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Configuration Design Studies of a LOX-LCH4 Booster Engine and Stage for a Futuristic Indian Launcher

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Abstract

Emergence of successful private space agencies has triggered a wave of changes in the global space industry in the recent days. Launcher configuration design is shifting from the historically used “most efficient” configurations to recently evolved “most effective” configurations. The current work details the theoretical study conducted in line with these global trends with an aim to configure the propulsion system to be used in all future Indian rockets. Inhouse developed Integrated Stage Cycle Analysis (ISCA) code was used for deriving the configuration and understanding the sensitivity of launcher payload to changes in various system parameters. Effect of introducing novel concepts like self-electric powering of stages and smart hybrid tank pressurisation system on payload are also explored.

1. Introduction

A wave of changes triggered by the emergence of successful private space launch provider agencies is sweeping across the global space industry. Heritage based selection of system parameters and design methodologies for development of new launch vehicles are being supplemented by novel ideas and bold decisions on launch vehicle configurations. While the space agencies are shifting over from the historical "most efficient" designs to the rather novel "most effective" designs, configuration design studies on futuristic launch vehicle gains more importance. The study reported herewith attempts to configure a high thrust liquid rocket engine and booster stages using a set of novel software tools developed to bridge the gap between the historically used launcher configuration tools and the current level of technological advancements.

All recent global developments in rocketry aims at reducing the cost of access to space by adopting frugal design and concurrent design concepts right from the configuration design phase. Often the costliest affair in the development of new launcher is the development of propulsion systems and associated sub-systems. Vehicle level standardisation of propulsion systems, judicious selection of sub-systems and finalisation of system parameters with an eye on vehicle level payload optimisation are sure to help in reducing the development cost of the launcher.

The study detailed in this paper details the configuration design of a propulsion system for use in future Indian launchers. The study was carried out using an inhouse developed code called ISCA which combines the propulsion system parameters and mission parameters in a concurrent mode. The propulsion system configuration is arrived after a series of sensitivity studies wherein the sensitivity of vehicle payload capacity to changes in various propulsion system parameters are derived and analysed. The interdependency of the engine and stage parameters are modelled into the code along with mission constraints like the restricted landmass constraints which are specific to the Indian space port, Shriharikota. The current paper gives an insight into the study and the results obtained thereof.

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2. Problem definition

The study being detailed is aimed at arriving at a suitable configuration for propulsion system to be used for future launcher of India. The propulsion system under study should cater to the requirements of both booster stages and upper stages, so that vehicle level standardisation of propulsion system is feasible. This would help reduce the overall cost of development of the vehicle and would also increase the reliability of the vehicle level propulsion system in general. The configuration of engine should ensure that it is clustering friendly by being self-sufficient in generating the additional resources that it would demand from the stage systems while being clustered. The stage sub-systems on the other hand shall be configured such that the concept of clustering could be employed to meet the requirements of different stages of the rocket. This feature would ensure that the launcher is configured with lesser type of sub-system while the number of each type per launcher increases, enhancing the industry friendliness of the launcher. Finally, once a suitable configuration is derived, the major parameters of the stage and engine systems shall be finalised based on payload sensitivity analysis.

3. Literature survey

Launch vehicle design is a multidisciplinary activity with the requirement of optimally configuring mutually interacting sub-systems. Achieving launcher level optimality is a challenge that requires multiple teams working in union. Configuration design plays the key role in deciding the success of a launcher, especially in a commercially competitive market. With changing tides, the rocket designers are currently focused on developing low-cost access to space through various methods ranging from use of cheaper propellant and other materials to recovery and reuse of rocket systems. A quick look at different launchers proposed to be launched in the market by the end of this decade reveals commonality in the chosen propellant combination, configuration design and sub-system selection. Literature on Ariane Next [1] and public domain information on Amur/Souyz7, Starship and Zhuque-2 all reveals a common affinity towards the use of LOX-LCH4 propellant combination, recovery-based launcher configuration design and selection of simple, easy to realise sub-systems.

