Concept and Key Technology Analysis of Electric Pump-Fed Liquid Propellant Rocket Engine

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Abstract. Electric pump-fed liquid propellant rocket engine is an engine that uses electric pumps for propellant supply and cooling cycle. The engine breaks through the traditional pressurization mode of using inert gas to squeeze the propellant or gas-driven turbo pump, and has the advantages of simple system, light structure, high reliability and easy implementation of thrust adjustment. This study introduces the composition, working principle and technical advantages of the electric pump-fed liquid propellant rocket engine, evaluates the factors affecting the mass of the supply system with sensitivity analysis method, and analyses the key technologies of the electric pump-fed rocket engine.

1. Introduction

Compared with the pressure-fed rocket engine, the electric pump-fed liquid propellant rocket engine has a higher working pressure in the combustion chamber and has the advantage of less structural mass when the engine works for a long time. The electric pump-fed liquid propellant rocket engine has the advantages of simple and reliable structure, short R&D cycle, low manufacturing cost, and flexible thrust adjustment, compared with the turbopump-fed rocket engine. Therefore, the electric pump-fed liquid propellant rocket engine is more suitable for the commercial satellite launch field, which has greater research significance.

2. Working principle of electric pump-fed liquid propellant rocket engine

Figure 1 is a schematic diagram of the working principle of an electric pump-fed liquid propellant rocket engine, which is mainly composed of a DC battery pack, an inverter, a controller, a motor, a fuel pump and an oxidant pump, a valve block, and a thrust chamber. Unlike conventional pressure-fed and pumped propellant supply systems, this engine utilizes batteries to provide energy to the motor, and the motor drives the pump to deliver the propellant to the thrust chamber for combustion to generate thrust. The battery generally uses a high-performance lithium polymer battery (Li-Po), and the motor uses the current technologically advanced rare earth brushless DC motor. The inverter and controller are used to control the motor speed to achieve flow regulation. Compared with traditional liquid rocket engines, electric pump-fed liquid propellant rocket engines mainly have the following technical characteristics:
(1) low cost, fast launch and high reliability; (2) easy to achieve deep variable thrust; (3) easy to modular design.

![Diagram of electric pump-fed liquid propellant rocket engine](image)

**Figure 1.** Working principle of the electric pump-fed liquid propellant rocket engine.

3. Comparative analysis of the mass of different supply systems

In the design of engines, the mass of the engine is usually required to be the least. Therefore, the pressure-fed supply system is generally applied for engines with low combustion chamber pressure and low thrust, while turbopump-fed supply systems are generally applied in high-thrust engines with higher combustion chamber pressure. Since there are few researches on electric pump-fed supply system and the scope of the application is not clear yet, this study will take the "Rutherford" engine as an example for parameter estimation.

3.1. Comparison of the mass of different supply systems

Based on the main parameters of the Rutherford engine shown in Table 1, this study will compare and analyze the mass of three supply systems in terms of working hours, combustion chamber pressure, and engine thrust. The structure of the three supply systems is shown in Figure 2 [1].

| Table 1. Main parameters of the Rutherford engine. |
|--------------------------------------------------|
| Thrust/kN | 22 | Oxidant pump inlet pressure/MPa | 0.4 |
| Combustion chamber pressure/MPa | 3 | Oxidant pump outlet pressure/MPa | 4.06 |
| Mixing ratio | 2.6 | Fuel pump inlet pressure/MPa | 0.3 |
| Isp/s | 298 | Fuel pump outlet pressure/MPa | 5.25 |
| O₂(L) flow rate/(kg/s) | 5.65 | Oxidant pump power/kW | 36.1 |
| Fuel flow rate/(kg/s) | 2.17 | Fuel pump power/kW | 29.1 |
| Working time/s | 150 | Oxidant pump efficiency | 0.5 |
| Max motor speed/rpm | 40000 | Fuel pump efficiency | 0.45 |

In order to simplify the analysis, only the structural mass of the main components of the supply system is considered, while the piping system, support system and control system are ignored. The mass of the main components of each system is calculated by the mass prediction model [1, 2]. Since the mass of the battery is limited by both power density and energy density, the mass of the battery must consider the influence of these two factors, and the maximum value of the two is used as the calculated mass of the battery. The calculation is shown in formula (1) ~ (3):
When the working time of the engine is short, the mass of the battery is determined by the power density, otherwise, it is determined by the energy density [1]. In general, the energy density of a battery with a higher power density is not necessarily high, as shown in Table 2. Therefore, when studying the influence of working hours on the mass of the three supply systems, the mass of the electric pump-fed supply system is calculated based on several different types of batteries.

