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Chemical and cold gas propulsion systems

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18.1 Historical background

The focus of this chapter will be on propulsion systems that generate a thrust force through thermodynamic expansion (and acceleration) of the propellant gas(es) in a nozzle, under the condition that the initial energy provided to the propellant before its acceleration in the nozzle does not come from an electrical energy source. The propulsion systems that fall under this category are either **cold gas** systems, in which the only input energy to the propellant comes from its pressurization, or **chemical** systems, where the input energy comes from both pressurization and chemical energy stored in the propellants. Chemical propulsion systems, in turn, can be based on either **liquid** propellants (**mono-propellant** and **bi-propellant** systems), or on **solid** propellants, or combinations of them (such as it happens in **hybrid** systems).

When looking at the historical heritage of the use of these systems in small spacecraft, a clear distinction should be made between the two above-mentioned types of propulsion.

Cold gas systems have historically been the first type of propulsion to be considered and successively demonstrated, on this category of spacecraft, due to their intrinsic simplicity, reliability and safety. However, they require significant propellant pressurization to allow for acceptable performance. Since the use of pressurized items was not allowed by the CubeSat standards, at least in their earliest versions, this significantly limited the implementation of cold gas-propelled satellites in the initial years of the CubeSat era.

On the other hand, as it will be better explained in the next section of this chapter, chemical propulsion systems typically suffer from significant down-scaling issues, caused by their much lower Reynolds number in the nozzle and by the heat transfer/cooling challenges associated with high temperatures in miniaturized thrust chamber dimensions, that initially made their miniaturization much more difficult to achieve (and still represent a significant technical barrier at the present day). For this reason, in the early age of CubeSats and small spacecraft, chemical propulsion was mostly not an option, except for a few very special cases of low-thrust engines (in the 1 N range or higher) designed and developed for larger spacecraft and somehow "adapted" to the requirements and needs of their smaller counterparts by just scaling down their dimensions and/or their performance.

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Among the first cold gas systems flown and demonstrated on CubeSats in their early years, the following ones can be mentioned:

- The butane micro-propulsion system developed by SSTL (Surrey Satellite Technology Ltd) and demonstrated on the **SNAP-1** satellite in 2000. This system used a standard titanium pipe as a propellant tank and was tested at a thrust level of 46 mN, for a specific impulse of 43 s [1].
- The Nano Propulsion System (**NANOPS**) from the University of Toronto Institute for Aerospace Studies (UTIAS), successfully demonstrated on CanX-2, a 3U CubeSat launched in April 2008 [2]. This system was designed specifically for formation flying applications, with a specific impulse of 46 seconds and a thrust of 35 mN. An updated version, the Canadian Nanosatellite Advanced Propulsion System (**CNAPS**) was launched on a 8U CubeSat, CanX-5, where it was used to perform drift recovery and station keeping [3]. Both these systems used Sulfur Hexafluoride as a propellant.
- The five-nozzles cold gas system developed by Aerospace Corporation for the MEMS PICOSAT Inspector (**MEPSI**) launched in 2006. This system, shown in Fig. 18.1, was manufactured using three-dimensional printing technology, so that the propellant tank, pipes and nozzles are all manufactured out of one piece, limiting the leakage risks. The propellant was Xenon. Only one of the five thrusters could be successfully demonstrated in space after satellite deployment [4].
- The **T3μPS** system developed by TNO, TU Delft, and the University of Twente (Netherlands), based on Nitrogen propellant stored in solid grains, and partially demonstrated in the Delfi-n3Xt 3U CubeSat in 2013 [5].
- The four-nozzles cold gas system developed by NanoSpace (Sweden) and successfully launched and operated on the microsatellite **PRISMA** in 2010. Although this microsatellite was not a CubeSat, the system was developed and demonstrated with a form factor that would fit the volume and interface constraints of CubeSats. Each nozzle delivered a minimum thrust of 0.1 mN, with a specific impulse up to 75 seconds [6]. The same system could be operated with several different propellants, ranging from liquid water to Xenon, Helium, and Nitrogen.

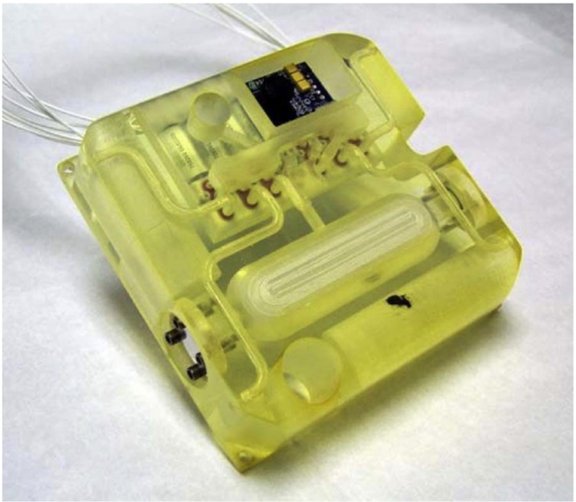

Figure 18.1 The MEMS PICOSAT Inspector cold gas micro-propulsion system from Aerospace Co. Lemmer [7].

18.2 Principle of operation of cold gas and chemical micro-propulsion systems

In **cold gas** systems, the propellant is stored at high pressure (often in its liquid phase to allow for higher density and therefore reduced volume, but in principle, it can also be stored in the gaseous phase) and accelerated in a nozzle without any additional heating or energy input. If the propellant is stored as a liquid, it is vaporized before reaching the nozzle. Given the simple design and extreme simplicity of the concept, the system mass is usually small, and a limited number of components are required. Fig. 18.2 shows a schematic representation of a typical cold gas micro-thruster and its most important components. In the concept shown in the figure, the propellant is stored in the tank under pressurized conditions, and a valve (V) is opened to make the pressurized propellant flow in the thruster. In some concepts, a pressure regulator may be used to ensure that the propellant flows in the thruster at a constant regulated pressure. However, pressure regulators are rarely used in micro-thrusters due to their mass and volume limitations. In this case, the propellant storage pressure in the tank continuously decreases while the propellant is extracted from it ("blow-down" operation), and the only required power is to activate the valve and keep it open when needed. Typical propellants for cold gas micro-thrusters include **Isobutane**, refrigerants (such as **R236fa** or **R134a**), **Sulfur Dioxide**, **Sulfur Hexafluoride**, but also gases such as **Nitrogen**, **Argon**, **Xenon**.

In **mono-propellant** systems (see Fig. 18.3), the propellant is typically stored in its liquid phase and pressurized by a pressurant gas. Similar to what was already discussed for cold gas systems, the pressurant gas is often stored in the same tank as the propellant. A pressure regulator is rarely used, and the thruster works under blow-down conditions. By opening the thrust valve (V), the propellant is then flown

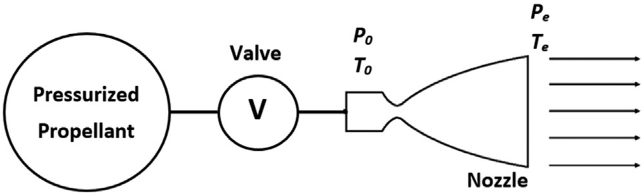

Figure 18.2 Schematic representation of a cold gas system.

