SP2018_00039

System Study of Slush Propellants for Future European Launch Vehicles

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KEYWORDS:
Slush, space transportation, slush hydrogen, slush methane, space propellant densification, reusable launch vehicle

ABSTRACT:

Usually cryogenic propellants in launch vehicles are stored at the normal boiling point, but the density can be increased by subcooling the propellant. In its most extreme form, this results in a mixture of solid and liquid propellant: the slush propellants. First, the possibility of employing slush fuels within the upper stages of prospective European launchers (Ariane 6 and Vega-E) is evaluated. Three methods of implementation are discussed and compared. In addition, their effect on possible future European launchers with a reusable Vertical Takeoff and Vertical Landing (VTVL) first stage are also investigated. While the application to existing designs only yields small improvements, results for the Reusable Launch Vehicles (RLV) show that the total mass of the launcher for the same payload could be reduced by up to 23 %. While not all complications of densified propellants are solved at this point in time, the potential for the improvement of future launch systems is substantial enough to warrant future investigation.

1 INTRODUCTION

The development of more performant, lighter and cheaper space launch systems still is one of the core goals of the space transportation industry. A technology that has the potential to support these goals is the densification of propellants through subcooling. Ordinarily, cryogenic propellants in launch vehicles are stored at the normal boiling point (NBP), but subcooling the propellant can be used to increase the density. A mixture of solid and liquid phase allows for a substantial density increase. These mixtures are knows as slush. The use of this technology could reduce the size, mass and consequently the cost of space transportation systems. However, the effect of the solid fraction on the behavior and handling of the propellant and its final impact on the launcher system have to be understood and addressed first.

2 STATE OF THE ART

Current European cryogenic stages employ their propellants at the boiling point at normal ambient pressure. This allows easier handling since the thermodynamic state of the propellant is constant and any boil-off losses can be compensated by refilling the tank to the desired fill height. Since the density is constant, the amount of propellant in the tank can be calculated precisely.

While the production and filling procedures for densified propellants are more complex, the use of slush propellants offers the following advantages:

- The higher density allows the use of smaller tanks or the accommodation of larger amount of propellant within the same volume.
- Boil-off losses during the flight are reduced or even eliminated completely thanks to the larger energetic distance from the boiling point. This factor gains in importance the longer the mission is designed to last.
- Risk of cavitation at the entry of the turbopumps of the engine is severely reduced since a much larger Net Positive Suction Pressure (NPSP) is available at the pump inlet because of the reduced vapor pressure. This reduces the requirements on the tank pressurization and, depending on the architecture, can allow tank pressures that are more favorable from a structure perspective.

2.1 History of slush

The possibility of using slush hydrogen in rocket stages has originally been investigated in the 1960's[1,2] and has been a part of multiple studies, most notably the NASP (National Aero-Space Plane) [3]. Within the scope of that project, large scale experiments with regard to the production and handling of slush hydrogen were undertaken. An overview over the historical programs as well as the general results from the large experiments of the NASP program can be found in [4].

3 METHODS

3.1 Study logic

Within this present work the application of slush was evaluated for two groups of launchers. First the use of slush fuel in the upper stages of already existing designs was studied. For this purpose the coming Ariane 6 and Vega E were chosen as reference launchers. Second, potential future launcher concepts with a reusable VTVL (Vertical Takeoff and Vertical Landing) booster stage were studied. For the sake of brevity the two groups will forthwith be called the ELV (Expendable Launch Vehicle) and RLV (Reusable Launch Vehicle) groups. It should be noted that the RLV are in fact only partially reusable, since the upper stage is expendable.

For the already existing ELV-designs an implementation of slush was chosen that minimizes the impact on the overall stage design. Only the fuel of the upper stage was assumed to be slush. This scenario leads to minimal redesign of the stage. But even so three different boundary conditions can be applied:

- Constant propellant mass
- Constant propellant volume
- Constant payload mass

These three options are discussed in section 3.5 in more detail.

The design space for these modifications is severely limited since only the upper stage is modified. Furthermore, even within this stage the modifications are kept to a minimum. This represents the use of the slush technology as a future improvement for those launchers, not as a basis for completely new launchers. As such, it is expected that this scenario leads to comparatively small performance increases.

The RLV designed within the ongoing DLR system study are a different case entirely [5,6]. Here the design space is only limited by the boundary conditions of the study and the entire stage can be optimally adapted to the propellant properties. Factors such as engine thrust, stage diameter, tank pressurization and more can be optimized so that the entire launcher size can be decreased in order to achieve the desired payload mass. In this case, the use of slush propellant results in an overall reduction of launcher size and mass.

3.2 Investigated Launchers

As mentioned previously, the ELV reference launchers are based on the upcoming European launchers Ariane 6 and Vega E. It should be noted that the models shown hereafter are approximations of the named launchers and do not claim to be exact representations. While the actual masses of both launch systems will deviate from the values used here (the design of both was not finished at the time the models were created and publically available data is limited), the values are close enough to give a reasonable approximation. The assumed values used in the following representations and the target orbits are listed in Table 1.

