A high flow rate apogee engine solenoid valve for the next generation of ESA planetary missions

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ABSTRACT

Moog has been contracted by the European Space Agency (ESA) to develop a higher thrust storable propellant in-space engine to support its planetary science and exploration mission programmes, principally to reduce trajectory gravity losses and allow larger payload mass insertion to planetary orbits such as Mars. The High Thrust Apogee Engine (HTAE) engine development which started in 2010 (with a nominal design point thrust of 1100 N and a target specific impulse of 321 s in vacuum) under a contract with ESA's ESTEC chemical propulsion section has a requirement for propellant flow control valves. Commercially available conventional solenoid flow control valves have a pressure drop >>3 bar at the high flow rates being considered (180g/s water). One of the objectives of the engine development is to minimise the valve pressure drop and thus maximise the combustion chamber pressure and associated performance.

The paper summarises Phase 1 of the development programme which has concluded with the hot-fire testing of a bolt-up engine using Development Model (DM) valves.

Keywords: Mars, apogee, flow, MREP, valve

INTRODUCTION

The Apogee Engine Valve (AEV), bench qualified at Moog Dublin Operations through ESA in 2012, is being used as a basis for the design of the High Thrust Apogee Engine Valve (HTAEV). The AEV has demonstrated a pressure drop of 1.1 bar at 95 g/s water flow rate. The preliminary requirement for the HTAEV is a pressure drop <2 bar at 180 g/s along with a 50% minimum force margin at end of life. The paper describes the design process carried out in Phase 1 of the ESA HTAEV development programme and will cover: the overall design methodology; engine derived constraints on physical dimensions and requirements for performance; valve scaling considerations; the engineering model valve design; materials, coatings and manufacturing process selection; AEV qualification results; preliminary HTAEV test results; the planned qualification test matrix as well as further planned milestones in this chemical propulsion programme.

Figure 1: Development Model High Thrust Apogee Engine Valve (HTAEV).

VALVE OVERVIEW

The valve is a normally closed solenoid operated flow control valve. It is fitted with redundant coils for improved reliability, and with an annular seat for high flow rates at low pressure drop. The valve consists of a fixed pole containing the coils, and a suspended moving pole to which the seal is attached. The dual flexures prevent radial and angular movement such that the same area of the seal contacts the seat after each actuation.

The design of the seal/seat interface ensures minimal flow discontinuities, therefore reducing susceptibility to contamination induced failures and minimising pressure losses. The valve is opened by energising the coil; the resulting force generated by the induced magnetic flux causing the armature to move towards the 'fixed pole', in doing so carrying the seal from its seat.

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The valve is closed when the coil is de-energised, collapsing the generated magnetic field. The moving pole now moves the seal to the closed position under the influence of a helical spring. It then remains closed under the combined influence of the spring and pressure forces applied by the working fluid.

The inlet interface incorporates an internal particle filter, swaged into the inlet. The outlet flange is welded to the valve and incorporates the interface with the injector body. The default inlet configuration is a straight stub tube however the design is such that many varieties of inlet tube can be accommodated.

The sleeve of the valve contains an internal dual-redundant heater rated to 2 W which is bonded in place.

BACKGROUND

The HTAEV is an evolution of the successfully qualified AEV developed by AMPAC ISP Dublin (now Moog Dublin Operations) in collaboration with AMPAC ISP Cheltenham (now Moog Cheltenham Operations) and was completed in 2012. The AEV was designed primarily for use with the LEROS 1c engine produced at AMPAC ISP Westcott (now Moog Westcott Operations). This valve development was co-funded by ESA and is ITAR-free.

The AEV valve was selected by Moog Westcott Operations as a baseline valve; one which could be scaled in order to meet the high flow rate, high force margin and low pressure drop requirements of the HTAE. The HTAEV development started in mid-2012 and has successfully completed an intermediate PDR review in December 2013.

Figure 2: Apogee Engine Valve (AEV).

Figure 3: Apogee Engine Valve (AEV) integrated on a LEROS 1c.

DESIGN PROCESS

The design of the valve follows the Moog Dublin Operations internal process which is an iterative design process based on output from the magnetic model and flow performance calculations. An initial design point is selected from a plot of pressure force vs. orifice dimension with pressure drop on the secondary axis. This design point forms the basis of the flow calculations from which minimum valve stroke is based. The magnetic model is then generated using this required stroke and the rest of the valve is modelled according to the volume and interface requirements of the engine. The key sizing criteria is then based on what size of coils can be accommodated and if they will provide sufficient magnetic force to actuate the moving pole, bearing in mind the customer force margin requirements. The process then iterates back to the orifice size until a model exists which meets all the customer requirements.

