Numerical Analysis of Electric Pump Feed System for Upper-Stage Rocket

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ABSTRACT

Due to advancements in battery technologies, electric propellant feed systems became an alternative to Gas pressure and Turbo-pump propellant feed systems in liquid rocket applications. For longer burn times, low thrust, and low chamber pressures, the Electric feed system offers reliable mass savings compared to Turbo-pumps and Pressure feed systems. Electric pump-fed propellant feed system provides cost savings and a simple design due to the elimination of high-temperature gas flow used in turbo-pumps. This paper addresses the power and energy requirements calculations for motors, pumps, and batteries. A maximum thrust of 25 kN is considered for the second stage rocket with minimum exit velocity of 2900 m/s and maximum exit velocity of 4500 m/s. The second stage of the rocket uses LO_2 *(Liquid Oxygen) and* LH_2 *(Liquid Hydrogen) as fuels. Two cases are considered to transfer the power from electric motors to pumps and are compared for weight, power, and energy requirements. In one case, two electric motors are considered to run two pumps, one for* LO_2 *and one for* LH_2*. In the second case, a single motor with a gearbox is considered to operate the two pumps at different speeds.*

Keywords: *Electric pump-fed propellant feed systems, Turbo-pumps, Gas pressure propellant feed system, Thrust.*

INTRODUCTION

In Liquid Rocket Engines feed systems are essential to supply the propellant from tanks to the combustion chamber. The propellant feed systems are classified as pressure-fed system, Turbopump feed system and electric-pump fed system. Due to weight constraints in rocket, it becomes necessary to choose a feed system which offers good performance with less weight.

Gas Pressure Feed System

Gas pressure feed system is based on a simple concept of pressurizing the propellants by applying force with high pressure gas forcing it out of respective tanks. Gas is fed into the propellant tanks at a controlled pressure, thereby giving a controlled propellant discharge. Gas Pressure feed system consists of a high-pressure gas tank, a gas starting valve, a pressure regulator, propellant tanks, propellant valves, and feed lines and some additional components like filling and draining provisions, check valves, filters, flexible elastic bladders for separating the liquid from the pressurizing gas, and pressure sensors or gauges.

After filling the fuel tank and the oxidizer tank, the high-pressure gas feed valve is actuated and the pressurized gas enters the respective tanks under constant pressure condition through the pressure regulator. Pressure regulator determines the magnitude of propellant flow which in turn determines the thrust level of rocket. When the unit is not in upright position, check valves prevent the mixing of oxidizer and fuel. As these valves are opened, propellant flows into the thrust chamber. It also provides an additional benefit of scavenging the residue in the feed lines after complete burning of the propellant. The propellant mixture ratio in this type of feed system is controlled by the hydraulic resistance of the liquid propellant lines, cooling jacket, and injector, and can usually be adjusted by means of variable or interchangeable restrictors.

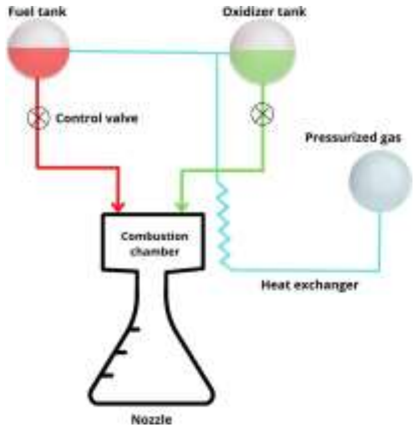


Figure 1: Gas pressure feed system

Turbo-pump Feed System

The propellants are pressurized using pumps, and turbines drive the pumps. These turbines derive their power from the expansion of warm flue gases. Turbo-pumps are high-precision accurately balanced pieces of high shaft speed (rpm) rotating machinery. It consists of centrifugal pumps and a turbine. The pumps and turbine are on singleor different shafts that are supported by high load bearings. The shaft seals prevent leakage of propellants and prevent the two propellants from mixing with each other inside the turbo-pump. Some turbo-pumps also have a gear transmission, which allows the pumps or turbine to rotate at a different speed. The turbo-pump operates in a very high-temperature range as the turbine is driven by expanding warm gases and the pump is used to pump cryogenic liquids. The pump must avoid cavitation while pumping relatively high-density fluids at low inlet pressures anddeliver them to the thrust chamber at very high pressures over a relatively wide throttling range.

The starting of turbo pump feed systems usually takes a longer time than the pressure-feed system because ittakes some time for the rotating components (pumps, turbines) to accelerate to operating shaft speed. Turbo-pump feed systems are usually preferred for the booster stages of space launch vehicles and when the engine has a relativelyhigh total impulse, high thrust, and long duration. Pressurized feed systems are chosen when engines with relatively low total impulse, low thrust, and often low cumulative firing duration.

