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# THE MERITS OF COLD GAS MICROPROPULSION IN STATE-OF-THE-ART SPACE MISSIONS

Hugo Nguyen, Johan Köhler and Lars Stenmark
The Ångström Space Technology Centre, Uppsala University,
Box 534, SE-751 21 Uppsala, Sweden.
Hugo.Nguyen@angstrom.uu.se Fax: +46 18 471 3572

Abstract: Cold gas micropropulsion is a sound choice for space missions that require extreme stabilisation, pointing precision or contamination-free operation. The use of forces in the micronewton range for spacecraft operations has been identified as a mission-critical item in several demanding space systems currently under development.

Cold gas micropropulsion systems share merits with traditional cold gas systems in being simple in design, clean, safe, and robust. They do not generate net charge to the spacecraft, and typically operate on low-power. The minute size is suitable not only for inclusion on high-performance nanosatellites but also for high-demanding future space missions of larger sizes.

By using differently sized nozzles in parallel systems the dynamic range of a cold gas micropropulsion system can be quite wide (e.g. 0 – 10 mN), while the smallest nozzle pair can deliver thrust of zero to 0.5 or 1 mN using continuously proportional gas flow control systems.

The leakage is turned into an advantage enabling the system for continuous drag compensation. In this manner, the propellant mass efficiency can be many times as higher than that in a conventional cold gas propulsion system using ON-OFF-control.

The analysis in this work shows that cold gas micropropulsion has emerged as a high-performance propulsion principle for future state-of-the-art space missions. These systems enable spacecraft with extreme demands on stability, cleanliness and precision, without compromising the performance or scientific return of the mission.



## 1. INTRODUCTION

For Attitude and Orbit Control System (AOCS) requirements on extreme stabilisation, pointing precision, contamination-free operation is the most important for many missions. Examples include DARWIN, LISA, SIM, NGST, and those which have optical or other equipments pointing exactly to a certain object or in a certain direction. Other obviously desirable properties include design simplicity, cleanliness, safety, robustness, low-power operation, no net charge generation to the craft, together with low mass, and a wide dynamic range. Cold gas micropropulsion has those merits and in the present paper, technological solutions will be treated emphatically, at the same time the mentioned merits will be brought out clearly.

## 2. SYSTEM DESCRIPTION

The nanosatellite designed at The Angstrom Space Technology Centre, Uppsala University, Sweden (ASTC) has four identical thrusters units, or thrusters pods (figure 1a). Each unit constitutes an autonomous cold gas micropropulsion system, which is presently under development. The spherical housing (figure 1b and c) accommodates four identical thrusters. The unit also contains electronics for local closed control loops of thrust and a serial data interface to the satellite AOCS. Each thruster is a complete microsystem, including a nozzle with internal heater, a proportional flow control valve, particle filter, and sensors for pressure, temperature and thrust. The total mass of the thruster unit is below 60 grams and the diameter of the spherical envelope is 41 mm. All gas control is performed in a central stack consisting of four silicon wafers. A common main shut-off valve is also included in this unit.

All control electronics are located as hybrids on three individual wafer stacks underneath the central stack. Each of these stacks is composed of three silicon wafers

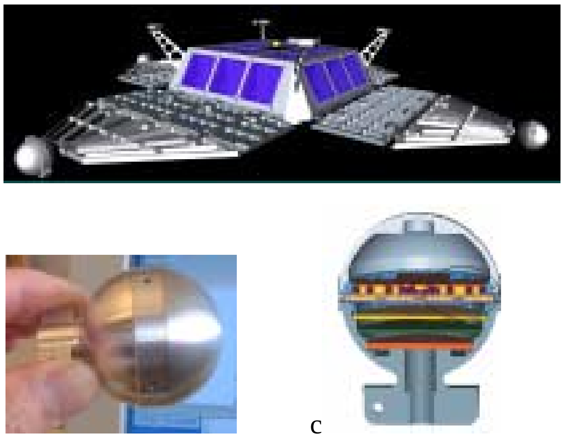

*Figure 1: a) The nanosatellite under development at Angstrom Space Technology Centre, Uppsala University, Sweden. b) and c) The 60-grams autonomous thruster unit with four nozzles, designed for thrust level 0-10 mN.*

## 3. COLD GAS MICROPROPULSION AND THE MERITS

### Cold gas as fuel

Cold gas is, by definition, not warm. The terms warm and cold on Earth usually refer to room, human body or water freezing temperature. For cold gas as propellant of propulsion system the temperature is not standardized. Nevertheless, two things are relevant for definition. The propellant has to be in gas phase when rushing out from thruster, and no combustion should occur. Yet, thawing and warming up are not restricted to the propellant to be called cold gas. Resistor jet propulsion in that classification will be an exception case.

