Electric Propulsion for CubeSats: a Review

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ELECTRIC PROPULSION FOR CUBESATS: A REVIEW

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This review aims at describing the state of the art of the electric propulsion for CubeSats as long as to identify general trends for the near-future. Electric propulsion is appealing for CubeSats because of the high specific impulse (up to 10000 s) and, in turn, the possibility of saving up propellant mass reducing costs. Integrating an electric thruster and its subsystems (i.e., fluidic, electronics, and thermo-structures) in a CubeSat is challenging. Therefore only in the last years consolidated systems have been successfully tested in orbit. In the paper, near-future mission scenarios are outlined, the state of the art of the electric propulsion for CubeSats is reviewed, and systems in progress are outlined. General trends in the market are identified, namely up scaling and research on innovative propellants.

I. INTRODUCTION

Electric Propulsion (EP) has been the subject of a thorough research activity for the last fifty years [1]. As a result, mature technologies as gridded ion and Hall effect systems have been successfully employed in hundreds of space missions [2]. Nonetheless, the widespread diffusion of CubeSats imposes new demanding requirements in terms of mass, volume and budget to EP systems [3]. Several companies and research centres are currently working at the development of EP for CubeSats [4] since a dedicated propulsion system is mandatory to satisfy mission needs in the near-future. For example, in commercial applications the capability of accomplishing orbital manoeuvers is required to CubeSats both for envisioning new mission scenarios and to enlarge the lifetime of these systems [5]. Reliable products have been developed only in the last years [6].

In this framework, EP is particularly appealing for applications as constellations of CubeSats [7] and solar system exploration [8]. In fact, the most suited mission scenarios present: (i) high ΔV (>100 m/s) so a significant portion of propellant mass can be saved up in respect to chemical rockets [1]; (ii) the time to accomplish the manoeuvre is not a major constraint since the thrust provided by EP systems for CubeSats is relatively low (i.e., << 0.1 N) [9]. The integration of an electric thruster on board of a CubeSats enables orbit change, maintenance, and attitude control (with precision pointing) [10]. In case of constellations, phasing, deployment and formation flying can be accomplished. Also deorbiting and drag compensation are possible with EP systems. Vice versa, applications such as collision avoidance seem not particularly suited for EP because of the lack of high thrust and, in turn, fast response.

The rest of the paper is organized as follows. In Section II near-future mission needs are outlined. In Section III the state of the art of the EP propulsion is reviewed. In Section IV general trends are discussed. Finally in Section V conclusions are drawn.

II. MISSION NEEDS

The requirements imposed to EP systems depend on the mobility needs of CubeSat missions. The number and the complexity of possible missions is drastically increasing, the most appealing scenarios for EP systems have been outlined in the following.

Constellations of CubeSats are particularly attractive both for scientific (e.g., Earth observation) and commercial (e.g., telecommunications) purposes [7,11]. EP allows to position satellites in the dedicated orbits after they have been deployment in batches from the launcher [12,13]. Orbit maintenance can be accomplished so the correct phasing between different elements of the constellation is ensured. This type of missions is particularly demanding if out of plane manoeuvers are needed since the required ΔV can be up to 500 m/s.

Drag compensation is needed to avoid the orbit decay in a time scale of few months for CubeSats operated in Low Earth Orbit (LEO) and Very Low Earth Orbit (VLEO). Therefore, a propulsion system is needed whenever the duration of the mission is scheduled for several months or years. The ΔV budget depends mainly on the altitude of the orbit, the front area of the spacecraft, and the mission duration [14]. At an altitude of 400 km a 6U CubeSat has a ΔV budget of approximately 25 m/s per year, at 600 km the value decreases to 5 m/s per year [14].

Due to the current regulation on the Space debris mitigation, an End-Of-Life (EOL) disposal manoeuvre shall be accomplished within 25 years from launch [15].