3.1 Propellant combinations selection

LOX-LCH4 seems to be the most preferred propellant combinations for future launch vehicles owing to its attractive advantages in terms of system simplicity with respect to LOX-LH2 and better performance with respect to LOX-RP1 combination. Overall launch vehicle cost estimation studied carried out by Hilda Vernin et al. [2] clearly points out the cost effectiveness of LOX-LCH4 launchers in comparison to LOX-LH2 based launchers. In fact the study highlights the fact that the complex nature of LOX-LH2 based system leads to over 45% higher cost at launcher level in comparison to all other combinations studied. This clearly ascertains the fact that the most efficient may not always be the best. Studies carried out by Holkar Burkhardt et al. [3] summarises the merits and de-merits of using LOX-LCH4 in rockets engines compared to LOX-Kerosene combination. Though both combinations are identical in performance while accounting for the counteracting effects of Specific impulse (Isp) and Stage Structural Factor (SF), LOX-LCH4 would be a much better choice for launchers with recovery and reuse strategy. The inherent resistance offered by LCH4 against coking and soot-formation reduces the refurbishment cost of engines tremendously. LOX-LCH4 combination hence seems to be the best choice for use in current study.

3.2 Engine operating cycle selection

Literatures on ~1000kN class LOX-LCH4 engine reveals an affinity towards the use of Gas Generator Cycle (GGC). PROMETHUSE [4] engine under development by ESA for Ariane Next vehicle, TQ12 engine developed by Landspace Technology Corporation and Archimedes engine proposed for Neturon launcher from Rocket Labs Inc. are all 1000kN class LOX-LCH4 engine being developed globally. All these engines are proposed around GGC. This is an obvious choice given the simplicity and designing and developing a GGC based engine in comparison to others. It may also be noted that LOX-LCH4 engines being designed to produce more than 1500kN thrust are configure with other cycles owing to the higher losses in GGC at higher chamber pressures. It is imperative that GGC be used for the current study as the aim of the study is to configure an engine that could be developed and used at ease and at lower cost.

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3.3 Software tools for propulsion system configuration studies

Most rocket engines under development globally are being optimized for performance, cost and reliability. Many tools are being developed for configuring engines that confirms to the aforementioned requirements. Tools developed by Sciorelli et al. [5] and J. E. Bradford et al. [6] comes close to the methodology being followed for the current study. In both these papers the sensitivity of launcher payload capability to changes in propulsion system parameters are studied. REDTOP-2 software by John Bradford et al. [7] is capable of predicting the engine mass and expected cost along with performance parameters. REDTOP-2 is equipped with flow path characteristic analysis and turbomachinery power balance analysis which enables it to be used for sensitivity analysis of engine performance parameters to changes in sub-system parameters, though only to a limited extend. The use of the above tools is limited mostly to the prediction of engine performance or stage level performance at most.

3.4 Launch vehicle configuration design and analysis tools

Literature survey also revealed the development of a few tools that are capable of carrying out launcher vehicle configuration design and optimisation. A multidisciplinary tool, capable of optimising launcher payload mass to launch cost ratio was developed by Robert Le Moyne [8]. It uses historical data in combination with fundamental analytical techniques to derive the output. In an impressive work by R.D. Braun et al. [9], the vehicle configuration problem was decomposed into a number of subspace optimization problems that are driven towards interdisciplinary compatibility and solution by a system-level coordination process. Both these tools concentrate more on the launch vehicle configuration analysis part and propulsion systems analysis remains at the basic parametric estimation level. A comprehensive tool capable of combining the engine cycle analysis, stage level parametric estimation and basic mission analysis as reported by Vishak et. al. [10] is used for the current study.

With inputs from the literature survey, it is obvious that an all LOX-LCH4 vehicle with 1000kN class GGC based engine used in the clustered configuration will be the ideal choice for a futuristic launcher. The current study is hence based on a reference rocket conforming to these characteristics.

4. Reference rocket configuration derivation

A hypothetical reference rocket configuration was derived using staging optimisation program. The vehicle configured is capable of delivering 6t of payload to GTO when launched from Shriharikota, the space port of India. A four-stage configuration was chosen with the first three stages using the same propulsion system elements with and without clustering. The terminal stage is a small stage with exclusive propulsion system components. The configuration of the reference rocket is provided in Table 1.

Table 1: Reference rocket configuration

Stage / Structure	Total Imp. (kN.s)	Total Mass (kg)	Propellant Loading (kg)
Stage-1	1136292	413267	351000
Stage-2	408165	136128	120600
Stage-3	169307	57891	50025
Stage-4	24296	8746	7077
Payload Fairing	-	2000	-
Payload Adaptor	-	500	-
Payload	-	6000	-
Gross Lift-off Mass		**624532 kg**	

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Staging optimisation algorithms takes in user provided inputs like stage Isp and SF. For the initial run of staging optimisation, these values were assumed from historical data. It may be kept in mind that Isp and SF both depends upon many factors including the stage propellant loading and overall envelop. Any error in the assumed values of Isp and SF could lead to non-realistic vehicle configurations. Staging optimisation was hence carried out in an iterative manner to arrive at a realistic configuration. The output provided by the staging optimisation code was used to derive a more realistic Isp and SF which were then provided as feedback to the staging optimisation code for arriving at a better solution. The reference rocket configuration provided in Table 1 is hence a realistic configuration.

