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Fluidic Microsystems for Micropropulsion Applications in Space

JOHAN BEJHED



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Abstract

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Spacecraft on interplanetary missions or advanced satellites orbiting the Earth all require propulsion systems to complete their missions. Introducing microelectromechanical systems technology to the space industry will not only reduce size and weight of the propulsion system, but can also increase the performance of the mission.

Fluid handling systems are used in chemical and electric propulsion. Some components incorporated in a fluidic handling system are presented and evaluated in this work.

Microsystems are very sensitive to contamination. Reliable, robust, and easily integrated filters were modeled, manufactured, and experimentally verified.

A fluid connector, designed to withstand large temperature variations and aggressive propellants was manufactured and characterized. Similar designs was also be used as a thermally activated minute valve.

The feasibility of a cold gas system for precise attitude control has been demonstrated. Steps towards improving the performance (from specific impulse 45 s) have been taken, by the integration of suspended heater elements.

For electric propulsion, two thermally regulated flow restrictors have been characterized. These devices can fine-tune the propellant flow to e.g. an ion engine.

A single-use valve using a soldered seal has also been successfully demonstrated within a pressure range of 5 to 100 bar.

The microsystem-based propulsion systems of tomorrow's spacecraft need to be demonstrated in space, in order to gain necessary credibility.

Keywords: microelectromechanical systems, MEMS, MST, microsystem, microfluidics, silicon, spacecraft, propulsion, space technology

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*Till minne av
Per-Erik Granholm*

List of papers

This thesis is based on the following appended papers, which are referred to in the text by their Roman numerals.

- I J. Köhler, J. Bejhed, H. Kratz, F. Bruhn, U. Lindberg, K. Hjort, and L. Stenmark, A hybrid cold gas microthruster system for spacecraft”, *Sensors and Actuators A (Physical)*, vol A97-98, pp. 587-98, 2002
- II H. Nguyen, J. Bejhed, L. Stenmark, J. Köhler, G. Thornell “Sealing mechanism of a dismountable microsystem-to-macropart fluidic connector for high pressure and a wide range of temperature”, *Journal of Spacecraft and Rockets*, 2006 (submitted)
- III H. Nguyen, J. Bejhed, J. Köhler, G. Thornell, “Thermally regulated valve for minute flows”, *Journal of Vacuum Science and Technology*, 2006 (submitted)
- IV J. Bejhed, H. Nguyen, A. Eriksson, L. Stenmark, J. Köhler, “Gas flow characterization of a network of crossed narrow v-grooves in silicon”, *Sensors and Actuators A (Physical)*, 2006 (submitted)
- V J. Bejhed, H. Nguyen, P. Åstrand, A. Eriksson, L. Stenmark, J. Köhler, “Numerical modeling and verification of gas through a network of crossed narrow v-grooves”, *Journal of micromechanics and microengineering*, vol 16, pp 2006-14, 2006
- VI H. Nguyen, J. Bejhed, J. Köhler, G. Thornell, “A solder sealing method for paraffin filled microcavities”, *Journal of micromechanics and microengineering*, 2006 (accepted)
- VII J. Bejhed, P. Rangsten, J. Köhler, “Demonstration of a single use microsystem valve for high gas pressure applications”, *Journal of microelectromechanical systems*, 2006 (submitted)

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The Author's Contribution to Appended Papers

- I Significant part of planning, substantial part of experimentals, significant part of evaluation, and part of writing
- II Significant part of planning, substantial part of experimentals, significant part of evaluation, and part of writing
- III Significant part of planning, experimentals and evaluation, part of writing
- IV Major part of planning, experimentals, evaluation and writing
- V Major part of planning, experimentals, evaluation and writing
- VI Major part of planning, significant part of experimentals and evaluation, part of writing
- VII Almost everything

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Introduction

In the 90s the concept of micro-propulsion was presented. With MEMS (micro-electro-mechanical systems) components a new era of space components would emerge. Complete micro-propulsion systems on a chip and functional pico-satellites, with a size of just 10 cm [1] were suggested. Some years later the state of the art micro propulsion systems were summarized by the Jet Propulsion Laboratory [2]

The space community spends large amounts of money in the development of space MEMS components. The driving forces from the space industry are essentially lower cost and better accuracy. However, as spacecraft are made smaller the propulsion system must also be reduced in both mass and size [1]. It could be argued that light nano and pico satellites will cost much less to launch and put in orbit. Of course it will, but a launcher is still needed. Many small satellites within the same launch vessel will give rise to new problems; how, for instance, should the individual spacecraft be separated from each other [3]? Traditionally, only one or a few spacecraft share the same launcher. However, a cluster of many small spacecraft would provide scientific answers to many questions.

Some possible future missions require more accurate propulsion systems, for example LISA [4] Micro-propulsion is one area where MEMS technology are emerging powerfully, and might fulfill the propulsion requirements on future space missions [5,6]. The propulsion system must deliver a minute and accurate thrust for several years, depending on the timetable of the mission. Also, the spacecraft has a limited amount of fuel, so the gained thrust per mass unit of fuel must be as efficient as possible.

MEMS technology emerged in the 60s with the quartz crystal used in many watches. More advanced MEMS components are found in ink cartridges and car accelerometers. Micro-devices are usually batch fabricated, i.e. many components are manufactured simultaneously. The structures are defined on a silicon wafer by the means of photolithograph, and etched out of the wafer. Complex structures are formed as two structured silicon wafers are bonded together, forming closed cavities or gas channels. A typical gas channel in a MEMS based propulsion system is less than 0.1 mm wide.

As a consequence of the long space qualification process in combination with the complexity of a propulsion system, advanced MEMS components may be widely employed in space applications not earlier than 2010 [7]. The development and evaluation of some MEMS components suitable for space-

craft propulsion are presented within the frame of this thesis, such as micro-isolation valve, filters, and nozzles. These components are planned to be space evaluated onboard the Swedish technology demonstrating satellite “Prisma” in 2008 [8,9].

Spacecraft attitude systems

Spacecraft generally require control systems for attitude and propulsion. Attitude control is required to orient the spacecraft and can be achieved using for example reaction wheels or gyros. This method does not produce a net force on the spacecraft; momentum stored in the spinning wheel is transferred to, and from the spacecraft. If the spacecraft needs to accelerate, a net force has to be applied to the spacecraft. Momentum transfer devices interact with the surroundings to achieve this force, catching the solar wind with solar sails is an example. This technology is however not yet mature enough to be used frequently. A more commonly used technique to achieve a net force is through reaction jets, where mass stored onboard the spacecraft is ejected from the spacecraft.

Chemical and electrical propulsion are both examples of reaction jets. The material expelled in one direction is balanced by a force in the opposite direction, in accordance with Newton's second law. This thesis is limited to chemical and electrical propulsion.

The need of a propulsion system

An orbiting satellite requires propulsion for various reasons. As the satellite leaves the carrier rocket some type of orbit injection is commonly needed. The orbit injection maneuver is a velocity increase, Δv , and the magnitude of the required Δv is strongly dependent of launcher and final orbit.

Spacecraft orbiting in low earth orbits (~600-2000 km) need station-keeping operations. Residues from the earth's atmosphere will reduce the velocity of the spacecraft, and the spacecraft will loose altitude. The only way to counteract this is to increase the spacecraft's velocity. These are costly, in terms of Δv , operations at low altitudes (where the effect from the atmosphere is stronger), especially for larger spacecrafts. On the other hand, satellites in high altitude orbits, as in the geostationary orbit (36000 km), do not need drag compensation.

During a satellite mission, orbit maneuvers might be needed. For instance a satellite can be parked in a lower orbit and at some point during the mission required to rise to a higher orbit. Changing satellite orbit is very costly in terms of Δv .

In addition, an inclination change might be needed. These changes require a velocity change in a direction perpendicular to the orbit velocity. This can be done using nozzles pointing in different directions.