Higher atom weight of the expelled gas is desirable due to the third Newton law. Together with the contamination free constraint (treated briefly below), the moderate low boiling and melting temperature are desirable features for a propellant gas from system point of view, where mass efficient storage of the gas is a major concern.

Xenon is a potential cold gas propellant, that is, a heavy and inert gas (table 1). However, there are some challenges when using this gas, since its viscosity increases with temperature within a certain range, that implies that the specific impulse, $I_{sp}$, for a Xenon system becomes very low if heating the gas.

Helium and Nitrogen are much lighter than Xenon and their temperatures for storage in liquid or solid form is technically more demanding, but the specific impulses are higher.

Propane, $C_3H_8$, has been used as cold gas propellant in microsatellites in past decades. Butane, $C_4H_{10}$, has been demonstrated successfully as propellant in the cold gas propulsion system on SNAP-1, a 6.5 kg-nanosatellite. However, these gases are organic compounds and hazard classified.

Carbon dioxide, $CO_2$, has the advantage to sublimate directly from -78°C at a pressure of 1 bar and the gas has a fairly high specific impulse.

*Table 1: Cold gas propellant performances*[2,3,9]

$M_r$ = Molecular weight. $t_m$ = Melting temperature. $t_b$ = Boiling temperature. $\rho$ = Density (241 bar, 0°C). $I_{sp,t}$ = Theoretical specific impulse. $I_{sp,m}$ = Measured specific impulse

| Cold gas | $M_r$ kg/kmol | $t_m$ (1 bar) °C | $t_b$ (1 bar) °C | $\rho$ (241 bar) g/cm$^3$ | $I_{sp,t}$ [a)] s | $I_{sp,m}$ [a)] s |
|---|---|---|---|---|---|---|
| $H_2$ | 2.0 | -259 | -253 | 0.02 | 296 | 272 |
| He | 4.0 | -272 | -269 | 0.04 | 179 | 165 |
| Ne | 20.4 | -249 | -246 | 0.19 | 82 | 75 |
| $N_2$ | 28 | -210 | -196 | 0.28 | 80 | 73 |
| Ar | 39.9 | -189 | -186 | 0.44 | 57 | 52 |
| Kr | 83.8 | -157 | -152 | 1.08 | 39 | 37 |
| Xe | 131.3 | -112 | -108 | 2.74 [b)] | 31 | 28 |
| $CCl_2F_2$ | 121 | -158 | -29.8 | --- | 46 [c)] | 37 |
| $CF_4$ | 88 | -184 | -128 | 0.96 | 55 | 45 |
| $CH_4$ | 16 | -182.5 | -161.5 | 0.19 | 114 | 105 |
| $NH_3$ | 17 | -78 | -33 | Liquid | 105 | 96 |
| $N_2O$ | 44 | -91 | -88 | --- | 67 [c)] | 61 |
| $C_3H_8$ | 41.1 | -187.7 | -42.1 | Liquid | --- | --- |
| $C_4H_{10}$ | 58.1 | -138.3 | -0.5 | Liquid | --- | --- |
| $CO_2$ | 44 | --- | -78 (S) | Liquid | 67 | 61 |
| $SF_6$ | 146.1 | --- | -64(S) | --- | --- | --- |

[a)] At 25°C. Assume expansion to zero pressure in the case of the theoretical value.
[b)] Likely stored at lower pressure value (138 bar) to maximize propellant-to-tank weight ratio.
[c)] At 38°C (560R) and area ratio of 100.
(S) Sublimation

Sulfur hexafluoride, $SF_6$, is one of the most interesting gases owing to its heavy molecular weight – heavier than Xenon – and it sublimates at barely -64°C at a pressure of 1 bar. $SF_6$ is non-flammable and not classified as a toxic gas. $SF_6$ is believed to be a strong candidate for cold gas micropropulsion systems under development.

