Propellant Tank Pressurisation with Helium Filled Hollow Glass Microspheres

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Abstract

A new type of pressurisation system is proposed for propellant tanks. The proposed system combines the simplicity of design of a traditional blowdown systems and the constant performance of a pressure-regulated system. A simplified propulsion tank system comparison of traditional systems with the newly proposed system shows potential mass savings in the range of 20% to 70% under certain circumstances. A simplified thruster performance analysis shows that the proposed system has very similar performance behaviour as a pressure-regulated system, at the benefit of less complexity. Both analyses are encouraging enough to continue with the development of the proposed system.

1. Introduction

Satellite propulsion systems use high pressure gas to force the propellant from the tank to the thruster and to ensure a certain pressure level just upstream of the nozzle for thrust generation. For satellite applications generally, two types of feed systems are available: blowdown systems and pressure-regulated systems.

In a pressure-regulated system a pressurant gas, typically helium or nitrogen, is stored under very high pressure in a pressurant tank, typically up to 600 bar [1]. This results in small but very heavy tanks. Pressure regulators are used to decrease this pressure to such an extent that the pressure in the combustion chamber is somewhere between 10 and 20 bar. They ensure a constant pressure in the combustion chamber throughout the nominal mission lifetime. However, pressure regulators are complex components with a relatively high risk of malfunctioning. For this reason they are often placed in series and parallel to increase the overall reliability of the feed system. This makes the pressure-regulated system relatively heavy and expensive.

In a blowdown system the propellant shares the propellant tank with a pressurisation gas, which occupies between 30 and 60% of the tank volume [1]. The initial pressure is high, but decreases over time as propellant is expelled from the tank and exhausted through the nozzle. Typical tank pressures range from about 40 bar at BOL down to 7 bar at EOL [2]. As a consequence, the thruster performance changes accordingly over the lifetime. For bipropellant thrusters this effect is amplified by the change in mixture ratio, and consequently performance, as tank volume and mass flow rates are generally different for the fuel and oxidiser. For MMH-NTO systems this problem is solved by designing the system for a mixture ratio of 1.64. This is the density ratio of NTO to MMH. As a consequence the volume flow rates are the same and therefore tanks with the same volume can be used [2]. However, this mixture ratio does not necessarily result in the highest performance. Besides that, for propellants with a stoichiometric mixture ratio very different from the oxidiser to fuel density ratio this strategy cannot be used. Contrary to a pressure-regulated system, a blowdown system is considerably less complex.

Both types of feed systems have in common that their mass and volume is determined by conditions that only exist at BOL. Consequently, the feed system is over-dimensioned for most of the lifetime. Ideally, a propellant feed system offers the controllability of a pressure-regulated system while having the simplicity of a blowdown system. Such a system would have a constant performance over the mission lifetime at a lower overall mass and be more cost effective. A promising and rather simple approach towards such a system is the storage of pressurant gas in hollow glass microspheres (HGMs). This paper presents the first part of a feasibility study into the use of HGMs for propellant tank pressurisation. It starts with a short description of the operating principle. This is followed by a propellant tank system analysis in which the different types of pressurisation methods are investigated. Subsequently, a more detailed analysis is presented about the expected consequences on the thruster performance over the mission lifetime. Finally, a short overview of the planned activities as part of the current feasibility study is given.

2. Hollow Glass Microspheres

The efficient storage of gases is represents a challenge of wide technological importance. For low mass gases with near-ideal characteristics, such as helium [3]–[5], hydrogen [6] and to a lesser extent nitrogen, a possible solution is storage under very high pressure in HGMs [7]. These are commercially available and primarily used as weight-saving fillers for polymer parts in the automobile and aerospace industry [8]. Typical size distribution is between 15 to 200 µm with wall thicknesses ranging from approximately 0.5 to 20 µm. A summary of the properties of the HGMs required for the analysis is given in Table 1 and is based on the type of HGMs that are currently under investigation at FOTEC [9].