5. Configuration design of the engine

ISCA code was extensively used for estimating the engine performance parameters and carrying out payload sensitivity analysis. Major focus was provided on making the engine clustering friendly while meeting the performance requirements.

5.1 Making engine clustering friendly

Clustering of engines is used extensively in the modern-day rockets. Each engine of a cluster demands some additional resources from the stage other than the propellant being consumed for generating thrust. An engine can be called clustering friendly if it is self-sufficient in generating these additional resources making the whole process of clustering hassle free from this point of view. The two major resources additionally demanded by each engine are,

1. Additional mass flow of tank pressurant to compensate for additional propellant drawn
2. Additional electrical power to power the engine actuators and control system

The current engine is configured with the ability to supply tank pressurisation gas in the autogenous mode. LCH4 in the supercritical, superheated condition is proposed to be tapped from the regenerative cooling passage for this purpose as shown in Figure 1. Required amount of LOX on the other hand is proposed to be tapped from the downstream of LOX pump, used for regeneratively cooling the gas generator (GG) prior to admitting to LOX tank for pressurisation.

The LCH4 while being tapped from the regenerative cooling passage possess very high energy in the form of fluid pressure and heat. This energy is proposed to be tapped by driving a gas turbine prior to injecting it into the tank. The turbine in turn could be connected to an electric power generator. The concept is also illustrated in Figure-1. Detailed studies as reported by Kiran Mohan et. al. [11] ascertains the theoretical possibility of implementing such a scheme.

5.2 Engine Cycle Description

The engine under consideration is a 1000kN class LOX-LCH4 engine working on GG cycle. Configuration studies on the engine along with sensitivity study on payload sensitivity with respect to change in engine parameters are reported by Kiran et. al. [11]. The salient features of the engine are described in this section for reference.

The chamber pressure of the engine is finalised to 120 bar(a) from both payload sensitivity study and from thermal constrains arising from the regenerative cooling channel configuration. The engine is proposed to be regeneratively cooled with film cooling augmentation up to the sea level area ratio (AR) of 28. The nozzle extension that will be added for vacuum version engine will be radiatively cooled and is proposed to be developed with thermal barrier nozzle interior coating. The engine is configured with independent turbo-pumps running at 13 000 rpm (LOX) and 27 000 rpm (LCH4). Thrust control is proposed to be achieved by controlling the propellant flow to the gas generator while mixture ratio (MR) control is proposed to be achieved by controlling the LOX flow with respect to LCH4 measured flow.

Figure 1 provides the basic fluid schematic of the engine used for study. To make engine clustering friendly LOX and LCH4 are tapped from within the engine and are throttled down to the tank pressures and are used for propellant tank pressurisation. This mode is used to satisfy major requirements of tank pressurisation. LCH4 tapped from regenerative cooling passage is also used to generate electrical power which can satisfy the electrical powering requirements of the engine making the engine electrically self-sufficient.

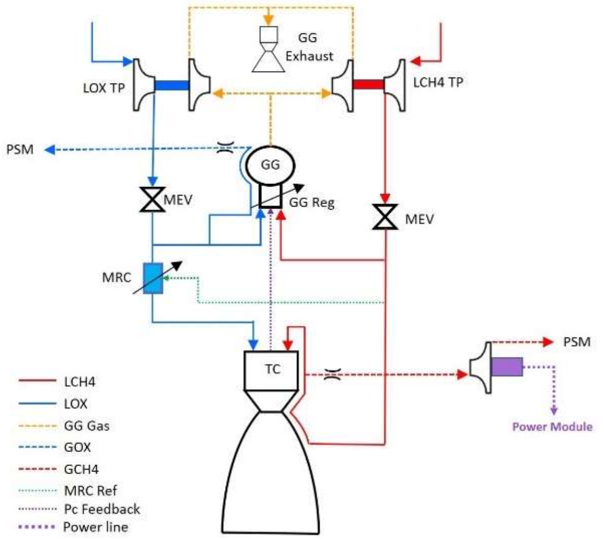

Figure 1: Engine cycle schematic

5.3 Engine working parameters

Table 2 provides the major engine working parameters as reported by Kiran et. al. [11]. All the working parameters and performance indices provided in the table has been arrived after conducting all required theoretical feasibility studies and payload sensitivity analysis using ISCA code. The mass of the engine is derived from historical data for engines of similar thrust and construction. The formulation and computational tool reported by Kiran et. al. [12] is used for generating the engine mass data.