A satellite orbiting the earth needs the ability to point in any required direction. The pointing operation does not change the satellite velocity around the earth, but rather introduces a small angular velocity around the satellite center of mass. This can be achieved by the use of reaction wheels, jets, or magnetic torque. Neither reaction wheels, nor magnetic torques require any propellant, enabling long missions. Other possible three-axis stabilization methods require thrust, thus relying on a type of propellant. These operations do not require large amounts of fuel, but the accuracy of the delivered force is reflected in the pointing precision.

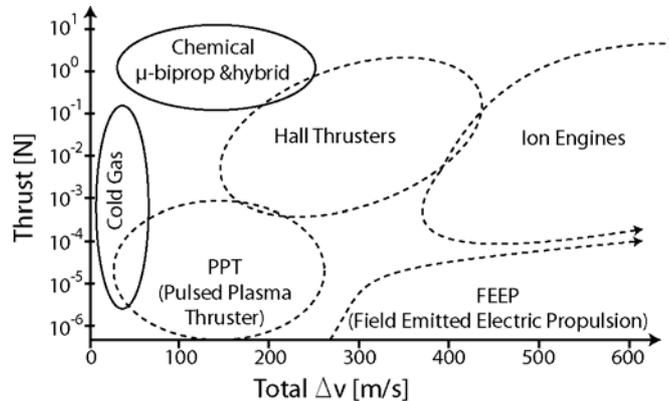


Figure 1. Thrust force for electric and chemical propulsion systems vs. required velocity change, Δv , as governed by the mission. Full lines represent chemical propulsion, dashed lines electrical propulsion. (Reproduced from [3].)

The total Δv required during the complete spacecraft mission is the sum of all individual Δv -s. Once the total required Δv is estimated, the propulsion system can be selected. Large Δv missions typically require electric propulsion, whilst for low Δv missions a cold gas propulsion system is sufficient, as shown in Figure 1.

As the mission is decided, and the engine has been selected, the total required propellant must be estimated. An engine with low efficiency must carry more propellant than a high efficiency engine.

The specific impulse

Reaction jet propulsion systems all carry propellant stored in a tank onboard the spacecraft. The amount of propellant carried on the spacecraft will determine the spacecraft's lifetime. Therefore, the propellant in the tank must be used as efficiently as possible. When it comes to chemical and electrical

propulsion, specific impulse, I_{sp} , is a commonly used figure of merit, or a propellant efficiency measure. A low I_{sp} propulsion system requires more propellant to achieve a certain velocity change than a high I_{sp} system. Hence if a low I_{sp} engine is used, more propellant must be stored onboard the spacecraft, which will increase its weight and so the launch cost. Accordingly if the same amount of propellant is used by a high I_{sp} system, the launch cost remains the same, but the lifetime will be longer. Either way it is more cost efficient to have a high I_{sp} propulsion system.

The I_{sp} for a cold gas system can be calculated using

$$I_{sp} = \frac{1}{g} \sqrt{\frac{2 k R_m T_0}{k-1} \left(1 - \frac{p_{out}}{p_{in}}\right)^{\frac{k-1}{k}}} \quad (\text{eq. 1})$$

where g is the gravitational acceleration constant, k the ratio of specific heat capacities, R_m the gas-specific constant, T_0 the gas temperature, p_{out} the pressure at the nozzle output, and p_{in} the inlet pressure [1]. It is evident, from eq. 1, that the only way to increase I_{sp} , once the propellant gas is selected, is to increase the gas temperature. The velocity change, Δv , is calculated using the rocket equation,

$$\Delta v = g I_{sp} \ln \left(\frac{m_0}{m_0 - m_p} \right) \quad (\text{eq. 2})$$

where m_0 is the initial spacecraft mass and m_p the mass of the used propellant. It becomes evident from eq 2 that a high I_{sp} is necessary to achieve a large change in velocity without consuming large amounts of propellant [10]. The obtained force follows $F = g I_{sp} \dot{m}$ (eq. 3), where \dot{m} is the mass flow.

High I_{sp} engines are typically found in electric propulsion systems. In electric propulsion the propellant is electrically charged, i.e. ionized, and accelerated using an electric field before leaving the spacecraft. The increased exhaust velocity is identical to an increased I_{sp} .

In Figure 1 electric propulsion is shown with four sub domains: Hall thrusters, ion engines, pulsed plasma thruster (PPT), and field emitted electric propulsion (FEEP). Clearly electric propulsion dominates in high Δv missions. Electric propulsion can also produce the small forces required for fine positioning. Chemical propulsion, on the other hand, is more easily integrated on a satellite. Also, chemical propulsion does not require large amounts of power, which makes the system lighter. If the mass budget is limited, e.g. as for a nanosatellite, chemical propulsion is the favorable propulsion system.

System-specific impulse

An aid when selecting propulsion system is the system-specific impulse [11,12]. The specific impulse only addresses the performance of the nozzle,

not including all surrounding equipment needed in the propulsion system. The system-specific impulse, I_{SSP} , on the other hand, includes the mass of the propellant tank, piping and housing, electric converters, etc, thus

$$I_{SSP} = \frac{I_{tot}}{m_{ps} + m_{el}} \quad (\text{eq. 4})$$

where I_{tot} is the total impulse delivered by the system, m_{ps} the propellant storage mass, and m_{el} the mass of the electric system. (In a cold gas system m_{el} can be ignored.)

Upon introducing the I_{SSP} parameter, it becomes apparent that heavy electric propulsion is suitable for heavier spacecraft with large Δv operations, or long time mission time. Due to the simplicity of cold gas propulsion system, m_{ps} is small, making them more suitable for low Δv missions or short time missions.

Chemical propulsion

Chemical propulsion systems come in a manifold of different appearances, all sharing the same physical property: Material is expelled in one direction to obtain a force in the opposite. The propellant in a chemical propulsion system can be stored either in solid, liquid or gas phase. The simplest chemical propulsion system is the cold gas system, where cold gas is expelled through a nozzle. The gas velocity, and hence the I_{sp} , depend on the propellant used, the temperature of the propellant, and the shape of the nozzle. In a cold gas system an inert gas is commonly used, e.g. nitrogen. For a given gas, only gas temperature and nozzle shape remain to vary in order to increase I_{sp} .

More sophisticated chemical propulsion systems involve chemical reactions before the propellant enters nozzle. Another method is to decompose the propellant, using some catalytic material. To increase I_{sp} as much as possible, it is required that the reaction occurs at the right place, and that the reaction produces the required substances.

In Table 1 some conventional chemical propulsion systems are listed. The I_{sp} for the systems ranges from 75 up to 220 s. The force ranges from mN to around 100 N.

Table I. *Thrust performance of different chemical propulsion systems for microsattelites [13]*

| Type | I_{sp} [s] | Thrust [N] |
|--------------------------|--------------|------------|
| Cold-gas thruster | 75 | 0.005 |
| Solid rocket | 185 | >100 |
| Hydrazine monopropellant | 220 | 1 |

The cold gas system has a very important benefit: It is simple. With reaction systems, separate storage tanks, with separate piping and valves are required for each propellant used. In the cold gas case, one tank and one set of piping is sufficient.

MEMS based cold gas propulsion

A cold gas system, either a conventional one or one using MEMS components, comprises [5,1] a gas storage tank, an isolation valve, a filter, a pressure transducer, a fill and drain valve, a pressure regulator, a pressure relief valve, a flow control valve and nozzles.

The control valve in such a system can either be an "on/off" valve, or a proportional valve. The on/off valve is only capable of delivering either full or no propellant flow. A proportional valve, on the other hand, can adjust the flow level, thus controlling the thrust proportionally.

An attractive method to increase I_{sp} of a cold gas system is to increase the gas exhaust temperature.