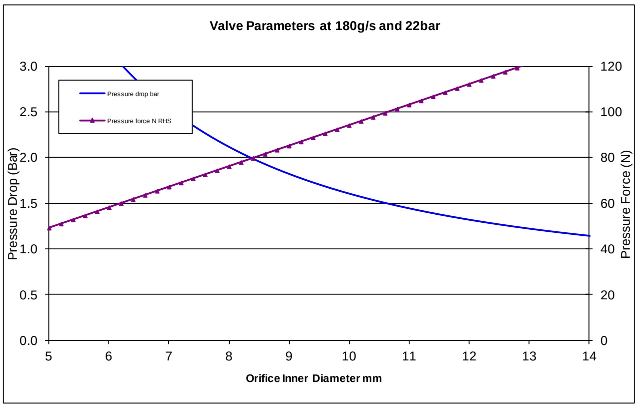

Figure 4: Initial orifice sizing graph.

VALVE DESIGN

The required flow rate / pressure drop requirement is less than 2 bar at 180 g/s water flow. Based on this design charts were generated in which orifice area, stroke, pressure force and pressure drop are plotted against orifice diameter. From these charts, selection of the orifice diameter and orifice width gives a design point for further evaluation. The initial diameter selected gave an estimated pressure drop of 1.97 bar, including an allowance for an internal filter. This design point was selected as it satisfied the flow rate and pressure drop requirements whilst keeping the amount of lift needed to open the valve at an acceptable value, especially when additional factors such as those discussed below are included in valve lift. The size of the valve grows disproportionately with the size of the stroke so it is important to keep the stroke minimised in order to maintain adequate force margin and keep the overall size of the valve acceptable. For example the pressure drop could be reduced to less than 1 bar however the valve mass may need to be > 1 kg.

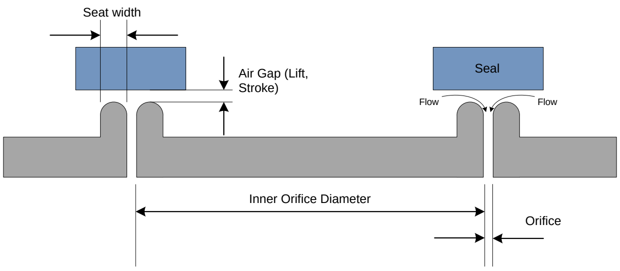

Figure 5: Typical orifice geometry.

The valve requirement was based on two inlet pressure specifications. The Nominal Design Point (NDP) is specified at 15.4 barA. The Maximum Expected Operating Pressure (MEOP) is specified at 19 barA. The force margin was also specified at two points; 1.15 at MEOP, 1.5 at NDP. The force margin is defined as the ratio of the magnetic actuating force to the sum of the resistive forces (which includes spring and pressure forces).

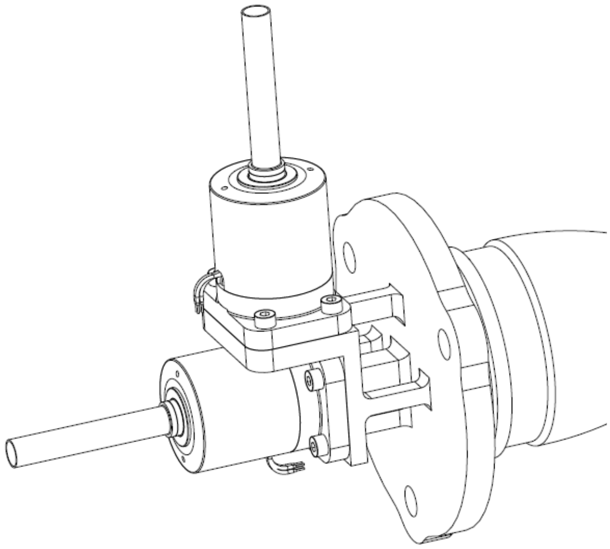

Figure 6: Valve mounting configuration for HTAE.