Table 1: Key data for hydrogen reference ELV based on Ariane 6

Core stage ascent propellant mass	150 t
Core stage mass at MECO	24 t
Upper stage ascent propellant mass	30 t
Upper stage mass at MECO	7.4 t
Payload to GTO	11.3 t
GLO mass (including four boosters)	864 t

Table 2: Key data used for methane reference ELV based on Vega E

Upper stage ascent propellant mass	9.9 t
Upper stage mass at MECO	1.9 t
Payload to 700 km PEO	3.5 t
GLO mass	213 t

The RLV launchers already mentioned above were taken from a DLR system study investigating the use of reusable booster stages for future European launcher systems. The assumptions and boundary conditions used for the design of these launchers are documented in [6] and thus will only be briefly summarized here: the goal of the study is the examination of different options for reusable booster stages. Different stagings, return options and propellants were considered. The cases modelled here are returned via downrange landing, equivalent to the method SpaceX uses nowadays for missions that do not allow a return to launch site.

3.3 Propellant properties

The properties of the liquid propellants were calculated for the relevant conditions with the REFPROP program [7], while the data for the solid phase was taken from [8]. The methods for calculation of the relevant properties for the slush mixture were taken from [9]. The calculation of the pressure drops within the feedlines was based on the correlations derived in [10]. On a final note, when hereafter referring to slush, a 50% solid mass fraction is meant.

3.4 Modelling of subsystems

For the ELV reference launchers the detail with which the subsystems were modelled was dependent on the relevance of the slush propellant for the subsystem and vice versa. This approach results in comparatively detailed models for the structure and the propellant supply system while other systems were mostly seen as unchangeable point masses since it was assumed that the change to slush fuel does not affect their function or mass to a significant degree.

Since for the RLV-stages the size of the entire stage was resized in order to achieve the desired payload the modelling of the subsystems in general had to be more detailed. The methods employed are presented and discussed in [5,6].

3.4.1 Propellant Supply System

The propellant supply system of each launcher was modelled with the in-house tool PMP [11]. The tool was used to perform simulation of the propellants in the feedlines as well as the tanks. In both cases 1D engineering models were used. The tool was extended in order to allow for analysis of slush flow, including the additional possible phase changes not found in conventional rocket systems: melting or freezing. The flow of the slush propellants was modelled using the methods developed within the PREDICT project [10]. Since the focus of the project was the feedline flow, these models are more detailed than the assumptions for the propellant in the tank where an ideal mixture was assumed. The results for the propellant supply system are shown in section 4.1.

3.4.2 Propulsion

All rocket engines modelled within this study are pump fed engines. As such, it is expected that the slush only interacts with the pump of the engine since the temperature increase caused by the losses of the turbopump are more than sufficient to melt the solid fraction and still raise the temperature. The impact of the solid fraction on the pump is not yet completely understood. However, the data that is publically available on this subject indicates no additional wear and tear as well as no decrease in pump efficiency [1]. In theory at least, the power requirements of the pump should decrease since it depends on the volume of the pressurized medium, which is reduced for a slush flow compared to a liquid with the same mass flow rate. Consequently, the following models assume that specific impulse and thrust-to-weight ratios of the selected engines are identical for the slush and liquid cases.

In the following models the possible mass of additional equipment for propellant management was not accounted for. In this sense the following models represent a best case in that no substantial internal hardware (e.g. a mixer) is needed to manage the slush propellant, but that the main complexities reside in the production and filling of the stage with slush of a predetermined quality.

3.5 Methods of employing slush

The following subsections describe the changes made to the reference launcher models in order to incorporate the slush propellants.

3.5.1 Design changes for existing ELV-designs

The three design change possibilities briefly mentioned in 3.1 are expanded upon in the following subsections.

3.5.1.1 Constant propellant volume

As the name implies, the volume and geometry of the tanks are kept constant with this approach. Ideally, this leads to a minimum of changes within an existing stage design. While the structure has to be re-evaluated, the influence on the overall launcher mass was assumed to be insignificant. The higher density means additional fuel can be loaded into the upper stage tanks. This additional propellant allows the acceleration of additional payload.

Preliminary structural analysis with the DLR in-house tool LSAP confirms that the additional propellant load has a negligible effect on the structural mass of the upper and lower stage. Thus, the creation of this variant consists mostly of assuming a higher propellant mass at a constant structural mass. The only components impacted by the use of slush fuel are the rocket engines and specifically their specific impulse. Because this part of the paper only investigates the possibility of densifying the fuel, either the mixture ratio or the relative tank proportions have to be adjusted in order to transport the correct amount of propellant. Only the first of these options was investigated here, since the advantage of minimal structural changes would be nullified if the tanks were resized in order to keep the mixture ratio constant. However, the change in specific impulse is negligible since the propellant combination of LOX/LH2 has a very flat performance maximum [12].

