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MARSLAND PRESS
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Presenting evaluation index for solid and liquid fuel propulsion systems

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Abstract: Status evaluation of propulsion systems in the requirements for the design of the output is very important. Performance evaluation is based on the Trust mass, missiles range, tanks weights which seem complicated. The present study attempts to examine the liquid and solid propulsion systems built in the world and present an index for evaluation of solid and liquid fuel engines. In this research an analysis is presented that enable designers to evaluate their products place with the existing situation by investigating the systematic major data of over a thousand solid and liquid fuel engines. Since the data come from experimental results, they are reliable as design recommendation. In this regard, liquid and solid propulsion system data results in the world illustrate mass to trust ratio of liquid propulsion system for low and average propulsion forces go from a number higher than two to the numbers less than one. However, in the solid propulsion systems for small trusts this value goes from the numbers less than half to about half.

[Naeim Rahimi **Presenting evaluation index for solid and liquid fuel propulsion systems**. *Rep Opinion* 2021;13(9):33-41]. ISSN 1553-9873 (print);ISSN 2375-7205 (online). http://www.sciencepub.net/report. 8. doi:10.7537/marsroj130921.08.

keywords: performance evaluation index, liquid fuel engines, solid fuel engines, propulsion systems.

1- Introduction

Liquid fuel engine is a chemical combustion engine that uses one or more of the chemical oxidant and liquid reduction. The aggregate of reduction (fuel) and the oxidant is called propulsion (Peters, 1965). This propulsion is stored and maintained separately in tanks in the rocket launcher and when the rocket is started it would be injected into the combustion chamber and causes combustion and propulsion is produced (Sutton, 1992). Russian Konstantin Tsiolkovsky, the father of rocket science, was the first person who introduced the liquid propulsion rockets fundamentals in his book titled “The Exploration of Cosmic Space by Means of Reaction Devices” in 1896. In the early twentieth century, research on rockets became serious. However, until 1930, only a few groups studied these sorts of experiments and they were not supported by the government funding and only in Germany rockets were considered as a war tool. In 1926, the first liquid fuel rocket was launched by American Goddard. The rocket fuel was a mixture of gasoline and liquid oxygen (Ghanbari et al, 1390).

2- Statement of Problem

Space rockets work like firework rockets. Fuel combines with a substance called oxidant which includes oxygen, the combustion catalyst gas. Then this combination that is propulsion burns and produces hot gases. The gases expand and exist from a nozzle and cause the rocket move upwards. This reaction for the first time in the seventeenth century was stated by English scientists, Isaac Newton, in its third law of movement (Pakdehy Ghanbari, 1380).

Liquid-fueled rocket engines usually move by high pressure compressors or compressed air chamber. The major role of these compressors and chambers are to spray the liquid fuel into the combustion chamber (compressors are used for large boards and compressed air chambers are used for small board). In the engines that work with liquid fuel, a good mixture of the two components is used: oxidants and combustible liquids. These two components can be placed in two separate tanks and ignition takes place in the combustion chamber (Thompson, 2000). For a more complete combustion, the ratio of the oxidant to the combustible liquid is considered several times more. The more oxidants contain oxygen the combustion takes place better. Combustible substances according to their chemical properties are located in one of two groups as following: The materials that can ignite spontaneously, (b) substances that cannot be ignited by themselves (Sutton, 2006). When the first group materials placed adjacent to oxidants may ignite without any external factor. These materials are such as aniline, Ksylydyn, Trytyl amine, hydrazine, methyl hydrazine and dimethyl hydrazine. These materials can be ignited in a mixing with nitric acid. For the second group materials cyclohexane - methyl cyclohexane - ethyl cyclohexane - benzol - toluene and petroleum derivatives can be named. If these materials are mixed with nitric acid, no flame is produced but cause significant temperature rise (Ghanbari et al, 1390).

The engine combustion chamber is a place where not only the mass flow rate exists, but also the supplies of energy production equipment is realized (Rycroft, 1990). Chamber, the injection system, control and valves equipment, regulators, safety valves and all pipes and fittings that are assembled into a single unit, called engine (Schwabacher, 2005). The main characteristic of the propulsion engine is that for great rockets the propulsion determines the type of missile engines and varies in a wide range (Turner, 2009).