Micromonopropellant rocket engine

An additional chemical propulsion system is the monopropellant micro kick engine [14,15], shown as a microsystem in figure 2. The propellant in this engine is hydrogen peroxide. As the propellant passes through the catalytic reaction chamber, it is reduced to oxygen and water [16,17], causing a large temperature increase, and increased flow velocity. Force is obtained when the reactants are lead through a nozzle. The I_{sp} of this engine should be around 150 s.

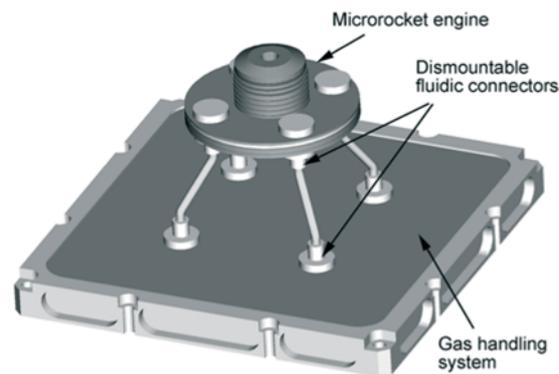


Figure 2. Conceptual monopropellant microrocket engine assembly. The engine is attached to a fluid handling MEMS module.

The micro kick engine operates at a relatively high pressure, with large variations of temperature, and with an acid as propellant. This harsh environment restricts the materials possible to use. The large temperature variation calls for the use of materials with thermal expansion coefficients similar to that of silicon. Also, the connector must be non-permanent, i.e. not welded, since the component might need to be replaced.

Electric propulsion system

Electric propulsion is the collective name of several different propulsion methods. In electric propulsion thrust is obtained through positively charged ions expelled from the spacecraft. (Negatively charged ions, or electrons, must also be expelled, to avoid charging of the spacecraft.) The performances of four types of electric propulsion system are visualized in Figure 1. The systems differ mainly in ionization technique and propellant.

In FEEP devices a liquid propellant is ionized by a strong electric field at a capillary apex, and the resulting ions are accelerated. The propellant is commonly cesium or indium. The propellant in PPT devices is commonly Teflon. A local plasma is achieved by a small electric discharge. The resulting ions are accelerated to increase the thrust.

Both the Hall and the ion propulsion system commonly use xenon as a propellant. Both technologies extract ions from a xenon plasma. The plasma density is generally lower in ion engines, compared to the Hall thruster, since the plasma is created through either DC electron bombardment or RF accelerated electrons. In the Hall thruster a static magnetic field is utilized, efficiently increasing the electron density and thereby the plasma density [18,19]. The flow of the gaseous propellant must be carefully controlled in both the ion and Hall engines. First the gas pressure from the storage tank must be significantly reduced before minute amounts of gas are fed to the thruster. Second, the thruster requires at least two independently controlled feed lines, one for the main discharge (thrust-generating flow) and one for the neutralizer (to avoid charging of the spacecraft). This kind of propellant feed system is normally rather heavy, around 10 kg [20]. The weight could be reduced significantly with MEMS technology.

MEMS based fluid handling system for electric propulsion

A xenon feed system comprises an isolation valve [VII], a high pressure reducer, a flow control unit, a pressure relief valve, and control electronics [21]. A possible design of such a system is depicted in Figure 3.

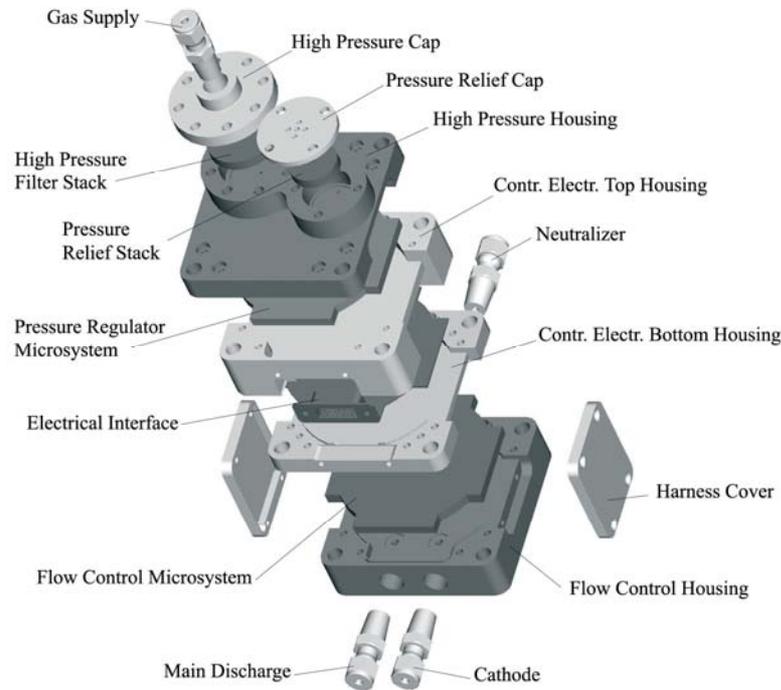


Figure 3. Exploded view of the xenon feed system.

The highly pressurized gas (~ 200 bar) from the propellant storage tank enters the isolation valve. This valve is perfectly leak-proof, opens irreversibly, and allows the gas to enter the high pressure unit. This unit reduces the pressure to around 5 bar and contains valves that can be closed if the thrusters are turned off. The flow control unit adjusts the flow to the thruster. It is also capable of measuring the flow fed to the thruster.

The development and characterization of some of these components are covered in this thesis, namely the flow restrictor, the flow sensor and the isolation valve [VII].

Selecting propulsion system

When selecting the propulsion or attitude control system for a spacecraft the required Δv , for the entire mission must be known. Also, the required maximum and minimum force must be known. An orbit maneuver requires large Δv , but not necessarily a large force. If the orbit change must be very fast, in just a few hours, a higher force is required. On the other hand, it is impossible to make small adjustments using a high force propulsion system.

Chemical propulsion systems generally have lower I_{sp} , but can deliver high forces. In chemical propulsion the gas, or the residues after a reaction, are led out from the spacecraft through a nozzle. Chemical propulsion in

general, and in particular cold gas propulsion, is easily integrated within a spacecraft. It does not require large amounts of power, but still large propellant tanks due to the low I_{sp} .

Electric propulsion utilizes high acceleration voltages and has a rather high power consumption. To achieve the high voltage, converters are required, and to meet the high power consumption, large solar panels are required. Both of these are quite heavy, which will affect on the mass budget of the spacecraft. The larger solar panels will also affect the size of the spacecraft. The increased mass and size is, however, easily compensated for in long time, or high Δv , missions.

Benefits with satellite MEMS components

There are two main reason to develop miniaturized propulsion systems, one economical, and one technical. To gain less expensive access to space, the launch cost must be reduced. Missions requiring multiple spacecraft will save launching cost, if they can share launcher. MEMS technology also offers true multifunctionality. A single module can, for instance, hold a thermal control module and simultaneously act as an RF antenna [22]. The same mass and volume can then serve two purposes.

Building a whole spacecraft using MEMS technology, will give rise to new demands. A nanosatellite (<10 kg) has not the mass or power budget to hold a conventional propulsion system. The development of nanosatellites demands the development of MEMS based propulsion system. Also, MEMS fabrication allows for putting multiple components in the same module, drastically changing the satellite design [23]. With this the complete module is treated as a “black box”, thus all components within are simultaneously space qualified. Normally, each individual component, together with the piping and electrical contacts, must be qualified separately. This is tremendously expensive.

All components comprising a micropropulsion system must be manufactured using MEMS technology. An ordinary valve, combined with a micronozzle is simply not good enough. The piping required to join the two components will raise the system mass and volume. Also, conventionally manufactured gas piping will still be very large compared with gas channels manufactured using MEMS technology. The extra volume introduced will increase the system’s dead volume, which will reduce the overall performance of the system significantly.

