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# Prospective of Self-Pressurized Technology for In-Space Satellite Missions

*Simone La Luna*, Davide Zuin**
**Politecnico di Milano*
*Via La Masa 34, 20156 Milano, Italy*

## Abstract

In the last few years, space companies are developing new subsystem architectures where commercial off-the-shelf components are implemented and innovative solutions are required to fulfil the market needs. Green and self-pressurized technology is one example of innovation in the field of small satellite propulsion where reduction of volumes and number of components is achieved.
In this paper, self-pressurization physical phenomenon is described and possible drawbacks are explained, like the difficulties of granting single phase fluid to the engine inlets. Starting from the summary on the main 0D models within the scientific panorama which simulate the dynamics of the self-pressurization, the work highlights the pros and cons of self-pressurization technology and details its possible applications. Finally, a focus on self-pressurization as a mean for satellite refuelling in orbit is presented, and space missions related to this application are considered.

## 1. Introduction

Sustainability and environmentally friendly solutions are becoming very important aspects of today's life. As one of the most disruptive and innovative industrial sectors, the space market is following this momentum. This trend is enhanced by the market expected growth rate, which is estimated to surge over $1 trillion by 2040 [1]. Alongside the growth of the market itself, the number of satellites, and consequently the number of launches, is expected to soar as well. Hence, as the sector expands, the need for "green" propulsion systems is starting to become a prioritized topic. Onto this perspective, industrial and academic efforts are moved towards finding peculiar propellants which comply with global environmental standards.

Whitin the aerospace segment, a propellant is labelled as "green" when it owns different characteristics, not only related to low emissions factors. In fact, in order to be defined as "green", propellants shall grant low-hazard and low-toxicity values during all their expected lifetime cycle: this covers the development, deployment, launch, and operations of the propulsion system [2]. Such propellants provide safe handling and storability when compared to handling protocols and when adhering to strict safety measurements. Due to their favourable characteristics, "green" propellants demonstrate higher commercial value: through their implementation, transportation, storage and handling costs can be reduced. Moreover, the space satellite industry is facing the need of replacing monopropellant hydrazine: this fuel, which is the current standard application in spacecrafts given its storability, low freezing point and high performance values, has been included on the Substances of Very High Concern (SVHC) by the European Chemical Agency (ECHA). This inclusion is going to open discussions related to the ban of hydrazine usage, together with its derivatives, as a space propellant amid European countries.

This work reports the latest developments in self-pressurizing technologies within the aerospace sector and in particular with respect to their application for in-space satellite missions. In the first chapter, "green" propellants classifications, properties and benefits are described. After that, self-pressurization phenomenon is described, starting from a generic description of the physics involved up to the description of the models capable of predicting mass flow rate during propellant discharge. In the second part of the work, self-pressurization applied to small satellites applications is analysed. The conclusion presents insights on the challenges which the technology faces in order to be applied for re-fuelling applications.

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# 2. “Green” Propellants Description

## 2.1 Classification

“Green” propellant can be divided in different ways, depending on their manufacturing, their toxicity levels, their safety hazard characteristics and others. However, a primary division can be derived from the typical chemical propulsion technology in which the “green” propellants are involved.
Three main technologies can be highlighted:

- *Monopropellants*: they are propellants stored in a single tank; they release energy through exothermic decomposition;
- *Premixed Propellants*: they are propellants which consist of an oxidizer and a fuel stored as a blend in a single tank; they release energy through a decomposition and/or combustion reactions;
- *Bipropellants*: they are propellants composed by an oxidizer and a fuel which are separately stored in dedicated reservoirs; they release energy through combustion reactions.

As a secondary characteristic, “green” propellants can be divided into cryogenic, semi-cryogenic, and storable. Within the in-space propulsion panorama, the major interest is drained by storable “green” fuels and oxidizers capable of replacing harmful hydrazine and its derivatives. Monopropellants follow, given their simplicity in system handling and manufacturing.
Noisser et al. [13] proposes the following classification:

- Energetic Ionic Liquids (EILs): they consist of oxidizer salts dissolved in aqueous solutions, called Ionic Liquids (ILs), mixed with Ionic Fuel (IF) or Molecular Fuel (MF), forming a premixed propellant. The propellant blend performances are increased by the addition of other fuel components. The EILs can be further categorized into HAN-based (Hydroxyl Ammonium Nitrate) and ADN-based (Ammonium DiNitramide);
- Liquid NOx: they are monopropellants which consist of nitrous compounds alone or premixed with hydrocarbons. Nitrous compounds have been generally considered as oxidizers in Hybrid Rocket Engines (HREs) and in bipropellant systems. Nitrous oxide belongs to this class: $N_2O$ shows very interesting properties, like the extremely high saturation pressure in the range of temperature suitable for storability (0° to 30°). Furthermore, it has also good storability features at room temperatures, especially for long term usage because it does not decompose or boils as time passes. This is an added feature in comparison with $H_2O_2$ or cryogenic LOx solutions;
- Hydrogen Peroxide ($H_2O_2$) Aqueous Solutions (HPAS) have been used as monopropellant in different aerospace applications since 1938. $H_2O_2$ is type-classified according to its concentration in aqueous solution, and grade-classified according to the concentration of stabilizers and impurities. High-Test Peroxide (HTP) is a highly concentrated $H_2O_2$ mixture, with weight concentration greater than 85%. Rocket grade HTP is used in space propulsion for low and medium thrust applications and is typically implemented with a 98% concentration. The high density of 98% HTP (1.43 g/cm$^3$), and its characteristic of being non-toxic, makes it an interesting candidate in propulsion systems where storability is a pivotal requirement. In monopropellant systems it may decompose reaching temperatures around 1200 K. Specific Impulse (Isp) performances of HTP 98% in monopropellant systems is 20% less than equivalent hydrazine system: however, in bipropellant systems, combined with hydrocarbons, such as ethanol, it can reach Isp > 325 s.

