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Configuration Studies on An Electric Pump Fed Upper Stage Rocket Engine

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Abstract

Electric Pump Fed Cycle (EPFC) based rocket engine is a novel addition to the rocket engine family. Simplicity and ease in control are the major attractions of EPFC, while the limitation in thrust achievable with the current level of maturity in battery and electric motor technologies poses a great disadvantage. The current paper details the configuration studies carried out on an EPFC based LOX-LCH4 engine. This engine is configured to be used in the upper stage of a futuristic micro-launcher with payload capability of 500kg payload to 500km Low Earth Orbit. The sensitivity of various sub-system parameters like chamber pressure, propellant temperature, battery type etc. with payload mass is studied using an in-house developed tool – Integrated Stage Cycle Analysis (ISCA) tool. Various advantages and specific constraints to be met while configuring such engines are also detailed.

1. Introduction

With the onset of commercialisation in launch vehicle industry, rocket designers have been experimenting to develop the most cost-effective method for space transportation. Among this array of new developments, Electric Pump Fed Cycle (EPFC) based rocket engine stands out. The use of electric motors to drive pumps in EPFC, simplifies the engine architecture significantly in comparison with conventional thermodynamic based cycles. Unlike conventional thermodynamic engine cycles, in EPFC, handling of hot gas in pre-burner and associated systems are totally avoided leading to its simple construction. In addition, the rapid advances in battery and motor technologies worldwide, makes EFPC a promising candidate for the future rocket engines. Though EPFC based rocket engines are simple in nature, limitation in battery and motor technologies constraints the thrust levels that can be generated by these engines. Thus, a judicious look into the merits and demerits of EPFC are warranted to understand the true effectiveness of this engine cycle.

The study being reported is undertaken to arrive at a realisable configuration of a low thrust EPFC based engine to be used in the upper stages of a futuristic micro-launcher. A reference, all solid micro-launcher capable of delivering 500kg payload to 500km Low Earth Orbit was configured using staging optimisation code. The upper stage of this reference rocket was then assumed to be replaced with an equivalent LOX-LCH4 stage powered with an EPFC based engine. The configuration of the engine was studied in detail with assessment of implications of sub-system selection on overall payload capability of the reference vehicle. The sub-system selection process was followed by iterations of system parameters like chamber pressure and propellant storage temperatures to arrive at optimal engine working parameters. The study was carried out using the Integrated Stage Cycle Analysis (ISCA) tool customised for this case. ISCA tool integrates the engine cycle analysis, stage parametric estimations and basic mission studies in a single interactive module.

The present article reports all details of the theoretical studies carried out while configuring the engine under consideration. Various advantages and specific constraints to be met while configuring such engines are also detailed. Finally, a sensitivity analysis of changes in system parameters on the reference rocket payload capability is also brought out.

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2. Literature Survey

EPFC based engines are rather new additions to the global space industry and studies to characterise these engines are being pursued with great interest across the globe. However, the level of maturity attained by the technology itself is low and so are the related studies. Many researchers across the globe however are seriously working on this novel concept in an attempt to understand it better and optimise it further.

Studies published by G. Waxenegger-Wilng et al. [1], explores the feasibility of using EPFC cycle in combination with the conventional liquid propellant combinations like LOX-LH2, LOX-RP1 and LOX-LCH4. This study clearly shows that the Gross Lift-off Mass (GLOM) of launchers fully configured with EPFC based propulsion systems will always be higher than the conventional rockets using GG cycle-based engines. This primarily happens due to the poor specific energy carrying capacity of batteries currently available. The system mass optimisation studies carried out by the team suggested that the overall system mass would be minimised at much lower chamber pressures of the engine in comparison to conventional thermodynamic cycle-based engines.

The methodology of study followed for the current work is basically inspired by the works reported by Juyeon Lee et al. [2] . Their studies clearly showed that the EPFC based engine would be best suited for use in upper stages where the high battery mass of EPFC engine-based stage gets negated by increase in specific impulse and reduction in propellant storage and feed system mass. They also established the fact that EPFC based engines would be a better option than GGC based engines for application in micro launcher upper stages owing to the lower thrust requirements.