3.5.1.2 Constant propellant mass

This approach assumes that the tank size is adjusted to the new density of the propellant. The mass saved by the smaller fuel tank is simply added to the payload. Since the upper stage does not alter its weight at all, no structural analysis of the first stage was needed. However the geometry of the upper stage has to be modified and reevaluated in order to account for the smaller fuel tank.

3.5.1.3 Constant payload mass

A main advantage or even a requirement of the two options above is that slush could be deployed in a launcher with minimum changes to the launcher design. The constant payload approach takes a different route that is closer to the actual design process: A payload capacity is given as a requirement for the system and the launcher is sized accordingly. It is assumed that the use of slush is considered from the beginning of the launcher design and thus the upper stage is sized accordingly. Depending on how much mass the upper stage can shed, a redesign of the lower stage structure could allow for additional mass savings.

3.5.2 Design changes for RLV-system study

In all the above mentioned cases an existing stage design is adapted to the slush propellant. While in some cases the modifications are more extensive they still remain constrained by the existing design. For example, while the loading was changed, the stage diameter or engine size was not altered. For the RLV cases a different approach was used: A payload performance is given as a requirement for the system and the entire launcher and all its subsystems are sized iteratively until the desired payload and staging are achieved. This approach is much more comprehensive since all parameters of the launcher can be recalculated and optimized. For example, with the three previously mentioned approaches the engine thrust would remain constant since the selection of current European rocket engines is limited but within the RLV study the engines are scaled to be optimal for the new configuration without regard for actually existing engine options. The same is true for the stage diameter which is usually limited by existing manufacturing capabilities. While this approach can be seen as a purely academic exercise it does allow an unbiased comparison. Otherwise the boundary conditions that are optimized for the NBP option would unduly influence the comparison.

4 RESULTS

4.1 Analysis of propellant supply system

In the following subsections not all three implementation methods from section 3.5.1 are discussed for each propellant. The consequences for the system performance are virtually identical for the three cases. Instead the hydrogen section focuses on the constant propellant mass case and the methane section focuses on the constant propellant volume approach. The results with regard to the launcher performance are discussed for all cases in section 4.2.

4.1.1 Hydrogen - ELV

As mentioned above the following section focuses on the constant propellant mass case. A geometrical comparison of the propellant supply system for the liquid hydrogen reference upper stage and the SLH2 (slush hydrogen) case is given in Fig. 1 and Fig. 2. As can be seen the shape of the fuel tank hardly changes, the cylindrical part is simply shortened. While the tank is smaller, the geometry actually becomes less efficient from a structural point of view since the portion shared with the outer shell decreases and the tank becomes less integrated within the launcher structure. This cannot be avoided since the diameter of the stage is fixed.

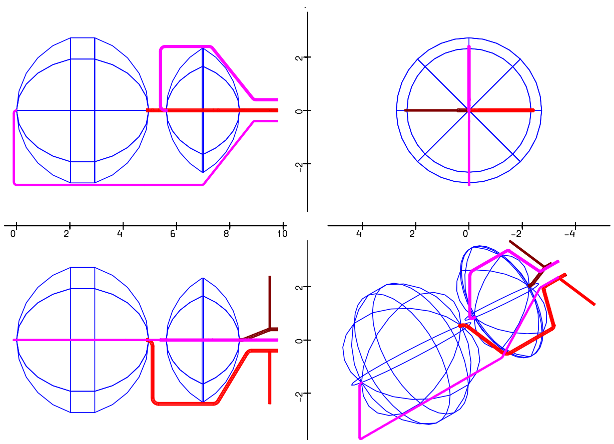

Figure 1: Reference propellant supply system for the LH2 upper stage

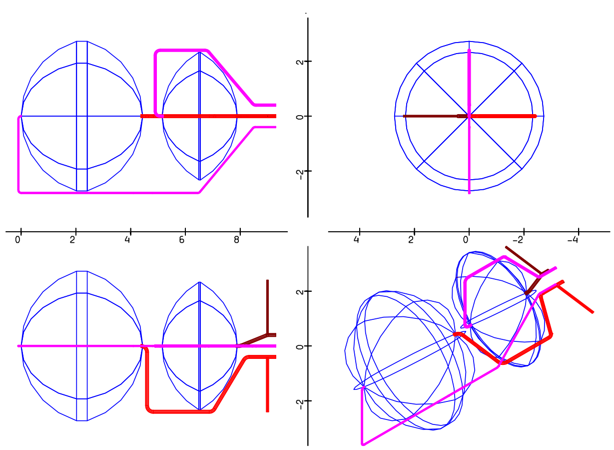

Figure 2: Reference propellant supply system for the SLH2 upper stage

One possible option for the management of the solid fraction of the mixture would be the separation of the phases by a sieve that only lets the liquid fraction enter the feedline. It was thought that the heat input from aerodynamic heating might be sufficient to melt the solid fraction during the rather long flight of the second stage. Fig. 3 shows the result of the simulation assuming a sieve.