In the liquid fuel propulsion engines, propulsion force is produced lower but in more time. The propulsion force can be controlled by changing the mixing ratio of propulsion components, similar to changing the speed of a car using the gas pedal, which was not possible in the primary solid fuel engines (Schwabacher, 2005). But in recent years, with advances in control technology of solid fuel propulsion engines, this liquid fuel engines feature became so faint (Streeter, 1966). Since controlling the propulsion force of the liquid fuel rocket engine is simpler, the number of liquid fuel rockets is far more than solid fuel propulsion rockets (Ghanbari et al, 1390). However, the liquid propellant rockets are not free from objection, because some of these propulsions should be stored at low temperature. At atmospheric temperatures, liquid propellants have become gas and accordingly occupy more space. Big rockets like Europe Space Agency Arian rockets or missiles and NASA's space shuttle use more than one liquid fuel engines simultaneously instead of one engine. The aforementioned engines produce enough propulsion force to launch a spacecraft into orbit. Also it should be noted that the major disadvantage of liquid propellant engines are inspection, maintenance and preparing operation that is very difficult and raise their costs (Davis, 2006). Also, complexity of this kind of engine's subsystems increases the cost and price. Hence, the world space industry in recent decades moves toward the solid propellant engines which generally are more economic with lower operating costs (Pakdehy Ghanbari, 1380). However, specific criteria for evaluation of propulsion systems have not been provided yet. The present study attempts to provide indexes to evaluate the solid and liquid propulsion system by examining more than 300 solid and liquid propellant engines. In this regard, specific impulse, flight board, the rocket's mass ratio and ... have their own unique benefits so a proper index can be introduced.

3- Investigation of propulsion systems index

The most important characteristic of a flying object such as rockets is the ultimate flight speed which in the ballistic missile specifies the flight board. Without considering the forces of gravity and aerodynamic resistance, the final speed of the rocket, which is called ideal final speed in this condition, is obtained by Tsiolkovsky formula (Koodriatsev, 1993).

$$V_{F.i} = \bar{I}_{sp} Ln \bar{M} \quad (1)$$

In this relation, $\bar{I}_{sp} = \int_0^t \frac{I_{sp}\, d\tau}{\tau}$ is the average specific impulse on the active part of the missile flight path, ، $\bar{M} = M_0 / M_F$ determines the rocket initial mass M_0, rocket final mass M_F and t is the operation time of engine. Considering the forces of gravity and aerodynamic resistance, the final speed of the rocket V_{Fi} is the ideal final speed of the rocket.

$$V_F = V_{F.i} - V_g - V_d \quad (2)$$

Assuming a constant initial mass, the effect of engine parameters on the ideal final speed of rocket is examined. It can be implied from equation (1) that the quantities $\bar{I}_{sp}$ and $\bar{M}$ influence on the final speed. The more the values $\bar{I}_{sp}$ and $\bar{M}$ increase the amount of V_{Fi} will be proportionally greater. $\bar{M}$ is the mass superiority criterion of the rocket structure. . The more the values $\bar{M}$ increases the amount of $(M_p = M_o - M_F)$ stored propulsion in the rocket will be proportionally greater. In this regard, the engine can operate more and the rocket can reach to higher V_{Fi} in flight. The mass of the engine is also a part of the rocket mass; thus, reducing the engine mass can provide increase in $\bar{M}$ and the rocket final flight speed. In mass balance, the mass of the engine is a significant amount, thus reducing the mass of the rocket engine is essential in reducing the mass of the rocket. In design, it is important to know the effect of specific impulse and engine mass reduction on the engine speed and the final flight board. In Figure 1 the calculation results of the effect of the specific impulse on the ballistic rocket flight board.