Propellant storage in solid phase, especially sublimating substances, onboard a spacecraft is favorable in comparison to storage in liquid phase. Liquid propellant in ordinary tank is known for causing sloshing problem, which can severely disturb high precision stabilization and pointing.

The gas propellant in our system will preferably be stored in solid or liquid phase. It will be transformed into gas phase before leaving the storage tank via the feeding lines, through a micromachined filter set and the proportional valve, and into the heat exchanger chamber for warming up. The gas temperature before leaving the nozzles may reach many hundreds degree C. Here, the material properties of the silicon structure at elevated temperatures are the major limiting factors to the allowed heating. Silicon is a good thermal conductor. The heat that should go to the gas can be lost into the wafer stack, seriously degrading the heater efficiency and possibly causing secondary heat induced failures in nearby microstructural elements. Thermal aspect in design and material selection is therefore an inevitable matter of concern in the proper engineering of microsystem.

The system specific impulse, $I_{ssp}$, as a function of delta-v has been presented by Köhler[1]. There different parameters of the system, such as available storage techniques, dimension of microfluidic system and nozzles, expelled gas viscosity, pressure control system, etc., was not taken into consideration in order to gain the maximum system specific impulse. Yet, the analysis showed how to estimate a system specific impulse versus delta-v using cold gas micropropulsion system in feasibility study for a certain mission.

## Simple design, clean, safe, robust, and low cost

Conventional cold gas propulsion systems have been used successfully since many years, for example on Astro-Spas, Hipparcos, EURECA, CHAMP and GRACE. Cold gas propulsion system is just a system that controls pressurized gas through a number of nozzles. It is the simplest form of rocket engine. By using inert gas it represents one of the cleanest and safest systems. However, conventional cold gas propulsion systems have for many years been considered "old fashioned", mainly because of the low efficiency, which makes the propellant gas supply bulky and heavy. Also, due to the valve technology traditionally involved, a minimum impulse bit obtained is disturbingly high in many applications. Microelectromechanical system (MEMS, or MST – Microsystem technology, which is another abbreviation for the same technology) provides the possibility to build a high performance system for use in many new demanding applications[1,10]. Cold gas propulsion systems are preferable in many cases where cleanliness, simplicity, and reliability are more important than other qualities. Due to their simplicity the conventional cold gas propulsion systems have even the lowest cost of manufacturing. However, this does not hold true in the same proportion when employing MEMS-technology for manufacturing.

## The desirable gas leakage – Proportional Gas Flow Control (PGFC)

Leakage always occurs when gas pressure inside and outside of a system differs. The propulsion system containing gas of high pressure in a high vacuum like space will be subjected to considerable leakage problems, mainly at its valves and connectors. For conventional spacecraft the acceptable leak rate has been found at $10^{-3}$–$10^{-4}$ scc/s GHe (gaseous Helium)[4]. For nanosatellites the leak rate is often calculated from the thrust generated just by the leak and it should be set to a lower value than the limit mentioned above. Of course the sum of leaked mass of gas has to be compared with the amount of gas on board for the whole mission duration.

Numerous variants of MEMS-based valves have been developed over the years, with varied solutions for actuation. The review by Mueller presents many of them[5]. The main principles of valve seat and lid features are also discussed here. The interesting approaches in order to suppress gas leakage are making the valve lid from a hard material that presses against a softer seat, or else a hard valve lid with a sharp circular edge that presses against a hard seat, crushing particles that obstruct the closing of the valve. Both valve lid and seat surfaces can also be made perfectly flat from hard material. The risk for spontaneous bonding is obvious here; hence different thin film coatings have to be employed. For all of the mentioned approaches the fatigue and wear are the other problem of great concern.

In our system approach, the drawback of gas leakage has been turned into an advantage by controlling the leak rate. Two different operation modes have been designed for the valves system. The first operation mode is called Proportional Gas Flow Control (PGFC), in which the valves will not be fully closed. Since the pairs of MEMS-based opposite thrusters are placed symmetrically in the same unit, leakage from them can be balanced. The valve actuators have been designed to operate at 10 Hz with virtually continuous stroke control. The PGFC mode works on a fairly low electrical bias and actually consumes negligible electric power (discussed below). The extremely low gas flow used in this mode make the continuous operation acceptable in terms of propellant mass efficiency.