Byungil Yu et al. [3] reported a detailed study on the O/F mixture ratio on the performance. The study also dealt with sizing of rockets powered by electric pump fed LOX-LCH4 stages. They also concluded that the system performance improves with a reduction in chamber pressure for any fixed mixture ratio. Their results seem to support the earlier findings that a lower chamber pressure will yield a better stage level performance owing to reduction in battery mass.

Theoretical studies by Kai Dresia et al. [4] and Kajon D et al.[5] were also referred for developing the system pararameter estimation techniques quoted in the current paper. Commercial success of Electron Rocket by Rocket Labs Inc. [6], which is fully powered by electric pump fed Rutherford engine, has proved beyond doubt the usability of electric pump fed rocket stages for profitably launching micro and nano satellites into low earth orbits.

3. Problem Statement

From literature survey, it is well understood that Electric Pump Fed Cycle is beneficial for lower thrust applications in the ranges of 30-40 kN. Thus, these engines will find applications in upper stages of Small Launch Vehicles (SLVs) whose design targets a maximum of 500 kg to 500 km Low Earth Orbit. Though such SLVs are generally configured with all solid stages, replacement of its upper stage with a liquid propellant EPFC engine proves to be beneficial in multiple aspects like increase in payload capability, better accuracy of satellite injection etc. From a re-look into the conventionally used propellant combinations, it is understood that LOX-LCH4 combination would be the most suitable candidate for this application.

The problem statement being dealt in this paper is to configure an EPFC based LOX-LCH4 engine delivering 30kN class thrust levels. Designed engine replaces the final stage of a 3-stage, all solid stages, reference rocket with a payload capability of ~500kg to 500km LEO. Equal mass at lift off constraint is imposed so that the performance of the lower stages remains fairly unaltered while replacing the upper stage with the designed engine. Optimisation of sub-system parameters is carried out based on its effect on overall payload mass.

4. Methodology of Study

The study was carried out to configure an EPFC based engine to suit the specific requirements of a micro launcher upper stage. Hence a reference rocket-based approach was used for the study, wherein an all-solid reference rocket configuration was derived and used for comparative study. The study was formulated as follows,

1. Configure an all-solid reference rocket with suitable inputs
2. Derive a configuration with upper stage of reference rocket replaced with an equivalent LOX-LCH4 stage such that the Gross Lift-off mass (GLOM) of the rocket remains same. This ensures that the lower stages

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performances are standerdise and the change in payload is exclusively due to variation in upper stage performance.
3. Assess the variation in payload with the two configurations derived
4. Vary the parameters of the LOX-LCH4 upper stage engine and assess the sensitivity of launcher payload on the variation in the parameter selected for study.

The sequence of study provided above are meticulously carried out to derive data which are then interpreted to get meaningful outcomes and understanding of the EPFC engine characteristics.

5. Reference Rocket Configuration

The reference rocket configuration for the study was derived using historical data as input to the staging optimisation codes developed inhouse. The configuration is provided in Table-1

Table 1 : Reference Rocket mass budgeting

Stage/Structure	**Str Mass (kg)**	**Prop Mass (kg)**	**Total Mass (kg)**
Stage - 1	15 000	90 000	105 000
Stage - 2	1 450	7 650	9 100
Stage – 3	700	4000	4 700
Payload Fairing	-	500	500
Payload Adapter	-	200	200
Payload	-	-	535
		Gross Lift-Off Mass (GLOM)	**120 035 kg**

Table 1 details the mass budget of the configured reference rocket. The ΔV apportioning of the reference rocket configuration is listed in Table 2.

Table 2 : Ideal ΔV budget for reference rocket

	Stg-1	**Stg-2**	**Stg-3**	**Tot.**	**Req.**	**Losses**
ΔV (km/s)	3.6	2.0	3.6	9.2	8.0	1.2

For the current study then loss in ΔV is assumed to be same for all configurations. This assumption will hold good if no major changes are implemented in vehicle engineering or trajectory design.