Table 2: Engine working parameters

Sl. No.	**Parameter**	**Unit**	**Value**	
			Vac. Ver.	**Sea Level Ver.**
1	Operating Cycle	-	GGC	GGC
2	Thrust (Vac.)	kN	1000	940
3	Chamber Pressure	bar	120	120
4	Expected Isp (Vac.)	s	337	318
5	Mass Flow Rate	kg/s	302.5	302.5
6	Area Ratio	-	66	28
7	Mixture Ratio	-	3.5	3.5
8	Nozzle Exit Dia.	m	2.00	1.30
9	Engine Mass	kg	1300	950

6. Configuration design of the stage

To the extent possible, the stages of the launcher shall be standardised and derived from the same pool of propulsion elements. The engine is already configured for being clustering friendly, thus reducing the complexity in standardising different stages of the launch vehicle. The vehicle under consideration has four stages of which the first three stages are expected to be configured using a common pool of propulsion sub-systems. The total impulse requirement to be met by each stage and the overall mass it has to propel is provided in Table 3. Table 3 also provides the number of 1000 kN class engine required to be clustered in each stage to meet the thrust requirements.

Table 3: Requirements to be me by lower stages

Stage	**Total Imp. (kN.s)**	**Total Mass to be Propelled (kg)**	**Thrust to be Generated (kN)**	**No. of Engines Required**
Stage-1	1136292	624532	~ 7600	9
Stage-2	408165	211265	~ 2000	2
Stage-3	169307	73137	~ 1000	1

6.1 Understanding the sensitivity of payload on changes in stage structural factor

The payload of launcher depends heavily on the stage structural factor. A study was done to understand the sensitivity of payload in the present launcher to the change in structural factor of the various stages. The sensitivity plot for Stage-1 is provided in Figure 2 as a sample data.

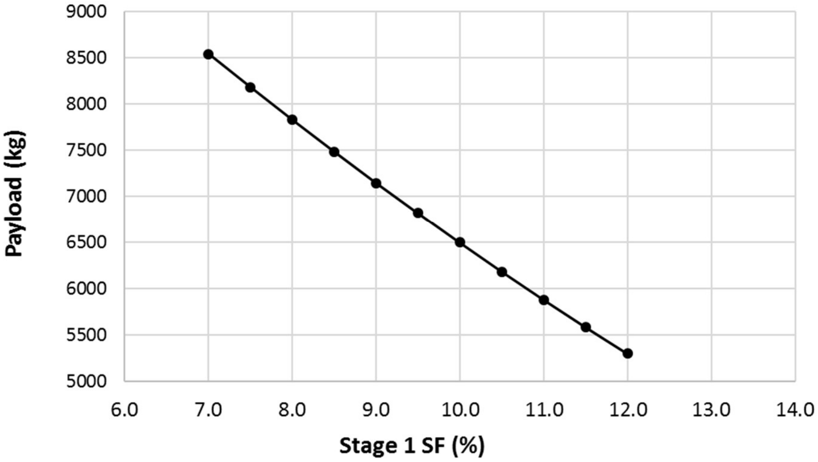

Figure 2: Payload sensitivity to change in Stage-1 SF

From this analysis a range of structural factors to be met by stage engineering for each stage is derived and is provided in Table 4. Meeting these structural factor range is essential for obtaining the desired vehicle level payload capability.

Table 4: Range of stage SF required to be met

Stage	Satge-1	Stage-2	Stage-3
SF range (%)	7.5 - 9.5	8.5 – 10.0	11.0 – 12.0

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6.2 Deriving propellant tank construction

The selection of propellant tank construction depends up on quite a number of parameters. Tanks could be designed to be independent tanks or tank with common bulkhead (CBH) where a single tank is used with a common bulk head acts as a partition between LOX and LCH4. CBH tank itself could be designed to resist reverse buckling (CBH RBR) or the reverse buckling possibility could be avoided by maintaining appropriate positive pressures. Three tanks constructions were studied for their effect on stage structural factors. Sample data for Stage-1 is provided in Table 5 for reference.

