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Detailed Design of a Monopropellant Microrocket Engine Using MEMS Technology

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Abstract

In this paper, a detailed design of a monopropellant microrocket engine demonstrator model is described, together with the thermal modelling and directions for manufacture and assembly. In order to reach the goal of an extremely miniaturized solution, the design draws heavily on Micro Electro Mechanical Systems (MEMS) manufacturing of silicon. The thermal modelling of the monopropellant decomposition chamber (using Hydrogen Peroxide, HTP, decomposed in a catalyst pack) shows that silicon as the engine bulk material can endure the thermal loads applied. Furthermore, the use of a suspended catalyst bed and a thermal standoff layer below the catalyst should enable rapid ignition times. The design is made by stacking structured silicon wafer parts together in order to form the main motor package. The thermal standoff bridges this part to the bottom interface part (electric and fuel) with a Pyrex wafer. The motor package is completed with a precision-machined boron nitride nozzle. The whole assembly is clamped and bonded together and reinforced by pin bolts. The model engine sits on four pipe legs, two for the fuel inlet and two for electric lines and pressure feedback to the fuel distribution unit. The pipe legs also assist in isolating the hot engine parts from the rest of the spacecraft.

Keywords: Microsatellite, MEMS, monopropellant, rocket, materials

1. INTRODUCTION

One of the fundamental reasons for scaling down rocket engine technology, can be summarised in terms of the cube-square-law. Here the thrust of an engine will scale in accordance with the nozzle exit area (L^2), whilst volume varies as L^3. Ignoring flow losses, the implication of this is that as the length scale of the rocket engine reduces, so the performance, as measured by power density and specific power, increase. As a result, there appears to be good potential for the application of high-performance microrocket engine systems to small satellite technology, which could further enable space missions in the future. Moreover, cost benefits from mass production, using MEMS technology and a highly modular design concept, further paves the way for miniature engines.

A review of the current status of miniaturised propulsion systems (including those based on MEMS technology approaches) has identified a near term performance gap in the market for small satellites, defined by the lack of proposed micropropulsion systems which could provide an Isp (specific impulse) in the range 100-300s. 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 paper describes the results from the detailed design of a Hydrogen Peroxide monopropellant microrocket engine demonstrator model. When completed with a fluid handling microsystem module, the total system mass envelope is targeted at 100g (excluding tank and propellant).

2. DESIGN OVERVIEW

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.

The presented monopropellant microrocket engine design contains a nozzle, clamp rings, and tubes, which are manufactured with traditional mechanical machining methods. The MEMS technology is used in the motor package which includes a thin film coated catalyst bed, with heaters in thin film CrPt. The motor is suspended by four pipes of which two work as propellant feed channels and the other two contain electric wires and return pressure piping. Non-active electric components or sensors are placed outside of the motor structure, with the exception of the heaters / temperature sensors. The motor package integrity is enhanced by four pin bolts which are screwed in the bottom clamp ring with bolts at the top. The clamp rings are manufactured in titanium in order to reasonably match the thermal expansion coefficient of silicon, and because of prior manufacturing experience at small scales.

2.1. The demonstrator monopropellant microrocket model

The design is based on Hydrogen Peroxide as monopropellant and a required nominal thrust of 200mN.

The design is summarized in Figure 1 and 2. Important points are the suspended catalyst bed, which allows for a very rapid temperature rise in the catalyst bed on start-up, and a thermal standoff wafer in Pyrex that protects the propellant inlets from excessive heat. Moreover, compact propellant, electric, and nozzle interfaces are enabled by micromechanical structures. The design successfully passed a European Space Agency review (August 27, 2004).

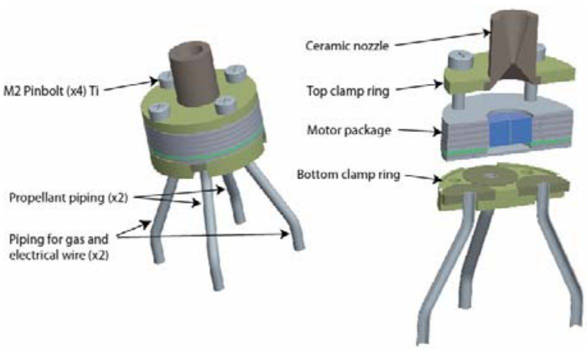

Figure 1: Monopropellant microrocket engine demonstrator model overview.