The valve has been able to take advantage of new magnetic iron alloys which have improved the performance of the valve over the current state-of-the-art. The new materials allow for higher saturation flux densities in the parts forming the magnetic circuit and therefore allows higher forces to be generated by the magnetic field for a given input power.

In order to prevent long term oxidation of the valve during ground handling and engine level acceptance testing the valve has been Gold coated.

DESIGN EVOLUTION

A number of design guidelines and ‘rules of thumb’ were updated from that used on the AEV development. These guidelines related to the minimum lift of the valve and the minimum seal stress required for a leak tight seal. It was found that the previous assumption on minimum stroke required was overly conservative. Using a smaller stroke to achieve the same pressure drop performance helps to make the overall valve smaller. This performance was mapped out over a number of different valve strokes using the water flow test facility at Moog Westcott Operations. Computational Fluid Dynamics software may have been useful during these developments however this software did not exist in the site portfolio.

The internal leakage was found to be well within specification for the AEV and it was decided to try finding the absolute minimum spring force necessary in order to maintain the internal leakage within specification. Reducing the required spring force also helps with improving the valve force margin. A development valve was used to probe the internal leakage rates at various spring forces. The results showed the assumed spring force was slightly over conservative and could be reduced for the next iteration of the design.

ENGINE INTEGRATION

The valve was initially designed to have a right angled 3/8" stub inlet (see Figure 1). This design will be updated to have a straight inlet similar to the qualified AEV design. The valve can easily accommodate different inlet options.

The conceptual flight engine configuration at I-PDR was such that the valves were mounted at right angles to each other (see Figure 6). This has been done to optimise the flow paths in the injector assembly and reduce the number of sealing interfaces compared to previous LEROS engines. The valve is given an o-ring groove and four mounting holes. Each valve has four power leads to service the primary and redundant coils. Each valve also has four power leads to service the in-built internal heater. The interface dimensions are shown in Figure 7.

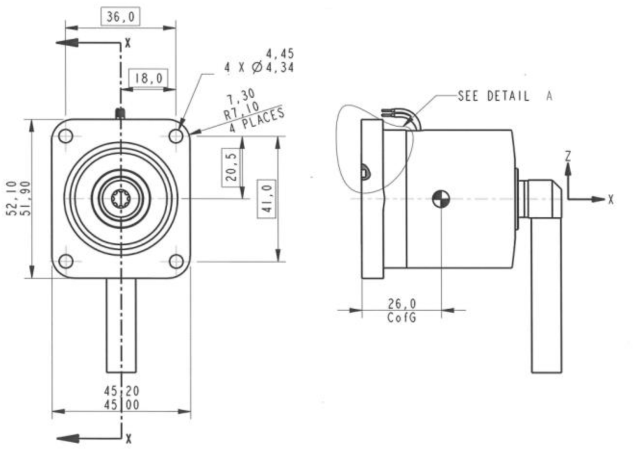

Figure 7: Interface information for HTAEV.

PROPELLANT TESTING

Substantial propellant testing with the AEV was completed during its development. This included MON-3 (Mixed Oxides of Nitrogen), MMH (Mono-Methyl Hydrazine) and Hydrazine. Recent valve testing has also included use with 87.5% concentrated Hydrogen Peroxide.

It is known that PTFE will swell with MON propellant. The early development testing at Moog Westcott Operations was able to confirm the long term stability of seal swell effects as well as quantify the level of volumetric swell seen in the valve application. This allowed a new design rule to be established at Moog Dublin Operations as to how flow control valves could be better designed for use with MON propellant. It is important to control any seal swell effects as seal swell has a direct effect on pressure drop through the oxidiser valve and could therefore affect the mixture ratio of the engine. This will manifest itself as a shifting fuel/oxidiser ratio during operational burns.

MON testing was performed with the propellant at temperatures ranging from +5°C to +54°C. Valve interface temperatures of up to 112°C were also tested. It was found that the propellant temperature has a very significant effect on the seal swell encountered. The effect of any seal swell was monitored through the use of a flow characteristic metric, k, calculated as follows:

$$k = \frac{\dot{m}}{\sqrt{\rho \cdot \Delta p}}$$

Where:

$\dot{m}$=mass flow rate
ρ=propellant density
Δp=pressure drop across valve

It was confirmed that the AEV maintained a stable k value within 1.6% (as per requirement specification) with a MON propellant temperature range of 10°C to 35°C. The same design rules have been applied to the HTAEV so the compliance here is by similarity of design.