Engine cycles

An engine cycle for turbo pump-fed engines describes the specific propellant flow paths through the major engine components, the method of providing the hot gas to one or more turbines, and the method of handling the turbine exhaust gases. There are open cycles and closed cycles. Open cycle signifies that exhaust fluid from the turbine is discharged after having been expanded in a separate nozzle or in the nozzle of the thrust chamber.

In closed cycles, the exhaust gas from the turbine is not discharged and is fed into the injector of the thrust chamber and is expanded through the full pressure ratio of the main thrust chamber nozzle. This provides additional performance than the open cycles as the remaining energy of the exhaust gases is utilized in providing the thrust.

There are three common engine cycles. The gas generator cycle has been the most common among three as itis simple, operates at a lower pressure, has a lower inert mass, and the engine cost is lower. In a gas generator cycle engine, the turbine flow is in parallel with the thrust chamber and is not used to develop thrust. A sufficient amount of propellants are pumped into the turbine, combusted in the gas generator, and expanded through the turbine to atmospheric pressure. The required pump flow rate is equal to the combustion chamber flow plus the flow requireddriving the turbine. The available energy per pound of flow is large due to the large pressure ratio. Maximizing the turbo-pump efficiency and increasing the turbine operating temperature to the available material limits reduces the required turbine flow rate while increasing the engine-specific impulse per second. Gas generator cycle engines minimize the pump-required discharge pressures, maximize the pump-required flow rate and the turbine operating temperature for a given combustion chamber pressure.

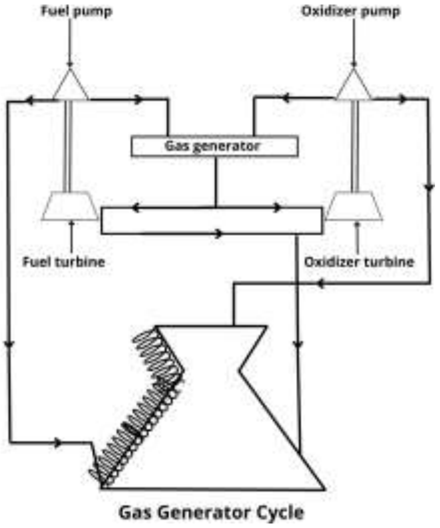


Figure 2: Gas generator cycle

In the staged combustion cycle engine, the turbine flow is in series with the thrust chamber. Fuel and oxidizerare discharged from the pump, combusted in the pre-burner, and fed to the turbine to expand. Expanded fluid is combusted in the combustion chamber. The remaining oxidizer is fed to the combustion chamber to complete the combustion process. A staged combustion cycle provides the benefit of maximizing the engine's specific impulse as the turbine flow is passed on to develop thrust. There is a rise in the turbine discharge pressure to a value more than the main combustion chamber injection pressure. The staged combustion engine maximizes the pump discharge pressures, minimizes the pump flow rates, and maximizes the turbine operating temperature.

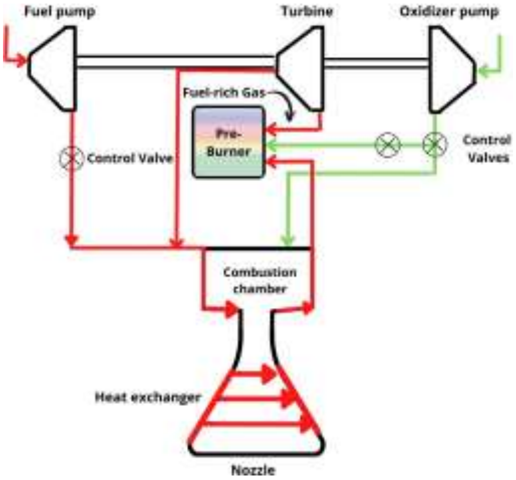


Figure 3: Staged Combustion Cycle

In the Expander cycle, the fuel cools the combustion chamber by taking heat and changing to a gaseous phase whichis then passed into the turbine. The turbine flow is in series with the thrust chamber. This cycle also provides the advantage of maximum specific impulse. The discharge pressure of the pump is equal to the injection pressure of the thrust chamber plus the pressure drop in the turbine.

