

FILE HISTORY
US 6,575,138

PATENT: 6,575,138
INVENTORS: WELCH ALAN B
RAHARDJA IRAWAN
HEBBES MIKE

TITLE: Directly actuated injection valve

APPLICATION NO: US2001863187A
FILED: 23 MAY 2001
ISSUED: 10 JUN 2003

COMPILED: 13 JAN 2022

(FACE)

6,575,138

DIRECTLY ACTUATED INJECTION VALVE

Transaction History

Date	Transaction Description
05-23-2001	Initial Exam Team nn
06-07-2001	Application Is Now Complete
06-07-2001	Notice Mailed--Application Incomplete--Filing Date Assigned
06-07-2001	Correspondence Address Change
07-23-2001	Application Dispatched from OIPE
07-28-2001	Case Docketed to Examiner in GAU
08-27-2001	Information Disclosure Statement (IDS) Filed
08-27-2001	Information Disclosure Statement (IDS) Filed
11-13-2002	Non-Final Rejection
11-14-2002	Mail Non-Final Rejection
02-21-2003	Workflow - Drawings Finished
02-21-2003	Workflow - Drawings Matched with File at Contractor
02-21-2003	Incoming Letter Pertaining to the Drawings
02-21-2003	Response after Non-Final Action
02-27-2003	Date Forwarded to Examiner
03-07-2003	Dispatch to Publications
03-07-2003	Mail Notice of Allowance
03-07-2003	Notice of Allowance Data Verification Completed
03-07-2003	Case Docketed to Examiner in GAU
04-02-2003	Issue Fee Payment Verified
04-02-2003	Issue Fee Payment Received
04-03-2003	Receipt into Pubs
04-11-2003	Workflow - File Sent to Contractor
05-12-2003	Receipt into Pubs
05-13-2003	Application Is Considered Ready for Issue
05-14-2003	Receipt into Pubs
05-21-2003	Issue Notification Mailed
06-10-2003	Recordation of Patent Grant Mailed
06-10-2003	Patent Issue Date Used in PTA Calculation
07-23-2012	Correspondence Address Change
07-24-2012	Change in Power of Attorney (May Include Associate POA)
01-27-2015	Correspondence Address Change
03-31-2017	Correspondence Address Change

PATENT APPLICATION



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jc973 U.S. PTO
09/863187



05/23/01

INITIALS K.S

CONTENTS

Date Received
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1. Application ✓ papers.

2. DEC. missy 1/10

3. DEC. Fee

6-29-01

4. DS

8-27-01

5. Rejection

11/14/02

6. Amendment on 2-21-03

7. Notice of Allowability

3-7-03

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POSITION	INITIALS	ID NO.	DATE
FEE DETERMINATION	AKKAM		
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FORMALITY REVIEW	MS	JC906	06/07/01
RESPONSE FORMALITY REVIEW	SLC	809	7-19-01

INDEX OF CLAIMS

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Class	Sub.	Date	Exmr.
123	498	11-12-02	✓
↓	467	↓	↓
↓	472	↓	↓
123	478	↓	↓
239	533.2	↓	↓
↓	533.9	↓	↓
↓	102.2	↓	↓
239	585.1	↓	↓
251	129.06	11-12-02	✓
updated		3/5/03	✓

INTERFERENCE SEARCHED			
Class	Sub.	Date	Exmr.
123	498	3/6/03	✓
↓	467	↓	↓
↓	472	↓	↓
123	478	↓	↓
239	533.2	↓	↓
↓	533.9	↓	↓
↓	102.2	↓	↓
239	585.1	↓	↓
251	129.06	3/6/03	✓

SEARCH NOTES (INCLUDING SEARCH STRATEGY)		
	Date	Exmr.
See BDS sheet	11-12-02	✓

L Number	Hits	Search Text	DB	Time stamp
1	842	engine and (piezoelectric or magnetostrictive) and direct\$2 and inject\$4 and valve	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB USPAT	2002/11/12 10:27
2	451	(engine and (piezoelectric or magnetostrictive) and direct\$2 and inject\$4 and valve) and (piston or plunger)	USPAT	2002/11/12 09:33
3	451	((engine and (piezoelectric or magnetostrictive) and direct\$2 and inject\$4 and valve) and (piston or plunger)) and valve	USPAT	2002/11/12 09:34
4	28	((engine and (piezoelectric or magnetostrictive) and direct\$2 and inject\$4 and valve) and (piston or plunger)) and valve) and (stratified or stratification)	USPAT	2002/11/12 09:35
5	423	((engine and (piezoelectric or magnetostrictive) and direct\$2 and inject\$4 and valve) and (piston or plunger)) and valve) not (((engine and (piezoelectric or magnetostrictive) and direct\$2 and inject\$4 and valve) and (piston or plunger)) and valve) and (stratified or stratification))	USPAT	2002/11/12 09:36
6	6	(engine and (piezoelectric or magnetostrictive) and direct\$2 and inject\$4 and valve) and directly adj actuated	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB USPAT	2002/11/12 09:37
7	14	("4284263" "4463727" "4825117" "5094430" "5150049" "5205147" "5376860" "5571363" "5626116" "5680841" "5740969" "5819710" "5875764" "6085990").PN.	USPAT	2002/11/12 09:38
8	1	6313568.URPN.	USPAT	2002/11/12 09:39
11	8	("2721100" "4649886" "4725002" "4750706" "4838233" "6253736" "6311950" "6313568").PN.	USPAT	2002/11/12 09:43
12	520	(engine and (piezoelectric or magnetostrictive) and direct\$2 and inject\$4 and valve) and (hydraulic\$4 or fluid)	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB USPAT	2002/11/12 10:28
13	520	((engine and (piezoelectric or magnetostrictive) and direct\$2 and inject\$4 and valve) and (hydraulic\$4 or fluid)) and (piezoelectric\$4 or magnetostrictive\$2)	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB USPAT	2002/11/12 11:21
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16	72	((engine and (piezoelectric or magnetostrictive) and direct\$2 and inject\$4 and valve) and (hydraulic\$4 or fluid)) and (piezoelectric\$4 or magnetostrictive\$2) and lift and duration	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB	2002/11/12 11:51

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17	1	5630550.pn. and current	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB	2002/11/12 12:05
18	1	5630550.pn. and current and (load or demand or condition\$1)	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB	2002/11/12 12:06



(12) **United States Patent**
Welch et al.

(10) **Patent No.: US 6,575,138 B2**
(45) **Date of Patent: Jun. 10, 2003**

(54) **DIRECTLY ACTUATED INJECTION VALVE**

(75) **Inventors:** Alan B. Welch, Vancouver (CA);
Irawan Rahardja, Vancouver (CA);
Mike Hebbes, Vancouver (CA)

(73) **Assignee:** Westport Research Inc., Vancouver (CA)

(*) **Notice:** Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 107 days.

(21) **Appl. No.:** 09/863,187

(22) **Filed:** May 23, 2001

(65) **Prior Publication Data**

US 2001/0032612 A1 Oct. 25, 2001

Related U.S. Application Data

(63) Continuation-in-part of application No. 09/522,130, filed on Mar. 9, 2000, now Pat. No. 6,298,829.

(60) Provisional application No. 60/159,791, filed on Oct. 15, 1999.

(51) **Int. Cl.** F02M 55/02

(52) **U.S. Cl.** 123/467; 123/498

(58) **Field of Search** 123/498, 467,
123/472, 478; 239/533.2, 533.9, 102.2,
585.1; 251/129.06

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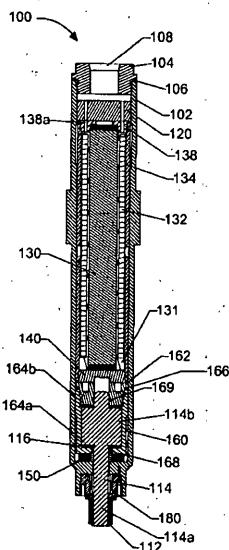
Primary Examiner—Mahmoud Gimie

(74) *Attorney, Agent, or Firm*—McAndrews, Held & Malloy, Ltd.

(57) **ABSTRACT**

A directly actuated injection valve comprises a hollow valve housing, a valve member disposed within the hollow interior, a biasing mechanism, an actuator assembly and a passive hydraulic link assembly. The valve member is movable between a closed position and an open position for governing the flow of fuel into the combustion chamber of an internal combustion engine. The biasing mechanism, preferably a spring, biases the valve member in the closed position. The actuator assembly generates an opening force that acts against the valve spring to open the valve. The hydraulic link assembly is interposed between the valve member and the valve spring and the actuator assembly. The hydraulic link assembly transmits respective closing and opening forces to the valve member. The hydraulic link preferably comprises a piston disposed within a cylinder that is filled with a hydraulic fluid.

41 Claims, 5 Drawing Sheets



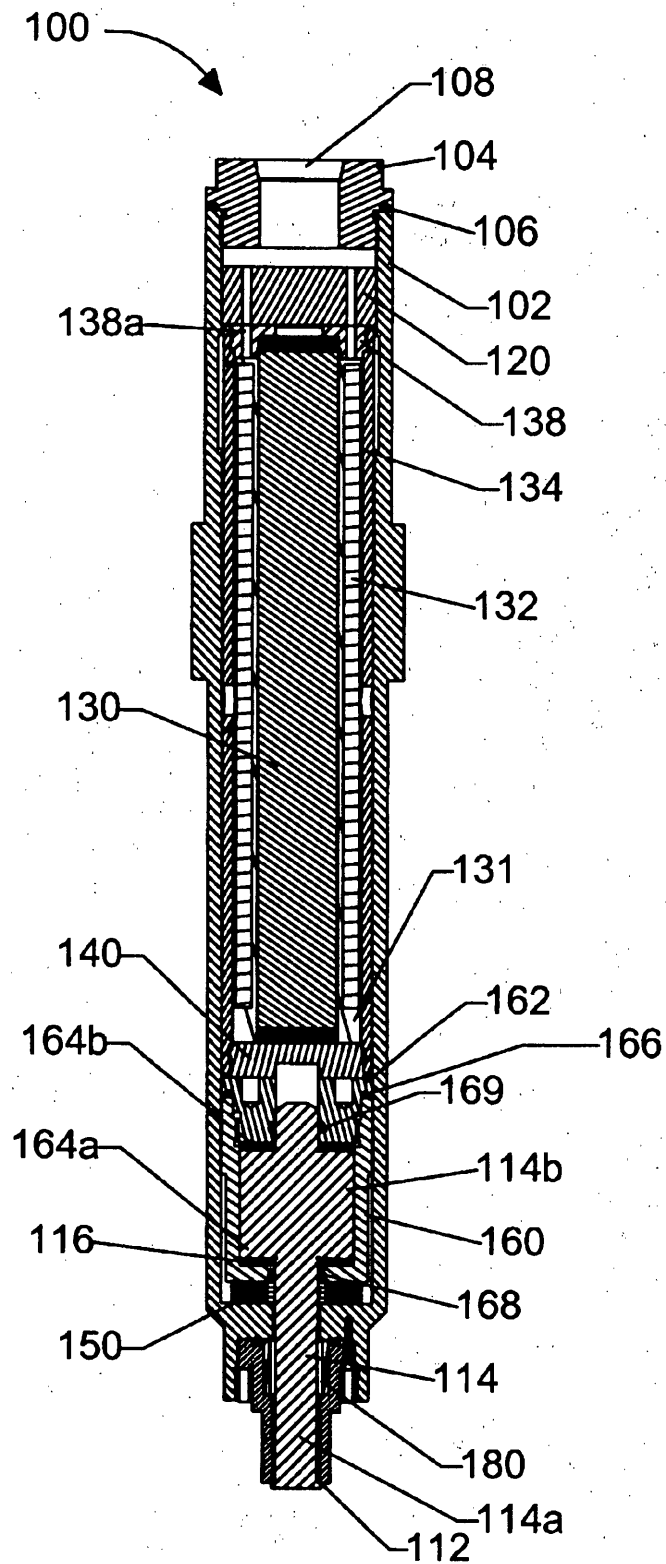


FIG. 1

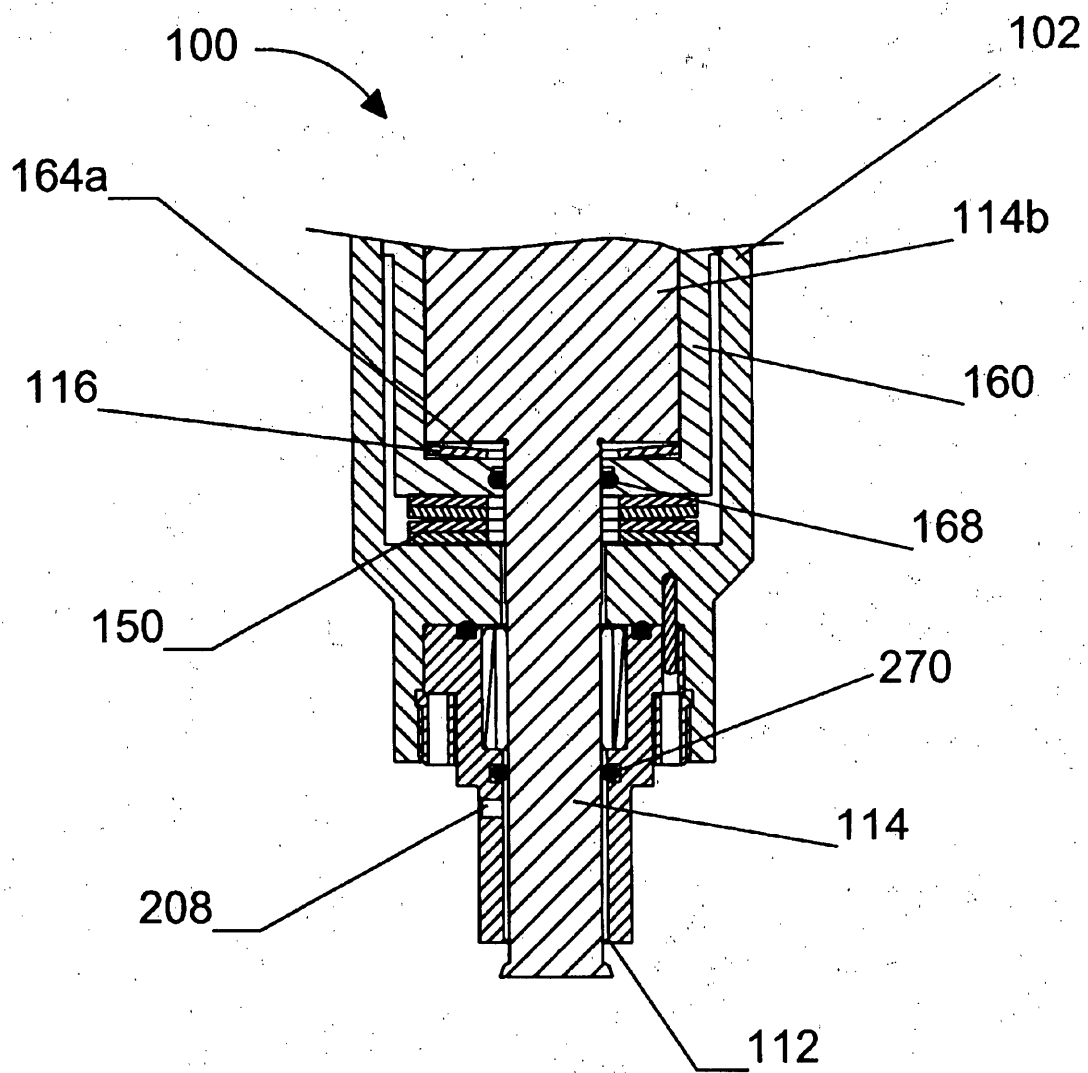


FIG. 2

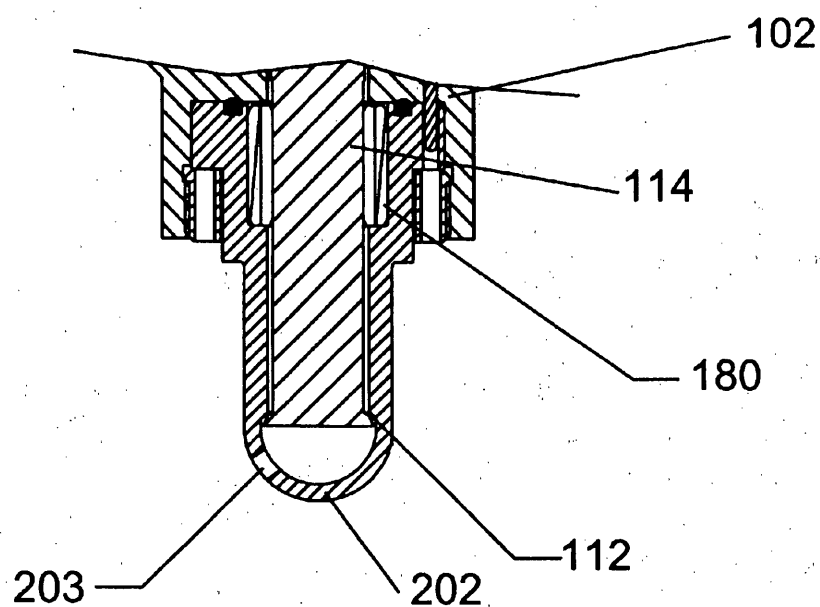


FIG. 2a

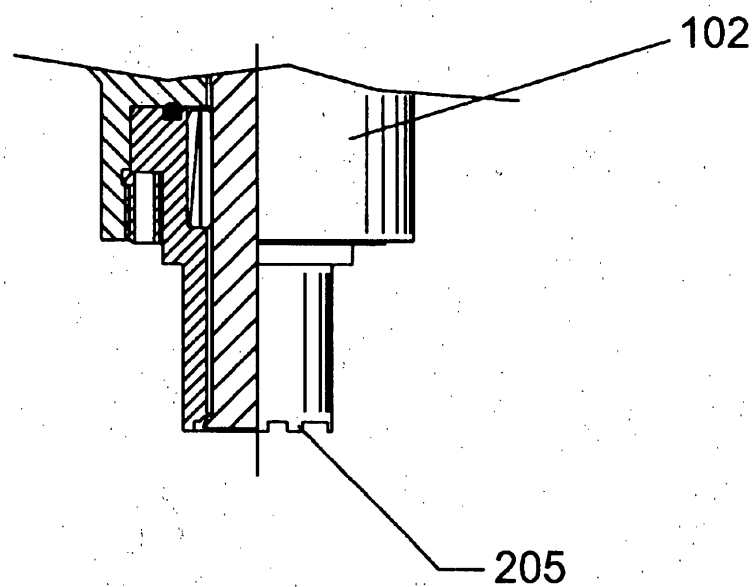


FIG. 2b

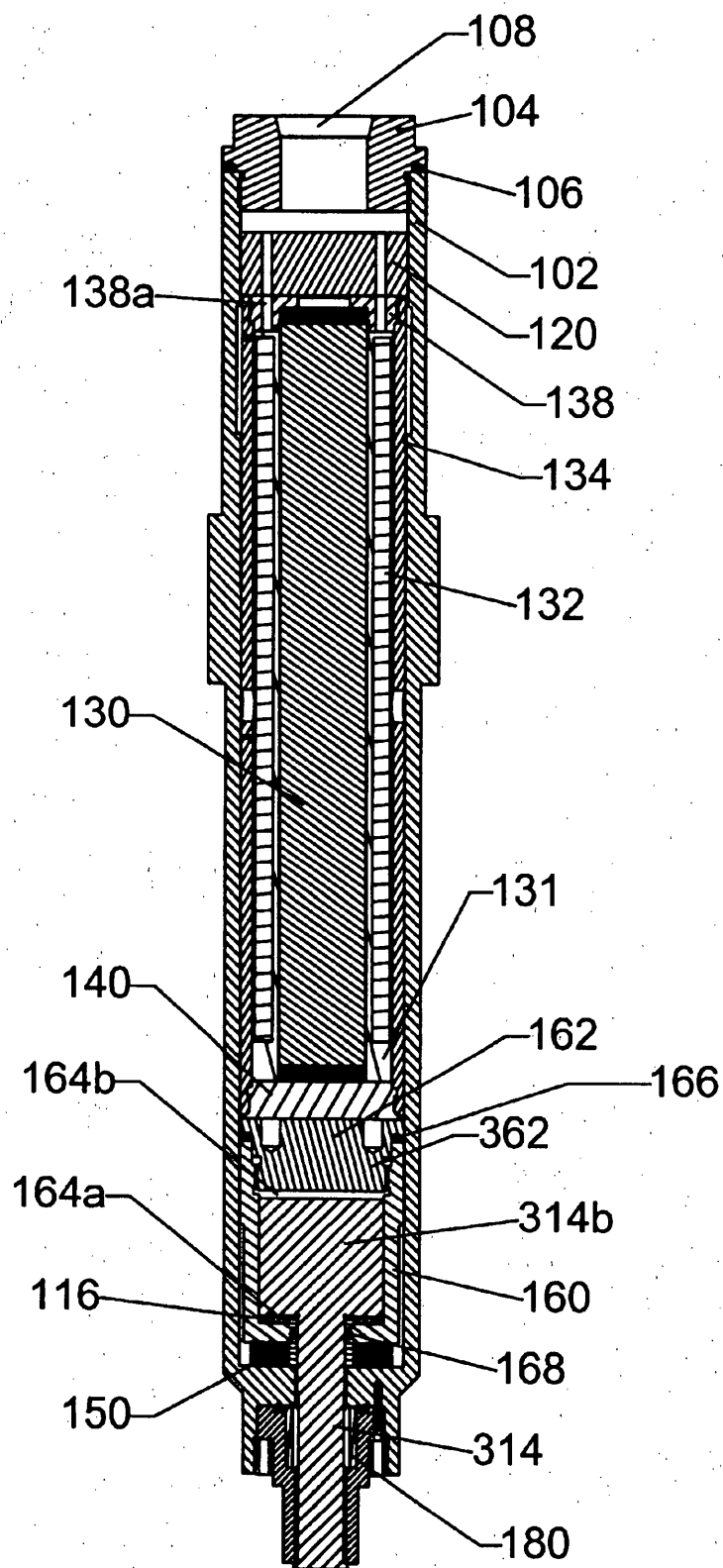


FIG. 3

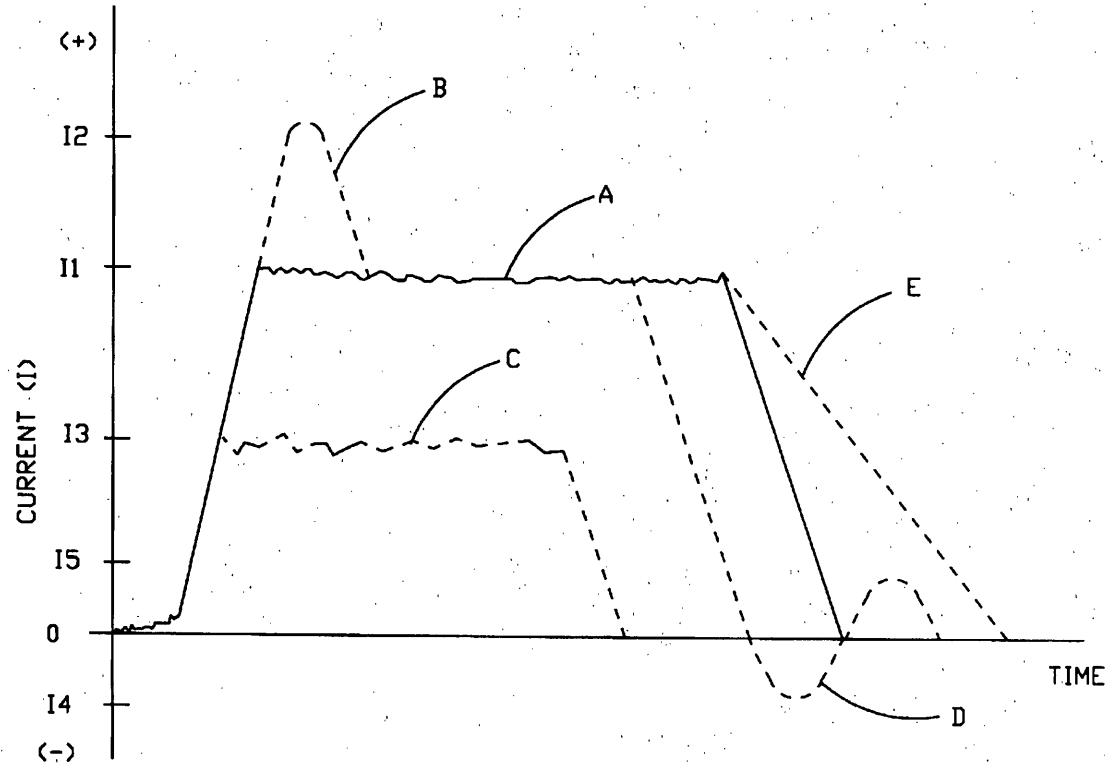


FIG. 4

DIRECTLY ACTUATED INJECTION VALVE**CROSS-REFERENCE TO RELATED APPLICATION(S)**

This application is a continuation-in-part of U.S. patent application Ser. No. 09/522,130 filed Mar. 9, 2000, entitled "Directly Actuated Injection Valve", now U.S. Pat. No. 6,298,829 issued Oct. 9, 2001. The '130 application relates to and claims priority benefits from U.S. Provisional Patent Application Serial No. 60/159,791 filed Oct. 15, 1999, entitled "Directly Actuated Injector". The '130 application and the '791 application are each incorporated herein by reference in their entirety.

FIELD OF THE INVENTION

The present invention relates generally to high pressure fuel injection valves or injectors for internal combustion engines, and, more specifically, to an injection valve that is directly controllable by a position actuating material (such as, for example, a piezoelectric or magnetostrictive material) and which includes a passive hydraulic link.

BACKGROUND OF THE INVENTION

Direct injection of a gaseous fuel into the combustion chamber of an internal combustion engine is desirable for several reasons. For example, direct injection allows charge stratification, eliminating throttling losses associated with homogeneous charge engines. Additionally, with direct injection late in the compression stroke, a high-compression ratio can be maintained, maintaining efficiency. Further, when the fuel that is directly injected comprises natural gas, propane, or hydrogen, the emissions of NO_x and particulate matter (PM) are significantly reduced. The directly injected gaseous fuel can be ignited with a glow plug, with a spark plug, with pilot diesel fuel, or with any other energy source. The gaseous fuel should be injected at high pressure to overcome the combustion chamber pressure, which is high at the end of the compression stroke. Preferably, the injection pressure is high enough to promote good mixing between the injected fuel and the combustion chamber air.

Direct injection at high pressures presents several challenges. The use of high-pressure fuels for direct injection results in high fuel pressures existing within the injection valve or injector. As a result, when closed, the injection valve should typically be strongly seated to avoid leakage of the fuel into the combustion chamber between injection events. When the valve is a needle valve, the valve is seated when the sealing surfaces of the movable valve needle and the valve seat are in fluid-tight contact with each other. The valve seat is generally part of the valve housing or body. For an outward opening valve, such as a poppet valve, the valve is closed when a valve member is retracted within the valve body so that the sealing surfaces of the valve member are pressed against the valve seat to form a fluid-tight seal. A fuel injection valve with an "outward" opening configuration is defined herein as an injection valve for an internal combustion engine which employs a valve member that is movable in the direction of the engine combustion chamber to an open position and in the opposite direction to a closed position. Terms used to describe such a valve member include, for example, pintle shaft, valve stem, and valve shaft. Outward opening injection valves typically comprise a circular valve head mounted transversely on the valve member for axial motion towards and away from a mating circular valve seat associated with the valve body.

Moreover, compared to low-pressure systems, higher forces are needed to open or close the injection valve. For

example, for a needle valve that employs an inwardly opening valve needle, when the needle is in the open position it may be subjected to high forces from the pressurized fuel. Conversely, with an outward opening injection valve, a high amount of force is required to keep the valve closed against the high fuel pressure within the injection valve body.

Additionally, there is only a small window of time during which the fuel can be injected. For example, at 4500 revolutions per minute (RPM), at full load, all of the fuel is preferably injected in less than 2-3 milliseconds.

Nearly all known direct fuel injection systems in internal combustion engines have been hydraulically actuated. These systems rely on a hydraulic fluid to provide the force that is needed to open an injection valve (or valves, when the engine comprises a plurality of combustion chambers). Accordingly, at typical engine operating speeds, hydraulically actuated injectors rely on rapid changes in the hydraulic fluid pressure to open and close the injection valve(s). An injection valve is typically opened by increasing the hydraulic fluid pressure and closed by reducing the hydraulic fluid pressure, such that the opening force applied to the injection valve is reduced, causing the valve to close. However, in the context of a conventional gaseous injection valve, hydraulic operation presents several drawbacks, including:

- the need for additional hydraulic hardware such as a hydraulic pump, valves, and a reservoir for the hydraulic fluid;

- the need for a seal to be established between the variable pressure hydraulic fluid and the high pressure gaseous fuel;

- increased bulkiness of the injection valve assembly because of the additional hardware requirements; and
- delayed response of the system caused by time delays associated with the dynamic flow of the hydraulic fluid, the actuation of the electronic hydraulic valve hardware and the movement of the needle that controls gas flow from the injection valve.

Moreover, the degree of controllability of the movement of the injection valve is low when the motive force is provided by a pressurized fluid rather than by a directly controllable source. In this respect, it is difficult to control lift, resulting in limited lift control capabilities when using hydraulically actuated injection valve with a double-spring configuration. Therefore, it is desirable to avoid the use of hydraulics to operate gaseous fuel injectors, particularly for high-speed engines. "Lift" in the context of injection valves is defined herein as the displacement of the valve needle or member away from its closed/seated position to its open position.

U.S. Pat. No. 5,779,149 describes an injector using a piezoelectric actuator acting on a hydraulic control valve through the intermediate of a hydraulic amplifier, which serves to amplify the movement of the actuator. The hydraulic control valve allows the main injection valve to open and close to meter the amount of fuel injected.

A problem with employing a piezoelectric or magnetostrictive actuator to operate a control valve, which in turn controls the flow of a hydraulic fluid to operate an injection valve, is that this arrangement requires the intermediate action of a hydraulic fluid. Any delays caused by the displacement of the hydraulic fluid causes delays in the actuation of the injector. Accordingly, there is a need for an injector that is directly actuated by an actuator without an intermediate active hydraulic operator generating any actuating forces. Another disadvantage of active hydraulically

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operated systems is that a hydraulic fluid needs to be supplied and drained from a hydraulic cylinder. When diesel fuel is the main fuel used by the engine, the diesel fuel may be used as the hydraulic fluid. However, when a gaseous fuel is the engine's main fuel, a separate hydraulic fluid system is needed to operate injectors that rely on hydraulic actuation.

SUMMARY OF THE INVENTION

An injection valve injects fuel into a combustion chamber of an internal combustion engine. The injection valve comprises:

- (a) a valve housing comprising:
 - a fuel inlet port;
 - an interior chamber fluidly connected to the fuel inlet port; and
 - a valve seat for cooperating with a valve member to seal the interior chamber from the combustion chamber when the injection valve is closed;
- (b) the valve member having one end disposed within the valve housing and an opposite end extendable from the valve seat toward the combustion chamber, wherein the valve member comprises a sealing surface that fluidly seals against the valve seat when the injection valve is closed and that is liftable away from the valve seat when the injection valve is open, wherein valve lift equals the distance traveled by the sealing surface away from the valve seat;
- (c) a biasing mechanism associated with the valve member, the biasing mechanism applying a closing force to the valve member when the valve member is in the closed position;
- (d) an actuator assembly associated with the valve member, wherein the actuator assembly may be actuated to apply an opening force to the valve member stronger than the closing force, for moving the valve member to the open position; and
- (e) a hydraulic link assembly comprising a passive hydraulic link having a hydraulic fluid thickness through which the opening and closing forces are transmitted, whereby the hydraulic fluid acts substantially as a solid with the thickness being substantially constant while the actuator assembly is actuated and wherein the thickness of the hydraulic link is adjustable while the actuator assembly is not actuated in response to changes in the dimensional relationship between components of the injection valve to maintain a desired valve lift upon actuation of the actuator assembly.

In a preferred embodiment, the thickness of the hydraulic link is auto-adjustable in response to changes in the dimensional relationship caused by differential thermal expansion, and/or wear to components of the injection valve. The hydraulic link assembly preferably comprises a fluidly sealed hydraulic cylinder that is fluidly sealed from the interior chamber. The hydraulic link assembly comprises a piston and hydraulic fluid disposed within the hydraulic cylinder. The hydraulic fluid is preferably a liquid such as, for example motor oil or grease. The piston may be an integral part of the valve member.

In a preferred injection valve the actuator assembly comprises a dimensionally responsive member. The dimensionally responsive member can be formed from a magnetostrictive material. The preferred magnetostrictive material comprises a metal alloy comprising terbium, dysprosium and iron. The preferred actuator assembly further comprises an electric coil disposed in an annular space around the

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dimensionally responsive member and a flux tube disposed in an annular space around the electric coil. The actuator assembly is preferably disposed within the interior chamber. The dimensionally responsive member can also be formed from a piezoelectric material. A preferred injection valve further comprises a compression spring member for applying a compressive force to the dimensionally responsive member.

In one embodiment, the fuel inlet is positioned so that fuel enters the valve housing and passes through the actuator and hydraulic link assemblies in the interior chamber. In this embodiment, the flow of fuel over these assemblies helps to remove heat generated by the activation of the actuator and reduces the effect of differential temperatures within the injection valve. In another embodiment, the fuel inlet is positioned near the valve tip so that the fuel flowing through the injection valve does not come into contact with the actuator assembly. This embodiment simplifies the construction of the actuator and hydraulic link assemblies since there is no need to provide fluid passages for the fuel to flow to the valve tip.

In a preferred injection valve, the lift is controllable by varying at least one of the electric current, the electric voltage and the magnetic field imposed upon the dimensionally responsive member. The valve member is preferably controllable such that the valve member moves between the open and closed positions in less than about 200 microseconds.

The injection valve preferably further comprises a biasing mechanism for applying a compressive force to the dimensionally responsive member. The biasing mechanism preferably comprises a spring. The spring preferably comprises at least one disc spring.

In a preferred injection valve, the fuel is gaseous and the hydraulic fluid is a liquid. The preferred hydraulic fluid is a liquid selected from the group consisting of motor oil and grease.

The present injection valve is particularly suited for injecting a gaseous fuel because the ability to modulate the movement of the valve member may be beneficially used to slow down the closing action of the valve member to reduce impact upon closing. When a liquid fuel is injected, the closing impact is dampened by the displacement of the thin liquid fuel layer, which is considerably denser than gaseous fuels. When the fuel is a gaseous fuel, it can be injected into the combustion chamber at a pressure greater than about 2000 psi (about 13.8 MPa).

While the hydraulic link in the present injection valve is designed to compensate for changes in the dimensional relationships between valve components, including changes caused by differential thermal expansion, the demands placed upon the hydraulic link may be reduced by the selection of materials for the valve components that have similar thermal expansion coefficients. In this regard, the valve housing, valve member and actuator assembly are preferably selected from materials having thermal expansion coefficients sufficiently compatible such that changes in the dimensional relationship between the components caused by changes in temperature are reduced.

A magnetostrictive material that is suitable for use in the present injection valve comprises a material known as ETREMA Terfenol-D® magnetostrictive alloy that is available from Etrema Products Inc. ETREMA Terfenol-D® magnetostrictive alloy is a metal alloy composed of terbium, dysprosium and iron.

In a preferred embodiment, the valve member, actuated by an actuator assembly that includes a dimensionally respon-

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sive member, is controllable to move between the closed and open positions in less than about 200 microseconds.