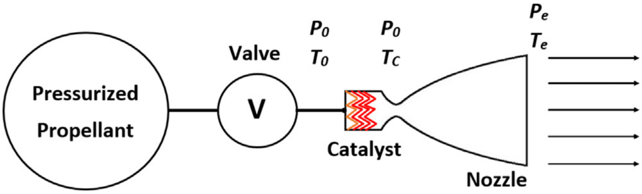

Figure 18.3 Schematic representation of a liquid mono-propellant system.

into the decomposition chamber, where it chemically decomposes into simpler molecules generating heat and, therefore, entering the nozzle inlet at high temperature. Decomposition is usually facilitated by a catalyst, which also needs in many cases to be preheated, with the need to use a nonnegligible amount of satellite power. In the case of mono-propellant micro-propulsion systems, "green" propellants are typically used (nontoxic, nonhazardous, easily storable and safe to handle). High-density liquids are usually preferred in order to reduce the required tank volume. Typical propellants meeting these characteristics are Hydroxyl-Ammonium Nitrate (**HAN**) and its recently developed, high-performance derivative **AF-M315E**; Ammonium DiNitramide (**ADN**) and its derivative **LMP-103S**. A less typically used green alternative is **hydrogen peroxide**. Some earlier developed mono-propellant systems were based on **hydrazine**, but this highly toxic propellant is gradually being abandoned in most recent concepts.

The working principle of **bi-propellant** systems (Fig. 18.4) is very similar to mono-propellant ones. However, instead of one single propellant there are two of them (an oxidizer and a fuel), also in this case stored in their liquid phase and pressurized by a pressurant gas. Two thrust valves (OV and FV) are present in this case, through which the propellants flow into the combustion chamber, where a chemical reaction between fuel and oxidizer generates heat and allows the combustion products to enter the nozzle inlet at a high temperature.

Solid propellant systems (Fig. 18.5) are basically the same as bi-propellant ones, with the only difference being that propellants are stored in the solid phase in the same grain and require energy from an igniter to start their combustion. Although extremely simple in terms of the number of components and operation, they suffer from the fact that the combustion of a single grain, once initiated, cannot be stopped and will continue until the propellants are completely consumed. This category of propulsion systems has not been extensively developed yet for small satellites and CubeSats, due to the typical limitations on pyrotechnic devices present in the requirements for this class of satellites; as such, they will not be further discussed in the following sections of this Chapter. However, some systems characterized by significantly high thrust levels (in the range of 10–100 N) have

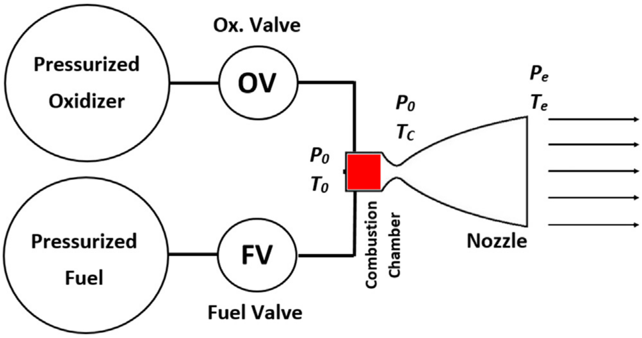

Figure 18.4 Schematic representation of a liquid bi-propellant system.

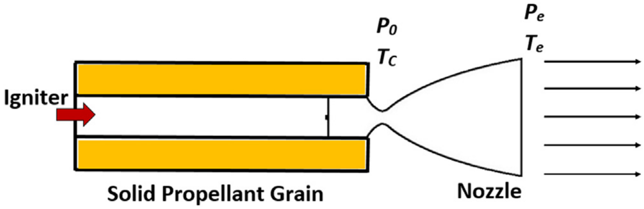

Figure 18.5 Schematic representation of a solid propellant system.

been proposed for specific applications, such as spacecraft de-orbiting at the end of life. Some examples are the 37 N system with orientable nozzles developed by Aerospace Co. (Zondervan et al. [8]), the CDM-1 solid rocket system developed by Digital Solid State Propulsion [7], and the STAR-4G 13 N thruster developed by Orbital ATK [9].

18.2.1 Theoretical performance equations

When referring to space propulsion systems, either at the macro- or micro-scale, the most important parameters used to characterize their performance are the **thrust** and the **specific impulse**.

The thrust is simply the force produced by the thruster, which in the most general case can be calculated using the following equation:

$$F_T = \dot{m} \cdot v_e + (p_e - p_a) \cdot A_e \tag{18.1}$$

where F_T is the thrust, $\dot{m}$ is the **mass flow rate** of propellant, v_e is the velocity at which the propellant is expelled relative to the rocket (usually called **jet velocity**), p_e is the pressure at which the propellant is expelled, p_a is the external ambient pressure, A_e is the nozzle exhaust area. A more detailed description of the assumptions and control volumes used to derive Eq. (18.1) can be found in classical rocket propulsion textbooks (see, e.g., [10]). The equation shows that the thrust is generally made of two different contributions: a "momentum term" (first term on the right-hand side of the equation), and a "pressure term" (second term on the right-hand side). However, in miniaturized propulsion systems, normally designed to operate under vacuum conditions in space, the pressure term is usually negligible. The thrust can therefore be calculated as the product of mass flow rate by jet velocity.

The specific impulse is defined as the ratio of the total impulse generated by the system (thrust integrated over the burn time), to the total weight of propellant used to generate it. It is typically measured in seconds, and gives a measure of the propellant consumption efficiency of the system: higher specific impulse means that a higher total impulse is generated with the same propellant mass (or, alternatively, the same total impulse can be obtained by using less propellant). Using the thrust Eq. (18.1), with the above-introduced assumption of negligible pressure term and the additional assumption of constant jet velocity over time, the specific impulse I_{sp} can be simply written as

$$I_{sp} = \frac{v_e}{g_0} \tag{18.2}$$

where g_0 is always the gravitational acceleration on Earth at sea level (=9.81 m/s^2), regardless of the place where the thruster or spacecraft is flying.

Eqs. (18.1) and (18.2) show that, in order to define in a sufficiently accurate way the performance of a propulsion system, it is important to find equations for at least two important flow parameters: the jet velocity and the mass flow rate. For systems based on the thermodynamic expansion of the propellant in a nozzle, such as those discussed in this Chapter, simplified equations for these two flow parameters are provided by the so-called **Ideal Rocket Theory**. This theory is based on a number of simplifying assumptions for the flow in the nozzle, the most important of which are:

- The fluid flowing in the nozzle is a calorically perfect gas of constant homogeneous chemical composition;
- Flow is steady, isentropic, mono-dimensional, with purely axial velocity;
- No friction or other external forces act on the gas flowing in the nozzle.

The nozzle is convergent-divergent, with an inlet section in which the flow is considered under stagnation conditions (negligible velocity), a throat section where the flow is sonic, and the exhaust section where the flow is typically highly supersonic.