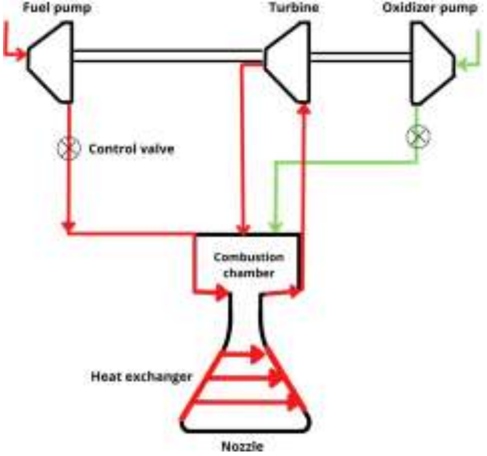


Figure 4: Expander cycle

Electric pump feed system

The electric-pump cycle feeds the propellant using pumps that are driven by electric motor and there is no gas generation, hence it is easier to develop and gives good control over the mass flow rates of propellants. Electric-pump fed cycles are being considered now a days because of technological advances in last 10-20 years related to batteries. Electric-pump fed cycle has outperformed pressure-fed cycle in low combustion chamber applications due to less weight. At high chamber pressure motor requires more power to drive the pumps which requires more energy from the batteries and leading to increase in overall weight of the system. Hence, Electric-fed system offers better perfor- mance than other cycles when an engine has lower combustion chamber pressures, low thrust, and longer burning time.

Electric motors and batteries replace the traditionally used gas and turbine for pressuring propellants in gas pressure and turbo pump feed systems. The electric pump feed system proposes the advantages over turbo pump feed system of being simple in design and having a reliable structure, having a shorter R&D cycle, and lower manufacturing cost. While comparing it with the gas pressure fed system, EPFS has higher chamber pressure and less structural mass while operating longer. EPFS consists of a battery pack, an inverter, a controller, a motor, a fuel pump, and an oxidizer pump. The battery provides electrical energy for the operation of the motor that drives the pump, and pumps create the necessary pressure to pump the fuel and oxidizer from the respective tanks to the combustion chamber.

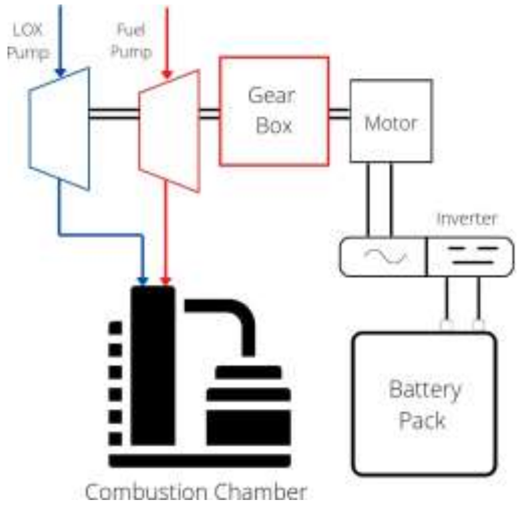


Figure 5: Electric pump feed system

LITERATURE REVIEW

Lorenzo Casalino and Dario Pastrone studied and proposed an electrical pump feed system to feed the oxidizer into the combustion chamber of a hybrid rocket motor, which is used as the third stage of a three-stage launcher. Lithium titanate batteries are used to power the pump, and the motor uses hydrogen peroxide as the oxidizer and polyethylene as the fuel. Parameters that affect the direct optimization of motor design are coupled with indirect trajectory optimization to maximize the launcher payload for assigned characteristics of the first and second solid- propellant stages and final orbit, providing the optimal values of the main engine design parameters. A mission profile based on the vega launcher is considered, the performance of the electrical pump feed system is compared with pressure-gas feed systems, and relevant improvements are suggested based on present technology.

Y.Demyanenko et al.'s study compares Staged combustion cycle liquid-propellant rocket engines turbopumps with Gas generator cycle engines turbopumps of KBKhA. Trade-off study analysis for turbopumps of the same thrust range was done taking RD-0110(gas generator) and RD-0124(staged combustion LOX-kerosene engines). Both enginesare four-chambered and differ from each other in the engine cycle. The latter one has a complex feed system.RD- 0110 engine pumps have a double-inlet design with back-to-back centrifugal impellers. In contrast, the other hasa high-speed turbopump rotor and boost pumps(Turbo-axial) for oxidizer and fuel lines. It is known that staged combustion engines have a higher performance than gas engines due to high specific impulses caused by increased chamber pressure. The chamber pressure of the RD-0124 machine rises by 2.3 times compared to the RD-0110 engine. It is essential to carefully design and develop turbopump systems for staged combustion engines, as they are influenced by higher power and stress. Moreover, the weight of staged combustion engines is almost ten times of gas generator engines. Consequently, they require innovative approaches, higher strength materials, new manufacturing techniques, and innovative methods of experimental development.

BASIC PRINCIPLE AND COMPONENTS OF ELECTRIC PUMP FEED SYSTEM

Pump driven by electric motors supplies fuel and oxidizer from the storage tanks to the combustion chamber. Thetwo separate pumps can be driven by two different motors or a single motor and gearbox.