To improve the range of valve lift for a given length of the dimensionally responsive member, a compressive force may be applied to the dimensionally responsive member. By pre-loading the dimensionally responsive member, net displacement may be increased per respective unit of applied magnetic field (in the case of a dimensionally responsive member formed of magnetostrictive material) or applied voltage (in the case of a dimensionally responsive member formed of piezoelectric material). Accordingly, a biasing mechanism may be employed for applying a compressive force to pre-load the dimensionally responsive member. The biasing member preferably comprises at least one spring, most preferably at least one disc spring (also known as a Belleville spring or Belleville washer).

The injection valve housing may comprise a plurality of parts that are joined with each other to provide a fluidly sealed body. For example, the valve housing may comprise a hollow main housing with a removable valve cap that allows access to the valve components disposed within the main housing. The valve housing may further comprise a separate valve tip so that it is replaceable when worn. In addition, the valve tip may be designed so that it is the only portion of the valve body that is directly exposed to the interior of the combustion chamber. In this case the valve tip may be made from a material that will provide greater durability when directly exposed to the conditions that might be expected within a combustion chamber.

A preferred fuel injection valve for injecting fuel into a combustion chamber of an internal combustion engine comprises:

- (a) a valve housing comprising:
 - a fuel inlet port;
 - an interior chamber fluidly connected to the fuel inlet port;
 - a valve seat provided on an end of the housing that faces the combustion chamber;
- (b) a valve member comprising a shaft portion having a first end to which a circular head is transversely mounted wherein the head provides an annular sealing surface that faces the valve seat, and a second end of the shaft is associated with a piston portion, the valve member movable between a closed position at which the sealing surface contacts the valve seat to fluidly seal the interior chamber from the combustion chamber, and an open position at which the sealing surface is spaced apart from the valve seat whereby the interior chamber is fluidly connected with combustion chamber, wherein valve lift equals distance traveled by the sealing surface away from the valve seat;
- (c) a biasing mechanism associated with the piston portion of the valve member, the biasing mechanism applying a closing force to the valve member when the valve member is in the closed position;
- (d) an actuator assembly for applying an opening force to the valve member that is stronger than the closing force, for moving the valve member to the open position, the actuator assembly comprising a member having dimensional responsiveness to the imposition of at least one of an electric current, an electric voltage and a magnetic field, the dimensionally responsive member disposed between a fixed pole maintained in a fixed position relative to the valve housing and a sliding pole, the sliding pole being displaceable by expansion of the dimensionally responsive member; and
- (e) a hydraulic link assembly comprising a fluidly sealed hydraulic cylinder disposed about the piston portion of

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the valve member, a hydraulic fluid disposed within the hydraulic cylinder, wherein the opening and closing forces applied to the valve member are transmitted through a thickness of the hydraulic fluid whereby the hydraulic fluid acts as a hydraulic link and the thickness is automatically adjustable in response to changes in the dimensional relationship between components of the injection valve to maintain a desired valve lift upon actuation of the actuator assembly.

A method of using a shaped waveform to control electric current to actuate an injection valve for an internal combustion engine employs a dimensionally responsive actuator assembly comprising at least one of a magnetostrictive and a piezoelectric material, and a controller to govern valve lift and duration according to values predetermined for engine load demands within the operating range of the engine by the controller controlling current and voltage directed to the actuator assembly. The method comprises, for each injection event:

- (a) initiating an injection event by rapidly increasing current to a magnitude that is known to correspond to a desired lift by applying high frequency voltage cycles and in each cycle maintaining a net positive voltage;
- (b) maintaining a current to control the desired lift for a duration predetermined by the controller; and
- (c) concluding an injection event by decreasing current until it is reduced to zero amps by applying high frequency voltage cycles and in each cycle maintaining a net negative voltage.

In a preferred shaped waveform method, the step of initiating an injection event further comprises initially increasing current to a spike value higher than the value for the desired lift to rapidly open the valve and then reducing current to the value to cause the desired lift. The spike value is preferably up to about an order of magnitude higher than the value needed to cause the desired lift. The preferred method further comprises applying high frequency voltage cycles between offsetting positive and negative voltages to generate a current of close to zero amps immediately prior to an injection event. The time to open the valve from a closed position to the desired lift is less than about 175 microseconds, more preferably less than about 100 microseconds. More typically, however, the time needed to move the valve member between the closed position and the desired open position may be as short as about 250 microseconds.

A method of operating a fuel injection valve for an internal combustion engine, in which the injection valve has a longitudinal axis, comprises:

- (a) actuating a dimensionally responsive member comprising at least one of a magnetostrictive material and a piezoelectric material, the dimensionally responsive member expanding in length in the direction of the longitudinal axis upon actuation of the actuator;
- (b) transferring movement caused by the actuated dimensionally responsive member through a passive hydraulic link to cause a corresponding movement of a valve member to open the valve by lifting the valve member away from a valve seat and compressing a biasing mechanism that biases the valve in a closed position, the passive hydraulic link comprising a hydraulic cylinder which houses a piston and is filled with a hydraulic fluid, wherein the hydraulic fluid forms a layer between the piston and a cylinder head and because of the short duration that the valve is open, the hydraulic fluid does not have time to flow from one side of the

piston to the other side and while the injection valve is open, the layer of hydraulic fluid acts as an incompressible solid so that movement caused by the actuation of the dimensionally responsive member is transmitted through the fluid layer;

(c) deactuating the dimensionally responsive member to contract the length of the dimensionally responsive member to unload the biasing mechanism and cause a corresponding movement of the valve member to close the valve;

(d) providing sufficient time between consecutive valve openings to allow at least some of the hydraulic fluid within the passive hydraulic link to flow from one side of the piston to the other side of the piston.

An advantage of the present injection valve is that it may be employed for late-cycle high-pressure direct injection of fuels into internal combustion engines. For example, the present injection valve may be used to inject a gaseous fuel into the combustion chamber of an internal combustion engine at pressures of between about 2000 and 5000 psi (about 13.8 and 34.5 MPa). The present injection valve may be employed to introduce liquid fuels into internal combustion engines at even higher pressures.

Still another advantage of the present injection valve is that it provides an injection valve that eliminates the need for an active hydraulic operator and the associated high-pressure hydraulic system for generating the actuation force to actuate the injection valve. Conventional active hydraulic operators are different from the hydraulic link of the present invention, which may be described as a passive hydraulic link because the hydraulic fluid sealed within the hydraulic link assembly merely transmits the actuating forces but is not employed to generate an actuating force for actuating the valve. Rather, the purpose of the hydraulic link is to provide a load path for the opposing actuating forces that originate from at least one spring member and the actuator assembly. A benefit of eliminating the need for a conventional active hydraulic operator is the elimination of the associated active hydraulic systems. Conventional active hydraulic actuators, such as those that employ rapidly increasing and decreasing hydraulic fluid pressure to actuate an injection valve, are connected to a source of high pressure hydraulic fluid and have valves for controlling the flow of hydraulic fluid in and out of the active hydraulic operator. Active hydraulic actuators employ hydraulic fluid that is moved in and out of a hydraulic cylinder and when the hydraulic cylinder is fluidly connected to a source of high pressure hydraulic fluid, the high pressure hydraulic fluid that flows into the hydraulic cylinder generates the actuating force that is used to move the valve member. The actuating force is removed when the hydraulic cylinder is disconnected from the source of high-pressure hydraulic fluid and the hydraulic fluid is drained from the hydraulic cylinder. A disadvantage of active hydraulic actuators of this type is that there is a lag time associated with moving the hydraulic fluid into and out of the hydraulic cylinder.

A further advantage of the passive hydraulic link is that it may be employed to correct for differential thermal expansion, wear and dimensional variability within permitted manufacturing and assembly tolerances. The disclosed passive hydraulic link accomplishes this by auto-adjusting itself in response to these effects by allowing movement of hydraulic fluid between opposite sides of the hydraulic piston. The actuator assembly thus re-zeroes itself to ensure that the desired valve member lift is maintained.

An advantage of employing a directly actuated injection valve is that a shaped control pulse may be employed to

control the acceleration and deceleration of the valve member as it moves between the open and closed positions. For example, when a magnetostrictive actuator is employed, the current applied to the electromagnetic coil can be controlled, for example, to reduce the current in a manner that will close the valve gently. Similarly, when a piezoelectric actuator is employed, the voltage applied to the piezoelectric stack can be controlled, for example, to accelerate the opening of the valve by initially providing an over-voltage (that is, a voltage that is higher than the voltage that is needed to provide the necessary displacement). Thus, control pulses may be employed to control the expansion and contraction of magnetostrictive or piezoelectric actuators to control the movement of the valve member. An advantage of controlling the deceleration of the valve member is that the impact of the valve member on the valve seat upon closing can be reduced to reduce the wear on the valve components, thereby improving durability.

Yet another advantage of the present injection valve is that the control pulse may be shaped to provide for partial lifting of the valve member in a repeatable manner. The amount of lift may be controlled by shaping the control pulse to control the amount of electric current or voltage directed to the respective magnetostrictive or piezoelectric actuator assembly.

Still another advantage of the disclosed injection valve is that the actual valve lift is very small (typically much less than 0.1 millimeter), so that compared to valves designed for greater valve lift, to fully open or close the valve, the valve member velocity can be lower resulting in less impact and wear.

These and other advantages are provided by a directly actuated injector as described below.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross-sectional view of a preferred embodiment of a directly actuated fuel injection valve with a passive hydraulic link assembly;

FIG. 2 is an enlarged view of a partial cross-sectional view of the lower portion of a fuel injection valve shown in the open position with an alternate location for the fuel inlet port;

FIG. 2a is a partial cross-sectional view of an embodiment of a nozzle tip for an injection valve;

FIG. 2b is a partial side elevation view of an embodiment of a nozzle tip for an injection valve;

FIG. 3 is a cross-sectional view of another preferred embodiment of a directly actuated fuel injection valve with a different arrangement for the passive hydraulic link assembly; and

FIG. 4 is a timing diagram for a preferred method of controlling electric current applied to the actuator assembly of a fuel injection valve.

In the figures, like reference numerals are used to identify like components in different embodiments.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENT(S)

FIGS. 1 and 3 show two different preferred embodiments of an outward opening directly actuated fuel injection valve for internal combustion engines. Opposed to a needle valve, which employs a needle that is retracted into the valve body to open the valve, an outward opening injection valve extends a valve member outward and away from the valve body to open the valve. To open an outward opening fuel

injection valve for injecting fuel into an engine, a valve member is moved away from a valve seat and towards the combustion chamber.

Referring to FIGS. 1 and 2, injection valve 100 includes elongated valve housing 102 that cooperates with valve cap 104 to provide a fluidly sealed valve body. Seal 106 may be employed to ensure that the assembled valve body is fluid-tight. Valve cap 104 comprises inlet port 108 through which fuel enters the valve body. Valve housing 102 further comprises valve seat 112, which is better shown in FIG. 2, which shows an injection valve in the open position.

The figures are schematic representations of preferred embodiments of fuel injection valves for internal combustion engines. However, those skilled in the technology involved here will recognize that the figures are not construction drawings and are not drawn to scale. For example, valve housing 102 is shown as a single element, but for manufacturing purposes, valve housing 102 may be constructed from several pieces. In the figures, the sizes of some components have also been exaggerated to better illustrate certain elements of the apparatus.

The enlarged view of FIG. 2 also shows how valve seat 112 is angled to form a cone-shaped surface and cooperates with the angled sealing surface of valve member 114 to provide a fluid tight seal when the two surfaces are pressed into contact. In addition to providing a desirable sealing arrangement, valve seat 112 and the sealing surface of valve member 114 are angled to guide the direction in which the fuel is injected into the combustion chamber. An advantage of this arrangement is that it allows an unbroken conical sheet of fuel to be injected which provides a continuous surface for the combustion flame. Another advantage of an outward opening injection valve is that when the valve is closed, there is less concern about combustion products fouling or clogging the injection valve because unlike a needle valve there are no exposed nozzle holes.

Valve housing 102 may further comprise features for influencing how the fuel is introduced into the combustion chamber. For example, FIG. 2a shows an embodiment of valve housing 102 that comprises nozzle tip 202 below where valve member 114 seats against valve seat 112. Nozzle tip 202 provides a chamber that is connected to the combustion chamber by nozzle ports or orifices 203. In this embodiment the chamber and orifices 203 may be advantageously sized to slow down the fuel injection velocity to improve ignitability.

In yet another embodiment, valve housing 102 may further comprise an injection tip that has projections 205 as shown in FIG. 2b, which serve to provide breaks in the conical sheet of fuel that is injected when the injection valve is opened. Persons skilled in the technology involved here will recognize that the present invention can be combined with other valve tip configurations. The preferred valve tip configuration may depend upon other features of the engine such as, for example, the shape of the piston bowl and the size and operating conditions of the engine.

Valve Member

With reference to FIG. 1, valve member 114 is disposed within the interior of valve housing 102 and extends through an opening in the tip of valve housing 102. The sealing surface of valve member 114 contacts valve seat 112 to close injection valve 100 by preventing fuel from passing beyond valve seat 112 and into the combustion chamber. In the embodiment of FIG. 1, valve member 114 comprises valve stem 114a, which moves into the open position by moving outward away from the valve body to lift away from valve

seat 112. Since the valve lift is generally small (for example, about 65 micrometers), the diameter of valve stem 114a and the size of the annular opening around valve stem 114a are selected to ensure sufficient flow capacity through the injection valve since flow area (A) is proportional to valve stem diameter. Hence, a small lift can be compensated for by a larger diameter. In the preferred embodiment illustrated by FIG. 1 valve member 114 further comprises an integral piston 114b. In another embodiment (not shown) a separate piston member may cooperate with valve member 114 to provide the same effect.

Spring Assembly

A spring assembly biases valve member 114 in the closed position. In a preferred arrangement, the spring assembly comprises at least one valve spring 116 for providing a closing force to valve member 114. With reference to the embodiment of FIG. 1, valve spring 116 is shown as a disc or washer spring. A different type of spring such as a coil spring could be used instead. Pre-load plate 120 is used to apply a pre-load to valve spring 116 so that valve 100 is biased in the closed position. Valve spring 116 should provide a closing force to counter the opposing opening forces generated by the high pressure of the fuel directed to the interior of the sealed valve body. In the arrangement shown in FIG. 1, respective threaded surfaces join pre-load plate 120 to valve housing 102. As is known in the art, after pre-load plate 120 has been rotated to compress valve spring 116 to provide the desired pre-load force to valve spring 116, pre-load plate 120 may be held in position by means of a locking nut (not shown).

Actuator Assembly

An actuator assembly may be actuated to provide an opening force that is opposite and greater than the closing force provided by the spring assembly. In the embodiment illustrated in FIG. 1, the actuator assembly comprises a member that expands or contracts in the direction of the longitudinal axis of valve housing 102 when the member is exposed to a magnetic field or subjected to an electric voltage, such as, for example, a magnetostrictive material or a piezoelectric stack, respectively.

In the embodiment illustrated by FIG. 1, the actuator assembly is a magnetostrictive actuator that comprises a solid magnetostrictive member 130, with bobbin 131, electric coil 132, and flux tube 134 disposed in the annular space between magnetostrictive member 130 and valve housing 102. As shown in FIG. 1, coil 132 is wound around bobbin 131 and flux tube 134 surrounds bobbin 131 and electric coil 132. Flux tube 134 may be made from common carbon steel with a lengthwise slit to break eddy currents. An electric current is supplied to electric coil 132 through electric leads (not shown). When an electric current is applied to electric coil 132 a magnetic flux develops that flows through magnetostrictive member 130, fixed pole 138, sliding pole 140, and flux tube 134. Poles 138 and 140 are made from a suitable material such as carbon steel (for example CS1018) or steel that has a low magnetic hysteresis. Fixed pole 138 is held in a "fixed" position between pre-load plate 120 and end faces of magnetostrictive member 130, bobbin 131 and flux tube 134. Accordingly, when the actuator assembly is actuated and magnetostrictive member 130 grows in length, sliding pole 140 is pushed towards valve member 114 to providing a force for opening injection valve 100.

In another preferred embodiment (not illustrated), flux tube 134 may be integrated with valve housing 102. That is, valve housing 102 could be constructed from a magnetically permeable material that is suitable both structurally and for acting as a flux path. For example, many steels are suitable

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as materials for housing 102. Stainless steels may be employed but more preferably, common carbon steels are better suited because of material hardness properties and durability. Similarly, fixed pole 138 could also be integrated with pre-load plate 120. Those skilled in the technology involved here will understand that such components can be advantageously integrated without departing from the spirit and scope of the present invention. An advantage of integration, for example, is the efficiencies and reduced costs of manufacturing devices comprising less parts.

An advantage of the preferred embodiments is that magnetostrictive member 130 can be made from a solid cylindrical rod of magnetostrictive material, which is easier and less expensive to manufacture compared to hollow tubular forms.

A pre-compression force is preferably applied to magnetostrictive member 130 to amplify the magnitude of expansion when a magnetic field is applied. Pre-compression of magnetostrictive member 130 increases the net displacement per unit of applied magnetic field. Similarly, when a piezoelectric member is substituted for magnetostrictive member 130, pre-compression increases the net displacement of the piezoelectric member per unit of applied electric voltage. A spring, such as, for example, disc spring 150 may be employed to provide the pre-compression force. Alternative compression elements may be employed in place of disc spring 150 to provide the pre-compression force, such as, for example, a coil spring or another type of spring with the same spring force. When a pre-compression force of, for example, about 1000 psi (about 6.9 MPa) is employed, the actuator's displacement can increase to about 0.13% of the total length of magnetostrictive member 130. However, the amount of displacement may decline as a function of increasing temperature. For example, at typical reciprocating engine cylinder head temperatures the actual displacement may be about 0.065% of the length of pre-compressed magnetostrictive member 130.

The dimensions of magnetostrictive member 130 are dictated by the requirements of injection valve 100. For example, if injection valve 100 is designed to provide a lift of at least about 65 μm , magnetostrictive member 130 is sized to have a length of at least about 100 mm. Additionally, the transverse cross-sectional area of cylindrical magnetostrictive member 130 is selected to provide sufficient force to overcome all of the opposing forces that hold injection valve 100 in the closed position. If the cross-sectional area of cylindrical magnetostrictive member 130 is not sufficient, the opposing forces can reduce or prevent longitudinal displacement of magnetostrictive member 130, even when electric coil 132 is fully energized. This mode is known as the "blocked force" mode. Accordingly, the magnitude of the closing forces acting on valve member 114 dictate the minimum cross sectional area of magnetostrictive member 130.

While FIG. 1 shows magnetostrictive member 130, electric coil 132, and flux tube 134 could be replaced with a piezoelectric stack (not shown). Electrical leads could be employed to direct an electric voltage to the piezoelectric stack. When an electric voltage is applied to a piezoelectric stack, the stack expands and develops a motive force for opening injection valve 100. Accordingly, the configuration of the present injection valve is essentially the same for magnetostrictive and piezoelectric actuators.

Hydraulic Link Assembly

The opening force generated by the actuator assembly is transmitted to valve member 114 through a hydraulic link assembly. The hydraulic link assembly comprises hydraulic

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cylinder 160, which is disposed in close-fitting relationship around hydraulic piston 114b, which is movable in the longitudinal direction within cylinder 160. As mentioned above, in the embodiment of FIG. 1, hydraulic piston 114b is preferably an integral part of valve member 114 and the sidewall of cylinder 160 helps to guide the movement of valve member 114 in the longitudinal direction. A viscous hydraulic fluid is sealed inside hydraulic cylinder 160 by cylinder cap 162 and seals 166, 168 and 169. Seals 168 and 169 permit valve member 114 to move relative to cylinder 160 and cylinder cap 162, respectively. Known seals may be employed, such as, for example elastomeric O-ring seals, packing, metal seals, or diaphragm/bellow seals.

The diametrical clearance gap between the outside diameter of hydraulic piston 114b and the inside diameter of hydraulic cylinder 160 is extremely small (on the order of 20 to 250 microns). The desired size of the clearance gap is dependent upon several factors such as the viscosity of the chosen hydraulic fluid, the axial length of the piston, and the thickness of the hydraulic fluid above and below the piston. The hydraulic flow in the clearance gap is governed by the Hagen-Poiseuille Flow and the hydraulic fluid and clearance gap are preferably selected so that the flow of hydraulic fluid through the gap is insignificant during the time span of fuel injection events when an opening force is transmitted through the hydraulic fluid. Furthermore, the hydraulic fluid preferably has a sufficiently high viscosity and bulk modulus so that it acts as an incompressible solid when actuation of the actuator assembly causes a valve opening force to be quickly transmitted through the hydraulic fluid between the bottom of cylinder 160 and hydraulic piston 114b. For consistency of operation, the hydraulic fluid is also preferably an extremely stable fluid that maintains its desired properties over a wide range of temperatures (that is, within the expected operating temperatures inside cylinder 160). Suitable hydraulic fluids are, for example, conventional motor oil, such as grade 15W40, or synthetic lubricants such as DuPont® Krytox® grease which is available in a range of viscosities. Krytox® is a perfluoropolyether (PFPE) synthetic lubricant that may be mixed with a thickener to form a grease. These types of hydraulic fluids also help to lubricate seals 168 and 169. Different injection valves may have different sized hydraulic pistons and clearance gaps, so the hydraulic fluid may be selected with consideration to the characteristics of an individual injection valve design.

When injection valve 100 is closed and at rest, the closing force is transmitted through the hydraulic fluid held between cylinder cap 162 and hydraulic piston 114b. Typically, during engine operation, injection valve 100 is closed most of the time (normally over 90% of the time). Accordingly, there is enough time between injection events for the hydraulic fluid to redistribute itself by flowing through the clearance gap so that hydraulic cylinder 160 moves relative to piston 114b to automatically "re-zero" itself. The initial zero-position is the position of hydraulic piston 114b within hydraulic cylinder 160 after assembly of injection valve 100. The initial zero position may not be the same for all injectors due to slight variations in the length of components within manufacturing tolerances. Also, during operation, the zero-position auto-adjusts in response to changes in the dimensional relationship between components, caused by, for example, component wear or the effects of differential thermal expansion.

Differential thermal expansion or contraction may be caused by differences in thermal expansion coefficients or uneven heat distribution between the components. Even though the components of injection valve 100, such as

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magnetostrictive member 130, valve member 114, and valve housing 102, are designed to be reasonably matched to the thermal expansion rates of the other components, because the valve lift and the displacement of the components that causes such lift are so small, the effects of thermal expansion or contraction should be taken into account to ensure the desired valve lift is achieved. The effects of thermal expansion and contraction may be amplified if the injection valve is exposed to a wide range of temperatures. For injection valves used in vehicles it would not be uncommon to expect a temperature range between -40° C. (in cold climates) and +125° C. (when the engine is running). An uneven temperature distribution may be the result of many factors, including, for example, the influence of (1) heat generated at electric coil 132; (2) magnetic hysteresis in the actuator assembly; and (3) heat transfer from the cylinder head or the combustion chamber via the injection valve tip and valve member 114. If unaccounted for, the total effect of differential thermal expansion or contraction on the displacement of valve member 114 may be greater than the targeted lift.

In summary, the hydraulic link assembly accounts for variations in component dimensions arising from the permitted tolerances in the manufacturing processes and the injection valve assembly methods. Therefore, the hydraulic link assembly reduces manufacturing costs by allowing the injection valve components to be manufactured to less exacting tolerances. In addition, during operation, the hydraulic link assembly auto-adjusts itself between injection events to account for changes in the dimensional relationship between injection valve components that may be caused, for example, by component wear or differential thermal expansion or contraction.

FIG. 2 illustrates an injection valve embodiment that has fuel inlet 208 located in the side of valve housing 102. An advantage of this arrangement is that fluid pathways are not required through the actuator and hydraulic link assemblies, simplifying the construction of these components and reducing the cross-section area needed for the upper valve assembly. Seal 270, shown in FIG. 2, which may be, for example, an o-ring or packing type seal, prevents the high-pressure fuel from entering the portion of the valve body that houses the hydraulic link and actuator assemblies. A guide (not shown in FIG. 2), similar to guide 180 shown in FIG. 1 may also be employed in the embodiment of FIG. 2 to help guide the movement of valve member 114.

FIG. 3 illustrates an injection valve embodiment that employs a valve member 314 that has a T-shaped cross-section. This embodiment operates in substantially the same manner as the embodiment of FIG. 1. One advantage of the embodiment of FIG. 3 is that seal 169 is eliminated. Another advantage is that valve member 314, sliding pole 340, and cylinder cap 362 are simpler shapes and thus easier to manufacture and there are less tolerance fits since there is no stem protruding from hydraulic piston 314b.

SUMMARY OF OPERATION

When injection valve 100 is at rest in the closed position, the closing force that biases valve member 114 against valve seat 112 originates from valve spring 116 and disc spring 150. In the illustrated preferred embodiments, valve spring 116 bears directly against hydraulic piston 114b to transmit a closing force directly to valve member 114. Disc spring 150 bears against hydraulic cylinder 160 and a pre-compression force is transmitted to the actuator assembly through the sliding assembly comprised of hydraulic cylinder 160, cylinder cap 162 and sliding pole 140. Disc spring 150 also applies a closing force to valve member 114 since

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it applies a force to hydraulic cylinder 160, which supports valve spring 116. It is preferable for the closing force to be provided by a mechanical spring member, such as the illustrated coil spring, so that the failure mode for injection valve 100 will be in the closed position. That is, if the actuating assembly is not energized or fails, injection valve 100 will remain in the closed position.

To initiate an injection event the actuator assembly is energized by directing an electric current to electric coil 132. A magnetic flux develops that flows through magnetostrictive member 130, poles 138 and 140, and flux tube 134. Under the influence of the magnetic field, magnetostrictive member 130 expands in length (in the direction of the magnetic field). Since fixed pole 138 is stationary, magnetostrictive member 130 expands in the direction of hydraulic cylinder 160. An opening force, originating from expanding magnetostrictive member 130 is transmitted through sliding pole 140, cylinder cap 162, hydraulic fluid 164b disposed within the space between cylinder cap 162 and a planar surface of hydraulic piston 114b, and finally, through piston 114b, which in the illustrated embodiments is integral with valve member 114. The opening force is greater than the closing force, which results in the compression of valve spring 116. The displacement of hydraulic cylinder 160 also results in some further compression of disc spring 150.

As previously discussed, because valve actuation occurs suddenly (on the order of 200 μ s), hydraulic fluid 164b does not have time to flow through the narrow clearance gap between piston 114b and hydraulic cylinder 160. Instead, hydraulic fluid 164b acts as a solid and transfers the movement of magnetostrictive member 130 to valve member 114 via piston 114b, causing valve member 114 to lift away from valve seat 112. Because injection valve 100 stays open for such a brief period (typically less than 3 milliseconds), as long as the viscosity of hydraulic fluid 164 is properly selected and the clearance gap is suitably sized, the flow of hydraulic fluid 164 through the clearance gap while injection valve 100 is open is insignificant so that any displacement caused by such flow is much less than the total displacement of valve member 114.

The movement of valve member 114 is guided near the valve tip by guide 180. Guide 180 comprises longitudinal grooves or longitudinal bores or slots (not shown) to allow the fuel to pass therethrough and into the valve tip. Valve member 114 is also guided by the cooperating between the side walls of hydraulic piston 114b and the internal walls of hydraulic cylinder 160.

As shown in the embodiment of FIG. 1, fuel inlet 108 is located in cap 104 and fuel flows through the hollow valve body. In the preferred application, the fuel is a gaseous fuel so small gaps between valve components are sufficient to allow the gaseous fuel to flow through the length of the valve body to the opposite end where the fuel is introduced into the engine combustion chamber through the tip of the injection valve. Fuel flow through the valve interior can also be facilitated by providing longitudinal grooves in the side walls of valve components (not shown) and/or holes or slots provided through components (see for example holes 138a through fixed pole 138). Causing the fuel to flow through the interior of the injection valve helps to cool the valve components and remove heat that may be generated in the actuator assembly. When the fuel is used to cool the actuator assembly in this manner, thermal modeling predicts that during normal operation heat generated by the actuator assembly will cause a temperature rise of less than 10° C.

To close injection valve 100, at the end of the injection event, electric coil 132 is deenergized, causing magneto-

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strictive member 130 to contract. When valve member 114 is moving from the open position to the closed position, the closing force originates from valve spring 116 and disc spring 150. The closing force from valve spring 116 is again transmitted to valve member 114 through hydraulic piston 114b. In the open position, the expanded magnetostrictive member 130 compressed disc spring 150, so upon closing, disc spring 150 de-compresses to push cylinder 160 towards the actuator assembly to compress to magnetostrictive member 130. Disc spring 150 also provides an additional closing force to valve member 114 by generating a closing force that is transmitted from disc spring 150 through hydraulic cylinder 160, valve spring 116 and hydraulic piston 114b.

Once valve member 114 contacts valve seat 112, injection valve 100 is closed. When injection valve 100 is closed, the hydraulic link assembly automatically self-adjusts so that the position of hydraulic cylinder 160 relative to hydraulic piston 114b is corrected to account for the effects of temperature, wear, and any small movements of valve member 114 relative to hydraulic cylinder 160 that may have occurred while valve member 114 was in the open position. Auto-adjustments are accomplished by the migration of hydraulic fluid from chamber 164b on one side of hydraulic piston 114b to chamber 164a on the other side of hydraulic piston 114b, while valve spring 116 and disc spring 150 ensure that the injection valve remains closed with valve member 114 seated against valve seat 112.

Control Strategy

Preferred waveforms representing the amount of electric current delivered to a valve actuator for controlling an injection valve are plotted in FIG. 4. The illustrated waveform shows that the control pulse may employ several features to control the movement of a magnetostrictive or piezoelectric member respectively.

For example, for an actuator employing a magnetostrictive member, an electric current is directed to an electric coil that is used to actuate the magnetostrictive member. The strength of the magnetic field is directly proportional to the amount of electric current that is directed to the electric coil. To promote fast opening, for a short time immediately prior to an injection event (for example 100 microseconds), a current is preferably initiated by high frequency voltage cycles between substantially equivalent positive and negative voltages. For example, these high voltage cycles may be on the order of 100 kHz.

Waveform A illustrates a preferred pulse shape for an injection event. An injection event is initiated when the valve is opened by rapidly increasing current to I_1 , which is of a magnitude that is known to correspond to a desired lift. When the valve is opening, the high frequency voltage cycles continue between positive and negative voltages but a net positive voltage. Once the desired valve lift is attained, the current is maintained at I_1 to maintain the valve lift for a duration predetermined by a controller. The controller is responsive to current engine load and demand.

The injection event is concluded by decreasing current until it is reduced substantially to zero amps by applying high frequency voltage cycles and in each cycle maintaining the negative voltage for a longer time than the positive voltage.

As shown by the dashed lines in FIG. 4, the shape of the waveform may be controlled to achieve desired effects. For example, dashed waveform B shows that upon initiating the injection event, to further accelerate valve opening and introduction of the fuel, the current may be initially increased to I_2 which is much higher than the magnitude needed to provide the desired lift. To conserve energy and to

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maintain the desired lift during the duration of the injection event, the current is later lowered to I_1 . In this example, current I_1 has a value corresponding to the current known to maintain the desired lift.

Waveform C shows that different amounts of valve lift can be achieved by changing the magnitude of the current maintained during the injection event. Waveform C maintains the current at I_3 to produce a lower lift to inject a smaller amount of fuel compared to the injection event of waveform A. Waveform C also shows an injection event with a shorter duration compared to the injection event that would be produced by waveform A.

Dashed line D shows that the shape of the waveform can be manipulated to influence the movement of the valve member. In this example the current is momentarily made negative to I_4 to accelerate the valve closing and then made momentarily positive again to I_5 to slow down the valve member to reduce impact and wear on the valve member and valve seat. The current could also be kept positive (that is I_4 equals zero) and current could be momentarily raised to I_5 to slow down the valve member before it contacts the valve seat. Dashed line E also shows that valve closing impact and wear to the valve seat and valve member can be reduced by slowing the rate at which the current is reduced to zero.

Persons skilled in the technology involved here will recognize that the time to open or close the injection valve may be decreased by increasing the slope of the control waveform, or increased, by decreasing the slope of the waveform. In summary, the shape of the control waveform may be manipulated to produce the desired effects on the speed of the valve member movement and its displacement with respect to the valve seat (to control lift).

The time span for the waveforms of FIG. 4 may be in the range of 100 to 5000 microseconds, and typically between 250 and 2000 microseconds for the majority of injection events.

The combination of the above described directly actuated injection valve and control strategy provides several benefits, including:

- elimination of the hydraulic fluid supply system that is needed by conventional hydraulically actuated injection valves. This simplifies injection valve construction, for example, by eliminating the need for hydraulic fluid supply and return passages and the hydraulic fluid control valves that are employed by conventional hydraulically actuated injection valves.

- automatic compensation for differential thermal expansion within the injection valve, for wear due to prolonged operation, and for small differences caused by limitations in manufacturing tolerances.

- an apparatus that permits the use of a control strategy that can throttle fuel flow and reduce valve seat wear. The ability to control the lift displacement permits reduced injection at lower loads and reduced pre-mixed burning. For example, using a magnetostrictive or piezoelectric actuator, the valve member movement can be controlled between about 10% and 100%. For lower load conditions it is important to be able to reduce the flow of fuel into the combustion chamber, since excess fuel may not be combusted, resulting in lower operating efficiency and higher emissions.

- improved manufacturability is made possible by the use of axisymmetric cylindrical parts and few tight tolerances between the injection valve components.

- valve operation is improved since the actuating assembly permits greater control of the valve member. For

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example, the injection valve may be used to inject a gaseous or liquid fuel. When the fuel is gaseous, there is a greater need to slow down the valve member upon closing because there is no liquid fuel to dampen the impact of the valve member on the valve seat.

By shaping the control pulse waveform applied to the actuator it is possible to slow down the closing of the injection valve to reduce impact on the valve member and the valve seat.

While particular elements, embodiments and applications of the present invention have been shown and described, it will be understood, of course, that the invention is not limited thereto since modifications may be made by those skilled in the art without departing from the scope of the present disclosure, particularly in light of the foregoing teachings.

What is claimed is:

1. An injection valve for injecting fuel into a combustion chamber of an internal combustion engine, said injection valve comprising:

(a) a valve housing comprising:

a fuel inlet port;

an interior chamber fluidly connected to said fuel inlet port; and

a valve seat for cooperating with a valve member to seal said interior chamber from said combustion chamber when said injection valve is closed;

(b) said valve member having one end disposed within said valve housing and an opposite end extendable from said valve seat toward said combustion chamber, wherein said valve member comprises a sealing surface that fluidly seals against said valve seat when said injection valve is closed and that is liftable away from said valve seat when said injection valve is open;

(c) a biasing mechanism associated with said valve member, said biasing mechanism applying a closing force to said valve member when said valve member is in said closed position;

(d) an actuator assembly associated with said valve member, wherein said actuator assembly may be actuated to apply an opening force to said valve member stronger than said closing force, for moving said valve member to said open position; and

(e) a hydraulic link assembly comprising a passive hydraulic link having a hydraulic fluid thickness through which said opening and closing forces are transmitted, whereby said hydraulic fluid acts substantially as a solid with said thickness being substantially constant while said actuator assembly is actuated and wherein said thickness of said hydraulic link is adjustable while said actuator assembly is not actuated in response to changes in the dimensional relationship between components of said injection valve to maintain a desired valve lift upon actuation of said actuator assembly.

2. The injection valve of claim 1 wherein said thickness of said hydraulic link is auto-adjustable while said actuator assembly is not actuated in response to changes in said dimensional relationship caused by differential thermal expansion.

3. The injection valve of claim 2 wherein said thickness of said hydraulic link is auto-adjustable while said actuator assembly is not actuated in response to changes in said dimensional relationship caused by wear to components of said injection valve.

4. The injection valve of claim 1 wherein said hydraulic link assembly comprises a fluidly sealed hydraulic cylinder that is fluidly sealed from said interior chamber, said hydraulic link assembly comprising a piston and said hydraulic fluid is disposed within said hydraulic cylinder.