Under the Ideal Rocket Theory assumptions, it is possible to derive the following equation for the jet velocity:

$$v_e = \sqrt{\frac{2\gamma}{\gamma - 1} \cdot \frac{R_A}{M_W} \cdot T_C \cdot \left[1 - \left(\frac{p_e}{p_0}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{18.3}$$

where p_0 and T_C are the pressure and temperature at the nozzle inlet, R_A is the universal gas constant (=8314 J/K*kmol), M_W and γ are the molecular mass and specific heat ratio of the gas flowing in the nozzle. In the case of a cold gas thruster, no chemical reaction happens, and therefore T_C is equal to the initial gas temperature T_0 (typically ambient).

Eq. (18.3) shows that higher jet velocity (thus, higher specific impulse) can be achieved by selecting a propellant that allows for higher nozzle inlet temperature and lower molecular mass of the gas flowing in the nozzle (which, in chemical propulsion systems, is a mix of the products of the chemical reaction in the chamber). This explains why cold gas thrusters, in which the propellant is not heated and the nozzle inlet temperature is low; the specific impulse is typically much lower than in chemical propulsion systems.

For the mass flow rate, assuming chocked conditions at the nozzle throat, the Ideal Rocket Theory allows to derive the following equation:

$$\dot{m} = \frac{p_0 \cdot A^*}{\sqrt{\frac{R_A}{M_W} \cdot T_C}} \cdot \sqrt{\gamma \cdot \left(\frac{1+\gamma}{2}\right)^{\frac{1+\gamma}{1-\gamma}}} \tag{18.4}$$

where A^* is the nozzle throat area. Also in this case, for cold gas thrusters, T_C is simply equal to the initial gas temperature T_0.

Combining Eqs. (18.3) and (18.4), it is possible to notice that the thrust is directly proportional to the nozzle throat area and to the nozzle inlet pressure. Therefore, in systems operating under blow-down conditions, where the nozzle inlet pressure is constantly decreasing with time, the thrust level generated by the system is also decreasing with time.

The above equations are general, and apply to any kind of system based on thermodynamic expansion of the propellant in a nozzle, independently on their size or thrust level. However, for miniaturized systems, a number of additional **down-scaling challenges** arise from their reduced size. The main one of these challenges is represented by the efficiency of the nozzle itself, with a reported dramatic decrease in nozzle performance starting at a throat Reynolds number in the range of 500–1000 [11]. The throat Reynolds number Re^* is defined in this case as

$$Re^* = \frac{a \cdot d^*}{\nu} \tag{18.5}$$

where a is the speed of sound and ν the kinematic viscosity of the gas flowing in the nozzle (evaluated at throat conditions in terms of pressure and temperature), and d^* is the throat diameter (or equivalent diameter, in case of a nonaxisymmetric throat).

It is therefore expected that conventional convergent-divergent nozzle shapes would not work properly at a throat Reynolds number lower than 1000, for which different types of nozzle shapes would need to be considered. One less conventional option to this respect can be represented by **aerospike** micro-nozzles, which have been shown to allow for a performance improvement up to 33% when compared to conventional convergent-divergent ones [12].

Another set of important down-scaling issues comes from the variations of **heat transfer** mechanisms with size. Heat transfer by conduction becomes much more effective in micro-propulsion systems because, for the same material and the same thermal conductivity, smaller size leads to smaller temperature gradients and, thus, a significantly more uniform temperature in the whole thruster. This may represent an issue, especially in thrusters where high temperatures are expected, such as chemical propulsion systems, where a large amount of heat power needs to be released by a smaller volume and, thus, the thermal stresses in the material are amplified. Conversely, the lower throat Reynolds number causes the Nusselt number to be lower too and, therefore, convective heat transfer becomes relatively less significant as compared to conduction. Other design challenges are generated by the significantly different thermal expansion coefficients of different materials used in the thruster, which may lead to an increased risk of leaks and additional thermal stresses. Finally, in propulsion systems where a chemical reaction takes place in the combustion chamber, the effectiveness of the chemical reaction strongly depends on the residence time of the propellants in the chamber and on the so-called characteristic length, a design parameter defined as the ratio of the chamber volume to the nozzle throat area. The characteristic length is therefore the length that the combustion chamber would have, in case there were no converging sections in the nozzle. This parameter gives an indication of the minimum acceptable combustion chamber length to allow for full combustion of the propellants. For a given combination of propellants, there is always a (fixed) optimum range of characteristic length values in order to achieve efficient combustion. Considering that the ratio of combustion chamber area to throat area is not expected to change significantly when going from macro- to micro-scale, this means that the combustion chamber length should be kept constant for any system size, which is obviously not practical when all other dimensions are reduced by several orders of magnitude.

These down-scaling challenges associated with heat transfer and combustion are particularly evident in liquid bi-propellant thrusters, due to the typically higher temperature levels in their combustion chamber. This explains why, at the current day, bi-propellant systems have not been developed at the micro-scale in the same extensive way as cold gas or mono-propellant systems, as it will be clearly shown in the next section. Nevertheless, some ways to circumvent these issues exist and have been employed in the current COTS miniaturized bi-propellant systems. The most obvious solution is to deliberately design the system for working at lower combustion temperature, therefore accepting a consequent reduction in performance which, however, at the same time, allows for easier thermal control. When looking at the currently available COTS options presented in Table 18.3, it can indeed be noted how their specific impulse is significantly lower than the values typically offered by larger-scale counterparts based on the same propellants. Another solution that is widely used in the current COTS systems is the use of additively manufactured parts, which allows for more complex shapes with, eventually, more efficient cooling and thermal control properties.

18.3 Current state-of-the-art commercial-off-the-shelf systems

This section provides an extensive overview of the currently available cold gas and liquid propulsion systems for small satellites and CubeSats. The overview, although not fully exhaustive, intends to be as complete as possible. A particular accent is put on systems that are already available on the market as COTS or have been used in specific missions, looking especially at the most recent developments in the field. Comparative tables are presented at the end of each subsection, including the main performance and design characteristics of the systems presented in that subsection.

For not all the systems presented in the following, it was possible to find a literature reference describing their characteristics and performance. In these cases, the reported information is derived from the official datasheets of the system, the company website, and/or general micro-propulsion overview papers such as Tummala and Dutta [13], Lemmer [7], Krejci and Lozano [14].

18.3.1 Cold gas systems

The current market of cold gas systems is typically limited to attitude control and orbital maintenance applications, and therefore mostly includes modules in which multiple thrusters are present, oriented in different directions depending on the type of maneuver for which they are intended.

The company **GomSpace** (Denmark/Sweden) offers several COTS systems fitting the typical constraints and needs of CubeSat spacecraft. Among these systems, it is worth mentioning:

- The **6DOF** cold gas module, originally designed for the RACE mission of the European Space Agency, includes two separate units with 6 thrusters each to provide six-degrees-of-freedom control authority (three rotations and three translations) to the spacecraft in which it is installed. The propellant is self-pressurized Butane, although the same module can in principle also be used with other propellants. Another peculiar characteristic of this module is the use of a closed-loop thrust control system.
- The **NanoProp 20000** and **NanoProp 6U** systems, based on the same technologies as the 6DOF module but opportunely scaled for different spacecraft sizes and total impulse requirements.