Table 1: Characteristics of typical HGMs

property	value	unit
bead density	0.57—0.63	g/cm^3
bulk density	0.30—0.40	g/cm^3
maximum pressure	2000	bar
mean bead diameter	16	µm

The specified bead diameter is a mean value. According specification 80% of the beads have a diameter between 9 and 25 µm. For a volume packed with glass sphere the percentage of volume occupied by helium can be calculated as follows:

$$He\ \%vol. = packing\ fraction \cdot \left(1 - \frac{bead\ density}{glass\ density}\right) \cdot 100\% \tag{1}$$

Here, the packing fraction is the ratio of bulk density to bed density. Based on the numbers provided in Table 1 this is 0.583. However, due to variation in bead diameter the true packing factor is slightly higher and specified to be 0.63. If it is now assumed that the glass density is 2.23 g/cm^3, a typical density for borosilicate glass, the resulting percentage of volume occupied by helium is found to be about 46.0% of the total volume. In a similar way the percentage of total volume occupied by glass can be calculated, which amounts to about 17.0%. The interstitial volume represent thus 37.0% of the total volume. That means that the percentage of the volume initially occupied by helium relative to the total volume that is available to gas, that is the total volume minus the volume occupied by glass, is 55.4%. That means that for a volume fully packed with loaded glass beads the volume expansion of the pressurant gas is very close to two when all the gas is released. This effect will be taken into account in the analysis presented in the next section.
Commercially available HGMs show an astonishing mechanical stability and stress resistance and with isostatic crush strengths of up to 2000 bar. The burst pressure P_b of the glass beads can be calculated as follows [7]:

$$P_b = \frac{4\sigma_{max}\Delta r}{D}, \tag{2}$$

where σ_{max} is ultimate tensile strength, Δr the wall thickness and D the glass sphere diameter. Based on the data provided in Table 1 and equation (1) the wall thickness was estimated to be 0.80 µm. The ultimate tensile strength is much harder to obtain. Based on the Si-O covalent bond energy, 435 kJ/mol, the theoretical strength is 17 GPa [10]. However, due to imperfections the value for normal glass is about 70 MPa. Due to safety concerns for design practices normally an ultimate yield strength of 7 MPa is assumed. The strength can be increased by physically and/or chemically tempering. For physically tempered glass, usually by thermal treatment, the ultimate tensile strength is 210 MPa and for chemically treated glass this value increases to 500 MPa [10]. Based on these numbers the burst pressure ranges from 14.0 bar for normal glass to 1000 bar for chemically tempered glass. The true tensile strength, and thus burst pressure, of the HGMs currently available at FOTEC is not known. This will be subject of further investigation during the experimental part of the feasibility study.
The release of stored gas is controlled by the temperature of the HGMs which changes the diffusion of helium through the glass wall. However, recent investigations have also shown that specific wavelengths in the electromagnetic spectrum can be used to control the permeability of the HGM walls [11], [12]. The influence of temperature on the permeability, K, and diffusivity, D, can be described with an Arrhenius type equations [13]:

$$K = K_0 T \exp(-E_K/RT), \tag{3}$$

$$D = D_0 T \exp(-E_D/RT), \tag{4}$$

where K_0 is the permeability constant, D_0 is the diffusivity constant, T the temperature, R the universal gas constant and E_K and E_D the activation energy for permeation and diffusion, respectively. The rate of gas release through the HGM wall is driven by the pressure drop across the wall. The total released amount per glass sphere is a function of the diffusivity, pressure drop across the wall and the wall surface area.

For loading of the HGMs with helium the same principle as for releasing the helium is applied. The HGMs are put in a high pressure environment, similar to the storage pressure aimed for of loaded HGMs. By increasing the temperature the permeability of the walls increases and due to the pressure difference across the wall helium will diffuse into the glass spheres. The diffusion process will continue until internal and external pressure are in equilibrium. The temperature for the loading process is limited by the maximum usage temperature of the glass (e.g. ~500 °C for borosilicate glass), but a noticeable softening can already be expected well below that temperature. At temperatures below 250 °C borosilicate glass is mechanically and thermally stable, yet show significant permeability towards helium and hydrogen gas. Cooling the spheres to room temperature reduces wall permeability significantly and traps the gas within.

After loading, the glass microspheres will be transferred into a lightweight low pressure tank. By adjusting the temperature the diffusion rate, and thus the gas pressure within the tank, can be controlled. This approach combines high pressure gas storage densities with lightweight low pressure tanks.