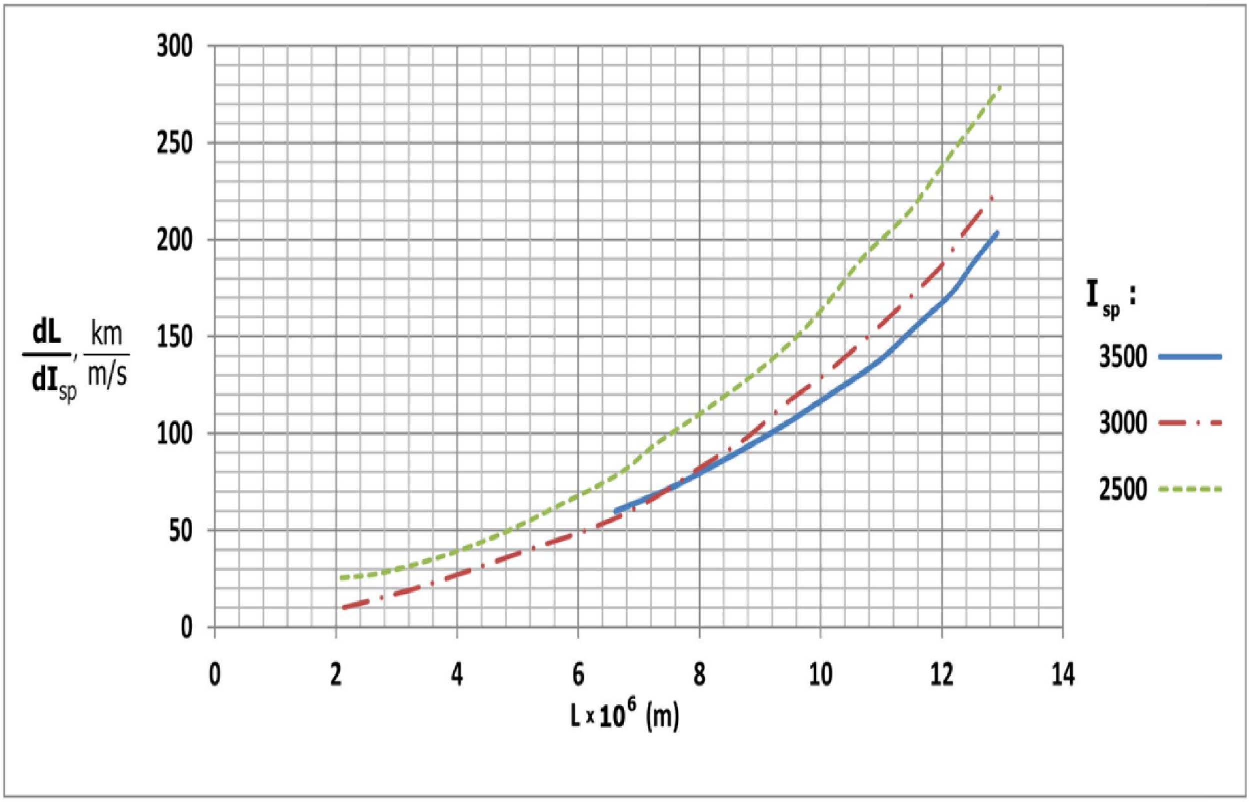

Figure 1: Change of the flight board with specific impulse

It can be implied from figure 1 that the effect of specific impulse range increases by rocket flight board increase. For example, in an intercontinental rocket with board 11 000 km and impulse 3000 meters per second, increasing the specific impulse of 0.3 percent results in board increase about 170 km and increasing the specific impulse of 1 percent results in board increase about 500 km. In order to assess the impact of $\bar{I}_{sp}$ and $\bar{M}$ on the ideal final speed, we assume that the rocket final speed is constant *const* = V_{Fi}, then after integration equation (1) and simplifying equation (3) is obtained:

$$d\bar{M}/\bar{M} = -\left(d\bar{I}_{sp}/\bar{I}_{sp}\right)Ln\bar{M} \quad (3)$$

If $\bar{M}$ is larger than the natural logarithm base e1% increase in $\bar{I}_{sp}$ compared with 1% increase in $\bar{M}$ in in terms of $V_{F.i}$ or flight board impact much greater. If *e* $=\bar{M}$, 1% increase in the specific impulse and structure change in order to increase or decrease in $\bar{M}$ weight is smaller than e. $\bar{M}$impact on the final speed will be more than $\bar{I}_{sp}$. This relation is shown in figure (2).