Another company offering a wide range of cold gas micro-propulsion systems and modules is **VACCO** (US). The systems available from this company include:

- The **C-POD** CubeSat Propulsion System, with a volume of exactly 1U and designed to be installed in the central unit of a 3U CubeSat. The system includes eight thrusters with a thrust level of 25 mN each, and is based on self-pressurized R134a refrigerant as a propellant.
- The **Standard MiPS** (Micro-Propulsion System), based on four 25 mN thrusters and scalable for different total impulse levels. The smallest option provides a total impulse of 82 Ns with a system volume of less than 0.5U. The propellant is the R236fa refrigerant.
- Other variants of the MiPS system specifically designed for dedicated missions, such as **MarCO** (tailored for a 6U CubeSat and offering a total impulse of 755 Ns, see: [15]) and **NEA Scout** (based on six 25 mN thrusters and providing a total impulse of 500 Ns to a 14 kg CubeSat).

The other US company **CU Aerospace**, in collaboration with VACCO, has developed the **PUC** system (Propulsion Unit for CubeSats). This system is very compact, with a volume of 0.25U in its smallest version, and uses Sulfur Dioxide (SO_2) as a self-pressurizing propellant. The system is based on a single thruster embedded in a welded titanium body, and can operate either in cold gas or “warm” gas mode (with slight propellant heating and improved performance).

Finally, the company **ThrustMe** (France) offers the **I2T5** propulsion system, which is characterized by the use of a propellant (Iodine) stored in its solid phase. This allows for a more compact system with a volume of 0.5U and for simplified propellant handling and feeding with no tank pressurization, but at the cost of a worse performance in terms of specific impulse and total impulse.

Table 18.1 summarizes the main performance parameters and characteristics of the cold gas systems mentioned in this subsection. In case it was not possible to obtain one of the parameters from the available literature or datasheets, that cell is left empty in the table. Note that “thrust” is intended, in this table, as the thrust level produced by a single thruster.

18.3.2 Liquid mono-propellant systems

The market of liquid mono-propellant systems for CubeSats has “exploded” in recent years, in parallel with the extension of the ambitions for this type of satellite platform, nowadays more and more are proposed also for interplanetary and deep-space scientific missions. The successful Mars flyby of the two MarCO CubeSats in 2018 has paved the way for a large number of more ambitious mission concepts, currently planned for launch in the decade 2021—30, including Lunar exploration and flyby or rendezvous with asteroids. This type of mission, characterized by a high level of autonomy of the CubeSat in terms of orbital transfer and propulsion capabilities, typically requires Delta-V levels that are unfeasible to be obtained with the performance of a cold gas system. They, therefore, need to be equipped either with electrical propulsion (low-thrust, long-duration transfer), or with a chemical system (high-thrust and shorter transfer).

One of the most active companies in the field of mono-propellant systems for CubeSat is **Aerojet Rocketdyne** (US), which offers several COTS systems based either on hydrazine or green propellants [16]:

- The **MPS-130** system is based on four thrusters with a thrust range from 0.25 to 1.25 N, placed at the corners of the system. It comes in two versions (1U and 2U), with different sizes and amounts of available total impulse. The propellant is AF-M315E, a high-density, high-performance, nontoxic green propellant. The main drawback associated to this propellant is the significant amount of power (7 W) required for preheating the catalytic bed.
- The **MPS-120** system (Fig. 18.6) is similar to the MPS-130, but based on hydrazine, a highly toxic and nongreen propellant. The advantages of using this propellant are mainly tied to the fact that, different from the version based on a green propellant, no additional power is required for catalyst preheating. The wet mass of the system is also slightly lower than the option based on a green propellant.

Another company that currently offers mono-propellant systems designed for use in CubeSats is **VACCO** (US). Among their products, it is worth mentioning:

Table 18.1 Comparative table of commercial-off-the-shelf cold gas systems for small satellites.

Name	Company	Propellant	Thrust [mN]	Specific Impulse [s]	Wet Mass [g]	Total Impulse [Ns]	Power, idle [W]	Power, thrust [W]
6DOF	GomSpace	Butane	1 or 10	50	804	100		
NanoProp 6U	GomSpace	Butane	1 or 10	50	900	80		
NanoProp 20000	GomSpace	Butane	1 or 10	50	445	40		
C-POD	VACCO	R134a	25	40	1244	186	0.25	5
Standard MiPS	VACCO	R236fa	25	40	848	82	1	12
MarCO MiPS	VACCO	R236fa	25	40	3490	755		
NEA Scout MiPS	VACCO	R236fa	25	40	2540	500	1.1	9
PUC	CUA/ VACCO	SO_2	5.5	47	718	124	0.05	9.8
I2T5	ThrustMe	Solid Iodine	0.2		900	75		10

Figure 18.6 The MPS-120 modular propulsion system from Aerojet Rocketdyne [7].

- The **ArgoMoon MiPS**, a compact micro-propulsion module with a volume of 1.3U, specifically designed for the ArgoMoon small satellite mission. The module is "hybrid," meaning that it combines one central 100 mN mono-propellant thruster with four 25 mN cold gas thrusters for attitude control or thrust stabilization maneuvers. The mono-propellant thruster can be adapted to work with different types of green propellant blends, including AF-M315E and LMP-103S.
- The **Green MiPS** module is based on four 100 mN mono-propellant thrusters, located at the four corners of the module in a "pyramid" configuration. The module has a volume of approximately 3U and, also in this case, can be adapted to different green propellants (AF-M315E and LMP-103S).

To complete the overview of US companies offering CubeSat mono-propellant systems, it is also possible to mention the following systems from **Busek** [17]:

- The **BGT-X5** module (Fig. 18.7) is a 1U system that features a 0.5 N mono-propellant thruster working with AF-M315E propellant. It is based on a patented "Post Launch Pressurization System" technology, that allows for launching the system unpressurized and pressurizing the propellant tank while in orbit, by means of a CO_2 gas generator.
- The company also offers other thruster options, the **BGT-X1** (0.1 N) and the **BGT-5** (5 N), based on the same heritage as the BGT-X5 thruster and working with the same AF-M315E propellant, but not specifically developed into complete COTS propulsion modules.

A mono-propellant CubeSat propulsion module is also offered by **MOOG** (US), although not much information is available on this system in the datasheets

Figure 18.7 The BGT-X5 mono-propellant system from Busek [7].

provided by the company. The most innovative feature of this module is that it is fully based on additive manufactured parts, including a nonmetallic decomposition chamber manufactured with stereolithography. The module can be used with different types of propellant and has a volume of exactly 1U.

