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Towards the Development of a Monopropellant Microrocket Engine Using MEMS Technology

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Abstract

Funded by ESA, this study team have identified a near term performance gap in the market for small satellites, defined by the lack of proposed MEMS-based propulsion systems providing Isp (specific impulse) in the range 100-300s. As part of this exercise, a Technology Roadmap has been developed, covering propellant feed, MEMS-based actuators (principally valves) and sensors, and materials considerations. Further to these studies, detailed analyses (including thermal, structural and reliability assessments) of a hydrogen peroxide-fuelled, MEMS-based monopropellant microrocket engine have led to the development of a concept which is shortly to be evaluated at breadboard level.

Keywords: Microsatellite, MEMS, monopropellant, hydrogen peroxide, materials

1. INTRODUCTION

Many low-cost space missions suffer from problems associated with securing a precise orbit injection from the launch vehicle, often as a result of a shared or secondary launch, leading to a compromise orbit. Furthermore, requirements for constellation forming, LEO drag compensation, manoeuvring for satellite inspection, formation flying, and end-of-life deorbiting indicate a need for significant ΔV capability in small spacecraft, ideally coupled with high thrust levels (up to 1N) to minimise energy losses. Conventionally engineered propulsion systems can deliver performance in the 100m/s ΔV range [1], but these are typically expensive solutions, using toxic propellants, and, in many case, do not scale favourably to the smaller sizes demanded.

Despite increasing interest in miniaturised propulsion systems [2] very few MEMS-based chemical propulsion systems exist other than as concepts. The ÅSTC has built and tested a MEMS hybrid system with a specific impulse (Isp) of 45s, with up to 100s projected [3]. Further, the Gas Turbine Laboratory at MIT has worked on a development programme with the objective of demonstrating a high performance bipropellant system with a target Isp of 300s, a thrust of 15N, and a notional MEMS-based centrifugal turbopump for feed of propellant to the combustion chamber [4]. These two examples illustrate the wide gap between MEMS propulsion today, and the potential for the technology.

The current study team have identified a near term performance gap in the market for small satellites, defined by the lack of proposed systems which could provide an Isp in the range 100-300s.

2. TECHNOLOGY ROADMAP

A candidate technology with the potential to fill the identified performance gap for micropropulsion systems in the near future, is that of a high-thrust, MEMS-based monopropellant microrocket engine. It is such a concept which is being pursued by this study team.

This will offer a large step increase in performance over what is currently available (cold- and warm-gas miniaturised propulsion systems) and has been specifically designed with potential for growth towards a bipropellant concept in mind. A technology selection roadmap, covering miniature pump technologies (for pressurised feed of propellant), micro-ancillary components (principally valves and environment sensors), and materials selection criteria, has been drawn up to aid in the design process.

The aim is to have developed and demonstrated a breadboard for a new MEMS micropropulsion system beneficial to microsatellites by the end of the programme, whilst simultaneously establishing where further developments towards higher performance bipropellant microrocket engines should proceed.

2.1. Propellant selection and feed

Hydrogen peroxide was selected as the preferred propellant, from a detailed trade-off including factors such as prior experience, performance (relative to cold gas), low toxicity and applicability to a bipropellant system as an oxidizer.

The system chamber pressure (P_c) and the resulting feed requirement were reviewed in detail. High P_c is desirable in micro rockets principally to increase residence time, compensating for small chamber sizes and high heat losses and maintaining c^* despite fixed chemical reaction times. However high P_c in a pressure fed system poses challenges for MEMS fabrication, principally due to limited bond strengths and planar designs ill-suited to act as pressure vessels. Pumped propellant would be attractive if small high power density pumps can be fabricated. Analyses considered 1-100kg wet mass missions with 0.1-10kg of propellant respectively, with P_c values between 0.2 and 2.0 MPa and a flow rate envelope of 0.01 to 0.5 g/s (equivalent to a thrust of 20-500 mN for an Isp of 100-150s). A pump fed propulsion system was considered to be competitive at low chamber pressures for the smallest (1kg) missions, a fully packaged pump mass of 15-50g being required. 10-100kg missions would benefit from 0.1-1kg mass pumps, which might also be able to meet the system requirements (head, flow rate) if based on miniaturized conventional materials. Several such pumps with 1-5kg mass are under test e.g. [5] and provide a basis for future development. However MEMS micropump technologies appear unable to meet the requirements in terms of flow rate *and* pressure rise, at present.

