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Multipurpose solenoid valve for pneumatic and hydraulic systems of launch vehicles liquid propellant engines

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Abstract

Solenoid valves are an important component of launch vehicles liquid propellant engines pneumatic & hydraulic system. They are used for the propellant supply, for piloting the engine main valves, etc.
Modern liquid propellant engines include many solenoid valves, which can increase cost and complexity. The task of creating a multipurpose solenoid valve, which would be able to operate at a wide range of pressures, flows and working media, have low weight, power consumption and cost would be very beneficial. Such a multipurpose valve was developed, created and tested by Firefly Aerospace Ukraine LLC company.

1. Introduction

The performance of a liquid propellant engine (LPE) is determined by reliable operation of its individual systems, components and units. One of important and difficult tasks arising when creating a liquid propellant engine is to ensure its operability at startup and shutdown, which is largely determined by control units operation timeline, by their opening and closing speed, change patterns of working media flowrates, hydraulic resistance and other characteristics.
The solenoid valves (SV) are among those very important units in the LPE pneumatic and hydraulic system. They are used for supplying propellants to the engine chamber and gas generator, for supplying pilot gas when actuating the LPE main valves, during prestarting and poststarting purging operations, when ejecting engine cavities before filling them with propellants, and when creating steering efforts in gas-jet orientation and stabilization systems. Also, the solenoid valves are one of the main engine units, which provide engine multiple operations and allow reducing engine development cost by performing multiple fire tests without engine demounting and overhauling.
The requirements upon the solenoid valves are determined by operational and service conditions. They should provide required characteristics such as working medium flowrate at minimal hydraulic losses, pressure-tightness of sealing elements and fast response time. At that the valves shall possess minimal mass and power consumption, simple design as well as be operable within wide range of pressures and temperatures under impact of vibrations and g-loads.
The pneumatic and hydraulic system of modern LPE can contain up to 15 types of solenoid valves of various sizes, which operate in a wide range of pressures and flowrates, thereby complicating the engine's pneumatic and hydraulic design and reducing its reliability. Thus, we have to solve a solenoid valve unification problem, which should lead to valves and engine cost reduction. However, to solve this problem, it is necessary to create a multipurpose solenoid valve that would meet the above requirements. At that, when manufacturing the valve, it is particularly important to eliminate or reduce the use of sophisticated and expensive technologies and materials while maintaining high reliability and operability of the valve.
Firefly Aerospace Ukraine LLC company has developed, manufactured and autonomously tested a multifunctional solenoid valve (Figure 1) intended to open and close (drain) working media supply pipelines at commands of control system in pneumatic and hydraulic systems of liquid rocket engines.
The main specifications of the solenoid valve are given in Table 1.

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Table 1: Specifications of the solenoid valve

Characteristics	**Value (characteristic)**
Valve type	Normally closed, 3-way (with drain channel on the outlet side) or 2-way (without drain channel)
Working medium	kerosene, water, air, nitrogen, helium
Operating pressure range, MPa	2…24
Main poppet passage diameter, mm	4…12
Leakage through the main poppet assembly, cm^3/s, not more than	10^{-3}
Leakage through the actuator assembly, cm^3/s, not more than	0.3
Response time, s, not more than	0.08
Voltage, Vdc	from 24 to 32
Max. consumed power, W (at 293 K)	37
Service life (activations number), not less than	1000
Operating temperature range, K	from 223 to 323
Solenoid valve mass, kg, not more than:	
- 3-way (with drain channel);	0.48
- 2-way (without drain channel).	0.42

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Figure 1: Multifunctional solenoid valve 3 way design (with drain)

1.1. Functional description

The SV with drain channel (Figure 2) consists of housing 1, drain poppet 2, seat of drain 3 and main poppet 4, filter 5, movable sealing elements 6 and 18, main poppet 7, springs 8 and 16, solenoid 9 with electric connector 10, carcass 11, armature 12, drain seat 13 of connector 14, pilot poppet 15, inlet seat 17 and drain connector 19.
Channels K are made in main poppet 7, which supply the working medium from inlet cavity A to pilot cavity E, from which the working medium is discharged into the drain channel upon activation (cavity D) via channel F of carcass 11, slots J of pilot poppet 15 and channels H of armature 12. Movable seals 6 and 18 consisting of the collar and rubber