Table 5: SF of Stage-1 with different tank constructions

Tank Construction	Independent tanks	CBH tank	CBH-RBR Tank
SF (%)	9.28	8.45	8.76

From the data for Stage-1, provided in Table 5, it is clear that the stage SF requirement of 7.5-9.5% can be met even with independent tanks. This hence becomes the obvious choice given the fact that the aim of the current study is to optimise the development time and effort while meeting the payload requirements rather than trying to maximise the launcher payload capability. Independent tank construction makes the design and development of the tanks much easier and hassle free. Operational requirements of such tanks are also comparably lower and the reliability of the system also improves with this selection.

6.3 Deriving propellant tank diameter

Assuming no constraints exists from launch pad and other vehicle sub-systems, a study was conducted to assess the best possible tank diameter. The requirement of standardisation of stages can be effective only if the tankages and associated system can also be standardised to the extent possible. It was hence decided to keep the tank configurations to be same for all stages by using the same tank dome for all stages and varying the tank shell length to meet the propellant loading requirements. Figure 3 provides the graphical representation of the data obtained from this study for the Stage-1 propellant tanks. The mass of the tanks is plotted against the tank diameter. It may be noted that the tank mass decreases with increase in tank diameter to some extend and then it starts increasing. The reversal point corresponds to the tank diameter where the length of the propellant tank shell becomes zero and the tank assumes a near spherical shape. Above this point if the tank diameter is increased, the propellant fill fraction of the tank would drop which is not desirable. Table 6 shows gives the tabulation of the maximum diameters to which different stage tanks could be designed without decreasing the tank fill fraction below 95%.

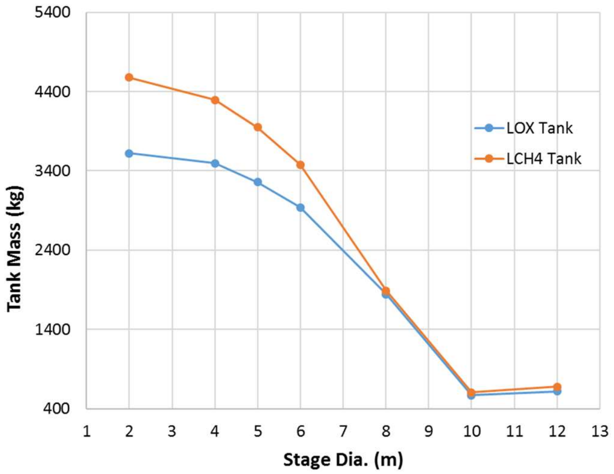

Figure 3: Stage diameter Vs Tank Mass for Stage-1

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Table 6: Maximum tank diameter for each stage

Stage	Satge-1	Stage-2	Stage-3
Max. tank diameter (m)	10.3	8.2	5.5

From Table 6 it is clear that the preferred core diameter of the vehicle would be 5.5m wherein the stage-3 will have propellant tank without cylindrical shell. An assessment of the payload sensitivity of the core vehicle diameter was also carried out and the result obtained is provided in Figure 4. It is observed that despite the reduction in propellant fill fraction of stage-3 tanks, the payload improves with increase in vehicle core diameter. The effect of increased tank mass of stage-3 is getting negated by the improvement in tank mass of stage-1 and stage-2. However, the increase in only marginal after 5.5m core diameter and hence can be neglected.