Propulsion systems, capable of operating accurately, with low noise levels, in the micro to milli Newton range, have been identified as key components in future missions [6]. Missions serving to gain deeper understanding of the universe simply demand accurate propulsion systems.

MEMS components for space propulsion applications

The fluid handling system for chemical and electrical propulsion require similar components, as shown in Figure 4

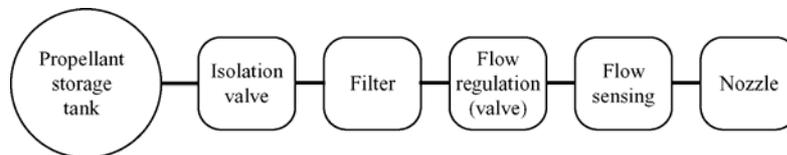


Figure 4. Schematic of a fluid handling system for chemical and electrical propulsion.

The propulsion system is isolated from the storage tank using an isolation valve, preventing leakage prior launch and during travel until the propulsion system is activated. The delicate MEMS structures require perfectly filtered gas, which is why particle filters must be incorporated. A key component in any propulsion system is the flow regulator. This component modulates the flow to the nozzle, and is commonly a proportional valve. Downstream the valve, some gas characteristics must be measured, such as pressure, temperature or flow. The last component in the propulsion system is the nozzle.

If the components are manufactured separately, and not as a complete propulsion system integrated on a single chip [2], some type of connection between the conventional tubing and the MEMS components must be used [II]. Standard o-rings are sufficient if the propellant is non-oxidizing, and limited temperature variations are expected.

In the following, the fundamental building blocks of a miniaturized propulsion system treated in this thesis (or slightly aside) will be briefly described.

Dismountable macro-to-micro fluidic connector

The sealing method investigated here [II] uses the deflection of a ridge-equipped membrane, as illustrated in Figure 5. The membrane with ridge – the micropart – is manufactured from a silicon wafer whereas the counter part – the macropart – is formed from stainless steel. This connector is in-

tended for use in harsh environments, with either aggressive fluids or large temperature variations, or both.

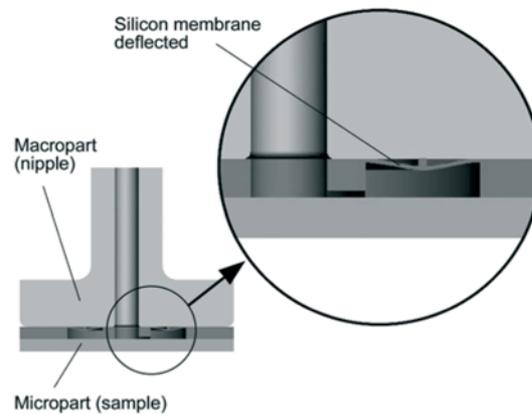


Figure 5. Cross section, with enlargement, of the dismountable macro-to-micro fluidic connector.

When pressed together the membrane is forced to deflect and the thin ridge will exert pressure on the nipple. The high pressure formed between the micro and macro part is sufficient to prevent leakage as gas pressure is applied.

The deflected membrane serves more than one purpose. First the deflection compensates for misalignment or non-parallel surfaces. Second, as the temperature increases, the thermal expansion mismatch will cause relaxation of the membrane without disengaging the ridge from the macropart.

The leakage behavior of the fluidic connector was evaluated and a sufficiently low leakage rate was confirmed in the temperature interval of $\pm 100^{\circ}\text{C}$, and an applied helium pressure of 9.7 bar.

The design of the membrane is very critical. A membrane too stiff will either easily break, or cause imprints in the macropart. In the latter case the connector is still leak tight, but the damaged macropart cannot be used again. A membrane too weak will not apply sufficient pressure to the macropart, and so result in leakage.

One-shot valve

In many space applications one-shot valves are used [24]. Such a valve is placed between the propellant storage tank and the propulsion system, and must be perfectly leak proof until activated. An interplanetary mission, involving long travel times, will fail if the propellant is lost due to leakage. Once the valve has been activated, it cannot be closed again. However, the valve must not fail to open, since the entire propulsion system relies on this.

The valve developed and verified [25, VII] is illustrated in Figure 6. It consists of a single inlet connected to a crossed v-groove filter [IV, V]. The inlet is solder-sealed leakage proof [VI]. Upon activation, a voltage is applied to the heater element, centralized around the inlet. The heat generated is sufficient to re-melt the solder, and the high pressure from the storage tank will force the solder into the filter, thus opening the valve. The filter will absorb the solder residues, and provide a particle-free gas.

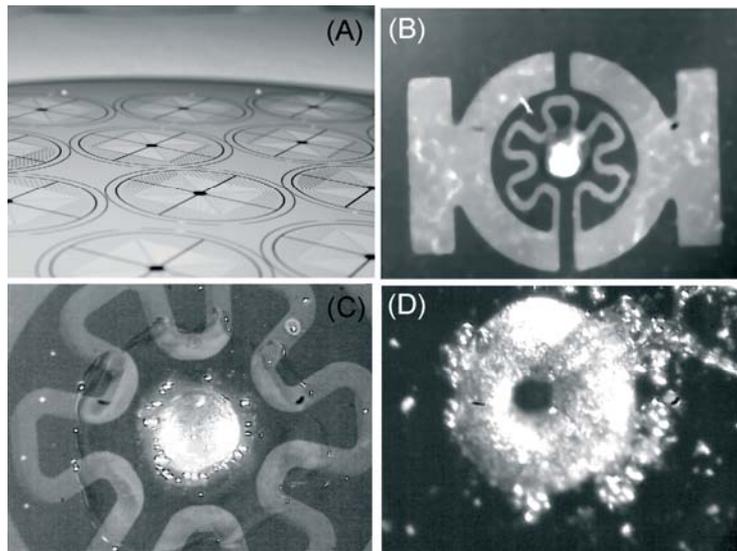


Figure 6. Pictures of single use valve. During manufacture (A), completed manufacture (B), close-up on the solder sealed inlet hole (C), and after activation (D).

The valves manufactured were evaluated in terms of pristine flow, post-activation flow, and power consumption. It was concluded that the main flow restriction was not caused by the filter itself, but rather the distribution channels within the filter. The valves required a high activation energy, typically around 100 J. The rather slow temperature increase raised the silicon temperature evenly, reducing the effect of the centralized heater element.

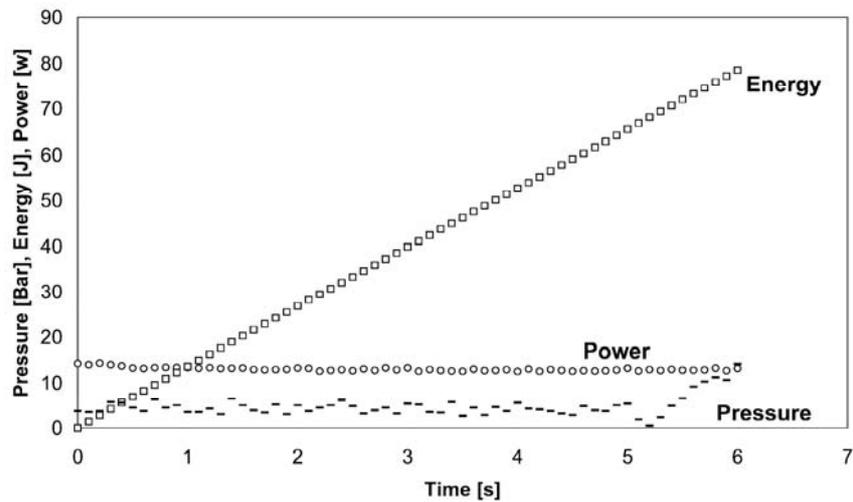


Figure 7. Activation process of a one shot valve. Power is instantly applied to the valve, which is opened at approximately 5.5 s.