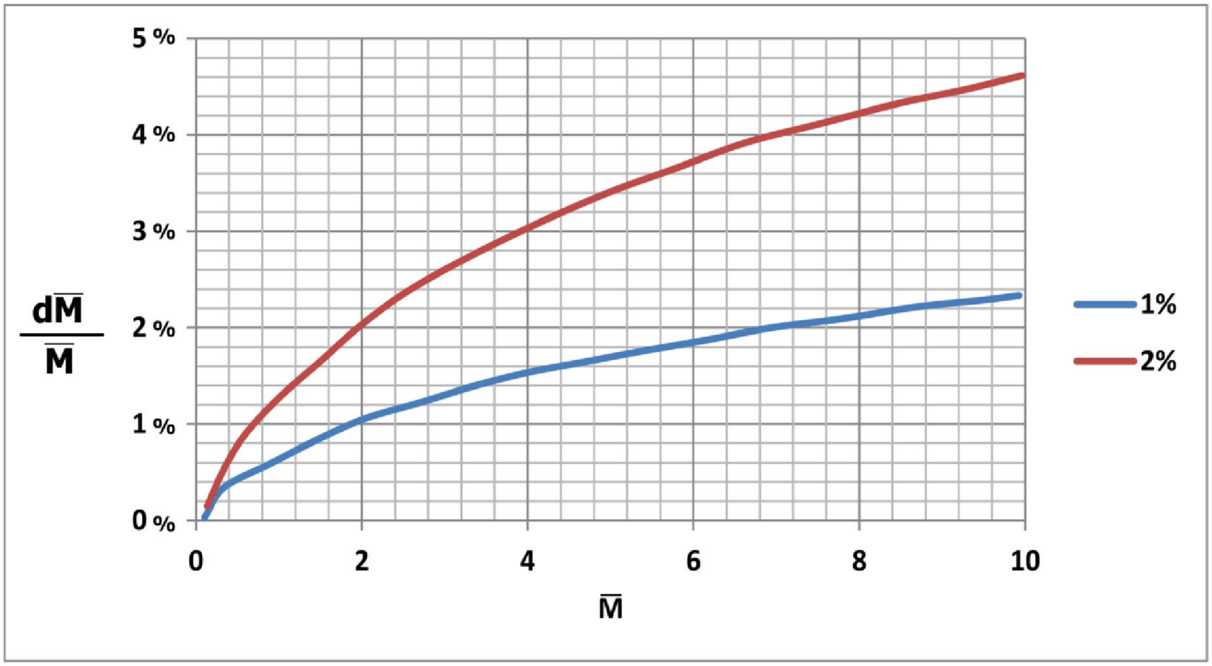

Figure 2: Rocket mass ratio change with $\bar{I}_{sp}$ increase

In ballistic missiles, the rockets carrying spacecraft and air-defense guided missiles, $\bar{M}$ is generally larger than e. And this means that the impact of specific impulse changes is more than the impact of mass changes on the final missiles velocity.

But for some short board missiles, $\bar{M}$ is smaller than e, which represents mass is more effective than the specific impulse impact on the final missiles velocity in this category. In these systems, liquid fuel engines without turbo-pump are used. For a more complete review of the impact of mass on the missile board, we assume that the amount of propulsion in the rocket structure has not changed, (M_P = M0 - MF = const). Now with the same mathematical simplification which was considered for determining the effect of $\bar{M}$ and $\bar{I}_{sp}$ on final velocity the following equation is obtained:

$$dM_F/M_F = \left(\bar{M}/(1-\bar{M})\right)Ln\bar{M}\left(d\bar{I}_{sp}/\bar{I}_{sp}\right) \quad (4)$$

If we assume that the mass of the rocket structure can be changed only by changing the engine mass M_E, equation (4) is expressed in the following form:

$$dM_E/M_E = (M_F/M_E)\left(\bar{M}/(\bar{M}-1)\right)Ln\bar{M}\left(d\bar{I}_{sp}/\bar{I}_{sp}\right) \quad (5)$$

The results graph of equation (5) is presented in Figure 3. It can be concluded from the diagram that 1% increase in the specific impulse compared to 1% reduction in engine mass has greater impact on the final velocity of rocket. Considering $\bar{M}$ and (M_F / M_E) of the modern ballistic missiles and carrier rockets structure, the impact of 1% increase in the specific impulse is equivalent to 10 to 15% reduction in engine mass to achieve the same final velocity or rocket board. However, it can be concluded that beside the specified initial mass of the rocket, the final flight velocity can be increased by engine specific impulse increase or rocket mass reduction.