Table 2. Performance parameters of different types of batteries.

| Battery type | Power density (W/kg) | Energy density (Wh/kg) | Single cell voltage (V) |
|--------------|----------------------|------------------------|-------------------------|
| Li-Ion       | 3000                 | 100–220                | 3.6                     |
| Li-Po        | 6000                 | 130                    | 3.7                     |
| Li-S         | 670–1200             | 350                    | 2.15                    |

The calculated results are shown in Figure 3, where Mfs/Mp represents the ratio of the mass of the supply system to the mass of the propellant. Under the same working conditions, the mass of the propellant delivered to the combustion chamber by different supply systems is the same. Therefore, the less the Mfs/Mp, the lighter the mass of the supply system is.
In Figure 3(a), since the mass of the pressure-fed supply system and the mass of the propellant are directly proportional to the working time, the \(\frac{Mfs}{Mp}\) does not change with the working time, but for the pumped supply system, some components do not change with the working hours, such as the motor, inverter in the electric pump-fed supply system or the turbine and gas generator in the turbopump-fed supply system. Therefore, in a pumped supply system, \(\frac{Mfs}{Mp}\) decreases as the working time increases. According to the data in Figure 3(a) and Table 1, when the working time of the engine is long, the electric pump-fed supply system is better than the pressure-fed type supply system, and the length of the working time is related to the battery type. The higher the battery power density is, the shorter the working time required. As the working time of the engine increases, the mass of the battery changes from the power density limit to the energy density limit. Therefore, the higher the energy density of the battery, the less the final mass achieved by the electric pump-fed liquid propellant rocket engine.

In conclusion, when the engine is working for a long time, the structural mass of the electric pump-fed liquid propellant rocket engine is less than that of the pressure-fed liquid propellant rocket engine, and it is close to the turbopump-fed liquid rocket engine. Due to its low cost, flexible thrust adjustment, and suitability, it is used in upper-level engines with long working hours.

From Figure 3(b) and (c), when the engine thrust and combustion chamber pressure are high, the structural mass of the electric pump-fed liquid propellant rocket engine is less than that of the pressure-fed liquid propellant rocket engine, but it is different from the turbopump-fed liquid propellant rocket engine. There is a big gap in comparison, and the main reason is that the battery and the motor are larger in mass. However, with the rapid development of battery and motor technology, the mass of the electric pump-fed liquid propellant rocket engine will continue to decrease, even become comparable to turbopump-fed liquid rocket engines eventually.

### 3.2. Mass sensitivity analysis method of supply system

For the electric pump-fed liquid propellant rocket engine, the total mass of the supply system is expressed as:

\[
me_p = m_g + m_{tg} + m_{to} + m_{tf} + m_{pu} + m_{ee} + m_{inv} + m_{bat}
\]  
(4)

Where, \(m_{ep}\) represents the total mass of the electric pump-fed supply system, \(m_g\) represents the mass of the extruded gas, \(m_{tg}\) represents the mass of the extruded gas cylinder, \(m_{to}\) represents the mass of the oxidant storage tank, \(m_{tf}\) represents the mass of the fuel storage tank, \(m_{pu}\) represents the mass of the pump, \(m_{ee}\) represents the mass of the motor, \(m_{inv}\) represents the mass of the converter and \(m_{bat}\) represents the mass of the battery.