Batteries provide power to the electric motor. A single battery pack consists of several battery cells interconnected either in series or parallel. Battery packs are sensitive to temperature changes, and as the temperature increases,the rate of reaction inside the battery also increases, leading to shortened battery life. While exposing the batteryto cold temperature for a longer duration may lower the battery's capacity. Hence batteries should be maintained at optimum temperature range. Battery pack mass is the subject of concern as it remains in calculating final mass.But with the advancement in technology, lighter and more efficient batteries have been proposed, which can deliver a large amount of energy with high energy density.

Electric motor drives the pumps. A motor with high speed and high power is required to develop the thrust.The pump's rotational speed depends on the motor's rotational speed, which altogether determines the motor power.Inverters regulate the rotational speed of the motor by controlling the frequency of the power supplied to the motor and also help save energy.

In the present study, the rocket engine utilizes LH_2 as fuel and LO_2 as the oxidizer for the second stage. As LH_2 has a lower density than LO_2, for developing a high head the LH_2 pump requires to be driven at a higherspeed than the LO_2 pump. In our case we are comparing two cases to transfer the power from motors to pumps. In first case two motors and two pumps are considered one for oxidizer and fuel. In this case there is no requirement forgear box as we can run motors at different speeds required for the pumps. In second case a single motor is consideredwith a gear box to run two pumps at different speeds.

The gearbox provides a mechanical advantage by mounting it on the motor shaft. Output torque depends onthe teeth ratio of gears and the efficiency of the gearbox. The motor gearbox assembly gives consistent output torque and smooth operation. With lightweight motors, there comes a disadvantage of difference in inertia between the engine and the load. If the load inertia increases, the time required by the system to achieve and maintain the demand increases. Gearbox makes the system more responsive. Using a gearbox, the motor experiences reduced inertia equal to load inertia divided by the square of gear teeth ratio. Using a gearbox also reduces the size of the motor required, and this way, it also reduces the cost.

METHODOLOGY

To calculate the power required for LO_2 and LH_2 pumps, we first need the volume flow rates, head rise, and density of the fluid. So, to calculate these values, we considered a maximum thrust of 25kN that our second stage engine can generate. We can calculate the mass flow rate for a given exit velocity using this thrust value. For the second stage, we considered optimal conditions, thereby eliminating thrust due to pressure. The exit velocities for the engine vary over time; we considered a minimum and maximum value for exit velocities. The minimum exit velocity is 2900 m/s, and the maximum is 4500 m/s. From here, we can calculate mass flow rates of propellant and then volume flow rates. The head rise values are taken from for Centaur rocket. The Centaur rocket uses LH_2 and LO_2 as the propellant for the second stage. By getting all the values, we can calculate hydraulic pump power.

Once we have the pump power, we can calculate the shaft power at different pump efficiencies for both LO_2 andLH_2. The pump efficiency ranges from 60% - 85%. So, we considered three values of pump efficiencies 60%, 70%, and 85%. Once we have the shaft power values, we can now calculate motor power using the shaft power and motor efficiency. According to Science Direct paper on Motor Efficiency, electric motor efficiencies vary from 70% - 96%. So, we considered 70% as minimum efficiency, 80% as average motor efficiency, and 96% as maximum efficiency. By calculating these values, we get the required motor power to run the pumps at the required power by considering the efficiencies of motor shaft power efficiency.

Using the motor power, we can calculate the energy required from the batteries. To know the energy required from the batteries, we need the mission's duration. For the case with an exit velocity of 2900 m/s, the considered time of operation is 400s, and for the case with an exit velocity of 4500 m/s, the considered time of operation is 500s. By multiplying the motor power with the duration in hours, we get the energy required in kWh (KiloWatt Hour);this is the energy required from the batteries to run the motors.

For the second case, when a gearbox is present to transfer the power from one motor to two pumps, the motor power for LO_2 and LH_2 are combined into one, and two shafts are considered for LO_2 and LH_2.

Mass Flow Rate

Using this thrust value, we can calculate the mass flow rate for a given exit velocity Mass flow rate is the amount of mass of the propellants flowing out per unit time. The considered minimum exit velocity is 2900 m/s, and the maximum exit velocity is 4500 m/s.

$$T = \dot{m}\ v_e + (P_e - P_a)A_e$$

where,

T= Thrust

$\dot{m}$= Total mass flow rate, v_e= Exit velocity

P_e= Exit pressure

P_a= Ambient pressure

A_e= Exit area of nozzle.