## 2.2 Economic Benefits

“Green” propellants guarantee a series of economic benefits in different aspects of design, production process and integration lifecycles. The most relevant, as suggested by [14], are:

- Propulsion Hardware: depending on the fuel choice, “green” propellants allow the implementation of cost-effective materials. They also help in the reduction of the number of components in the assembly;
- System Complexity: toxic propellants require the implementation of three barriers in the system: one generated by a pyrotechnical device or a latch valve; the other two implemented by the thruster flow control valves. On the contrary, “green” propellants require only two barriers with a consequent reduction of the number of components and so of the overall system complexity;
- Handling during MAIT operations: harmful propellants require additional care during handling and testing operations with respect to their “green” counterpart; when dealing with toxic substances, demanding requirements in terms of cleaning procedures of tanks and piping lines after testing are mandatory.
- Logistic for propellant transport: toxic and explosive propellants may add additional logistic constraints and

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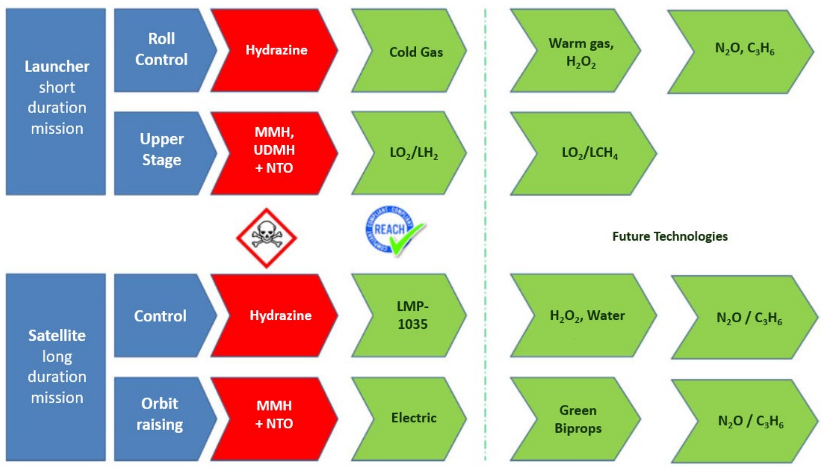


Figure 1: Application areas for space propulsion.

costs with respect to their “green” counterparts;
- Handling during launch: toxic propellants may add several constraints during launcher integration due to the requirement of protective equipment, impossibility to perform parallel operation during filling and cost for disposal of contaminated equipment.

### 2.3 Applications

Among the flight-proven spacecrafts fuelled by “green” propellants, the following stand out:
- Mango-PRISMA (ADN-based monopropellant) satellite by the Swedish National Space;
- ION-mk02 Satellite carrier by D-Orbit company;
- Rocket Motor Two Hybrid Rocket Engine (HRE, $N_2O$/HTPB) by Virgin Galactic and flown in July 2021 [16];
- Green Propellant Infusion Mission (GPIM) powered by NASA and Ball Aerospace to test practical abilities of AF-M315E, developed by the Air Force Research Laboratory (launched on June 25, 2019, and demonstrated on August 20, 2020), [17];
- NASA’s Pathfinder Technology Demonstrator (PTD-1), demonstrating a water-based propulsion system in low-Earth orbit [15].

Moreover, as resumed in Figure 1, several more propulsion applications are available or are under development in the space propulsion panorama, each one tailored to the mission requirements needed. Within this framework, the literature [18] identifies HAN-based and ADN-based monopropellants as well as $N_2O$/light hydrocarbons as the most interesting and effective substitutes for hydrazine and NTO/MMH/UDMH solutions in small upper stages, spacecrafts, and Reaction Control Systems (RCS).

When considering self-pressurization characteristics, which are detailed in the next chapter, nitrous oxide stands out as the most interesting “green” propellant candidate given its useful properties to be implemented in satellite applications. Nitrous Oxide ($N_2O$, IUPAC name: dinitrogen monoxide) is a potent greenhouse gas which is implemented in multiple applications spanning several industrial fields: from the medical industry to the chemical one, from automotive to the aerospace [5]. Nitrous oxide is a colour-less, sweet-smelling substance: it is easy to store, non-corrosive, and relatively nontoxic. It has a vapor pressure of 50 bar at 293 K , and this characteristics allows to use it as self-pressurized propellants.

## 3. Self-Pressurization Phenomenon

### 3.1 Self-Pressurization Description

A self-pressurizing system is a pressurization scheme that utilizes the internal energy of a liquid stored in a closed vessel to perform the work required to expel the same fluid in liquid or gaseous state from the container [3]. In its experiments, when considering liquid draining of a self-pressurized fluid, Zimmerman [6] highlights four different phases. These phases, which are depicted in Figure 2 in terms of pressure variation in a closed vessel, are:

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- **Liquid Draining (Vapor Condensation):** in this phase, liquid boiling is absent or limited to few nucleation pockets; this leads to the rapid pressure drop shown in Figure 2 in light blue;
- **Liquid Boiling on-set**: pressure recovery (green line) is due to the onset of homogeneous/heterogeneous nucleation, which starts when a certain level of superheat is overcame;
- **Equilibrium phase**: during this phase (red line), the condensation and evaporation rates are equal, leading to a linear trend of pressure;
- **Blowdown phase**: once the liquid is finished in the tank, the pressure trace resembles the one of a gas in blowdown phase (purple line);

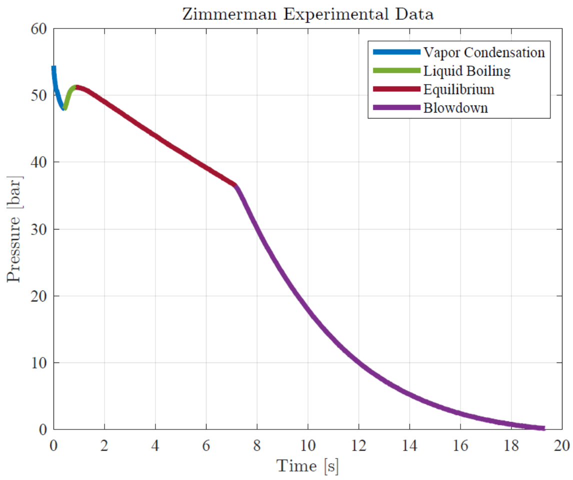


Figure 2: Experimental pressure trace retrieved by Zimmerman during its experimental campaign.