2.2. MEMS-based Ancillary Components

A) Sensor technology For an operational monopropellant microrocket engine, MEMS based pressure sensors and temperature sensors will provide crucial telemetry points for monitoring performance of the system. MEMS-fabricated sensors and actuators have been the subject of significant research effort, resulting in components which include, pressure regulators, pressure transducers, sensors for measuring fluid flow rate, microheaters, and temperature sensors.

In many cases it is difficult to accurately define the physical conditions in which such micro sensor components must survive and operate because of the poorly-defined nature of miniaturised propulsion systems in general. It is, however, clear that improvements to existing technology will be necessary, particularly when more demanding bipropellant concepts begin to emerge.

In particular the performance requirements for micro ancillary component technologies can be divided into two distinct areas:

1) The requirement to be able to measure the parameters of interest to the level of accuracy, stability, etc., required;
2) The requirement to be able to survive the harsh environmental conditions to which some of these technologies will be subjected (i.e. pressure and temperature), so-called environmental susceptibility.

For example, MEMS pressure sensing techniques employing corrugated silicon diaphragms, with capacitive pick-offs appear highly applicable, provided that sufficient thermal isolation can be achieved with respect to the hot decomposed gas. Similarly, thin film temperature sensors (platinum / titanium or possibly platinum / tantalum, if eutectic formation proves to be a key concern) can be used to monitor thermal performance or permit pre-heating of the system to reduce thermal losses at startup.

B) Valve technology A complete integrated microrocket engine system also needs microvalve technology development and integration efforts. Phase-change material valves [6] separated thermally from the hot engine parts need particular attention, as do compact and dismountable fluidic and electric interfaces between system parts. At the microscale, surface energy dominates over body forces, causing unexpected problems when surfaces are not intended to 'stick together' (e.g. in dismountable interfaces). This could be a particular problem where surfaces are required to seal tightly (fuel feed interface and valves).

2.3. Materials Options

For the decomposing hydrogen peroxide monopropellant microrocket engine concept presented in section 3, silicon can safely be used without concern over issues such as creep in the high temperature environment. Detailed thermal analyses have been performed for both transient and steady-state heat flows within the system in order to confirm this.

As the concept evolves and higher performance bipropellant mode systems begin to be considered, silicon will no longer be an applicable material; alternative refractory ceramics, particularly SiC, Si_3N_4 and Sialons will become of key interest, although the maturity of bulk MEMS processing of these materials is currently a limiting factor. Table 1 presents candidate materials, together with key physical characteristics, that were considered during the early stages of the technology selection phase of the programme.

Table 1: Candidate materials for a mono- or bipropellant microrocket engine

	Si	**Sialon**	**Si_3N_4**	**SiC**	**$MoSi_2$**	**Al_2O_3**	**ZrO_2**	**Pyrex**
Thermal expansion coefficient, $\times 10^{-6}$	2.6	3	3	4	8	8	10	3.25
Young's modulus, GPa	170	300	310	400	430	350	200	64
Thermal conductivity, W/mK	148	22	25	100	20	22	2.5	1.1
Failure Stress at ~300 K, MPa	300	950	650	400	250	300	800	69

Sialon, SiC and Si_3N_4 materials offer attractive combinations of properties (high failure stress level coupled with relatively low thermal conductivity), and may well be ideal choices for future bipropellant concepts where thermal endurance is critical. Detailed thermal analyses conducted during the study, have indicated that $MoSi_2$, Al_2O_3, and ZrO_2 do not lend themselves to micropropulsion concepts, primarily due to their poor performance in terms of thermal shock. However, the key limitation at present is the scarcity of data on microfabrication using such ceramics.