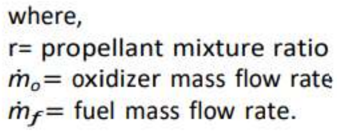
Our case is for the second stage; we considered optimal conditions to eliminate thrust due to pressure. Hence the thrust for an optimal condition is

$$T = \dot{m}\ v_e$$

From this formula, we can calculate the total mass flow rate for both cases. Once we have the total mass flow rate, we can calculate the individual mass flow rates of oxidizer and fuel using the propellant mixture ratio.

$$r = \dot{m}_o / \dot{m}_f$$

where,



where,
r= propellant mixture ratio
$\dot{m}_o$= oxidizer mass flow rate
$\dot{m}_f$= fuel mass flow rate.

we know total mass flow rate is the mixture of fuel and oxidizer mass flow rates.Therefore,

$$\dot{m} = \dot{m}_o + \dot{m}_f$$

$$\dot{m}_o = r * \dot{m}/(r+1)$$

$$\dot{m}_f = \dot{m}/(r+1)$$

In our case, the propellant mixture ratio is a lean mixture ratio of 8. Therefore, taking the value of r=8 and calculatingtotal mass flow rates, we can evaluate individual oxidizer and fuel mass flow rates for each case.

Volume Flow Rate

Now we can use oxidizer and fuel mass flow rates to calculate Volume flow rates of oxidizer and fuel using,

$$\dot{m} = \rho * \dot{V}$$

where,
$\dot{m}$= mass flow rate
ρ= density of fluid
$\dot{V}$ = Volume flow rate
Mass flow rate of Oxidizer $\dot{m}_o = \rho * \dot{V}_O$
Mass flow rate of Fuel $\dot{m}_f = \rho * \dot{V}_f$

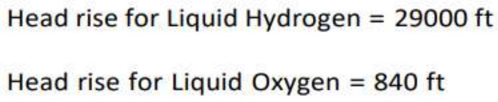
$\rho_O = 1155 kg/m^3$ 2

$\rho_H = 71 kg/m^3$ 2

Using these values, we can evaluate the volume flow rates of oxidizer and fuel for both cases.

Head Rise

We need head rise values, for liquid hydrogen and liquid oxygen for the second stage to calculate pump power. Head rise value depends upon the density of fluids. The values for the head rise are taken from the paper "Centrifugal Pumps for Rocket Engines" by W.E. Campbell and J. Farquhar, for Centaur Rocket. The Centaur is a family of rocket-propelled upper stages currently produced by U.S launch service provider United Launch Alliance. Centaurwas the first rocket stage to use liquid hydrogen and liquid oxygen propellants. The values for head rise for Centaur are 29000 ft for Liquid Hydrogen and 840 ft for liquid oxygen.

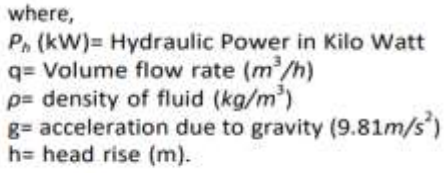

Head rise for Liquid Hydrogen = 29000 ft

Head rise for Liquid Oxygen = 840 ft

Pump Power

Hydraulic power, also known as absorbed power, represents the energy imparted on the fluid pumped to increase its velocity and pressure.[10]
Power is calculated using,

$$P_h(kW) = q * \rho * g * h/(3.6 * 10^6)$$


where,
P_h (kW)= Hydraulic Power in Kilo Watt
q= Volume flow rate (m^3/h)
ρ= density of fluid (kg/m^3)
g= acceleration due to gravity ($9.81 m/s^2$)
h= head rise (m).

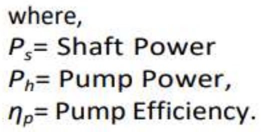
We convert all the parameters like volume flow rate, density, head rise, and acceleration due to gravity (g) intorequired units to get power in kW (Kilo Watt) for both cases.

Shaft Power

The shaft power is the power supplied by the motor to the pump shaft. Shaft power is the sum of the hydraulic power and power loss due to inefficiencies in power transmission from the shaft to the fluid. Once we get the powerfor Liquid oxygen and Liquid Hydrogen pumps, we can calculate the shaft power using pump power and pump efficiency. The pump efficiencies vary for different pumps, so we considered a range of minimum and maximum valuesto calculate for shaft power. The values of pump efficiency are 60%, 70% and 85%.

The shaft power formula is,

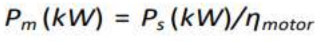
$$P_s(kW) = P_h(kW)/\eta_p,$$

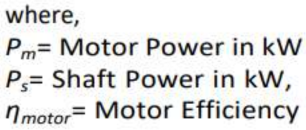

where,
P_s= Shaft Power
P_h= Pump Power,
η_p= Pump Efficiency.

Motor Power

The motor power is the power consumed by the pump motor to turn the pump shaft. The motor power is the sumof the shaft power and power loss due to inefficiencies in converting electric energy into kinetic energy. Motor power is calculated using shaft power divided by motor efficiency.