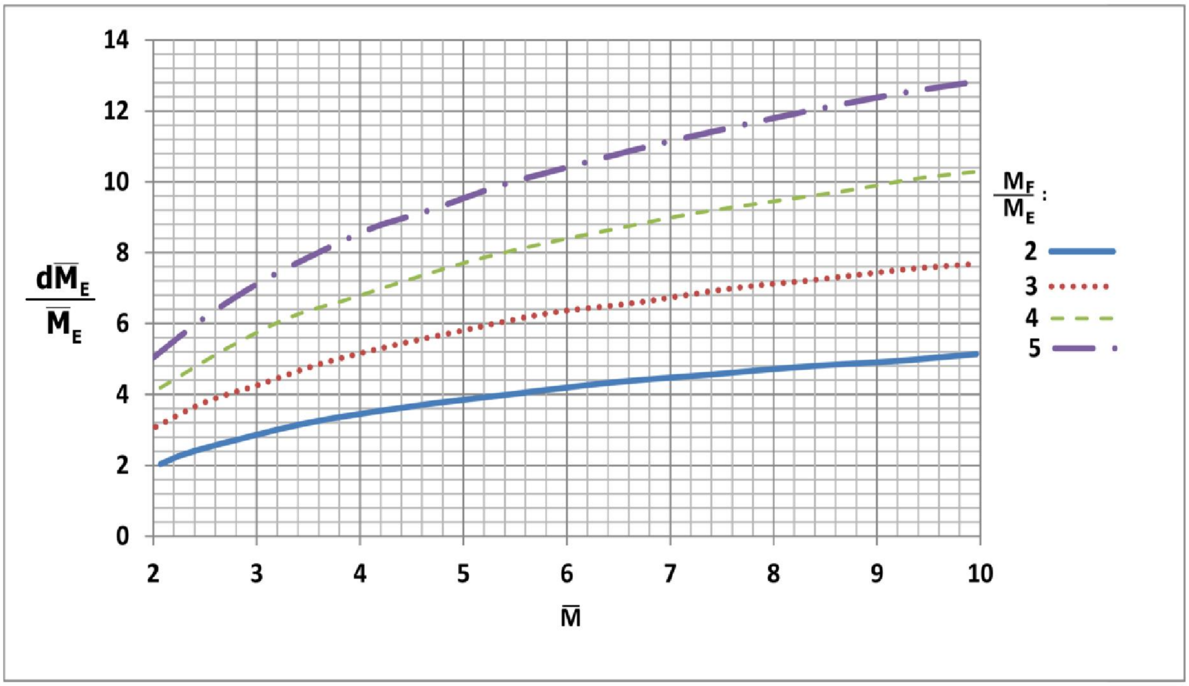

Figure 3: Diagram of the mass ratio changes dM_E/M_E by 1% increase in $\bar{I}_{sp}$

So to achieve the desired final velocity of flight, the initial mass of the rocket can be reduced by increasing the specific impulse of engine and decreasing its mass. Thus, the optimal design of the engine cannot be assessed only by the value of specific impulse and mass, but the effect of these parameters should be examined on the rocket total profile. For comparison the constant initial mass or M_0, a parameter can be defined as the rocket total impulse $I_T = \bar{I}_{sp} M_P$. The more the engine specific impulse $\bar{I}_{sp}$ and rocket mass M_P are, the rocket total impulse I_T proportionally becomes more. Therefore, the quantity I_T is the superior index and criterion for rocket. For comparison of various initial mass M_0 rockets, the ratio of initial mass to total impulse can be selected for as the superior index. In fact, the ratio I_T / M_0 is obtained by dividing the left and right parts of equation $I_T = \bar{I}_{sp} M_P$ and considering the following equation:

$$M_P/M_0 = 1 - M_F/M_0 = 1 - 1/\bar{M}$$

$$I_T/M_0 = \bar{I}_{sp}\left(1 - 1/\bar{M}\right) \quad (6)$$

Comparing equations (1) and (5), it can be concluded that the quantities $V_{F.i}$ and I_T / M_0 depend on the specific impulse $\bar{I}_{sp}$ and $\bar{M}$ that their increase lead to increase in the quantities $V_{F.i}$ and I_T / M_0 In this regard, for comparing the rockets, both parameters $V_{F.i}$ and I_T / M_0 can be used. It can be concluded from equation 6 that if $\bar{M} \to \infty$ the following limit is correct: $I_T / M_0 \to \bar{I}_{sp}$. It means that the limit I_T/M_0 is the engine average specific impulse and the vicinity of I_T / M_0 to $\bar{I}_{sp}$ is considered as a superior index. For evaluation of propulsion system, the parameter I_T / M_E can be used. Considering this parameter as the engine superior index, engine optimum parameters can be calculated and selected.

3-1- Liquid fuel engines

The liquid fuel propulsion system consists of engines, propulsion, propulsion tanks, blower fluid and all components of the blowing system. Now the effect of combustion chamber pressure on the ratio I_T /M_{PS} in liquid fuel engines will be examined. This ratio can be expressed as follow.

$$I_T/M_{PS} = \bar{I}_{sp}.M_P/M_{PS} = \bar{I}_{sp}.\bar{M}_P \quad (7)$$

By investigating the dependency of each of the terms average specific impulse and mass ratio of propulsion $\bar{M}_P$.on chamber pressure, the ratio I_T /M_{PS} is expressed. Using data from 300 liquid fuel engines (Figure 4) that is almost the entire statistics of turbo-pump engines in the world, independency of $\bar{M}_P$ to chamber pressure in turbo-pump engines can be concluded (Ramesh and Saremi Rad, 1386).