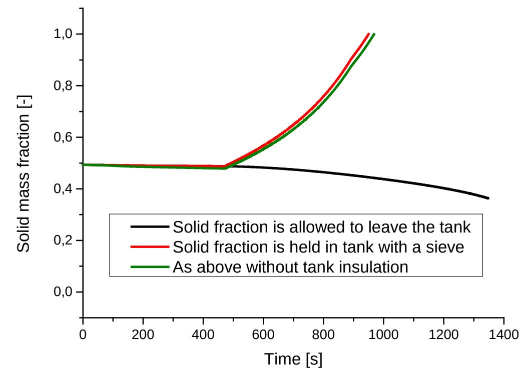

Figure 3: Solid mass fraction over time

It is clear that the heat transfer into the propellant is not sufficient to melt the solid particles fast enough. Even when the insulation is completely removed, the trend of the solid mass fraction barely changes. While the simulation was performed until the solid mass fraction reached 1, this is purely theoretical as draining the liquid fraction would become extremely difficult at high solid mass fractions. Since the results were already discouraging, the pressure drop caused by the sieve and the solid particles gathering above were not investigated further.

If the entry of solid particles into the pump has to be avoided, a remaining option is a heated sieve. Fig. 4 depicts the heater power necessary in order to completely melt the solid fraction as it leaves the tank through some type of heater element at the feedline outlet. The total energy necessary is 123 MJ. Assuming the energy density of a lithium-ion battery this amounts to ca. 140 kg worth of batteries, which of course would have to be deducted from the payload performance. This mass is an extremely optimistic estimation since additional equipment is needed to actually transfer the energy into the slush and the energy transfer will include inefficiencies that will lead to an increased energy requirement.

Alternatively, the energy could be taken from the rocket engine cycle. This option, however, would be highly complex since it would unavoidably impact the rocket engine cycle and would necessitate a redesign of the same.

The kink in the trend of Fig. 4, Fig. 5 and the other figures showing results from the hydrogen reference stage results from the Vinci engine being throttled down after about half the flight time of the upper stage. This is modelled as an instantaneous change in mass flow rate and mixture ratio.

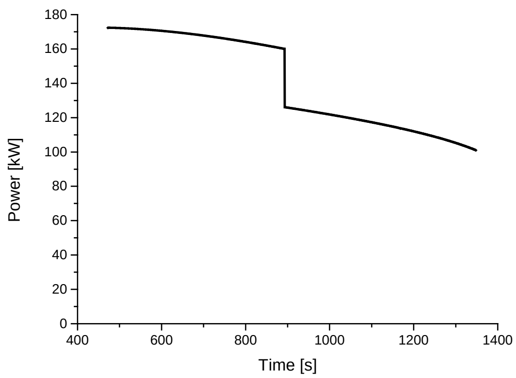

Figure 4: Heater power necessary to continuously melt the solid fraction

Consequently, if a low impact on the stage design is the goal, the turbopump has to be exposed to the solid fraction as discussed in section 3.4.2. The following results are based on that approach.

The key values of the propellant supply system are shown in Fig. 5 and Table 3. Table 3 contains the projected pressure drops for the liquid and the slush case for both operating points of the Vinci engine. The pressure drop for the slush is actually lower than for the liquid case. This is caused by the reduced flow velocity since the mass flow rate was kept constant. So while the pressure drop for a slush flow of the same velocity should be higher than for the liquid case, here the lower volume flow rate is sufficient to compensate that. The resulting trend for the NPSP at the entry of the turbopump is shown in Fig. 5. The NPSP for the slush case is approximately one bar higher even though the pressure drops are similar. This is caused by the lower temperature which results in a very low vaporization pressure. This NPSP reserve opens up new options with regard to possible tank pressures that can be used to optimize the pressurization of the upper stage from a structural perspective.

Table 3: Pressure drop in hydrogen feedlines for liquid and slush case

	NBP-hydrogen		Slush hydrogen with experimental correlations from [10]	
Total pressure drop [kPa]	10.8	7.7	9.8	7.1

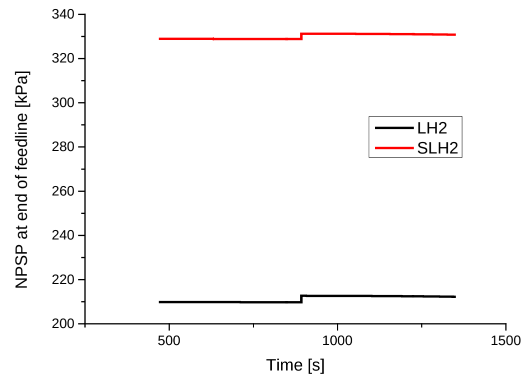

Figure 5: NPSP over time for the hydrogen upper stage

4.1.2 Methane – ELV

In the case shown hereafter, the total propellant volume was kept constant. Since the LCH4 reference case includes a common bulkhead design, the mixture ratio can be kept constant by shifting the position of the common bulkhead, a comparatively minor adjustment. In Fig. 6 and Fig. 7 the geometry of the upper stage are sketched before and after the changes. The smaller green tanks are for the helium pressurization system.