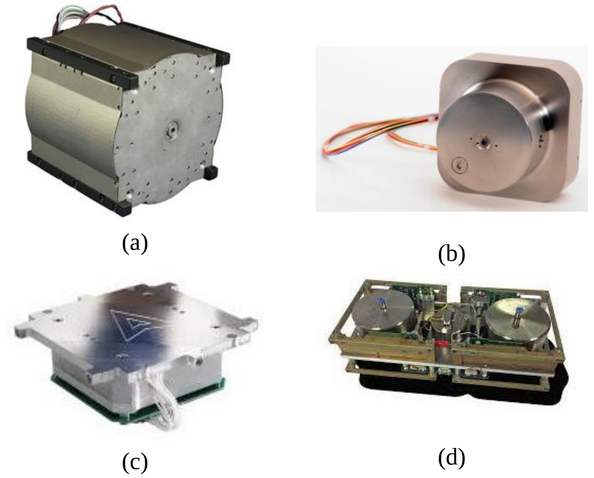


Figure 1. Pictures of electrothermal systems: (a) MRJ Busek [22], (b) PUC CU-Aerospace [29], (c) ARM-A Aurora [23], (d) NanoProp20000 GOMspace [32].

Systems operating in LEO below 600 km tend to re-enter the Earth atmosphere within the prescribed timeline, so a propulsive system is nowadays no mandatory. Nonetheless, the number of CubeSats operating in the altitude range 400-600 km is increasing [5], so new regulations might be introduced in the near-future to avoid the production of further space debris. An EP system is a valuable alternative for EOF disposal since time is not a major constraint and the ΔV budget for a satellite at 1000 km altitude is approximately 250 m/s.

Proximity operations between CubeSats or a larger spacecraft and a CubeSat are usually performed via chemical or cold-gas systems [16] since a fast response time is usually required. Nonetheless a niche where EP can be applied is the monitoring of large spacecrafts or debris (e.g., ENVISAT [17]). Typical requirements in terms of ΔV are 10-50 m/s per year.

CubeSats can be employed for deep-space application by in-situ deployment or deep-space cruise. The former mission scenario is appealing for scientific missions in order to reduce costs. The MarCO mission is an example of two CubeSats launched in the orbit of Mars [8]. On the other hand, interplanetary cruises are nowadays unfeasible for CubeSats since the ΔV budget for an Earth-Lunar transfer is in the order of 3 km/s [18].

III. STATE OF THE ART

In this section, the state of the art of the CubeSat propulsion is reviewed. The focus is “high” Technology Readiness Level (TRL) systems. In this paper the definition of “high” TRL refers to propulsion units compliant with CubeSat standards [19] that integrate thruster and sub-systems (i.e., fluidic, electronics and thermos-structures). Both systems that accomplished an In-Orbit-Demonstration (IoD) or that scheduled one are discussed. Systems with a lower maturity are outlined in Section IV. In the rest of this section electric thrusters are classified as electrothermal, electrostatic, and electromagnetic [1]. In the first class, electric power is used to heat up a neutral gas that produces thrust via its expansion. In the second class ions are accelerated via an electrostatic field. In the third class electromagnetic forces are used to accelerate plasma.

III.A Electrothermal

Table 1. Performance of electrothermal thruters.

Thruster	T [mN]	Isp [s]	Pw [W]	Ref.
MRJ Busek	2-10	150	3-15	[22,24]
ARM-A Aurora	0.6-4	100	2-20	[23]
Comet Bradford	17	180	55	[25,26]
AQUARIUS Uni-Tokio	2-4	70	<8	[27,28]
CHIPS CU-Aerospace	<30	<75	25	[29,30]
PUC CU-Aerospace	5	70	15	[29,31]
NanoProp20000 GOMspace	1-10	50	<10	[32]

Electrothermal systems for CubeSats are usually derived from cold-gas thrusters [20] and are designed to enhance the performance while maintaining a simple concept (see Figure 1). Electrothermal systems are usually operated with inert and non-combustible gas so restrictions on the propellant choice are mainly related to the maximum operation temperature of the thruster’s walls [21].