Motor Power Formula is,


$$P_m(kW) = P_s(kW)/\eta_{motor}$$


where,
P_m= Motor Power in kW
P_s= Shaft Power in kW,
η_{motor}= Motor Efficiency

Motor efficiencies vary for different motors. Efficiency of electric motor vary from 70% to 96%. So in our case, we are considering motor efficiencies for three values, i.e., 70%, 80% and 96% . Now we can calculate motor power for different values of shaft power at different pump efficiencies.

Operation Duration and Energy Required

We can calculate the energy required to find the batteries by using the motor power values. The energy required depends on how long we run the motors at that power. So, it’s important to calculate the duration of the operation. To calculate the duration, we calculated specific impulse for each case.

$$I_{sp} = F/\dot{w},$$

where,
P_m= Motor Power in kW
P_s= Shaft Power in kW,
η_{motor}= Motor Efficiency

For case 1, the specific impulse is 295.64s. Still, to consider a margin factor due to losses from temperature difference and efficiency, we considered 400s as operation time to ensure we have enough battery power to run the motors after considering some energy loss. For case 2, the specific impulse is 458.35s; the considered value is 500s. Once we have the operation time, we can calculate the energy required by multiplying the power value with the operation time in h (hours) to get the result in kWh (KiloWatt Hour).

Table 1: Parameters used for Calculation

Parameter	**Values**
Thrust	25 kN
Exit velocity	2900-4500 m/s
Propellant mixture ratio	8
Density of Liquid Oxygen	1155 kg/m3
Density of Liquid Hydrogen	71 kg/m3
Boiling point Temperature of Liquid Hydrogen	20.28 K
Boiling point Temperature of Liquid Oxygen	90.37 K
Head rise for Liquid Hydrogen	8839.2 m
Head rise for Liquid Oxygen	256.032 m
Combustion chamber pressure	30 bar
Time of Operation for exit velocity of 2900 m/s	400 s
Time of Operation for exit velocity of 4500 m/s	500 s

Motor Power and Energy Requirements with single Motor and Gearbox

For the second case, we consider a gearbox mechanism coupled with a single motor shaft instead of two different motors for the two pumps. The overall efficiency of the assembly considers the two efficiencies, i.e., the motor efficiency and gearbox efficiency. The efficiency of the gearbox is in the range of 70% to 95% . Hence, the required motor power is calculated by considering the minimum and maximum gearbox efficiency.

$$\eta overall = \eta motor * \eta gearbox$$

By multiplying individual motor efficiency and gearbox efficiency the range of overall efficiency is 49 to 91.2%. Using the Power of motor formula explained earlier we can calculate the Motor power.

$$P motor\ (\mathrm{kW}) = P shaft(\mathrm{kW})/\eta overall$$

RESULTS

The results are calculated using the input parameters taken from Table 1. The results are evaluated for each case to find the power required by the motors and energy needed from the batteries to power the motors for the complete duration of the mission.

Case with Exit velocity of 2900 m/s

Table 2: Shaft Power calculated by considering two different motors for the two pumps for Exit velocity of 2900 m/s

Parameter	**Values**
Exit velocity (m/s)	2900
Total mass flow rate (m/s)	8.62
Mass flow rate of oxidizer (m/s)	7.662
Mass flow rate of fuel (m/s)	0.95
Volumetric flow rate of oxidizer (m^3/s)	$6.63\ e^{-03}$
Volumetric flow rate of fuel (m^3/s)	0.0135
Specific impulse (s)	295.64
Time of operation (s)	400
Hydraulic power of LO_2 pump (kW)	19.44
Hydraulic power of LH_2 pump (kW)	83.114
Shaft power (60% pump efficiency) for LO_2 (kW)	32.4
Shaft power (60% pump efficiency) for LH_2 (kW)	138.52
Shaft power (70% pump efficiency) for LO_2 (kW)	27.77
Shaft power (70% pump efficiency) for LH_2 (kW)	118.73
Shaft power (85% pump efficiency) for LO_2 (kW)	22.87
Shaft power (85% pump efficiency) for LH_2 (kW)	97.78

The results for the case with an exit velocity of 2900 m/s are inserted into table 2. The power required by the pumps is 19.44 kW for LO_2 and 83.114 kW for LH_2. Using these power values, the shaft power at 60% pump efficiency is

32.4 kW for LO_2 and 138.52 kW for LH_2. The shaft power at 70% pump efficiency is 27.77 kW for LO_2 and 118.73kW for LH_2, the shaft power at 85% pump efficiency is 22.87 kW for LO_2 and 97.78 kW for LH_2.