In the European market, the company **NanoAvionics** (Lithuania) offers the compact mono-propellant module **EPSS-C1**, with a volume of 1U and based on a single thruster operating in blow-down mode, which provides a thrust level ranging from 1 N (initial) to 0.22 N (final). The green propellant is an ADN-based blend. The module has been demonstrated in orbit in the LituanicaSAT-2 mission. Other versions of the module are available upon customer request, with larger volume (2U or 3U) and therefore higher total impulse capabilities.

The company **ECAPS** (Sweden) offers a wide range of mono-propellant thrusters operating with LMP-103S as a propellant, which can eventually be employed in custom-designed propulsion modules. Among them, the most widely used and most demonstrated in flight is the **HPGP-1N** thruster, successfully used in missions such as PRISMA or the SkySat series. Other thrusters available from this company, based on the same propellant and similar technology, cover thrust levels from 0.1 N up to a maximum of 220 N.

Table 18.2 summarizes the main performance parameters and characteristics of the liquid mono-propellant systems mentioned in this subsection. Also in this case, the thrust value is intended as the thrust level produced by a single thruster and, when it was not possible to obtain one of the parameters from the available literature or datasheets, that cell is left empty in the table.

Table 18.2 Comparative table of commercial-off-the-shelf liquid mono-propellant systems for small satellites.

Name	Company	Propellant	Thrust [mN]	Specific Impulse [s]	Wet Mass [g]	Total Impulse [Ns]	Power, idle [W]	Power, thrust [W]
MPS-130–1U	Aerojet Rocketdyne	AF-M315E	250–1250	235	1660	1200		18
MPS-130–2U	Aerojet Rocketdyne	AF-M315E	250–1250	235	2760	3360		18
MPS-120–1U	Aerojet Rocketdyne	Hydrazine	250–1250	217	1480	775		11
MPS-120–2U	Aerojet Rocketdyne	Hydrazine	250–1250	217	2380	2000		11
ArgoMoon MiPS	VACCO	AF-M315E LMP-103S	100	177	2065	783	1	4.3
Green MiPS	VACCO	AF-M315E LMP-103S	100	169	5000	3320	10	15
BGT-X5	Busek	AF-M315E	500	225	1500	565		20
BGT-X1	Busek	AF-M315E	100	214				
BGT-5	Busek	AF-M315E	5000	230				
MP module	MOOG		500	224	1010	500		45
EPSS-C1	NanoAvionics	ADN blend	220–1000	213	1200	400	0.19	1.7
HPGP-1N	ECAPS	LMP-103S	250–1000	231				10

18.3.3 Liquid bi-propellant systems

The market of liquid bi-propellant systems for CubeSats is significantly less developed at the current date when compared to the much wider range of existing options for mono-propellant systems presented in the previous subsection. The main reason can be identified in the significant technical challenges associated with the down-scaling of this class of propulsion systems, as explained in detail in the previous section.

One of the first historically active players in the market of bi-propellant systems for CubeSats is **Hyperion** (Netherlands). The company currently offers the **PM200** propulsion module, based on a bi-propellant thruster using nitrous oxide and propene as propellants, in a self-pressurizing configuration. The system makes large use of additive manufactured components and is characterized by a unique gimbaled thrust vector control system.

Another, more recent, Dutch actor in the field is **DAWN Aerospace**, which has picked up the technology initially developed by Hyperion and extended its use to additional propulsion module options. Their product portfolio currently includes a **0.7U** and a **1U** module, based on the same features and the same thruster as the PM200 module from Hyperion.

In the US, the company **Benchmark Space Systems** offers two CubeSat bi-propellant system options. The **Halcyon** system is a dual-mode module, that can be used either as a mono-propellant or as a bi-propellant, with Hydrogen Peroxide and Butane as propellants. The **Peregrine** system is based on Hydrogen Peroxide and NHMF as propellants and employs a proprietary "micromixing" technology that allows for eliminating the use of catalytic beds. Both modules are based on a proprietary pressurization technology and allow for choosing a thrust level in the range from 100 mN to a maximum of 22 N.

Finally, a special mention can be made for the company **Tethers Unlimited** (US). They have developed the **HYDROS** thruster (Fig. 18.8), based on water propellant and electrolysis to convert water into hydrogen and oxygen [18]. This is, therefore as a matter of fact, a bi-propellant thruster, although it has a single propellant tank and allows for launching the satellite with a benign, nontoxic, and nonexplosive liquid. The obvious drawback is the additional amount of power (and additional system complexity) required by the electrolysis process. Two types of propulsion modules based on this thruster are currently available as COTS products: a smaller one (**HYDROS-C**), with a volume of approximately 2U and specifically designed for use in CubeSats, and a larger one (**HYDROS-M**), scaled up for microsatellite use. Both options offer a thrust level of 1.2 N.

Table 18.3 summarizes the main performance parameters and characteristics of the liquid bi-propellant systems mentioned in this subsection. Also here, in case it was not possible to obtain one of the parameters from the available literature or datasheets, that cell is left empty in the table.

18.4 Applications to small satellite missions

The performance data of cold gas and chemical micro-propulsion systems, as presented in the previous section in Tables 18.1–18.3, can be combined in

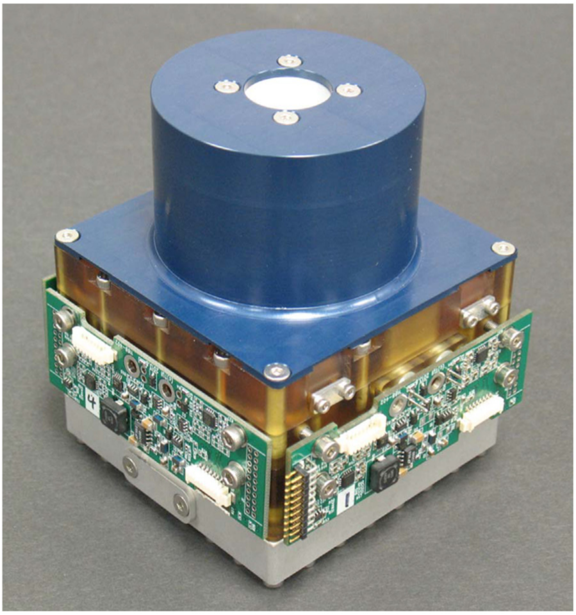

Figure 18.8 The HYDROS water electrolysis thruster from tethers unlimited [7].

performance charts that allow for better characterizing the applicability of these systems to specific missions and tasks. Three of these performance charts are presented in the following: thrust versus specific impulse (Fig. 18.9), thrust versus total impulse (Fig. 18.10), total impulse versus wet mass (Fig. 18.11).

Figs. 18.9 and 18.10 clearly show that cold gas systems and chemical propulsion systems belong to two distinct quadrants of the performance spectrum: low thrust-low specific impulse, or low thrust-low total impulse (cold gas); higher thrust-higher specific impulse, or higher thrust-higher total impulse (chemical). This clear quadrant separation already drives in a direct way the selection of a system for a given application, as it will be better shown in the following.

The charts also show that the main difference between mono-propellant and bi-propellant systems lies in the slightly higher specific impulse level of the latter, while for all other performance parameters (thrust, total impulse, wet mass) they cover almost overlapping regions in the charts. For this reason, in the following analysis, no distinction will be made between these two types of propulsion, and they will be denoted together with the more generic definition “chemical systems.”