Current microfabrication capabilities are heavily focussed on silicon, with fabrication process heritage from microelectronics. The fabrication of non-silicon microsystems is a much less mature discipline, although certain techniques, such as focussed ion beam (FIB) fabrication, may allow microfabrication of ceramics. Chemical vapour deposition of SiC coatings on Si may also hold promise. However, these may reduce the potential cost-savings associated with batch processing of Si, which is one of the main attractions of MEMS.

From a MEMS fabrication point of view, silicon is a well-understood material with a mature status in terms of micromachining processes having being developed (masking, etching, diffusion bonding etc). Silicon also offers good potential for application to monopropellant microrocket engine concepts such as that being pursued here (silicon is known to suffer from reduced strength at elevated temperatures, above about 675°C).

3. CONCEPT DEVELOPMENT

A vertically integrated monopropellant design concept has been pursued by the project team (Figure 1), on the basis that such an architecture can provide better pressure endurance than the more usual laminar architecture often seen in fluidic MEMS systems. Further, the vertical architecture provides an axisymmetric configuration, allowing more familiar design rules to be put into practice.

Starting with a preliminary model of the monopropellant microrocket demonstration development model (DDM), thermal analyses quantified the expected start-up and steady state operating conditions of the system.

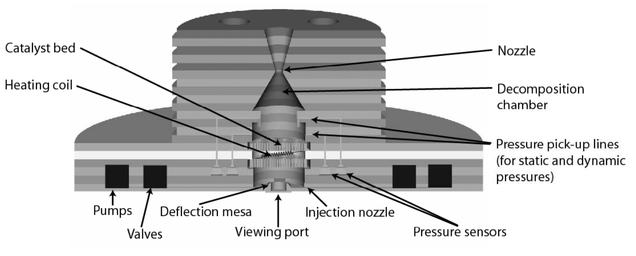

Figure 1: Preliminary design concept

The outputs of these initial analyses, yielded several recommendations aimed at improved the heating profile in the device. As a consequence, a number of modifications were made to the early concept:

- The bulk of the nozzle section was reduced in order to remove unnecessary heat sink;
- The heat sink of the bulk material around the decomposition chamber was reduced by removal of unnecessary material;
- The catalyst bed is suspended on very thin, perforated arms, etched in the silicon wafers, in order to minimise conductive losses between the catalyst bed and the bulk of the microrocket engine (Figure 2);
- A thermally insulating Pyrex wafer has been added to the current design configuration, immediately below the catalyst bed wafers. This wafer is designed to reduce conductive heat losses between the catalyst bed and propellant feed section of the microrocket engine.

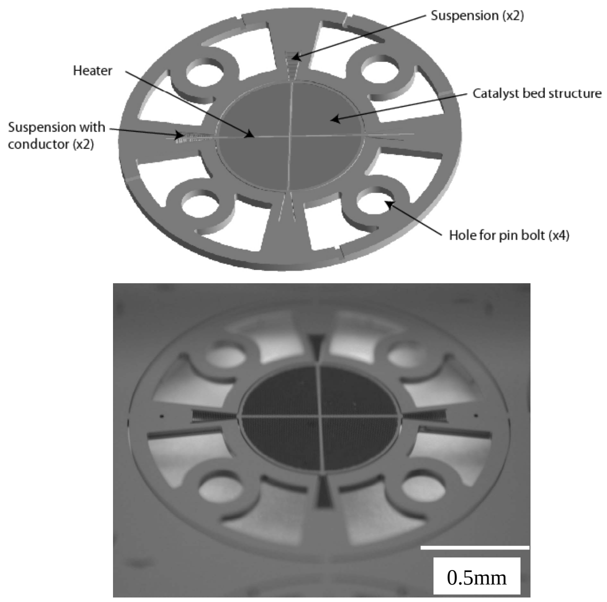

Figure 2: (Top) Layout of a single catalyst bed wafer. (Bottom) A sample catalyst bed wafer from an early fabrication trial

The final iteration of the design concept, following these modifications is illustrated in Figure 3 and Figure 4.

