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Development of a high flow rate piston pump for rocket engines

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Development of a high flow rate piston pump for rocket engines

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Abstract. There is a need for cheaper small satellite rocket launchers. One way of reducing costs is to reduce the cost of individual components. We describe here the development of an inexpensive piston pump for rocket engine applications. It demonstrates that it can deal with the combined requirements of high flow rate and operating speed at cryogenic temperatures without incurring the costs normally associated with such performance.

1. Introduction

Currently all launch vehicles use turbopumps in order to pump propellant and oxidiser to a combustion chamber from low pressure tanks. The combustion results in a high pressure gas being formed which is expelled at high velocity via a nozzle, imparting momentum, and hence thrust, to the rocket. The thrust is affected primarily by chamber pressure [1], and for a given geometry of nozzle, a higher chamber pressure leads to higher thrust. Turbopumps are currently the only pump designs that are able to provide the performance necessary to generate sufficiently high pressures in the chamber. For instance, the Soyuz-2-1v, one of the smallest liquid powered orbital launch vehicles with a gross life off mass (GLOM) of only 157 tonnes, nonetheless requires a total propellant mass flow rate of 225kg s^{-1} [2]. However, the resulting complexity of turbopumps makes them one of the most expensive components in a modern launcher.

Other options have also been considered to provide pressurisation, including pumps based on the use of pistons, gears, screws, lobes and vanes [3]. However, complexities arising from the extreme demands on the pumps, combining high flow rates, high operating speeds, and the use of cryogenic liquids, along with crucial constraints of weight and size, determined the direction of development of pump technology towards turbopumps for this application. Nonetheless, advances in manufacturing techniques, such as CNC cutting and 3D printing have driven a revision of these pump technologies with a view to this application. Following a review of the advantages and disadvantages of each of these technologies, as well as the time and budgetary constraints arising within a doctoral training programme, it was decided to pursue the development of piston pump that could meet the exacting requirements described above.

2. Piston pump - design and development

Piston pumps, a form of reciprocating pump, generate sufficient pressure to maintain flow rate [4], and are often used in high pressure applications. Compared with rotary displacement pumps, such as turbopumps, they are more widely used for pumping cryogenic liquids [5], and cryogenic reciprocating pumps that can operate up to 690bar are commercially available [6]. This is considerably higher than pressure achievable by turbopumps.

Following initial designs and subsequent evaluation, a series of single-piston pumps were designed and constructed, with reed valves selected for flow control. A target operating speed of 1000 rpm was chosen, and tests demonstrated that the reed valves can open and close in 0.032s, corresponding to ≈1930 rpm, almost double the target operating speed. Figure 1 shows CFD modelling indicating the flow patterns around 2-slot and 3-slot reed valve designs, Figure 2a shows a CAD image of the pump system itself, and Figure 2b a picture of the constructed system.

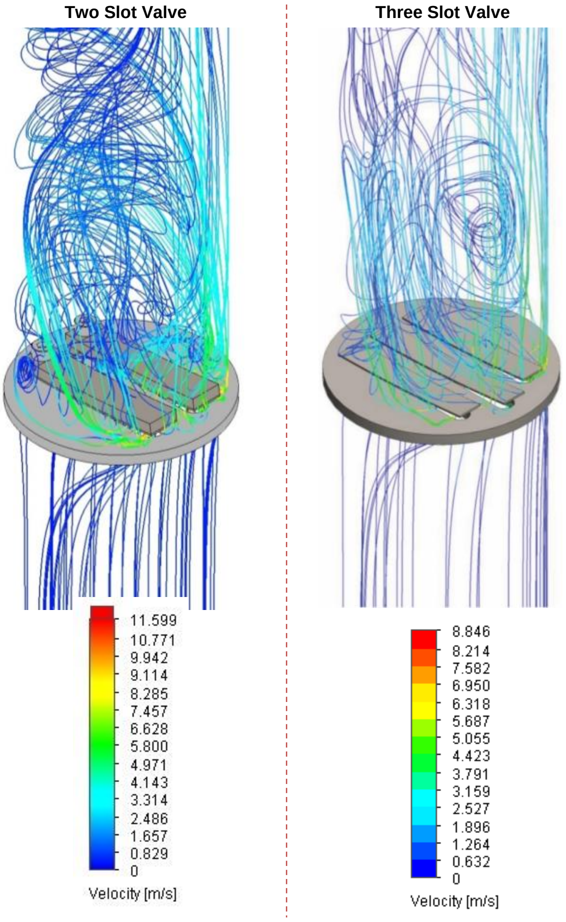

Figure 1. Two and Three Slot Valve Designs – Velocity Graphs

In order to minimise wear of the reciprocating seals and hence to minimise liquid leakage, the surface roughness and the tolerance of the geometry must meet exacting standards. In particular, for the seals this typically requires a surface Roughness Average (RA) of less than 0.1μm. This was achieved using an external subcontractor for honing with a fine polish stone, which offers the following tolerances [7]

- Geometry within 0.001mm
- Roundness within 0.001mm
- Surface finish within 0.01μm

The finished pump was measured using a CMM, Roundness and Cylindricity Measuring Instrument and a Mitutoyo SurftestSJ-400 surface finish tool, giving the following results

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- Bore Diameter: 53.36mm
- Maximum Roundness error: 48.762µm
- Surface Finish Ra: 0.04µm

3. Testing

The prototype pump was subjected to a series of tests, initially at room temperature to check operation and seal quality and latterly at cryogenic temperatures using liquid oxygen. Pressure measurements recorded during initial tests with water are displayed in Figure 3. The nominal theoretical average pressure calculated was 2.6bar, and a value of approximately 1.7bar was achieved. The slight negative excursions also indicate weaknesses of the seal performance.