The second operation mode is the shut down mode, which needs higher electric potential to assure the complete closing of the valves. Since this mode is only rarely used, when for instance drifting freely or if rebooting of satellite is required. In this way, the fatigue and wear problem is reduced almost to zero.

Spacecraft, especially those on Low Earth Orbit (LEO), experience a certain drag, which implies that their attitude has to be corrected. Conventional AOCS with cold gas propellant operate by the ON-OFF principle, which is known as a bang-bang-system. Mission requirement on pointing precision determines the minimum impulse bit of the AOCS. For an ON-OFF operating system the propellant used during minimum impulse bit generation is not very efficient due to the response delay of valve actuation, and gas flow. The cold gas micropropulsion system developed at ASTC with continuous PGFC meets the ideal requirement on pointing precision, that is, continuous drag compensation. In other words, the minimum impulse bit does not exist. The minimum gas amount does not leak undesired through the valve system, but is meant to be released variably in order to counteract the disturbances continuously. The use of gas propellant in this manner is estimated three or four times as effective as that in an ON-OFF system. It is in fact legitimate to maintain that the gas leakage is desirable. For a cold gas propulsion system with continuous PGFC the common opinion about the propellant inefficiency of a cold gas propulsion system does not hold true.

Extreme stabilisation and pointing precision

Cold gas micropropulsion system that operates in the continuous PGFC-mode eliminates the minimum impulse bit. The resolution of a single unit, containing two pair of opposite thrusters, is only dependent on the control voltage applied to the valve actuators. This technological feature makes the extreme stabilisation and pointing precision of a satellite possible. Furthermore, the broad dynamic range and particularly quick transition from one thrust level to another – simply by changing the valves actuation voltage – make this cold gas micropropulsion system unique regarding the precision control of the satellite.

Nevertheless, realisation of a microfluidic system encounters some delicate problems due to fluidic mechanical behaviours, such as pulsation and turbulence in larger system sections, which constitute the system noise. This in turn determines the lowest flow rate of a single thruster, and that implies the minimum continuous consumption of propellant.

Many experiments and measurements in space demand vibration-free environment for the payload and pointing precision of spacecraft. When free drift does not meet the requirements the spacecraft has to be actively and continuously controlled by thrusters. The thrust levels for mini and microsatellites in that case must be very low and the thrust resolution has to be below 1 mN. Gravity and Ocean Circulation Explorer (GOCE), for example, is a minisatellite of 800 kg under development. It will operate in LEO (250-300 km) and will be subjected to residual air drag. Two ion thrusters with a thrust between 1-12 mN will be used for the drag compensation. However, small variations of both thrust and thrust vector call for an additional three-axis system with 0.7 mN maximum thrust and a resolution of 0.25 $\mu$N (see more in references 6 and 7). A cold gas micropropulsion system investigated at ASTC would be one of the suitable AOCS for the spacecraft, since it has a 12-bits wide dynamic range. By employing differently sized nozzles in parallel systems the dynamic range of the cold gas micropropulsion system can be increased to 0-10 mN, where the smallest nozzle pair can deliver thrust of zero to 0.5 or 1 mN using PGFC. A single smallest nozzle works with a resolution of 0.2 μN.

The influence of mass in motion when actuating the valve lids on spacecraft stabilisation and pointing precision was a subject of discussion. However, calculation for piezoelectric actuated valve designed at ASTC (figure 2) showed that the valve will contribute an acceleration of $<10^{-22}$ g, while the requirement on maximum vibration level for GOCE, for instance, was set to $<10^{-15}$ g. Therefore, redesign of the valve in order to balance its mass in motion was not considered necessary.