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5. The injection valve of claim 4 wherein said piston is an integral part of said valve member.

6. The injection valve of claim 1 wherein said actuator assembly comprises a dimensionally responsive member.

7. The injection valve of claim 6 wherein said dimensionally responsive member is formed from a magnetostrictive material.

8. The injection valve of claim 7 wherein said magnetostrictive material comprises a metal alloy comprising terbium, dysprosium and iron.

9. The injection valve of claim 7 wherein said actuator assembly further comprises an electric coil disposed in an annular space around said dimensionally responsive member.

10. The injection valve of claim 9 wherein said actuator assembly further comprises a flux tube disposed around said electric coil.

11. The injection valve of claim 10 wherein said a flux tube is disposed in an annular space around said electric coil.

12. The injection valve of claim 10 wherein said actuator assembly is disposed within said interior chamber.

13. The injection valve of claim 6 wherein said dimensionally responsive member is formed from a piezoelectric material.

14. The injection valve of claim 6 further comprising a compression spring member for applying a compressive force to said dimensionally responsive member.

15. The injection valve of claim 1 wherein said fuel inlet port is positioned such that fuel enters said valve housing and passes through said actuator and hydraulic link assemblies.

16. The injection valve of claim 1 wherein said fuel inlet port is positioned near the valve tip such that fuel flowing through said interior chamber does not contact said actuator assembly.

17. The injection valve of claim 6 wherein said actuator assembly is controllable to maintain said desired lift between 10 and 100 percent of maximum lift.

18. The injection valve of claim 17 wherein said lift is controllable by varying at least one of the electric current, the electric voltage and the magnetic field imposed upon said dimensionally responsive member.

19. The injection valve of claim 6 wherein said valve member is controllable such that said valve member moves between said open and closed positions in less than about 200 microseconds.

20. The injection valve of claim 6 further comprising a biasing mechanism for applying a compressive force to said dimensionally responsive member.

21. The injection valve of claim 1 wherein said biasing mechanism comprises a spring.

22. The injection valve of claim 21 wherein said spring comprises at least one disc spring.

23. The injection valve of claim 1 wherein said fuel is a gaseous fuel.

24. The injection valve of claim 23 wherein said hydraulic fluid is a liquid.

25. The injection valve of claim 24 wherein said hydraulic fluid is a liquid selected from the group consisting of motor oil and grease.

26. The injection valve of claim 1 wherein said fuel is injected into said combustion chamber at a pressure greater than about 2000 psi (about 13.8 Mpa).

27. The injection valve of claim 1 wherein said valve housing comprises a plurality of parts which are joined with each other to provide a fluidly sealed body.

28. The injection valve of claim 1 wherein said valve housing, said valve member and said actuator assembly are selected from materials having thermal expansion coefficients sufficiently compatible such that changes in the dimensional relationship between said components caused by changes in temperature are reduced.

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29. An injection valve for injecting fuel into a combustion chamber of an internal combustion engine, said injection valve comprising:

- (a) a valve housing comprising:
 - a fuel inlet port;
 - an interior chamber fluidly connected to said fuel inlet port;
 - a valve seat provided on an end of said housing that faces said combustion chamber;
- (b) a valve member comprising a shaft portion having a first end to which a circular head is transversely mounted wherein said head provides an annular sealing surface that faces said valve seat; and a second end of said shaft is associated with a piston portion, said valve member movable between a closed position at which said sealing surface contacts said valve seat to fluidly seal said interior chamber from said combustion chamber, and an open position at which said sealing surface is spaced apart from said valve seat whereby said interior chamber is fluidly connected with combustion chamber;
- (c) a biasing mechanism associated with said piston portion of said valve member, said biasing mechanism applying a closing force to said valve member when said valve member is in said closed position;
- (d) an actuator assembly for applying an opening force to said valve member that is stronger than said closing force, for moving said valve member to said open position, said actuator assembly comprising a member having dimensional responsiveness to the imposition of at least one of an electric current, an electric voltage and a magnetic field, said dimensionally responsive member disposed between a fixed pole maintained in a fixed position relative to said valve housing and a sliding pole, said sliding pole being displaceable by expansion of said dimensionally responsive member; and
- (e) a hydraulic link assembly comprising a fluidly sealed hydraulic cylinder disposed about said piston portion of said valve member, a hydraulic fluid disposed within said hydraulic cylinder, wherein said opening and closing forces applied to said valve member are transmitted through a thickness of said hydraulic fluid whereby said hydraulic fluid acts as a hydraulic link and said thickness is automatically adjustable in response to changes in the dimensional relationship between components of said injection valve to maintain a desired valve lift upon actuation of said actuator assembly.

30. The injection valve of claim 29 wherein said dimensionally responsive member is formed from a magnetostrictive material.

31. The injection valve of claim 30 wherein said magnetostrictive material comprises a metal alloy comprising terbium, dysprosium and iron.

32. The injection valve of claim 30 wherein said actuator assembly further comprises an electric coil disposed in an annular space around said dimensionally responsive member.

33. The injection valve of claim 32 wherein said actuator assembly further comprises a flux tube disposed in an annular space around said electric coil.

34. The injection valve of claim 29 wherein said dimensionally responsive member is formed from a piezoelectric material.

35. The method of claim 29 further comprising applying high frequency voltage cycles between offsetting positive and negative voltages to generate a current of close to zero amps immediately prior to an injection event.

36. The method of claim 29 wherein the time to open said valve from a closed position to said desired lift is less than about 100 microseconds.

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37. The injection valve of claim 29 further comprising a compression spring member for applying a compressive force to said dimensionally responsive member.

38. A method of using a shaped waveform to control electric current to actuate an injection valve for an internal combustion engine that employs a dimensionally responsive actuator assembly comprising at least one of a magnetostrictive and a piezoelectric material, and a controller to govern valve lift and duration according to values predetermined for engine load demands within the operating range of said engine by said controller controlling current and voltage directed to said actuator assembly, said method comprising for each injection event:

- (a) initiating an injection event by rapidly increasing current to a magnitude that is known to correspond to a desired lift by applying high frequency voltage cycles and in each cycle maintaining a net positive voltage;
- (b) maintaining a current to control said desired lift for a duration predetermined by said controller; and
- (c) concluding an injection event by decreasing current until it is reduced to zero amps by applying high frequency voltage cycles and in each cycle maintaining a net negative voltage.

39. The method of claim 38 whereby the step of initiating an injection event further comprises initially increasing current to a spike value higher than the value for the desired lift to rapidly open said valve and then reducing current to the value to cause the desired lift.

40. The method of claim 39 wherein said spike value is up to about an order of magnitude higher than the value needed to cause the desired lift.

41. A method of operating a fuel injection valve for an internal combustion engine, said injection valve having a longitudinal axis, said method comprising:

- (a) actuating a dimensionally responsive member comprising at least one of a magnetostrictive material and a piezoelectric material, said dimensionally responsive member expanding in length in the direction of said longitudinal axis upon actuation of said actuator;
- (b) transferring movement caused by said actuated dimensionally responsive member through a passive hydraulic link to cause a corresponding movement of a valve member to open said valve by lifting said valve member away from a valve seat and compressing a biasing mechanism that biases said valve in a closed position, said passive hydraulic link comprising a hydraulic cylinder which houses a piston and is filled with a hydraulic fluid, wherein said hydraulic fluid forms a layer between said piston and a cylinder head and because of the short duration that said valve is open, said hydraulic fluid does not have time to flow from one side of said piston to the other side and while said injection valve is open, said layer of hydraulic fluid acts as an incompressible solid so that movement caused by the actuation of said dimensionally responsive member is transmitted through said fluid layer;
- (c) deactuating said dimensionally responsive member to contract the length of said dimensionally responsive member to unload said biasing mechanism and cause a corresponding movement of said valve member to close said valve;
- (d) providing sufficient time between consecutive valve openings to allow at least some of said hydraulic fluid within said passive hydraulic link to flow from one side of said piston to the other side of said piston.

* * * * *



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Bib Data Sheet

CONFIRMATION NO. 2084

SERIAL NUMBER 09/863,187	FILING DATE 05/23/2001 RULE	CLASS 123	GROUP ART UNIT 3747	ATTORNEY DOCKET NO. 12541US03
APPLICANTS Alan B. Welch, Vancouver, CANADA; Irawan Rahardja, Vancouver, CANADA; Mike Hebbes, Vancouver, CANADA; ** CONTINUING DATA ***** THIS APPLICATION IS A CIP OF 09/522,130 03/09/2000 AND CLAIMS BENEFIT OF 60/159,791 10/15/1999 ** FOREIGN APPLICATIONS ***** none				
IF REQUIRED, FOREIGN FILING LICENSE GRANTED ** 06/07/2001				
Foreign Priority claimed ☐ yes ☒ no 35 USC 119 (a-d) conditions met ☐ yes ☒ no ☐ Met after Allowance Verified and Acknowledged		STATE OR COUNTRY CANADA	SHEETS DRAWING 5	TOTAL CLAIMS 41 INDEPENDENT CLAIMS 4
ADDRESS Robert W. Fieseler McAndrews, Held & Malloy, Ltd. 34th Floor 500 West Madison Street Chicago ,IL 60661				
TITLE Directly actuated injection valve				
FILING FEE RECEIVED 1298	FEES: Authority has been given in Paper No. _____ to charge/credit DEPOSIT ACCOUNT No. _____ for following:		☐ All Fees ☐ 1.16 Fees (Filing) ☐ 1.17 Fees (Processing Ext. of time) ☐ 1.18 Fees (Issue) ☐ Other _____ ☐ Credit _____	

PATENT APPLICATION SERIAL NO. _____

U.S. DEPARTMENT OF COMMERCE
PATENT AND TRADEMARK OFFICE
FEE RECORD SHEET

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*U.S. GPO: 2000-468-987/39595

jc839 U.S. PTO
05/23/01

05-24-1

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PATENT APPLICATION

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Attorney Docket No: 12541US03

PATENT APPLICATION TRANSMITTAL

jc973 U.S. PTO
09/863187
05/23/01

Box Patent Application
Assistant Commissioner for Patents
Washington, D.C. 20231

Sir:

Transmitted herewith for filing is the patent application of

Inventor(s): Alan Welch, Irawan Rahardja and Mike Hebbes.

Title: DIRECTLY ACTUATED INJECTION VALVE

1. Type of Application

This new application is for a:

- ☒ utility patent.
- ☐ design patent.

This application is a:

- ☐ continuation
- ☐ divisional
- ☒ continuation-in-part (CIP)

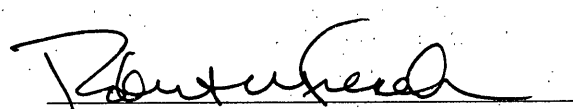
of prior U.S. Patent Application Serial No.
09/522,130 filed March 9, 2000.

2. Application Papers Enclosed

- Title Page
- 50 Pages of Written Description (excluding Claims, Abstract & Drawings)
- 14 Page(s) of Claims (1-41)
- 1 Page(s) of Abstract
- 5 Sheet(s) of Drawings (Figs. 1, 2, 2a, 2b, 3, and 4)
- ☐ Formal
- ☒ Informal

CERTIFICATION UNDER 37 CFR 1.10

I hereby certify that this Patent Application Transmittal and the documents referred to as enclosed therewith are being deposited with the United States Postal Service on **May 23, 2001**, in an envelope addressed to the Assistant Commissioner for Patents, Washington, D.C. 20231 utilizing the "Express Mail Post Office to Addressee" service of the United States Postal Service under Mailing Label No. EL567274376US.


Robert W. Fieseler

3. Declaration or Oath

☐ Enclosed

Executed by (check all applicable boxes)

☐ Inventor(s) (copy from prior application)

☐ Legal representative of inventor(s)
(37 CFR 1.42 or 1.43)

☐ Joint inventor or person showing a proprietary interest on behalf of inventor who refused to sign or cannot be reached

☐ The petition required by 37 CFR 1.47 and the statement required by 37 CFR 1.47 are enclosed. See Item 5D below for fee.

☒ Not enclosed - the undersigned attorney or agent is authorized to file this application on behalf of the applicant(s). An executed declaration will follow.

4. Additional Papers Enclosed

☐ Preliminary Amendment

☐ Information Disclosure Statement, including copies of cited references

☐ Declaration of Biological Deposit

☐ Computer readable copy of sequence listing containing nucleotide and/or amino acid sequence

☐ Verified statement(s) claiming small entity status under 37 CFR 1.9 and 1.27

☐ Associate Power of Attorney

☐ Verified translation of a non-English patent application

☐ An assignment of the invention (copy of recorded assignment(s) from prior application)

☐ Certified copy(ies) of application(s):

COUNTRY	APPLICATION NO.	FILED

from which priority under 35 USC 119 is claimed

☐ is(are) attached.

☐ will follow.

☐ Other

5. Filing Fee Calculation (37 CFR 1.16)

A. ☒ Utility Application

CLAIMS AS FILED - INCLUDING PRELIMINARY AMENDMENT (IF ANY)						
			SMALL ENTITY		OTHER THAN A SMALL ENTITY	
	NO. FILED	NO. EXTRA	RATE	FEE	RATE	FEE
BASIC FEE				\$ 355.00		\$ 710.00
TOTAL	41 - 20	= 21	X 9 =	\$	X 18 =	\$ 378.00
INDEP.	4 - 3	= 1	X 40 =	\$	X 80 =	\$ 80.00
☐ First Presentation of Multiple Dependent Claim			+ 135 =	\$	+ 270 =	\$.00
Filing Fee:				\$	OR	\$1148.00

B. ☐ Design Application (\$160.00/\$320.00) Filing Fee: \$ _____

C. ☐ Plant Application (\$245.00/\$490.00) Filing Fee: \$ _____

D. Other Fees

☐ Recording Assignment [Fee -- \$40.00 per assignment] \$ _____

☐ Petition fee for filing by other than all the inventors or person on behalf of the inventor where inventor refused to sign or cannot be reached [Fee -- \$130.00] \$ _____

☐ Other \$ _____

Total Fees Enclosed \$ 1148.00

6. Method of Payment of Fees

☒ Enclosed check in the amount of: \$ 1148.00

☐ Charge Deposit Account No. 13-0017 in the amount of: \$ _____
A copy of this Transmittal is enclosed.

☐ Not enclosed

7. **Deposit Account and Refund Authorization**

The Commissioner is hereby authorized to charge any deficiency in the amount enclosed or any additional fees which may be required during the pendency of this application under 37 CFR 1.16 or 37 CFR 1.17 or under other applicable rules (except payment of issue fees), to Deposit Account No. 13-0017. A copy of this Transmittal is enclosed.

Please refund any overpayment to Deposit Account No. 13-0017.

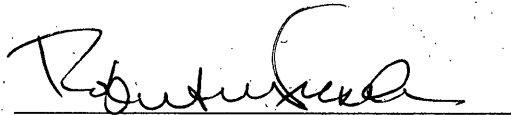
Please direct all future communications to Robert W. Fieseler at the address below.

McAndrews, Held & Malloy, Ltd.
500 West Madison Street, 34th Floor
Chicago, Illinois 60661

Please direct all telephone calls to Robert W. Fieseler at (312) 775-8123. Please direct all facsimile transmissions to Robert W. Fieseler at (312) 775-8100. Please direct all e-mail transmissions to rfieseler@mhmlaw.com.

Respectfully submitted,

By:



Robert W. Fieseler
Registration No. 31,826

Date: May 23, 2001

DIRECTLY ACTUATED INJECTION VALVE

Cross-Reference to Related Application(s)

Sub 12
This application is a continuation-in-part of U.S. Patent Application Serial No. 09/522,130 filed March 9, 2000, entitled "Directly Actuated Injection Valve", now U.S. Patent No. _____ issued _____. The '130 application relates to and claims priority benefits from U.S. Provisional Patent Application Serial No. 60/159,791 filed October 15, 1999, entitled "Directly Actuated Injector". The '130 application and the '791 application are each incorporated herein by reference in their entirety.

Field of the Invention

The present invention relates generally to high pressure fuel injection valves or injectors for internal combustion engines, and, more specifically, to an injection valve that is directly controllable by a position actuating material (such as, for example, a piezoelectric or magnetostrictive material) and which includes a passive hydraulic link.

Background of the Invention

Direct injection of a gaseous fuel into the combustion chamber of an internal combustion engine is desirable for several reasons. For example, direct injection allows charge stratification, eliminating throttling losses associated with homogeneous charge engines. Additionally, with direct injection late in the compression stroke, a high-compression ratio can be maintained, maintaining efficiency. Further, when the fuel that is directly injected comprises natural gas, propane, or hydrogen, the emissions of NO_x and particulate matter (PM) are significantly reduced. The directly injected gaseous fuel can be ignited with a glow plug, with a spark plug, with pilot diesel fuel, or with any other energy source. The gaseous fuel should be injected at high pressure to overcome the combustion chamber pressure, which is high at the end of the compression stroke. Preferably, the injection pressure is high enough to promote good mixing between the injected fuel and the combustion chamber air.

Direct injection at high pressures presents several challenges. The use of high-pressure fuels for direct injection results in high fuel pressures existing within the injection valve or injector. As a result, when closed, the

injection valve should typically be strongly seated to avoid leakage of the fuel into the combustion chamber between injection events. When the valve is a needle valve, the valve is

5 seated when the sealing surfaces of the movable valve needle and the valve seat are in fluid-tight contact with each other. The valve seat is generally part of the valve housing or body. For an outward opening valve, such as a poppet valve,

10 the valve is closed when a valve member is retracted within the valve body so that the sealing surfaces of the valve member are pressed against the valve seat to form a fluid-tight seal. A fuel injection valve with an "outward"

15 opening configuration is defined herein as an injection valve for an internal combustion engine which employs a valve member that is movable in the direction of the engine combustion chamber to an open position and in the opposite direction to

20 a closed position. Terms used to describe such a valve member include, for example, pintle shaft, valve stem, and valve shaft. Outward opening injection valves typically comprise a circular valve head mounted transversely on the valve

25 member for axial motion towards and away from a mating circular valve seat associated with the valve body.

Moreover, compared to low-pressure systems, higher forces are needed to open or close the injection valve. For example, for a needle valve that employs an inwardly opening valve needle, 5 when the needle is in the open position it may be subjected to high forces from the pressurized fuel. Conversely, with an outward opening injection valve, a high amount of force is required to keep the valve closed against the 10 high fuel pressure within the injection valve body.

Additionally, there is only a small window of time during which the fuel can be injected. For example, at 4500 revolutions per minute 15 (RPM), at full load, all of the fuel is preferably injected in less than 2-3 milliseconds.

Nearly all known direct fuel injection systems in internal combustion engines have been 20 hydraulically actuated. These systems rely on a hydraulic fluid to provide the force that is needed to open an injection valve (or valves, when the engine comprises a plurality of combustion chambers). Accordingly, at typical 25 engine operating speeds, hydraulically actuated injectors rely on rapid changes in the hydraulic fluid pressure to open and close the injection valve(s). An injection valve is typically opened

by increasing the hydraulic fluid pressure and closed by reducing the hydraulic fluid pressure, such that the opening force applied to the injection valve is reduced, causing the valve to close. However, in the context of a conventional gaseous injection valve, hydraulic operation presents several drawbacks, including:

- the need for additional hydraulic hardware such as a hydraulic pump, valves, and a reservoir for the hydraulic fluid;
- the need for a seal to be established between the variable pressure hydraulic fluid and the high pressure gaseous fuel;
- increased bulkiness of the injection valve assembly because of the additional hardware requirements; and
- delayed response of the system caused by time delays associated with the dynamic flow of the hydraulic fluid, the actuation of the electronic hydraulic valve hardware and the movement of the needle that controls gas flow from the injection valve.

Moreover, the degree of controllability of the movement of the injection valve is low when the motive force is provided by a pressurized

fluid rather than by a directly controllable source. In this respect, it is difficult to control lift, resulting in limited lift control capabilities when using hydraulically actuated injection valve with a double-spring configuration. Therefore, it is desirable to avoid the use of hydraulics to operate gaseous fuel injectors, particularly for high-speed engines. "Lift" in the context of injection valves is defined herein as the displacement of the valve needle or member away from its closed/seated position to its open position.

U.S. Patent No. 5,779,149 describes an injector using a piezoelectric actuator acting on a hydraulic control valve through the intermediate of a hydraulic amplifier, which serves to amplify the movement of the actuator. The hydraulic control valve allows the main injection valve to open and close to meter the amount of fuel injected.

A problem with employing a piezoelectric or magnetostrictive actuator to operate a control valve, which in turn controls the flow of a hydraulic fluid to operate an injection valve, is that this arrangement requires the intermediate action of a hydraulic fluid. Any delays caused by the displacement of the hydraulic fluid causes delays in the actuation of the injector.

Accordingly, there is a need for an injector that is directly actuated by an actuator without an intermediate active hydraulic operator generating any actuating forces. Another disadvantage of active hydraulically operated systems is that a hydraulic fluid needs to be supplied and drained from a hydraulic cylinder. When diesel fuel is the main fuel used by the engine, the diesel fuel may be used as the hydraulic fluid. However, when a gaseous fuel is the engine's main fuel, a separate hydraulic fluid system is needed to operate injectors that rely on hydraulic actuation.

15 Summary of the Invention

An injection valve injects fuel into a combustion chamber of an internal combustion engine. The injection valve comprises:

- (a) a valve housing comprising:
 - 20 a fuel inlet port;
 - an interior chamber fluidly connected to the fuel inlet port; and
 - a valve seat for cooperating with a valve member to seal the interior
 - 25 chamber from the combustion chamber when the injection valve is closed;
- (b) the valve member having one end disposed within the valve housing and

an opposite end extendable from the valve seat toward the combustion chamber, wherein the valve member comprises a sealing surface that fluidly seals against the valve seat when the injection valve is closed and that is liftable away from the valve seat when the injection valve is open, wherein valve lift equals the distance traveled by the sealing surface away from the valve seat;

(c) a biasing mechanism associated with the valve member, the biasing mechanism applying a closing force to the valve member when the valve member is in the closed position;

(d) an actuator assembly associated with the valve member, wherein the actuator assembly may be actuated to apply an opening force to the valve member stronger than the closing force, for moving the valve member to the open position; and

(e) a hydraulic link assembly comprising a passive hydraulic link having a hydraulic fluid thickness through which the opening and closing forces are transmitted, whereby the hydraulic

fluid acts substantially as a solid
with the thickness being substantially
constant while the actuator assembly is
actuated and wherein the thickness of
5 the hydraulic link is adjustable while
the actuator assembly is not actuated
in response to changes in the
dimensional relationship between
components of the injection valve to
10 maintain a desired valve lift upon
actuation of the actuator assembly.

In a preferred embodiment, the thickness of
the hydraulic link is auto-adjustable in response
to changes in the dimensional relationship caused
15 by differential thermal expansion, and/or wear to
components of the injection valve. The hydraulic
link assembly preferably comprises a fluidly
sealed hydraulic cylinder that is fluidly sealed
from the interior chamber. The hydraulic link
20 assembly comprises a piston and hydraulic fluid
disposed within the hydraulic cylinder. The
hydraulic fluid is preferably a liquid such as,
for example motor oil or grease. The piston may
be an integral part of the valve member.

25 In a preferred injection valve the actuator
assembly comprises a dimensionally responsive
member. The dimensionally responsive member can
be formed from a magnetostrictive material. The

preferred magnetostrictive material comprises a metal alloy comprising terbium, dysprosium and iron. The preferred actuator assembly further comprises an electric coil disposed in an annular space around the dimensionally responsive member and a flux tube disposed in an annular space around the electric coil. The actuator assembly is preferably disposed within the interior chamber. The dimensionally responsive member can also be formed from a piezoelectric material. A preferred injection valve further comprises a compression spring member for applying a compressive force to the dimensionally responsive member.

15 In one embodiment, the fuel inlet is positioned so that fuel enters the valve housing and passes through the actuator and hydraulic link assemblies in the interior chamber. In this embodiment, the flow of fuel over these assemblies helps to remove heat generated by the activation of the actuator and reduces the effect of differential temperatures within the injection valve. In another embodiment, the fuel inlet is positioned near the valve tip so that the fuel flowing through the injection valve does not come into contact with the actuator assembly. This embodiment simplifies the construction of the actuator and hydraulic link assemblies since

there is no need to provide fluid passages for the fuel to flow to the valve tip.

In a preferred injection valve, the lift is controllable by varying at least one of the electric current, the electric voltage and the magnetic field imposed upon the dimensionally responsive member. The valve member is preferably controllable such that the valve member moves between the open and closed positions in less than about 200 microseconds.

The injection valve preferably further comprises a biasing mechanism for applying a compressive force to the dimensionally responsive member. The biasing mechanism preferably comprises a spring. The spring preferably comprises at least one disc spring.

In a preferred injection valve, the fuel is gaseous and the hydraulic fluid is a liquid. The preferred hydraulic fluid is a liquid selected from the group consisting of motor oil and grease.

The present injection valve is particularly suited for injecting a gaseous fuel because the ability to modulate the movement of the valve member may be beneficially used to slow down the closing action of the valve member to reduce impact upon closing. When a liquid fuel is injected, the closing impact is dampened by the

displacement of the thin liquid fuel layer, which is considerably denser than gaseous fuels. When the fuel is a gaseous fuel, it can be injected into the combustion chamber at a pressure greater
5 than about 2000 psi (about 13.8 MPa).

While the hydraulic link in the present injection valve is designed to compensate for changes in the dimensional relationships between valve components, including changes caused by
10 differential thermal expansion, the demands placed upon the hydraulic link may be reduced by the selection of materials for the valve components that have similar thermal expansion coefficients. In this regard, the valve housing,
15 valve member and actuator assembly are preferably selected from materials having thermal expansion coefficients sufficiently compatible such that changes in the dimensional relationship between the components caused by changes in temperature
20 are reduced.

A magnetostrictive material that is suitable for use in the present injection valve comprises a material known as ETREMA Terfenol-D[®] magnetostrictive alloy that is available from
25 Etrema Products Inc. ETREMA Terfenol-D[®] magnetostrictive alloy is a metal alloy composed of terbium, dysprosium and iron.

In a preferred embodiment, the valve member, actuated by an actuator assembly that includes a dimensionally responsive member, is controllable to move between the closed and open positions in
5 less than about 200 microseconds.

To improve the range of valve lift for a given length of the dimensionally responsive member, a compressive force may be applied to the dimensionally responsive member. By pre-loading
10 the dimensionally responsive member, net displacement may be increased per respective unit of applied magnetic field (in the case of a dimensionally responsive member formed of magnetostrictive material) or applied voltage (in
15 the case of a dimensionally responsive member formed of piezoelectric material). Accordingly, a biasing mechanism may be employed for applying a compressive force to pre-load the dimensionally responsive member. The biasing member preferably
20 comprises at least one spring, most preferably at least one disc spring (also known as a Belleville spring or Belleville washer).

The injection valve housing may comprise a plurality of parts that are joined with each
25 other to provide a fluidly sealed body. For example, the valve housing may comprise a hollow main housing with a removable valve cap that allows access to the valve components disposed.

within the main housing. The valve housing may further comprise a separate valve tip so that it is replaceable when worn. In addition, the valve tip may be designed so that it is the only
5 portion of the valve body that is directly exposed to the interior of the combustion chamber. In this case the valve tip may be made from a material that will provide greater durability when directly exposed to the
10 conditions that might be expected within a combustion chamber.

A preferred fuel injection valve for injecting fuel into a combustion chamber of an internal combustion engine comprises:

- 15 (a) a valve housing comprising:
a fuel inlet port;
an interior chamber fluidly connected to the fuel inlet port;
a valve seat provided on an end of
20 the housing that faces the combustion chamber;
- (b) a valve member comprising a shaft
portion having a first end to which a circular head is transversely mounted
25 wherein the head provides an annular sealing surface that faces the valve seat, and a second end of the shaft is associated with a piston portion; the

valve member movable between a closed position at which the sealing surface contacts the valve seat to fluidly seal the interior chamber from the combustion chamber, and an open position at which the sealing surface is spaced apart from the valve seat whereby the interior chamber is fluidly connected with combustion chamber, wherein valve lift equals distance traveled by the sealing surface away from the valve seat;

- (c) a biasing mechanism associated with the piston portion of the valve member, the biasing mechanism applying a closing force to the valve member when the valve member is in the closed position;
- (d) an actuator assembly for applying an opening force to the valve member that is stronger than the closing force, for moving the valve member to the open position, the actuator assembly comprising a member having dimensional responsiveness to the imposition of at least one of an electric current, an electric voltage and a magnetic field, the dimensionally responsive member disposed between a fixed pole

maintained in a fixed position relative to the valve housing and a sliding pole, the sliding pole being displaceable by expansion of the dimensionally responsive member; and
5 (e) a hydraulic link assembly comprising a fluidly sealed hydraulic cylinder disposed about the piston portion of the valve member, a hydraulic fluid
10 disposed within the hydraulic cylinder, wherein the opening and closing forces applied to the valve member are transmitted through a thickness of the hydraulic fluid whereby the hydraulic
15 fluid acts as a hydraulic link and the thickness is automatically adjustable in response to changes in the dimensional relationship between components of the injection valve to
20 maintain a desired valve lift upon actuation of the actuator assembly.

A method of using a shaped waveform to control electric current to actuate an injection valve for an internal combustion engine employs a
25 dimensionally responsive actuator assembly comprising at least one of a magnetostrictive and a piezoelectric material, and a controller to govern valve lift and duration according to

values predetermined for engine load demands within the operating range of the engine by the controller controlling current and voltage directed to the actuator assembly. The method
5 comprises, for each injection event:

- (a) initiating an injection event by rapidly increasing current to a magnitude that is known to correspond to a desired lift by applying high
10 frequency voltage cycles and in each cycle maintaining a net positive voltage;
- (b) maintaining a current to control the desired lift for a duration
15 predetermined by the controller; and
- (c) concluding an injection event by decreasing current until it is reduced to zero amps by applying high frequency voltage cycles and in each cycle
20 maintaining a net negative voltage.

In a preferred shaped waveform method, the step of initiating an injection event further comprises initially increasing current to a spike value higher than the value for the desired lift
25 to rapidly open the valve and then reducing current to the value to cause the desired lift. The spike value is preferably up to about an order of magnitude higher than the value needed

to cause the desired lift. The preferred method further comprises applying high frequency voltage cycles between offsetting positive and negative voltages to generate a current of close to zero
5 amps immediately prior to an injection event.

The time to open the valve from a closed position to the desired lift is less than about 175 microseconds, more preferably less than about 100 microseconds. More typically, however, the time
10 needed to move the valve member between the closed position and the desired open position may be as short as about 250 microseconds.

A method of operating a fuel injection valve for an internal combustion engine, in which the
15 injection valve has a longitudinal axis, comprises:

- (a) actuating a dimensionally responsive member comprising at least one of a magnetostrictive material and a
20 piezoelectric material, the dimensionally responsive member expanding in length in the direction of the longitudinal axis upon actuation of the actuator;
- 25 (b) transferring movement caused by the actuated dimensionally responsive member through a passive hydraulic link to cause a corresponding movement of a

valve member to open the valve by
lifting the valve member away from a
valve seat and compressing a biasing
mechanism that biases the valve in a
closed position, the passive hydraulic
link comprising a hydraulic cylinder
which houses a piston and is filled
with a hydraulic fluid, wherein the
hydraulic fluid forms a layer between
the piston and a cylinder head and
because of the short duration that the
valve is open, the hydraulic fluid does
not have time to flow from one side of
the piston to the other side and while
the injection valve is open, the layer
of hydraulic fluid acts as an
incompressible solid so that movement
caused by the actuation of the
dimensionally responsive member is
transmitted through the fluid layer;

- (c) deactuating the dimensionally
responsive member to contract the
length of the dimensionally responsive
member to unload the biasing mechanism
and cause a corresponding movement of
the valve member to close the valve;
- (d) providing sufficient time between
consecutive valve openings to allow at

least some of the hydraulic fluid within the passive hydraulic link to flow from one side of the piston to the other side of the piston.

5 An advantage of the present injection valve is that it may be employed for late-cycle high-pressure direct injection of fuels into internal combustion engines. For example, the present injection valve may be used to inject a gaseous
10 fuel into the combustion chamber of an internal combustion engine at pressures of between about 2000 and 5000 psi (about 13.8 and 34.5 MPa). The present injection valve may be employed to introduce liquid fuels into internal combustion
15 engines at even higher pressures.

Still another advantage of the present injection valve is that it provides an injection valve that eliminates the need for an active hydraulic operator and the associated high-
20 pressure hydraulic system for generating the actuation force to actuate the injection valve. Conventional active hydraulic operators are different from the hydraulic link of the present invention, which may be described as a passive
25 hydraulic link because the hydraulic fluid sealed within the hydraulic link assembly merely transmits the actuating forces but is not employed to generate an actuating force for

actuating the valve. Rather, the purpose of the hydraulic link is to provide a load path for the opposing actuating forces that originate from at least one spring member and the actuator assembly. A benefit of eliminating the need for a conventional active hydraulic operator is the elimination of the associated active hydraulic systems. Conventional active hydraulic actuators, such as those that employ rapidly increasing and decreasing hydraulic fluid pressure to actuate an injection valve, are connected to a source of high pressure hydraulic fluid and have valves for controlling the flow of hydraulic fluid in and out of the active hydraulic operator. Active hydraulic actuators employ hydraulic fluid that is moved in and out of a hydraulic cylinder and when the hydraulic cylinder is fluidly connected to a source of high pressure hydraulic fluid, the high pressure hydraulic fluid that flows into the hydraulic cylinder generates the actuating force that is used to move the valve member. The actuating force is removed when the hydraulic cylinder is disconnected from the source of high-pressure hydraulic fluid and the hydraulic fluid is drained from the hydraulic cylinder. A disadvantage of active hydraulic actuators of this type is that there is a lag time associated

with moving the hydraulic fluid into and out of the hydraulic cylinder.

A further advantage of the passive hydraulic link is that it may be employed to correct for differential thermal expansion, wear and dimensional variability within permitted manufacturing and assembly tolerances. The disclosed passive hydraulic link accomplishes this by auto-adjusting itself in response to these effects by allowing movement of hydraulic fluid between opposite sides of the hydraulic piston. The actuator assembly thus re-zeroes itself to ensure that the desired valve member lift is maintained.

An advantage of employing a directly actuated injection valve is that a shaped control pulse may be employed to control the acceleration and deceleration of the valve member as it moves between the open and closed positions. For example, when a magnetostrictive actuator is employed, the current applied to the electromagnetic coil can be controlled, for example, to reduce the current in a manner that will close the valve gently. Similarly, when a piezoelectric actuator is employed, the voltage applied to the piezoelectric stack can be controlled, for example, to accelerate the opening of the valve by initially providing an

over-voltage (that is, a voltage that is higher than the voltage that is needed to provide the necessary displacement). Thus, control pulses may be employed to control the expansion and contraction of magnetostrictive or piezoelectric actuators to control the movement of the valve member. An advantage of controlling the deceleration of the valve member is that the impact of the valve member on the valve seat upon closing can be reduced to reduce the wear on the valve components, thereby improving durability.

Yet another advantage of the present injection valve is that the control pulse may be shaped to provide for partial lifting of the valve member in a repeatable manner. The amount of lift may be controlled by shaping the control pulse to control the amount of electric current or voltage directed to the respective magnetostrictive or piezoelectric actuator assembly.

Still another advantage of the disclosed injection valve is that the actual valve lift is very small (typically much less than 0.1 millimeter), so that compared to valves designed for greater valve lift, to fully open or close the valve, the valve member velocity can be lower resulting in less impact and wear.

These and other advantages are provided by a directly actuated injector as described below.