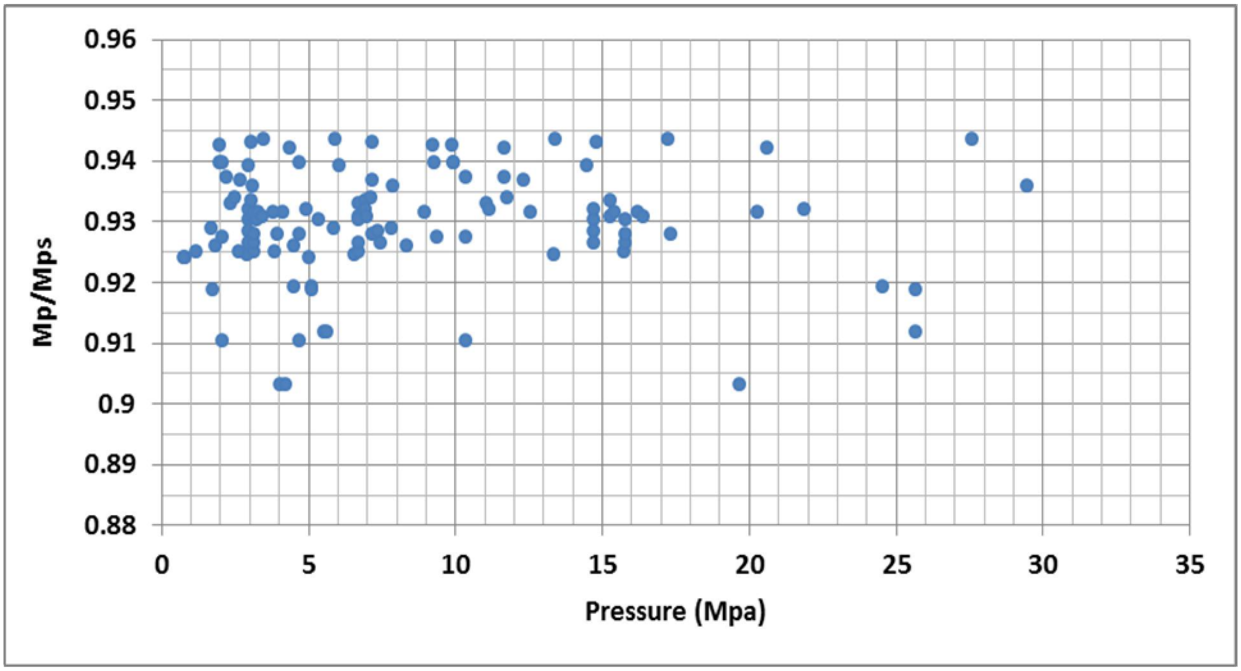

Figure (4): Statistics of Mp/Mps versus chamber pressure for 300 liquid fuel engines

In the liquid fuel engines, the optimum value for I_T /M_{PS} and Specific impulse are distinct in terms of pressure. As it can be seen in figure (5), increase in the chamber pressure leads to increase in the supply system mass ratio (propulsion tanks and blowing system). Despite the lack of any significant change in pipe mass and the chamber, the total mass of the propulsion system increases. This pressure increase at a certain point even overcomes the specific impulse impact. So that further increase in chamber pressure, the superior index will be reduced. But in this class of liquid fuel engines, we are faced with another limiting factor. Due to unsuitable mass index for high pressures of chamber, use of these engines is only suitable in the mission with low value of thrust.