According to the research in literature [1], the mass prediction model of each component of the electric pump-fed supply system is shown in equations (5)–(17). The equations (15)–(17) show that the mass of the battery can be estimated based on the power density or energy density, but since the battery must meet the power demand and energy demand of the electric pump-fed supply system, its final mass should be determined by the maximum of the two.

\[
\alpha_o = \frac{0}{\rho_o} \left( \frac{1}{1 + \frac{1}{\rho}} \right)
\]  
(5)

\[
\alpha_f = \frac{1}{\rho_f} \left( \frac{1}{1 + \frac{1}{\rho}} \right)
\]  
(6)

\[
\alpha = \alpha_o + \alpha_f
\]  
(7)

\[
m_g = k_g k_p k_u \gamma_g \alpha M_g R_{u_o} \frac{m_{pc}}{1 - k_p P_{po}}
\]  
(8)

\[
m_{tg} = \frac{3 \rho_{tg}}{2 \alpha_{tg}} k_g k_p k_{ug} \gamma_g M_g R_{u_o} \frac{m_{pc}}{1 - k_p P_{po}}
\]  
(9)

\[
m_{tp} = \frac{3 \rho_{tp}}{2 \alpha_{tp}} k_g k_p k_{ug} \alpha m_{pc} P_{pc}
\]  
(10)
In the above formulas, \( \frac{O}{F} \): the oxygen-fuel ratio, \( \rho_o \): the oxidant density, \( \rho_f \): the fuel density, \( k_g \): the extruded gas mass safety factor, \( k_p \): the ratio of tank pressure to combustion chamber pressure, \( k_u \): the ratio of tank volume to propellant volume, \( \gamma_g \): the specific heat ratio of extruded gas, \( M_g \): the molar mass of the extruded gas, \( R_u \): the general gas constant, \( T_0 \): the initial temperature, \( P_c \): the pressure of the combustion chamber, \( P_t \): the initial pressure of the gas cylinder, \( \rho_t \): the density of the material of the gas cylinder, \( \sigma_g \): the strength of the material of the gas cylinder, \( k_t \): the safety factor of the gas cylinder, \( m_{tp} \): the mass of the propellant tank, \( \rho_{tp} \): the strength of the tank material, \( \sigma_{tp} \): the density of the tank material, \( k_{tp} \): the safety factor of the propellant tank, \( k_{pi} \): the ratio of pipeline pressure drop to the combustion chamber pressure, \( \delta_{puf} \): the power density of the oxidant pump, \( \delta_{puo} \): the power density of the fuel pump, \( \delta_{inv} \): the power density of the motor, \( \delta_{bap} \): the power density of the battery, \( \delta_{baw} \): the energy density of the battery.

Based on the different degree of analysis, sensitivity analysis can be divided into single factor analysis and multiple factor analysis [2, 3]. The single factor analysis method only examines the change of one influencing factor at a time, and can simply and intuitively reflect the sensitivity of the mass of the supply system to each influencing factor. Considering that there is almost no interaction between the various influencing factors in the mass model, in order to simplify the analysis, this study uses the single factor analysis method.

Assuming that there are m influencing factors \( a \) (\( a_1, a_2, ..., a_m \)) of the parameter \( M \) that affects the mass of the supply system, the following model can be established:

\[
M = f(a_1, a_2, ..., a_m)
\]

The status of the design point is \( \hat{a} = \{\hat{a}_1, \hat{a}_2, ..., \hat{a}_n\} \), and the mass reference value of the supply system is \( \hat{M} \). Assuming that the deviation of the mass parameter \( M \) of the supply system will be caused when the influencing factor changes in its possible variation range. The sensitivity of mass parameter \( M \) to influencing factors \( a_i \) is defined as the ratio of the relative deviation of mass parameter \( M \) to the relative deviation of influencing factors

\[
S(a_i) = \frac{|\Delta M|/\hat{M}}{|\Delta a_i|/\hat{a_i}}
\]

The variation range of each influencing factor is called the number of impact levels. In order to reflect the changing trend of the impact better, this study selects the impact level of the four scales, respectively -10%, -5%, 5%, 10%.