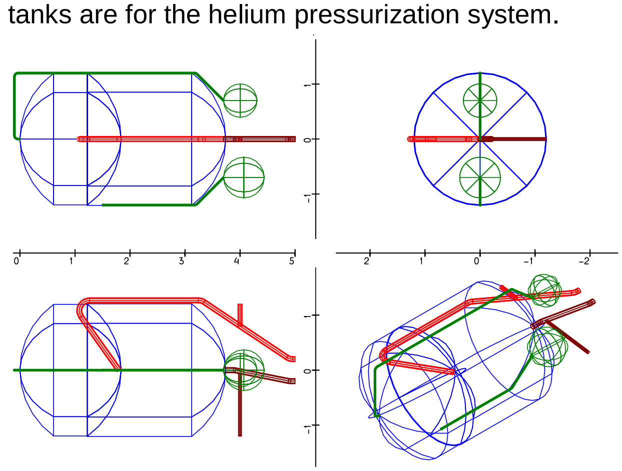

Figure 6: Reference propellant supply system for the LCH4 upper stage

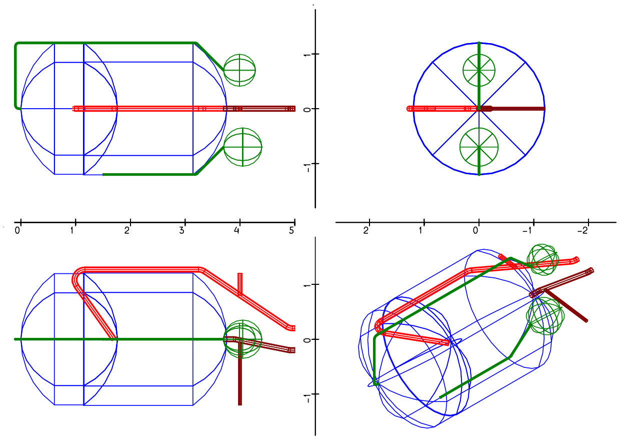

Figure 7: Reference propellant supply system for the SLCH4 upper stage

As with the Hydrogen-ELV, the propellant supply system was evaluated for both NBP and slush methane. The results shown in Fig. 8 and Fig. 9, are similar in nature to the hydrogen case. The available NPSP is again approximately one bar higher for the slush case, although the results have to be seen with care since the specific geometry of this stage was not evaluated within [10] and there could be unexpected flow phenomena that impact the pressure drop within the particular feedline path taken by the fuel line shown in red in Fig. 7. As with the hydrogen case the additional NPSP opens up new optimization possibilities with regard to the pressurization of the tank.

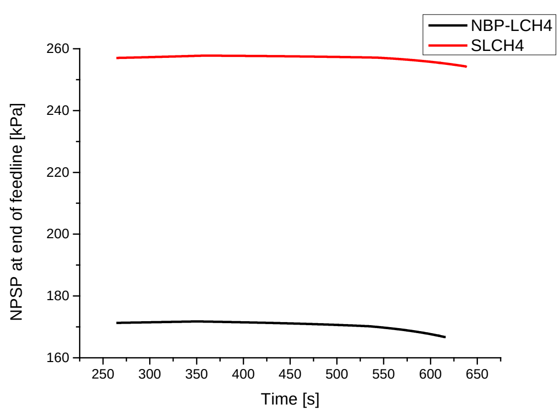

Figure 8: NPSP over time for the methane upper stage

As for the hydrogen case, the power needed for a heated sieve was also evaluated, as can be seen in Fig. 9. The total power requirement is about half of the hydrogen reference case even though the propellant loading is only about a third. This can be explained by the lower mixture ratio employed for a LOX/LCH4 engine.

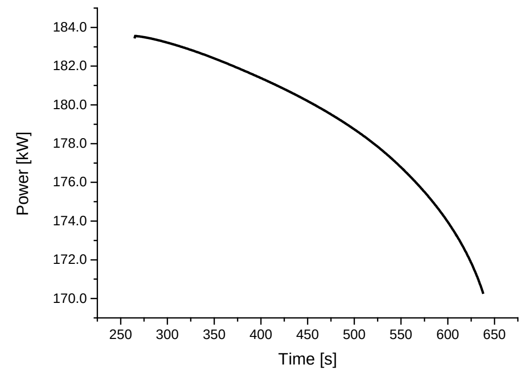

Figure 9: Heater power necessary to continuously melt the solid fraction

4.1.3 Propellant supply system of RLV

As described in section 3.1 the RLV launchers are part of a larger system study where the propellant supply systems have not yet been simulated with the same degree of detail as for the ELV reference cases. Thus the slush propellant supply systems were also not assessed in detail. The investigation and discussion of the RLV will instead focus on the stage sizing aspects.

4.2 ELV-Performance

The following Table 4 shows the results for the ELV launchers. These results will be discussed in section 5.1.