To enhance the performance of this device the applied power, as shown in Figure 7, should be raised. However, in this design, the intention was to draw the power directly from the target spacecraft power bus which is limited to 28V.

Filter

Throughout the space components manufactured, particle filters are present. These filters must be easy to integrate with a system. They must also be quite mechanically strong if high pressures are involved. They must also remove particles from the gas at a reasonable loss of performance in terms of pressure drop.

The filter [IV] is manufactured from two silicon wafers. Narrow v-grooves are formed in the surfaces of the wafers together with wider distribution channels and through wafer holes. When two wafers are bonded together the v-grooves overlap completing the filter. Some filters only held v-grooves in one wafer in order to verify the flow properties in straight narrow channels.

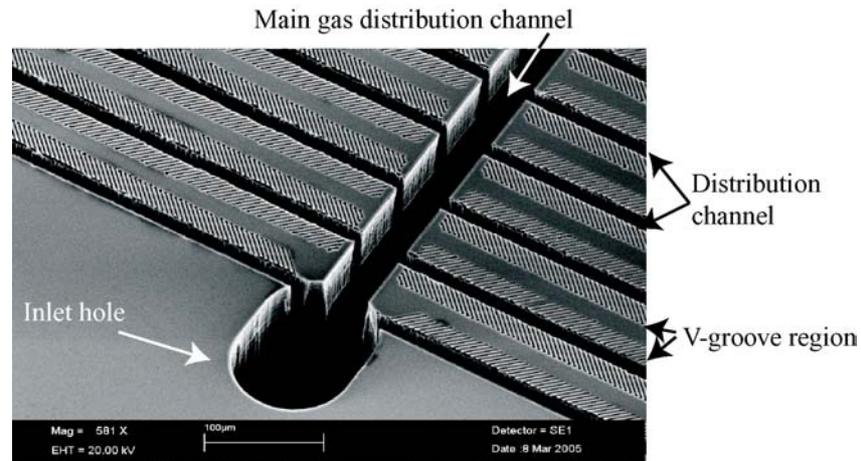


Figure 8. SEM picture of one filter wafer.

The filters were characterized in terms of mass flow versus pressure. The characteristics of the filters were correlated to their geometrical properties. By this, proportional constants were obtained for both the crossing v-groove filter and for the straight v-groove filter.

This approach lacks the possibility to predict the behavior of an arbitrarily designed v-groove filter, since measurements must be made on similar structures. A numerical approach was used making it possible to predict the behavior of any crossed v-groove filter, without the need for measurements [V]. In the numerical approach the filter was divided into several regions with corresponding pressure drops. First, the pressure drop is calculated over the small distance leading to, and from, the main gas distribution channels into the crossing region, as well as within the crossing region, and then the total pressure drop is calculated as the sum of the individual pressure drops.

The flow and pressures were all calculated using the finite element method. The results were compared with those from the measurements with reasonable good agreement. Figure 9 shows the ratio between modeled and measured mass flows for the filters manufactured.

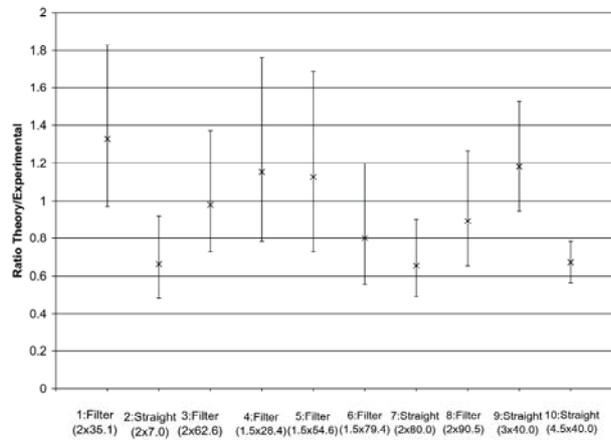


Figure 9. Evaluation of the filters, presented as the ratio of theoretical and experimental flows

The numerical approach enables the possibility to design a filter, given the required mass flow, allowable pressure drop, and maximum particle size (width of the groove), without the need of preliminary measurements.

Flow regulation

A valve is the typical flow regulation method. The flow rate varies as the distance between a valve seat and a valve cap is changed. In addition, the fluid properties can be changed in order to modulate the flow rate; viscosity, for instance, changes with temperature.

Minute flow gas valve

A system, similar to the fluidic interface [see page 20], was manufactured [III]. A very flat stainless steel macropart was pressed against a silicon chip. The silicon chip was prepared with a well-defined silicon ridge. As the macropart is forced into contact with the chip, the ridge elastically deforms the stainless steel. Upon heating this system, the difference in thermal expansion will separate the ridge from the macropart, since the silicon chip is not equipped with a membrane. Upon decreasing the temperature again the ridge will again come in contact with the macropart.

The movement of a lid from a seat is the general principle of a valve. This thermally actuated valve was found suitable for low mass flows, since the stroke length is small.

Thermal flow restrictor

A thermally-actuated flow restriction was selected as the base-line for the design of the flow-control unit for electric propulsion. This device utilizes the temperature-dependent viscosity of xenon [26]; As the temperature is increased the viscosity of xenon increases [27] and the mass flow will decrease.

Figure 10 contains one type of thermally actuated flow restrictor [28]. Long meander-shaped arms, containing the gas channels, lead the gas into a heat-exchange chamber [29]. These arms are long and suspended to reduce thermal losses from the heated chamber. Heat is generated from thin film platinum heaters on the outside of the chamber. This heat is conducted through the silicon into the streaming gas by lamellas in the chamber. In addition the lamellas act as restrictors.

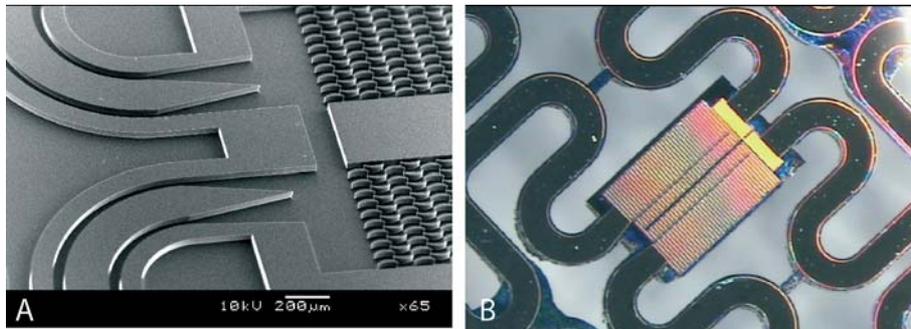


Figure 10. (A) Thermal flow restrictor, with heat transferring lamellas, (B) Overview of complete, sealed device.

Upon characterizing the functionality of the device, it was found that the main flow restriction was not caused by the lamellas in the heat exchange chamber, but rather by the long winding channels leading into the chamber. Figure 11 shows an example of measurements from a thermal flow restrictor. Clearly, the mass flow decreases with increased temperature. Unfortunately the effect was not good enough for the application.

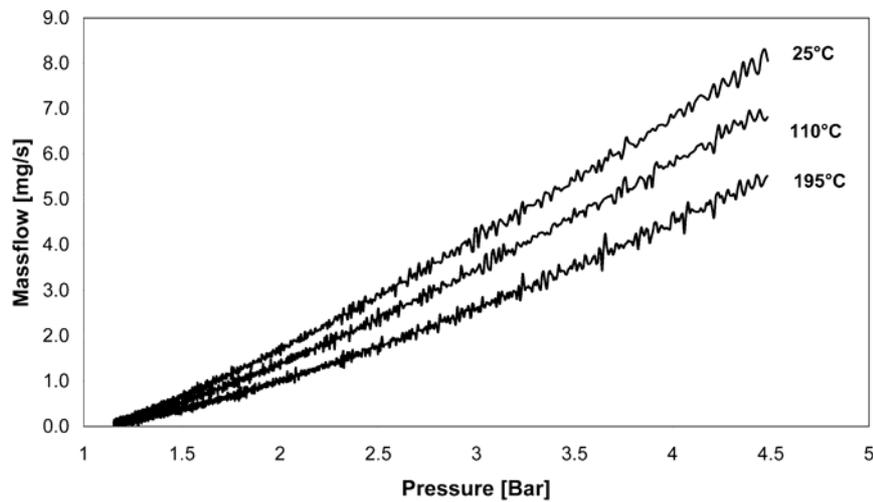


Figure 11. Flow characteristics of the thermal flow restrictor.