The initial functional design consisted of the sizing of propellant mass flows, the dimensions of the combustion chamber and nozzle, the dimensions of the catalyst bed for ignition and the sizing of the propellant injection channels. The applied engineering tools are mostly validated for larger scale applications and therefore assessments were made of possible shortcomings of these tools for micro-scale. The experiments will yield valuable data for tool validation and enhancement.

2.2. Thermal modelling

Heat leakage from the hot decomposed gases within the combustion chamber towards the structure will strongly influence thruster performance. This concern arises from the cube-square law, as mentioned in the Introduction. Decreasing the length scale of the thruster increases the contact of the propellant with the combustion chamber walls, relative to the propellant volume flow, causing increased heat transfer to the walls. Detailed thermal analyses have been performed of both transient and steady-state heat flows within the system. Results indeed confirm thermal losses which exceed the losses experienced within larger scale applications, leading to long start-up times (10s or 100s of seconds) and low decomposition temperatures and c* performance. Test data from ultra small conventionally machined ducted rocket engines at QinetiQ supports the model results *(personal communication, M. Wedlock, QinetiQ, October 2004)*. The thermal analysis however suggested several design options for reducing start-up transients as well as improving performance. It was decided to insulate the catalyst bed (see figure 4) and remove unnecessary bulk material. The thermal analysis also assisted with the material choices (see figure 3), to allow higher temperature operation and tolerate thermal shock.

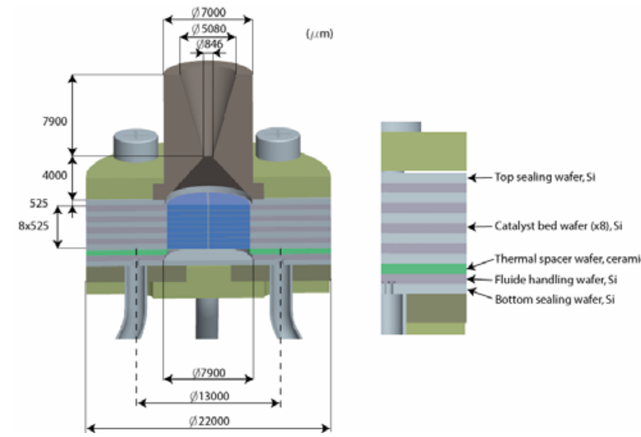

Figure 2: Detailed overview of Monopropellant microrocket engine design. The dimensions are given, and the materials: Silicon for the main motor package, Pyrex for the thermal spacer wafer, Titanium for the clamp rings, and boron nitride for the nozzle. The pin bolts are either tungsten or molybdenum.

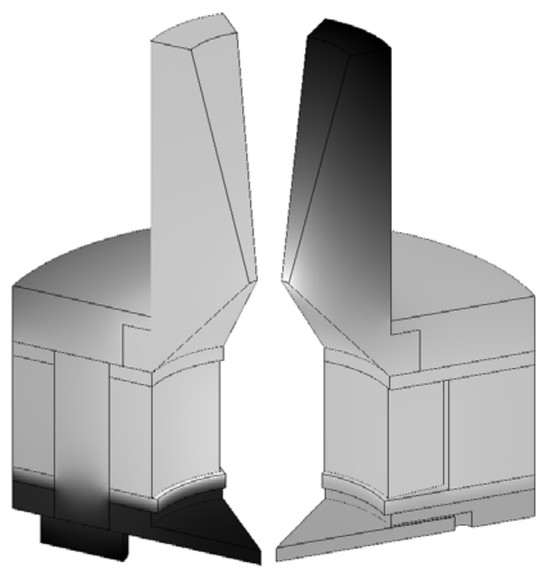

Figure 3: Effect of nozzle material on temperatures. Left a (hot) silicon nozzle. Also note the effect of the insulating wafer and the pin bolt. Right a Pyrex insulating nozzle with a hot spot near the throat. Darker = cooler (~650K), lighter = hotter (max. 900K)