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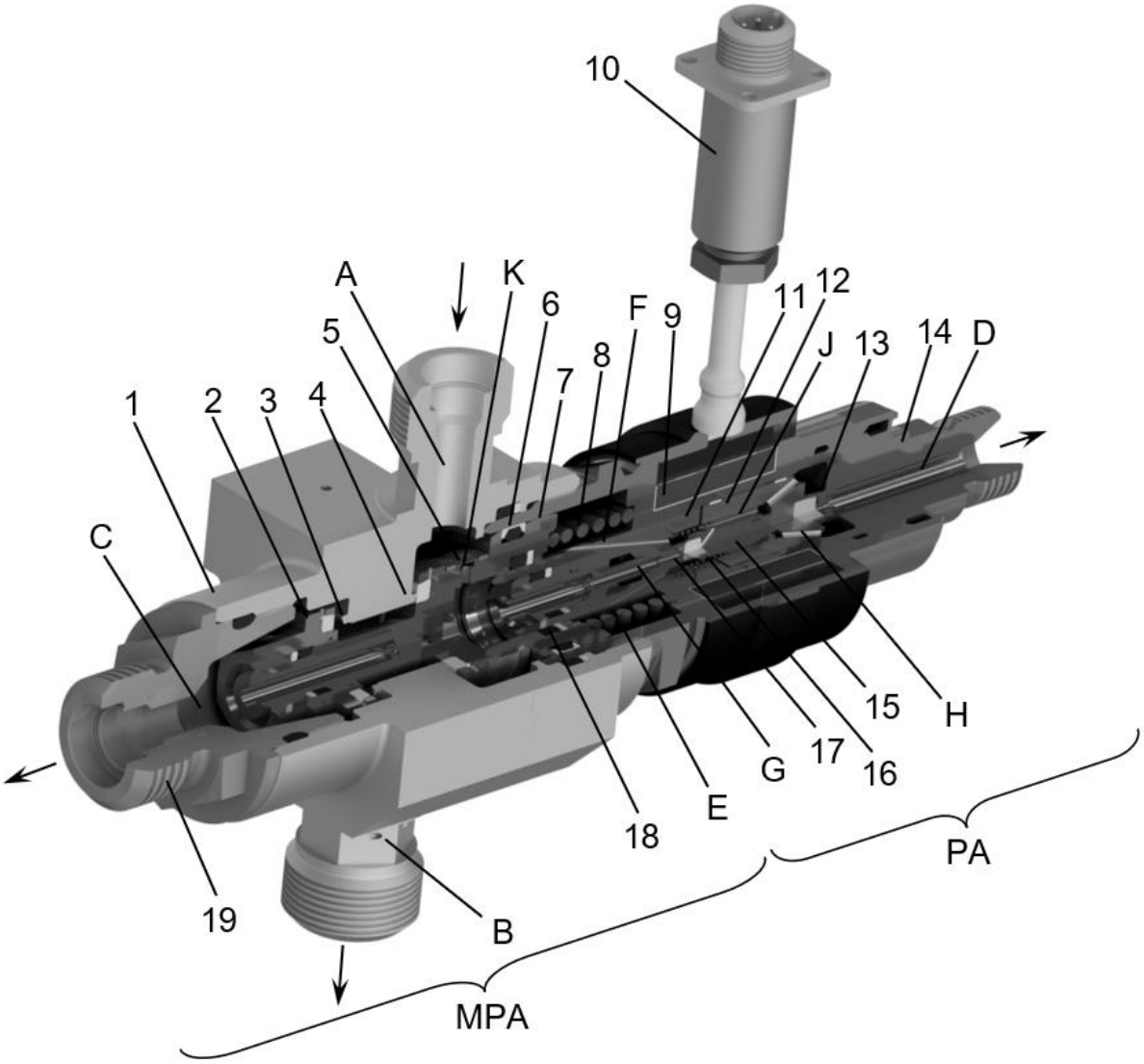
ring are installed at the movable connection of main poppet 7 with carcass 11. The SV threaded joints are sealed with rubber rings with protective washers, and the armature is moved on the guide fluoroplastic rings.
Armature 12, carcass 11 and the components of solenoid 9 are made of soft-magnetic stainless steel. The solenoid winding is made of enamelled copper wire. The guide rings and sealing element of armature 12, the collars of movable sealing elements 6 and 18, the protective washers of the rubber rings are made of PTFE. The sealing elements of main 7 and drain poppet 2 are made of polyamide-6, and the sealing elements of pilot poppet 15 are made of polyamide-610. The SV housing is made of aluminium alloy, and other parts are made of stainless steel.



1 – housing; 2 – drain poppet; 3 – drain poppet seat; 4 – main poppet seat; 5 – filter; 6, 18 - movable sealing element; 7 – main poppet; 8, 16 – spring; 9 – solenoid; 10 – electric connector; 11 – carcass of solenoid; 12 – armature; 13 – drain seat; 14, 19 – drain connector; 15 – pilot poppet; 17 – inlet seat. A – inlet cavity; B – outlet cavity; C, D – drain cavity; E– pilot cavity; F, G, H, K – channels; J – slot.

MPA – main poppet assembly. PA – pilot assembly.