Finally, Fig. 18.11 shows a direct relationship, as it could have been expected, between the higher total impulse provided by the system and higher wet mass. This figure also shows that, for the same wet mass, chemical systems provide a total impulse that can be up to one order of magnitude higher than cold gas systems. This outcome is not surprising, considering the different specific impulse capabilities of these two types of propulsion.

Table 18.3 Comparative table of commercial-off-the-shelf liquid bi-propellant systems for small satellites.

Name	Company	Propellant	Thrust [mN]	Specific Impulse [s]	Wet Mass [g]	Total Impulse [Ns]	Power, idle [W]	Power, thrust [W]
PM200	Hyperion	Nitrous Oxide Propene	500	285	1420	850	0.1	12
0.7U Module	DAWN Aerospace	Nitrous Oxide Propene	500	285	1170	425		12.5
1U Module	DAWN Aerospace	Nitrous Oxide Propene	500	285	1410	850		12.5
Halcyon	Benchmark Space	H_2O_2 Butane	100	320			0.1	3
Peregrine	Benchmark Space	H_2O_2 NHMF	100	270	2500	1750	0.1	3
HYDROS-M	Tethers Unlimited	Water	1200	310	13700	18000		40
HYDROS-C	Tethers Unlimited	Water	1200	310	2700	2151		25

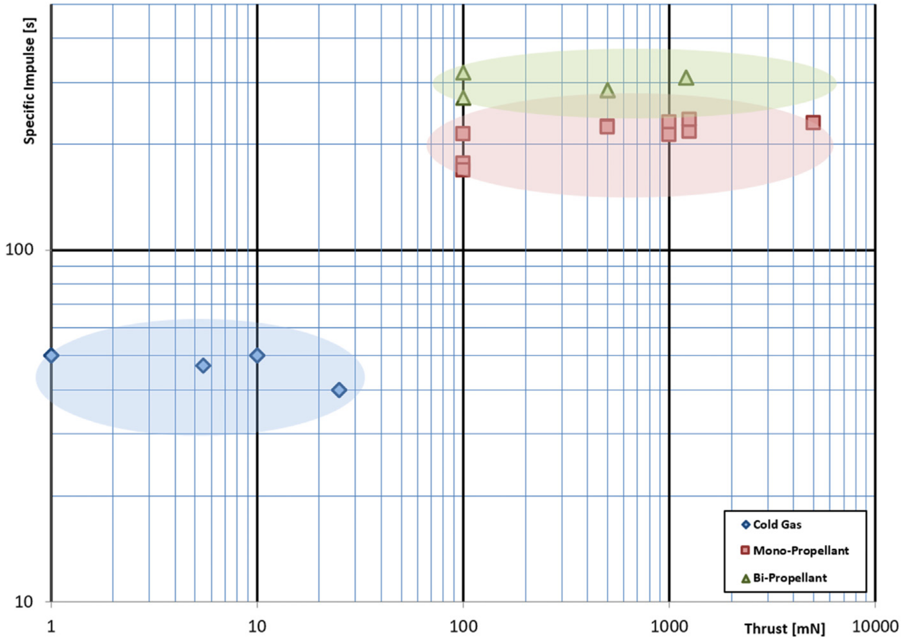

Figure 18.9 Thrust-specific impulse performance chart of commercial-off-the-shelf cold gas and chemical micro-propulsion systems.

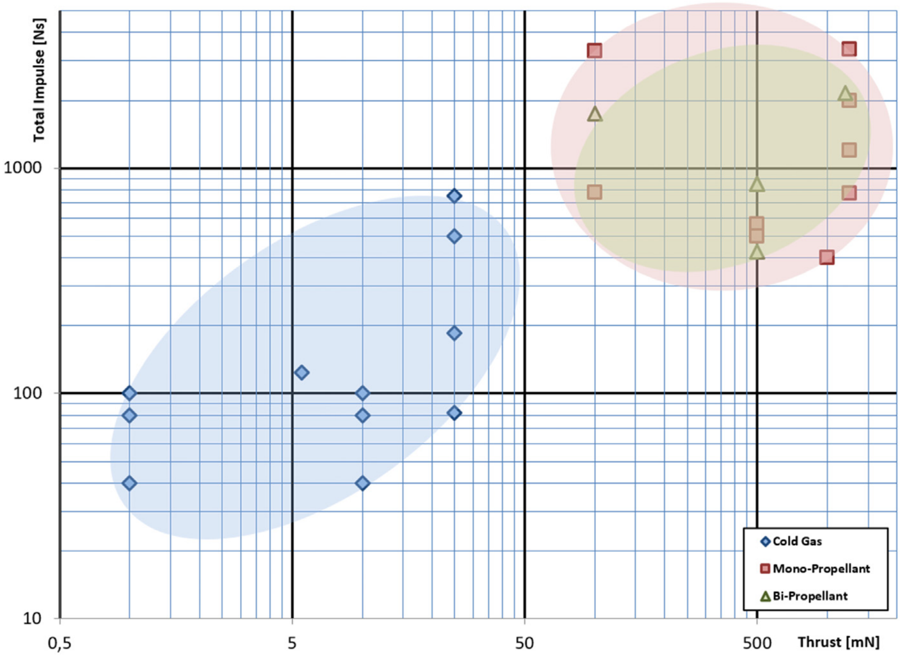

Figure 18.10 Thrust-total impulse performance chart of commercial-off-the-shelf cold gas and chemical micro-propulsion systems.

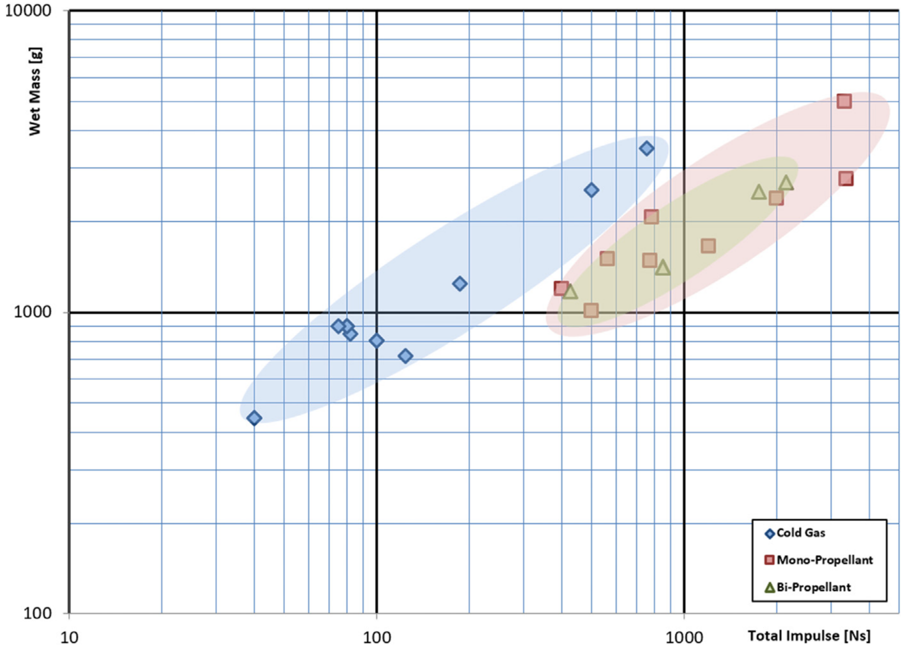

Figure 18.11 Total impulse-wet mass performance chart of commercial-off-the-shelf cold gas and chemical micro-propulsion systems.