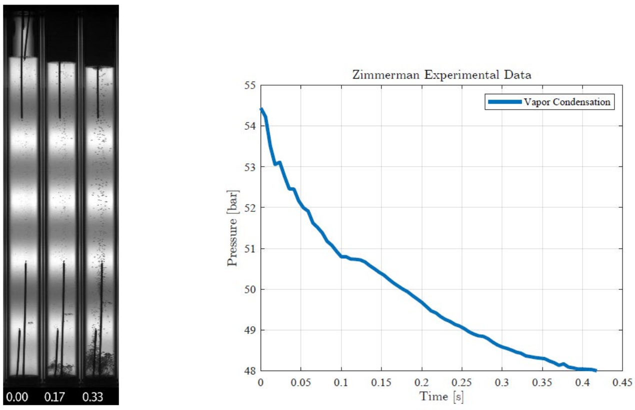


Figure 3: Condensation phase: experimental visualization and pressure trace.

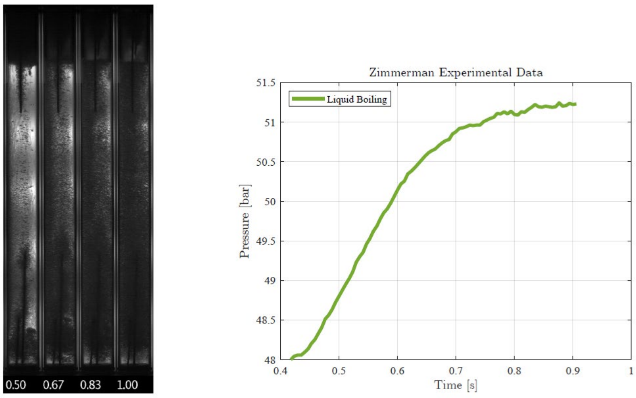


Figure 4: Evaporation phase: experimental visualization and pressure trace.

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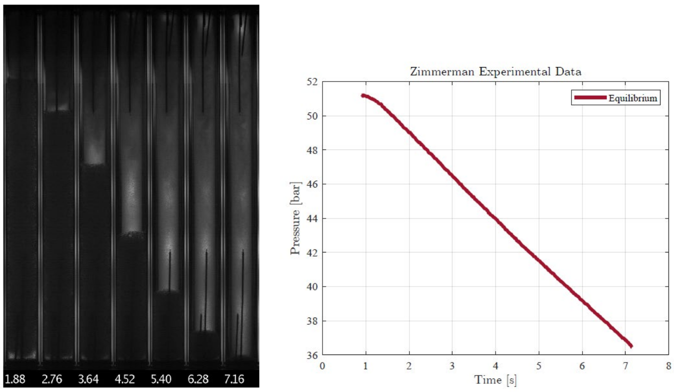


Figure 5: Evaporation phase: experimental visualization and pressure trace.

A comparison between the pressure traces of the different phases is shown in Figure 3, Figure 4 and Figure 5 [31]. On the left, each figure reports the video imagery of the corresponding experimental campaign from [6], where for each phase fluid behaviour inside a run tank filled with liquid nitrous is depicted

### 3.2 Mass Flow Rate Equations

When draining a self-pressurized fluid from a tank, mass flow prediction models are still lacking accuracy. This is due to the presence of multiple phases occurring at the same time in the closed vessel, which defy the implementation of a universal predictive model. The starting point is the analysis of the different phases previously mentioned. During the first phase, the fluid remains almost a single-phase liquid: therefore, the Single Phase Compressible (SPC) model can be applied without adding significant error in the computation:

$$\dot{m}_{SPC} = C_d Y' A_{orifice} \sqrt{2\rho_1 (P_1 - P_2)} \qquad Eq.1$$

where one and two represent upstream and downstream conditions respectively. $Y'$ represents the compressibility coefficient and allows to account for fluid compressibility: it is defined as [7]:

$$Y' = \sqrt{\frac{P_1}{2\Delta P}\left(\frac{2n}{n-1}\right)\left(1 - \frac{\Delta P}{P_1}\right)^{\frac{2}{n}} [1 - \left(1 - \frac{\Delta P}{P_1}\right)^{\frac{n-1}{n}}]} \qquad Eq.2$$

where $\Delta P$ is the pressure drop across the orifice and n is the isentropic exponent for a real gas, which is described as suggested by Cornelius et al. [7] and detailed in Eq.3.

$$n = \gamma [\frac{Z + T\left(\frac{\delta Z}{\delta T}\right)_\rho}{Z + T\left(\frac{\delta Z}{\delta T}\right)_P}] \qquad Eq.3$$

It is significant to notice that the SPC model can be also applied to the blowdown phase, where only gas remains in the closed vessel.

Once the boiling starts, the liquid drained from the tank presents an higher tendency to flash across the orifice and to become a bi-phase flow, leading to a significant reduction of the mass flow rate. In order to correctly account for the bi-phase fluid behaviour, Dyer mass flow model [8] is considered a more suitable assumption: in fact, the model combines the Single Phase Incompressible (SPI) and the Homogeneous Equilibrium (HEM) mass flow models in the following equation:

$$\dot{m}_{DYER} = (\left(1 - \frac{1}{1+k}\right) \dot{m}_{SPI} + \frac{1}{1+k} \dot{m}_{HEM}) \qquad Eq.4$$

The HEM [9] is valid under the assumption of isentropic flow across the orifice and is defined as:

$$\dot{m}_{HEM} = C_d A_{orifice} \rho_2 \sqrt{2(h_1 - h_2)} \qquad Eq.5$$

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Instead, the SPI fluid formula is shown in the following equation:

$$\dot{m}_{SPI} = C_d A_{orifice} \sqrt{2\rho_1 (P_1 - P_2)} \qquad Eq.6$$

Finally, k is the non-equilibrium coefficient, that is used to weight the contribution of the two mass flow models:

$$k = \sqrt{\frac{P_1 - P_2}{P_v - P_2}}\, \alpha\, \frac{\tau_b}{\tau_r} \qquad Eq.7$$

where $P_v$ is the upstream fluid pressure at saturation conditions evaluated at the fluid temperature, $\tau_b$ and $\tau_r$ are the bubble growth time and the fluid resident time respectively.