3. Propellant Tank Analysis

To investigate the possible impact of the proposed pressurant gas storage under high pressure in HGMs a propellant tank system analysis is performed. To facilitate this analysis, first a small database of existing propellant tanks was established. It includes data such as tank dimensions, volume, mass, operating, design and proof pressure, construction material and expulsion method. The database currently contains information of just over 210 propellant tanks from various manufacturers and obtained from freely available sources.

An analysis was performed on the relation between the tank volume and tank mass prior to comparing it to a tank pressurised by HGMs. In this analysis mass and volume of any tank appendages, fittings and tubing is not included. However, also in the proposed HGM concept this is not taken into account.

The relation between tank volume and mass for tanks used in blowdown systems was investigated. However, for only a small number of tanks in the database it was indicated whether they are used in blowdown systems or as part of a pressure-regulated system. For most tanks the maximum propellant volume was indicated or sometimes the maximum propellant mass in combination with the propellant the tank was designed for. It was thus possible to determine the fill fraction of each tank. It was then assumed that a tank used in a blowdown system is a tank with a minimum empty volume of 30%, equivalent to a blowdown ratio of 1.33, a typical lower bound for blowdown systems [2]. In total 38 tanks met this criterion. It was further noticed that the highest blowdown ratio was 2.13.

From 8 of 38 tanks the material was not indicated. All 38 tanks had typical operating pressure of about 25 bar. It was further determined that based on the operating pressure and the blowdown ratio the tank pressure at EOL varies between 5.5 and 14.5 bar. Here, the higher EOL tank pressures are generally encountered for higher blowdown ratios. Figure 1 shows the tank volume and corresponding mass of the selected tanks. Also shown is the result of a least squares regression analysis performed on the data. It goes without saying that this results should be interpreted carefully given the crude selection criteria and the differences in design pressure and shape of the tanks.

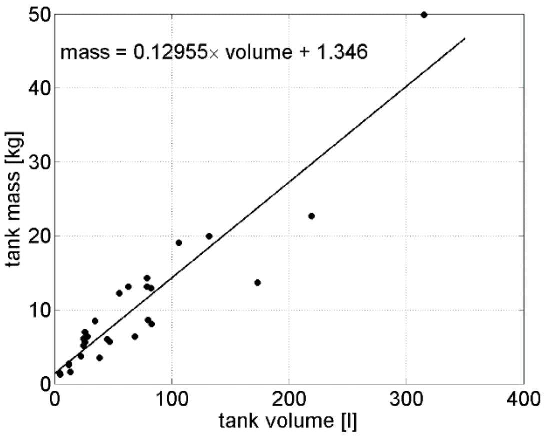

Figure 1: Tank volume versus tank mass for blowdown systems

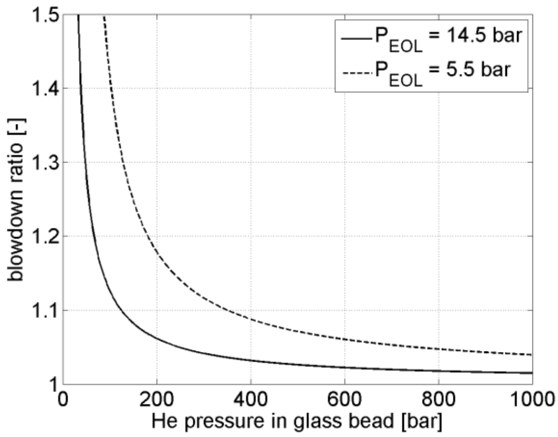

Figure 2: Required blowdown ratio as function of helium pressure in HGMs

Ideally, the blowdown ratio is kept as close to unity as possible to save volume and thus tank mass. However, for the same EOL tank pressure a lower blowdown ratio requires a higher initial tank pressure which requires a thicker tank to withstand the pressure. For a pressurisation system based on HGMs the required blowdown ratio as a function of internal pressure can be calculated. The result is shown in Figure 2 for two limiting EOL tank pressures. Real gas effects have been taken into account by employing the Redlich-Kwong equation of state [14]. In this figure the volume occupied by the glass beads as well as the interstitial volume between the beads is accounted for. Note that for even a low initial helium pressure the required blowdown ratio is significantly reduced. The gain in blowdown ratio reduces for initial HGM pressure above 500 bar, a very moderate pressure from a microsphere point of view. The reason for this moderate increase is that at higher pressures the influence of real gas effects is so strong that the density increases only marginally with pressure.