The propulsive performance of several electrothermal thrusters is reported in Table 1. Resistojet [9] systems have been developed by Busek [22] and Aurora Propulsion Technology [23]. The former, MRJ [24], is propelled by ammonia, the latter by water. The thruster developed by Aurora Propulsion Technologies is the core technology of the attitude and control system ARM-A whose IoD is scheduled in 2021 [23]. Other water-based systems are Comet by Bradford space [25], tested on orbit during the HawkEye 360 mission [26], and AQUARIUS by the University of Tokyo [27]. The latter has been operated during the mission AQT-D in 2019 [28] but no data regarding its testing have been published yet. The company CU Aerospace [29] developed two electrothermal systems, namely the CHIPS [30] and the PUC [31]. The former is based on a resistojet concept and, even though compact (from 0.6U to 1.5U depending on the propellant stored), it requires a “tuna can” extension. The PUC relies on a micro-cavity discharge [31] to heat up the propellant. Both thrusters can be operated with R134a and R236fa propellants, but PUC works as an electric thruster, and not as a cold gas system, only if operated with sulfur dioxide. Finally, the CubeSat MEMS [32] technology has been adopted by GOMspace for the NanoProp-20000 and NanoProp-6DOF attitude and control systems [32]. The propellent used is butane.

Electrothermal systems are usually compact (less than 2U), apart from Comet by Bradford that can have an envelope up to 24U. They provide a relatively high thrust (i.e., tens of mN) with a modest specific impulse (< 200 s). As a result electrothermal thrusters are mainly employed for the attitude and control system of the CubeSat rather than to accomplish manoeuvres where an high ΔV budget (>100 m/s) is required.

III.B Electrostatic

Table 2. Performance of electrostatic thrusters.

Thruster	T [mN]	Isp [s]	Pw [W]	Ref.
BIT-1 Busek	0.1-0.18	2150-3200	10-55	[22]
BIT-3 Busek	<1.25	<2300	56-80	[22]
NPT-30 ThrustMe	0.4-1.1	700-1000	30-60	[34,35]
ExoMG-nano Exotrail	2.0	800	60	[41,42]
Halo ExoTerra	7.0	1110	185	[43]
IFM-nano Enpulsion	0.01-0.35	2000-6000	8-40	[44,45]
IFM-micro Enpulsion	0.2-1.35	1500-6000	30-120	[44]
NanoFEEP Morpheus	0.04	3000-8500	3	[46,47]
S-iEPS MIT	0.075	>1150	1.5	[49]
TILE-2 Accion	0.04	1650	4	[50]
TILE-3 Accion	0.45	1650	20	[50]

Thanks to a consolidated flight heritage, gridded ion thrsuters [2] have been adapted also in the CubeSat field. Nonetheless, a careful design is needed to avoid problems of grid erosion [21]. Moreover, the neutralizer necessary to emit a globally neutral plasma is a device that usually consumes power and propellant along with requires a carful thermal control [21]. Busek [22] developed the BIT series to propel small satellites (mass lower than 200 kg [3]) and CubeSats. The BIT-3 targets 6U or larger spacecrafts while the BIT-1 is a miniaturized version intended for 3U CubeSats. In spite of the contamination issues associated to the operation of the neutralizer, the thrusters of the BIT series have been operated with both noble gases and iodine propellants [22]. In particular the IoD of the BIT-3 propelled with iodine is planned on board of the Lunar IceCube [33]. The company ThrustMe [34] developed the NPT-30 system [35] that is a gridded ion thruster for 6 U or larger CubeSats. It can be operated both with