### 3.3 Self-Pressurization Models: Assumptions and Common Features

Starting from the definition of the mass flow rate equation in each phase, the work has moved towards the analysis and comparison of different models presented in literature. The work has considered nitrous oxide as case study fluid, which is drained in liquid phase; furthermore, only 0D/1D hybrid models are retrieved for the comparison.
Three most relevant 0D frameworks are retained:

- Homogeneous Equilibrium Model (HEM);
- Casalino & Pastrone Model (CP);
- Zilliac & Karabeyoglu Model (ZK);

Furthermore, a more sophisticated 0D/1D developed by Dr. Zimmerman has been retained: the model accounts for the proper modelling of the gaseous bubble evolution and development in the liquid phase.

As reported by [4], these models share similar assumptions. First, each proposed model involves a division of the tank into multiple regions, each one represented by a single node with average properties. Figure 6 shows on the left all the nodes used by the model to discretize the domain: the liquid part, the vapor part, the portion of the tank in contact with the liquid, and the portion of the tank wall in contact with the vapor. On the right, all the different heat and mass transfer processes occurring between the nodes are numbered [10]. Then, depending on the model considered, they may account for a reduced number of contributions:

1. Mass flow of liquid nitrous oxide out of the tank;
2. Heat and mass transfer from the vapor to the liquid via condensation, diffusion and convection;
3. Heat and mass transfer from the liquid to the vapor via boiling, evaporation, diffusion and condensation;
4. Heat transfer from the liquid side of the tank wall to the liquid;
5. Heat transfer from the vapor side of the tank wall to the vapor;
6. Heat transfer from the atmosphere to the liquid side of the tank wall;
7. Heat transfer from the atmosphere to the vapor side of the tank wall;
8. Heat and mass transfer from the liquid side of the tank wall to the vapor side via conduction and motion of the boundary.

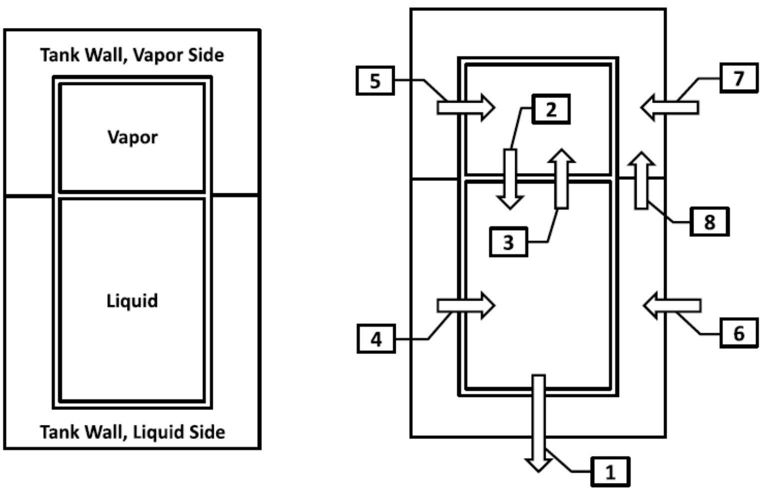


Figure 6: Diagram showing the nodes and the heat and mass transfer processes between the phases.

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As further assumption, all the aforementioned models share the same governing equations that are mass and energy conservation laws. The mass conservation equation is defined as:

$$\frac{dm}{dt} = \sum(\dot{m})_{in} - \sum(\dot{m})_{out} \qquad Eq.8$$

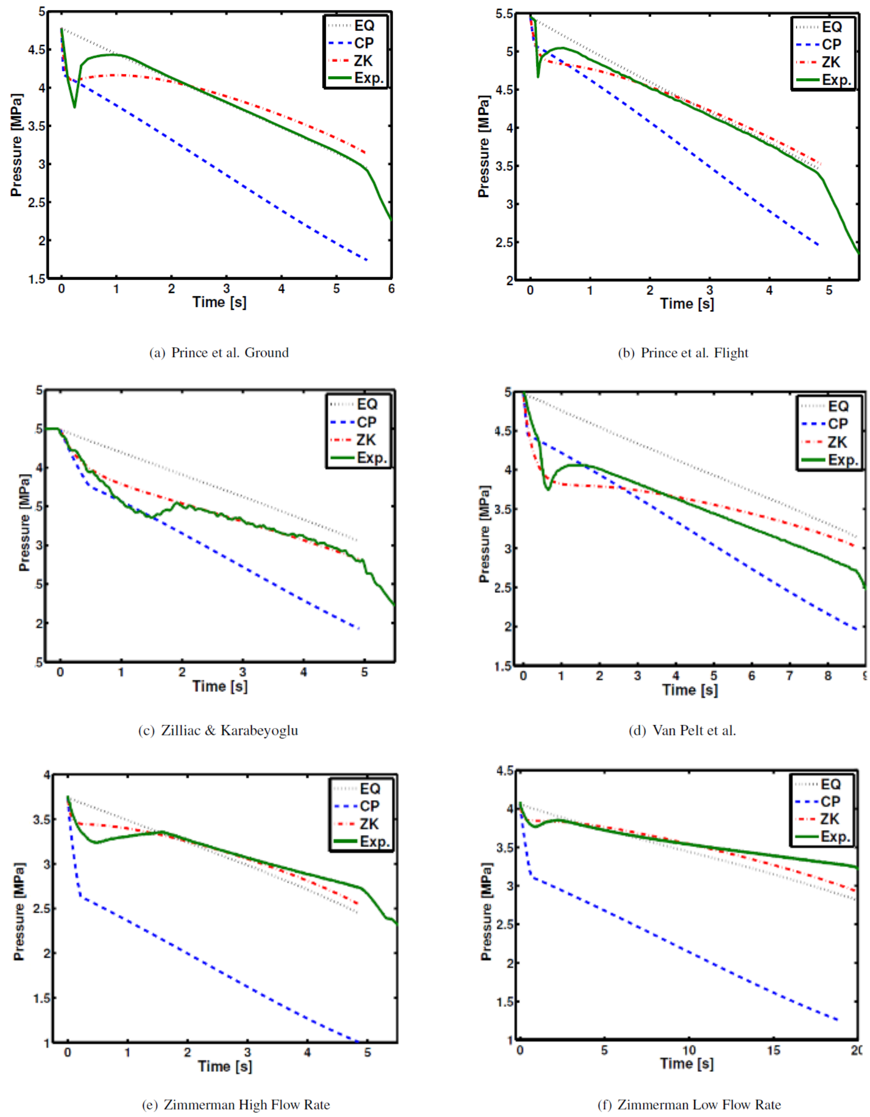
The general form of the energy conservation equation is given by:

$$\frac{dU}{dt} = \sum[\dot{m}\left(h + \frac{v^2}{2} + gz\right)]_{in} - \sum\left[\dot{m}\left(h + \frac{v^2}{2} + gz\right)\right]_{out} + \dot{Q}_{in} + \dot{W}_{in} \qquad Eq.9$$

where $\dot{Q}_{in}$ is the rate of net heat input, $\dot{W}_{in}$ is the rate of net work output and $\frac{dU}{dt}$ or $\frac{dE_{cv}}{dt}$ is the rate of accumulation of the total energy within the control volume.

### 3.4 0D Models Comparison

A comparison between the data predicted by 0D models presented in the previous sections [4] [31] and two experimental set of data provided by Prince et al. [11] both in flight and on ground is reported in Figure 7.




(a) Prince et al. Ground

(b) Prince et al. Flight

(c) Zilliac & Karabeyoglu

(d) Van Pelt et al.

(e) Zimmerman High Flow Rate

(f) Zimmerman Low Flow Rate

Figure 7: Comparison of the pressure traces of the three 0D models with 6 different experimental data.

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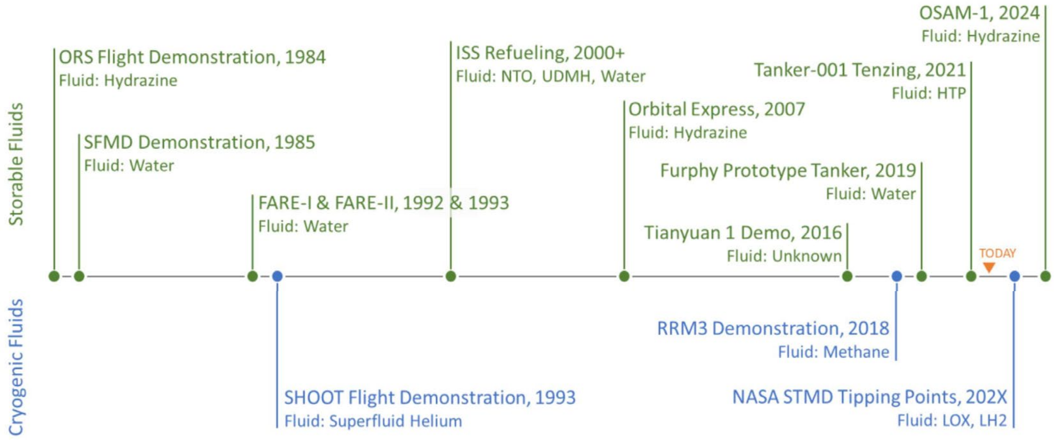


Figure 8: The timescale of future and past missions regarding in-orbit re-fuelling and fluid transfer update until January 2022.

As it can be seen from the results, the ZK model is more accurate than other models since it is capable to correctly predict the linear discharge phase and it also approximates the initial transient. Moreover, the HEM performs well, even if it is capable to predict only the linear phase while the initial transient is completely missed. Differently from the two previous models, CP performs quite poorly by largely underpredicting the pressure trace. As suggested by Zimmerman [6], this may be due to two different reasons: the uncertainty of Eq. 14, whose derivation is not well characterized by Casalino & Pastrone, and to the hypothesis of adiabatic tank.

## 4. Self-Pressurization as Re-Fuelling Application

The study of self-pressurizing propellants behaviour as well as the development of precise models capable of predicting the behaviour of the fluid drained from the tank is of pivotal importance in the space propulsion panorama. In fact, the application of self-pressurizing propellants is not only important within the recent quest for “green” propellants, but also in the research of cost-effective and reliable solutions for in-space refuelling applications.
The second part of this work is centred on the application of self-pressurized systems in the small satellite market. After a preliminary overview of previous missions related to in-space refuelling, the criticalities showed during the modelling of the nitrous oxide liquid discharge are commented in the context of refuelling applications.

### 4.1 State of the Art

In-orbit re-fuelling and fluid transfer is the capability to move a fluid from one spacecraft to another while in orbit [30]. The purpose of this process is life extension of a system, to augment its capability beyond what a single launch can deliver, and/or to enable reusable transportation systems. The most mature fluid transfer capabilities have been developed for storable fluids given the fact that these do not require active cooling to remain liquid. Water, hydrazine, and nitrogen tetroxide (NTO) fall under this category. On the other hand, cryogenic fluids such as liquid oxygen, hydrogen, or methane, are affected by thermal issues over prolonged periods of time and are not considered in this analysis.

Figure 8 presents a summary of the various activities performed so far in re-fuelling and fluid transfer applications [12]. As it can be seen from the timescale, interest in the re-fuelling programmes for in space satellites is well present in the industry, starting with initial experiments in 1984 up to the latest commercial applications. However, only in the last decade this activity has gained momentum.
In the following paragraphs, a list of major past missions involved in re-fuelling of in-orbit satellites is listed.