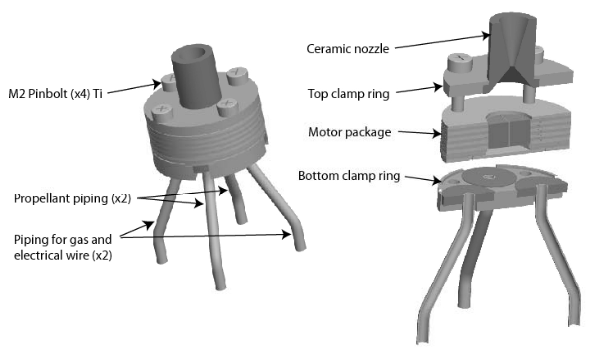

Figure 3: Identification of the key components of the updated DDM concept

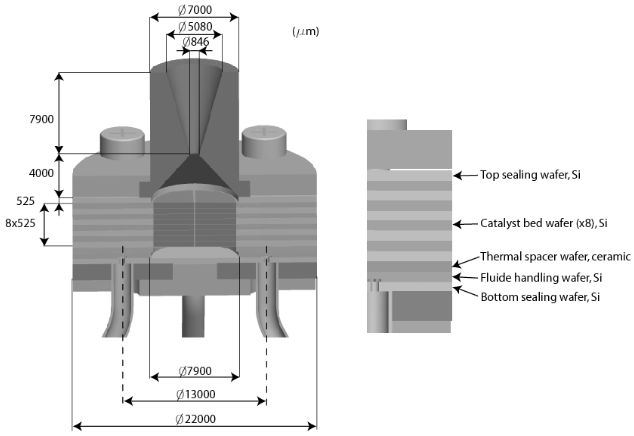

Figure 4: Basic geometry of the motor assembly in the monopropellant concept

4. CONCLUSIONS

Small, light, high power density micropumps would enable miniature or MEMS pump-fed propulsion systems to directly compete with pressure-fed or blowdown systems. These might enable efficient performance at high Isp (>100s) in low chamber residence time micro-rockets, an achievement which has to date eluded micropropulsion designers. However MEMS pumps which can meet rocket propulsion pressure head and flow rate demands do not appear to be feasible. Although ultra-miniaturised precision engineered pumps made using conventional materials, such as steel, may be more practical; their limited technology readiness at present suggests that a conventional engine cycle using MEMS-based turbopumps does not appear to be ideal for a micro bipropellant engine. A pressure-fed / blowdown pressurisation method is most practical for micropropulsion and is being tested for the micro-monopropellant demonstrator outlined in this paper.

MEMS-fabricated sensors and actuators have been the subject of significant research effort, resulting in components which include valves, pressure regulators, pressure transducers, sensors for measuring fluid flow rate, microheaters, and temperature sensors. As is often the case, the majority of these microfluidic MEMS components have been developed for terrestrial applications and in most cases would be unsuitable for direct application to the demanding environment posed by a spacecraft micro rocket engine. However, given further development there appears to be little reason why these devices could not be adapted for such use.

Further research and development for micro-valve technologies is recommended to ensure that valve capabilities meet the demanding requirements, including acceptable leak rates, sufficient opening / closure forces in a high pressure environment, tolerance to high temperature environment operation, and low actuation response times.

The key focus in the area of materials of high thermal endurance must be the identification and development of suitable techniques permitting microfabrication to be applied to materials other than silicon (and silicon carbide). Current microfabrication processes are quite limited compared with technologies available for large-scale manufacturing; most efforts have concentrated on technology employed for semiconductor fabrication i.e. silicon micromachining (machining of other ceramic materials being less mature). However, manufacturing techniques such as Focussed Ion Beam (FIB) and laser machining may become increasingly applicable to microfabrication with new ceramic materials (provided they can be applied to batch fabrication as per silicon).

This programme continues with the fabrication and test of an integrated monopropellant microrocket engine motor assembly. Achieving efficient hydrogen peroxide decomposition will be of key interest. Initial tests have suggested the key challenges to overcome will be:

- Achieving sufficient catalyst bed loading in a MEMS wafer stack to give stable, complete decomposition;
- Fabricating robust catalyst bed wafers which survive repeated hot and cold starts;
- Optimising thermal input and heat losses to achieve rapid decomposition.

5. ACKNOWLEDGEMENT

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