Brief Description of the Drawings

5 FIG. 1 is a cross-sectional view of a preferred embodiment of a directly actuated fuel injection valve with a passive hydraulic link assembly;

10 FIG. 2 is an enlarged view of a partial cross-sectional view of the lower portion of a fuel injection valve shown in the open position with an alternate location for the fuel inlet port;

15 FIG. 2a is a partial cross-sectional view of an embodiment of a nozzle tip for an injection valve;

 FIG. 2b is a partial side elevation view of an embodiment of a nozzle tip for an injection valve;

20 FIG. 3 is a cross-sectional view of another preferred embodiment of a directly actuated fuel injection valve with a different arrangement for the passive hydraulic link assembly; and

25 FIG. 4 is a timing diagram for a preferred method of controlling electric current applied to the actuator assembly of a fuel injection valve.

In the figures, like reference numerals are used to identify like components in different embodiments.

5 **Detailed Description of Preferred Embodiment(s)**

FIGs. 1 and 3 show two different preferred embodiments of an outward opening directly actuated fuel injection valve for internal combustion engines. Opposed to a needle valve, which employs a needle that is retracted into the valve body to open the valve, an outward opening injection valve extends a valve member outward and away from the valve body to open the valve. To open an outward opening fuel injection valve for injecting fuel into an engine, a valve member is moved away from a valve seat and towards the combustion chamber.

Referring to FIGs. 1 and 2, injection valve 100 includes elongated valve housing 102 that cooperates with valve cap 104 to provide a fluidly sealed valve body. Seal 106 may be employed to ensure that the assembled valve body is fluid-tight. Valve cap 104 comprises inlet port 108 through which fuel enters the valve body. Valve housing 102 further comprises valve seat 112, which is better shown in FIG. 2, which shows an injection valve in the open position.

The figures are schematic representations of preferred embodiments of fuel injection valves for internal combustion engines. However, those skilled in the technology involved here will
5 recognize that the figures are not construction drawings and are not drawn to scale. For example, valve housing 102 is shown as a single element, but for manufacturing purposes, valve housing 102 may be constructed from several
10 pieces. In the figures, the sizes of some components have also been exaggerated to better illustrate certain elements of the apparatus.

The enlarged view of FIG. 2 also shows how valve seat 112 is angled to form a cone-shaped
15 surface and cooperates with the angled sealing surface of valve member 114 to provide a fluid tight seal when the two surfaces are pressed into contact. In addition to providing a desirable sealing arrangement, valve seat 112 and the
20 sealing surface of valve member 114 are angled to guide the direction in which the fuel is injected into the combustion chamber. An advantage of this arrangement is that it allows an unbroken conical sheet of fuel to be injected which
25 provides a continuous surface for the combustion flame. Another advantage of an outward opening injection valve is that when the valve is closed, there is less concern about combustion products

fouling or clogging the injection valve because unlike a needle valve there are no exposed nozzle holes.

Valve housing 102 may further comprise
5 features for influencing how the fuel is introduced into the combustion chamber. For example, FIG. 2a shows an embodiment of valve housing 102 that comprises nozzle tip 202 below where valve member 114 seats against valve seat
10 112. Nozzle tip 202 provides a chamber that is connected to the combustion chamber by nozzle ports or orifices 203. In this embodiment the chamber and orifices 203 may be advantageously sized to slow down the fuel injection velocity to
15 improve ignitability.

In yet another embodiment, valve housing 102 may further comprise an injection tip that has projections 205 as shown in FIG. 2b, which serve to provide breaks in the conical sheet of fuel
20 that is injected when the injection valve is opened. Persons skilled in the technology involved here will recognize that the present invention can be combined with other valve tip configurations. The preferred valve tip
25 configuration may depend upon other features of the engine such as, for example, the shape of the piston bowl and the size and operating conditions of the engine.

Valve Member

With reference to FIG. 1, valve member 114 is disposed within the interior of valve housing 102 and extends through an opening in the tip of valve housing 102. The sealing surface of valve member 114 contacts valve seat 112 to close injection valve 100 by preventing fuel from passing beyond valve seat 112 and into the combustion chamber. In the embodiment of FIG. 1, valve member 114 comprises valve stem 114a, which moves into the open position by moving outward away from the valve body to lift away from valve seat 112. Since the valve lift is generally small (for example, about 65 micrometers), the diameter of valve stem 114a and the size of the annular opening around valve stem 114a are selected to ensure sufficient flow capacity through the injection valve since flow area (A) is proportional to valve stem diameter. Hence, a small lift can be compensated for by a larger diameter. In the preferred embodiment illustrated by FIG. 1 valve member 114 further comprises an integral piston 114b. In another embodiment (not shown) a separate piston member may cooperate with valve member 114 to provide the same effect.

Spring Assembly

A spring assembly biases valve member 114 in the closed position. In a preferred arrangement, the spring assembly comprises at least one valve
5 spring 116 for providing a closing force to valve member 114. With reference to the embodiment of FIG. 1, valve spring 116 is shown as a disc or washer spring. A different type of spring such as a coil spring could be used instead. Pre-load
10 plate 120 is used to apply a pre-load to valve spring 116 so that valve 100 is biased in the closed position. Valve spring 116 should provide a closing force to counter the opposing opening forces generated by the high pressure of the fuel
15 directed to the interior of the sealed valve body. In the arrangement shown in FIG. 1, respective threaded surfaces join pre-load plate 120 to valve housing 102. As is known in the art, after pre-load plate 120 has been rotated to
20 compress valve spring 116 to provide the desired pre-load force to valve spring 116, pre-load plate 120 may be held in position by means of a locking nut (not shown).

25 Actuator Assembly

An actuator assembly may be actuated to provide an opening force that is opposite and greater than the closing force provided by the

spring assembly. In the embodiment illustrated in FIG. 1, the actuator assembly comprises a member that expands or contracts in the direction of the longitudinal axis of valve housing 102 when the member is exposed to a magnetic field or subjected to an electric voltage, such as, for example, a magnetostrictive material or a piezoelectric stack, respectively.

In the embodiment illustrated by FIG. 1, the actuator assembly is a magnetostrictive actuator that comprises a solid magnetostrictive member 130, with bobbin 131, electric coil 132, and flux tube 134 disposed in the annular space between magnetostrictive member 130 and valve housing 102. As shown in FIG. 1, coil 132 is wound around bobbin 131 and flux tube 134 surrounds bobbin 131 and electric coil 132. Flux tube 134 may be made from common carbon steel with a lengthwise slit to break eddy currents. An electric current is supplied to electric coil 132 through electric leads (not shown). When an electric current is applied to electric coil 132 a magnetic flux develops that flows through magnetostrictive member 130, fixed pole 138, sliding pole 140, and flux tube 134. Poles 138 and 140 are made from a suitable material such as carbon steel (for example CS1018) or steel that has a low magnetic hysteresis. Fixed pole 138 is

held in a "fixed" position between pre-load plate 120 and end faces of magnetostrictive member 130, bobbin 131 and flux tube 134. Accordingly, when the actuator assembly is actuated and
5 magnetostrictive member 130 grows in length, sliding pole 140 is pushed towards valve member 114 to providing a force for opening injection valve 100.

In another preferred embodiment (not
10 illustrated), flux tube 134 may be integrated with valve housing 102. That is, valve housing 102 could be constructed from a magnetically permeable material that is suitable both structurally and for acting as a flux path. For
15 example, many steels are suitable as materials for housing 102. Stainless steels may be employed but more preferably, common carbon steels are better suited because of material hardness properties and durability. Similarly,
20 fixed pole 138 could also be integrated with pre-load plate 120. Those skilled in the technology involved here will understand that such components can be advantageously integrated without departing from the spirit and scope of
25 the present invention. An advantage of integration, for example, is the efficiencies and reduced costs of manufacturing devices comprising less parts.

An advantage of the preferred embodiments is that magnetostrictive member 130 can be made from a solid cylindrical rod of magnetostrictive material, which is easier and less expensive to manufacture compared to hollow tubular forms.

A pre-compression force is preferably applied to magnetostrictive member 130 to amplify the magnitude of expansion when a magnetic field is applied. Pre-compression of magnetostrictive member 130 increases the net displacement per unit of applied magnetic field. Similarly, when a piezoelectric member is substituted for magnetostrictive member 130, pre-compression increases the net displacement of the piezoelectric member per unit of applied electric voltage. A spring, such as, for example, disc spring 150 may be employed to provide the pre-compression force. Alternative compression elements may be employed in place of disc spring 150 to provide the pre-compression force, such as, for example, a coil spring or another type of spring with the same spring force. When a pre-compression force of, for example, about 1000 psi (about 6.9 MPa) is employed, the actuator's displacement can increase to about 0.13% of the total length of magnetostrictive member 130. However, the amount of displacement may decline as a function of increasing temperature. For

example, at typical reciprocating engine cylinder head temperatures the actual displacement may be about 0.065% of the length of pre-compressed magnetostrictive member 130.

5 The dimensions of magnetostrictive member 130 are dictated by the requirements of injection valve 100. For example, if injection valve 100 is designed to provide a lift of at least about 65 μ m, magnetostrictive member 130 is sized to
10 have a length of at least about 100 mm. Additionally, the transverse cross-sectional area of cylindrical magnetostrictive member 130 is selected to provide sufficient force to overcome all of the opposing forces that hold injection
15 valve 100 in the closed position. If the cross-sectional area of cylindrical magnetostrictive member 130 is not sufficient, the opposing forces can reduce or prevent longitudinal displacement of magnetostrictive member 130, even when
20 electric coil 132 is fully energized. This mode is known as the "blocked force" mode. Accordingly, the magnitude of the closing forces acting on valve member 114 dictate the minimum cross sectional area of magnetostrictive member
25 130.

While FIG. 1 shows magnetostrictive member 130, electric coil 132, and flux tube 134 could be replaced with a piezoelectric stack (not

shown). Electrical leads could be employed to direct an electric voltage to the piezoelectric stack. When an electric voltage is applied to a piezoelectric stack, the stack expands and
5 develops a motive force for opening injection valve 100. Accordingly, the configuration of the present injection valve is essentially the same for magnetostrictive and piezoelectric actuators.

10 **Hydraulic Link Assembly**

The opening force generated by the actuator assembly is transmitted to valve member 114 through a hydraulic link assembly. The hydraulic link assembly comprises hydraulic cylinder 160,
15 which is disposed in close-fitting relationship around hydraulic piston 114b, which is movable in the longitudinal direction within cylinder 160. As mentioned above, in the embodiment of FIG. 1, hydraulic piston 114b is preferably an integral
20 part of valve member 114 and the sidewall of cylinder 160 helps to guide the movement of valve member 114 in the longitudinal direction. A viscous hydraulic fluid is sealed inside hydraulic cylinder 160 by cylinder cap 162 and
25 seals 166, 168 and 169. Seals 168 and 169 permit valve member 114 to move relative to cylinder 160 and cylinder cap 162, respectively. Known seals may be employed, such as, for example

elastomeric O-ring seals, packing, metal seals, or diaphragm/bellow seals.

The diametrical clearance gap between the outside diameter of hydraulic piston 114b and the inside diameter of hydraulic cylinder 160 is extremely small (on the order of 20 to 250 microns). The desired size of the clearance gap is dependent upon several factors such as the viscosity of the chosen hydraulic fluid, the axial length of the piston, and the thickness of the hydraulic fluid above and below the piston. The hydraulic flow in the clearance gap is governed by the Hagen-Poiseuille Flow and the hydraulic fluid and clearance gap are preferably selected so that the flow of hydraulic fluid through the gap is insignificant during the time span of fuel injection events when an opening force is transmitted through the hydraulic fluid. Furthermore, the hydraulic fluid preferably has a sufficiently high viscosity and bulk modulus so that it acts as an incompressible solid when actuation of the actuator assembly causes a valve opening force to be quickly transmitted through the hydraulic fluid between the bottom of cylinder 160 and hydraulic piston 114b. For consistency of operation, the hydraulic fluid is also preferably an extremely stable fluid that maintains its desired properties over a wide

range of temperatures (that is, within the expected operating temperatures inside cylinder 160). Suitable hydraulic fluids are, for example, conventional motor oil, such as grade 15W40, or synthetic lubricants such as DuPont® Krytox® grease which is available in a range of viscosities. Krytox® is a perfluoropolyether (PFPE) synthetic lubricant that may be mixed with a thickener to form a grease. These types of hydraulic fluids also help to lubricate seals and 169. Different injection valves may have different sized hydraulic pistons and clearance gaps, so the hydraulic fluid may be selected with consideration to the characteristics of an individual injection valve design.

When injection valve 100 is closed and at rest, the closing force is transmitted through the hydraulic fluid held between cylinder cap 162 and hydraulic piston 114b. Typically, during engine operation, injection valve 100 is closed most of the time (normally over 90% of the time). Accordingly, there is enough time between injection events for the hydraulic fluid to redistribute itself by flowing through the clearance gap so that hydraulic cylinder 160 moves relative to piston 114b to automatically "re-zero" itself. The initial zero-position is the position of hydraulic piston 114b within

hydraulic cylinder 160 after assembly of injection valve 100. The initial zero position may not be the same for all injectors due to slight variations in the length of components within manufacturing tolerances. Also, during operation, the zero-position auto-adjusts in response to changes in the dimensional relationship between components, caused by, for example, component wear or the effects of differential thermal expansion.

Differential thermal expansion or contraction may be caused by differences in thermal expansion coefficients or uneven heat distribution between the components. Even though the components of injection valve 100, such as magnetostrictive member 130, valve member 114, and valve housing 102, are designed to be reasonably matched to the thermal expansion rates of the other components, because the valve lift and the displacement of the components that causes such lift are so small, the effects of thermal expansion or contraction should be taken into account to ensure the desired valve lift is achieved. The effects of thermal expansion and contraction may be amplified if the injection valve is exposed to a wide range of temperatures. For injection valves used in vehicles it would not be uncommon to expect a temperature range

between -40°C (in cold climates) and +125°C (when the engine is running). An uneven temperature distribution may be the result of many factors, including, for example, the influence of (1) heat generated at electric coil 132; (2) magnetic hysteresis in the actuator assembly; and (3) heat transfer from the cylinder head or the combustion chamber via the injection valve tip and valve member 114. If unaccounted for, the total effect of differential thermal expansion or contraction on the displacement of valve member 114 may be greater than the targeted lift.

In summary, the hydraulic link assembly accounts for variations in component dimensions arising from the permitted tolerances in the manufacturing processes and the injection valve assembly methods. Therefore, the hydraulic link assembly reduces manufacturing costs by allowing the injection valve components to be manufactured to less exacting tolerances. In addition, during operation, the hydraulic link assembly auto-adjusts itself between injection events to account for changes in the dimensional relationship between injection valve components that may be caused, for example, by component wear or differential thermal expansion or contraction.

FIG. 2 illustrates an injection valve embodiment that has fuel inlet 208 located in the side of valve housing 102. An advantage of this arrangement is that fluid pathways are not required through the actuator and hydraulic link assemblies, simplifying the construction of these components and reducing the cross-section area needed for the upper valve assembly. Seal 270, shown in FIG. 2, which may be, for example, an o-ring or packing type seal, prevents the high-pressure fuel from entering the portion of the valve body that houses the hydraulic link and actuator assemblies. A guide (not shown in FIG. 2), similar to guide 180 shown in FIG. 1 may also be employed in the embodiment of FIG. 2 to help guide the movement of valve member 114.

FIG. 3 illustrates an injection valve embodiment that employs a valve member 314 that has a T-shaped cross-section. This embodiment operates in substantially the same manner as the embodiment of FIG. 1. One advantage of the embodiment of FIG. 3 is that seal 169 is eliminated. Another advantage is that valve member 314, sliding pole 340, and cylinder cap 362 are simpler shapes and thus easier to manufacture and there are less tolerance fits since there is no stem protruding from hydraulic piston 314b.

Summary of Operation

When injection valve 100 is at rest in the closed position, the closing force that biases
5 valve member 114 against valve seat 112 originates from valve spring 116 and disc spring 150. In the illustrated preferred embodiments, valve spring 116 bears directly against hydraulic piston 114b to transmit a closing force directly
10 to valve member 114. Disc spring 150 bears against hydraulic cylinder 160 and a pre-compression force is transmitted to the actuator assembly through the sliding assembly comprised of hydraulic cylinder 160, cylinder cap 162 and
15 sliding pole 140. Disc spring 150 also applies a closing force to valve member 114 since it applies a force to hydraulic cylinder 160, which supports valve spring 116. It is preferable for the closing force to be provided by a mechanical
20 spring member, such as the illustrated coil spring, so that the failure mode for injection valve 100 will be in the closed position. That is, if the actuating assembly is not energized or fails, injection valve 100 will remain in the
25 closed position.

To initiate an injection event the actuator assembly is energized by directing an electric current to electric coil 132. A magnetic flux

develops that flows through magnetostrictive member 130, poles 138 and 140, and flux tube 134. Under the influence of the magnetic field, magnetostrictive member 130 expands in length (in the direction of the magnetic field). Since fixed pole 138 is stationary, magnetostrictive member 130 expands in the direction of hydraulic cylinder 160. An opening force, originating from expanding magnetostrictive member 130 is transmitted through sliding pole 140, cylinder cap 162, hydraulic fluid 164b disposed within the space between cylinder cap 162 and a planar surface of hydraulic piston 114b, and finally, through piston 114b, which in the illustrated embodiments is integral with valve member 114. The opening force is greater than the closing force, which results in the compression of valve spring 116. The displacement of hydraulic cylinder 160 also results in some further compression of disc spring 150.

As previously discussed, because valve actuation occurs suddenly (on the order of 200 μ s), hydraulic fluid 164b does not have time to flow through the narrow clearance gap between piston 114b and hydraulic cylinder 160. Instead, hydraulic fluid 164b acts as a solid and transfers the movement of magnetostrictive member 130 to valve member 114 via piston 114b, causing,

valve member 114 to lift away from valve seat 112. Because injection valve 100 stays open for such a brief period (typically less than 3 milliseconds), as long as the viscosity of hydraulic fluid 164 is properly selected and the clearance gap is suitably sized, the flow of hydraulic fluid 164 through the clearance gap while injection valve 100 is open is insignificant so that any displacement caused by such flow is much less than the total displacement of valve member 114.

The movement of valve member 114 is guided near the valve tip by guide 180. Guide 180 comprises longitudinal grooves or longitudinal bores or slots (not shown) to allow the fuel to pass therethrough and into the valve tip. Valve member 114 is also guided by the cooperating between the side walls of hydraulic piston 114b and the internal walls of hydraulic cylinder 160.

As shown in the embodiment of FIG. 1, fuel inlet 108 is located in cap 104 and fuel flows through the hollow valve body. In the preferred application, the fuel is a gaseous fuel so small gaps between valve components are sufficient to allow the gaseous fuel to flow through the length of the valve body to the opposite end where the fuel is introduced into the engine combustion chamber through the tip of the injection valve.

Fuel flow through the valve interior can also be facilitated by providing longitudinal grooves in the side walls of valve components (not shown) and/or holes or slots provided through components (see for example holes 138a through fixed pole 138). Causing the fuel to flow through the interior of the injection valve helps to cool the valve components and remove heat that may be generated in the actuator assembly. When the fuel is used to cool the actuator assembly in this manner, thermal modeling predicts that during normal operation heat generated by the actuator assembly will cause a temperature rise of less than 10°C.

To close injection valve 100, at the end of the injection event, electric coil 132 is de-energized, causing magnetostrictive member 130 to contract. When valve member 114 is moving from the open position to the closed position, the closing force originates from valve spring 116 and disc spring 150. The closing force from valve spring 116 is again transmitted to valve member 114 through hydraulic piston 114b. In the open position, the expanded magnetostrictive member 130 compressed disc spring 150, so upon closing, disc spring 150 de-compresses to push cylinder 160 towards the actuator assembly to compress to magnetostrictive member 130. Disc

spring 150 also provides an additional closing force to valve member 114 by generating a closing force that is transmitted from disc spring 150 through hydraulic cylinder 160, valve spring 116
5 and hydraulic piston 114b.

Once valve member 114 contacts valve seat 112, injection valve 100 is closed. When injection valve 100 is closed, the hydraulic link assembly automatically self-adjustments so that
10 the position of hydraulic cylinder 160 relative to hydraulic piston 114b is corrected to account for the effects of temperature, wear, and any small movements of valve member 114 relative to hydraulic cylinder 160 that may have occurred
15 while valve member 114 was in the open position. Auto-adjustments are accomplished by the migration of hydraulic fluid from chamber 164b on one side of hydraulic piston 114b to chamber 164a on the other side of hydraulic piston 114b, while
20 valve spring 116 and disc spring 150 ensure that the injection valve remains closed with valve member 114 seated against valve seat 112.

Control Strategy

25 Preferred waveforms representing the amount of electric current delivered to a valve actuator for controlling an injection valve are plotted in FIG. 4. The illustrated waveform shows that the

control pulse may employ several features to control the movement of a magnetostrictive or piezoelectric member respectively.

For example, for an actuator employing a
5 magnetostrictive member, an electric current is directed to an electric coil that is used to actuate the magnetostrictive member. The strength of the magnetic field is directly proportional to the amount of electric current
10 that is directed to the electric coil. To promote fast opening, for a short time immediately prior to an injection event (for example 100 microseconds), a current is preferably initiated by high frequency voltage
15 cycles between substantially equivalent positive and negative voltages. For example, these high voltage cycles may be on the order of 100 kHz.

Waveform A illustrates a preferred pulse shape for an injection event. An injection event
20 is initiated when the valve is opened by rapidly increasing current to I_1 , which is of a magnitude that is known to correspond to a desired lift. When the valve is opening, the high frequency voltage cycles continue between positive and
25 negative voltages but a net positive voltage. Once the desired valve lift is attained, the current is maintained at I_1 to maintain the valve lift for a duration predetermined by a

controller. The controller is responsive to current engine load and demand.

The injection event is concluded by decreasing current until it is reduced substantially to zero amps by applying high frequency voltage cycles and in each cycle maintaining the negative voltage for a longer time than the positive voltage.

As shown by the dashed lines in FIG. 4, the shape of the waveform may be controlled to achieve desired effects. For example, dashed waveform B shows that upon initiating the injection event, to further accelerate valve opening and introduction of the fuel, the current may be initially increased to I_2 which is much higher than the magnitude needed to provide the desired lift. To conserve energy and to maintain the desired lift during the duration of the injection event, the current is later lowered to I_1 . In this example, current I_1 has a value corresponding to the current known to maintain the desired lift.

Waveform C shows that different amounts of valve lift can be achieved by changing the magnitude of the current maintained during the injection event. Waveform C maintains the current at I_3 to produce a lower lift to inject a smaller amount of fuel compared to the injection

event of waveform A. Waveform C also shows an injection event with a shorter duration compared to the injection event that would be produced by waveform A.

5 Dashed line D shows that the shape of the waveform can be manipulated to influence the movement of the valve member. In this example the current is momentarily made negative to I_4 to accelerate the valve closing and then made
10 momentarily positive again to I_5 to slow down the valve member to reduce impact and wear on the valve member and valve seat. The current could also be kept positive (that is I_4 equals zero) and current could be momentarily raised to I_5 to slow
15 down the valve member before it contacts the valve seat. Dashed line E also shows that valve closing impact and wear to the valve seat and valve member can be reduced by slowing the rate at which the current is reduced to zero.

20 Persons skilled in the technology involved here will recognize that the time to open or close the injection valve may be decreased by increasing the slope of the control waveform, or increased, by decreasing the slope of the
25 waveform. In summary, the shape of the control waveform may be manipulated to produce the desired effects on the speed of the valve member

movement and its displacement with respect to the valve seat (to control lift).

The time span for the waveforms of FIG. 4 may be in the range of 100 to 5000 microseconds, and typically between 250 and 2000 microseconds for the majority of injection events.

The combination of the above described directly actuated injection valve and control strategy provides several benefits, including:

- 10 • elimination of the hydraulic fluid supply system that is needed by conventional hydraulically actuated injection valves. This simplifies injection valve construction, for example, by eliminating the need for
15 hydraulic fluid supply and return passages and the hydraulic fluid control valves that are employed by conventional hydraulically actuated
20 injection valves.
- automatic compensation for differential thermal expansion within the injection valve, for wear due to prolonged operation, and for small differences
25 caused by limitations in manufacturing tolerances.
- an apparatus that permits the use of a control strategy that can throttle fuel

flow and reduce valve seat wear. The ability to control the lift displacement permits reduced injection at lower loads and reduced pre-mixed burning. For example, using a magnetostrictive or piezoelectric actuator, the valve member movement can be controlled between about 10% and 100%. For lower load conditions it is important to be able to reduce the flow of fuel into the combustion chamber, since excess fuel may not be combusted, resulting in lower operating efficiency and higher emissions.

- 15 • improved manufacturability is made possible by the use of axisymmetric cylindrical parts and few tight tolerances between the injection valve components.
- 20 • valve operation is improved since the actuating assembly permits greater control of the valve member. For example, the injection valve may be used to inject a gaseous or liquid
- 25 fuel. When the fuel is gaseous, there is a greater need to slow down the valve member upon closing because there is no liquid fuel to dampen the impact

of the valve member on the valve seat.
By shaping the control pulse waveform
applied to the actuator it is possible
to slow down the closing of the
5 injection valve to reduce impact on the
valve member and the valve seat.

While particular elements, embodiments and
applications of the present invention have been
shown and described, it will be understood, of
10 course, that the invention is not limited thereto
since modifications may be made by those skilled
in the art without departing from the scope of
the present disclosure, particularly in light of
the foregoing teachings.

15

What is claimed is:

1. An injection valve for injecting fuel into a combustion chamber of an internal combustion engine, said injection valve comprising:

- 5 (a) a valve housing comprising:
a fuel inlet port;
an interior chamber fluidly
connected to said fuel inlet port; and
a valve seat for cooperating with
10 a valve member to seal said interior
chamber from said combustion chamber
when said injection valve is closed;
- (b) said valve member having one end
disposed within said valve housing and
15 an opposite end extendable from said
valve seat toward said combustion
chamber, wherein said valve member
comprises a sealing surface that
fluidly seals against said valve seat
20 when said injection valve is closed and
that is liftable away from said valve
seat when said injection valve is open;
- (c) a biasing mechanism associated with
said valve member, said biasing
25 mechanism applying a closing force to

said valve member when said valve member is in said closed position;

(d) an actuator assembly associated with said valve member, wherein said actuator assembly may be actuated to apply an opening force to said valve member stronger than said closing force, for moving said valve member to said open position; and

(e) a hydraulic link assembly comprising a passive hydraulic link having a hydraulic fluid thickness through which said opening and closing forces are transmitted, whereby said hydraulic fluid acts substantially as a solid with said thickness being substantially constant while said actuator assembly is actuated and wherein said thickness of said hydraulic link is adjustable while said actuator assembly is not actuated in response to changes in the dimensional relationship between components of said injection valve to maintain a desired valve lift upon actuation of said actuator assembly.

2. The injection valve of claim 1 wherein said thickness of said hydraulic link is auto-

adjustable while said actuator assembly is not actuated in response to changes in said dimensional relationship caused by differential thermal expansion.

3. The injection valve of claim 2 wherein said thickness of said hydraulic link is auto-adjustable while said actuator assembly is not actuated in response to changes in said dimensional relationship caused by wear to components of said injection valve.

4. The injection valve of claim 1 wherein said hydraulic link assembly comprises a fluidly sealed hydraulic cylinder that is fluidly sealed from said interior chamber, said hydraulic link assembly comprising a piston and said hydraulic fluid is disposed within said hydraulic cylinder.

5. The injection valve of claim 4 wherein said piston is an integral part of said valve member.

6. The injection valve of claim 1 wherein said actuator assembly comprises a dimensionally responsive member.

7. The injection valve of claim 6 wherein said dimensionally responsive member is formed from a magnetostrictive material.

8. The injection valve of claim 7 wherein said magnetostrictive material comprises a metal alloy comprising terbium, dysprosium and iron.

9. The injection valve of claim 7 wherein said actuator assembly further comprises an electric coil disposed in an annular space around said dimensionally responsive member.

10. The injection valve of claim 9 wherein said actuator assembly further comprises a flux tube disposed around said electric coil.

11. The injection valve of claim 10 wherein said a flux tube is disposed in an annular space around said electric coil.

12. The injection valve of claim 10 wherein said actuator assembly is disposed within said interior chamber.

13. The injection valve of claim 6 wherein said dimensionally responsive member is formed from a piezoelectric material.

14. The injection valve of claim 6 further comprising a compression spring member for applying a compressive force to said dimensionally responsive member.

15. The injection valve of claim 1 wherein said fuel inlet port is positioned such that fuel enters said valve housing and passes through said actuator and hydraulic link assemblies.

16. The injection valve of claim 1 wherein said fuel inlet port is positioned near the valve tip such that fuel flowing through said interior chamber does not contact said actuator assembly.

17. The injection valve of claim 6 wherein said actuator assembly is controllable to maintain said desired lift between 10 and 100 percent of maximum lift.

18. The injection valve of claim 17 wherein said lift is controllable by varying at least one of the electric current, the electric voltage and the magnetic field imposed upon said dimensionally responsive member.

19. The injection valve of claim 6 wherein said valve member is controllable such that said valve member moves between said open and closed positions in less than about 200 microseconds.

20. The injection valve of claim 6 further comprising a biasing mechanism for applying a compressive force to said dimensionally responsive member.

21. The injection valve of claim 1 wherein said biasing mechanism comprises a spring.

22. The injection valve of claim 21 wherein said spring comprises at least one disc spring.

23. The injection valve of claim 1 wherein said fuel is a gaseous fuel.

24. The injection valve of claim 23 wherein said hydraulic fluid is a liquid.

25. The injection valve of claim 24 wherein said hydraulic fluid is a liquid selected from the group consisting of motor oil and grease.

26. The injection valve of claim 1 wherein said fuel is injected into said combustion chamber at a pressure greater than about 2000 psi (about 13.8 Mpa).

27. The injection valve of claim 1 wherein said valve housing comprises a plurality of parts which are joined with each other to provide a fluidly sealed body.

28. The injection valve of claim 1 wherein said valve housing, said valve member and said actuator assembly are selected from materials having thermal expansion coefficients sufficiently compatible such that changes in the dimensional relationship between said components caused by changes in temperature are reduced.

29. An injection valve for injecting fuel into a combustion chamber of an internal combustion engine, said injection valve comprising:

- 5 (a) a valve housing comprising:
 - a fuel inlet port;
 - an interior chamber fluidly connected to said fuel inlet port;
 - 10 a valve seat provided on an end of said housing that faces said combustion chamber;
- (b) a valve member comprising a shaft portion having a first end to which a circular head is transversely mounted
15 wherein said head provides an annular

sealing surface that faces said valve seat, and a second end of said shaft is associated with a piston portion, said valve member movable between a closed position at which said sealing surface contacts said valve seat to fluidly seal said interior chamber from said combustion chamber, and an open position at which said sealing surface is spaced apart from said valve seat whereby said interior chamber is fluidly connected with combustion chamber;

(c) a biasing mechanism associated with said piston portion of said valve member, said biasing mechanism applying a closing force to said valve member when said valve member is in said closed position;

(d) an actuator assembly for applying an opening force to said valve member that is stronger than said closing force, for moving said valve member to said open position, said actuator assembly comprising a member having dimensional responsiveness to the imposition of at least one of an electric current, an electric voltage and a magnetic field,

45 said dimensionally responsive member
disposed between a fixed pole
maintained in a fixed position relative
to said valve housing and a sliding
pole, said sliding pole being
displaceable by expansion of said
50 dimensionally responsive member; and
(e) a hydraulic link assembly comprising a
fluidly sealed hydraulic cylinder
disposed about said piston portion of
said valve member, a hydraulic fluid
55 disposed within said hydraulic
cylinder, wherein said opening and
closing forces applied to said valve
member are transmitted through a
thickness of said hydraulic fluid
60 whereby said hydraulic fluid acts as a
hydraulic link and said thickness is
automatically adjustable in response to
changes in the dimensional relationship
between components of said injection
65 valve to maintain a desired valve lift
upon actuation of said actuator
assembly.

30. The injection valve of claim 29 wherein
said dimensionally responsive member is formed
from a magnetostrictive material.

31. The injection valve of claim 30 wherein said magnetostrictive material comprises a metal alloy comprising terbium, dysprosium and iron.

32. The injection valve of claim 30 wherein said actuator assembly further comprises an electric coil disposed in an annular space around said dimensionally responsive member.

33. The injection valve of claim 32 wherein said actuator assembly further comprises a flux tube disposed in an annular space around said electric coil.

34. The injection valve of claim 29 wherein said dimensionally responsive member is formed from a piezoelectric material.

³⁷
~~35.~~ The injection valve of claim 29 further comprising a compression spring member for applying a compressive force to said dimensionally responsive member.

³⁸
~~36.~~ A method of using a shaped waveform to control electric current to actuate an injection valve for an internal combustion engine that employs a dimensionally responsive actuator

5 assembly comprising at least one of a
magnetostrictive and a piezoelectric material,
and a controller to govern valve lift and
duration according to values predetermined for
10 said engine by said controller controlling
current and voltage directed to said actuator
assembly, said method comprising for each
injection event:

- 15 (a) initiating an injection event by
rapidly increasing current to a
magnitude that is known to correspond
to a desired lift by applying high
frequency voltage cycles and in each
cycle maintaining a net positive
20 voltage;
- (b) maintaining a current to control said
desired lift for a duration
predetermined by said controller; and
- 25 (c) concluding an injection event by
decreasing current until it is reduced
to zero amps by applying high frequency
voltage cycles and in each cycle
maintaining a net negative voltage.

³⁹
~~37~~. The method of claim ³⁸~~36~~ whereby the step
of initiating an injection event further
comprises initially increasing current to a spike

value higher than the value for the desired lift
5 to rapidly open said valve and then reducing
current to the value to cause the desired lift.

⁴⁰
~~38~~. The method of claim ³⁹~~37~~ wherein said
spike value is up to about an order of magnitude
higher than the value needed to cause the desired
lift.

³⁵
~~29~~. The method of claim 29 further
comprising applying high frequency voltage cycles
between offsetting positive and negative voltages
to generate a current of close to zero amps
5 immediately prior to an injection event.

³⁶
~~40~~. The method of claim 29 wherein the time
to open said valve from a closed position to said
desired lift is less than about 100 microseconds.

41. A method of operating a fuel injection
valve for an internal combustion engine, said
injection valve having a longitudinal axis, said
method comprising:

- 5 (a) actuating a dimensionally responsive
member comprising at least one of a
magnetostrictive material and a
piezoelectric material, said
dimensionally responsive member

10 expanding in length in the direction of
 said longitudinal axis upon actuation
 of said actuator;

 (b) transferring movement caused by said
 actuated dimensionally responsive
15 member through a passive hydraulic link
 to cause a corresponding movement of a
 valve member to open said valve by
 lifting said valve member away from a
 valve seat and compressing a biasing
20 mechanism that biases said valve in a
 closed position, said passive hydraulic
 link comprising a hydraulic cylinder
 which houses a piston and is filled
 with a hydraulic fluid, wherein said
25 hydraulic fluid forms a layer between
 said piston and a cylinder head and
 because of the short duration that said
 valve is open, said hydraulic fluid
 does not have time to flow from one
30 side of said piston to the other side
 and while said injection valve is open,
 said layer of hydraulic fluid acts as
 an incompressible solid so that
 movement caused by the actuation of
35 said dimensionally responsive member is
 transmitted through said fluid layer;

- 40 (c) deactuating said dimensionally responsive member to contract the length of said dimensionally responsive member to unload said biasing mechanism and cause a corresponding movement of said valve member to close said valve;
- 45 (d) providing sufficient time between consecutive valve openings to allow at least some of said hydraulic fluid within said passive hydraulic link to flow from one side of said piston to the other side of said piston.