The design was altered, according to the device in Figure 12. The heat exchange chamber was replaced with a long suspended spiral channel with platinum heaters on its outer surfaces.

The evaluation showed that the heat generated was insufficient to modulate the flow because of losses to the surroundings.

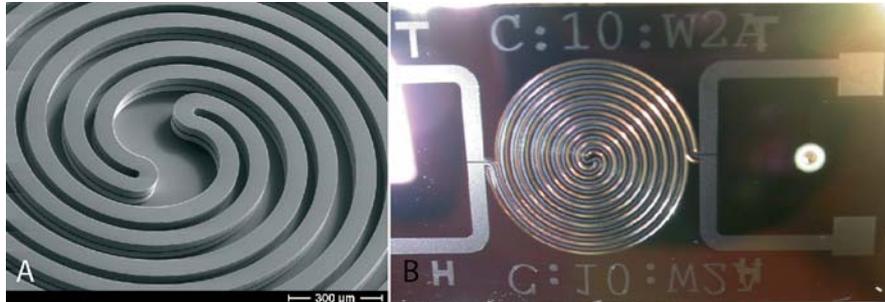


Figure 12. The spiral thermal flow restrictor prior bonding (A), and completed (B).

The thermal flow restrictor could thus not work alone as the main flow controller. It can, however, be coupled in series with an ordinary valve, acting as a main restrictor, and fine tune the flow.

Solder seal

The phase change material paraffin has been studied as an actuation agent for valves, as its expansion when changing from solid to liquid form is large [30]. If a paraffin container has a weak, pliable part such as a membrane, a large and directed stroke can be achieved. This stroke could be used to con-

control the flow of a valve, if valve seat and valve cap are properly designed [31].

After filling a cavity with paraffin the filling hole needs to be permanently sealed. The method proposed here [VI] is to solder-seal the paraffin filling hole.

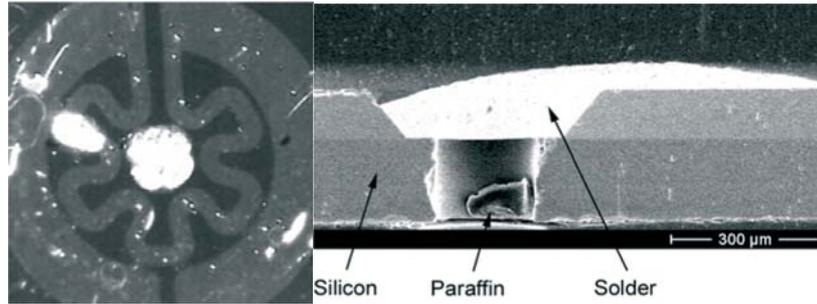


Figure 13. Top view of the paraffin seal (left), and cross section of the seal (right)

In order to evaluate the solder sealing properties, numerous samples were manufactured. Each of these silicon chips had a square cavity etched in potassium hydroxide, KOH, around a circular through hole, formed by Deep Reactive Ion Etch, DRIE. On the surface close to the cavity Ti/Cu were evaporated through a shadow mask. The evaporated patterns were a solder region, i.e. a circular region covering the area around the square cavity, and a surrounding meander-shaped heater. Before a solder paste was screen printed onto the samples, each chip was covered with paraffin to mimic actual sealing conditions. When voltage was applied to the heater element, first the paraffin, and later the solder melted. The molten solder will align perfectly to the copper pad. Figure 13(left) shows a successful solder seal seen from above, and Figure 13(right) shows a diced and polished sample, in cross section.

The solder sealed hole was leak tested at temperatures above the melting point of the paraffin for several hours. No leakage was observed. This method is promising for sealing paraffin-filled actuators. However the alignment of the solder pad and the screen print method need further optimization.

Hot wire flow sensor

The basic principle of this sensor type is to measure the temperature increase of a streaming gas after a small, and well known, amount of power has been injected to the gas [32,33]. If the pressure of the gas is known, the temperature increase measured corresponds to the mass flow.

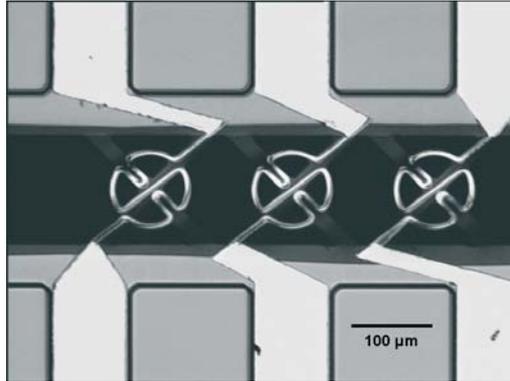


Figure 14. An anemometric flow sensor, with thin film Pt heaters on silicon oxide bridges. The first and last bridge measures temperatures, whilst the center bridge provides power.

Figure 14 depicts three oxide bridges, patterned with thin film platinum. The first and last bridges serve as temperature sensors, and the middle as a heater element.

The goal of these sensors was to demonstrate a more robust integration method than what is usually achieved, with respect to thermal and mechanical loads, also in order to obtain high yield of production. During the project, this goal was partly fulfilled, although problems remain with lifetime and sensitivity.

Cold/Hot Gas Micropropulsion System

It is inefficient just to expel the gas out through a channel. To increase the I_{sp} the velocity must be increased, using for instance a Laval nozzle, shown in Figure 15. The gas velocity must increase through the throat of the nozzle, to keep the mass flow through the whole nozzle constant. If the design of the nozzle is correct, the gas will reach sonic speed at the throat [34]. In the diverging zone, the gas velocity can continue to increase, to a supersonic flow level.

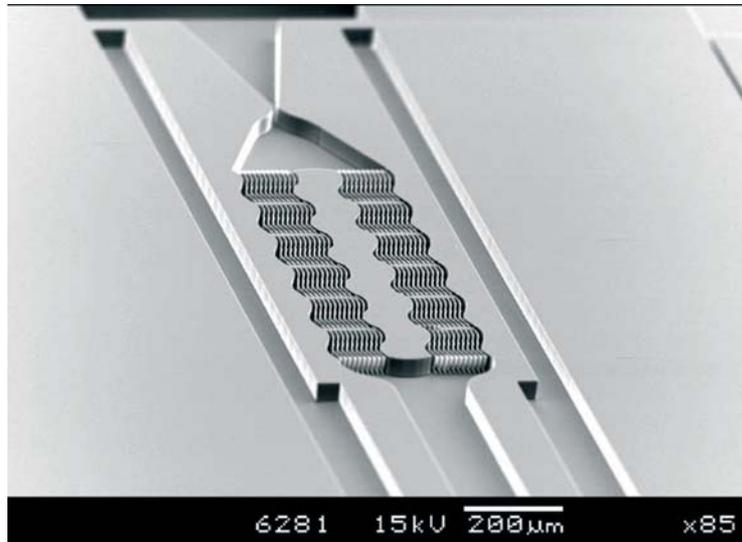


Figure 15. A cold gas micro nozzle manufactured using deep reactive ion etching

The I_{sp} of the nozzles was measured to around 45 s, which should be compared with the theoretical limit of 75 s for nitrogen at room temperature [35]. The nozzles here are merely two dimensional, why the theoretical limit is inaccessible. However, there is room for improvements, except for making a perfect 3-D nozzle. As clearly shown in equation 1, I_{sp} is proportional to the square root of the gas temperature, suggesting heating for an efficiency gain.

