with said air intake passage;

fluid resistance means connected between said conduit means and said air intake passage;

variable impedance means connected to said conduit means, said variable impedance means operable to admit

a quantity of air into said conduit means according to parameters associated with the operation of the engine;

pulse modifying means in communication with said pulse generating means and said conduit means, said pulse modifying means for varying the duration of said fluid pulses according to pressure in said conduit means;

fuel valve means connected to said pulse modifying means for energization upon occurrence of a fluid pulse for the duration thereof; and

injector means operatively connected to said fuel valve means, said injector means adapted for supplying fuel to the engine upon energization of said fuel valve means.

2. Apparatus according to claim 1 wherein said variable impedance means comprises means responsive to engine temperature.

3. Apparatus according to claim 1 wherein said variable impedance means comprises means responsive to atmospheric pressure.

4. Apparatus according to claim 1 wherein said variable impedance means comprises means responsive to air temperature.

5. The apparatus of claim 1 further including fuel cutoff

means connected to said pulse generating means and said air intake passage for producing fuel cutoff signals whenever a low pressure condition exists in said air intake passage and the frequency of said train of fluid pulses exceeds a predetermined value, said fuel cutoff means further connected to said pulse modifying means for supplying said fuel cutoff signals thereto, and wherein said pulse modifying means is adapted to prevent the flow of fuel to the engine when said fuel cutoff signals are received.

6. Apparatus according to claim 5 wherein said fuel cutoff means includes fluid amplifier means.

7. The apparatus of claim 1 wherein said internal combustion engine includes throttle means, and further including fuel cutoff means connected to said pulse generating means and said throttle means for producing fuel cutoff signals whenever said throttle means is closed and the frequency of said train of fluid pulses exceeds a predetermined value, said fuel cutoff means further connected to said pulse modifying means for supplying said fuel cutoff signals thereto, and wherein said pulse modifying means is adapted to prevent the flow of fuel to the engine when said fuel cutoff signals are received.

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