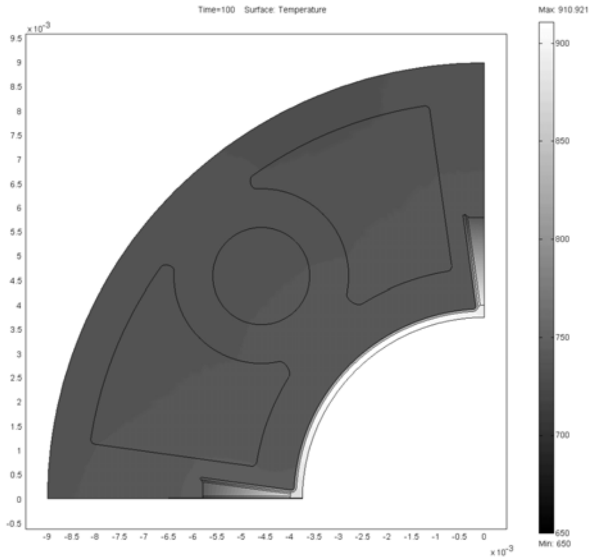

Figure 4: .Clearly visible is the strong temperature gradient from the combustion chamber (light colour) to the bulk material (dark colour) which proves the good isolating quality of the catalyst suspension. (Temperature scale in Kelvin).

2.3. Materials selection

For the decomposing hydrogen peroxide monopropellant microrocket engine concept presented in *Figure 1* and *Figure 2*, 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 (see previous section).

For added simplicity during the development stage, certain parts of the motor package have been fabricated with conventional precision machining techniques and using more common engineering materials (e.g. titanium). Most notable here are the nozzle and the reinforcing parts (clamp rings and pin bolts). Boron nitride has been selected for the nozzle section due to extensive prior experience, with titanium being used in the clamp rings, and tungsten (or molybdenum) in the pin bolts.

All silicon parts make extensive use of Deep Reactive Ion Etching (DRIE) in the manufacture, which allows deep trenches and perforations with high aspect ratio to be readily fabricated. This is complimented by different thin film deposition techniques to add, for example the catalyst material, electric wiring, solder, and insulators.

3. DETAILED DESIGN

3.1. Nozzle

The nozzle in this design is a first iteration concept that is used for the test and verification of the top sealing wafer. This nozzle is mechanical machined in HTP (High Temperature Pressured) Boron Nitride. The nozzle is clamped against a thin flexible silicon ring membrane integral to the top wafer by the upper metal clamp.

3.2. Clamp rings

The top and the bottom clamp rings are mechanically machined in titanium. Titanium is a low density metal with good resistance to hydrogen peroxide. The top ring clamps the nozzle to the motor package, and contains the pin-bolt fittings.

The bottom ring has four milled-out portions for the piping connection housing. The height of the piping connection is slightly larger then the depth of these holes to preclude the ring contacting the entire bottom silicon wafer.

This clamp ring is designed in such a way that the propellant and electrical interface housing units with piping easily can be placed and removed from the mounting places. The clamp has a lip at the top surface with four openings of two different dimensions. The openings with same dimensions are located in diagonally opposing corners. Matching etched cavities are located on the bottom sealing wafer. This should help to prevent accidental substitution of the fluidic and pressure/electrical lines during engine package assembly.

3.3. Catalyst bed

The catalyst bed design is given in detail in a separate paper [2] together with results from the manufacture. In figure 5, the general overview is presented. The motor package contains eight bonded catalyst bed wafers where four wafers contain recessed Platinum/Chromium heaters and the other four without. The heaters become sealed from the gas chamber, which will contain reactive hydrogen peroxide, when one of each are bonded together. The catalyst bed structure is a honeycomb with through etched thin film coated flow channels. The deposited thin film is designed to catalyse the decomposition of hydrogen peroxide. Proposed catalyst film materials are silver or manganese oxide, which are being researched at present with the University of Surrey chemistry department. Each catalyst bed wafer is suspended by four perforated beams to thermally isolate it from the engine structure.