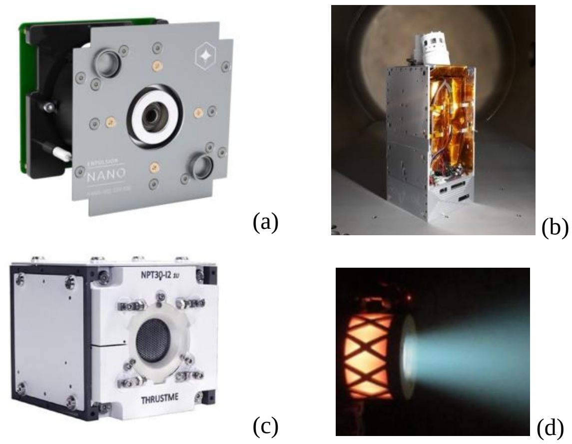


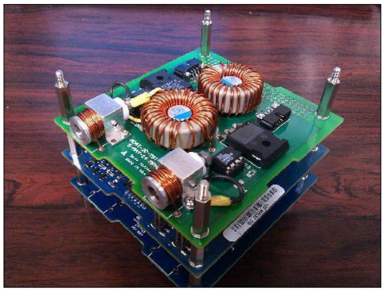
Figure 2. Pictures of electrostatic systems: (a) IFM-nano Enpulsion [44], (b) ExoMG-nano Exotrail [41], (c) NPT-30 ThrustMe [34], (d) BIT-3 Busek [22].

xenon and iodine propellants. The latter version has been demonstrated on orbit in 2021 during the mission Beihangkongshi-1 [34]. Interestingly, ThrustMe has developed also a patented system to operate its thrusters in ambipolar mode without a neutralizer [36]. Finally, there is a series of thrusters originally developed for north-south station keeping or for scientific missions that guarantee a propulsive performance appealing for the CubeSats but that have never been customized for this application. An example is the RIT series by Ariane Group [37]. The RIT-µX and RIT-10 are xenon-based thruster that might target 6U or larger CubeSats [38]. The same holds for the MiXI developed at JPL [39,40].

The Hall effect thrusters [2], as the gridded ion systems, have a consolidated flight heritage so they have been customized to the CubeSat application in spite of channel erosion and neutralizer contamination issues [21]. The ExoMG-nano by Exotrail [41,42] is the only consolidated technology capable of targeting CubeSats down to 6U (i.e., power budget less than 100 W). This thruster, propelled with xenon, has been tested in orbit in 2021 on board of the M6P bus by NanoAvionics [21]. Considering the inherent difficulty of downscaling Hall effect thrusters, several systems that target CubeSats work in the 100-200 W power range [3,21]. The Halo thruster has been developed by ExoTerra for its 12U CubeSat carrier [43]. The IoD is scheduled in the frame of the Tipping Point mission [21]. Also Exotrail is developing systems in this power range, namely the ExoMG-micro [41], but its detailed characterization has not been published yet. Considering the large flight heritage of the Hall effect thrusters, there are systems developed in the past years that have appealing performance but are not targeted at the CubeSat market. An example it the BHT-200 by Busek [22].

Electrospray systems [9] are very appealing for CubeSats since the production of a plasma discharge is not required and the emitter, from which droplets of


(a)


(b)


(c)

Figure 3. Pictures of electromagnetic systems: (a) BmP-220 Busek [22], (b) µCAT GWU [62,63], (c) Regulus T4i [54-56].

propellant are ejected, is in the micrometric scale. Therefore electrospray thrusters are prone to miniaturization. The main drawback of these systems is that propellants (liquid metals or ionic liquids) tend to contaminate surfaces [21]. Enpulsion developed the IFM class of electrospray systems propelled by indium [44,45]. Notably, the IFM-nano has been tested on orbit in 2018 [45] and nowadays tens of propulsive units have been successfully operated in space. The same company developed the IFM-micro which is an up scaled version of the IFM-nano that targets CubeSats larger than 6U. Also the IFM-micro system has been successfully tested in orbit [44]. Systems developed for CubeSats down to 1U are the NanoFEEP by Morpheus Space [46,47], tested on orbit during the UWE-4 mission [48], and the S-iEPS by MIT [49]. The latter has been operated during the AeroCube-8 mission but data on the test have not been published [4]. The Accion [50] company developed the TILE series of thrusters propelled with ionic liquids. TILE-2 is targeted to small CubeSats (down to 1U) and its IoD is scheduled in the frame of the BraveCube mission. The TILE-3 system consists on multiple TILE-2 propulsion units clustered together in order to target 3U or larger CubeSats. Finally, the CMNT by Busek [22,51,52] has been developed for the LISA Pathfinder (ST-7) mission [53] but is not compliant with CubeSat standards.