To better understand how these performance charts can be used to assess the applicability of a given type of propulsion to a given mission, it is useful to first provide an overview of the possible tasks required to a propulsion system in different types of small satellite missions (referring in particular to CubeSats) and their corresponding requirements in terms of thrust and Delta-V. In this analysis, for the sake of simplicity, just two possible CubeSat sizes will be considered: a "small" one (where "small" refers to a spacecraft with 3 kg wet mass, approximately corresponding to a 3U form factor), and a "large" one (where "large" means a spacecraft with 20 kg wet mass, which is a realistic value for a 12U CubeSat). Note that the range of values provided in the following represents typical, approximate order-of-magnitude estimates for the requirements of CubeSat missions, as suggested by the experience of the author of this chapter; it is possible that, for specific missions of peculiar characteristics, their requirements slightly differ from those indicated here. This, however, does not affect the general validity of the analysis. Also, note that the range of requirements provided in the following will refer explicitly to the high-thrust case or, in other terms, the case when the given propulsion tasks can be performed by quasiimpulsive burns. For all the tasks described in the following, it is also possible to perform them with a low-thrust strategy (usually by means of an electric propulsion system), for which, however, a different range of requirements would be derived, both in terms of Delta-V and required thrust level.

Generally speaking, four main categories of propulsion tasks/maneuvers will be considered here, each with its own specific requirements in terms of thrust and Delta-V:

- **Attitude control** or, more generally, **reaction control** maneuvers (such as reaction/momentum wheel desaturation, spacecraft de-tumbling, etc.). This type of task typically requires small impulse bit capability and, consequently, low thrust levels. For the "small CubeSat" case (3U form factor, 3 kg wet mass) this typically translates into a thrust of 10 mN or less, while for the "large CubeSat" case (12U, 20 kg) the required thrust is typically 100 mN or less. The required Delta-V for performing this type of attitude control tasks, for a spacecraft lifetime of one year, is typically in the range of 5–50 m/s.
- **Drag compensation** (or, more generally, compensation of other disturbance forces in orbit). This is a crucial task for CubeSats flying in Earth orbit at low altitudes, in the order of 300–350 km or less, to avoid rapid orbital decay caused by the effects of the drag/disturbance force. For 1-year orbital altitude maintenance, the typical Delta-V level is in the range of 50–100 m/s. A slightly higher thrust force is usually deemed acceptable for this type of task, up to 20 mN for the 3U case and up to 200 mN for the 12U case.
- **Station keeping** maneuvers, for example, to maintain the orbital position of observation or geostationary satellites. This type of task requires a similar Delta-V budget as drag compensation but is performed more efficiently when the thrust level is higher. Typical thrust levels for station keeping are in the range of 20–100 mN (3U case) and 200–500 mN (12U case).

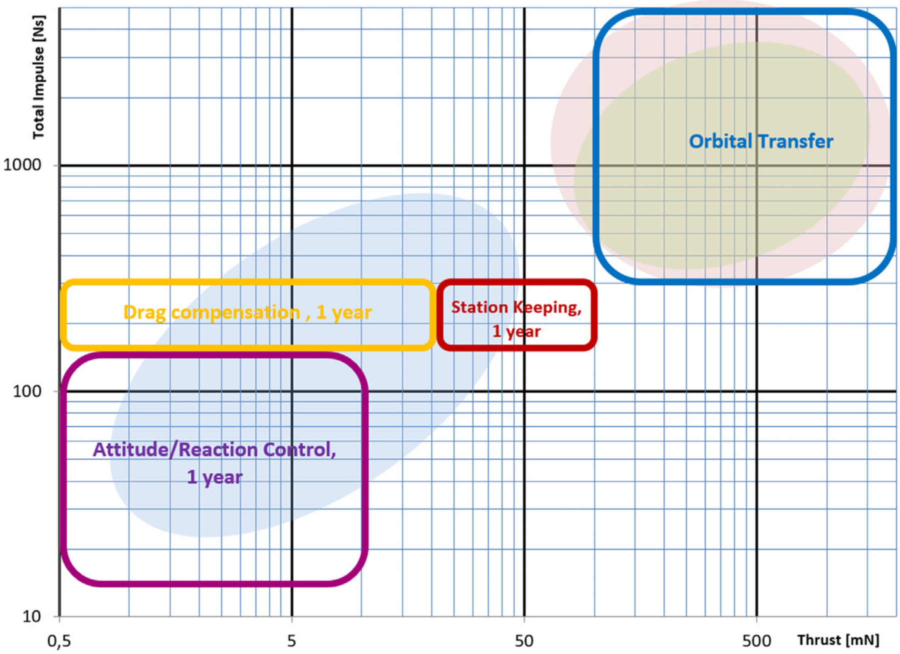

Figure 18.12 Typical thrust/total impulse requirements for different types of propulsion tasks (3 kg/3U CubeSat).

- **Orbital transfer**, which can be done either between two different Earth orbits or for more complex interplanetary missions. For this category of maneuvers a significantly higher Delta-V is required, which can be in the order of 100 m/s for less demanding transfers between two relatively close orbits, up to several km/s for longer interplanetary travels. To alleviate the Delta-V requirements, it is normally desirable that these orbital transfer maneuvers are performed as closely as possible to impulsive shots; therefore, they require a high thrust level (more than 100 mN for smaller CubeSats, more than 500 mN for larger ones).

The above general requirements can be overlapped with the thrust-total impulse performance chart for the two CubeSat sizes considered in the analysis, leading to the plots shown in Figs. 18.12 and 18.13.

It is apparent from the charts that cold gas systems are always the preferable choice for attitude/reaction control maneuvres, while the orbital transfer is always preferably performed by means of chemical propulsion systems. For drag/disturbance force compensation and station keeping, the scenario is different depending on the spacecraft size: while a cold gas system represents an adequate option for this type of maneuvres in smaller CubeSats, a chemical propulsion system would typically be preferable in the case of a larger spacecraft.