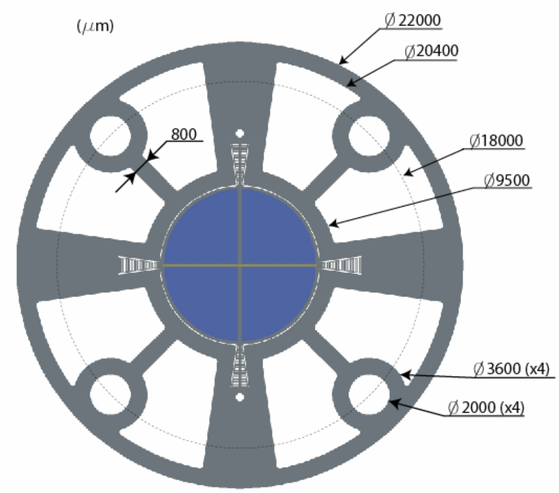

Figure 5: A top view of the catalyst bed wafer with outline dimensions.

3.4. Bottom wafers

The bottom sealing wafer is the interface to the four inlet (I/F) tubes. Thin, flexible silicon membranes surrounding the propellant inlet holes and the electrical via holes offer a sealing function. Sealing will be enforced in operation mode when the membrane cavities become pressurized with chamber pressure. The inlets of the chamber gas are placed in the I/F type B membrane cavities, while the outlet to the fluid handling unit, where the actual pressure is sampled, is in I/F type A (figure 6).

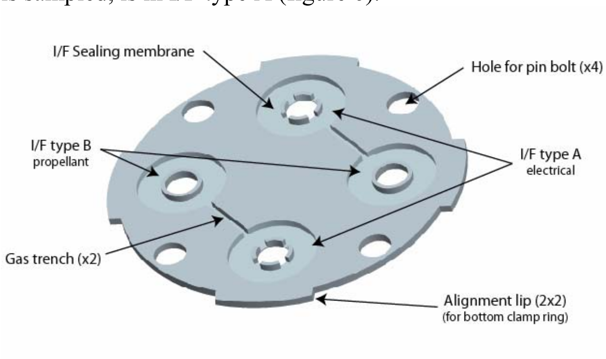

Figure 6: The bottom sealing wafer

The propellant feed channel in the fluid handling wafer (figure 7) is a deep etched trench that surrounds the camber hole. The channel is fed with propellant from both propellant I/Fs in order to have redundancy in the fluid handling unit upstream. The surrounding channel should also result in a more uniform cooling of the wafer around the chamber. The fluid handling unit support propellant to six flow restricting nozzles, injecting fuel to the catalyst chamber. All channels are sealed with the thermal spacer wafer.

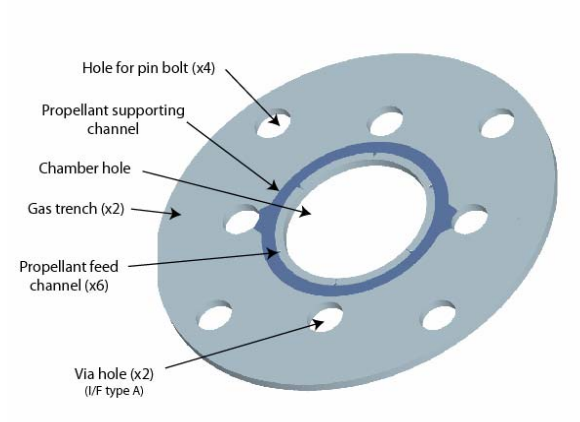

Figure 7: The fluid handling wafer

The thermal spacer wafer consists of a thermally insulating material which can be processed or manufactured with sufficient accuracy, and is capable of being bonded to silicon using established processes. Pyrex has been selected for testing in the first design demonstrator model. The wafer will be integrated using anodic bonding.

4. CONCLUSIONS

Silicon offers good potential for application to the monopropellant microrocket engine concept being developed here, having sufficient thermal endurance for the expected operating environment. From a MEMS point of view silicon is also a well-understood material with suitable microfabrication processes being available. In key areas other materials such as Pyrex and Boron Nitride should enhance performance. In order that this project can focus on the critical MEMS aspects of the design (primarily the suspended catalyst bed assembly) and evaluation of typical flow and combustion phenomena on micro-scale, some of the less critical components (e.g. the nozzle) are to be manufactured using standard precision engineering techniques. In conclusion, the thorough design work has arrived at a robust and adaptable demonstrator model design for the monopropellant microrocket engine.

5. ACKNOWLEDGEMENT

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References

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