A big advantage of using HGMs for helium storage is that the tank design pressure does not change with the increase in pressure inside the HGMs. Consequently, the reduction in volume results in a saving in tank mass. The potential gain can be calculated as follows by first considering the saving in volume. The new volume can be calculated as:

$$V_{new} = \frac{V_{old}}{R} \cdot \frac{1}{1 - \frac{\rho_{EOL}}{\rho_{HGM}}} \tag{3}$$

Here V_{old} is the original tank volume, R the blowdown ratio ρ_{EOL} the required pressurant density at the end of life and ρ_{HGM} the initial pressurant density inside the HGMs. Here, the calculation is based on density rather than pressure in order to take into account real gas effects. The density is calculated with the Redlich-Kwong equation of state. The corresponding mass can be estimated by using the correlation found from the least squares analysis and shown in Figure 1. The result expressed in terms of percentage mass saving is shown in Figure 3 and Figure 4 for a blowdown ratio of 1.3 and 2.2, respectively. In both plots the original tank volume varies between 5 and 300 l, corresponding to the volume range found during the analysis of the tank database. As was mentioned before, the higher EOL tank pressure is typical for tanks with a higher blowdown ratio. For this reason an EOL pressure of 5.5 bar was chosen for a blowdown ratio of 1.3 and an EOL pressure of 14.5 bar for a blowdown ratio of 2.2, Figure 3 and Figure 4 respectively. The results are shown for three different initial HGM pressures. Here, the mass of the glass has been taken into account.

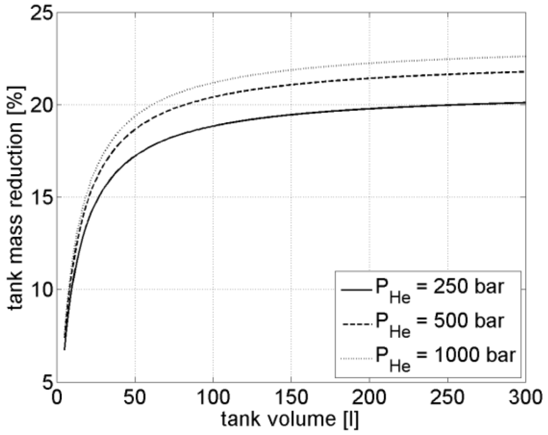

Figure 3: Tank mass reduction as a function of volume for R = 1.33 and PEOL = 5.5 bar

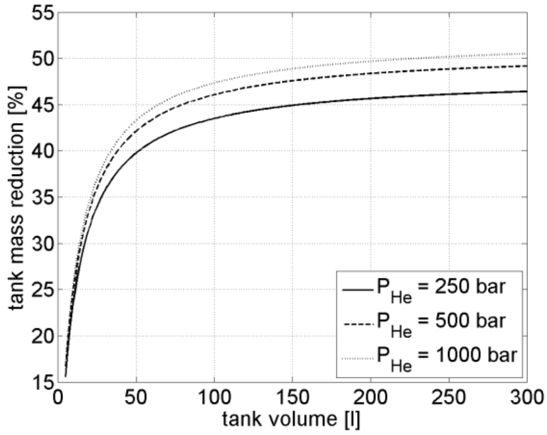

Figure 4: Tank mass reduction as a function of volume for R = 2.2 and PEOL = 14.5 bar

As shown in the figures, the reduction in tank mass only increases with a couple of percent point when the initial helium pressure is increased from 500 to 1000 bar. Furthermore, the tank mass reduction is similar for tank volumes of 100 l and more. For an HGM pressurised propellant tank the maximum tank pressure will in general be lower than the maximum tank pressure of a tank operated in blowdown mode. Consequently, the wall thickness and thus the tank mass will be lower in case of HGMs pressurising the tank. This effect has not been taken into account in the figures above.

Another advantage of HGM pressurisation is that the performance of the thruster becomes much less dependent on the amount of propellant that is still present in the tank and thus mitigating a typical drawback of blowdown propellant feed systems. This aspect will be further analysed in the next section. It should be noted that in this analysis the mass of any system to influence the permeability of the beads is not included.