DIRECTLY ACTUATED INJECTION VALVE

Abstract

Suban A directly actuated injection valve comprises a hollow valve housing, a valve member disposed within the hollow interior, a biasing mechanism, an actuator assembly and a hydraulic link assembly. The valve member is movable between a closed position and an open position for governing the flow of fuel into the combustion chamber of an internal combustion engine. The biasing mechanism, preferably a spring, biases the valve member in the closed position. The actuator assembly generates an opening force that acts against the valve spring to open the valve. The hydraulic link assembly is interposed between the valve member and the valve spring and the actuator assembly. The hydraulic link assembly transmits respective closing and opening forces to the valve member. The hydraulic link preferably comprises a piston disposed within a cylinder that is filled with a hydraulic fluid. The opening and closing forces are transmitted through a thickness of the hydraulic fluid that is trapped between the planar surfaces of the piston and the head and base of the hydraulic cylinder.

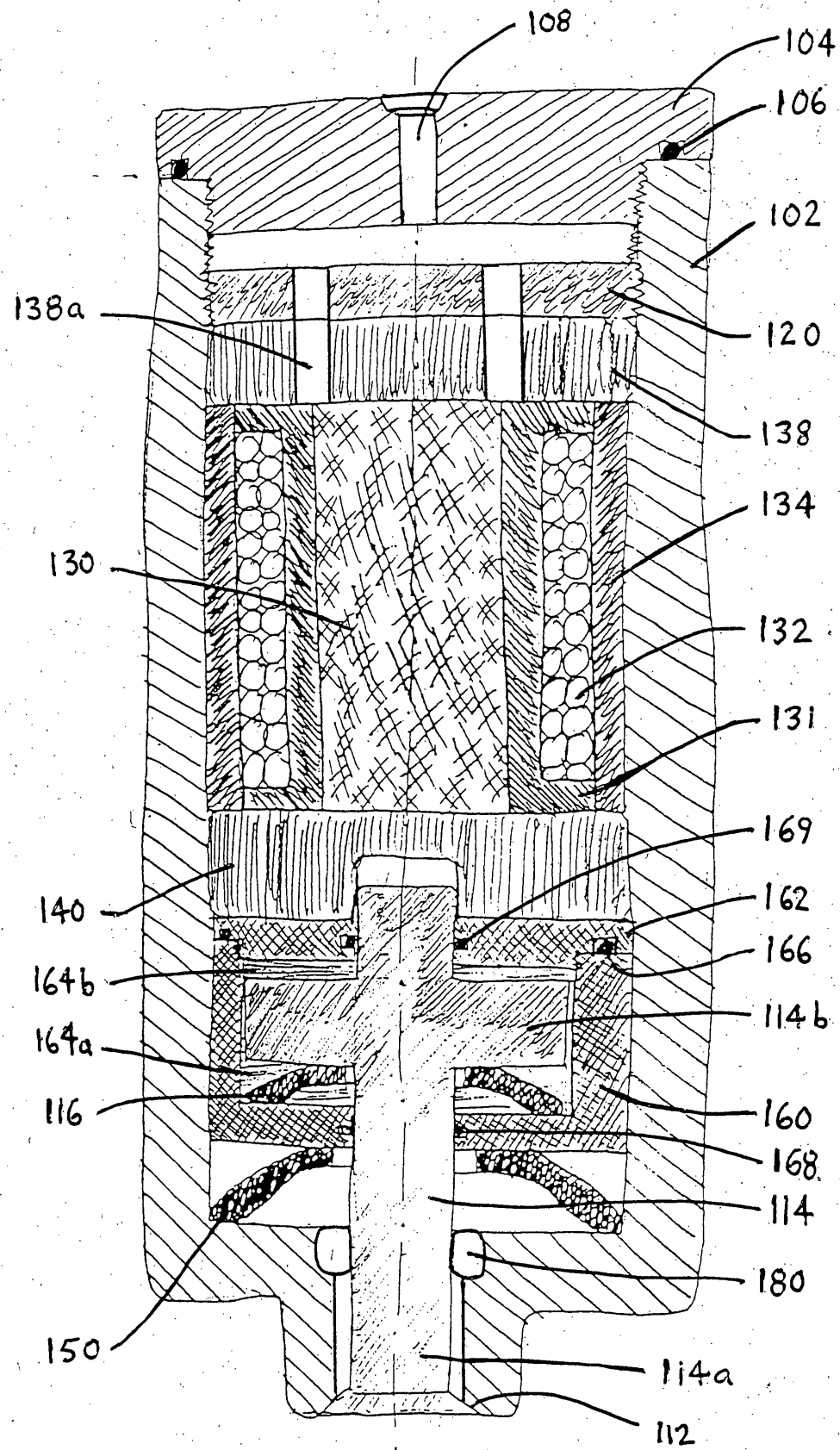


FIG. 1

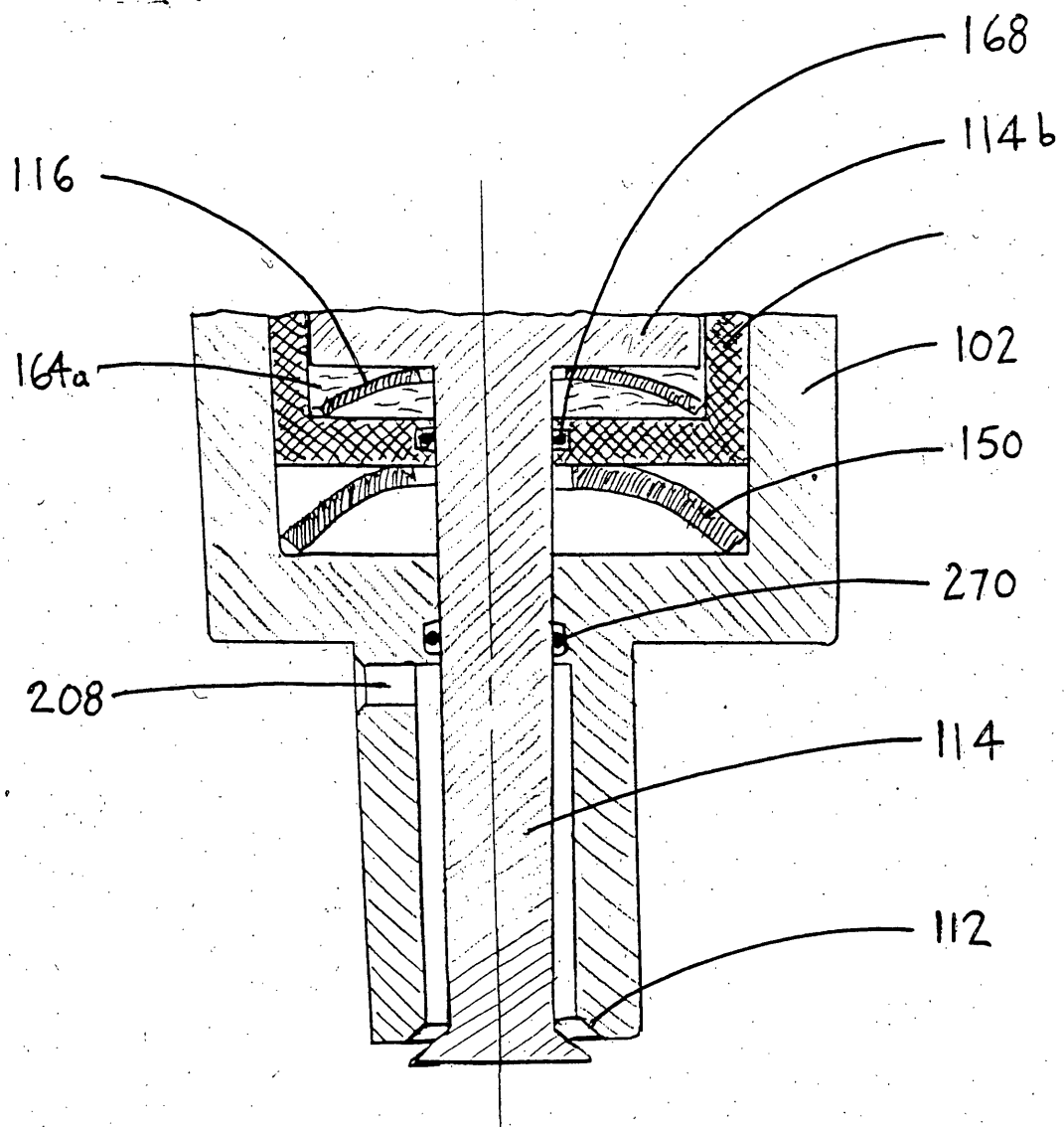


FIG. 2

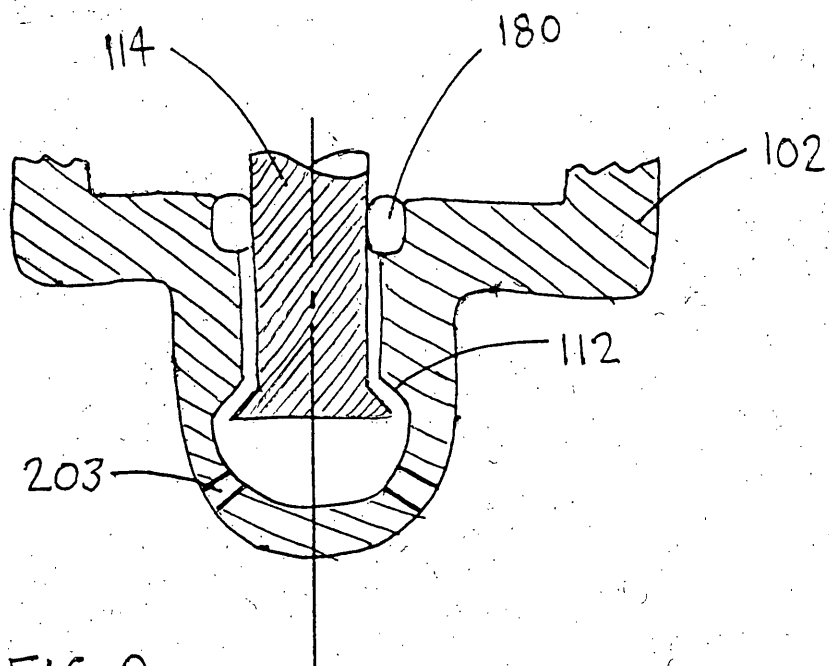


FIG. 2a

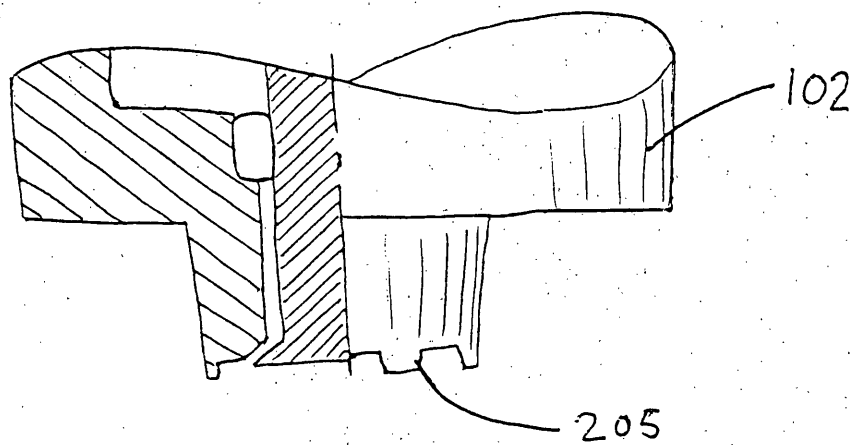


FIG. 2b

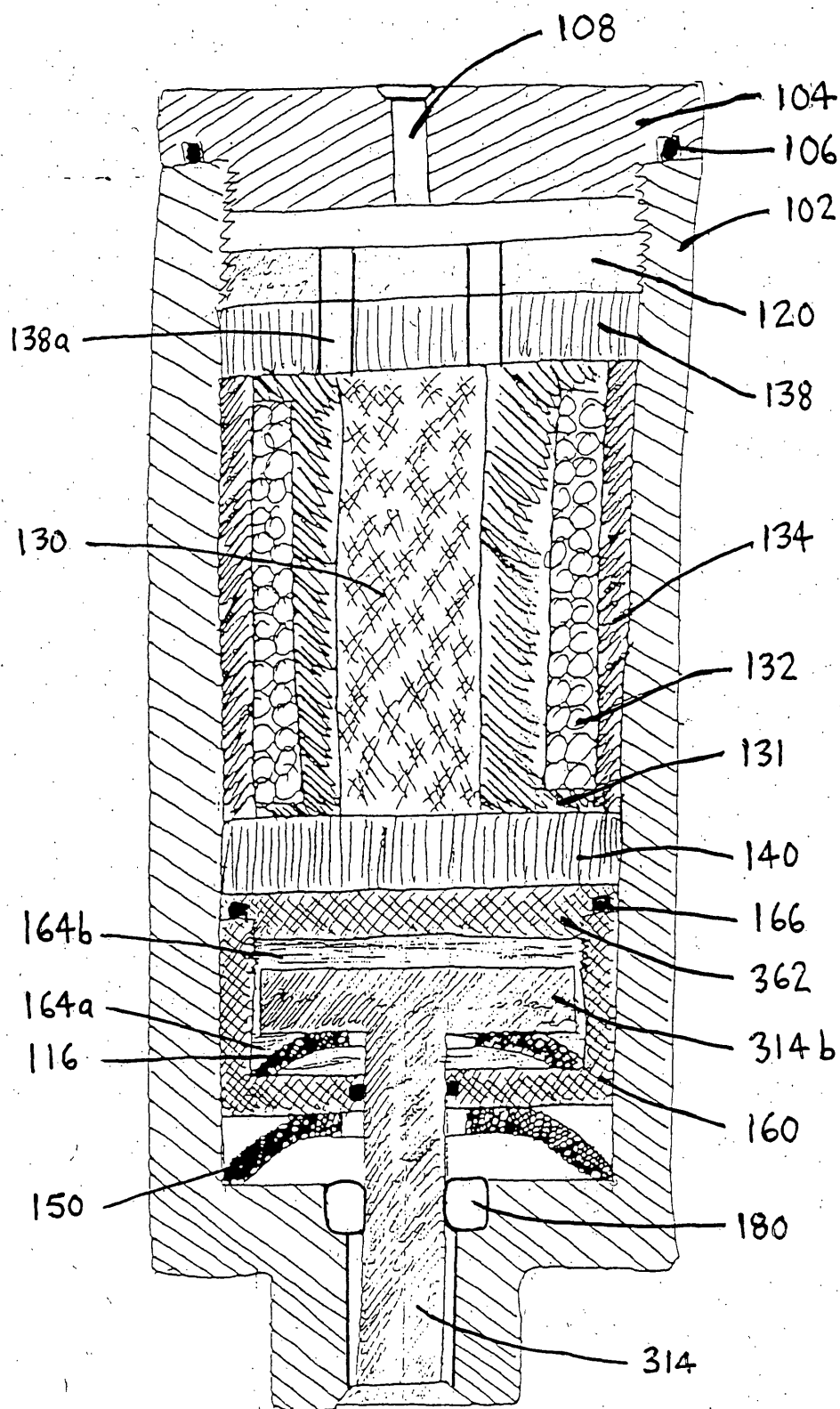


FIG. 3

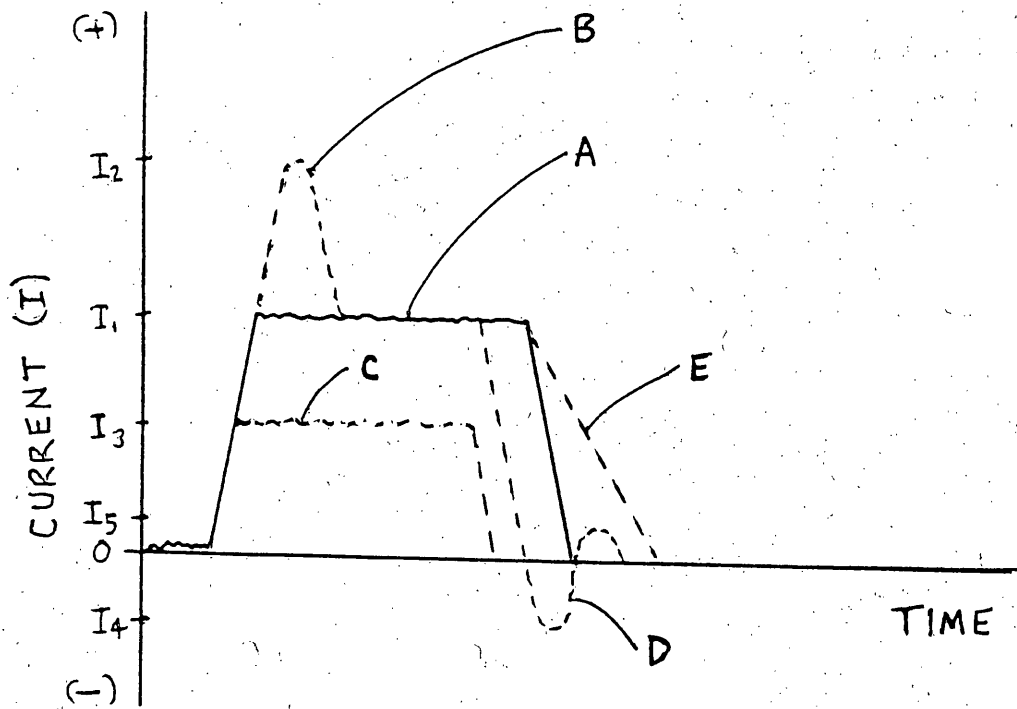


FIG. 4

CANCELED 3/5/63

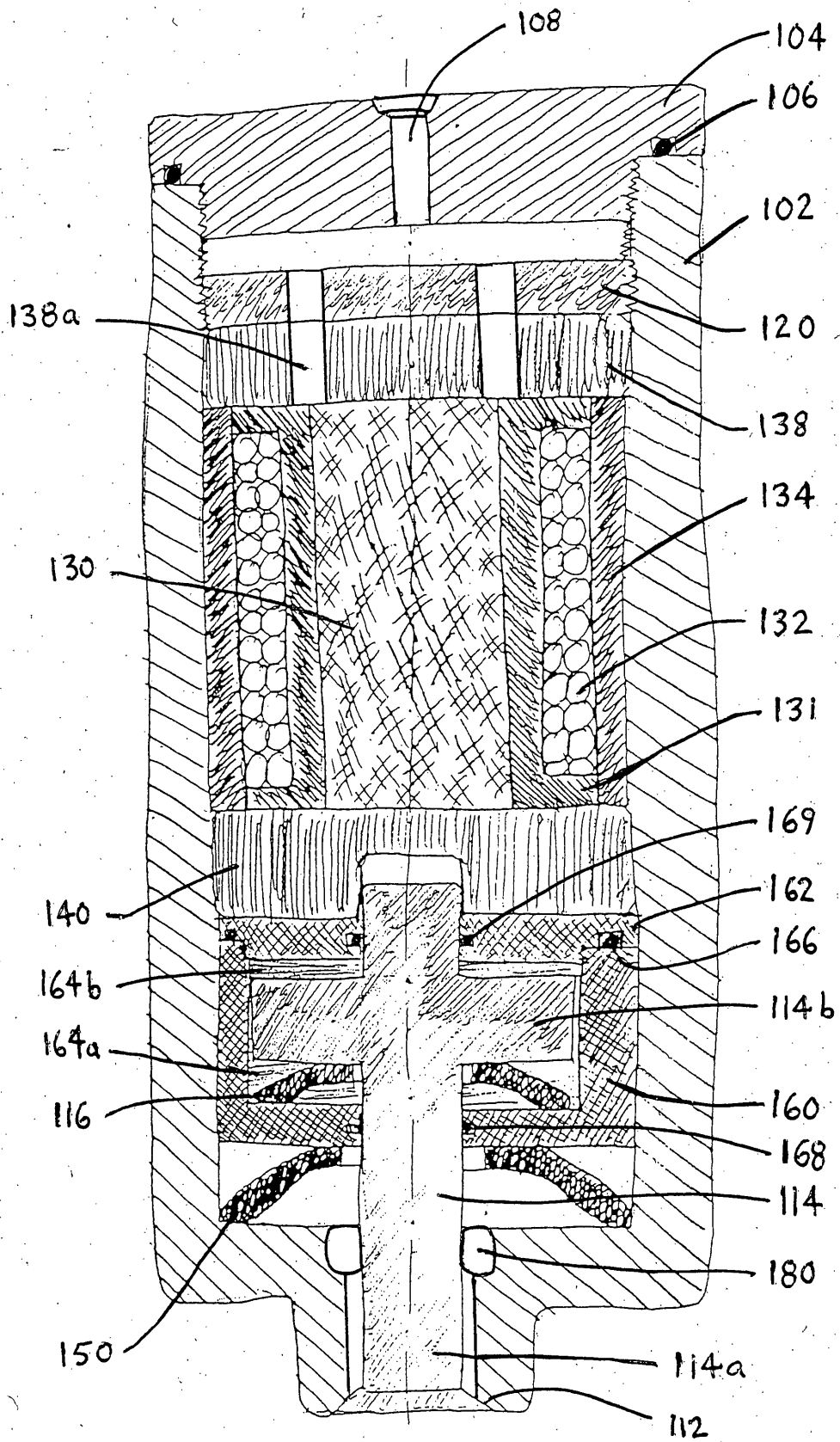


FIG. 1

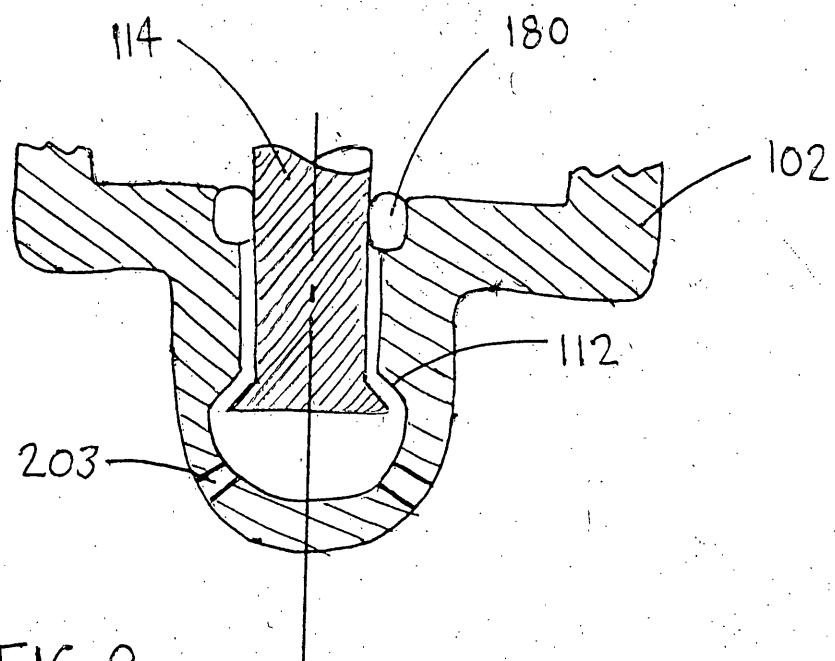


FIG. 2a

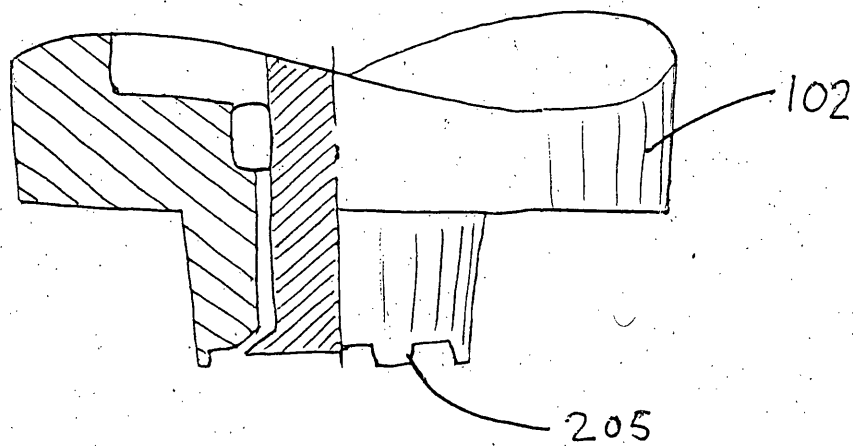


FIG. 2b

Petitioner Ex. 1002, p. 104
Robert Bosch et al v. Westport
IPR2023-00293

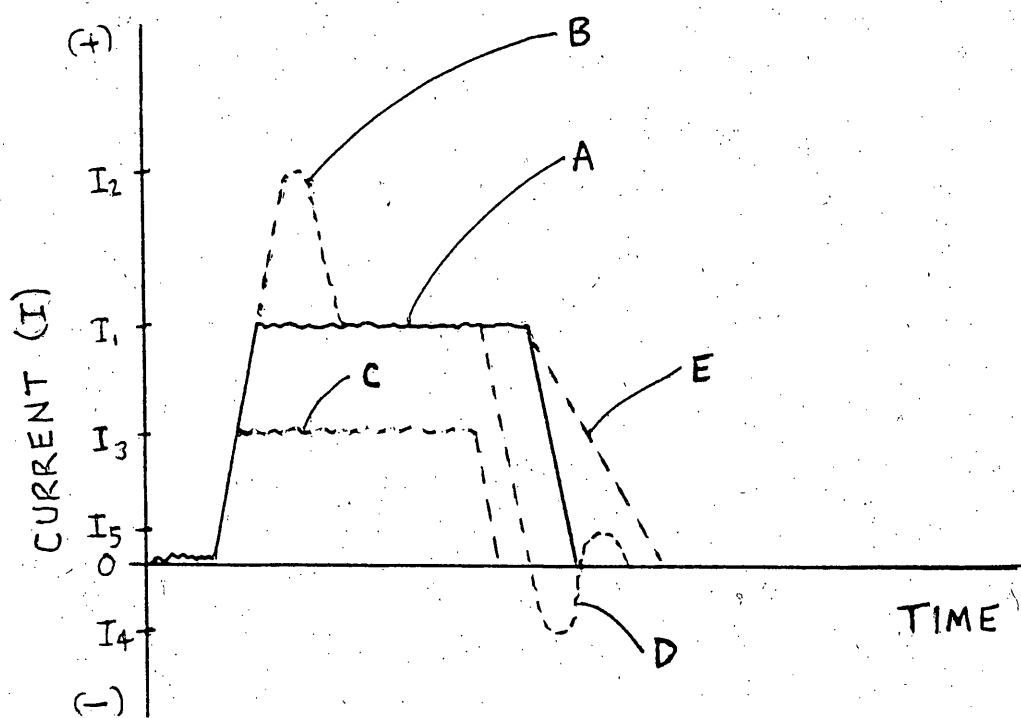


FIG. 4



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APPLICATION NUMBER	FILING/RECEIPT DATE	FIRST NAMED APPLICANT	ATTORNEY DOCKET NUMBER
09/863,187	05/23/2001	Alan Welch	12541 US03

CONFIRMATION NO. 2084

FORMALITIES LETTER



OC000000006161456

Robert W. Fieseler
McAndrews, Held & Malloy, Ltd.
34th Floor
500 West Madison Street
Chicago, IL 60661

Date Mailed: 06/07/2001

NOTICE TO FILE MISSING PARTS OF NONPROVISIONAL APPLICATION

FILED UNDER 37 CFR 1.53(b)

Filing Date Granted

An application number and filing date have been accorded to this application. The item(s) indicated below, however, are missing. Applicant is given **TWO MONTHS** from the date of this Notice within which to file all required items and pay any fees required below to avoid abandonment. Extensions of time may be obtained by filing a petition accompanied by the extension fee under the provisions of 37 CFR 1.136(a).

- The oath or declaration is missing.
A properly signed oath or declaration in compliance with 37 CFR 1.63, identifying the application by the above Application Number and Filing Date, is required.
- To avoid abandonment, a late filing fee or oath or declaration surcharge as set forth in 37 CFR 1.16(e) of \$130 for a non-small entity, must be submitted with the missing items identified in this letter.
- **The balance due by applicant is \$ 130.**

*A copy of this notice **MUST** be returned with the reply.*

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PART 3 - OFFICE COPY

File History Content Report

The following content is missing from the original file history record obtained from the United States Patent and Trademark Office. No additional information is available.

Document Date - 2001-06-07
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Sector
#3

PATENT

Attorney Docket No. 12541US03

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

PATENT APPLICATION OF:

ALAN B. WELCH, IRAWAN
RAHARDJA and MIKE HEBBES

SERIAL NO. 09/863,187

FILED: May 23, 2001

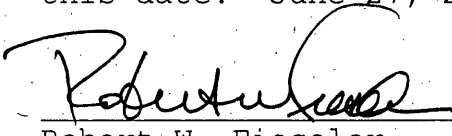
FOR: DIRECTLY ACTUATED
INJECTION VALVE

GROUP ART UNIT: 3747

EXAMINER: Not Assigned

CERTIFICATE OF MAILING

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correspondence is being
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this date: June 27, 2001.


Robert W. Fieseler
Registration No. 31,826
Attorney for Applicant(s)

RESPONSE TO NOTICE TO FILE MISSING PARTS

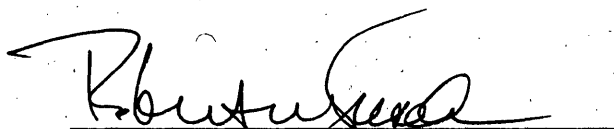
Box Missing Parts
Assistant Commissioner For Patents
Washington, D.C. 20231

Sir:

In response to the Notice To File Missing Parts Of
Application dated June 7, 2001 (return copy enclosed), enclosed
is the executed Declaration and Power Of Attorney for the above
application. Also enclosed is a check in the amount of \$130.00
to cover the surcharge due for a large entity.

Please charge any additional fees, or credit any
overpayment, incurred in connection with this submission to
Deposit Account No. 13-0017.

Respectfully submitted,



Robert W. Fieseler
Registration No. 31,826
Attorney For Applicants

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500 West Madison Street, 34th Floor
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Telephone (312) 775-8000
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Date: June 27, 2001



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APPLICATION NUMBER	FILING/RECEIPT DATE	FIRST NAMED APPLICANT	ATTORNEY DOCKET NUMBER
09/863,187	05/23/2001	Alan Welch	12541 US03

CONFIRMATION NO. 2084

FORMALITIES LETTER



OC000000006161456

Robert W. Fieseler
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34th Floor
500 West Madison Street
Chicago, IL 60661

Date Mailed: 06/07/2001

NOTICE TO FILE MISSING PARTS OF NONPROVISIONAL APPLICATION

FILED UNDER 37 CFR 1.53(b)

Filing Date Granted

An application number and filing date have been accorded to this application. The item(s) indicated below, however, are missing. Applicant is given **TWO MONTHS** from the date of this Notice within which to file all required items and pay any fees required below to avoid abandonment. Extensions of time may be obtained by filing a petition accompanied by the extension fee under the provisions of 37 CFR 1.136(a).

- The oath or declaration is missing.
A properly signed oath or declaration in compliance with 37 CFR 1.63, identifying the application by the above Application Number and Filing Date, is required.
- To avoid abandonment, a late filing fee or oath or declaration surcharge as set forth in 37 CFR 1.16(e) of \$130 for a non-small entity, must be submitted with the missing items identified in this letter.
- The balance due by applicant is \$ 130.

*A copy of this notice **MUST** be returned with the reply.*

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PART 2 - COPY TO BE RETURNED WITH RESPONSE



#3

Attorney Docket No. 12541US03

DECLARATION AND POWER OF ATTORNEY

As a below-named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

I believe that I am the original inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

DIRECTLY ACTUATED INJECTION VALVE

the specification of which was filed as U.S. Patent Application Serial No. 09/863,187 on May 23, 2000.

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims. I acknowledge the duty to disclose information which is material to the examination of this application in accordance with Title 37, Code of Federal Regulations, Section 1.56(a).

I hereby claim foreign priority benefits under Title 35, United States Code, section 119(a)-(d) or section 365(b) of any foreign application(s) for patent or inventor's certificate, or section 365(a) of any PCT international application which designated at least one country other than the United States of America, listed below and have also identified below any foreign application(s) for patent or inventor's certificate or any PCT international application(s) designating at least one country other than the United States of America filed by me on the same subject matter having a filing date before that of the application on which priority is claimed:

NONE.

I hereby claim the benefit under Title 35, United States Code, section 119(e) of any United States provisional application(s) listed below:

U.S. Provisional Patent Application
Serial No. 60/159,791 filed October 15, 1999.

I hereby claim the benefit under Title 35, United States Code, section 120 of any United States application(s), or section 365(c) of any PCT international application designating the United States of America, listed below and, insofar as the

subject matter of each of the claims of this application is not disclosed in such prior application(s) in the manner provided by the first paragraph of Title 35, United States Code, section 112, I acknowledge the duty to disclose material information as defined in Title 37, Code of Federal Regulations, section 1.56(a) which became available between the filing date of the prior application(s) and the national or PCT international filing date of this application:

U.S. Patent Application
Serial No. 09/522,130 filed March 9, 2000.

I hereby appoint:

George P. McAndrews	Reg. No. 22,760
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William M. Wesley	Reg. No. 26,521
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Herbert D. Hart III	Reg. No. 30,063
Robert W. Fieseler	Reg. No. 31,826
D. David Hill	Reg. No. 35,543
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Ronald E. Larson	Reg. No. 24,478
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Sandra A. Frantzen	Reg. No. P-48,799
Christopher V. Carani	Reg. No. 44,049
Jennifer E. Lacroix	Reg. No. 46,852
Joseph F. Harding	Reg. No. P-48,450
Joseph M. Butscher	Reg. No. P-48,326
Stephen M. Miller	Reg. No. 40,728
Troy A. Groetken	Reg. No. 46,442
Michael J. Fitzpatrick	Reg. No. P-48,510

the address and telephone number of each of whom is McAndrews, Held & Malloy, Ltd., 500 West Madison Street, 34th Floor, Chicago, Illinois 60661, (312) 775-8000, as our attorneys with full power of substitution and revocation to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith.

Please direct telephone calls to Robert W. Fieseler at (312) 775-8123. Please direct facsimiles to Robert W. Fieseler at (312) 775-8100.

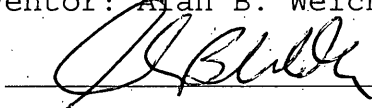
Please address correspondence to:

Robert W. Fieseler
McAndrews, Held & Malloy, Ltd.
500 West Madison Street, Suite 3400
Chicago, Illinois 60661

I hereby declare that all statements made herein of our own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Full name of first inventor: Alan B. Welch

Inventor's signature



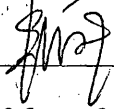
Date 7-20-20

Residence Address: 2828 West 34th Avenue
Vancouver, British Columbia, Canada V6N 2J6

Citizenship: Canadian

Post Office Address: Westport Innovations Inc.
1691 West 75th Avenue
Vancouver, B.C., Canada V6P 6P2

Full name of second inventor: Irawan P. Rahardja

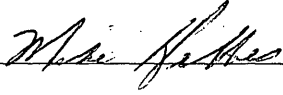
Inventor's signature  Date 20 June 2001

Residence Address: Suite 206 - 3727 West 10th Avenue
Vancouver, British Columbia, Canada V6R 2G5

Citizenship: Canadian

Post Office Address: Westport Innovations Inc.
1691 West 75th Avenue
Vancouver, B.C., Canada V6P 6P2

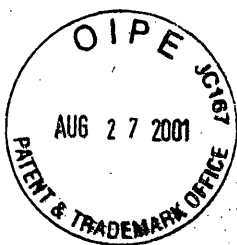
Full name of third inventor: Mike Hebbes

Inventor's signature  Date 20 June 2001

Residence Address: Suite 804 - 501 Pacific Street
Vancouver, British Columbia, Canada V6Z 2X6

Citizenship: Canadian

Post Office Address: Westport Innovations Inc.
1691 West 75th Avenue
Vancouver, B.C., Canada V6P 6P2



3747
#4

PATENT

Attorney Docket No. 12541US03

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

PATENT APPLICATION OF:

ALAN WELCH,
IRAWAN RAHARDJA and
MIKE HEBBES

SERIAL NO. 09/863,187

FILED: MAY 23, 2001

FOR: DIRECTLY ACTUATED
INJECTION VALVE

GROUP ART UNIT: 3747

EXAMINER: Not yet assigned

CERTIFICATE OF MAILING

I hereby certify that this
correspondence is being
deposited with the United
States Postal Service as
first class mail, postage
prepaid, in an envelope
addressed to: Assistant
Commissioner for Patents,
Washington, D.C. 20231, on
this date:

August 23, 2001

Robert W. Fieseler
Registration No. 31,826
Attorney for Applicants

INFORMATION DISCLOSURE STATEMENT

Assistant Commissioner for Patents
Washington, D.C. 20231

Sir:

Applicants submit herewith a copy of each of the
following references for consideration by the U.S. Patent
and Trademark Office in connection with the above
application.