Table 3: Motor Power calculated for Exit velocity of 2900 m/s

Shaft Power (kW)			**Motor Power (kW)**					
Pump η	**LO_2**	**LH_2**	$\eta motor = 70\%$		$\eta motor = 80\%$		$\eta motor = 96\%$	
			LO_2	**LH_2**	**LO_2**	**LH_2**	**LO_2**	**LH_2**
60%	32.4	138.52	46.28	197.88	40.5	173.15	33.75	144.23
70%	27.77	118.73	39.68	169.6	34.71	148.4	28.9	123.68
85%	22.87	97.78	32.68	139.69	28.56	122.2	23.8	101.86

The motor power is calculated using the shaft power values, and the results are inserted into Table 3. As motor power is dependent upon the shaft power and motor efficiency, the motor power is calculated for each shaft power ata pump efficiency and respective motor efficiencies. From Table 3, the motor power is 46.28 kW for LO_2 and 197.88 kW for LH_2, when the shaft power is at 60% pump efficiency and motor at 70% efficiency. When the motor has 80% efficiency, the motor power is 40.5 kW for LO_2 and 173.15 kW for LH_2, with a shaft power at 60% pump efficiency. Likewise, we have each value for motor power at different shaft powers with varying pump efficiencies at respective motor efficiencies.

Table 4: Energy requirement for Exit velocity of 2900 m/s

$\eta pump$	$\eta motor$	**Motor Power(kW)**		**Energy (kWh)**	
		LO_2	**LH_2**	**LO_2**	**LH_2**
60%	70%	46.28	197.88	5.137	21.96
70%	70%	39.68	169.6	4.4	18.82
85%	70%	32.68	139.69	3.6	15.5
60%	80%	40.5	173.15	4.49	19.22
70%	80%	34.71	148.4	3.85	16.47
85%	80%	28.56	122.2	3.17	13.56
60%	96%	33.75	144.23	3.74	16
70%	96%	28.9	123.68	3.2	13.72
85%	96%	23.8	101.86	2.64	11.3

Using the motor power values, we calculated energy requirements from batteries to power the motors for the complete duration of the mission. The results for energy requirements are inserted into table 4. The energy required for 46.28 kW LO_2 motor and 197.88 kW LH_2 motor when motor efficiency is 70% and shaft power at 60% pump efficiency is 5.137 kWh for LO_2 and 21.96 kWh for LH_2. Similarly, a 23.8 kW LO_2 motor and 101.86 kW LH_2 motor would require the energy of 2.64 kWh for LO_2 and 11.3 kWh for LH_2 when motor efficiency is 96% with shaft powerat 85% pump efficiency.

To run a LO_2 pump of 19.44 kW power, we require a shaft power of 32.4 kW at 60% pump efficiency and a motor power of 46.28 kW at 70% motor efficiency. To run this motor of 46.28 kW requires the energy of 5.137 kWh from the batteries. Likewise, an LH_2 pump of 83.114 kW of power would need a motor power of 197.88 kW and 21.96 kWh of energy to run that pump at 70% motor efficiency with shaft power at 60% pump efficiency.

Case with Exit velocity of 4500 m/s

The results for the case with exit velocity of 4500 m/s are inserted into table 5.

Table 5: Shaft Power calculated by considering two different motors for the two pumps for Exit velocity of 4500 m/s

Parameter	**Values**
Exit velocity (m/s)	4500
Total mass flow rate (m/s)	5.56
Mass flow rate of oxidizer (m/s)	4.94
Mass flow rate of fuel (m/s)	0.617
Volumetric flow rate of oxidizer (m^3/s)	$4.28\ e^{-03}$
Volumetric flow rate of fuel (m^3/s)	$8.7\ e^{-03}$
Specific impulse (s)	458.35
Time of operation (s)	500
Hydraulic power of LO_2 pump (kW)	12.54
Hydraulic power of LH_2 pump (kW)	53.562
Shaft power (60% pump efficiency) for LO_2 (kW)	20.9
Shaft power (60% pump efficiency) for LH_2 (kW)	89.27
Shaft power (70% pump efficiency) for LO_2 (kW)	17.91
Shaft power (70% pump efficiency) for LH_2 (kW)	76.52
Shaft power (85% pump efficiency) for LO_2 (kW)	14.75
Shaft power (85% pump efficiency) for LH_2 (kW)	63.01

Power required by the pump is 12.54 kW for LO_2 and 53.562 kW for LH_2. The shaft power at 60% pump efficiencyis 20.9 kW for LO_2 and 89.27 kW for LH_2. Likewise, it's the same as in for the case with exit velocity of 2900 m/s.