Heated gas

To enhance the performance of a cold gas micronozzle the temperature of the gas in the subsonic, convergence zone, could be increased [36]. As the I_{sp} is proportional to the square root of temperature, a fourfold increase of the gas temperature will double I_{sp} .

It is most favorable to heat the gas as close to the nozzle as possible. Heating the gas far away from the nozzle is disadvantageous since the flow resistance, and so the pressure loss, will increase. Also, as a heated gas passes through the microchannels some heat will be lost to the surroundings, reducing the gas temperature and increasing the temperature of the bulk silicon.

Before the nozzle a heat exchange chamber is positioned. The chamber is equipped with heat transferring lamellas, shown in Figure 15, to increase heat transfer.

Experiments with freely suspended heater coils of diamond like carbon (DLC), and tungsten covered DLC [37,38] indicated temperature increases of up to almost 1000°C, efficiently doubling the I_{sp} . Another method would be to use low resistive silicon heaters in the gas flow. However, silicon is not

very temperature resistant, compared to DLC-coils or tungsten covered DLC-coils. Silicon will start softening at 700-800°C, thus they cannot operate at the same temperature levels as the DLC-coils. Figure 16 depicts heaters integrated in the stagnation chamber prior to the nozzle to the left.



Figure 16. DLC heater elements integrated in a micro nozzle (The gas flow is from right to left)

The functionality of a nozzle with internal heaters has been verified in terms of mass flow change. First, the mass flow was measured through the nozzle without active heaters, then the mass flow change was recorded as power was applied to the heaters, shown in Figure 17. It is evident that the heater elements transfers heat to the streaming gas, as the mass flow is reduced as the heaters are activated, hence increasing the I_{sp} .

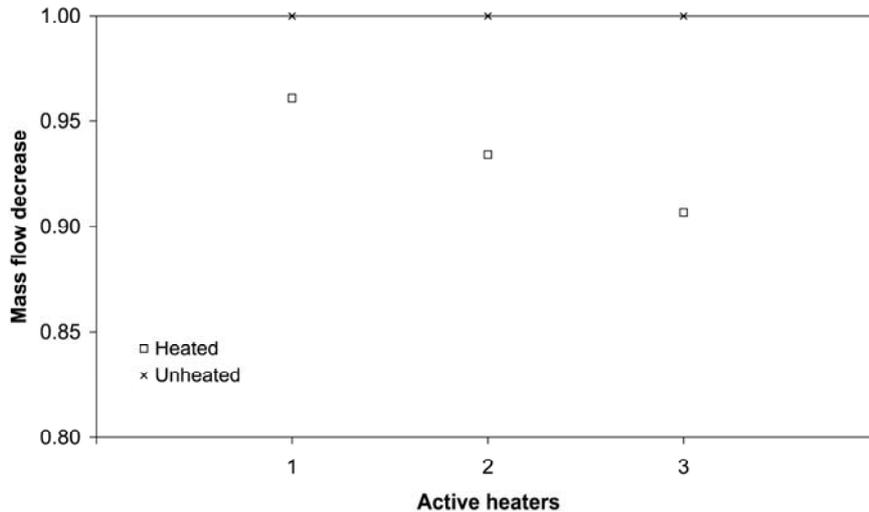


Figure 17. Mass flow decreases as power are applied to the heaters. Diagram shows the ratio of mass flow decrease as a function of number of heated coils.

Outlook

Propulsion systems for the next generation spacecraft will look different from the systems used today once MEMS components are readily accessible. Of course they will be smaller and lighter, but also more accurate and precise.

A single component is not very interesting for the space community when similar, conventional and flight proven, components are accessible. Replacing a single component with a newly developed MEMS component will not improve the propulsion system enough to justify jeopardizing the mission. In addition, many of the benefits with miniaturization will be lost if microcomponents must be interfaced with macroparts instead of integrating with other microcomponents. This makes the not-allowed-to-fly-before-certified-by-flying threshold even higher for MEMS than other technology shifts in the space community.

Complete propulsion on a chip is unfortunately still far away. However, several components have been demonstrated, other have been evaluated. Some components are close to becoming usable products. A MEMS module, comprising the most critical propulsion components is not very far away. A successful launch, in the nearby future, of a moderately advanced MEMS-based propulsion system is necessary.

Swedish summary

Satelliter och interplanetära rymdfarkoster behöver dels ett attitydkontrollsystem, samt ett framdrivningssystem. Attitydkontrollsystemet används för att rikta satelliten medan ett framdrivningssystem behövs för att korrigera satellitens bana. Två system som ofta används är kemisk och elektrisk framdrivning. Ett enkelt kemiskt system består av en bränsletank, en ventil och ett munstycke. Bränslet släpps ut genom munstycket under högt tryck, vilket resulterar i en kraft på satelliten. I det elektriska systemet så accelereras joner upp till mycket höga hastigheter innan de kastas ut i rymden.

De två olika systemen har sina respektive för- och nackdelar. Ett elektriskt system kräver relativt mycket kringutrustning och förbrukar hög effekt. Detta ökar satellitens massa, men motorn blir bränslesnål, så massa kan sparas i den änden.

Ett kemiskt framdrivningssystem är mycket enklare än ett elektriskt. Det behöver vanligen inte lika mycket kringutrustning och förbrukar inte heller lika mycket effekt. Däremot används inte bränslet lika effektivt varför mer bränsle förbrukas.

Vilket system man använder beror helt på vilken uppgift satelliten skall genomföra. En resa till den mest avlägsna planeten, Neptunus är olämplig att genomföra med ett kemiskt system. Mängden bränsle som behövs blir snabbt för stor.

Gemensamt för de båda systemen är att de behöver hantera bränsle, ofta vätskor eller gaser. Detta kräver ett system som sitter mellan tanken och munstycket och reglerar mängden gas till munstycket. Sådana system skulle kunna tillverkas som mikromekaniska komponenter. Dessa komponenter kan leverera väldigt exakta mängder bränsle, vilket skulle höja precisionen på framdrivningssystemet. Flödesmängderna i dessa framdrivningssystem är mycket små, varför gaskanaler med en tiondels millimeters bredd är fullt tillräckligt. Ett kallgassystem skulle kunna tillverkas helt mikromekaniskt, med kraftfullt höjd prestanda. Nästa generation av vetenskapliga rymdmissioner kommer att behöva bättre prestanda för att kunna svara på många astronomiska frågor. Kanske kan mikromekaniska gas- och vätskehanteringssystem vara en viktig del av framtida forskningsatelliter, som slutligen besvarar frågan om universums uppkomst?

Denna avhandling visar att ett sådant mikromekaniskt framdrivningssystem är fullt möjligt. Delkomponenter av ett system har tillverkats och verifierats, till exempel gasfilter [IV,V], en förslutningsmetodik till paraffin-

ventiler [VI] och en isolationsventil [VII]. Grundläggande förståelse för hur man kontakterar t.ex. bränsletanken till ett mikromekaniskt system studerades [II]. Med liknande komponenter utvärderades en termiskt styrd ventil, tänkt för mycket små gasflöden [III]. Även helhetsaspekten av ett komplett mikromekaniskt kallgassystem studerades [I].

Några av komponenterna, t.ex. munstycket till ett kallgassystem och isolationsventilen i sin helhet har visat sig så framgångsrika att det första riktiga rymdtestet är planerat med den svenskbyggda teknikdemonstrations-satelliten Prisma, med uppskjutning 2009. Om de mikromekaniska komponenterna fungerar som väntat på den missionen, öppnas dörren för fler avancerade mikromekaniska system för rymdbruk, och nya fantastiska upptäckter därute.