**FARE I & FARE II**

The Fluid Acquisition and Resupply Experiment (FARE) was a Shuttle middeck-mounted experiment developed in order to demonstrate techniques for handling liquids in zero gravity. The purpose of the mission was the applications of fluid transfer during in-orbit re-fuelling operations. The program consisted of two flights: FARE I and FARE II. FARE I flew in December 1992 on STS-53: it was provided with a screen channel Liquid Acquisition Device (LAD),

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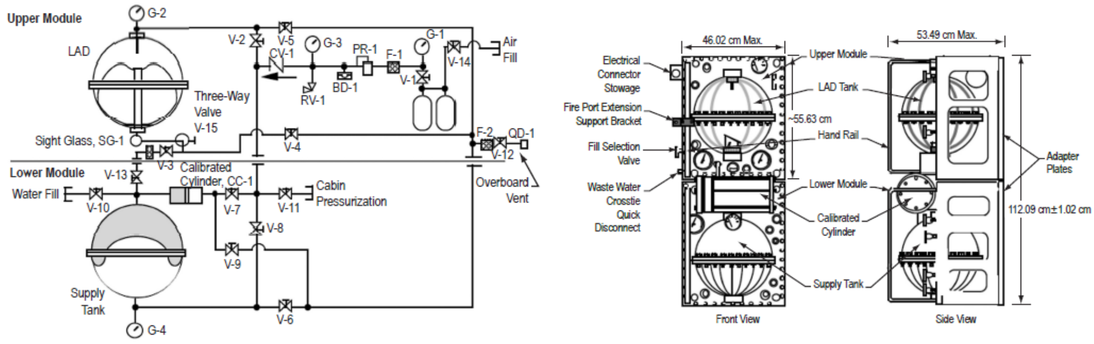


Figure 9: Drawing of FARE fluid scheme and module arrangement.

which was a device for images acquisition during propellant loading. Similarly, FARE II flew in June 1993 on STS-57 with an equal device [19].

The objectives of the FARE I flight were the characterization of payload performances using LAD during expulsion and refill of fluids; to perform vented fills of the screen channel tank using only surface tension forces to orient the liquid towards the tank outlet; to demonstrate liquid response to specific accelerations. The objectives of the FARE II flight were the demonstration of LAD during low-gravity operations while fluid was expelled; to evaluate the vane device capabilities to orient the ullage bubble over the tank vent during the filling process; to demonstrate the static behaviour of the liquid under low-gravity conditions and its dynamic behaviour with specific accelerations; to determine the ability of the vane device to keep the liquid and gas oriented during adverse accelerations.

Although the FARE program consisted of two flight experiments, most of test bed hardware and operations were the same on both flights. The most significant difference was in the LAD design, as FARE's missions were composed of two modules mounted on the front wall of the orbiter middeck. Each module occupied two middeck lockers and was mounted on one standard double adapter plate supplied as government-furnished equipment by the space shuttle program. Moreover, each module contained a clear acrylic tank as well as other equipment such as lines, valves, regulators, and air storage bottles. The two modules were connected by three flex lines installed in the ground support equipment cart or in the space shuttle orbiter. In addition to the LAD tank, the upper module contained two pressurant air storage tanks, a relief valve and a burst disk, valves, pressure gauges as well as other fluidic components. The lower module contained a spherical diaphragm tank that served as the supply tank, valves, gauges, and plumbing. The graphical description of the system is reported in Figure 9 [19].

During flight, a NASA-provided MicroGravity Acceleration Measurement System (MGAMS) was used to record the acceleration environment encountered during testing. The results of the mission where promising: significant improvements in the understanding of how capillarity LADs actually work in space were made. Furthermore, criticalities on the re-filling procedures during specific accelerations were collected for the first time.

**Orbital Express**

The Orbital Express program [20] was designed to prove that satellite servicing was technically and economically feasible. The program involved the development of a standard satellite servicing architecture for future operational systems: it also served as demonstrator for the readiness level of various technologies required in autonomous satellite servicing.

The flight demonstration consisted of two independent satellites in a mated configuration: the two satellites were launched aboard an Atlas-V rocket into a 492 km, 46 degrees inclined and circular orbit from the Cape Canaveral Air Force Station on March 8, 2007. The mission was funded by Defense Advanced Research Projects Agency (DARPA) and Boeing [20]. The system consisted of two spacecrafts, depicted in Figure 10: an Autonomous Space Transport Robotic Operations (ASTRO) vehicle; and a Prototype modular NEXT generation serviceable Satellite (NextSat). NextSat was designed to be served by ASTRO during orbit operations. During the mission, ASTRO successfully performed autonomous docking with NextSat and demonstrated fuel transfer as well as some Orbit Replacements Units (ORU) activities such as the insertion of a battery into NextSat and the change of a flight computer on ASTRO. During its 4-month mission, Orbital Express provided confirmation that key technologies needed for satellite servicing were in place and ready to be further industrialized [21].

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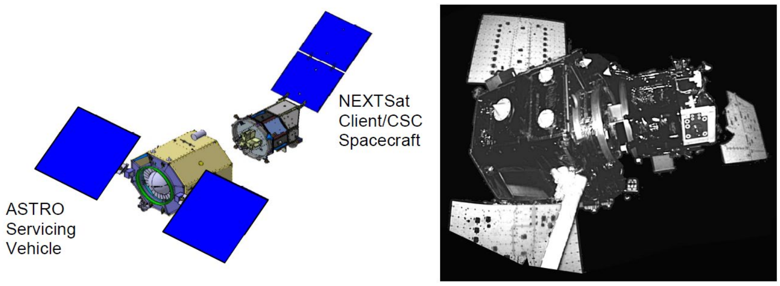


Figure 10: ASTRO and NextSat.