TEST RESULTS

Initial test results have been generated from the test of the Development Model (DM) valves manufactured during Phase 1 of the HTAEV development.

The DM valves were shown to produce a pressure drop of 2.4 bar at a water flow rate of 180 g/s. These DM valves did not satisfy the full design recommendations to reduce the pressure drop below 2 bar. The Engineering Model (EM) valves will satisfy all design recommendations and are estimated to produce a pressure drop of 1.9 bar at 180 g/s. These results include the inbuilt internal 25 micron filter.

The internal leakage of the DM valves has been shown to be better than 3 x 10^{-5} scc/s GHe across an inlet pressure range of 1-29 barA at 21°C. This is against a requirement specification of 1 x 10^{-4} scc/s.

The DM valves have also been functionally tested up to 130°C. As expected the opening response times of the valve are slower than those at the previous AEV qualified temperature maximum of 102°C. Opening response times at 21°C of less than 35 ms have been observed on the DM valves. Opening response times of better than 50 ms are observed at 130°C.

The DM valves were installed onto the HTAE bolt-up DM engine which was successfully hot-fire tested in the second half of 2013. These valves have been returned to Moog Dublin Operations and are due for performance testing in June 2014 before being returned to Moog Westcott Operations for further hot-fire testing as part of Phase 2.

DESIGN CHALLENGES

One of the key design challenges for any PTFE seal valve is to address the issue of seal creep during service life. Creep is by its very nature a long term phenomenon and so there is a difficulty when a service life of 15+ years is to be justified/verified in the design. Other development projects have attempted to derive an acceleration factor for thermal tests which can make a seal test much shorter however these methods do require further research and development. The methods employed on both the AEV and HTAEV are based on more basic direct measurement with displacement sensors.

The first test which was set up in 2010 early in the AEV program consisted of valve representative hardware physically loaded with a weight equivalent to the MEOP plus spring force. A number of reference points were marked on the assembly and measurements were taken using a digital height gauge with accuracy of ±0.1 microns. The setup was left loaded for extended periods of time and measurements were taken at regular intervals. The main drawback of this test is that the weight had to be removed in order to take the measurement; therefore no compensation is made for elastic springback of the PTFE material. A separate study on this phenomenon has however shown that the elastic springback is no more than 2%. This assembly was also placed in a thermal oven to try recreate the thermal cycles which the valve is expected to encounter. As expected the creep was noticeable and found to be on the order of 50 microns which can be significant when designing for force margin. It was however found that for the seal stress chosen for the AEV design that the creep at 21°C was found to be <5 microns over a 3 year period.

A further creep test was commissioned as part of the HTAEV development. This test consisted of HTAEV representative valve hardware again subjected to weight equivalent to MEOP plus spring force. This time LVDT’s were used using equipment borrowed from ESA (see Figure 8). An LVDT reference and three separate samples of the same configuration were used. This test has been in operation since February 2014. Initial results at room temperature indicate the creep is negligible (less than 2 microns measured). This test will continue indefinitely.

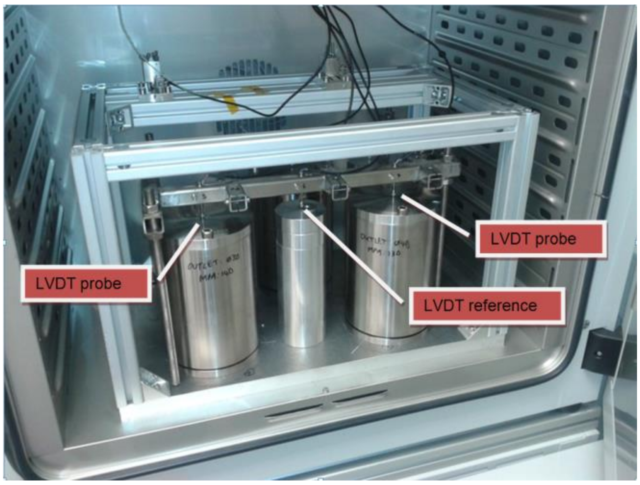

Figure 8 HTAEV creep test setup with LVDT’s.

Another challenge of this development is the required operational temperature range for the valve. Although the AEV was qualified for an interface temperature of 102°C, the HTAEV requires an interface temperature of 130°C. The higher temperature reduces the available magnetic opening force for a given coil size. The issue of seal creep also becomes more important at higher temperature.