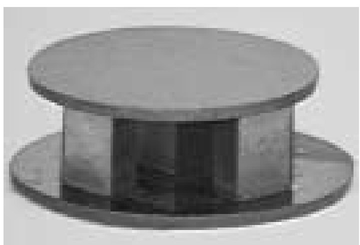

*Figure 2: Piezoelectric proportional valve (14x5 mm) with microfabricated silicon parts*

Contamination-free operation

The expelled particles from firing thrusters for attitude control or when leaking in unfavourable condition, for instance while the satellite is in shadow and has no surrounding plasma, can follow the satellite for a certain time. Their chemical reactivity towards materials on satellite surfaces can play a crucial roll in propellant selection. If an expelled particle is statically charged, it can be attracted to the satellite surface. This matter raises concerns due to the size of nanosatellites and its surfaces of multifunctional films and devices. A single defected spot on the very limited multifunctional surface of the tiny satellite is more harmful than on the larger surface of a conventional satellite. Contamination problems due to propellant type are also severe in cases where spacecraft carry optical instruments with sensitive surface of lenses and mirrors. Furthermore, if spacecraft in close formation within distances of 25 to 50 metres, for instance, the risk of surface contamination on neighbours in the constellation is not negligible.

No net charge generation to the spacecraft

The cold gas micropropulsion system does not ionize the expelled gas particles, thus efforts and power needed for active plume neutralisation can be spared. A charged spacecraft in relation to space particles and the expelled gas tends to attract them to its surface as mentioned above.

In despite of the fact that the spacecraft will be subjected to electromagnetic forces that would cause incorrect pointing, these forces are too small to significantly increase the consumption of propellant for attitude control. A rough calculation of the electromagnetic force $F$ that exerts on a charged spacecraft in LEO can be made as follow. Assume that the spacecraft is spherical with radius $r$=1m, moving with velocity of $v$=10 km/s in LEO with magnetic flux density $B=5\cdot10^{-5}$ T. The spacecraft is charged to $U$=1 kV. The maximum value of the force will be $F = Q\cdot V\cdot B = C\cdot U\cdot V\cdot B = 4\pi\varepsilon_o r\cdot U\cdot V\cdot B = 5.56\cdot10^{-8}$ N $= 5.56\cdot10^{-2}$ μN. Further calculation for 10 year mission assuming that the $I_{sp}$= 700 Ns/kg for $N_2$ in mission average, shows that an additional 0.025 kg of propellant would be needed to counteract the mentioned electromagnetic force. The same calculation for monopropellant Hydrazine, $N_2H_4$, with $I_{sp}$=2150 Ns/kg results in 0.008 kg increase of the propellant. This rough estimation shows that the force does not constitute any problem in propellant budget for attitude control. However, it is comfortable to realize that by using a cold gas we do not need to care about the impact of electromagnetic force on attitude control, while the propulsion system can be kept simpler in design.

Low-power operation

The electric power needed for operation of a cold gas micropropulsion system is mainly determined by the valve actuators and the electronic system. In the ASTC design, the piezoelectric elements in the valve actuator work at 0-50 volts. They function like a capacitor, that is, they consume no power in the charged state at constant voltage. The capacitance of a single piezoelectric element is 130-250 nF, depending on size and operation temperature. Thus, the actuation power is very low. Changing from one thrust level to another does not require any considerable consumption of power.

In comparison to conventional satellites and other spacecraft a nanosatllite should have a limited number of AOCS in order to minimize the total mass. Momentum flywheel system for attitude correction can be omitted to make the satellite more robust, and to save mass and power consumption. The cold gas micropropulsion system itself, with its large dynamic range, covering thrust level from zero to 10 mN, already guaranties the required precision of the attitude and orbit control. Nevertheless, a simple magnetorquers system, that does not require much power, space, or mass on board, can be justified as a complementary system in order to save a significant part of available propellant.

Silicon microsystems can be much smaller

Industrial standard NC-machines have tolerance 0.01 mm or slightly narrower. Today, there are machines that goes with 75,000 rpm or twice that speed, and they are capable to mill or drill a row of holes in a human hair without missing it. Yet, as the dimensions of work pieces shrink in order to miniaturize a device, more exotic machining methods have to be employed, such as laser or electron beam machining. However, those machining methods, especially when material is removed mechanically, leave residual stress and coarse surfaces. These flaws are not negligible in the small features concerned.

Silicon, with its perfect atom lattice, offers incredible mechanical, electrical, chemical, and thermal properties compared to conventional mechanic construction materials. The main manufacturing methods are different etching, deposition, and bonding techniques. By choosing proper methods, chemicals, and combinations of materials the residual stress and other problems can be avoided or minimized. Silicon microsystems technology is not restricted to fit standard component or tools, but rather to the perfection of the atom lattice and the precision of pattern transfer. Dimensions can be reduced from few millimetres down to size of few atom layers.