The parameters required for the mass estimation of the supply system of the "Rutherford" engine are shown in Table 3.
Table 3. Design parameters.

| Parameter | Design value | Parameter | Design value | Parameter | Design value | Parameter | Design value |
|-----------|--------------|-----------|--------------|-----------|--------------|-----------|--------------|
| $F$       | 20 kN        | $\delta_{P, Li-Po}$ | 6 kW/kg      | $\eta_{pu}$ | 0.5          | $\eta_{inv}$ | 0.85         |
| $P_e$     | 3 MPa        | $\delta_{E, Li-Po}$ | 130 Wh/kg    | $P_o$      | 20 MPa       | $k_p$      | 0.3          |
| $Q/F$     | 2.6          | $\sigma_{tg}$ | 3300 MPa     | $k_{pi}$   | 1.5          | $k_g$      | 1.3          |
| $t_b$     | 120 s        | $\sigma_{tp}$ | 455 MPa      | $k_{tg}$   | 2.5          | $k_{tp}$   | 1.25         |
| $\delta_{ee}$ | 3.8 kw/kg    | $\rho_{tg}$ | 1700 kg/m$^3$ | $k_u$      | 1.05         | $k_b$      | 1.2          |
| $\delta_{inv}$ | 60 kw/kg   | $\rho_{tp}$ | 2800 kg/m$^3$ | $\gamma_g$ | 1.667        | $M_g$      | 4 kg/kmol    |
| $\delta_{pu}$ | 10 kW/kg     | $\eta_{ee}$ | 0.9          | $\rho_o$   | 1140 kg/m$^3$ | $\rho_f$ | 820 kg/m$^3$ |

According to the mass model and design point parameters of the electric pump-fed supply system, the ratio of each component to the total mass of the system is calculated as shown in Figure 4. The figure shows that the mass of the motor and the battery account for more than 80% of the total mass of the electric pump-fed supply system, and the mass of the battery will increase rapidly with the increase of working time, and its proportion will exceed 50%, or even higher, so in order to reduce the mass of the electric pump-fed supply system requires reducing the mass of the motor and battery.

Table 4. Mass sensitivity of supply system.

| Impact level | Average sensitivity | Sensitivity ranking |
|--------------|---------------------|---------------------|
| -10%         | 0.624               | 1                   |
| -5%          | 0.591               | 6                   |
| 5%           | 0.534               | 2                   |
| 10%          | 0.510               | 3                   |
| $\eta_{puo}$ | 0.565               |                      |
| $\eta_{puf}$ | 0.333               |                      |
| $\eta_{ee}$  | 0.589               |                      |
| $\eta_{inv}$ | 0.533               |                      |
| $\delta_{ee}$| 0.368               |                      |
| $\delta_{inv}$ | 0.349             |                      |
| $\delta_{puo}$ | 0.563             |                      |
| $\delta_{puf}$ | 0.026             |                      |
| $\delta_{puo}$ | 0.046             |                      |
| $\delta_{baw}$ | 0.563             |                      |
| $\delta_{bap}$ | 0.445             |                      |

Through sensitivity analysis, the sensitivity of the mass of the supply system to various factors is calculated, as shown in Table 4, and the average sensitivity is shown in Figure 5.

The Table 4 and Figure 5 show that the efficiency factors of the electric pump-fed supply system, the energy density of the motor and battery, and the power density of the battery have the greatest impact on the mass of the system. Being attributed to the only impact of $\delta_{inv}$, $\delta_{puf}$, $\delta_{puo}$ on the mass of the
inverter and pump, and the mass of these components accounts for a relatively insignificant proportion, the sensitivity is slight. $\delta_{\text{baw}}$ and $\eta_{\text{inv}}$ are equivalent to the impact on the mass of the supply system. As $\eta_{\text{inv}}$ increases, the required battery energy decreases, which is equivalent to $\delta_{\text{baw}}$ increase. Therefore, the sensitivity of the two is the same.

In conclusion, the efficiency of motor and battery technology and other components is still the key factor restricting the development of electric pump-fed supply systems.

4. Analysis of key technologies

It can be seen from the above that the technology of the motor and battery and the efficiency of other components are still key factors restricting the development of electric pump-fed supply systems.