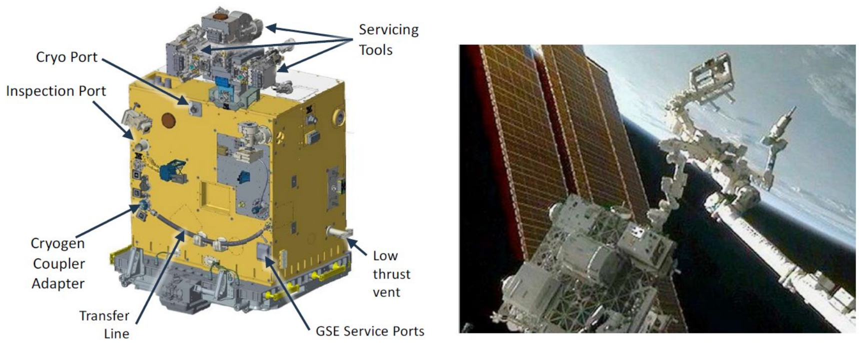


Figure 11: RRM3 Servicer Module Features (left) and the Dextre arm performing a demo of a robotic re-fuelling task (right).

**RRM Demostration**

RRM demonstration missions, depicted in Figure 11, were a series of robotic re-fuelling missions developed and managed by NASA Goddard's Satellite Servicing Capabilities Office. They involved the installation of a re-fuelling system on the International Space Station (ISS): the launch of the robotic system occurred in July 2011 through one of the last missions of the Space Shuttle Programme [22]. The Canadian Special Purpose Dexterous Manipulator robot, also known as Dextre, was used with RRM tools to demonstrate an array of fuelling tasks in cooperation with the Canadian Space Agency (CSA) [23]. Dextre was a 3.5m two-armed 6-DOF robot that was used to cut and manipulate thermal blankets and wires, then unscrew caps to access RRM valves prior to fluid transfer operations. The missions were intended to be completed through the application of a new cap on the tank outlet for future re-fuelling activities.

During the first orbit operations, the RRM multifunction tool was successfully involved by Dextre to remove launch locks, securing RRM tool adapters. This was followed by cutting wires and removing gas fittings required to fill the spacecraft with propellant. The operations of propellant transfer occurred in January 2013: although only 1.7 L of ethanol was transferred, RRM successfully demonstrated on-orbit fuel transfer [24]. The first phase of RRM mission demonstrated that the tasks needed to service a satellite in orbit could be performed by robotic arms. This experiment paved the way for future usage of specialized tools during experimental on-orbit satellite servicing operations.

A following mission, called Robotic Re-fuelling Mission-3 (RRM3) [25], developed a series of technologies and processes for the storage and transfer of liquid in a microgravity environment. This phase also demonstrated robotic manipulation of cryogenic transfer lines, a capability that would allow on-orbit re-fuelling of rockets for lunar exploration as well as other deep space missions. RRM3 was launched from Cape Canaveral Air Station aboard SpaceX Commercial Resupply Service (CRS-16) on December 5, 2018, and berthed on the ISS Express Logistics Carrier on December 15, 2018 [25]. In the following years, RRM3 demonstrated the applicability of cryogenic fluid transfer in orbit, a more complex task with respect to fluid transfer with storability propellants.

**Commercial Applications**

Following the agency applications, a series of commercial applications were implemented. These allowed the implementation of innovative commercial approaches to the problems of in-space re-fuelling.

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Furphy was the first mission performed by OrbitFab company in order to increase the TRL of their own propellant feed system. The aim of the mission was to prove the feasibility of transferring fluids in microgravity from a rigid tank to a flexible tank with the purpose of validating re-fuelling capabilities of in orbit satellites. These tests involved handling and transfer manoeuvres of water propellant between two separate tanks mounted on the ISS. The mission successfully proved the application [26].

Following their previous success, OrbitFab developed the first on-orbit propellant tanker. Called Tanker-001 Tenzing, it was launched in June 2021: its purpose was to store and supply customers in orbit with High-Test Peroxide (HTP) directly in space to their satellites. The mission acted as an in-space laboratory too, allowing Orbit Fab and its partners to test other critical technologies for fuelling applications [27]. The Tenzing depot was a 35 kg small satellite equipped with two Rapidly Attachable Fluid Transfer Interface (RAFTI) service valve: one for the spacecraft's primary payload storage tank and one for the spacecraft's propulsion system. Orbit Fab's RAFTI interface is proposed as replacement for typical spacecraft fill/drain valves used in ground filling operations. It is designed to enable on-orbit re-fuelling by incorporating the necessary features for grappling between spacecrafts and subsequently to move fluids in the space environment. Moreover, RAFTI is compatible with a variety of propellant fluids, from water to HTP. Thanks to the alignment markers arranged around the valve, satellites are capable to performed autonomous rendezvous and proximity operations without the need of robotic arm, thus significantly reducing the cost and complexity of the system [27].

## 4.2 Challenges of Self-Pressurization for In-Orbit Re-Fuelling

Given the peculiar characteristics of self-pressurization technologies, where no pressurant gas is involved, usage of self-pressurization for in space re-fuelling applications faces few challenges. These challenges have been retrieved from the literature analysis of past missions involving fluid transfers in orbit: propellant management inside the tank becomes the major critical issue, in particular when subjected to important heat loads. The uncertainty is directly related to the knowledge of the position of liquid-vapor interface during the fluid transfer over time. The knowledge of the fluid-vapor surface is of primary importance in order to determine an accurate mass flow output during the fluid transfer, as previously detailed through the mass flow model characterization. This uncertainty may increase the unreliability of the technology, thus leading to potential issues in the development of future missions involving re-fuelling.

The *effect of temperature* increase due to radiation from the sun, planet, albedo or others adds further criticalities when dealing with cryogenic propellants: given their low boiling point, even small amount of heat may lead to significant evaporation from liquid phase and to sudden tank pressure spikes with undesired propellant movements in the tanks. Due to these criticalities, self-pressurization technologies involving cryogenic propellant tanks have still to be properly characterized, even if several past experimental and numerical studies have been implemented [29].