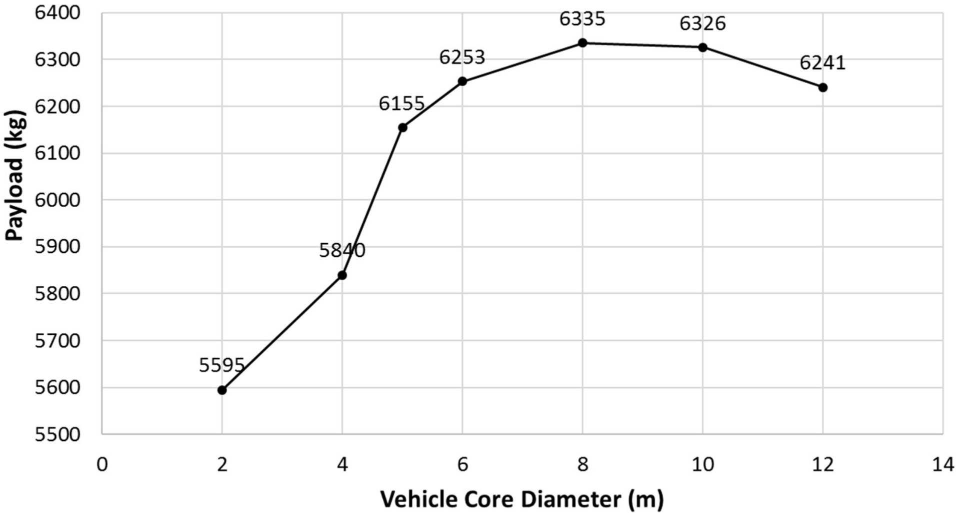

Figure 4: Sensitivity of payload to variation in vehicle core diameter

6.4 Selection of propellant storage temperature

A study was also carried out to see the effect of sub-cooling of the LOX and LCH4 on payload capability through reduction in propellant tank mass. This was studied with respect to sub-cooling of LOX alone as temperature band at which LCH4 remains as a liquid is narrow and the variation in density of LCH4 is not as appreciable in this narrow band as in case of LOX. Figure 5 provides the improvement in payload with sub-cooling of LOX. The payload advantage observed is in fact the cumulative advantage from tank mass reduction and engine Isp improvement with LOX sub-cooling.

The data obtained from the study suggests that a cumulative advantage of 200kg in payload can be gained by sub-cooling LOX to 70K from 90K. It was decided to carry out the current studies with 90K as in theory the required payload could be achieved even with 90K propellant temperature. Also, the process of sub-cooling could be easily employed at a later stage of vehicle development to compensate for payload reduction due to any other reason or to improve payload if found necessary at a later stage.

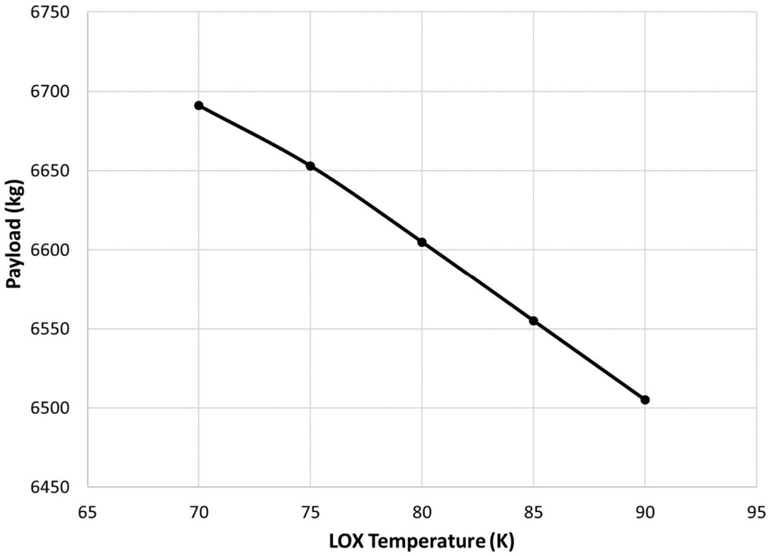

Figure 5: Effect of propellant storage temperature on payload

6.5 Tank pressurisation system configuration

Tank pressurisation system configuration plays a major role in deciding the structural factor of the stage. The mass of pressurant gas to be stored, the mode of pressurisation to be used etc. is to be finalised before finalising the stage level configurations. Four modes of tank pressurisation scheme were studied in detail for use in the current work.

a) Cold Gas Pressurisation System (CGPS) where GHe stored in high pressure bottles are regulated and used.
b) Autogenous pressurisation for LCH4 and CGPS for LOX tank
c) Both LOX and LCH4 tanks pressurised with autogenous system
d) Hybrid system with autogenous and CGPS working in tandem with each other

A comparative study to estimate the effect of use of each of these systems on stage SF was studied. The results obtained for stage-1 is provided in Table 7. From the data, it is clear that the CGPS and LCH4 autogenous systems alone cannot be used as the stage SF would exceed the requirement of 7.5-9.5%.