Mass reduction

One of the most important advantages in silicon microsystem technology is the possibility to integrate a multitude of MEMS-devices and electronic chips. Here, it is not the matter of miniaturization, but “microturization”. MEMS technology offers many advantages, such as higher level of integration of devices, higher sensitivity and reliability, better mechanical properties of materials, and many other properties, which do not show significantly or not at all in macro-mechanical designs. Of course there are a number of aspects that have to be taken into account when using MEMS-solutions. For instance, flat surfaces of thin element can be bonded spontaneously; toxic gas, substances, and solutions must be employed in manufacturing. Furthermore, the yield of the manufacturing process typically decreases with increasing level of system integration.

To illustrate the possible level of device integration we can consider how many mass percent is the “payload” in a Pentium processor, that is, the total mass minus the mass of the carrier substrate and the plastic envelope. This is compared with the ratio in case the processor is built of individual transistors, capacitors, resistor, circuit board, and solder. The comparison can be made in the same manner to grasp the mass saving possible by the transition from conventional mechanics to microsystem integration of MEMS devices.

The autonomous cold gas thruster unit designed at ASTC for AOSC weights lees than 60 grams (figure 1b and c), of which 40 grams is the AA7075-aluminum housing. The aluminium mass in the present design is mainly needed for radiation protection reason. Both crumb and housing are still targets for further mass reduction. A bulkier hybrid unit has previously been designed without built-in control electronics, and weighs around 150 grams (figure 3).

The mass reduction naturally saves launch cost, but can also be used to incorporate more redundancy by allowing parallel systems. For instance, in a satellite swarm, loss of one or few satellites would not jeopardise the whole mission. On individual spacecraft, the vital microsystem may also be multiplied without incurring mass penalty. Function failure at a thruster or even a thruster unit would not erase the whole operation of the spacecraft.


*Figure 3: 150-grams hybrid thruster unit without build-in control electronics, designed for thrust level 0-1 mN or higher*

The launch cost per mission using nanosatellites and State-of-the-art launch vehicles is low, but the cost per kilo of go-to-orbit mass is much higher compared to using a huge lifting rocket for a satellite of hundreds or thousands times more than the nanosatellites mass[8]. However, there is a belief that strong and fast development of nanosatellites will initiate an evolution of new launching technology that suits tiny satellites. Launching such satellites may not have to be from a launch pad. It can be made from a jetfighter or from something else that we just cannot imagine today.

Examples on future demanding space missions

Using components off-the-shelf is the most practical approach to build a spacecraft, or anything else, due to well known performances of the components. The time-to-completion and costs for a planned mission can reduce substantially. However, when the components do not meet the mission requirements new components or the whole system have chance to emerge. New technological challenges will be overcome by creative ideas. New missions require such technologically demanding spacecraft, which can help us to understand the solar and interstellar systems. Examples on demanding future missions are LISA, DARWIN, SIM, NGST and many other planned and proposed missions. LISA (Laser Interferometer Space Antenna) has the task to detect gravitational waves from massive black holes and galactic binaries. DARWIN aims to look for life. Both missions will use flotilla of spacecraft, flying in formation in vast distances of thousands kilometers from each other with an accuracy of less than 20 microns. The SIM (Space Interferometry Mission) will carry a telescope which can determine positions and distances to stars with an accuracy several hundreds times greater than current telescope technology allows, in order to street-map our Milky Way galaxy. The NGST (Next Generation Space Telescope) will look into our history back to the Big Bang with a telescope that can capture images beyond the visible portion of the electromagnetic spectrum. LISA and DARWIN are conducted by European Space Agency (ESA), while the SIM and NGST are conducted by the American NASA. Considering that the attitude control subsystems currently available would provide 15 arc-seconds pointing precision per axis, the AOCS with continuous thrust control, using cold gas micropropulsion, should be a tempting offer.