This outcome, however, needs to also be checked in terms of the wet mass of the propulsion system, see Fig. 18.11. A cold gas system for attitude/reaction

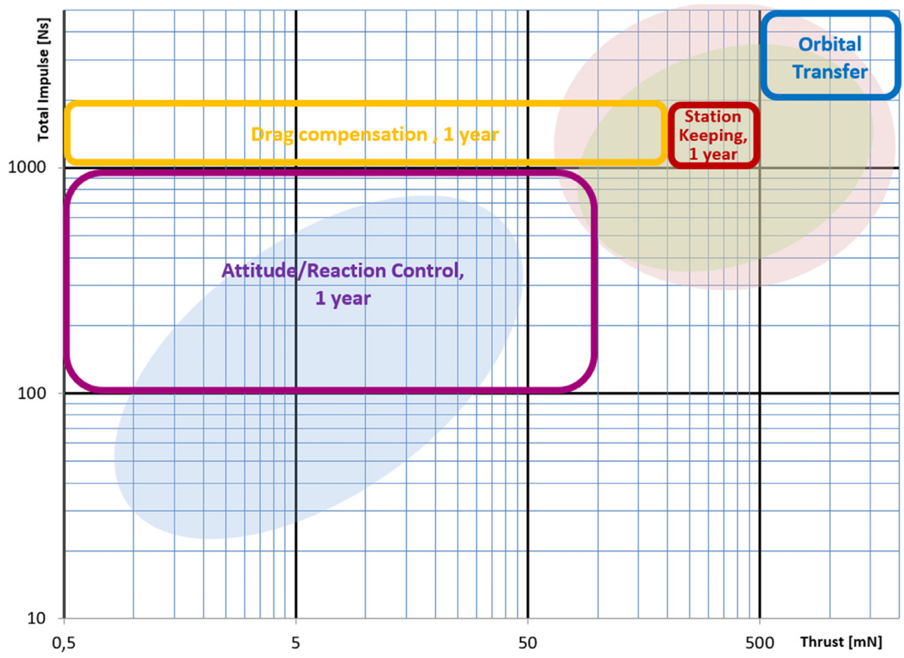

Figure 18.13 Typical thrust/total impulse requirements for different types of propulsion tasks (20 kg/12U CubeSat).

control in a 3U CubeSat can have a wet mass up to 900 g, while for drag compensation and station keeping its wet mass can go up to 1200 g. These values, although still feasible for a typical 3U CubeSat design, need to be carefully considered because they represent a significant percentage of the total wet mass of the spacecraft. For orbital transfer of the 3U CubeSat, the required chemical propulsion system would have a wet mass of no less than 1000 g, but its mass can be as high as 2000 g or more, thus posing even more significant challenges in the design and configuration of the whole spacecraft.

The situation for the larger CubeSat option (12U) is significantly better, for all considered propulsion tasks. All tasks allow in this case for a propulsion system with a mass between 1000 and 3000 g, well compatible with the size and configuration challenges of this type of spacecraft.

18.5 Conclusions and future challenges

As clearly shown by the analysis presented in this chapter, both cold gas and chemical micro-propulsion systems have a nonnegligible range of potential applications in CubeSats, and therefore represent an asset for this class of spacecraft. While cold gas systems are crucial for ensuring accurate pointing and positioning of the spacecraft, chemical propulsion systems are required for more demanding tasks in terms of Delta-V, such as orbital transfer maneuvers.

However, the future perspectives for these two types of micro-propulsion systems are clearly different. While cold gas systems already have a relatively long heritage also in their miniaturized version and have reached in their current state-of-the-art good level of maturity with limited expectable additional improvements in the future, the situation for chemical micro-propulsion is much more dynamic and still presents a large number of improvements opportunities.

In the current state-of-the-art, green propellants have become a reality and have allowed to almost eliminate the use of hydrazine, at least in miniaturized propulsion. The introduction of HAN-based and ADN-based propellant blends has allowed to achieve specific impulse levels similar (or in some cases even better) than those of hydrazine, combining the benefits of multipropellant systems with the advantage of still using a single, premixed liquid as a propellant. The next step will be represented by extending the current market offer of miniaturized bi-propellant systems by solving the intrinsic design challenges associated with their down-scaling: combustion inefficiencies, difficulties in achieving effective thruster cooling and, as a direct consequence, very short achievable burn durations and/or deliberately reduced performance levels. The recent implementation of additive manufacturing technologies in the development of these systems might represent a crucial turning point in this respect by allowing for much more complex thruster geometries. The MPS-120 mono-propellant system from Aerojet Rocketdyne previously presented in Section 18.3.2, as an example, makes wide use of additively manufactured components, and this company is at the forefront of applying additive manufacturing also to more complex and more innovative systems. Recent research on additively manufactured energetic materials at micro-scales, such as the work conducted at Purdue University [19], can open the way to the production of very small combustion chambers for micro-thrusters based on solid and hybrid propellants. Finally, recent rapid advancements in additively manufactured metallic thrust chambers (see, e.g., [20]) show a clear potential for being applied at the micro-scale too, which would allow among other things to produce efficient micro-nozzles with embedded micro-cooling channels.

The introduction of reliable mechanical or electronic systems (such as gimballed thrusters) for active thrust control might represent another fundamental turning point, allowing for the effective implementation of higher thrust levels also in relatively small CubeSat form factors without the undesired side effects caused by possible thrust misalignment.

Another possible way forward can be represented by the use of alternative nozzle geometries, such as the aerospike, to mitigate the performance losses associated with low Reynolds number in conventional convergent-divergent nozzles and eventually allow for chemical propulsion systems capable of even lower thrust levels than the current ones. The work from Ganani and Cervone [12], as an example, was focused on double-depth aerospike nozzles with 45 μm throat width, 100 μm nozzle depth and spike depth ranging from 200 to 1000 μm. A significant performance increase of up to 33% was predicted as compared to conventional nozzle shapes, due to the elimination of end-wall losses and the reduction of over-the-edge expansion losses typical of single-depth aerospikes. It was also shown that it is possible to manufacture this type of aerospike nozzle geometries in a silicon MEMS wafer, using a combination of Deep Reactive Ion Etching and a photo-resist mask.

Finally, further miniaturization of the fluidic components in the feeding system, with more massive use of MEMS technologies (micro-valves, micro-pumps, micro-sensors) is expected to allow for significant reductions in the volume of chemical micro-propulsion systems. The combined advantage of using a miniaturized pump and an autogenously-pressurized mono-propellant based on an Energetic Ionic Liquid has been clearly shown by the innovative micro-propulsion design proposed by Nosseir et al. [21]. The system takes advantage of one of the micro-electric pump models produced by the company Flight Works and is targeted for a thrust level of 0.5 N, with a predicted vacuum-specific impulse of 266 seconds and total impulse of 1369 Ns in its 1U CubeSat format. The use of a micro-pump is a crucial feature of this system, allowing for a stable thrust level over time and relatively low propellant storage pressure, in the order of 20 bar. In the future this class of micro-electric pumps are expected to be used in a more massive way in commercially available propulsion systems, thus boosting their performance capabilities both in terms of increased achievable Delta-V and reduced propulsion system dry mass (due to the lower required pressure level in the propellant tank).

In conclusion, it can be anticipated that in a not-too-far temporal horizon (5–10 years from now), the scenario of chemical micro-propulsion systems will have reached its full maturity, allowing for designing systems that will be almost perfectly down-scaled copies of their larger rocket engine counterparts, and thus paving the way to a quantum leap in the current capabilities and range of missions for CubeSats.

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