Table 7: SF Vs tank pressurisation system

System	CGPS	LCH4 Autogenous	LOX & LCH4 Autogenous	Hybid
Stage-1 SF	9.62	9.54	9.20	9.22

Autogenous system employed for both LOX and LCH4 tanks seems to be the best solution. However, the system will be tougher to engineer as regulating the superheated gas, especially oxygen will be a tough job. Also, variation in the tank pressurisation gas requirements could lead to variation in engine thermal profile also. Hybrid system where a major portion of the tank pressurisation requirements is met by autogenous mode in non-regulated mode and the rest handled by a regulated cold gas system could be an attractive alternative. Later studies showed that the system with 80% pressurant requirements satisfied by autogenous mode and the rest handled by CGPS with GHe as the working fluid will be the best among feasible configurations.

This mode of pressurisation also helps in making the engine and stage cluster friendly. The addition of an engine by itself satisfy 80% of the additional resource demanded by the engine with regard to tank pressurisation. The CGPS modules can be designed with a coarse regulator followed by a solenoid valve commanded to meet the engine inlet pressure requirements. The module is proposed to be designed to meet the flow requirements of the stage-3. The same shall be used in clustered mode for stage-1 and stage-2 with an appropriate valve ON/OFF control algorithm. The use

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of engine inlet pressure as the feedback in place of generally used tank pressure feedback is expected to make the system standardised for use in different stages with different engine inlet pressure requirements. A general schematic of the Smart Auxiliary Pressurisation System is provided in Figure 6 for reference.

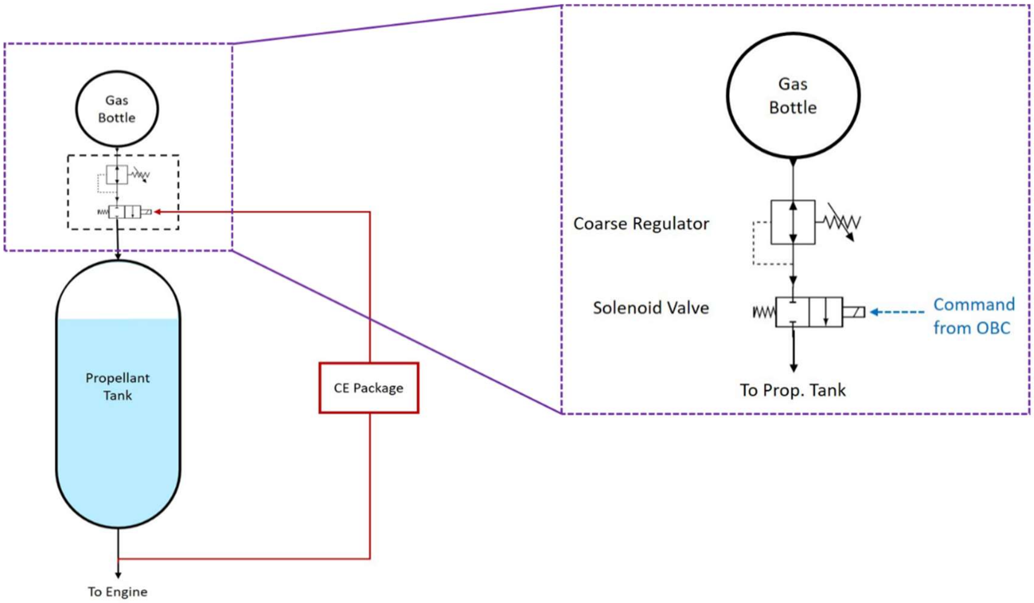

Figure 6: Schematic of smart auxiliary pressurisation system

6.6 Overall stage configuration

Figure 7 provides an overall stage fluid schematic as derived in the present study.