4.1. Battery Technology

The mass of the battery is not only related to the working time of the engine, but also related to its own power density and energy density. When the engine is working for a short time, the mass of the battery is determined by the power density, otherwise, it is determined by the energy density. In fact, the energy density of batteries with high power density is not necessarily high. For example, the power density of supercapacitor batteries [4, 5] is up to 250 kW/kg, but the energy density is only 70 Wh/kg, much less than that of Li-PO batteries (Table 2). Therefore, in the design of electric pump-fed type LRE, it is necessary to select the type of the battery reasonably according to the working time of the engine to reduce the mass of the battery. The commonly used battery types in the aerospace field are fuel cells and batteries.

Fuel cells usually have a higher energy density than batteries, but they are not suitable for electric pump-fed LRE. Firstly, fuel cells have low power density, slow start-up speed, low energy conversion efficiency, and many moving parts, so its reliability is lower than that of batteries. Secondly, fuel cells need to use precious metals as catalysts. The production costs are much higher than batteries, which do not meet the "low cost" requirements of electric pump-fed liquid rockets. Currently, the commonly applied batteries in the market are lithium batteries, such as lithium-ion batteries, lithium polymer batteries, and lithium-sulfur batteries, etc.

Although the lithium battery has higher energy density, it is difficult to meet the requirements of large current output in a short working time due to its slow charging and discharging rate, so it is not suitable for the short working time of the electric pump-fed type LRE, and it is not suitable for the rapidly start, shutdown, or flow adjustment of the engine. Therefore, by referring to the development status of electric vehicles to combine high-energy-density batteries with high-power-density supercapacitor batteries to form composite batteries [5], it can not only meet the performance requirements of the electric pump-fed LRE, but also help to reduce the mass of the electric pump-fed supply system.

At the present stage, the mass of the electric pump-fed supply system is relatively high, and it is still at a disadvantage compared with the turbopump-fed supply system. However, with the progress of battery technology, the mass of the battery will continue to decrease, and the mass gap between the two systems will also keep shrinking.

4.2. High-speed and high-efficiency electric gear pump technology

Increasing the motor speed is conducive to reducing the structure mass of the motor. However, the friction loss of the motor will increase at high speeds which will affect the mechanical efficiency. The high speed of the motor will also involve the filling of the pump inlet and reduce the volumetric efficiency of the pump. Eventually, the speed of increasing in battery mass is greater than the speed of decreasing in motor mass, and the general mass of the electric pump-fed liquid propellant rocket engine increases. Therefore, it is necessary to break through the key technology of achieving high efficiency under the high speed of the motor.
For centrifugal pumps, an inducer is often applied to pre-pressurize the propellant at the pump inlet to increase the speed of the pump, which not only reduces the size and weight of the pump, but also prevents cavitation and reduces the boost pressure of the propellant tank.

For high-speed gear pumps, a small pre-boosted centrifugal pump can be inserted in front of the inlet of the gear pump to increase the inlet pressure of the gear pump, which increases the volumetric efficiency. Although it will increase the mass of the electric pump, the improvement of efficiency will greatly reduce the mass of the battery, and reduce the mass of the electric pump-fed liquid propellant rocket engine.

5. Conclusion

The electric pump-fed liquid propellant rocket engine has more obvious advantages than the pressure-fed liquid propellant rocket engine when the combustion chamber pressure is relatively high or the engine thrust is high, and the working time is long. Although there is still a big gap compared with the turbopump-fed liquid propellant rocket engine, the electric pump-fed liquid propellant rocket engine uses the mature motor and battery technology in the commercial market which results in lower cost, and a relatively simple and reliable system structure.

With the rapid development of motor and battery technology, the structural mass of the electric pump-fed liquid propellant rocket engine will continue to decrease, and the gap with turbopump-fed liquid propellant rocket engines will become smaller and smaller. Due to its flexible thrust adjustment capability, the electric pump-fed liquid propellant rocket engine can take the place of the turbopump-fed liquid propellant rocket engine to a certain extent. Therefore, electric pump-fed liquid propellant rocket engine has greater development potential and broader application prospects.

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