Electrostatic systems (see Table 2 and Figure 2), present in general a very high specific impulse (<10000 s). Gridded ion and Hall effect thrusters provide high thrust levels (<10 mN) but also electrostatic systems can achieve comparable values if clustered. For this reason electrostatic systems are the most adapt to propel CubeSats when an high ΔV budget (>100 m/s) is required.

III.C Electromagnetic

Table 3. Performance of electromagnetic thrusters.

Thruster	T or I_b	Isp [s]	Pw [W]	Ref.
REGULUS T4i	0.25-0.7 mN	<700	20-60	[54,55,56]
Maxwell Phase4	<7 mN	<400	300-500	[57]
BmP-220 Busek	20 µNs	536	1.5-7.5	[22]
PPTCUP Mars Space	40 µNs	600	2	[58,59]
µPPT Fotec	5-15 µNs	900	<2	[60]
FPPT CU-Aerospace	90-240 µNs	<2400	48	[29,61]
µCAT GWU	1-50 µNs	3000	<10	[62,63]

Ambipolar systems as the Helicon Plasma Thrusters (HPT) [9] are appealing for the CubeSat application since their geometry is simple being the plasma accelerated via the magnetic nozzle effect [9]. Namely no grids or neutralizers are needed. Regulus is a propulsion unit developed by T4i [54] that relies on a cathodeless plasma thruster [55,56]. The main target is CubeSats larger than 6U or CubeSat carriers. Regulus is propelled with iodine and its IoD is ongoing [56]. The company Phase4 developed a very high power (up to 500 W) ambipolar system: the Maxwell thruster [57]. The latter is relatively compact (less than 4U) and targets large systems where hundreds Watt of electrical power are available (e.g., CubeSat carriers).

Thanks to the simple design and the possibility of using solid propellants pulsed systems, namely Pulsed Plasma Thrusters (PPT) and Vacuum Arc Thrusters (VAT) [9], are among the first technologies used for CubeSat propulsion [21]. Busek [22] developed the BmP-220 that is a PPT propelled with PTFE. This system was originally intended for the attitude control of small satellites, not CubeSats. Other PPTs propelled with PTFE are the PPTCUP by Mars Space [58,59], the µPPT by Fotec [60], the FPPT by CU aerospace [29,61]. The latter is notable since it can produce a thrust up to

0.24 mN, that is far higher in respect to competitors (see Table 3). The George Washington University has developed the μCAT which is a magnetically enhanced VAT [62,63]. The addition of a magnetic field allows for a more uniform erosion of the system in respect to the classical configurations. The μCAT has been installed on the BRIC-Sat-P (1.5U) and has been tested in obit. The firing has successfully de-tumble the spacecraft.
The electromagnetic systems can be divided into two very distinct categories depending on the working principle and the propulsive performance, namely ambipolar and pulsed thrusters (see Figure 3). The former target medium-large CubeSats and are designed mainly as primary propulsion systems. The latter can provide a much lower thrust so they usually target very small CubeSats (down to 1U) to provide attitude and control.