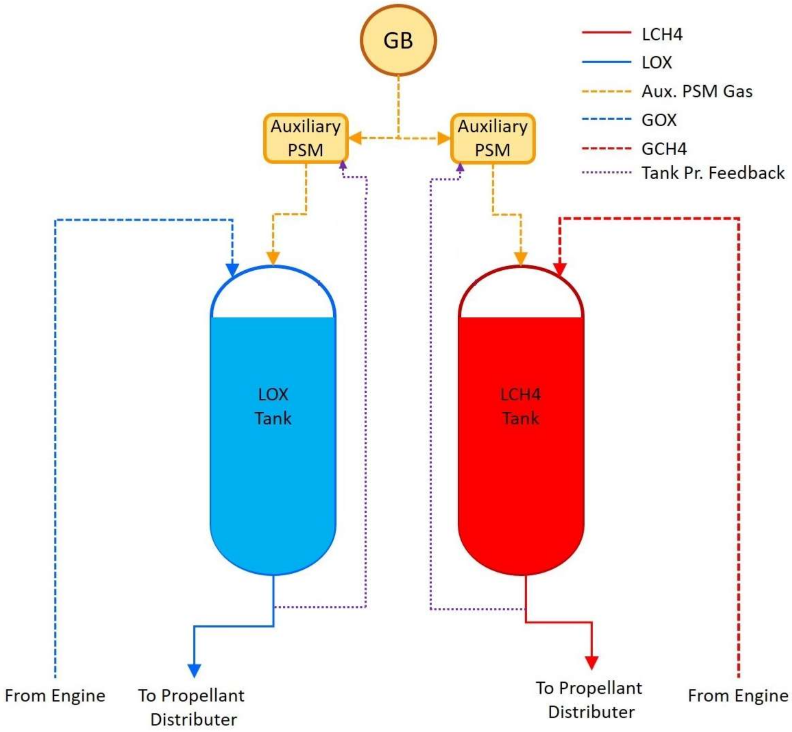

Figure 7: Stage fluid schematic

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7. Conclusion

A LOX-LCH4 based propulsion system was configured using inhouse generate software tools. Through detailed configuration studies a 1000kN class engine and various stage configurations were derived with emphasis on vehicle level standardisation of propulsion system elements. Novel concepts like hybrid propellant tank pressurisation with autogenous mode of pressurisation augmented with electronically controlled auxiliary cold gas system and proposal for self-electric powering of the stage during the thrusting phase are introduced in line with the concept of vehicle level propulsion system standardisation. The sensitivity of launcher payload capability to changes in various stage parameters was also mapped and used to determine the parameters to be critically followed up. These parameters were then iterated in combinations to arrive at a feasible solution were the payload requirements of the launcher could be met with the lowest development and realisation challenges.

References

[1] A. Patureau de Mirand, J.-M. Bahu, O. Gogdet, Ariane Next, a vision for the next generation of Ariane Launchers, Acta Astronautica, https://doi.org/10.1016/j.actaastro.2020.02.003

[2] Hilda Vernin and Pascal Pempie (2009). LOX/CH4 and LOX/LH2 Heavy Launch Vehicle comparison, AIAA 2009-5133.

[3] Holger Burkhardt et al. (2002). Comparative study of kerosene and methane propellant engines for reusable liquid booster stages. In 4th International Conference on Launcher Technology "Space Launcher Liquid Propulsion".

[4] P.Simontacchi et al. (2019), PROMETHEUS: Precursor of new low-cost rocket engine family. DOI: 10.13009/EUCASS2019-743

[5] Sciorelli, F., Jones, M., and Forde, S., "Collaborative propulsion system analysis tool for pump-fed liquid rocket engines," Proc. of the 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Tucson, Arizona, AIAA, (2005).

[6] J. E. Bradford et al. (2004), REDTOP-2: Rocket Engine Design Tool Featuring Engine Performance, Weight, Cost, and Reliability. AIAA-2004-3514

[7] Bradford, J., Charania, A., and Germain, B. S., "Redtop-2: Rocket engine design tool featuring engine performance, weight, cost, and reliability," Proc. of the 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Fort Lauderdale, Florida,AIAA, (2004).

[8] LeMoyne, R., "Multidisciplinary cost and performance optimization of a two-stage liquid propulsion-based launch vehicle," Proceedings of the 15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Dayton, USA, AIAA, (2008).

[9] Braun, R. D., Moore, A. A., and Kroo, I. M., "Collaborative approach to launch vehicle design," Journal of Spacecraft and Rockets, 34(4), pp. 478–486, (1997).

[10] Vishak Sasidharan, Kiran Mohan, Fahd Bin Abdul Hasis, Nandakumar V., Suresh Kumar C., and Jayan N., "Integrated Stage Cycle Analysis of all LOX-LCH4 Indian Micro-Launcher", 7th Thermal and Fluids Engineering Conference (TFEC), partially online virtual and in Las Vegas Conference, (2022).

[11] Kiran Mohan, Vishak Sasidharan, Fahd B. A. Hasis, Nandakumar V., Suresh Kumar C. and Jayan N., "Configuration studies on a futuristic 1000 kN class LOX-Methane engine", Space Propulsion 2022 Conference, Estoril, Portugal, (2022).

[12] Kiran Mohan, Vishak Sasidharan, Fahd B. A. Hasis, Nandakumar V., Suresh Kumar C. and Jayan N., "Tool for Engine Design (TED): Development, Features and Utility", Space Propulsion 2022 Conference, Estoril, Portugal, (2022).