Table 6: Motor Power calculated for Exit velocity of 4500 m/s

Shaft Power (kW)			**Motor Power (kW)**					
Pump η	**LO_2**	**LH_2**	$\eta motor$ = 70%		$\eta motor$ = 80%		$\eta motor$ = 96%	
			LO_2	**LH_2**	**LO_2**	**LH_2**	**LO_2**	**LH_2**
60%	20.9	89.27	29.85	127.5	26.125	111.59	21.78	92.99
70%	17.91	76.52	25.59	109.3	22.39	95.65	18.65	79.7
85%	14.75	63.01	21.07	90.01	18.43	78.76	15.36	65.63

The motor power is calculated with shaft power at different pump efficiencies and motor efficiencies. The results formotor power at different motor efficiencies and shaft powers are inserted into table 6.

Table 7: Energy requirement for Exit velocity of 4500 m/s

$\eta pump$	$\eta motor$	**Motor Power(kW)**		**Energy (kWh)**	
		LO_2	**LH_2**	**LO_2**	**LH_2**
60%	70%	29.85	127.5	4.14	17.72
70%	70%	25.59	109.3	3.55	15.12
85%	70%	21.07	90.01	2.92	12.51
60%	80%	26.125	111.59	3.63	15.51
70%	80%	22.39	95.65	3.11	13.23
85%	80%	18.43	78.76	2.56	10.95
60%	96%	21.78	92.99	3.02	12.92
70%	96%	18.65	79.7	2.56	11.07
85%	96%	15.36	65.63	2.13	9.12

Using the motor power values from table 6, the energy required for each motor is inserted into table 7. To run a LO_2 pump of 12.54 kW power, we require a shaft power of 20.9 kW at 60% pump efficiency and a motor power of 29.85 kW at 70% motor efficiency. Running this motor of 29.85 kW requires the energy of 4.14 kWh from the batteries. Likewise, a LH_2 pump of 53.562 kW of power would need a motor power of 127.5 kW and 17.72 kWhof energy to run that pump at 70% motor efficiency with shaft power at 60% pump efficiency.
In all the cases, the power requirement for LH_2 is always greater than LO_2 due to the density of the fluid. Therefore, lower density fluids require high power to generate the same chamber pressure. These higher power requirements also lead to increased energy requirements from batteries, increasing the system's overall weight

Case with Gear Box

Table 8: Motor Power calculated by considering single motor for the two pumps with Gearbox to produce exitvelocity of 2900 m/s

Shaft Power (kW)	**Motor Power (kW)** $\eta overall$		**Energy (kWh)** $\eta overall$	
	η_{min} = 49%	η_{max} = 91.2%	η_{min} = 49%	η_{max} = 91.2%
170.92	348.81	187.41	38.72	20.8
146.5	298.97	160.63	33.18	17.83
120.65	246.22	132.29	27.33	14.68

Table 9: Motor Power calculated by considering single motor for the two pumps with Gearbox to produce exitvelocity of 4500 m/s

Shaft Power (kW)	**Motor Power (kW)** $Hoverall$		**Energy (kWh)** $\eta overall$	
	$\eta_{min} = 49\%$	$\eta_{max} = 91.2\%$	$\eta_{min} = 49\%$	η_{max}=91.2%
110.17	224.83	120.8	31.25	16.8
94.43	192.7	103.54	26.78	14.39
77.76	158.7	85.26	22.06	11.85

In this case, a single motor with a gearbox is considered. A single motor is preferred, the shaft power required for LO2 and LH2 are added to get the total Shaft power. The overall efficiency of the motor is calculated by multiplyingη_{motor} and $\eta_{gearbox}$. Motor power is calculated by dividing the total shaft power by $\eta_{overall}$. Energy Requirement from the battery is then calculated using the product of Motor Power(kW) and Time of Operation(h). The calculated value Motor Power and Energy requirements for time of operation of 400 s and 500 s are mentioned in Tables 8 and 9, respectively.

CONCLUSION

The overall power and energy requirements for the case with a gearbox are higher when compared with the case withno gearbox. This is mainly due to inefficiencies from the gearbox, shafts, and motor, to overcome these inefficiencies,the motor requires high power to run the pumps at required speeds. Hence, choosing a system with two motors to transfer the power to two pumps offers reliable cost and weight savings. The power requirements are also more significant when exit velocity is 2900 m/s than with an exit velocity of 4500 m/s due to high mass flow rates of propellant. The mass flow rate is higher for the exit velocity of 2900 m/s, because the calculations are done by considering exit velocities for the same amount of 25kN thrust. Hence, for the same thrust value with less exit velocity gives high mass flow rate and less mass flow rate for high exit velocities. Therefore, power requirements for motors are also more significant when the mass flow rate is higher, as pumps require more power to push the propellants out from the tanks. As power requirements increase, energy requirements also increase, which means high battery capacities are needed, leading to an overall increase in the system's weight.

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