6. Configuration of EPFC based engine and stage

Configuration of rocket engines are generally carried out in multiple stages. The first step is to clearly understand the design requirements and identify the constraints for engine design. Based on these data. a baseline configuration of engine and corresponding stage systems shall be carried out. To derive a baseline configuration, an in-house developed, Integrated Stage Cycle Analysis (ISCA) code is used. The configured stage is then used to replace the last stage of the reference rocket and comparison studies of both rockets are carried out. Sensitivity of sub-system parameters are also analysed to optimise the configuration of engine. In this section, the steps carried out for configuration design of the engine under consideration has been detailed.

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6.1 Design Drivers and Assumptions

Cost-effectiveness of launch vehicle is the primary requirement posed to rocket designers in the current scenario. In addition, SLV's generally tends to end up with higher cost per kg of payload due to its lower payload capabilities. From the customer point of view, it would be cheaper for the customer to wait for a larger satellite and piggy-back or ride-share aboard a bigger rocket than hire an exclusive launch. But in case of a piggy-back or a ride-share, the customer will have to wait for another satellite to a similar orbit and this increases the lead time to launch. So, a cost-effective SLV, with similar or lower cost per payload mass compared to larger rockets is the need of the hour. Hence the major design driver for this study for the replacement stage would be cost effectiveness with improvement in payload fraction.

The major assumptions made during the configuration design of stages are as follows:

1. The core vehicle diameter is assumed to be 2m and the engine exit diameter is constrained to 1.2m
2. From thrust to weight studies on upper stage of reference rocket, a thrust level of 30kN is assumed to be adequate for the current application.
3. All tankages are designed using a common-bulk head construction to reduce the structural factor
4. All cryo-systems are assumed to be un-insulated based on preliminary analysis of thermal requirements.
5. Motor and driver electronics are assumed as a single package and motor efficiency is inclusive of any losses incurred through driver electronics.
6. Cooling mechanism for batteries are assumed to be an independent system and no propellant budget has been allocated for the same.
7. Based on market survey on BLDC motors in India, it is understood that maximum power of motor to be limited to 35kW limited by feasibility of harness design.

6.2 Preliminary engine configuration

An EPFC based rocket engine consists of a thrust chamber, propellant pumps driven by electric motors and main ~motors (BLDC). BLDC motors have inherent advantages compared to DC motors in regards to efficiency, control, handling and development easiness. The driver electronics with the BLDC motor enables the motor to be commanded to run at various speeds and torque ratings. This feature enables rocket designers to actively control thrust and Mixture Ratio (MR) by adjusting the speed of pumps assuming independent pump configuration for fuel and oxidiser. Nominal speed for both pumps can also be varied based on the pump efficiency point of view. Thus, in the configuration design of an EPFC engine, LOX and LCH4 pumps can be designed to run at different speeds where over-all stage performance (dictated by the pump efficiency and pump NPSP requirement) becomes optimal.

Unlike conventional thermodynamic cycles-based engine, the chamber pressure achievable in EPFC is limited by motor power limitations. The motor power constraint imposed for the study is a maximum of 35kW and the chamber pressure corresponding to this power rating is also estimated. The preliminary configuration of engine is carried out based on design requirement of delivering 30kN thrust constraining the motor power to a maximum of 35kW and limiting nozzle exit diameter to 1.2m. The major attributes of the configured engine are provided in table 3. Parameters like C* efficiency and Cf efficiencies have been chosen from historic data while parameters like pump and motor efficiencies were derived through theoretical design and CFD studies.