Table 4: Improvements for ELV's with slush fuel in upper stage

Constant Value	Propellant volume		Propellant mass		Payload mass	
Reference case	H2	CH4	H2	CH4	H2	CH4
Payload Increase [%]	+0.6	+2.5	+2.7	+0.5	-	-
Total upper stage MECO mass decrease [%]	-	-	-	-	4.0	2.3

4.3 RLV

The following subsections are sorted by the different fuel options since the comparison between NBP and slush propellants always has to be for the same fuel species. In contrast to the ELV-cases shown above, in the following results both the oxygen and the fuel were assumed to be densified.

4.3.1 Hydrogen

As can be seen in Fig. 10 the GLOM (Gross Lift-Off Mass) of the hydrogen RLV's are substantial. Only the historical LOX/LH2 stages from the Saturn and Energia rockets are of similar size. This is caused by the demanded payload into GTO (Geostationary Transfer Orbit), the two-stage architecture and the reusability of the first stage. The choice of an all hydrogen launcher with the associated high specific impulse leads to much smaller total masses than for the methane case. For the targeted payload the slush version has a substantially lower GLOM as shown in Fig. 10. The difference is even more pronounced when limiting the comparison to the dry mass, which is shown in Fig. 11. Table 5 contains the comparison of the final masses for both versions.

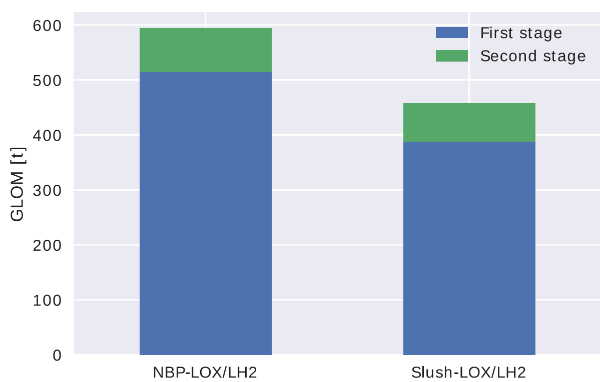

Figure 10: Comparison of GLOM for RLV using NBP and slush propellants

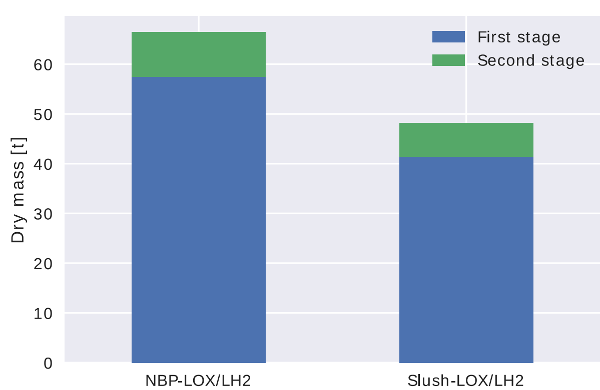

Figure 11: Comparison of dry mass for RLV using NBP and slush propellants

As expected the structural indexes for both stages are slightly lower when using the slush propellants. This is shown in Fig. 12. The decrease of the structural index is more pronounced for the second stage. This is caused by the structure mass being a larger fraction of that stage since it lacks the recovery hardware that drives the dry mass of the first stage. In contrast to the main structure, the recovery hardware is not directly affected by the density increase.

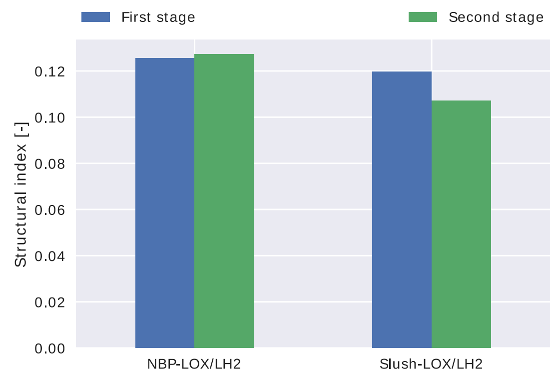

Figure 12: Comparison of structural index of first stage of RLV using NBP or slush propellants

The mass composition of the first stage is shown in Figure 13. The differences are minimal, but on closer inspection it can be seen, that the structure fraction decreases slightly, which is expected since the structure is the prime beneficiary of the use of slush. It should be noted that the fraction occupied by subsystems in these launchers is larger than usually found in ELV designs, since the recovery hardware, i.e. aerodynamic control surfaces and landing legs, is included in the category.