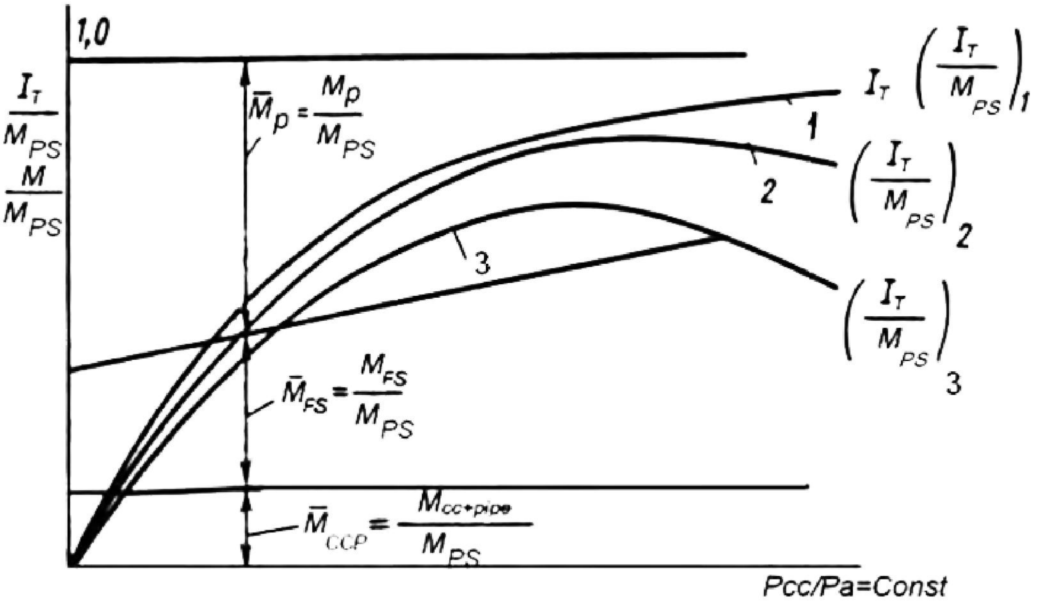

Figure 5: Changes in the superiority of liquid fuel engines in terms of chamber pressure

Statistical analysis of results of liquid fuel engines shows the mass situation of these engines in figure (6). This statistical data graph shows the decrease in the engine ratio of mass to thrust with increasing thrust. Based on these studies, the ratio of mass to thrust for liquid fuel propulsion systems goes from low values of trust - that are related to the high level engines - to the high values, from values more than 2 to values less than one.

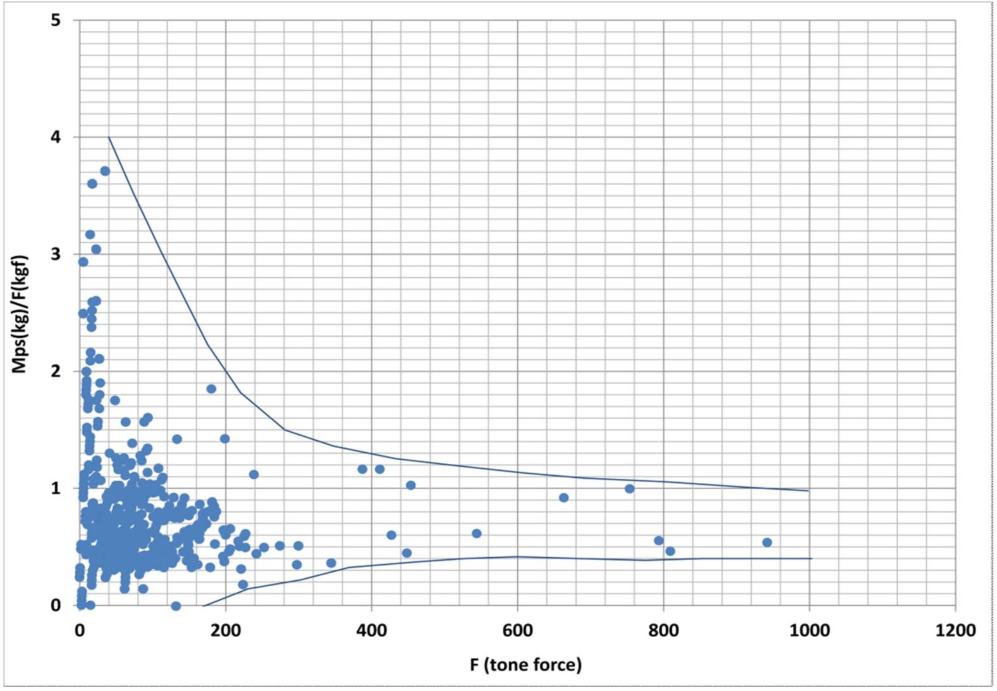

Figure 6: Statistical data for the mass to thrust ratio for liquid propellant engine

3-2- Solid fuel engines

In the solid fuel engines, a mass index is defined as the relative mass (Lipanov & Alief, 1995):

$$\alpha = M_c / M_p \quad (8)$$

The symbols of the numerator and the denominator represent the structural mass and propellant mass. The above equation can be stated as follow.

$$1/(\alpha+1) = M_p / (M_p + M_p) = M_p / M_{ps} = \overline{M}_p \quad (9)$$

Figure (6) shows how the index of solid fuel propulsion systems changes in terms of chamber pressure. As can be seen, the chamber pressure is optimum for each of the stages. In this figure, another parameter λ_i is defined as the ratio of i_{th} stage length to the diameter d_i :

$$\lambda_i = l_i / d_i \quad (10)$$

In this study, other statistical studies are presented on solid propulsion systems in the world which are presented in figure (7). Based on these studies, the mass to thrust ratio for solid propulsion systems for the small values of thrust, it goes from the values lower than half to the value around half. This index is considered as an appropriate factor in the acceleration of solid systems.