TC 3700 MAIL ROOM

SEP -4 2001

RECEIVED

<u>U.S. Patent No.</u>	<u>Inventor(s)</u>	<u>Issue Date</u>
4,158,368	Clark	06/79
4,725,002	Trachte	02/88
4,813,601	Schwerdt et al.	03/89
5,031,841	Schafer	07/91
5,035,360	Green et al.	07/91
5,697,554	Auwaerter et al.	12/97
5,779,149	Hayes, Jr.	07/98
5,819,710	Huber	10/98
5,845,852	Waldman et al.	12/98
5,875,764	Kappel et al.	03/99
6,062,533	Kappel et al.	05/00

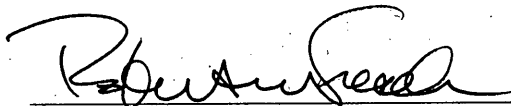
<u>Foreign Patent No.</u>	<u>Country</u>	<u>Publication Date</u>
WO 85/02445	PCT	06/85
09-324723	Japan	12/97
10-009084	Japan	01/98
2 321 501	Great Britain	07/98
0 869 278	EPO	08/98
197 27 992	Germany	01/99

The above references are listed on the enclosed Form PTO-1449 entitled "Information Disclosure Citation."

This Information Disclosure Statement is being submitted within three (3) months of the filing date of the application and/or before the receipt of a first Office Action on the merits of the application.

Please charge any fees incurred in connection with this submission to Deposit Account No. 13-0017 in the name of McAndrews, Held & Malloy, Ltd.

Respectfully submitted,



Robert W. Fieseler
Registration No. 31,826
Attorney for Applicants

Russell A. Garrison
McANDREWS, HELD & MALLOY, LTD.
500 West Madison Street, 34th Floor
Chicago, Illinois 60661

Telephone (312) 775-8000
Facsimile (312) 775-8100

Dated:

August 23, 2001



Form PTO-141 (Rev. 8-83) (modified)	U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE	ATTY. DOCKET NO. 12541US03	SERIAL NO. 09/863,187
		APPLICANT(s): Welch et al.	
		FILING DATE May 23, 2001	GROUP ART UNIT: 3747

INFORMATION DISCLOSURE CITATION
(Use several sheets if necessary)

U.S. PATENT DOCUMENTS							
EXAMINER INITIAL		DOCUMENT NO.	DATE	NAME	CLASS	SUBCLASS	FILING DATE, IF APPROPRIATE
UK		4,158,368	06/79	Clark	137	487.5	
		4,725,002	02/88	Trachte	239	102.2	
		4,813,601	03/89	Schwerdt et al.	239	91	
		5,031,841	07/91	Schafer	239	585	
		5,035,360	07/91	Green et al.	239	585	
		5,697,554	12/97	Auwaerter et al.	239	88	
		5,779,149	07/98	Hayes, Jr.	239	124	
		5,819,710	10/98	Huber	123	498	
		5,845,852	12/98	Waldman et al.	239	533.8	
		5,875,764	03/99	Kappel et al.	123	467	
		6,062,533	05/00	Kappel et al.	251	57	

TO 3700 MAIL ROOM

SEP-4 2001

RECEIVED

FOREIGN PATENT DOCUMENTS							
EXAMINER INITIAL		DOCUMENT NO.	PUBLICATION DATE	COUNTRY	CLASS	SUBCLASS	TRANSLATION
							YES NO
UK		WO 85/02445	06/85	PCT			
		09-324723	12/97	Japan			X (abstract)
		10-009084	01/98	Japan			X (abstract)
		2 321 501	07/98	Great Britain			
		0 869 278	08/98	EPO			
		197 27 992	01/99	Germany			

OTHER DOCUMENTS (Including Author, Title, Date, Pertinent Pages, Etc.)	

EXAMINER <i>Mahmood M. Gamil</i>	DATE CONSIDERED: 11-10-02
*EXAMINER: Initial citation considered, whether or not citation is in conformance with MPEP 609; Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.	

EUROPEAN PATENT OFFICE

Patent Abstracts of Japan

PUBLICATION NUMBER : 09324723
PUBLICATION DATE : 16-12-97

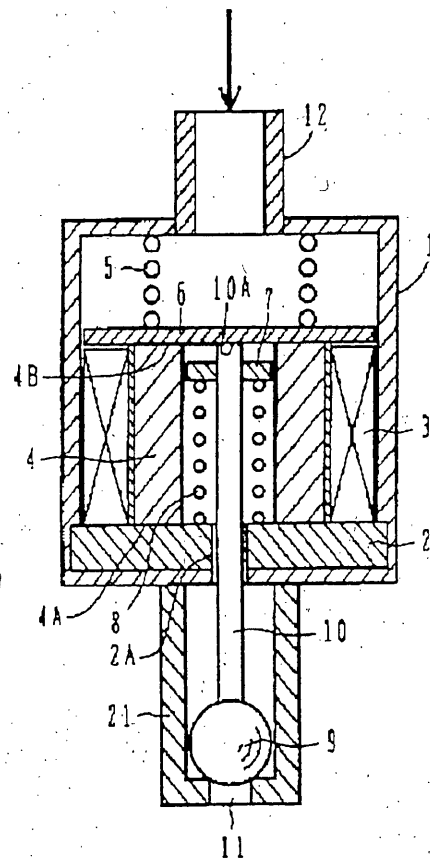
APPLICATION DATE : 03-06-96
APPLICATION NUMBER : 08140050

APPLICANT : HITACHI LTD;

INVENTOR : MORIYA HISATOKU;

INT.CL. : F02M 51/06 H02N 2/00

TITLE : FUEL INJECTION VALVE



ABSTRACT : PROBLEM TO BE SOLVED: To provide a reliable fuel injection valve, in an internally open type fuel injection valve using a magnetostrictive element.

SOLUTION: An electro-magnetic coil 3 for generating a magnetic field and an electricity-machine conversion element 4 extending when the magnetic field is impressed by this electro-magnetic coil 3 are fixed in the box body 1 of a fuel injection valve. Further, a rod 10 on which a ball valve 9 is fixed on a tip is pressed downward by the electricity-machine conversion element 4. Therefore, when the magnetic field is impressed on the electricity-machine conversion element 4 by the electro-magnetic coil 3, the electricity-machine conversion element 4 is displaced and the rod 10 is driven by this displacement and the fuel is injected.

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EUROPEAN PATENT OFFICE

Patent Abstracts of Japan

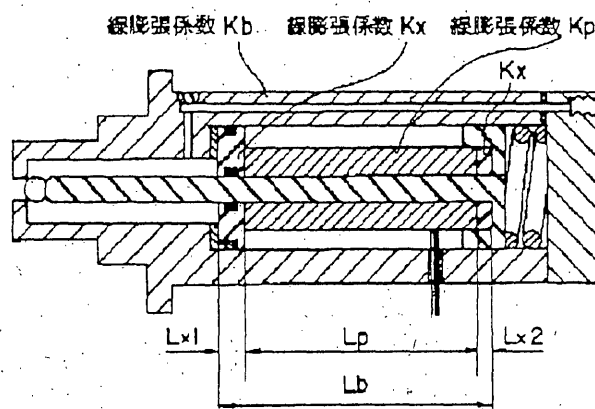
PUBLICATION NUMBER : 10009084
PUBLICATION DATE : 13-01-98
APPLICATION DATE : 24-06-96
APPLICATION NUMBER : 08162947

APPLICANT : NISSAN MOTOR CO LTD;

INVENTOR : ARAI TAKAYUKI;

INT.CL. : F02M 51/06 F16K 31/02 H02N 2/00

TITLE : PIEZOELECTRIC FUEL INJECTION VALVE



ABSTRACT : PROBLEM TO BE SOLVED: To make the fuel injection valve free from the influence of thermal expansion in any service temperature area, and make effective use of the displacement of a piezoelectric element even when the piezoelectric element high in responsiveness is applied to the needle valve of a fuel injection valve, and lower production costs with the piezo-electric element made small in size.

SOLUTION: The piezoelectric type fuel injection valve is formed out of a needle valve opening/closing an injection port to inject fuel, a spring which energizes the needle valve to the direction that the valve is closed, and concurrently presses the needle valve to a nozzle, and of a piezoelectric element which drivingly extends the needle valve to a valve open condition. An expansion correction member is provided in series with the piezoelectric element, and it is so constituted that a relation expressed by $Lx = (Kb \times Lb - Kp \times Lp) / Kx$ is thereby satisfied where Lx represents the dimension of a linear expansion correction member, Kb represents the linear expansion coefficient of a casing part, Lb represents the length of the casing concerned with expansion, Kp represents the linear expansion coefficient of the electrostrictive element, Lp represents the length of the electrostrictive element, Kx represents the linear expansion coefficient of a linear expansion absorbing member, and Lx represent the linear expansion coefficient of the linear expansion absorbing member.

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UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER OF PATENTS AND TRADEMARKS
Washington, D.C. 20231
www.uspto.gov

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
09/863,187	05/23/2001	Alan B. Welch	12541US03	2084

7590 11/14/2002
Robert W. Fieseler
McAndrews, Held & Malloy, Ltd.
34th Floor
500 West Madison Street
Chicago, IL 60661

EXAMINER

GIMIE, MAHMOUD

ART UNIT	PAPER NUMBER
----------	--------------

3747

DATE MAILED: 11/14/2002

Please find below and/or attached an Office communication concerning this application or proceeding.

Office Action Summary	Application No.	Applicant(s)	
	09/863,187	WELCH ET AL.	
	Examiner	Art Unit	
	Mahmoud M Gimie	3747	

-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address --

Period for Reply

A SHORTENED STATUTORY PERIOD FOR REPLY IS SET TO EXPIRE 3 MONTH(S) FROM THE MAILING DATE OF THIS COMMUNICATION.

- Extensions of time may be available under the provisions of 37 CFR 1.136(a). In no event, however, may a reply be timely filed after SIX (6) MONTHS from the mailing date of this communication.
- If the period for reply specified above is less than thirty (30) days, a reply within the statutory minimum of thirty (30) days will be considered timely.
- If NO period for reply is specified above, the maximum statutory period will apply and will expire SIX (6) MONTHS from the mailing date of this communication.
- Failure to reply within the set or extended period for reply will, by statute, cause the application to become ABANDONED (35 U.S.C. § 133).
- Any reply received by the Office later than three months after the mailing date of this communication, even if timely filed, may reduce any earned patent term adjustment. See 37 CFR 1.704(b).

Status

1) ☒ Responsive to communication(s) filed on 27 August 2002.

2a) ☐ This action is **FINAL**. 2b) ☒ This action is non-final.

3) ☐ Since this application is in condition for allowance except for formal matters, prosecution as to the merits is closed in accordance with the practice under *Ex parte Quayle*, 1935 C.D. 11, 453 O.G. 213.

Disposition of Claims

4) ☒ Claim(s) 1-41 is/are pending in the application.

4a) Of the above claim(s) _____ is/are withdrawn from consideration.

5) ☐ Claim(s) _____ is/are allowed.

6) ☒ Claim(s) 1-41 is/are rejected.

7) ☐ Claim(s) _____ is/are objected to.

8) ☐ Claim(s) _____ are subject to restriction and/or election requirement.

Application Papers

9) ☒ The specification is objected to by the Examiner.

10) ☒ The drawing(s) filed on 23 May 2001 is/are: a) ☐ accepted or b) ☒ objected to by the Examiner.

Applicant may not request that any objection to the drawing(s) be held in abeyance. See 37 CFR 1.85(a).

11) ☐ The proposed drawing correction filed on _____ is: a) ☐ approved b) ☐ disapproved by the Examiner.

If approved, corrected drawings are required in reply to this Office action.

12) ☐ The oath or declaration is objected to by the Examiner.

Priority under 35 U.S.C. §§ 119 and 120

13) ☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

a) ☐ All b) ☐ Some * c) ☐ None of:

1. ☐ Certified copies of the priority documents have been received.

2. ☐ Certified copies of the priority documents have been received in Application No. _____

3. ☐ Copies of the certified copies of the priority documents have been received in this National Stage application from the International Bureau (PCT Rule 17.2(a)).

* See the attached detailed Office action for a list of the certified copies not received.

14) ☐ Acknowledgment is made of a claim for domestic priority under 35 U.S.C. § 119(e) (to a provisional application).

a) ☐ The translation of the foreign language provisional application has been received.

15) ☐ Acknowledgment is made of a claim for domestic priority under 35 U.S.C. §§ 120 and/or 121.

Attachment(s)

1) ☒ Notice of References Cited (PTO-892)

2) ☐ Notice of Draftsperson's Patent Drawing Review (PTO-948)

3) ☒ Information Disclosure Statement(s) (PTO-1449) Paper No(s) 4

4) ☐ Interview Summary (PTO-413) Paper No(s). _____

5) ☐ Notice of Informal Patent Application (PTO-152)

6) ☐ Other:

DETAILED ACTION

Drawings

1. This application has been filed with informal drawings, which are acceptable for examination purposes only. Formal drawings will be required when the application is allowed.
2. The drawings are objected to as failing to comply with 37 CFR 1.84(p)(5) because they do not include the following reference sign(s) mentioned in the description: (a) 100 mentioned on various parts of the specification including page 25, line 19 and page 28, line 8. (b) 202 mentioned on page 27, line 8. A proposed drawing correction or corrected drawings are required in reply to the Office action to avoid abandonment of the application. The objection to the drawings will not be held in abeyance.

Specification

3. The abstract of the disclosure is objected to because it exceeds 150 words in length.

Correction is required. See MPEP § 608.01(b).

Claim Rejections - 35 USC § 103

4. The following is a quotation of 35 U.S.C. 103(a) which forms the basis for all obviousness rejections set forth in this Office action:

(a) A patent may not be obtained though the invention is not identically disclosed or described as set forth in section 102 of this title, if the differences between the subject matter sought to be patented and the prior art are such that the subject matter as a whole would have been obvious at the time the

invention was made to a person having ordinary skill in the art to which said subject matter pertains. Patentability shall not be negated by the manner in which the invention was made.

5. Claims 1-41 are rejected under 35 U.S.C. 103(a) as being unpatentable over Kurishige et al (5,630,550).

Kurishige, et al, discloses an injection valve for injecting fuel into a combustion chamber of an internal combustion engine, said injection valve comprising: (a) a valve housing comprising: a fuel inlet port (17); an interior chamber fluidly connected to said fuel inlet port (3a); and a valve seat for cooperating with a valve member (4) to seal said interior chamber from said combustion chamber when said injection valve is closed; (b) said valve member having one end disposed within said valve housing and an opposite end extendable from said valve seat toward said combustion chamber, wherein said valve member comprises a sealing surface that fluidly seals against said valve seat when said injection valve is closed and that is liftable away from said valve seat when said injection valve is open; (c) a biasing mechanism associated with said valve member, said biasing mechanism applying a closing force to said valve member when said valve member is in said closed position; (d) an actuator assembly associated with said valve member, wherein said actuator assembly may be actuated to apply an opening force to said valve member stronger than said closing force, for moving said valve member to said open position; and (e) a hydraulic link assembly comprising a passive hydraulic link having a hydraulic fluid thickness through which said opening and closing forces are transmitted, whereby said hydraulic fluid said thickness being substantially constant while said actuator assembly is actuated and wherein said thickness of said hydraulic link is adjustable while said actuator assembly is not actuated in response to changes in

the dimensional relationship between components of said injection valve to maintain a desired valve lift upon actuation of said actuator assembly.

Kurishige, et al, does not teach the pressure transmitting fluid acts substantially as a solid. However, teaches that an increase/decrease of the viscosity coefficient can be of the pressure transmitting medium can be controlled between -30° C and 200°C which suggests that the fluid acts substantially as a solid.

Therefore, It would have been obvious to one of ordinary skill in the art at the time of the invention was made to modify the invention of Kurishige et al by realizing that the pressure transmitting fluid acts as a solid. The motivation to do so would have been to show that the pressure transmitting fluid characteristics does not heavily depend on ambient temperature.

With regard to claim 4, the hydraulic link assembly comprises a fluidly sealed hydraulic cylinder (18) that is fluidly sealed from said interior chamber, said hydraulic link assembly comprising a piston (6) and said hydraulic fluid is disposed within said hydraulic cylinder.

With regard to claim 5, said piston (6) is an integral part of said valve member (4).

With regard to method claims see above and figures 8A-8C and 13A-B.

All other claims see above and figures 1-15.

Conclusion

6. The prior art made of record and not relied upon is considered pertinent to applicant's disclosure. The cited references show directly actuated fuel injectors.

Art Unit: 3747

7. This application currently names joint inventors. In considering patentability of the claims under 35 U.S.C. 103(a), the examiner presumes that the subject matter of the various claims was commonly owned at the time any inventions covered therein were made absent any evidence to the contrary. Applicant is advised of the obligation under 37 CFR 1.56 to point out the inventor and invention dates of each claim that was not commonly owned at the time a later invention was made in order for the examiner to consider the applicability of 35 U.S.C. 103(c) and potential 35 U.S.C. 102(e), (f) or (g) prior art under 35 U.S.C. 103(a).

Any inquiry concerning this communication or earlier communications from the examiner should be directed to Mahmoud M Gimie whose telephone number is 703-305-1037. The examiner can normally be reached on 7 a.m. -3:30 p.m.

If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, Henry Yuen can be reached on 703-308-1946. The fax phone numbers for the organization where this application or proceeding is assigned are 703-872-9302 for regular communications and 703-872-9302 for After Final communications.

Any inquiry of a general nature or relating to the status of this application or proceeding should be directed to the receptionist whose telephone number is 703-308-0861.



M Gimie, Examiner
November 12, 2002

Mahmoud M Gimie
Examiner
Art Unit 3747

Notice of References Cited	Application/Control No. 09/863,187	Applicant(s)/Patent Under Reexamination WELCH ET AL.	
	Examiner Mahmoud M Gimie	Art Unit 3747	Page 1 of 1

U.S. PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Name	Classification
	A	US-5,630,550	05-1997	Kurishige et al.	239/533.8
	B	US-2,721,100	10-1955	Bodine, Jr.	239/99
	C	US-4,750,706	06-1988	Schlagmuller, Walter	251/129.06
	D	US-6,311,950	11-2001	Kappel et al.	251/129.06
	E	US-6,313,568	11-2001	Sullivan et al.	310/346
	F	US-			
	G	US-			
	H	US-			
	I	US-			
	J	US-			
	K	US-			
	L	US-			
	M	US-			

FOREIGN PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Country	Name	Classification
	N					
	O					
	P					
	Q					
	R					
	S					
	T					

NON-PATENT DOCUMENTS

*		Include as applicable: Author, Title Date, Publisher, Edition or Volume, Pertinent Pages)
	U	
	V	
	W	
	X	

*A copy of this reference is not being furnished with this Office action. (See MPEP § 707.05(a).)
Dates in MM-YYYY format are publication dates. Classifications may be US or foreign.



Attorney Docket No. 12541US03

3747

Drwg
H6/A
2/27/03
W. Brewer

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

PATENT APPLICATION OF:

ALAN B. WELCH
IRAWAN RAHARDJA and
MICHAEL HEBBES

SERIAL NO. 09/863,187

FILED: May 23, 2001

FOR: DIRECTLY ACTUATED
INJECTION, VALVE

Group Art Unit 3747

Examiner M. Gimie

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FEB 26 2003

TECHNOLOGY CENTER R3700

AMENDMENT AND REQUEST FOR RECONSIDERATION

Commissioner of Patents
Washington, D.C. 20231

Sir:

This Amendment and Request for Reconsideration is submitted in response to the Office Action dated November 14, 2002. A marked-up version of the abstract and specification (insertions underlined; deletions bracketed) is attached as Appendix A. Appendix B hereto contains the substitute formal drawings. Appendix C hereto contains a version of the substitute formal drawings with the added reference numerals shown in red.



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FEB 26 2003

TECHNOLOGY CENTER R3700

IN THE DRAWINGS:

Please substitute the five (5) sheet(s) of formal drawings containing FIG. 1, FIG. 2, FIGS. 2a and 2b, FIG. 3, and FIG. 4, respectively, for the five (5) sheets of informal drawings presently of record in the present application.

IN THE ABSTRACT:

Please substitute the following abstract for that presently of record in the present application, as follows:

A directly actuated injection valve comprises a hollow valve housing, a valve member disposed within the hollow interior, a biasing mechanism, an actuator assembly and a passive hydraulic link assembly. The valve member is movable between a closed position and an open position for governing the flow of fuel into the combustion chamber of an internal combustion engine. The biasing mechanism, preferably a spring, biases the valve member in the closed position. The actuator assembly generates an opening force that acts against the valve spring to open the valve. The hydraulic link assembly is interposed between the valve member and the valve spring and the actuator assembly. The hydraulic link assembly transmits respective closing and opening forces to the valve member. The hydraulic link preferably comprises a piston disposed within a cylinder that is filled with a hydraulic fluid.

IN THE SPECIFICATION:

Please amend the paragraph in the "Cross-Reference to Related Application(s)" section of the specification at page 1, lines 2-13, to read as follows:

Cross-Reference to Related Application(s)

5 *az*
This application is a continuation-in-part
of U.S. Patent Application Serial No. 09/522,130
filed March 9, 2000, entitled "Directly Actuated
Injection Valve", now U.S. Patent No. 6,298,829
issued October 9, 2001. The '130 application
relates to and claims priority benefits from U.S.
Provisional Patent Application Serial No.
10 60/159,791 filed October 15, 1999, entitled
"Directly Actuated Injector". The '130
application and the '791 application are each
incorporated herein by reference in their
entirety.

REMARKS

Claims 1-41 remain pending in the present application.

Amendments to the Drawings

As to the drawing objection set forth in the November 14, 2002 Office Action, five (5) sheets of formal drawings containing FIG. 1, FIG. 2, FIGs. 2a and 2b, FIG. 3, and FIG. 4, respectively, have been substituted for the five (5) sheets of informal drawings presently of record in the present

application. In the substitute drawings, reference numeral 100 has been added to designate the corresponding element in FIGs. 1 and 2, and reference numeral 202 has been added to designate the corresponding element in FIG. 2a, all as shown in Appendices B and C. Applicants submit that the written description in the specification, taken in combination with the drawings as originally filed, fully supports the substitute drawings, and that the substitute drawings submitted herewith overcome the drawing objection(s) set forth in the Office Action.

Amendments to the Abstract

The Abstract of the disclosure has been amended so as not to exceed 150 words in length, as set forth in Appendix A hereto, and as required in the Office Action.

Amendments to the Specification

The specification has been amended to insert the number and issue date of the patent that was granted from the application, Serial No. 09/522,130 filed March 9, 2000, of which the present application is a continuation-in-part.

Claim Rejections

In the Office Action dated November 14, 2002, claims 1-41 were rejected for obviousness under 35 U.S.C. §103(a) in view of

Kurishige U.S. Patent No. 5,630,550 (the '550 patent). The '550 patent discloses a fuel injection system that permits the use of a hydraulic control oil as a pressure transmitting medium in a hydraulically actuated injector. At column 3 of the '550 patent, beginning at line 25, Kurishige states,

It is an object of the present invention to provide a fuel injection system which permits the use of hydraulic control oil as a pressure transmitting medium for transmitting the driving force of a piezoelectric element to a needle valve.

The '550 patent thus distinguishes its fuel injection system from prior hydraulically actuated injection valve arrangements, such as the one illustrated in Figure 16 of the '550 patent. Like conventional fuel injectors, however, the fuel injector disclosed and claimed in the '550 patent relies upon the displacement and dynamic flow of hydraulic fluid to cause movement of the needle valve. For example, as shown in Figure 1 of the '550 patent, when a voltage is applied to piezoelectric element 8, it expands and displaces hydraulic oil from pressure control chamber 10. The hydraulic oil flows into cylinder 19 through inflow/outflow hole 22, thereby increasing the fluid pressure applied the opening pressure receiving section 6. The '550 patent describes the operation of this first embodiment at column 5, beginning at line 48.

The "dynamic" hydraulic system of the '550 patent is the same type of conventional hydraulically actuated injection valve discussed in the background portion of the present application at, for example, page 4, beginning at line 18:

Nearly all known direct fuel injection systems in internal combustion engines have been hydraulically actuated. These systems rely on a hydraulic fluid to provide the force that is needed to open an injection valve (or valves, when the engine comprises a plurality of combustion chambers). Accordingly, at typical engine operating speeds, hydraulically actuated injectors rely on rapid changes in the hydraulic fluid pressure to open and close the injection valve(s). An injection valve is typically opened by increasing the hydraulic fluid pressure and closed by reducing the hydraulic fluid pressure, such that the opening force applied to the injection valve is reduced, causing the valve to close. However, in the context of a conventional gaseous injection valve, hydraulic operation presents several drawbacks, including:

...

- delayed response of the system caused by time delays associated with the dynamic flow of the hydraulic fluid, the actuation of the electronic hydraulic valve

hardware and the movement of the needle that controls gas flow from the injection valve.

Moreover, the degree of controllability of the movement of the injection valve is low when the motive force is provided by a pressurized fluid rather than by a directly controllable source. In this respect, it is difficult to control lift, resulting in limited lift control capabilities when using hydraulically actuated injection valve with a double-spring configuration. Therefore, it is desirable to avoid the use of hydraulics to operate gaseous fuel injectors, particularly for high-speed engines.

A conventional "dynamic" hydraulic system, which relies upon the flow of hydraulic fluid to actuate a needle valve, is structurally and functionally distinguished from the applicants' "passive" hydraulic link. In a "dynamic" hydraulic system, the hydraulic fluid does not "act substantially as a solid with the thickness being substantially constant while the actuator assembly is actuated", as recited in claim 1 (subparagraph (e)), because the hydraulic fluid must flow from one chamber to another to cause needle movement. This is even acknowledged in the Office Action itself: "Kushige, et al, does not teach [that] the pressure transmitting fluid acts substantially as a solid."

The Office Action cited the description of preferred viscosity in the '550 patent as suggesting "that the fluid acts substantially as a solid". To the contrary, the '550 patent discloses an apparatus that relies upon the flow of hydraulic oil as a liquid from one chamber to another chamber in order move the valve needle between closed and open positions; The '550 patent describes the preferred viscosity of the hydraulic oil at, for example, column 6, beginning at line 32 (emphasis added):

The pressure transmitting medium is required to have a low saturated vapor pressure even under high temperature to control the generation of bubbles. Further, the medium provides lubrication for the needle valve 4 to move as well as it transfers pressure; therefore, the medium is also required to exhibit stable lubricating property for the needle valve 4 to move smoothly, i.e., stable viscosity coefficient against temperature changes. For these reasons, the liquid used for the pressure transmitting medium should be a lubricant such as engine oil and gear oil or hydraulic oil for a hydraulic circuit which do not reach the saturated vapor pressure at 200.degree. C. and atmospheric pressure to survive the operating temperature of the internal-combustion engine and which have good lubricating property.

By employing the engine oil, gear oil, or the hydraulic oil for a hydraulic circuit, the occurrence of bubbles in the pressure transmitting medium filled in the pressure control chamber 10 can be prevented and therefore the deterioration in the

pressure transmitting characteristic can be prevented even when, for example, the ambient temperature reaches 150.degree. C. to 200.degree. C. from continuous operation in an automotive internal-combustion engine. Moreover, an increase in the viscosity coefficient of the pressure transmitting medium can be controlled and the lubricating property can be maintained to ensure smooth operation of the piston 9 and the needle valve 4 even if the ambient temperature goes down to -30.degree. C. or less at the time of startup in a cold region.

Applicants therefore submit that the '550 patent cannot be interpreted as disclosing or suggesting that the hydraulic oil acts as a solid when the valve needle is actuated. Rather, the description of preferred viscosity in the '550 patent simply states that the hydraulic oil must be suitable to avoid the formation of bubbles and to provide favorable lubricating properties over a broad range of temperatures.

A major difference between a "dynamic" hydraulic system and a "passive" hydraulic system is the presence in dynamic hydraulic systems of fluid passages that allow the hydraulic fluid to flow during an actuation event (that is, inflow/outflow hole 22 in Figure 1 of the '550 patent). In passive hydraulic systems like the applicants', the hydraulic oil is substantially contained, thereby avoiding the flow of hydraulic fluid during an actuation event when the valve member is moving from a closed

position to an open position. As set forth in the present application at page 41, beginning at line 21, for example:

As previously discussed, because valve actuation occurs suddenly (on the order of 200 μ s), hydraulic fluid 164b does not have time to flow through the narrow clearance gap between piston 114b and hydraulic cylinder 160. Instead, hydraulic fluid 164b acts as a solid and transfers the movement of magnetostrictive member 130 to valve member 114 via piston 114b, causing valve member 114 to lift away from valve seat 112. Because injection valve 100 stays open for such a brief period (typically less than 3 milliseconds), as long as the viscosity of hydraulic fluid 164 is properly selected and the clearance gap is suitably sized, the flow of hydraulic fluid 164 through the clearance gap while injection valve 100 is open is insignificant so that any displacement caused by such flow is much less than the total displacement of valve member 114.

As to the method claims pending in the present application, the Office Action cited Figures 8A-8C and 13A-13B of the '550 patent as the basis for rejecting those claims. The '550 patent's method for controlling an injection valve employs a piezoelectric actuator and a needle element that moves inward

from the nozzle tip to open. The '550 patent describes and illustrates an "undesirable nonlinear relationship between a set valve opening period of time and an actual valve opening period of time". Figure 8A shows a difference between the desired "set valve opening period of time T1" and the "actual valve opening period of time T2", thus supporting the applicants' submission that a characteristic of conventional hydraulically actuated injection valves is a delay associated with the dynamic flow of hydraulic fluid. Figure 8A also shows a "bounce" effect when the stopper 4a collides with the cylinder main body (immediately after time T1) and when the needle valve 4 collides with the nozzle (immediately after time T3). Figures 8B and 8C of the '550 patent illustrate alternative strategies for controlling displacement of the needle valve with the objective of avoiding needle bounce by closing the valve immediately following the collision between stopper 4a and cylinder main body 41 (Figure 8B), or by starting to close the needle valve immediately preceding collision between stopper 4a and cylinder main body 41 (Figure 8C). Figures 13A and 13B of the '550 patent show Kurishige's preferred strategies for controlling applied voltage and displacement of a piezoelectric element.

The problem addressed and illustrated by Figures 8A-8C of the '550 patent is needle bounce and controlling the duration of

the injection event. Such problems are typically associated with hydraulically actuated injection valves, and the method of the '550 patent overcomes those problems as follows:

[The] step-up rate of the driving voltage applied to the piezoelectric element 8 is decreased immediately before the completion of the valve opening operation and the step-down rate is also decreased immediately before completion of the valve closing operation.

(Column 15, lines 8-43.) The objective of the '550 patent is thus to slow down the needle to avoid needle bounce when the inward moving needle strikes the needle stopper.

The applicants' claimed technique differs markedly from that disclosed in the '550 patent because of their important structural differences. Unlike the '550 patent's injection valve, the applicants' claimed injection valve employs a valve member that moves outwardly from the nozzle tip to the open position. The applicants' claimed directly actuated injection valve therefore contains no feature that corresponds to stopper 4a in the '550 patent. The valve element of the '550 patent moves between a closed position and an open position defined by the needle stopper. In the applicants' claimed technique, the movement of the valve member is defined by the controllable length of the actuator, and not by a stopper. For example, in

FIG. 4 of the present application, waveform A depicts an injection event with a larger valve member displacement than the injection event represented by waveform C. In the outward opening arrangement disclosed and claimed in the embodiments described in the present application, a mechanical stopper is not necessary to limit the travel of the valve member, so there is no problem with "bounce" due to collision of the actuated part with the stop upon opening the injection valve. In closing the applicants' injection valve, a negative current can be applied to rapidly contract the dimensionally-responsive actuator, followed by the application of a positive current immediately before the valve member is seated in the closed position.

Because the applicants' claimed actuator is used to control the "lift" of the valve member, claim 36, for example, in subparagraph (a), defines the claimed method as comprising:

initiating an injection event by rapidly increasing current to a magnitude that is known to correspond to a desired lift.

In the '550 patent, current is not controlled in this way because the needle stopper controls the degree of lift at a fixed constant.

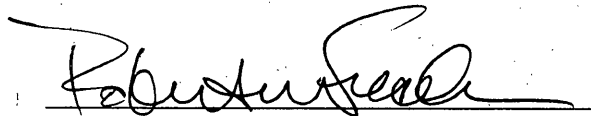
As to the concerns regarding common ownership set forth in paragraph 4 of the October 24, 2002 Office Action, applicants confirm that the subject matter of the various claims pending in the present application was commonly owned at the time they inventions covered therein were made.

* * * * *

In view of the foregoing amendments and remarks, applicants submit that claims 1-41 are allowable. The Examiner is invited to telephone the applicant's undersigned attorney at (312) 775-8123 if any unresolved matters remain.

Please charge any fees incurred in connection with this submission to Deposit Account No. 13-0017.

Respectfully submitted,



Robert W. Fieseler
Registration No. 31,826
Attorney for Applicants

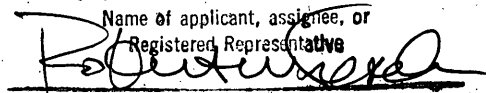
McANDREWS, HELD & MALLOY, LTD.
500 West Madison Street, 34th Floor
Chicago, Illinois 60661
Telephone (312) 775-8000
Facsimile (312) 775-8100

Dated: February 14, 2003

I hereby certify that this correspondence is being deposited with the United States Postal Service as first class-mail in an envelope addressed to: Commissioner of Patents and Trademarks, Washington, D.C. 20231, on 2-14-03
Date of Deposit

ROBERT W. FIESELER

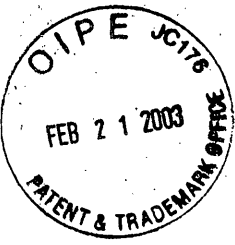
Name of applicant, assignee, or
Registered Representative



Signature

2-14-03

Date of Signature



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Attorney Docket No. 12541US03
Serial No. 09/863,187
Welch et al.
Group Art Unit 3747
Examiner M. Gimie

APPENDIX A

MARKED-UP VERSION SHOWING AMENDMENTS MADE

The Abstract has been amended as follows:

5 A directly actuated injection valve
comprises a hollow valve housing, a valve member
disposed within the hollow interior, a biasing
mechanism, an actuator assembly and a passive
hydraulic link assembly. The valve member is
movable between a closed position and an open
position for governing the flow of fuel into the
combustion chamber of an internal combustion
10 engine. The biasing mechanism, preferably a
spring, biases the valve member in the closed
position. The actuator assembly generates an
opening force that acts against the valve spring
to open the valve. The hydraulic link assembly
is interposed between the valve member and the
15 valve spring and the actuator assembly. The
hydraulic link assembly transmits respective
closing and opening forces to the valve member.
The hydraulic link preferably comprises a piston
disposed within a cylinder that is filled with a
20 hydraulic fluid. [The opening and closing forces
are transmitted through a thickness of the
hydraulic fluid that is trapped between the

planar surfaces of the piston and the head and
base of the hydraulic cylinder.]