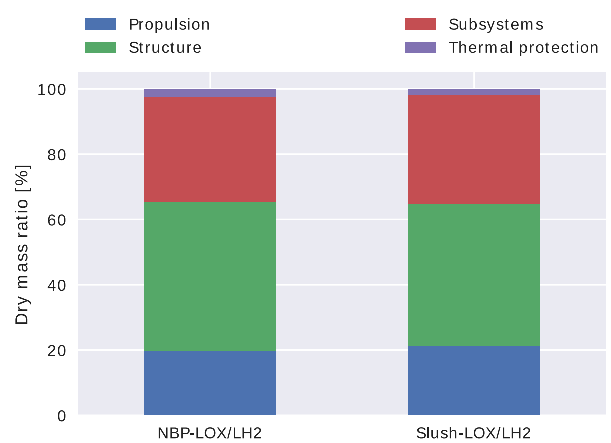

Figure 13: Mass composition of the first stage of RLV using NBP or slush propellants

Table 5: Comparison of key masses of NBP and slush hydrogen RLVs

	Unit	NBP	slush	Difference
GLOM	t	601	465	-22.6 %
Dry mass 1st stage	t	57.4	41.4	-27.9 %
Dry mass 2nd stage	t	9.0	6.8	- 24.4 %
Payload	t	7.47	7.51	-
Payload Fraction	%	1.24	1.62	+30.6 %

Table 6: Comparison of key masses of NBP, triple-point and slush methane RLVs

	NBP	TP		slush	
		Value	Difference to NBP in %	Value	Difference to NBP in %
GLOM	1761 t	1571 t	-10.8	1363 t	- 22.6
Dry mass 1st stage	126.9 t	108.8 t	-14.3	87.8 t	- 30.8
Dry mass 2nd stage	11.6 t	10.0 t	-13.8	8.5 t	- 26.7
Payload	7.47 t	7.2 t	-3.6	7.33 t	-1.9
Payload Fraction	0.42	0.46	+9.5	0.54	+28.6

4.3.2 Methane

The following results for the methane-based launchers include a variant in which the propellants were modelled at the triple point in order to assess the improvements possible while remaining in the liquid phase.

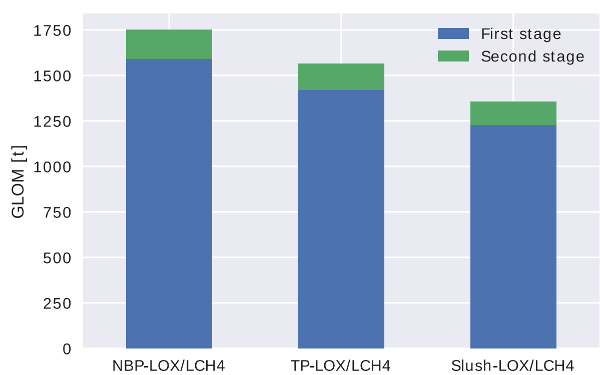

Figure 14: Comparison of GLOM of RLV using NBP, triple-point and slush propellants

The trend of the results is similar to the hydrogen cases discussed above: GLOM and dry mass can be substantially reduced, with the reduction more pronounced for the dry mass. Table 6 contains the key information for all methane RLV's.

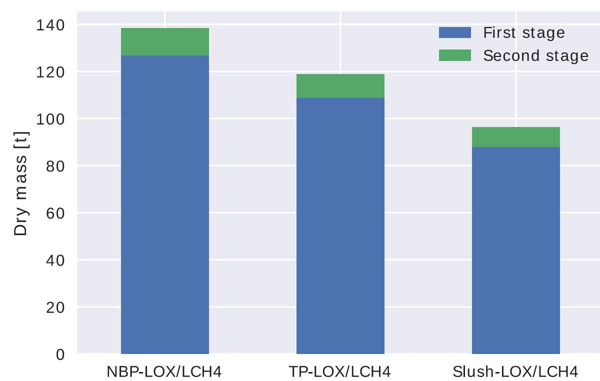

Figure 15: Comparison of dry mass of RLV using NBP, triple-point and slush propellants

It is noteworthy that the difference is higher than for the hydrogen cases even though the density reduction of the fuel is actually slightly lower (ca. 18% for hydrogen and ca. 15% for methane). A possible explanation is that for the lower specific impulse propellant combination the reduction of the structural index has a larger impact. Another possible explanation is the smaller size of the hydrogen stages, since the size reduction enabled by the denser propellant causes higher structural indexes because certain components cannot be reduced beyond a certain size.

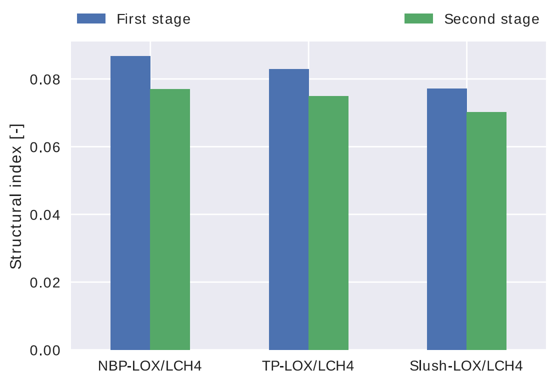

Figure 16: Comparison of structural index of first stage of RLV using NBP, triple-point and slush propellants

The decrease of the structural index for both stages is shown in Figure *16*. Finally the mass composition of the first stage is depicted in Figure 17. The trends are similar to the hydrogen case: The structure fraction decreases slightly. But again the changes in composition are small since most elements are resized to the actual launcher size.