Improvement of cold gas micropropulsion system

Up to the present time, the MEMS technology that produces autonomous ad hoc systems with several micromechanic and electronic parts, highly integrated into a single chip, is not matured, neither in fabrication nor in attitude of the presumptive users. Cold gas micropropulsion systems are not any exceptions. However, the traditional flaws and weakness of the system will eventually be overcome. For instance, heating of propellant gas is limited by silicon structure. At temperature $500^0$C and above the mechanical properties of silicon will be degraded. The measure for this problem may be replacement of silicon by another material. The heat loss into the structure when heating the propellant gas is a reason for a new creative design, in order to make the specific impulse of cold gas higher[11,12]. The fabrication yield will be significantly improved as the manufacturing steps and material systems are optimized. However, the progress in research and development support the strong belief that cold gas micropropulsion systems will be flight-proven within this decade.

## 4. CONCLUSION

The cold gas micropropulsion system benefits greatly from using a continuously proportional control on the thrust. The configuration of two opposite thrusters in the same unit balances the thrusts against each other, so the impulse obtained as the difference of them may be reduced to zero. Simultaneously, any troubles emerging from extremely low flows at near-zero thrust from a single thruster can be avoided. The same strategy can be extended to continuous operation, never closing the valves completely. In this way, leakage-induced thrust fluctuations are bypassed, and sticking problem and wear of the valve seats is heavily reduced. The extremely low gas flow used in the system make this continuous operation acceptable in terms of propellant mass efficiency.

Main concerns are the low specific impulse and the consequent large amount of propellant required. System analysis shows that low delta-v missions or their equivalent (e.g. attitude and orbit control) are suitable missions for cold gas micropropulsion. The choice of propellant is naturally of prime importance – carbon dioxide and sulfur hexafluoride is possible to store in solid form to avoid sloshing problem, while liquid gas may act as a cooling fluid for the scientific payload in addition to being used as propellant.

The analysis in this work shows that cold gas micropropulsion has emerged as a high-performance propulsion principle for future state-of-the-art space missions. These systems enable missions with extreme demands on stability, cleanliness, and precision, without compromising the performance or scientific return of the mission.

## References

[1] Köhler, J., et al. *A Hybrid Cold Gas Micothruster System for Spacecraft*. Sensor and Actuators. A97-98, pp 587-598, 2002

[2] Ayward G. And Findlay T. *SI Chemical Data - 4th edition.* Wiley 1998

[3] Mueller J., in *Micropropulsion for Small Spacecraft*, Ed. Michael M. et. al., Chapter 3: *Thruster Options for Microspacecraft…*, AIAA Progress in Astronatics and Aeronautics Vol. 187

[4] Mueller J., in "*Micropropulsion for Small Spacecraft*" (M.M. Micci and A.D. Ketsdever, eds.), Chap. 19, AIAA Progress in Astronautics and Aeronautics Vol.187

[5] Mueller J., in "Micropropulsion for Small Spacecraft" (M.M. Micci and A.D. Ketsdever, eds.), Chap. 19. AIAA Progress in Astronautics and Aeronautics Vol.187

[6] Gonzalez J., *Electric Propulsion for ESA Scientific and Earth Observation Mission*, SP-465, ESA 3rd International Conference on Spacecraft Propulsion 10-13 December 2000

[7] Bassner H., et.al. *RITA for Drag Compensation on GOCE*. SP-465, ESA 3rd International Conference on Spacecraft Propulsion 10-13 December 2000

[8] Fleeter R., *New Propulsive Module for nanosatellites. Smaller Satellies: Bigger Business?* Edited by M. Rycroft, et al. Space Studies, Vol 6. International Space University. Kluwer Academic Publisher 2002

[9] Lide D.R., Hanbook of Chemistry and Physics. 77th edition. CRC Press 1966-1997

[10] Bayt R.L. et al., *DRIE-fabricated nozzles for generating supersonic flow in micropropulsion systems.* Technical Digest. Solid-State Sensor and Actuator Workshop. Transducer Res. Found, USA 1998

[11] Bayt R.L. et al., *A Silicon Heat Exchanger with Integrated Intrinsic-point Heater Demonstrated in a Micropropulsion application.* Technical Digest. Solid-State Sensor and Actuator Workshop. Transducer Res. Found, USA 2000

[12] Stenmark L., *Cold Gas Microthruster – Final Edition*. Conference NanoTech 2002. Houston September 2002