4. Performance simulation model

To investigate the differences between classical pressurisation systems and the proposed HGM-based system, a simulation of the time-dependent behaviour of a representative bi-propellant propulsion system was created. Propellant tank pressurization was controlled with a blowdown, pressure-regulator and HGM system, respectively. The Python code DAETools [15] was used for the computation of the arising differential-algebraic system of equations. In what follows, the model structure and constituent components will be described. Then, the compared configurations will be defined. Finally, the simulation results will be presented.

4.1. Model and component description

A simple representation of a bi-propellant propulsion system was defined as shown in Figure 5, consisting of a thruster, oxidiser and fuel valves, oxidiser and fuel tanks, a Y-fitting splitting the pressurant flow between the oxidiser and fuel tank, and a pressure regulator. The pressure regulator behaviour was modified to behave appropriately for a blowdown, pressure-regulated, and HGM system, respectively. The relevant parameter values involved are presented in Table 2.

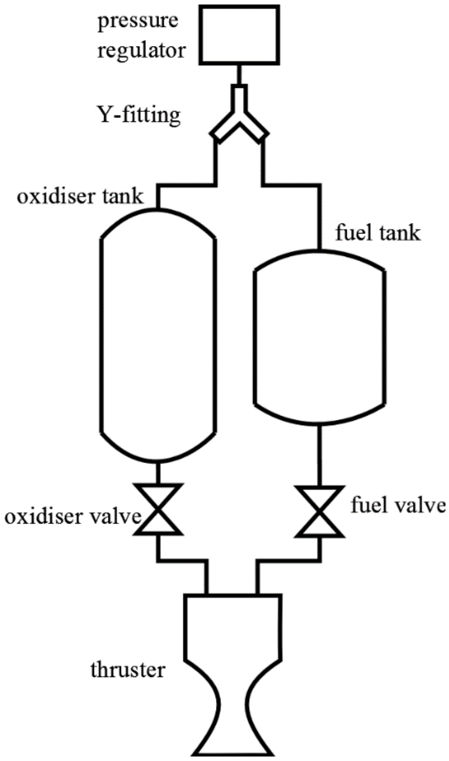

Figure 5: Schematic of the simulation model logical structure

The oxidiser/fuel combination 87.5% H_2O_2/12.5% water and Jet-A was chosen for this investigation. Simulations using an NTO/MMH combination were also performed, but are omitted here because the results are very similar to those obtained for the former propellant combination.

Thruster performance is calculated under the assumption of adiabatic conditions in the combustion chamber and nozzle. The actual calculations were performed with NASA's Chemical Equilibrium with Applications [16] for the combustion part of the process. Transient effects in the combustion chamber and nozzle are neglected and the nozzle is assumed to be always choked. The pressure at the injector is assumed to be identical to the combustion chamber pressure. Furthermore, the thruster mass flow rate is the sum of the oxidiser and fuel mass flow rates. The oxidiser and fuel valves are simple linear valves with a corresponding pressure drop. They were implemented to accommodate pulsed firing simulations. However, the results presented in this paper discuss continuous steady state firing only. The oxidiser and fuel tanks remain at a constant temperature, containing an incompressible propellant of constant density and helium as pressurant gas following the ideal gas law. The Y-fitting connects the propellant tank pressurant ports to a single pressure regulator. To achieve a simple representation of the physical design while allowing self-balancing pressurisation even if the oxidiser and fuel tanks were at different pressures, it contains linear valves in the oxidiser and fuel branches with corresponding pressure drops. The pressure regulator component is modified to represent the different pressurisation systems analysed in this work, while the composition of the rest of the system is kept unchanged, with the exception of initial tank pressures and tank sizes. They are calculated from a desired blowdown ratio and total propellant mass.

In the simplest configuration, a blowdown system with no re-pressurisation, i.e. no flow through the tanks' pressurant ports, and two different blowdown ratios is investigated. The blowdown systems are designed with an initial tank pressure higher than in the "active", i.e. the pressure-regulated and HGM, systems, in accord with common design practice.