IV. GENERAL TRENDS

IV.A Near Future Perspectives

In order to meet the increasingly demanding requirements imposed by CubeSat missions, both thrusters and sub-systems need improvements.
The numbers of companies involved in the EP for CubeSats is going to increase in the near future, this can be inferred from the number of IoDs scheduled in 2020/2021 [41,54] and the numerous technologies under development. Considering the variety of the mission scenarios, it is likely to expect that no technology will overwhelm competitors. Nonetheless a clear trend is that CubeSats are becoming larger, the electrical power on board is increasing and the higher ΔV budgets are needed [5]. For this reason, companies are developing systems in the power range 100-200 W (or above [57]) up scaling consolidated technologies.
Regarding subsystems, the general goal is to reduce mass, volume and cost. For what the propellant management is concerned, miniaturized components compatible with innovative propellants (e.g., iodine) shall be available in the market [56] to drastically reduce development time and cost. Power Processing Units (PPU) shall be designed to maximize the electrical power provided to the thruster. An interesting approach is the so-called "direct drive" in which the propulsion system is operated at the solar panel array voltage [5].

IV.B Technologies Under Development

The systems discussed in Section III are only a portion of all the technologies under development for the CubeSat market. There are both products under development that are likely to reach an "high" TRL in the near-future and new concepts that might reach maturity in the mid-future.
Among the products under development, it is worth mentioning the gridded ion thruster which is in progress at the University of Tokyo [64]. The plasma is produced via a microwave excitation and the system can be operated both with water or xenon. Interestingly, also the plasma discharge in the neutralizer is produced via a microwave antenna. For what Hall effect thrusters are concerned, the BHT-100 by Busek [65] is a prototype currently under development whose nominal power is 150 W. The BHT-100 is propelled with xenon but feasibility tests have been performed with iodine. Also Sitael [66] is developing a similar product, namely the HT100. The HT100 is scheduled to be tested on orbit in the frame of the μHETSat mission; the date of the launch is not public [67]. Among the pulsed systems, the Petrus PPT [68] is under development at the University of Stuttgart. This system is rapidly reaching maturity since a PPU for its operation has just been developed [69]. Finally, a VAT for CubeSat application has been designed at the Technion-Israel Institute of Technology [70]. The system has been tested in terms of propulsive performance but, according to the literature, no subsystem compliant with CubeSat standards is available.
Among new concepts, the Microwave Electrothermal Thruster (MET) [9] is appealing for CubeSats since a neutral gas is heated up via a plasma discharge sustained by microwaves, namely the concept is electrodeless. Regardless this technology can be defined electrothermal, a moderate specific impulse can be achieved (up to 600 s) [71]. Studies are in progress to limit the input power in the 100 W range [72] and to reduce the thruster size via increasing the operation frequency up to 30 GHz [73]. Another promising technology using microwave power is the Electro Cyclotron Resonance (ECR) thruster [9]. In fact a thrust of approximately 1 mN can be obtained with 50 W input power [74,75]. Moreover, the acceleration of the plasma is driven by a magnetic nozzle, so no electrode in contact with plasma is needed. Research on this technology is particularly active at Onera and AVS [76]. In METs and ECRs, namely technologies that rely on microwaves, the aspect that needs major improvements is the miniaturization of the PPU. High Efficiency Multistage Plasma Thrusters (HEMPT) are electrostatic thrusters that have a consolidated flight heritage on geostationary satellites [77]. At Ariane Group, research is ongoing to miniaturize HEMPTS in order to target this technology at 3U CubeSats [78].
Finally, it is worth mentioning a technology in which electric power is used to produce H_2 and O_2 from water, namely water electrolysis thrusters [79]. The latter gases generate thrust as in a bipropellant rocket [80]. Generally speaking, this technology provide thrust in

the range of 1 N [79] so it is not worth to be compared with EP discussed in this review. Nonetheless AVS [76] is developing the ICE system [81], namely a water electrolysis thruster that exploits Micro Electro Mechanical Systems (MEMS). As a result, ICE is expected to produce 5 mN thrust with 30 W input power, namely it might become a competitor of the propulsive systems previously discussed.