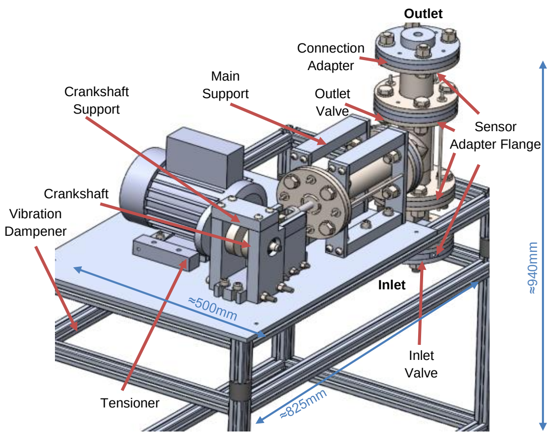

Figure 2a. Isometric CAD image of pump system with dimensions

Figure 2b. Assembled system

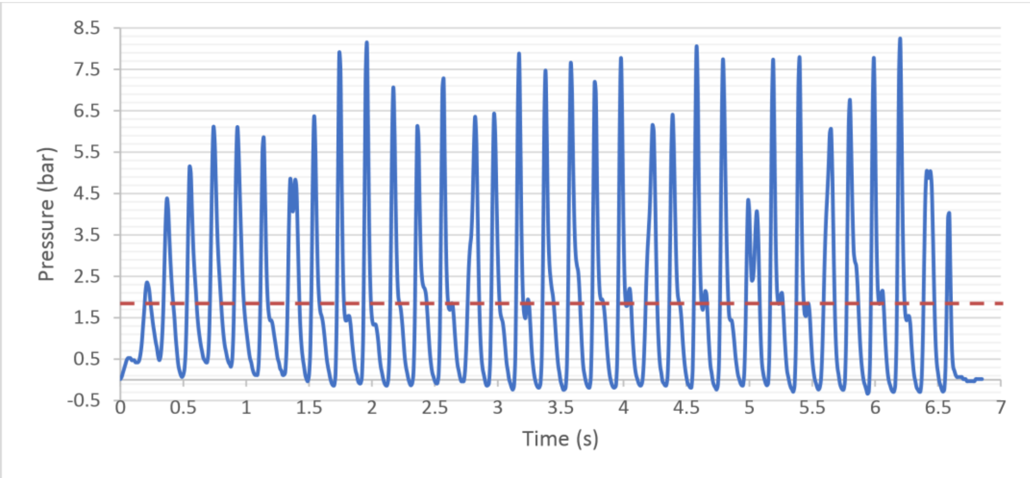

Figure 3. Pressure measured during ambient temperature tests with water. The red dotted line indicates an average pressure of 1.7bar.

Improvements to the seals were carried, including the addition of coil-energised stiffener seals provided by Saint Gobain Ltd. The sealing jacket is made from Fluoroloy® A12 and the coil stiffener from cobalt nickel alloy. In addition the piston itself was also modified and the edges were chamfered to reduce the possibility of scratching the cylinder or the seals. Following these improvements, additional testing was undertaken with cryogenic fluids, including liquid oxygen. Target pressures were achieved, with the results displayed in Figure 4.

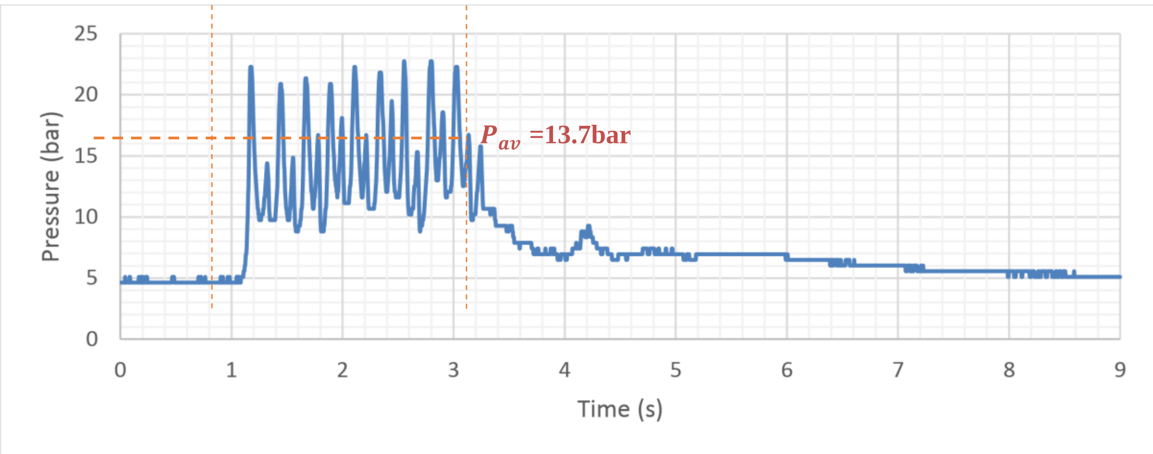

Figure 4. Pressure measured during cryogenic tests with liquid oxygen. The red dotted line indicates an average pressure of 13.7bar.

4. Conclusion

A prototype piston pump for small satellite rocket launcher applications has been designed, modelled, constructed and characterised. It has demonstrated that it can achieve both high operating speeds and flow rates as well as substantial pressures in cryogenic conditions. Further improvements are required to reduce weight and to investigate further the relative advantages of geared connections compared to drivebelts in order to provide power to the system. An extension to a triplex pump, with three pistons operating 120^{o} out of phase with each other to smooth the pressure and flow variations has been modelled, and further work would involve the construction of such a system.

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