In the pressure-regulated system configuration, the pressure regulator supplies pressurant such that the pressure at the pressure regulator outlet remains at a set value. The blowdown ratio has been chosen such that the initial ullage volume in the propellant tanks is approximately 5%.
Finally, in the HGM system re-pressurisation is controlled in a bang-bang fashion, where the system is activated as soon as the tank pressure drops below a certain permissible value and switches off when the target pressure is reached. That means that in between the re-pressurisation moments the tanks are operated in a blowdown mode. The re-pressurisation itself can be viewed as the pressure-regulated mode.
Re-pressurisation is initiated by increasing the temperature in the container containing the HGMs. This changes the rate of permeability of the HGM and thus the diffusion rate through the walls as was explained in section 2 and mathematically described with equation (3) and (4). During re-pressurisation the HGM system temperature is set to a “high” value and during the dormant periods the system temperature is set to a “low” value. Note that the pressure difference across the HGM walls, which drives the diffusion rate, is not considered in this simple, first, model. Furthermore, during the dormant periods, the pressurant mass flow rate has a small but finite rate. This is a consequence of applying equation (4) and in accordance with reality.
The value for the activation energy E_D has been taken as an average of values given in [13] for the appropriate temperature range. The value for the pre-factor D_0 has been, in a first iteration, chosen such that a quick re-pressurization and a slow dormant pressurant release are achieved. Scaling D_0 can be achieved by varying the amount of HGMs or adjusting the inner pressure of the HGMs, for example, but this has not been considered in this simple model. The propellant tanks in the HGM pressurisation system have the same ullage volume as for the pressure-regulated system of approximately 5%.
The values of the parameters that are common for all the investigated configurations are presented in Table 2. The values of the parameters for the different systems investigated are given in

Simulation results

For the systems defined in the previous section, simulation results are presented in what follows. First, time-dependent plots of representative quantities are shown in Figure 6 and Figure 7 for the different systems considered for a total propellant mass of 500 kg. The mixture ratio is approximately constant across the systems examined and has a value of 8.19. Similarly, the specific impulse at the nozzle exit is approximately constant at about 310 s. Other quantities like combustion chamber pressure or temperature, thruster mass flow rate or thrust vary in a manner equivalent to Figure 6.
Figure 6 shows the average oxidiser/fuel tank pressure. Recognisable features are the different initial pressures for the blowdown and the active systems, the monotonic pressure decline for the blowdown systems, the constant pressure for the pressure-regulated system, and the periodic re-pressurisation phases for the HGM system. Note that the time between the re-pressurisation moments is a function of the amount of propellant that is left in the propellant tank. The different termination times for the individual plot lines indicate the different thruster burn durations of the respective system configurations.

Table 3.

Table 2: Parameter values which are common between the different systems investigated, for 87.5% H_2O_2/water oxidiser and Jet-A fuel

parameter	value	units
thruster throat area	5.3	mm²
nozzle expansion ratio	40	-
nominal thruster mass flow rate	3.3	g/s
nominal mixture ratio	8.2	-
nominal pressure drop between tank and combustion chamber	25	bar
87.5%wt. H_2O_2 density	1367	kg/m³
Jet-A density	800	kg/m³

ambient temperature	300	K

4.2. Simulation results

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Table 3: Parameter values for the different systems investigated. The “BD” prefix indicates a blowdown system, and the pressure-regulated configuration is denoted by “preg”.

quantity	BD_1.33	BD_2.2	preg	HGM	units
(total) propellant mass	1-500	1-500	1-500	1-500	kg
initial tank pressure	60	60	40	40	bar
blowdown ratio	1.33	2.2	1.05	1.05	-
low HGM system temperature				300	K
high HGM system temperature				600	K
activation energy E_D				23.2[a]	kJ/mol
pre-factor D_0				$7 \cdot 10^{-5}$	kg/(s·K)
Permissible pressure drop in tank				15	%

[a] average of values given in [13] for the appropriate temperature range

Figure 7 shows the total amount of pressurant in the tanks. The blowdown systems, of course, remain at a constant amount of pressurant, while the pressure-regulated system exhibits a release rate rising linearly to keep the pressure in the continuously emptying tank at a constant value. Finally, the HGM system shows a step-like progression, in line with the pressurization episodes. It is notable that even in the inactive periods, the HGM system continues to release pressurant, as can be recognised by the non-zero slope of the HGM curve in the dormant sections. The ratio of release rates between the “hot” and “cold” periods is an important design parameter, and has been indicated in the bottom right of the figure. It is desirable that this ratio is as high as possible, so that the slow pressure increase even when the thruster is not firing is minimized, while still enabling a quick re-pressurisation. The value of that ratio is influenced by the activation energy E_D, and by the ratio of hot to cold temperatures.