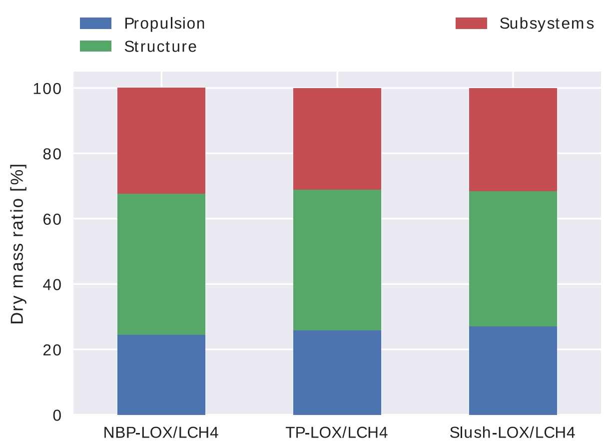

Figure 17: Mass composition of RLV using NBP, near triple point and slush propellant

5 DISCUSSION

While the main metric of comparison for the different launchers has to be the final cost of placing a specific payload into a designated orbit, the estimation of the cost of launcher or technology development programs is a notoriously difficult undertaking with large uncertainties. Since cost estimation is not the focus of this paper, the launcher mass is taken as a substitute metric of comparison. While the propellant mass usually dominates the mass composition, the dry mass contributes far more to the actual cost of liquid-propellant launcher. At least within the RLV-study it is planned to include cost estimation at a later stage of the study.

The following discussion will focus on the comparison of the slush propellants to their NBP counterparts. A comparison of the propellant species is shown in [6] and includes propane as well as hydrogen and methane.

5.1 ELV

The results shown in Table 4 are clearly disappointing. Developing a new fuel technology in order to increase the payload by a small fraction does not appear to be an attractive investment. Yet some secondary advantages might yield interesting benefits for more specific use cases: The target orbit for the hydrogen reference ELV was a direct insertion into GTO with a comparatively short mission time. For other orbits, such as MEO (Medium Earth Orbit), the upper stage has to perform multiple burns and keep the propellant in a useable state for a longer period of time. Since the slush mixture can absorb far larger quantities of heat than the NBP-liquid before evaporating, this might provide a sizable performance increase for these types of missions or even enable missions that might not be possible otherwise.

Two main reasons were identified as drivers for the low performance gain. Firstly, only a small fraction of the loaded propellant was actually densified: the fuel for the upper stage. While this would make the actual implementation easier, it leads to a smaller impact on the performance.

The second reason is related to the constraints imposed on this case: The reference launcher dictates a lot of parameters that constrain the possible payload gains: engine thrust, stage diameter, tank pressurization etc. The change of these parameters would allow for larger performance gains for slush propellants. But then the undertaking can the no longer be classified as a small modification of the stage but has to be considered a substantial redesign.

5.2 RLV

The dry mass reductions shown in section 4.3 are substantial and are much more promising than the results for the ELV cases.

The reasons for this large impact on RLV are threefold: Firstly, the mission is highly energetic, in addition to delivering the payload to a GTO the first stage has to be decelerated sufficiently to safely reenter the atmosphere and land on a barge. To put it simply, the first stage dry mass has to be accelerated and then decelerated again, so any dry mass savings lead to a twofold performance improvement. Secondly, the two-stage architecture demands high Δv from each stage in order to even reach orbit and even for ELV it has been shown that more energetic missions benefit particularly from propellant densification [13]. Thirdly, both fuel and oxidizer were assumed to be slush for both stages so that the entire vehicle was affected, not only a portion of the upper stage as for the ELV's.
About half of the possible benefits of slush propellant could also be achieved while remaining in the liquid phase and cooling the propellants down close to the triple point. While it simplifies the propellant handling within the rocket, a prior study has shown that it might impact the filling procedure and infrastructure even more than slush propellants [14]. However, if the filling procedure can be adapted, the changes necessary for the rocket will be minimal so that the effort-benefit-ratio might be better for the triple point liquid than for the slush mixture.

Compared to the findings in [5], the identified mass reductions of this study are lower. This can be caused by the fact that for these earlier launcher designs the entire dry mass fraction was scaled with the bulk density of the propellants while here the subsystems where evaluated individually and the structure benefitted the most from the densification.

6. CONCLUSION

Within the paper, possible benefits of slush propellants for different use cases are shown and impacts on the propellant supply system discussed.
The cases involving the modification of existing designs in order to accommodate a slush fuel in the upper stage result in small performance increases. The cases involving a resizing of the entire launcher in order to achieve a specific payload show that the dry mass of the affected stages can be reduced by up to 27 % and 30% for LOX/LH2 and LOX/LCH4 respectively. However, these benefits can only be reached if the entire stage design is optimized around the new propellant properties, simply modifying an existing stage will not necessarily lead to similar results.

While not all complications of densified propellants are solved in their entirety at this point in time, the potential for the improvement of future launch systems is substantial enough to warrant future investigation.

Acknowledgement
The present study was supported by ESA in the framework of the TRP "PREDICT".

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