IV.C Research on Innovative Propellants

The selection of an appropriate propellant is a critical aspect of each mission involving EP since it has a strong impact on performance and costs. Regarding electrothermal, electrospays and pulsed thrusters, a significant variety of propellants have been successfully used, including solid and liquid compounds (see Section III). Instead xenon is the most diffused propellant for electrostatic (apart from electrosprays) and ambipolar thrusters thanks to the good propulsive performance attainable along with the simplicity to be stored and handled [9]. On the contrary, xenon is expensive (about 1000$/kg) and must be stored in pressurized tanks. So a wide research activity is ongoing to identify valuable alternatives [82].

To select a valuable propellant for the CubeSat application, physical and practical factors must be considered. The most important physical characteristics are molecular mass, ionization energy, and state. Usually, in electrostatic systems, high molecular mass is associated to a higher thrust with a reduction of the specific impulse [9]. A low ionization energy is fundamental to maximize the thruster efficiency. The state of the propellant influences drastically the design of the fluidic line to connect the tank to the thruster. Regarding practical considerations, a propellant shall be non-toxic, easy to store and to handle, along with non-expensive. As a result, solid and liquid propellants are preferable in terms of storability even though additional power budget is usually required to melt or sublimate them. Vice versa, handling condensable propellants is complex due to the potential deposition on solar panels or the obstruction of the fluidic line [9].

Two of the main alternatives in respect to xenon are krypton and iodine [9]. Krypton is a noble gas with a lower cost in respect to xenon (≈100 $/kg) that guarantees a good propulsive performance [22]. Nonetheless, krypton must be stored in pressurized tanks (up to 300 bar). Iodine guarantees a similar propulsive performance in respect to xenon even though it is a molecular compound (I_2) so part of the energy coupled to the plasma is wasted in dissociation and excitation reactions [56]. The main advantage of iodine is that it can be stored at the solid state, so in a non-pressurized tank. This is a great advantage for CubeSats since the absence of a pressurized tanks is a mandatory requirement to launch satellites as secondary payloads [56]. Vice versa iodine is corrosive and condensable, so a careful design of the thermal control and material selection is mandatory. Other alternative propellants are under evaluation both for gridded ion [82] and Hall effect thrusters [83,84]. Specifically, preliminary tests performed on a Hall thruster propelled with zinc and magnesium [83] proved the feasibility of exploiting these elements in EP. Similarly, triethylamine (TEA) and tripropylamine (TPA) provide comparable propulsive performance to xenon if used as a propellant of a Hall effect thruster [84]. These two organic compounds have been selected since they are non-toxic and highly available, moreover TEA is used in chemical propulsion as an alternative to hydrazine.

In conclusion, the optimal propellant does not exist since it derives from a trade-off which depends on each mission specifications. For this reason, an intense research activity is ongoing to identify valuable alternatives to classic solutions.

V. CONCLUSIONS AND REMARKS

In this review of the EP for CubeSats, first near-future mission scenarios have been identified. Subsequently, technologies which present an “high” TRL, namely whose IoD is scheduled or concluded, are reviewed. The most promising prototypes under development and the concepts appealing for CubeSat application have been outlined too. Finally, general trends of the market of EP for CubeSats have been identified. Companies are developing systems working in the 100-200 W power range that can provide high thrust (10 mN range) and high ΔV (hundreds of m/s). Moreover an intense research activity on new propellants is ongoing.

Final remarks concern testing and simulating EP for CubeSats. Testing is particularly challenging since thrusters must be operated in vacuum and the resolution required can be below 1 μN [85]. For this reason facilities that allow to test thrusters for hundreds of hours with a low impact on the performance (i.e., background pressure below 10^{-5} mbar [5]) and compatible with new propellant will be designed in higher number. At the same time, numerical models are necessary to significantly improve the performance of new technologies (e.g., HPTs) along with to drive the downscaling of mature technologies (e.g., gridded ion or Hall effect thrusters) [86-92].

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