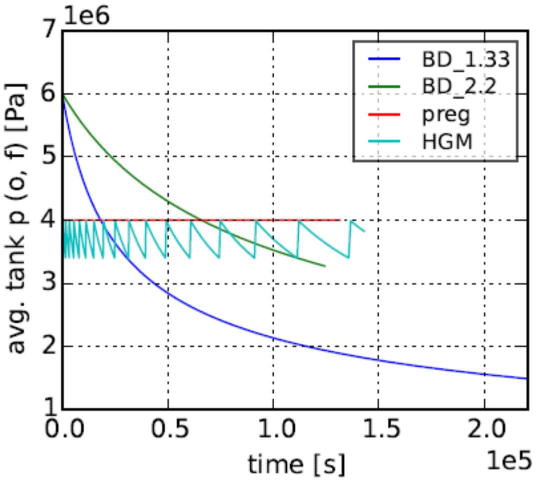

Figure 6: Average oxidiser/fuel tank pressure over time, for a simulation with 500 kg propellant mass

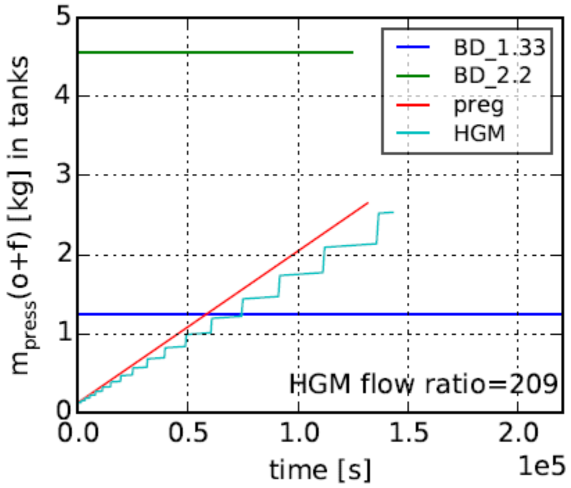

Figure 7: Total mass of pressurant in the propellant tanks over time, for a simulation with 500 kg propellant mass

Figure 8 shows the variation in the final mass of pressurant in the tanks, when varying the total propellant mass. Figure 9 shows the total propellant tank volume vs. propellant mass. Here, the volume of the pressurant tank for the pressure-regulated and the HGM systems is not considered. Note that the lines for the pressure-regulated system coincides with the line for the HGM system. Owing to the low ullage volume, the pressure-regulated and HGM systems show the lowest tank volumes.

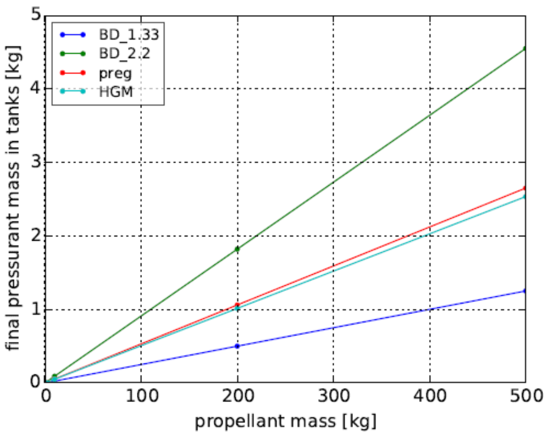

Figure 8: Final mass of pressurant in the tanks vs. propellant mass

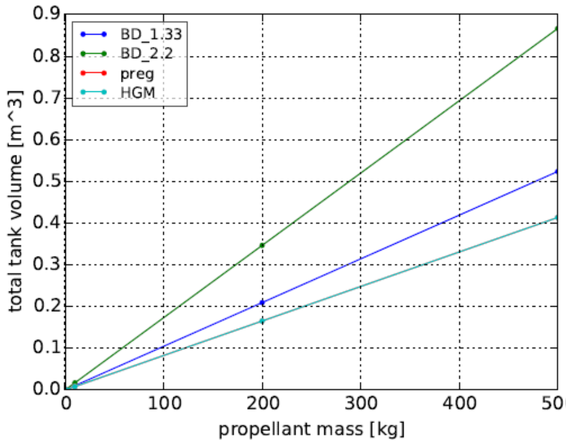

Figure 9: Total propellant tank volume vs. propellant mass

Figure 10 shows the variation of thrust for the different systems under consideration. The variation of thrust is independent of the total propellant mass. Figure 11 shows the total burn duration vs. propellant mass, for the different systems under consideration. The quantities plotted in Figure 8, Figure 9 and Figure 11 vary linearly with the amount of propellant, as expected.