Acknowledgement

As I begun my journey the department of ÅSTC was growing. Here, at the end of my journey, not much remains. Hopefully the department will grow again.

I'd like to thank the inventor, Lars Stenmark, for starting the ÅSTC with your somewhat crazy ideas. Now I've got an invention of my own, what could possibly be a better proof of what I learned during this time?

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I'm not very good at keeping my workplace in order, neither the office nor the lab. I think my former room mate Henrik Kratz, and co-worker in the lab Hugo Nguyen will agree. I'm sorry, and thank you both.

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References

1. Janson, S.W. *Chemical and electric micropropulsion concepts for nanosatellites*. in *30th AIAA/ASME/SAE/ASEE joint propulsion conference*. 1994. Indianapolis, USA.
2. Mueller, J., et al. *Towards micropropulsion systems on-a-chip: initial results of component feasibility studies*. in *2000 IEEE Aerospace Conference Proceedings, 18-25 March 2000*. 2000. Big Sky, MT, USA: IEEE.
3. Bayt, R.L., A.A. Ayon, and K.S. Breuer. *A performance evaluation of MEMS-based micronozzles*. in *33rd AIAA/ASME/SAE/ASEE joint propulsion conference & Exhibit*. 1997. Seattle, Washington.
4. Leach, R. and K.L. Neal. *Discussion of micro-Newton thruster requirements for a drag-free control system*. in *16th annual/USU conference on small satellites*. 2002.
5. Grönland, T.-A., et al. *Development of MEMS-Based Spacecraft Propulsion*. in *Joint Propulsion Conference*. 2006.
6. Nguyen, H., J. Köhler, and L. Stenmark. *The Merits of Cold Gas Micropropulsion in State-of-the-art Space Missions*. in *THE 53:rd International Astronautical Congress*. 2002. Huston, Texas.
7. Lafontan, X., et al., *The advent of MEMS in space*. *Microelectronics Reliability*, 2003. **43**(7): p. 1061-83.
8. Rangsten, P., et al. *Development of MEMS-Based Components and Subsystems for Spacecraft Propulsion*. in *Caneus*. 2006. Toulouse, France.
9. <http://www.prismasatellites.se/>, "Prisma Satellit", September 2006.
10. Wertz, J.R. and W.J. Larson, eds. *Space mission analysis and design*. 5 ed. Space Technology. 2003: El Segundo.
11. Erichsen, P. *Performance evaluation of spacecraft propulsion systems in relation to mission impulse requirements*. in *2nd European Spacecraft Propulsion Conference*. 1997. Estec.
12. Erichsen, P. *Directions of potential increase in impulse performance of spacecraft propulsion systems*. in *10th International Workshop on Combustion and Propulsion*. 2003. La Spezia, Italy.
13. Ketsdever, A.D., et al., *Experimental and numerical determination of micropropulsion device efficiencies at low Reynolds numbers*. *AIAA Journal*, 2005. **43**(3): p. 633-41.

14. Hebden, R., et al. *Development of a monopropellant microrocket engine as a step towards a high-performance bipropellant micro-rocket*. in *PowerMEMS*. 2004. Kyoto, Japan.
15. Köhler, J., et al. *Detailed design of a monopropellant microrocket engine using MEMS technology*. in *PowerMEMS*. 2004. Kyoto, Japan.
16. Hitt, D.L., C.M. Zakrzewski, and M.A. Thomas, *MEMS-based satellite micropropulsion via catalyzed hydrogen peroxide decomposition*. *Smart Materials and Structures*, 2001. **10**(6): p. 1163-75.
17. Bejhed, J., et al. *Catalyst microsystem design and manufacture for a monopropellant microrocket engine*. in *PowerMEMS*. 2004. Kyoto, Japan.
18. Guerrini, G., et al., *An intense Hall-type ion source for satellite propulsion*. *Review of Scientific Instruments*, 1998. **69**(2): p. 804-6.
19. Mueller, J. *Thruster options for microspacecraft: a review and evaluation of existing hardware and emerging technologies*. in *33rd AIAA/ASME/SAE/ASEE joint propulsion conference & exhibit*. 1997. Seattle, USA.
20. Brophy, J., *Advanced ion propulsion systems for affordable deep-space missions*. *Acta Astronautica*, 2003. **52**(2-6): p. 309-316.
21. Bejhed, J., U. Lindberg, and L. Stenmark. *A Miniaturized Xenon Feed System for Electric Propulsion*. in *Proceedings The World Space Congress 53rd International Astronautical Congress*. 2002. Houston, Texas, USA.
22. Kratz, H., et al., *Design and modelling of an integrated communications and thermal management module for microsystem-based spacecraft*. 2005.
23. Bruhn, F., J. Kohler, and L. Stenmark, *Nanospace-1: The impacts of the first swedish nanosatellite on spacecraft architecture and design*. *Acta Astronautica*, 2003. **53**(4-10): p. 633-643.
24. Mueller, J., S. Vargo, and D. Bame, *Micro-Isolation Valve Concept: Initial Results of a Feasibility Study*, in *Micropropulsion for small Spacecraft*, M.M. Micci and A.D. Ketsdever, Editors. 2000. p. 399-422.
25. Swedish Patent pending SE0502953-3.
26. Diligenti, A., et al., *A micromachined Xenon flow regulator for space applications*. *Microelectronic Engineering*, 2000. **53**(1-4): p. 565-8.
27. Ulybin, S.A. and V.I. Makarushkin, *Viscosity of xenon at temperatures of 170-1300K and pressures up to 1000 bar*. *Teplofizika Vysokikh Temperatur*, 1977. **15**(3): p. 509-14.
28. Bejhed, J., et al. *The development of a micro machined xenon feed system*. in *40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*. 2004. Fort Lauderdale, Florida.
29. Kawano, K., et al., *Development of micro channel heat exchanging*. *JSME International Journal, Series B (Fluids and Thermal Engineering)*, 2001. **44**(4): p. 592-8.

30. Klintberg, L., et al., *A large stroke, high force paraffin phase transition actuator*. Sensors and Actuators, A: Physical, 2002. **96**(2-3): p. 189-195.
31. Klintberg, L., et al., *A thermally activated paraffin-based actuator for gas-flow control in a satellite electrical propulsion system*. Sensors and Actuators, A: Physical, 2003. **105**(3): p. 237-246.
32. van Oudheusden, B.W., *Silicon thermal flow sensors*. East-West Workshop on Microelectronic Sensors, May 7-9 1991 Sensors and Actuators, A: Physical, 1992. **30**(1-2): p. 5-26.
33. Bruschi, P., et al., *A double heater integrated gas flow sensor with thermal feedback*. Sensors and Actuators A (Physical), 2005. **123-124**: p. 210-15.
34. Chen, K., M. Winter, and R.F. Huang, *Supersonic flow in miniature nozzles of planar configuration*. Journal of Micromechanics and Microengineering, 2005. **15**(9): p. 1736-1744.
35. Hao, P.-F., et al., *Size effect on gas flow in micro nozzles*. Journal of Micromechanics and Microengineering, 2005. **15**(11): p. 2069-2073.
36. Bayt, R.L. and K.S. Breuer, *Analysis and testing of a silicon intrinsic-point heater in a micropropulsion application*. Sensors and Actuators A, 2001. **91**(3): p. 249-255.
37. Williams, K.L., et al., *The electrothermal feasibility of carbon microcoil heaters for cold/hot gas microthrusters*. Journal of Micromechanics and Microengineering, 2006. **16**(7): p. 1154-1161.
38. Williams, K.L., J. Kohler, and M. Boman, *Fabrication and mechanical characterization of LCVD-deposited carbon micro-springs*. Sensors and Actuators, A: Physical, 2006. **130-131**(SPEC ISS): p. 358-364.

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