Table 3 Major parameters of EPFC engine after preliminary configuration design

Parameter	Value	
Chamber Pressure	30 bar (a)	
Area Ratio	208	
Vacuum Isp	358 sec	
	LOX	**LCH4**
Pump Speed	12000 rpm	27000 rpm
Pump Efficiency	62%	59%
Motor power	35.02 kW	28.65 kW
Battery power	56.30 kW	43.00 kW

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From table 4, it is understood that a maximum of 30 bar chamber pressure can be development with motor power constraint of 35kW. It may be noted that the maximum chamber pressure attained is lower than the critical pressure of LCH4 (46 bar(a)) hence making regenerative cooling channel flow sub-critical. After carrying out detailed analysis, it was observed that regenerative cooling of thrust chamber with sub-critical LCH4 will not be feasible due to occurrence of 2 phase flow in these passages. Hence, the engine being configured utilises an ablative thrust chamber with 5% film cooling provision. Figure 1 depicts the schematic of the configured EPFC based engine.

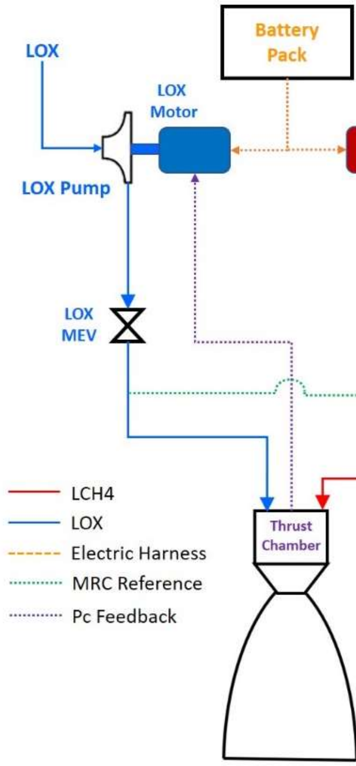

Figure 1 EPFC engine flow schematic

From Figure 1, it may be noted that sensor feedbacks from thrust chamber and downstream of LOX main engine valve provides necessary inputs to driver electronics to control thrust and mixture ratio. In comparison to any conventional cycle, no sub-systems except the thrust chamber is subjected to extreme high temperatures, thus making it simple in construction.

6.3 Preliminary stage configuration

The stage systems are configured such that the GLOM of the reference rocket remains unaltered. This means that the sum of the cumulative mass of stage-3 and payload remains constant or that any reduction in stage mass possible will be accounted as an improvement in payload mass. The inputs used for stage configuration are detailed in table 5.

Table 1 Details of LOX-LCH4 stage for replacement

Parameter	LOX-LCH4 Stage
Propellant Loading	~ 3800 kg
Tank Construction	Common bulk head
Tank Material	AA2219
Tank Pressurisation mode	Cold gas with GHe

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Common bulk-head construction is assumed for propellant tankages. This is easily possible since LOX-LCH4 propellant combination has a similar storage temperature of 90 K for LOX and 100 K for LCH4. Pressurisation system for LOX and LCH4 is configured as a cold based system with GHe for tank pressurisation. Construction of tankages are assumed to be with AA2219 (Aluminium alloy) material. Battery mass, assuming Li-ion battery packs with in-built cooling mechanism, is derived from the total energy requirement and battery energy density. The stage mass and structural factor is derived by the ISCA code using historical data and empirical relations derived from them.

6.4 Integrated Stage Cycle Analysis (ISCA) tool

Integrated Stage Cycle Analysis tool is an in-house developed tool kit combining three aspects of rocket design which are engine cycle analysis, stage parametric analysis and ideal ΔV based payload estimation. The basic architecture of ISCA toolkit is shown in figure 2.