ADDITIVE MANUFACTURING

The baseline plan for the Engineering Model (EM) valves is to incorporate an Additive Manufactured (AM) outlet. The outlet has been identified as a good candidate for AM due to its size, material and geometry complexity. The existing outlet is a sub-assembly which consists of two parts which must be welded prior to a post-machining operation. The AM outlet will have the added benefit that it removes one external weld from the valve assembly therefore increasing reliability.

Key challenges of the use of an AM outlet part in the valve include:

- Ensuring the weld to the rest of the valve is of sufficient strength and quality
- Ensuring the surface finish of the part is controlled where necessary

These challenges will be addressed before being fitted into the EM valves.

VALVE SPECIFICATION

Table 1 shows the predicted technical specification of the valve and is subject to change based on EM design updates and EM test results.

Table 1 : HTAEV preliminary specification.

Characteristics	***Value***
Operational	
Operating media	MON-3, MMH, Hydrazine, GN2, GHe
Maximum Operating Pressure (MEOP)	22 BarA
Proof Pressure	1.5 x MEOP
Burst Pressure	2.5 x MEOP
Flowrate/pressure drop	< 2Bar at 180g/s water
Internal leakage	1 x 10^{-4} scc/s GHe over pressure range at 21°C
External leakage	1 x 10^{-6} scc/s GHe over pressure range at 21°C
Response	< 50ms opening, < 30ms closing under all conditions
Operating voltage	18.0 – 27Vdc / 40W max
Cycle life	6,000 cycles
Filter rating	25 micron absolute
Environmental Characteristics	
Operating Temperature Range	-5°C to +130°C
Non Operating Temperature	-34°C to +130°C
Vibration	50grms random in all axes, 60g sine
Life	15 years
Physical Characteristics	
Materials	Stainless steel
Mechanical Interfaces	Welded 3/8" stub tubes
Mass	0.53Kg

TEST PLAN

The baseline plan is to manufacture four EM valves, all of which will go through a full acceptance test sequence. Two of these valves will undergo engine-level testing when used on the EM engine . Two valves will go through a full valve-level qualification test campaign which will include vibration, shock, thermal vacuum and functional performance tests.

The HTAE program is scheduled for Phase 2 kick-off in April 2014. This phase will encompass PDR in late 2015 and CDR in 2017.

FUTURE APPLICATION

The HTAEV has been specifically developed for the HTAE 1100 N engine as preparation for future ESA planetary missions however this valve is capable of meeting a range of other potential applications.

Moog has been investigating the potential use of both the AEV and HTAEV in Hydrogen Peroxide propellant applications. An EM AEV valve has already gone through extensive thruster testing with 87.5% Hydrogen Peroxide at Moog Westcott Operations. The valve was operated under steady state conditions for durations up to 90 s and also under pulse-mode with pulse durations down to 125 ms. In excess of 2800 cycles were performed with a total throughput of over 50 kg and maximum flow rate of 10.5 g/s. There was no indication that the valve was decomposing the Hydrogen Peroxide and no indication that the Hydrogen Peroxide was deteriorating the valve.

Under a separate development Moog Dublin Operations has been working with Nammo where a Qualification Model (QM) AEV has gone through extensive testing as part of their Hydrogen Peroxide propulsion system development. This testing has subjected the valve to flowrates up to 160g/s, a total throughput of over 210 kg, and 2700 actuations. The valve was operated under steady state conditions for durations up to 260 s and also under pulse-mode.

Both valves have performed very well in these applications. The main challenge to future use of these valves with Hydrogen Peroxide is the long term compatibility of the valve materials. It has already been shown that short term exposure does not result in any degradation of the valve performance and no corrosion has been detected. These compatibility tests will be conducted in partnership with Nammo in 2014.

CONCLUSION

It is concluded that the HTAEV design is at an advanced level of maturity as it was based on the previous qualification work on the AEV. The design work to date, in conjunction with the test results from the DM test program, provide a high degree of confidence that the valve development can proceed to EM level with a low risk profile. This HTAEV development remains ITAR free.

Although the valve has been designed specifically for use on apogee engines and for interplanetary science missions of the future, it is clear that this valve can meet a variety of other engine/launcher applications for the aerospace industry.

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