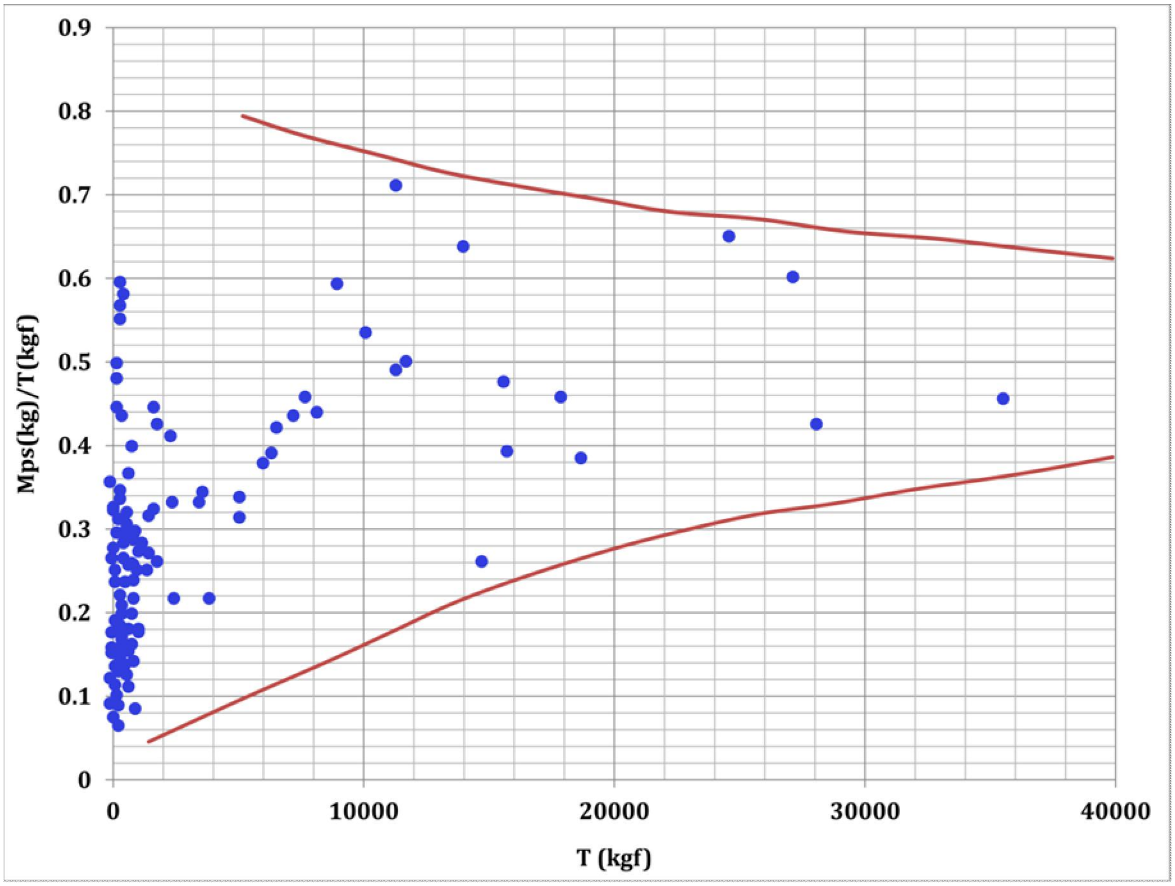

Figure 7: Statistical data of the mass to thrust ratio for solid propulsion engine

4- Conclusion

For the mass – energetic propulsion systems evaluation, relative total impulse index can be used to in which M_{PS} is propulsion system initial mass. However, mass evaluation of with requirements of design output is very important for the designers. In this situation, the ratio of mass to thrust can be used. Investigation of the liquid and solid fuel propulsion systems statistical data illustrates that the ratio of mass to thrust for the liquid fuel propulsion system for low to average propulsion forces, which usually is related to space control engines and upper levels of spacecraft. It goes from values lower than one to the values more than 2. However, in the solid propulsion systems, it goes from values lower than half to the values around half. This study examined the original systematic data of over one thousands of liquid and solid fuel engines, an analysis is presented upon which designers can evaluate their product positions by comparing with the existing situation. Since the data come from experimental results, they are reliable as design recommendations.

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