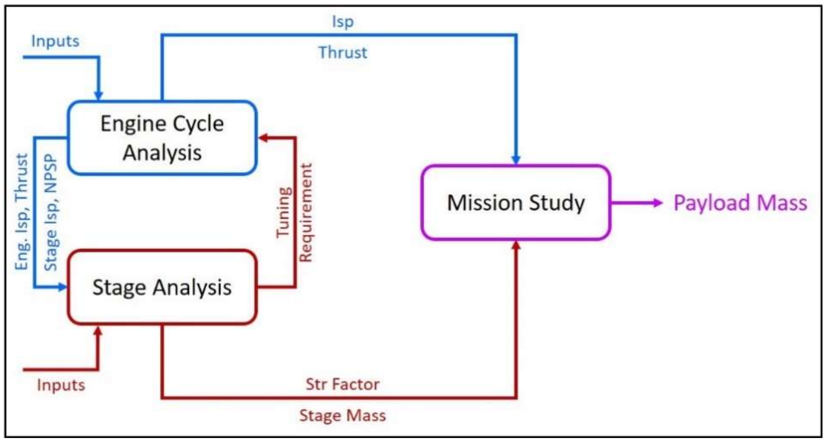

Figure 2 Architecture of integrated stage cycle analysis toolkit.

ISCA code, as reported by Vishak Sasidharan et. al. [7], derives the effect of sub-system parameters on over-all vehicle payload capability and helps in understanding the system interdependencies in a comprehensive way. The code is inbuilt with a host of theoretical equations sets and empirical relations derived from historical data. The tool is also capable of communicating with external open sources codes like codes on combustion chemical equilibriums and fluid property generation codes. This code was extensively used in carrying out the study reported in the current paper.

7. Results and Discussions

The engine configuration studies were taken up in a sequential manner starting with parametric sensitivity study wherein the variation of various engine parameters was studied against the variation in chamber pressure. The engine design space was clearly defined by imposing the feasible motor power constraints. The engine chamber pressure was then fixed using inputs from this study along with the data derived from the study of payload sensitivity to varying engine chamber pressure. The engine configuration was then finalised using the chamber pressure chosen and various performance and operating parameters were compared with the reference rocket and preliminary engine configuration.

7.1 Variation in Engine Isp with Chamber pressure

The engine Isp varies with changes in chamber pressure due to the changes in combustion characteristics as well as the changes in area ratio owing to fixed nozzle exit area constraint posed. With increase in chamber pressure the throat diameter reduces for the fixed thrust leading to an increase in area ratio. The increased area ratio leads to increased Isp along with an additional increase in Isp due to improved combustion characteristics. The variation observed in engine Isp with variation in chamber pressure is provided in Figure 3 provided below.

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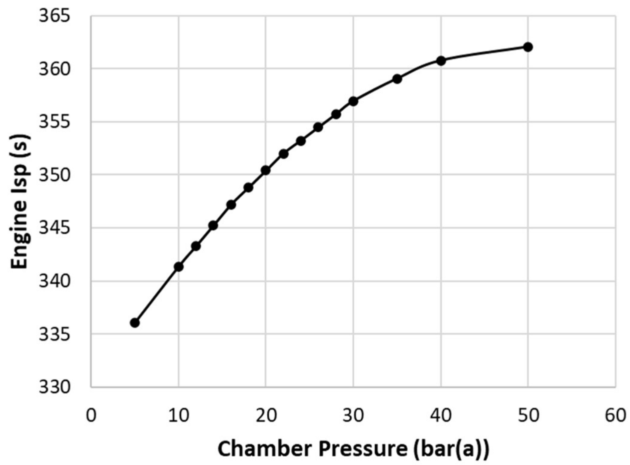

Figure 3 Variation in engine Isp with change in engine chamber pressure.

7.2 Variation in motor power with engine chamber pressure

The power of the pumps used in the engine is expected to increase with increase in chamber pressure owing to the higher head rise requirements. This increase will lead to an increase in the power generated by the BLDC motors. Figure 4 provides the data collected in this regard. The red line in the Figure 4 represents the maximum feasible motor power. From the data it is clear that chamber pressure of more than 30 bar(a) cannot be tolerated from LOX side BLDC motor power constraint point of view.