Figure 2: Multifunctional solenoid valve

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The solenoid valve operates as follows. At de-energized mode, armature 12 is pressed to seat 13 of connector 14 by the force of spring 16 and working medium pressure. Cavity E is connected with inlet cavity A via channels K, G, F and its pressure is equal to inlet one. Main poppet 7 is pressed to seat 4 under the action of spring 8 and pressures in inlet cavity A and pilot cavity E, so inlet cavity A and outlet cavity B are disconnected. Meanwhile, outlet B and drain C cavities are connected.
When voltage is delivered to winding of solenoid 9, armature 12 is attracted to the solenoid carcass face, and this leads to opening drain seat 13. Pilot poppet 15, which is connected to the armature, is moved all the way to inlet seat 17, thereby interrupting the working medium flow from inlet cavity A into cavity E via channels K and G. Cavity E communicates with drainage cavity D via channels F, H and slots J and its pressure drops to a value equal to the drain cavity pressure. Under the action of occurred pressure difference between inlet cavity A and pilot cavity E main poppet 7 is moved until drain poppet 2 reaches seat 3. Inlet cavity A and outlet cavity B are connected, while the outlet and drain cavities are disconnected.
The working medium is filtered passing through filter 5 with mesh size of 20 μm prior to entering pilot cavity E in order to improve the solenoid valve reliability.
At voltage removal from the winding of solenoid 9, pilot valve 15 moves from seat 17 by the force of spring 16 and travels until the sealing element of armature 12 reaches drain seat 13. Pressure in cavity E is being equalized with inlet cavity A pressure. The pressure difference keeping the poppet 7 in opened state falls to zero, and under action of spring 8 and pressure difference on poppets 2 and 7 the latter (main valve) is positioned on seat 4, and poppet 2 (drain poppet) moves from the seat of drainage 3. Inlet cavity A and outlet cavity B are disconnected, meanwhile outlet cavity B and drainage cavity C are connected.

1.3 Solenoid valve design features

Structurally the solenoid valve is an internally piloted valve and neutral DC solenoid.
The main design features of the solenoid valve are the following:

1. The SV has modular design and it consists of the main poppet assembly (MPA) and pilot assembly (PA). This allows to use the SV in two modifications – 3-way (with drain channel) and 2-way (without drain channel). A single pilot assembly with main spring 8 is used for these modifications, and the main poppet assembly may vary depending on modification. At the same time no additional settings of MPA and PA are required.

2. A magnetic shunt in the form of a thin-walled section of a magnetic conductor is used in the solenoid structure in the operating magnetic clearance area. Upon activation of the solenoid, this section of the magnetic conductor gets saturated, creating resistance to magnetic flux, thereby directing it through the operating clearance. This significantly simplifies the magnetic conductor design, its manufacturability, and also reduces its cost.

3. Use of drain seat 13 design with limitation of the sealing penetration into the seat, which prevents destruction of the sealing at high pressures of the working medium.

4. Use of structural layout of the main poppet assembly with double movable sealing. In this case the sealing passes along the outer and inner diameters of the main poppet assembly in the guiding circumferential cavity of the carcass. Such technical solution allows to make the pilot assembly structurally and technologically simplified and, as a result, to decrease mass and size of both the solenoid and solenoid valve as a whole. It also increases the SV response time due to reduction of the pilot cavity E volume which is structurally limited by a circumferential cavity of the carcass.

5. Since all the SV movable elements are moved on the guide fluoroplastic rings which have low friction coefficient and exclude release of particles in the friction pairs, we have reached the SV service life of more than 1000 activations without noticeable wear of the valve parts.

6. The SV mass is not more than 0.48 kg, which is 2…2.5 times less than the mass of similar purpose solenoid valves belonging to the unified AU series used in existing engines developed by Yuzhnoye SDO (Ukraine) and NPO Energomash (Russia).

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2. Solenoid valve development

Design and technical solutions implemented when developing the solenoid valve were verified during its autonomous tests of the first phase as well as during operation in integration with the experimental assembly of the gas-dynamic ignition system.
The aim of the autonomous tests of the first stage was to check the SV functionality in conditions close to operational. In addition, a series of electric, strength and dynamic tests was conducted in environments with high and low temperatures. Leakage through the SV sealing elements within the operating pressure range, as well as its performance limits were determined.
As a result, correctness of adopted design solutions was verified during the autonomous tests of the solenoid valve, and the SV assembly and test technology and corresponding production tools were experimentally tested.
In the near future it is planned to conduct the second phase autonomous tests, which will include in-depth tests of the first phase and operational loads and hydraulic tests as well.

3. Potential application

Owing to the wide range of operating pressures - from 2 to 24 MPa, low mass - not exceeding 0.48 kg for a 3-way valve (with a drain line), manufacturability and, as a consequence, low cost, the created solenoid valve has great prospects for use in pneumatic-hydraulic systems of LPE and propulsion systems being operated or developed. In particular, as on-off valves for non-cryogenic propellants with flowrates up to 2 kg/s of gas generators or combustion chambers of engines with thrust up to 20 kN. This valve can also be used for supplying pilot gas when actuating the LPE main valves of high thrust, when purging pipelines and pressurizing fuel tanks with required gas flow rate of up to 0.5 kg/s, or as a propulsion unit in gas-jet systems (thrusters) with thrust level of up to 50 N.

4. Conclusion

Firefly Aerospace Ukraine LLC has created a multipurpose solenoid valve with technical and operational characteristics meeting the most advanced international requirements. The solenoid valve has passed the separate development phase and we have commenced its serial production at Firefly Aerospace Ukraine LLC production facility.
Application of a multipurpose solenoid valve as part of a pneumatic-hydraulic system allows to develop a liquid propellant engine with high technical and operational parameters, which creates strong commercial prospects for its application in the launch services market.