Whitin the work presented in this paper, the case study propellant presented has been $N_2O$, which is a non-cryogenic fluid. The issues presented in cryogenic and self-pressurized propellants are mitigated with this specific propellant, although not removed. In particular, tank thermal management seems to play an important role in re-pressurize propellant after the accomplishment of a re-fuelling task for a satellite. The control of this phenomenon, which depends on the amount of mass drained from the tank, is easier than the management of re-pressurization in cryogenics. The process spans in the order of seconds, and the pressure rise due to liquid boiling is less prominent, avoiding undesired pressure spikes in a very short time. Nonetheless, give its high pressure values in the ambient temperature range (from 0 to 30°C, this storable propellant shall be controlled during pressurization in order to not allow the tank pressure to increase reaching undesired values.

Pressure spikes in a very short time are predicted through some of the self-pressurizing models reported above, as previously shown. Only the HEM fails in predicting the initial transient due to liquid boiling: it becomes evident that this method is not suggested when predicting and modelling propellant fluid transfer between satellites. The other models are capable of retrieving the behaviour of the pressure spike, even if certain models fail in accurate predictions values.

The definition and computation of the pressure recovery is only the preliminary step in the path of a reliable control of in-space propulsion re-fuelling operations. Further steps are involved when considering the countermeasures which are put in place in order to control the rise of pressure spikes. Few methods have been proposed for controlling the pressure in the tank [29]:

- Isolation Method: in order to reduce self-pressurization and boiling phenomena in the tank, the reservoirs are significantly isolated from the environment;
- Tank Thickness Method: the effect of temperature transients is dampened through the addition of mass and volume to the reservoir system; this method, although effective in past simulations and tests, has the issue of adding significant costs to the overall propulsion system in terms of inert masses and volumes;

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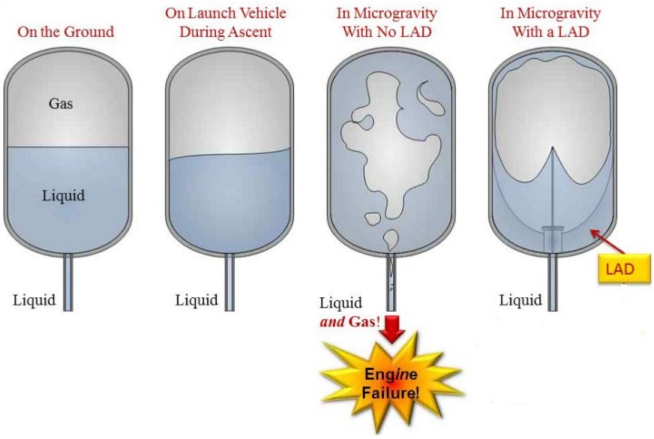


Figure 12: Illustration reporting the effects provided by Liquid Acquisition Devices (LAD) within reservoirs in space applications.

- Tank Venting Method: the tank system is ventilated during time, in order to control the temperature through evaporation of the liquid in the tank itself. Also, this method is affected by drawbacks in terms of propellants losses which impact on the overall propulsion system performances.

All the proposed solutions shall also consider the challenges related to the microgravity environment presented in space missions. *Microgravity* in small satellites affects different aspects of self-pressurization, the major one related to the separation of the liquid and vapor phases within a propellant tank. In general, the lowest achievable potential energy state within a tank governs the location of the liquid/vapor interface. When considering Earth applications, this state is easily defined by the presence of the standard Earth gravity field: in microgravity conditions, surface tension becomes the controlling mechanism for phase separation. Liquid tends to stick and adhere to the tank surfaces, leaving the gaseous core in the middle of the tank [28]. This effect becomes critical when considering re-fuelling, as a single-phase propellant shall be transferred.

Usually, within propellant tank management in space for propulsive subsystems, microgravity effects are counteracted through the application of dedicated Propellant Management Devices (PMD) in the reservoir system. Their purpose is to separate liquid and gas phases within a propellant tank and to transfer vapor-free propellant from a storage tank to an engine or receiver tank, in any gravitational or thermal environment. The PMDs applied to orbit re-fuelling purposes are also called Liquid Acquisition Devices (LAD). On ground or during launch, LADs are generally not required due to gravity/apparent gravity effects, as reported in Figure 12. Without this fundamental force, there are very few ways which are capable to guarantee vapor-free propellant flow out of the tank. Only PMDs or complicated satellite in-orbit operations may attenuate this phenomenon. Thus, research in the field of LADs for in space re-fuelling applications is still under development.

## 5. Conclusions

This paper has presented the self-pressurization phenomenon and the prospectives of this application for in space satellite missions, starting from the quest of reliable "green" propellants in the space propulsion panorama. Moreover, different models and their criticalities in predicting the mass flow drained from a reservoir were highlighted. Furthermore, the paper has focused on the application of self-pressurization phenomenon to in-space satellite re-fuelling applications. Efforts within agencies and commercial entities have been highlighted, and the criticalities subjected to the technologies involved have been identified.

Re-fuelling capabilities are becoming important in the commercial framework provided by the new space economy. Within this framework, the capabilities and advantages of self-pressurization phenomenon seem to be promising. However, two main criticalities can be highlighted as an output of this preliminary analysis. First, self-pressurization of storable propellants, such as nitrous oxide presented during the case study in this paper, has the capability to challenge current solutions involving hydrazine in terms of performances, operators' safety, costs of the technology involved. However, a deep review and extension of the predictive models available in literature shall be performed in order to gain maturity of the technology at analytical level.

As a second point, the predictive models for mass flow draining in re-fuelling applications, even if promising, are still not well applied in space applications. The lack of comprehensive models predicting the behaviour of self-pressurized fluids in gravity conditions is pushing back against the application of the same models for in-space propulsive environments. In fact, thermal control of the system and microgravity effects still challenge the validation

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of possible models during representative tests in space. The increase in applications of self-pressurizing $N_2O$ and light hydrocarbons propellants in self-pressurized conditions for commercial space missions shall lead agencies and companies to invest towards the development of reliable models for system prediction and criticality solutions. Furthermore, more research and effort shall be posed towards the development of alternative solutions to the microgravity effects and thermal issues in re-fuelling applications: the research for effective PMDs and LADs as well as thermal management devices becomes pivotal for the development of reliable orbital re-fuelling systems based onto self-pressurizing propulsion units.

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