The paragraph in the "Cross-Reference to Related
Application(s)" section of the specification at page 1, lines 5-
16 has been amended as follows:

Cross-Reference to Related Application(s)

This application is a continuation-in-part
of U.S. Patent Application Serial No. 09/522,130
filed March 9, 2000, entitled "Directly Actuated
Injection Valve", now U.S. Patent No. 6,298,829
issued October 9, 2001. The '130 application
relates to and claims priority benefits from U.S.
Provisional Patent Application Serial No.
60/159,791 filed October 15, 1999, entitled
"Directly Actuated Injector". The '130
application and the '791 application are each
incorporated herein by reference in their
entirety.

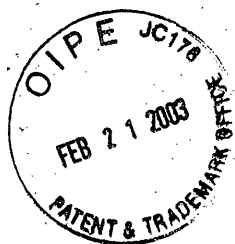


#6

Attorney Docket No. 12541US03
Serial No. 09/863,187
Alan B. Welch et al.
Group Art Unit 3747
Examiner M. Gimie

ATTACHMENT B
SUBSTITUTE FORMAL DRAWINGS

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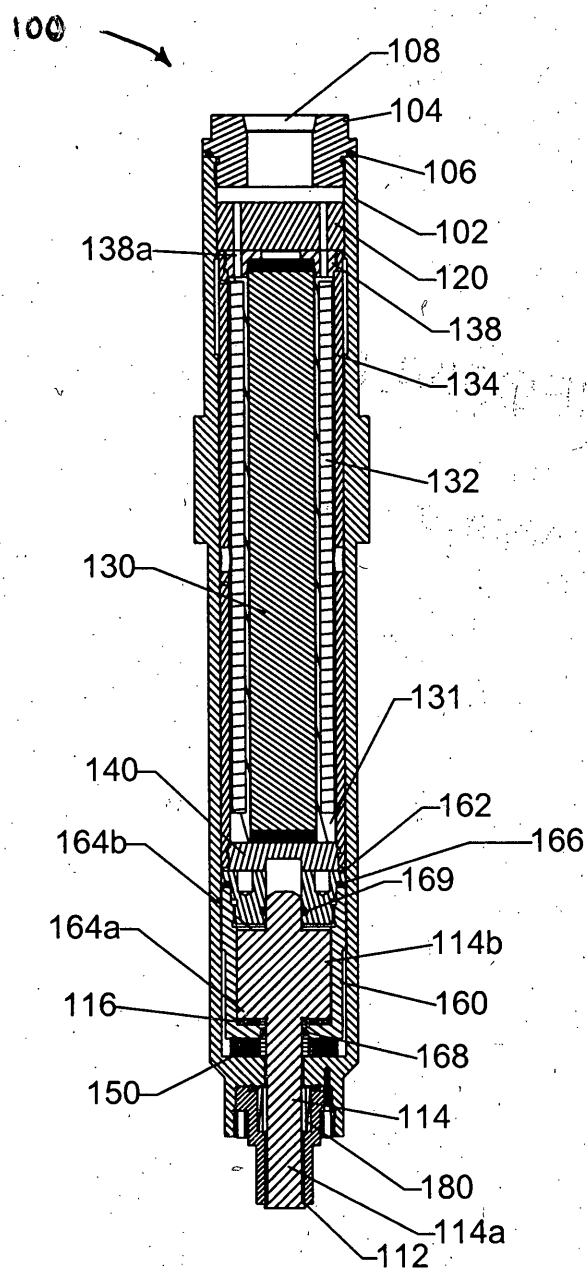


FIG. 1

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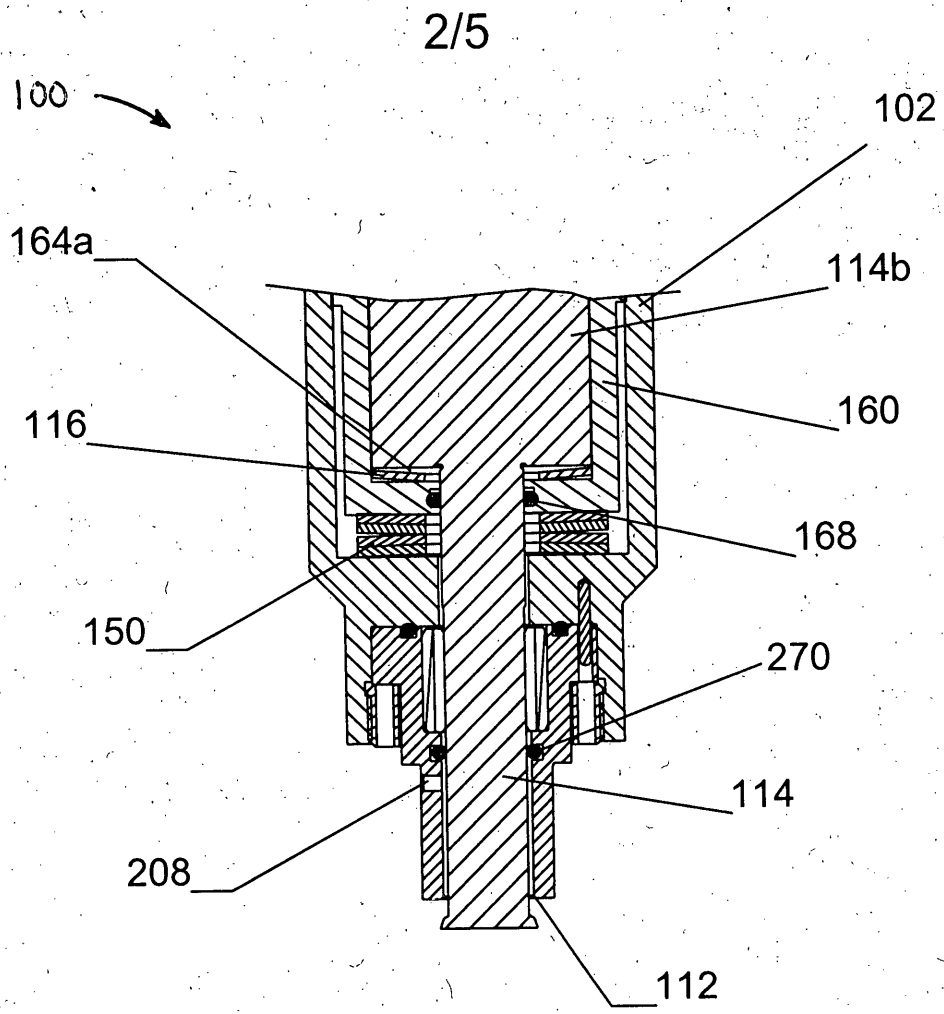
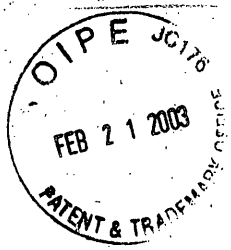
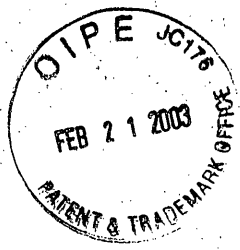


FIG. 2

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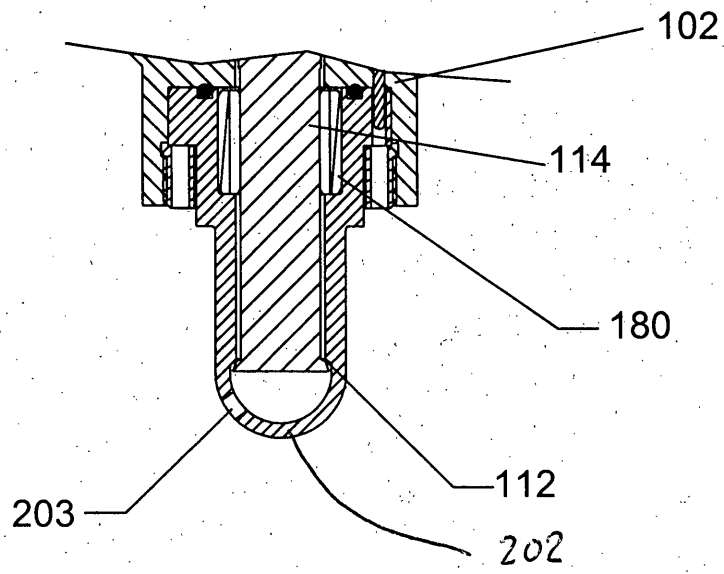


FIG. 2a

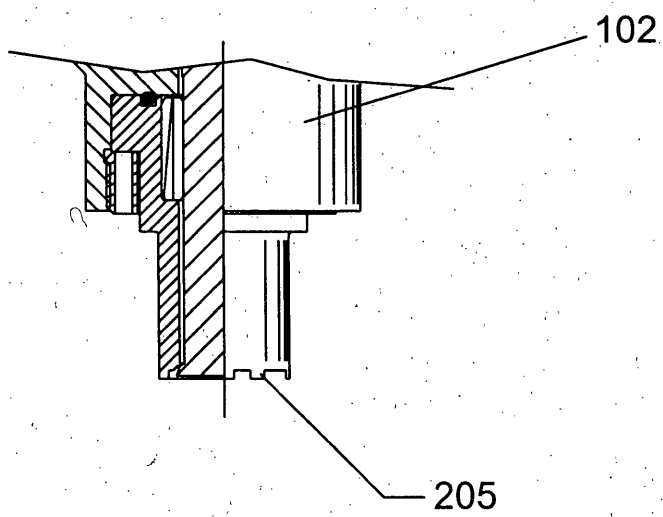
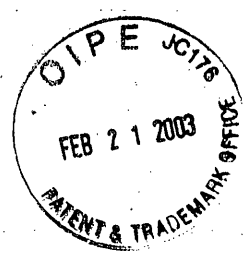


FIG. 2b

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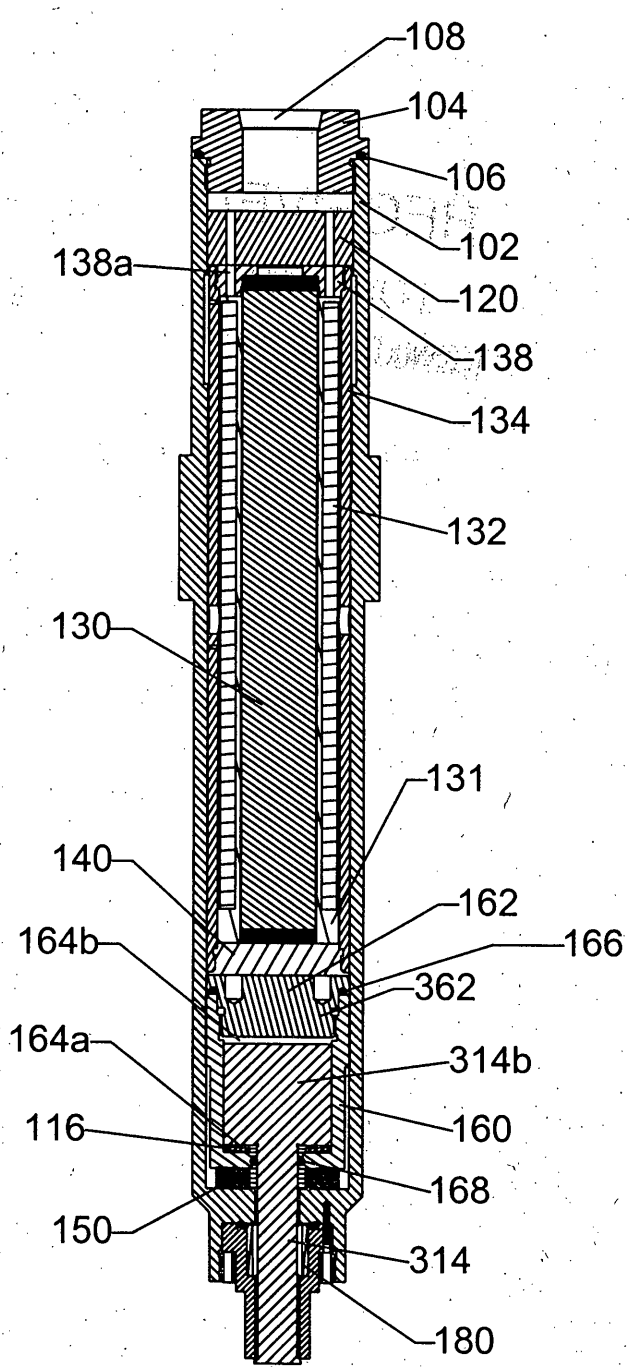


FIG. 3

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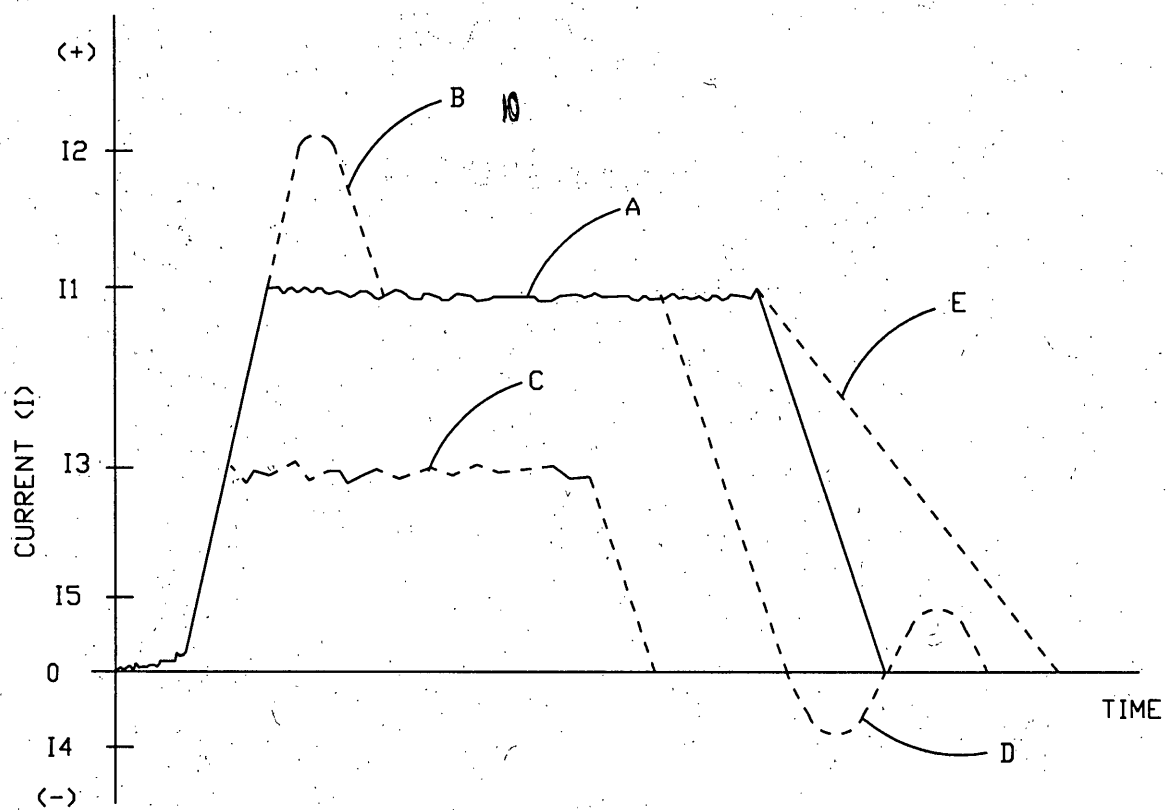


FIG. 4

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Attorney Docket No. 12541US03
Serial No. 09/863,187
Alan B. Welch et al.
Group Art Unit 3747
Examiner M. Gimie

ATTACHMENT C

SUBSTITUTE FORMAL DRAWINGS WITH
ADDED REFERENCE NUMERALS SHOWN IN RED

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Approved 3/5/03
WG

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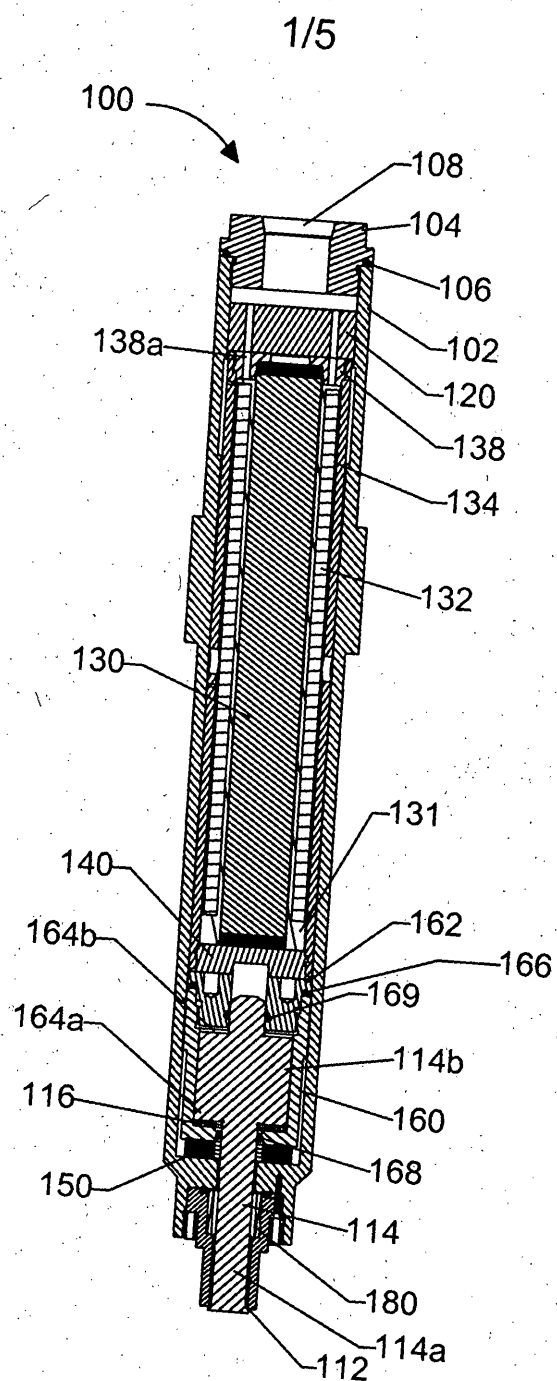


FIG. 1

(6)

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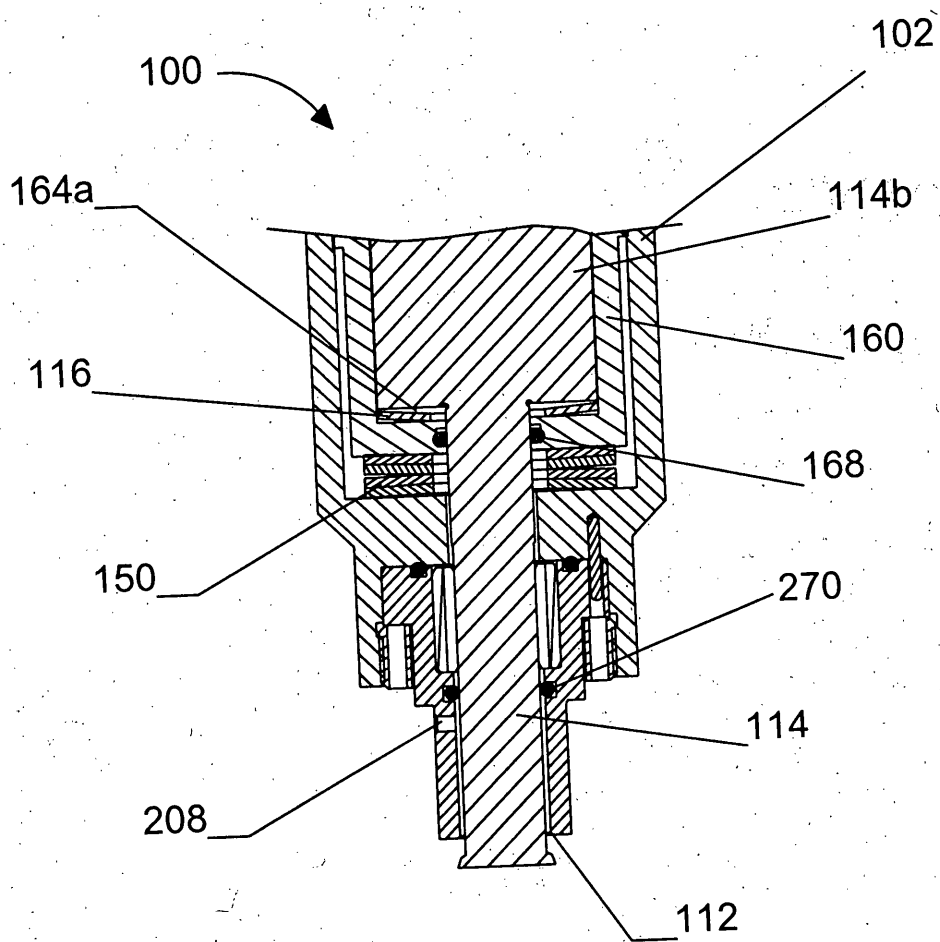
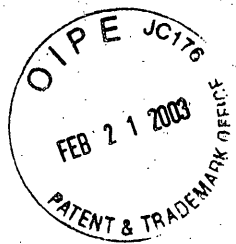


FIG. 2

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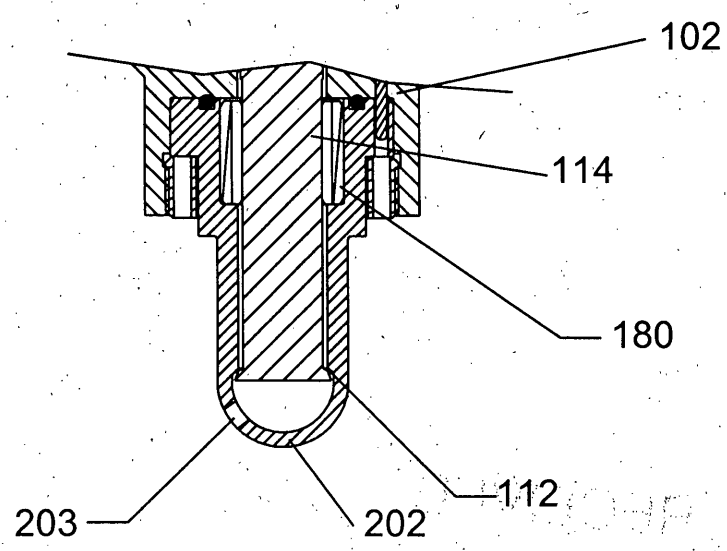


FIG. 2a

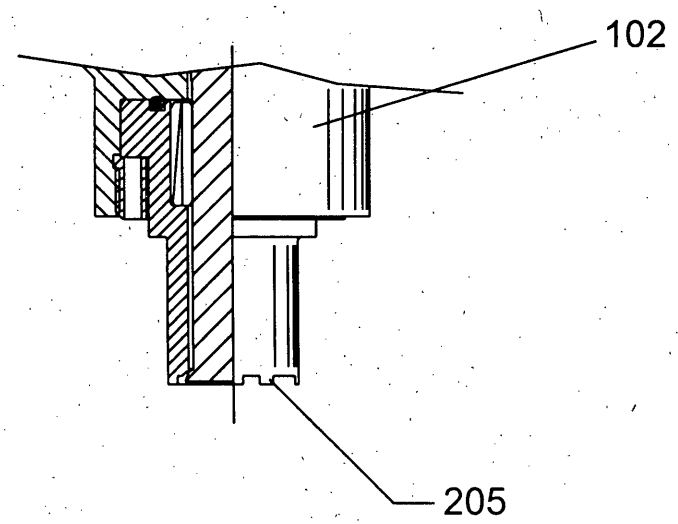
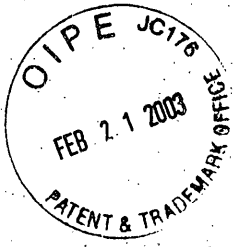


FIG. 2b

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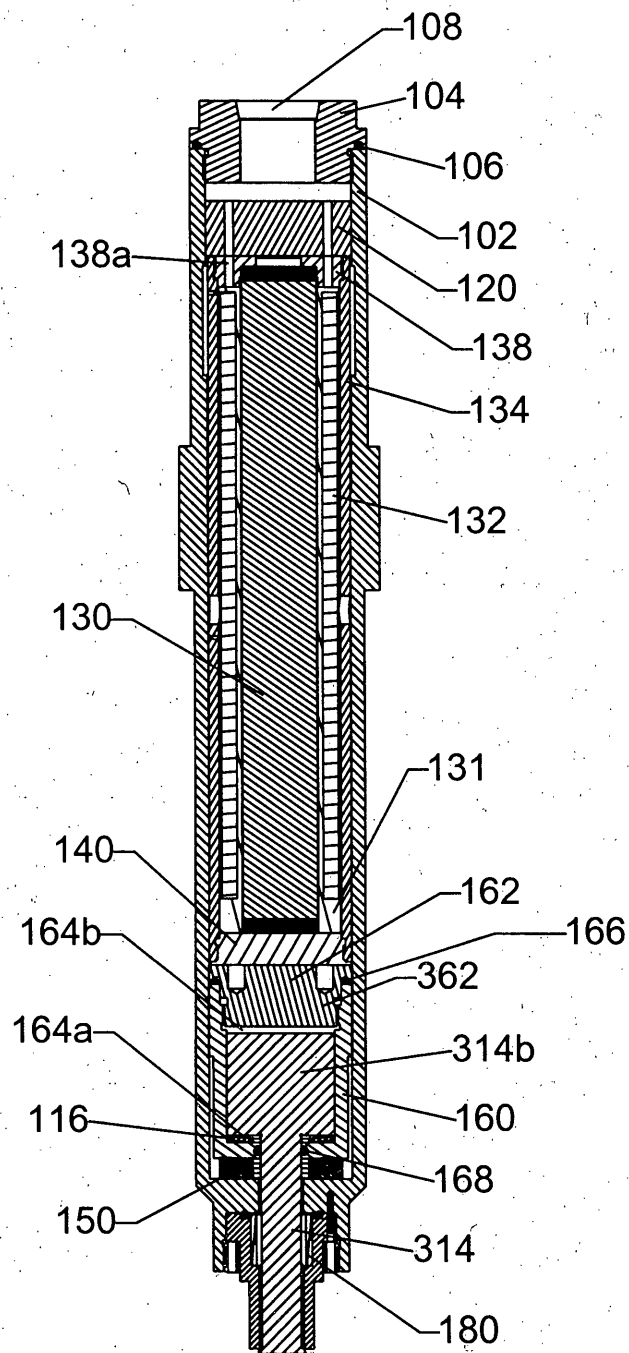
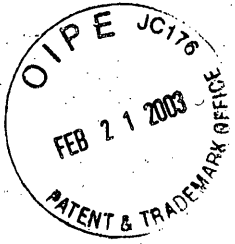


FIG. 3

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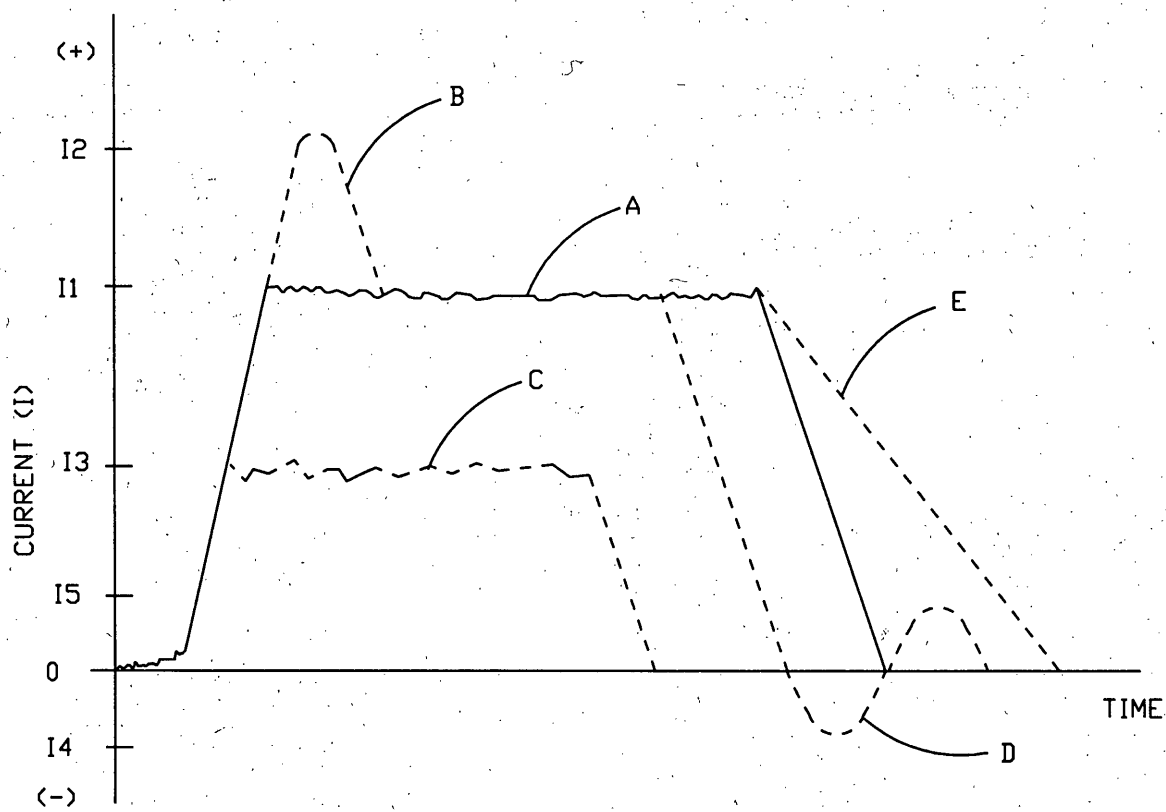


FIG. 4

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Notice of Allowability

Application No.

09/863,187

Applicant(s)

WELCH ET AL.

Examiner

Mahmoud M Gimie.

Art Unit

3747

-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address--

All claims being allowable, PROSECUTION ON THE MERITS IS (OR REMAINS) CLOSED in this application. If not included herewith (or previously mailed), a Notice of Allowance (PTOL-85) or other appropriate communication will be mailed in due course. **THIS NOTICE OF ALLOWABILITY IS NOT A GRANT OF PATENT RIGHTS.** This application is subject to withdrawal from issue at the initiative of the Office or upon petition by the applicant. See 37 CFR 1.313 and MPEP 1308.

1. ☒ This communication is responsive to amendment filed on 2/21/03.
2. ☒ The allowed claim(s) is/are 1-41.
3. ☒ The drawings filed on 21 February 2003 are accepted by the Examiner.
4. ☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).
a) ☐ All b) ☐ Some* c) ☐ None of the:
1. ☐ Certified copies of the priority documents have been received.
2. ☐ Certified copies of the priority documents have been received in Application No. _____.
3. ☐ Copies of the certified copies of the priority documents have been received in this national stage application from the International Bureau (PCT Rule 17.2(a)).

* Certified copies not received: _____

5. ☒ Acknowledgment is made of a claim for domestic priority under 35 U.S.C. § 119(e) (to a provisional application).
(a) ☐ The translation of the foreign language provisional application has been received.
6. ☐ Acknowledgment is made of a claim for domestic priority under 35 U.S.C. §§ 120 and/or 121.

Applicant has THREE MONTHS FROM THE "MAILING DATE" of this communication to file a reply complying with the requirements noted below. Failure to timely comply will result in ABANDONMENT of this application. **THIS THREE-MONTH PERIOD IS NOT EXTENDABLE**

7. ☐ A SUBSTITUTE OATH OR DECLARATION must be submitted. Note the attached EXAMINER'S AMENDMENT or NOTICE OF INFORMAL PATENT APPLICATION (PTO-152) which gives reason(s) why the oath or declaration is deficient.
8. ☐ CORRECTED DRAWINGS must be submitted.
(a) ☐ including changes required by the Notice of Draftsperson's Patent Drawing Review (PTO-948) attached
1) ☐ hereto or 2) ☐ to Paper No. _____.
(b) ☐ including changes required by the proposed drawing correction filed _____, which has been approved by the Examiner.
(c) ☐ including changes required by the attached Examiner's Amendment / Comment or in the Office action of Paper No. _____.

Identifying indicia such as the application number (see 37 CFR 1.84(c)) should be written on the drawings in the top margin (not the back) of each sheet. The drawings should be filed as a separate paper with a transmittal letter addressed to the Official Draftsperson.

9. ☐ DEPOSIT OF and/or INFORMATION about the deposit of BIOLOGICAL MATERIAL must be submitted. Note the attached Examiner's comment regarding REQUIREMENT FOR THE DEPOSIT OF BIOLOGICAL MATERIAL.

Attachment(s)

- | | |
|--|---|
| 1 ☐ Notice of References Cited (PTO-892) | 2 ☐ Notice of Informal Patent Application (PTO-152) |
| 3 ☐ Notice of Draftsperson's Patent Drawing Review (PTO-948) | 4 ☐ Interview Summary (PTO-413), Paper No. _____ |
| 5 ☐ Information Disclosure Statements (PTO-1449), Paper No. _____ | 6 ☐ Examiner's Amendment/Comment |
| 7 ☐ Examiner's Comment Regarding Requirement for Deposit of Biological Material | 8 ☒ Examiner's Statement of Reasons for Allowance |
| | 9 ☐ Other |

REASONS FOR ALLOWANCE

1. The following is an examiner's statement of reasons for allowance:

The primary reason for allowance of claims 1,29,36 and 41 is the inclusion of the limitations of

"A hydraulic link assembly comprising a passive hydraulic link having a hydraulic fluid thickness through which said opening and closing forces are transmitted, whereby said hydraulic fluid acts substantially as a solid with said thickness being substantially constant while said actuator assembly is actuated and wherein said thickness of said hydraulic link is adjustable while said actuator assembly is not actuated in response to changes in the dimensional relationship between components of said injection valve to maintain a desired valve lift upon actuation of said actuator assembly." in claim 1;

"A hydraulic link assembly comprising a fluidly sealed hydraulic cylinder disposed about said piston portion of said valve member, a hydraulic fluid disposed within said hydraulic cylinder, wherein said opening and closing forces applied to said valve member are transmitted through a thickness of said hydraulic fluid whereby said hydraulic fluid acts as a hydraulic link and said thickness is automatically adjustable in response to changes in the dimensional relationship between components of said injection valve to maintain a desired valve lift upon actuation of said actuator assembly." In claim 29;

"Initiating an injection event by rapidly increasing current to a magnitude that is known to correspond to a desired lift by applying high frequency voltage cycles and in each cycle maintaining a net positive voltage; concluding an injection event by decreasing current until it is reduced to zero amps by applying high frequency voltage cycles and in each cycle maintaining a net negative voltage." in claim 36; and

"Said passive hydraulic link comprising a hydraulic cylinder which houses a piston and is filled with a hydraulic fluid, wherein said hydraulic fluid forms a layer between said piston and a cylinder head and because of the short duration that said valve is open, said hydraulic fluid does not have time to flow from one side of said piston to the other side and while said injection valve is open, said layer of hydraulic fluid acts as an incompressible solid so that movement caused by the actuation of said dimensionally responsive member is transmitted through said fluid layer" in claim 41 that the prior art of record neither taught nor suggested.

Any comments considered necessary by applicant must be submitted no later than the payment of the issue fee and, to avoid processing delays, should preferably

Application/Control Number: 09/863,187

Page 3

Art Unit: 3747

accompany the issue fee. Such submissions should be clearly labeled "Comments on Statement of Reasons for Allowance."

Any inquiry concerning this communication or earlier communications from the examiner should be directed to Mahmoud M Gimie whose telephone number is 703-305-1037. The examiner can normally be reached on 7 a.m. -3:30 p.m.

If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, Henry Yuen can be reached on 703-308-1946. The fax phone numbers for the organization where this application or proceeding is assigned are 703-872-9302 for regular communications and 703-872-9302 for After Final communications.