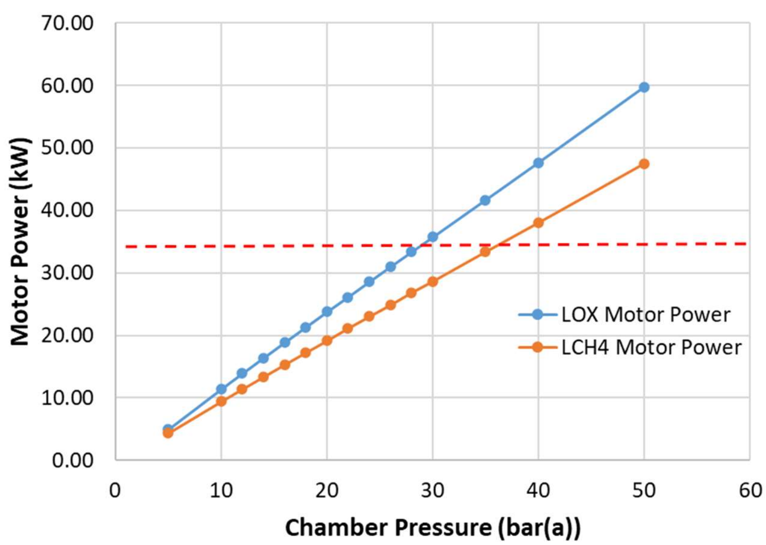

Figure 4 Variation in pump power with change in engine chamber pressure.

7.3 Variation in stage structural factor (SF) with engine chamber pressure

Variation in chamber pressure of the engine is sure to have a profound impact on the SF of the corresponding change in case of EPFC cycle-based stages. Increase in chamber pressure is known to increase the motor power which in turn is sure to increase the battery mass. In case of EPFC cycle the battery, mass will be a significant contributor to the structural mass. The SF data obtained for different conditions of chamber pressure is provided in Figure-5. From the data derived from the study it is evident that in case of stages based on EPFC cycle, battery mass will play a substantial

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role in increasing the stage SF. Development of better and more efficient battery units with high specific power and specific energy carrying capacity is a must for use of EPFC cycle in rocketry.

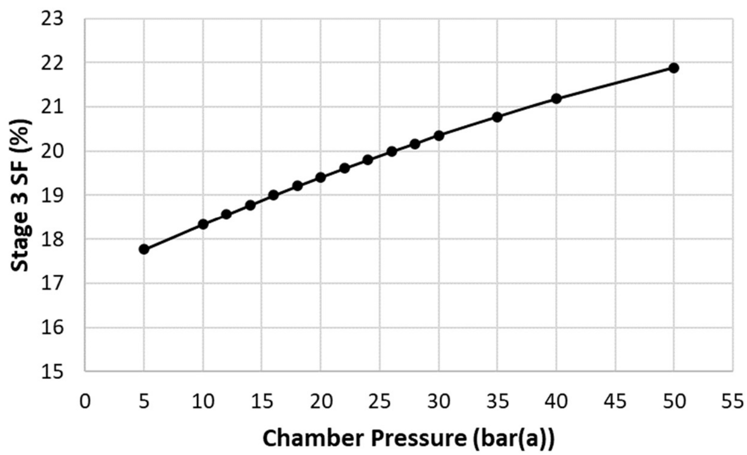

Figure 5 Variation in stage-3 SF with change in engine chamber pressure.

7.4 Selection of engine chamber pressure

The chamber pressure of the engine reported in Table 3 was chosen such that the motor power does not exceed 35kW which is the maximum achievable value. This was chosen as the starting point of the design iterations as in conventional liquid rocket engines running on closed cycles with no propellant loss, the engine performance improves with increasing chamber pressure. The effect of increasing chamber pressure on then overall payload capacity of the launcher was studied with ISCA code and results in line with the literature predictions were obtained. The data derived in this study is provided in Figure 6.

The data obtained from the study clearly shows the distinct trend in payload vs chamber pressure curve as predicted by literature. The payload increases as chamber pressure increases from 5 bar(a) to around 20 bar(a) and then starts to show a drooping trend. This behaviour can be explained to be the combined effect of Isp and stage SF variations with chamber pressure as depicted in Figure 3 and 5 respectively. This behaviour is peculiar to the electric pump fed cycle and needs to be looked into in detail for better understanding. From the data provided in the above figure, it is evident that the range of chamber pressures best suited for the present engine is 18-22 bar(a). All configuration reported henceforth has been derive assuming 22 bar(a) as the chamber pressure to be conservative on the motor power and such aspects.