The simple blowdown system with a blowdown ratio of 1.33 has a tank which is a little larger than the active systems' tanks, and needs the least amount of pressurant for a given amount of propellant. On the downside, it suffers from the biggest thrust variation and the longest burn duration, because of the low average mass-flow rate through the thruster caused by a rapidly dropping combustion chamber pressure.

Choosing a higher blowdown ratio of 2.2 improves the thrust variation and brings the burn duration approximately in line with the active systems', at the price of needing the most pressurant and the largest tanks, which are about twice as big as for the active systems, with a corresponding mass penalty.

The pressure-regulated system exhibits no thrust variation, at a low burn duration due to the constant tank pressures, and needs the lowest tank volume, and a medium amount of pressurant. On the downside, the higher system complexity and mass of the active components are known drawbacks.

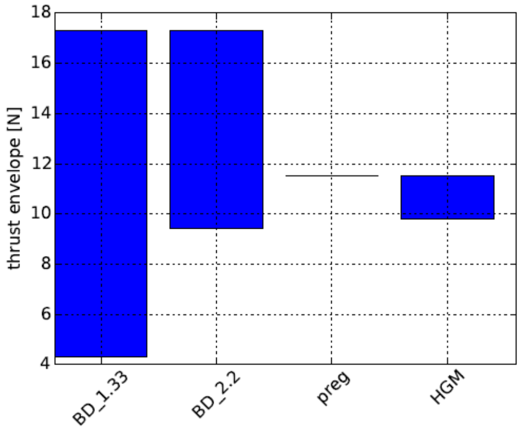

Figure 10: Variation of thrust during the burn

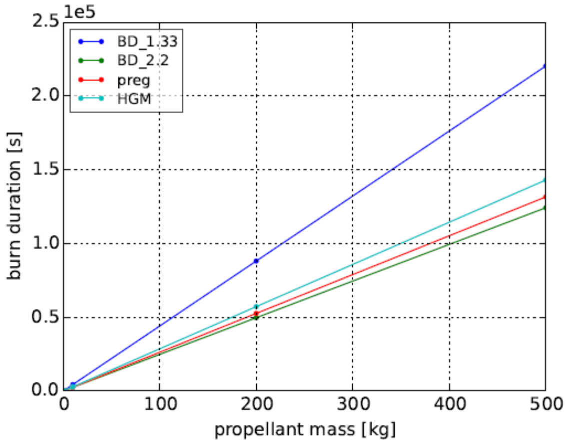

Figure 11: Thruster burn duration vs. propellant mass

Finally, the HGM system has a low thrust variation at a low burn duration. Furthermore, the thrust variation can, in principle, be made arbitrarily small by reducing the permissible pressure drop below the value of 15% chosen here, or choosing a continuous temperature control scheme instead of the bang-bang scheme employed here. In the amount of pressurant needed, and the tank volume, the HGM system shows values similar to the pressure-regulated system, and therefore seems to be an appropriate replacement candidate.

5. Conclusions and future work

A new pressurisation system was presented which combines the simplicity of a blowdown system and the performance of a pressure-regulated system. A tank system analysis showed that a pressurisation system based on HGMs can result in significant mass savings compared to blowdown systems.

A subsequent thruster performance analysis showed that an HGM pressurisation system is very similar in performance to a pressure-regulated system. By adjusting the maximum permissible pressure drop in the propellant tanks, the HGM system can be further tuned to the mission needs. In the current simulations the maximum was set at 15% and only a continuous thruster firing was simulated.

Large unknown factors at this point in time are how well the release of helium from the glass beads can be regulated, how heavy the activation system is and how much power it requires. To shed light on these factors an experimental study is currently under preparation. The results will be used to verify some of the assumptions made in the analyses presented in this paper and to further assess the feasibility of the proposed system.

Finally, it would be interesting to see the performance of a thruster with an HGM-type pressurisation system under pulsed mode firing. However, such an investigation would only make sense once a representative relation has been established between the temperature of the glass beads, the pressure drop across the wall and the rate of diffusion of helium.

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