Any inquiry of a general nature or relating to the status of this application or proceeding should be directed to the receptionist whose telephone number is 703-308-0861.



Mahmoud M Gimie
Examiner
Art Unit 3747

M Gimie, Examiner
March 6, 2003



UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER OF PATENTS AND TRADEMARKS
Washington, D.C. 20231
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NOTICE OF ALLOWANCE AND FEE(S) DUE

7590 03/07/2003

Robert W. Fieseler
McAndrews, Held & Malloy, Ltd.
34th Floor
500 West Madison Street
Chicago, IL 60661

EXAMINER

GIMIE, MAHMOUD

ART UNIT CLASS-SUBCLASS

3747

123-467000

DATE MAILED: 03/07/2003

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
09/863,187	05/23/2001	Alan B. Welch	12541US03	2084

TITLE OF INVENTION: DIRECTLY ACTUATED INJECTION VALVE

APPLN. TYPE	SMALL ENTITY	ISSUE FEE	PUBLICATION FEE	TOTAL FEE(S) DUE	DATE DUE
nonprovisional	NO	\$1300	\$300	\$1600	06/09/2003

THE APPLICATION IDENTIFIED ABOVE HAS BEEN EXAMINED AND IS ALLOWED FOR ISSUANCE AS A PATENT. **PROSECUTION ON THE MERITS IS CLOSED.** THIS NOTICE OF ALLOWANCE IS NOT A GRANT OF PATENT RIGHTS. THIS APPLICATION IS SUBJECT TO WITHDRAWAL FROM ISSUE AT THE INITIATIVE OF THE OFFICE OR UPON PETITION BY THE APPLICANT. SEE 37 CFR 1.313 AND MPEP 1308.

THE ISSUE FEE AND PUBLICATION FEE (IF REQUIRED) MUST BE PAID WITHIN THREE MONTHS FROM THE MAILING DATE OF THIS NOTICE OR THIS APPLICATION SHALL BE REGARDED AS ABANDONED. **THIS STATUTORY PERIOD CANNOT BE EXTENDED.** SEE 35 U.S.C. 151. THE ISSUE FEE DUE INDICATED ABOVE REFLECTS A CREDIT FOR ANY PREVIOUSLY PAID ISSUE FEE APPLIED IN THIS APPLICATION. THE PTOL-85B (OR AN EQUIVALENT) MUST BE RETURNED WITHIN THIS PERIOD EVEN IF NO FEE IS DUE OR THE APPLICATION WILL BE REGARDED AS ABANDONED.

HOW TO REPLY TO THIS NOTICE:

I. Review the SMALL ENTITY status shown above.

If the SMALL ENTITY is shown as YES, verify your current SMALL ENTITY status:

A. If the status is the same, pay the TOTAL FEE(S) DUE shown above.

B. If the status is changed, pay the PUBLICATION FEE (if required) and twice the amount of the ISSUE FEE shown above and notify the United States Patent and Trademark Office of the change in status, or

If the SMALL ENTITY is shown as NO:

A. Pay TOTAL FEE(S) DUE shown above, or

B. If applicant claimed SMALL ENTITY status before, or is now claiming SMALL ENTITY status, check the box below and enclose the PUBLICATION FEE and 1/2 the ISSUE FEE shown above.

☐ Applicant claims SMALL ENTITY status.
See 37 CFR 1.27.

II. PART B - FEE(S) TRANSMITTAL should be completed and returned to the United States Patent and Trademark Office (USPTO) with your ISSUE FEE and PUBLICATION FEE (if required). Even if the fee(s) have already been paid, Part B - Fee(s) Transmittal should be completed and returned. If you are charging the fee(s) to your deposit account, section "4b" of Part B - Fee(s) Transmittal should be completed and an extra copy of the form should be submitted.

III. All communications regarding this application must give the application number. Please direct all communications prior to issuance to Box ISSUE FEE unless advised to the contrary.

IMPORTANT REMINDER: Utility patents issuing on applications filed on or after Dec. 12, 1980 may require payment of maintenance fees. It is patentee's responsibility to ensure timely payment of maintenance fees when due.

PART B - FEE(S) TRANSMITTAL

Complete and send this form, together with applicable fee(s), to: **Mail** **Box ISSUE FEE**
Commissioner for Patents
Washington, D.C. 20231
Fax **(703)746-4000**

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CURRENT CORRESPONDENCE ADDRESS (Note: Legibly mark-up with any corrections or use Block 1)
7590 03/07/2003

Robert W. Fieseler
McAndrews, Held & Malloy, Ltd.
34th Floor
500 West Madison Street
Chicago, IL 60661

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Certificate of Mailing or Transmission
I hereby certify that this Fee(s) Transmittal is being deposited with the United States Postal Service with sufficient postage for first class mail in an envelope addressed to the Box Issue Fee address above, or being facsimile transmitted to the USPTO, on the date indicated below.

(Depositor's name)
(Signature)
(Date)

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
09/863,187	05/23/2001	Alan B. Welch	12541US03	2084

TITLE OF INVENTION: DIRECTLY ACTUATED INJECTION VALVE

APPLN. TYPE	SMALL ENTITY	ISSUE FEE	PUBLICATION FEE	TOTAL FEE(S) DUE	DATE DUE
nonprovisional	NO	\$1300	\$300	\$1600	06/09/2003

EXAMINER	ART UNIT	CLASS-SUBCLASS
GIMIE, MAHMOUD	3747	123-467000

1. Change of correspondence address or indication of "Fee Address" (37 CFR 1.363). ☐ Change of correspondence address (or Change of Correspondence Address form PTO/SB/122) attached. ☐ "Fee Address" indication (or "Fee Address" Indication form PTO/SB/47; Rev 03-02 or more recent) attached. Use of a Customer Number is required.	2. For printing on the patent front page, list (1) the names of up to 3 registered patent attorneys or agents OR, alternatively, (2) the name of a single firm (having as a member a registered attorney or agent) and the names of up to 2 registered patent attorneys or agents. If no name is listed, no name will be printed. 1 _____ 2 _____ 3 _____
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3. ASSIGNEE NAME AND RESIDENCE DATA TO BE PRINTED ON THE PATENT (print or type)
PLEASE NOTE: Unless an assignee is identified below, no assignee data will appear on the patent. Inclusion of assignee data is only appropriate when an assignment has been previously submitted to the USPTO or is being submitted under separate cover. Completion of this form is NOT a substitute for filing an assignment.
(A) NAME OF ASSIGNEE (B) RESIDENCE: (CITY and STATE OR COUNTRY)

Please check the appropriate assignee category or categories (will not be printed on the patent) ☐ individual ☐ corporation or other private group entity ☐ government

4a. The following fee(s) are enclosed: ☐ Issue Fee ☐ Publication Fee ☐ Advance Order - # of Copies _____	4b. Payment of Fee(s): ☐ A check in the amount of the fee(s) is enclosed. ☐ Payment by credit card. Form PTO-2038 is attached. ☐ The Commissioner is hereby authorized by charge the required fee(s), or credit any overpayment, to Deposit Account Number _____ (enclose an extra copy of this form).
--	--

Commissioner for Patents is requested to apply the Issue Fee and Publication Fee (if any) or to re-apply any previously paid issue fee to the application identified above.

(Authorized Signature)	(Date)
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UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER OF PATENTS AND TRADEMARKS
Washington, D.C. 20231
www.uspto.gov

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
-----------------	-------------	----------------------	---------------------	------------------

09/863,187

05/23/2001

Alan B. Welch

12541US03

2084

7590

03/07/2003

EXAMINER

GIMIE, MAHMOUD

ART UNIT

PAPER NUMBER

3747

DATE MAILED: 03/07/2003

Robert W. Fieseler
McAndrews, Held & Malloy, Ltd.
34th Floor
500 West Madison Street
Chicago, IL 60661

Determination of Patent Term Adjustment under 35 U.S.C. 154 (b)
(application filed on or after May 29, 2000)

The patent term adjustment to date is 107 days. If the issue fee is paid on the date that is three months after the mailing date of this notice and the patent issues on the Tuesday before the date that is 28 weeks (six and a half months) after the mailing date of this notice, the term adjustment will be 107 days.

If a continued prosecution application (CPA) was filed in the above-identified application, the filing date that determines patent term adjustment is the filing date of the most recent CPA.

Applicant will be able to obtain more detailed information by accessing the Patent Application Information Retrieval (PAIR) system. (<http://pair.uspto.gov>)

Any questions regarding the patent term extension or adjustment determination should be directed to the Office of Patent Legal Administration at (703)305-1383.



UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER OF PATENTS AND TRADEMARKS
Washington, D.C. 20231
www.uspto.gov

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
09/863,187	05/23/2001	Alan B. Welch	12541US03	2084
7590	03/07/2003		EXAMINER	
Robert W. Fieseler McAndrews, Held & Malloy, Ltd. 34th Floor 500 West Madison Street Chicago, IL 60661 UNITED STATES			GIMIE, MAHMOUD	
			ART UNIT	PAPER NUMBER
			3747	
DATE MAILED: 03/07/2003				

Notice of Fee Increase on January 1, 2003

If a reply to a "Notice of Allowance and Fee(s) Due" is filed in the Office on or after January 1, 2003, then the amount due will be higher than that set forth in the "Notice of Allowance and Fee(s) Due" since there will be an increase in fees effective on January 1, 2003. See Revision of Patent and Trademark Fees for Fiscal Year 2003; Final Rule, 67 Fed. Reg. 70847, 70849 (November 27, 2002).

The current fee schedule is accessible from: <http://www.uspto.gov/main/howtofees.htm>.

If the issue fee paid is the amount shown on the "Notice of Allowance and Fee(s) Due," but not the correct amount in view of the fee increase, a "Notice to Pay Balance of Issue Fee" will be mailed to applicant. In order to avoid processing delays associated with mailing of a "Notice to Pay Balance of Issue Fee," if the response to the Notice of Allowance and Fee(s) due form is to be filed on or after January 1, 2003 (or mailed with a certificate of mailing on or after January 1, 2003), the issue fee paid should be the fee that is required at the time the fee is paid. If the issue fee was previously paid, and the response to the "Notice of Allowance and Fee(s) Due" includes a request to apply a previously-paid issue fee to the issue fee now due, then the difference between the issue fee amount at the time the response is filed and the previously paid issue fee should be paid. See Manual of Patent Examining Procedure, Section 1308.01 (Eighth Edition, August 2001).

Questions relating to issue and publication fee payments should be directed to the Customer Service Center of the Office of Patent Publication at (703) 305-8283.

PART B - FEE(S) TRANSMITTAL

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Washington, D.C. 20231
Fax (703)746-4000

INSTRUCTIONS: This form should be used for transmitting the ISSUE FEE and PUBLICATION FEE (if required). Blocks 1 through 4 should be completed where appropriate. All further correspondence including the Patent, advance order and notification of maintenance fees will be mailed to the current correspondence address as indicated unless corrected below or directed otherwise in Block 1, by (a) specifying a new correspondence address; and/or (b) indicating a separate "FEE ADDRESS" for maintenance fee notifications.

CURRENT CORRESPONDENCE ADDRESS (Note: Legibly print-up. With any correction of this Block 1)

7590 03/07/2003
Robert W. Fieseler
McAndrews, Held & Malloy, Ltd.
34th Floor
500 West Madison Street
Chicago, IL 60661



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Robert W. Fieseler (Depositor's name)
[Signature] (Signature)
March 28, 2003 (Date)

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
09/863,187	05/23/2001	Alan B. Welch	12541US03	2084

TITLE OF INVENTION: DIRECTLY ACTUATED INJECTION VALVE

APPLN. TYPE	SMALL ENTITY	ISSUE FEE	PUBLICATION FEE	TOTAL FEE(S) DUE	DATE DUE
nonprovisional	NO	\$1300	\$300	\$1600	06/09/2003

EXAMINER	ART UNIT	CLASS-SUBCLASS
GIMIB, MAHMOUD	3747	123-467000

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McAndrews, Held &
Malloy, Ltd.
2 _____
3 _____

3. ASSIGNEE NAME AND RESIDENCE DATA TO BE PRINTED ON THE PATENT (print or type)

PLEASE NOTE: Unless an assignee is identified below, no assignee data will appear on the patent. Inclusion of assignee data is only appropriate when an assignment has been previously submitted to the USPTO or is being submitted under separate cover. Completion of this form is NOT a substitute for filing an assignment.

(A) NAME OF ASSIGNEE

Westport Research Inc.

(B) RESIDENCE: (CITY and STATE OR COUNTRY)

Vancouver, BC, Canada

Please check the appropriate assignee category or categories (will not be printed on the patent) ☐ individual ☒ corporation or other private group entity ☐ government

4a. The following fee(s) are enclosed:

- ☒ Issue Fee
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- ☒ A check in the amount of the fee(s) is enclosed.
☐ Payment by credit card. Form PTO-2038 is attached.

☒ The Commissioner is hereby authorized by charge the required fee(s), or credit any overpayment, to Deposit Account Number 13-0017 (enclose an extra copy of this form).

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(Authorized Signature)

[Signature]

(Date)

3/28/03

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04/07/2003 SSITHIB2 00000087 09863187

01 FC:1501
02 FC:1504

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PTOL-85 (REV. 04-02) Approved for use through 01/31/2004. OMB 0651-0033

U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE

File History Content Report

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Document Date - 2003-06-10
Document Title - USPTO Grant

File History Content Report

The following content is missing from the original file history record obtained from the United States Patent and Trademark Office. No additional information is available.

Document Date - 2012-07-23

Document Title - USPTO Communication Re: Change of Address

File History Content Report

The following content is missing from the original file history record obtained from the United States Patent and Trademark Office. No additional information is available.

Document Date - 2012-07-24
Document Title - USPTO Communication Re: Power of Attorney

File History Content Report

The following content is missing from the original file history record obtained from the United States Patent and Trademark Office. No additional information is available.

Document Date - 2015-01-27
Document Title - USPTO Communication Re: Change of Address

File History Content Report

The following content is missing from the original file history record obtained from the United States Patent and Trademark Office. No additional information is available.

Document Date - 2017-03-31

Document Title - USPTO Communication Re: Change of Address

PATENT APPLICATION FEE DETERMINATION RECORD

Effective October 1, 2000

Application or Docket Number

125414503

CLAIMS AS FILED - PART I

(Column 1) (Column 2)

TOTAL CLAIMS	41	
FOR	NUMBER FILED	NUMBER EXTRA
TOTAL CHARGEABLE CLAIMS	41 minus 20 =	21
INDEPENDENT CLAIMS	4 minus 3 =	1
MULTIPLE DEPENDENT CLAIM PRESENT ☐		

* If the difference in column 1 is less than zero, enter "0" in column 2

CLAIMS AS AMENDED - PART II

(Column 1) (Column 2) (Column 3)

AMENDMENT A		CLAIMS REMAINING AFTER AMENDMENT		HIGHEST NUMBER PREVIOUSLY PAID FOR	PRESENT EXTRA
	Total	*	Minus	**	=
	Independent	*	Minus	***	=
	FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM ☐				

SMALL ENTITY
TYPE ☐

OR

OTHER THAN
SMALL ENTITY

RATE	FEE
BASIC FEE	355.00
X\$ 9=	
X40=	
+135=	
TOTAL	

OR

RATE	FEE
BASIC FEE	710.00
X\$18=	378.00
X80=	80.00
+270=	
TOTAL	1168.00

CLAIMS AS AMENDED - PART II

(Column 1) (Column 2) (Column 3)

AMENDMENT B		CLAIMS REMAINING AFTER AMENDMENT		HIGHEST NUMBER PREVIOUSLY PAID FOR	PRESENT EXTRA
	Total	*	Minus	**	=
	Independent	*	Minus	***	=
	FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM ☐				

SMALL ENTITY

OR

OTHER THAN
SMALL ENTITY

RATE	ADDI- TIONAL FEE
X\$ 9=	
X40=	
+135=	
TOTAL ADDIT. FEE	

OR

RATE	ADDI- TIONAL FEE
X\$18=	
X80=	
+270=	
TOTAL ADDIT. FEE	

(Column 1) (Column 2) (Column 3)

AMENDMENT C		CLAIMS REMAINING AFTER AMENDMENT		HIGHEST NUMBER PREVIOUSLY PAID FOR	PRESENT EXTRA
	Total	*	Minus	**	=
	Independent	*	Minus	***	=
	FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM ☐				

RATE	ADDI- TIONAL FEE
X\$ 9=	
X40=	
+135=	
TOTAL ADDIT. FEE	

OR

RATE	ADDI- TIONAL FEE
X\$18=	
X80=	
+270=	
TOTAL ADDIT. FEE	

(Column 1) (Column 2) (Column 3)

AMENDMENT C		CLAIMS REMAINING AFTER AMENDMENT		HIGHEST NUMBER PREVIOUSLY PAID FOR	PRESENT EXTRA
	Total	*	Minus	**	=
	Independent	*	Minus	***	=
	FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM ☐				

RATE	ADDI- TIONAL FEE
X\$ 9=	
X40=	
+135=	
TOTAL ADDIT. FEE	

OR

RATE	ADDI- TIONAL FEE
X\$18=	
X80=	
+270=	
TOTAL ADDIT. FEE	

* If the entry in column 1 is less than the entry in column 2, write "0" in column 3.

** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 20, enter "20."

*** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 3, enter "3."

The "Highest Number Previously Paid For" (Total or Independent) is the highest number found in the appropriate box in column 1.

CLAIMS ONLY

SERIAL NO.	09863187	FILING DATE
APPLICANT(S)		

CLAIMS

	AS FILED		AFTER 1st AMENDMENT		AFTER 2nd AMENDMENT	
	IND.	DEP.	IND.	DEP.	IND.	DEP.
1	1					
2		1				
3		1				
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TOTAL IND.	4					
TOTAL DEP.	37					
TOTAL CLAIMS	41					

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	IND.	DEP.	IND.	DEP.	IND.	DEP.
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TOTAL IND.						
TOTAL DEP.						
TOTAL CLAIMS						

* MAY BE USED FOR ADDITIONAL CLAIMS OR ADMENDMENTS

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Search results for: PNS=(US6575138);

Collections searched: DWPI; ARIPO grant; Argentina UM; Argentina app; Armenia grant; Australia UM; Australia app; Australia grant; Austria UM; Austria app; Austria grant; Belarus UM; Belarus grant; Belgium app; Belgium grant; Brazil UM; Brazil app; Brazil grant; Bulgaria UM; Bulgaria app; Bulgaria grant; Canada app; Canada grant; China, Mainland UM; China, Mainland app; China, Mainland grant; Colombia app; Costa Rica UM; Costa Rica app; Croatia UM; Croatia app; Croatia grant; Cuba app; Cuba grant; Czech Republic UM; Czech Republic app; Czech Republic grant; Czechoslovakia grant; Denmark UM; Denmark app; Denmark grant; Estonia UM; Estonia app; Estonia grant; Eurasian (EAPO) grant; Europe (EP) app; Europe (EP) grant; Finland app; Finland grant; France app; France grant; Georgia grant; German Democratic Republic app; German Democratic Republic grant; Germany UM; Germany app; Germany grant; Greece app; Greece grant; Gulf Cooperation Council grant; Hong Kong UM; Hong Kong app; Hong Kong grant; Hungary grant; Iceland grant; India app; India grant; Indonesia UM; Indonesia app; Ireland UM; Ireland app; Ireland grant; Israel grant; Italy grant; Italy grant; Italy grant; Italy grant; Japan UM; Japan app; Japan grant; Korea UM; Korea app; Korea grant; Latvia grant; Lithuania grant; Luxembourg app; Luxembourg grant; Malaysia app; Malaysia grant; Mexico app; Mexico grant; Moldova UM; Moldova grant; Monaco grant; Mongolia UM; Mongolia grant; Morocco app; Morocco grant; Netherlands app; Netherlands grant; New Zealand grant; Norway app; Norway grant; OAPI grant; PCT (WO) app; Philippines UM; Philippines app; Philippines grant; Poland UM; Poland grant; Portugal UM; Portugal app; Portugal grant; Romania UM; Romania app; Romania granted; Russia UM; Russia app; Russia grant; Serbia UM; Serbia app; Serbia grant; Singapore app; Singapore grant; Slovakia UM; Slovakia app; Slovakia grant; Slovenia UM; Slovenia grant; South Africa app; Spain UM; Spain app; Spain grant; Sweden app; Sweden grant; Switzerland app; Switzerland grant; Taiwan UM; Taiwan appl; Taiwan grant; Thailand UM; Thailand app; Thailand grant; Tunisia app; Turkey UM; Turkey app; Turkey grant; UK app; UK grant; USSR grant; Ukraine UM; Ukraine grant; United States app; United States grant; Uruguay app; Vietnam UM; Vietnam app; Vietnam grant; Other

Table of Contents

- 1. US6575138B2 Directly actuated injection valve
-

Family 1/1

1 record(s) per family

Record 1/1 US6575138B2 Directly actuated injection valve

Title: Directly actuated injection valve

Title - DWPI: Injection valve for injecting fuel into a combustion chamber of an IC engine, has housing, valve member, biasing mechanism, actuator assembly and hydraulic link assembly

Priority Number: US1999159791P | US2000522130A

Priority Date: 1999-10-15 | 2000-03-09

Application Number: US2001863187A

Application Date: 2001-05-23

Publication Date: 2003-06-10

IPC Class Table:

IPC	Section	Class	Subclass	Class Group	Subgroup
F02M005100	F	F02	F02M	F02M0051	F02M005100
F02D004120	F	F02	F02D	F02D0041	F02D004120
F02M002102	F	F02	F02M	F02M0021	F02M002102
F02M004700	F	F02	F02M	F02M0047	F02M004700
F02M004704	F	F02	F02M	F02M0047	F02M004704
F02M005106	F	F02	F02M	F02M0051	F02M005106
F02M006108	F	F02	F02M	F02M0061	F02M006108
F02M006110	F	F02	F02M	F02M0061	F02M006110
F02M006116	F	F02	F02M	F02M0061	F02M006116
F02M006300	F	F02	F02M	F02M0063	F02M006300

IPC Class Table - DWPI:

IPC - DWPI	Section - DWPI	Class - DWPI	Subclass - DWPI	Class Group - DWPI	Subgroup - DWPI
F02M004702 (IPC 1-7)	F	F02	F02M	F02M0047	F02M004702 (IPC 1-7)
F02M005106 (IPC	F	F02	F02M	F02M0051	F02M005106 (IPC

1-7)					1-7)
F02M005946 (IPC 1-7)	F	F02	F02M	F02M0059	F02M005946 (IPC 1-7)
F02M006116 (IPC 1-7)	F	F02	F02M	F02M0061	F02M006116 (IPC 1-7)
F02M006300 (IPC 1-7)	F	F02	F02M	F02M0063	F02M006300 (IPC 1-7)
F02D004120	F	F02	F02D	F02D0041	F02D004120
F02M002102	F	F02	F02M	F02M0021	F02M002102
F02M004700	F	F02	F02M	F02M0047	F02M004700
F02M004702	F	F02	F02M	F02M0047	F02M004702
F02M004704	F	F02	F02M	F02M0047	F02M004704
F02M005100	F	F02	F02M	F02M0051	F02M005100
F02M005106	F	F02	F02M	F02M0051	F02M005106
F02M005946	F	F02	F02M	F02M0059	F02M005946
F02M006108	F	F02	F02M	F02M0061	F02M006108
F02M006110	F	F02	F02M	F02M0061	F02M006110
F02M006116	F	F02	F02M	F02M0061	F02M006116
F02M006300	F	F02	F02M	F02M0063	F02M006300

Assignee/Applicant: Westport Research Inc.,Vancouver,CA

JP F Terms:

JP FI Codes:

Assignee - Original: Westport Research Inc.

Any CPC Table:

Type	Invention	Additional	Version	Office
Current	F02D 41/20	F02B 2275/14	20130101	EP; US
Current	F02M 21/0254	F02D 41/2096	20130101	EP; US
Current	F02M 21/0269	F02D 2041/2037	20130101	EP; US
Current	F02M 51/005	F02M 2200/30	20130101	EP; US
Current	F02M 51/0603	F02M 2200/304	20130101	EP; US
Current	F02M 51/0607	F02M 2200/507	20130101	EP; US
Current	F02M 61/08	Y02T 10/12	20130101	EP; US
Current	F02M 61/10	Y02T 10/30	20130101	EP; US
Current	F02M 61/166		20130101	EP; US
Current	F02M 61/167		20130101	EP; US

Original	F02D 41/20	F02B 2275/14	20130101	US
Original	F02M 21/0254	F02D 41/2096	20130101	US
Original	F02M 21/0269	F02D 2041/2037	20130101	US
Original	F02M 51/005	F02M 2200/30	20130101	US
Original	F02M 51/0603	F02M 2200/304	20130101	US
Original	F02M 51/0607	F02M 2200/507	20130101	US
Original	F02M 61/08	Y02T 10/12	20130101	US
Original	F02M 61/10	Y02T 10/30	20130101	US
Original	F02M 61/166		20130101	US
Original	F02M 61/167		20130101	US

ECLA: F02D004120 | F02M002102S10 | F02M005100C | F02M005106A | F02M005106A2 | F02M006108 | F02M006110 | F02M006116F | F02M006116G | R02D004120P | R02B027514 | R02D004120C6 | R02M020030 | R02M020030H | R02M020050C

Abstract:

A directly actuated injection valve comprises a hollow valve housing, a valve member disposed within the hollow interior, a biasing mechanism, an actuator assembly and a passive hydraulic link assembly. The valve member is movable between a closed position and an open position for governing the flow of fuel into the combustion chamber of an internal combustion engine. The biasing mechanism, preferably a spring, biases the valve member in the closed position. The actuator assembly generates an opening force that acts against the valve spring to open the valve. The hydraulic link assembly is interposed between the valve member and the valve spring and the actuator assembly. The hydraulic link assembly transmits respective closing and opening forces to the valve member. The hydraulic link preferably comprises a piston disposed within a cylinder that is filled with a hydraulic fluid.

Language of Publication: EN

INPADOC Legal Status Table:

Gazette Date	Code	INPADOC Legal Status Impact
2021-07-16	AS	-
Description: ASSIGNMENT WESTPORT FUEL SYSTEMS CANADA INC., BRITISH COLUMBIA CHANGE OF NAME; ASSIGNOR:WESTPORT POWER INC.; REEL/FRAME:056898/0199 2021-03-31		
2021-06-09	AS	-
Description: ASSIGNMENT WESTPORT POWER INC., BRITISH COLUMBIA RELEASE BY SECURED PARTY; ASSIGNOR:CANADIAN IMPERIAL BANK OF COMMERCE; REEL/FRAME:056887/0499 2010-06-15		
2016-01-14	AS	-

Description: ASSIGNMENT PANGEA TWO MANAGEMENT, LP, NEW YORK SECURITY INTEREST; ASSIGNOR:WESTPORT POWER INC.; REEL/FRAME:037529/0579 2016-01-11		
2014-12-10	FPAY	+
Description: FEE PAYMENT FEE PAYMENT YEAR 12		
2010-12-10	FPAY	+
Description: FEE PAYMENT FEE PAYMENT YEAR 8		
2007-08-01	AS	-
Description: ASSIGNMENT WESTPORT POWER INC., CANADA RELEASE BY SECURED PARTY; ASSIGNOR:PERSEUS, L.L.C.; REEL/FRAME:019617/0680 2007-07-26		
2006-11-17	FPAY	+
Description: FEE PAYMENT FEE PAYMENT YEAR 4		
2006-09-21	AS	-
Description: ASSIGNMENT PERSEUS, L.L.C., DISTRICT OF COLUMBIA SECURITY AGREEMENT; ASSIGNOR:WESTPORT POWER INC; REEL/FRAME:018279/0449 2006-07-24		
2006-09-18	AS	-
Description: ASSIGNMENT CANADIAN IMPERIAL BANK OF COMMERCE, CANADA SECURITY AGREEMENT; ASSIGNOR:WESTPORT POWER INC; REEL/FRAME:018260/0357 2006-07-24		
2006-08-31	AS	-
Description: ASSIGNMENT WESTPORT POWER INC., CANADA ASSIGNMENT OF ASSIGNORS INTEREST; ASSIGNOR:WESTPORT RESEARCH INC.; REEL/FRAME:018184/0812 2006-08-16		
2003-05-21	STCF	-
Description: INFORMATION ON STATUS: PATENT GRANT PATENTED CASE		
2002-03-06	AS	-
Description: ASSIGNMENT WESTPORT RESEARCH INC., CANADA CORRECTIVE DOCUMENT TO CORRECT THE ORIGINAL ASSIGNMENT PREVIOUSLY RECORDED ON REEL 011943 FRAME 0881, ASSIGNOR CONFIRMS THE ASSIGNMENT OF THE ENTIRE INTEREST.; ASSIGNORS:WELCH, ALAN B.; RAHARDJA, IRAWAN; HEBBES, MIKE; REEL/FRAME:012679/0462 2001-12-18		
2001-06-29	AS	-
Description: ASSIGNMENT WESTPORT RESEARCH INC., CANADA ASSIGNMENT OF ASSIGNORS INTEREST;		

ASSIGNORS:WELCH, ALAN B.; RAHARDJA, IRAWAN; HEBBES, MIKE; REEL/FRAME:011943/0881 2001-06-20

Post-Issuance (US):

Reassignment (US) Table:

Assignee	Assignor	Date Signed	Reel/Frame	Date
WESTPORT FUEL SYSTEMS CANADA INC.,VANCOUVER,CA	WESTPORT POWER INC.	2021-03-31	056898/0199	2021-07-16
Conveyance: CHANGE OF NAME (SEE DOCUMENT FOR DETAILS).				
Corresponent: CAMERON KYLE 1750 75TH AVE W SUITE 101 VANCOUVER, BCC V6P 6G2				
PANGEA TWO MANAGEMENT LP,NEW YORK,NY,US	WESTPORT POWER INC.	2016-01-11	037529/0579	2016-01-14
Conveyance: SECURITY INTEREST (SEE DOCUMENT FOR DETAILS).				
Corresponent: ROSEANN B. CALDWELL, BENNETT JONES LLP 4500 BANKERS HALL EAST, 855 - 2ND STREET SW CALGARY, T2P 4K7 CANADA				
WESTPORT POWER INC.,VANCOUVER,CA	CANADIAN IMPERIAL BANK OF COMMERCE	2010-06-15	056887/0499	2021-06-09
Conveyance: RELEASE BY SECURED PARTY (SEE DOCUMENT FOR DETAILS).				
Corresponent: CAMERON KYLE 1750 75TH AVE W SUITE 101 VANCOUVER, V6P 6G2 CANADA				
WESTPORT POWER INC.,VANCOUVER,CA	PERSEUS, L.L.C.	2007-07-26	019617/0680	2007-08-01
Conveyance: RELEASE BY SECURED PARTY (SEE DOCUMENT FOR DETAILS).				
Corresponent: COLLEEN HOLCOMB MCDUFFIE 1600 TYSONS BOULEVARD SUITE 900 MCLEAN, VA 22102				
WESTPORT POWER INC.,VANCOUVER, BRITISH COLUMBIA,CA	WESTPORT RESEARCH INC.	2006-08-16	018184/0812	2006-08-31
Conveyance: ASSIGNMENT OF ASSIGNORS INTEREST (SEE DOCUMENT FOR DETAILS).				
Corresponent: MCANDREWS, HELD & MALLOY, LTD. 500 WEST MADISON STREET 34TH FLOOR CHICAGO, IL 60661				
PERSEUS L.L.C.,WASHINGTON,DC,US	WESTPORT POWER INC	2006-07-24	018279/0449	2006-09-21

Conveyance: SECURITY AGREEMENT				
Corresponent: STUART BARKOFF 555 TWELFTH STREET, N.W. IP DOCKETING, ARNOLD & PORTER LLP WASHINGTON, DC 20004				
CANADIAN IMPERIAL BANK OF COMMERCE,TORONTO,CA	WESTPORT POWER INC	2006-07-24	018260/0357	2006-09-18
Conveyance: SECURITY AGREEMENT				
Corresponent: STUART BARKOFF 555 TWELFTH STREET, N.W. IP DOCKETING, ARNOLD & PORTER LLP WASHINGTON, DC 20004				
WESTPORT RESEARCH INC.,VANCOUVER, BC,CA	WELCH, ALAN B.	2001-12-18	012679/0462	2002-03-06
	RAHARDJA, IRAWAN	2001-12-18	-	-
	HEBBES, MIKE	2001-12-18	-	-
Conveyance: CORRECTIVE DOCUMENT TO CORRECT THE ORIGINAL ASSIGNMENT PREVIOUSLY RECORDED ON REEL 011943 FRAME 0881, ASSIGNOR CONFIRMS THE ASSIGNMENT OF THE ENTIRE INTEREST.				
Corresponent: MCANDREWS, HELD & MALLOY, LTD. ROBERT W. FIESELER 500 WEST MADISON STREET 34TH FLOOR CHICAGO, IL 60661				
WESTPORT RESEARCH INC.,VANCOUVER, BC,CA	WELCH, ALAN B.	2001-06-20	011943/0881	2001-06-29
	RAHARDJA, IRAWAN	2001-06-20	-	-
	HEBBES, MIKE	2001-06-20	-	-
Conveyance: ASSIGNMENT OF ASSIGNORS INTEREST (SEE DOCUMENT FOR DETAILS).				
Corresponent: MCANDREWS, HELD & MALLOY, LTD. ROBERT W. FIESELER 500 WEST MADISON STREET 34TH FLOOR CHICAGO, ILLINOIS 60661				

Maintenance Status (US):

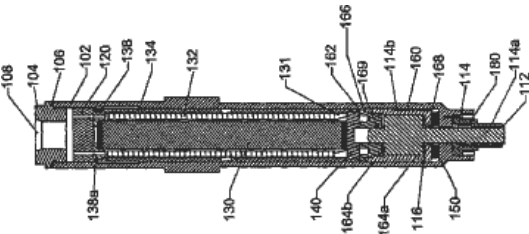
Litigation (US): 2021-12-15 2021 Westport Fuel Systems Canada Inc. Nissan North America, Inc. E.D. Texas 2:21cv00455 | 2021-12-15 2021 Westport Fuel Systems Canada Inc. Mercedes-Benz USA, LLC E.D. Texas 2:21cv00454 | 2021-12-15 2021 Westport Fuel Systems Canada Inc. General Motors, LLC E.D. Texas 2:21cv00456 | 2021-12-15 2021 Westport Fuel Systems Canada Inc. Ford Motor Company E.D. Texas 2:21cv00453 | 2021-12-15 2021 Westport Fuel Systems Canada Inc. FCA US LLC d/b/a FCA Group US LLC E.D. Texas 2:21cv00457

Opposition (EP):

License (EP):

EPO Procedural Status:

Front Page Drawing:



Priority Number - DWPI: US1999159791P | US2000522130A | US2001863187A
Priority Date - DWPI: 1999-10-15 | 2000-03-09 | 2001-05-23
Assignee - Current US: WESTPORT FUEL SYSTEMS CANADA INC.



United States Patent and Trademark Office

Office of the Commissioner for Patents

DIRECTLY ACTUATED INJECTION VALVE

PATENT #

6575138

APPLICATION #

09863187

FILING DATE

05/23/2001

ISSUE DATE

06/10/2003

Payment Window Status

WINDOW		STATUS		FEES	
11.5 Year		Closed		Paid	
Window	First Day to Pay	Surcharge Starts	Last Day to Pay	Status	Fees
3.5 Year	06/10/2006	12/12/2006	06/11/2007	Closed	Paid
7.5 Year	06/10/2010	12/11/2010	06/10/2011	Closed	Paid
11.5 Year	06/10/2014	12/11/2014	06/10/2015	Closed	Paid

No maintenance fees are due.

Patent Holder Information

Customer #

133599

Entity Status

UNDISCOUNTED

Phone Number

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