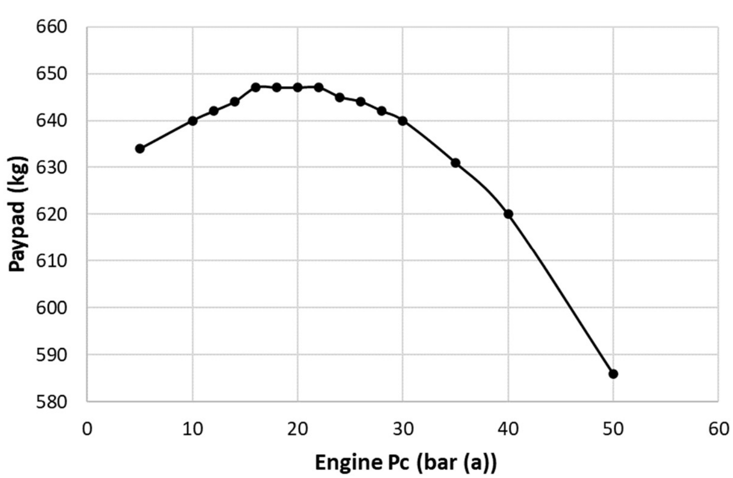

Figure 6 Variation in payload with change in engine chamber pressure.

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7.5 Comparison of finalised rocket with reference rocket

Table 6 provides a general comparison between the SLV with EPFC based upper stage and the reference all solid rocket. For the same GLOM an improvement of 110 kg is obtained in payload which is substantial for micro-launchers. EPFC based upper stage is hence an attractive proposal for future micro-launchers.

Table 6 : Comparison of EPFC upper stage rocket with reference rocket

Stage/Structure	**Reference Rocket Mass (kg)**	**EPFC Based Upper Stage Configuration Mass (kg)**
Stage - 1	105 000	105 000
Stage - 2	9 100	9 100
Stage – 3	4 700	4 590
Payload Fairing	500	500
Payload Adapter	200	200
Payload	535	645
GLOM	**120 035 kg**	**120 035 kg**

7.6 Comparison of finalised engine parameters with engine derived during preliminary studies

The finalised engine configuration details as compared to the preliminary configuration is provided in Table 7. As predicted by literature, EPFC cycle-based engine gives better payload with lower chamber pressures. Hence such engines are more suitable for upper stages with low thrust requirements.

Table 7 : Comparison of engine parameters between preliminary configuration and finalised configuration

Parameter	**Preliminary Configuration**		**Finalised Configuration**	
Chamber Pressure	30 bar (a)		22 bar (a)	
Area Ratio	208		151	
Vacuum Isp	358 sec		352 sec	
	LOX	**LCH4**	**LOX**	**LCH4**
Pump Speed	12000 rpm	27000 rpm	12000 rpm	27000 rpm
Pump Efficiency	62 %	59 %	54 %	52 %
Motor power	35.02 kW	28.65 kW	27.45 kW	21.13 kW
Battery power	56.30 kW	43.00 kW	41.18 kW	31.69 kW

8. Conclusions

An EPFC based engine capable of producing 30 kN thrust is configured using inhouse developed codes. The engine parameters are optimised to obtain the maximum payload while used as an upper stage engine. The study confirms the fact that EPFC based engines provide better payload while configured with lower chamber pressures. This is primarily because of the increase in stage SF, on account of increasing battery mass, negating the corresponding improvement in Isp due to increase in chamber pressure. EPFC based engines are hence best suited for use in upper stages with low thrust requirements. The operating parameters of the engine and the design space available are heavily constrained by the power of the BLDC motors that can be realised with the current industrial capabilities and may improve in near future.

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