SUPERSONIC COMBUSTION RAMJET: ANALYSIS ON FUEL OPTIONS

by
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ABSTRACT

STEPHANIE BARONE: Supersonic Combustion Ramjet: Analysis on Fuel Options

This report focuses on different fuel options available to use for scramjet engines. The advantages and disadvantages of JP-7, JP-8, and hydrogen fuels are covered, also the effectiveness and requirements for each fuel are discussed. The recent history of the scramjet engine is included as well as its advantages and disadvantages. An explanation of what each fuel option encompasses and engineering analysis for each fuel are shown. The equations presented for the parametric analysis are shown as functions of the freestream Mach number, with the combustion Mach number as a parameter. The results can be seen for the theoretical possibilities of the scramjet engine and the most likely operating situations. Hydrogen has the highest lower heating value which makes it very appealing to use as a fuel, but it is not very dense so more volume of it is needed to create enough energy. The hydrocarbon fuels, JP-7 and JP-8, have half the value of hydrogen for the lower heating value but have many other advantages as stated in the following report.

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NOMENCLATURE

A^*/A	Area ratio, Eq.(12)
A_2	Diffuser exit area; combustor entrance area, cm^2
a_o	Freestream speed of sound, m/s
c_p	Specific heat at constant pressure, kJ/(kg *K)
F	Thrust, N
$F/\dot{m}_o$	Specific thrust, N/(kg/s)
f	Fuel-to-air ratio
g_c	Newton’s constant, (kg*m)/(N*s^2)
h_{pr}	Fuel lower heating value, kJ/kg
M_c	Combustion Mach number
M_o	Mach number at freestream flight conditions
P_o	Freestream static pressure, Pa
R	Gas constant for air, kJ/(kg*k)
S	Thrust-specific fuel consumption, mg/(N*s)
T	Temperature, K
T_{max}	Material temperature limit, K
T'_{max}	Burner exit total temperature, Eq.(3a), K
T''_{max}	Burner exit total temperature, Eq.(3b), K
T_o	Freestream ambient temperature, K
γ	Ratio of specific heats
η_o	Overall efficiency, %
η_p	Propulsive efficiency, %
η_T	Thermal efficiency, %
τ_r	Inlet temperature ratio, Eq.(1)
τ_λ	Total temperature to freestream temperature, Eq.(2)

INTRODUCTION

The scramjet engine is where the future of aerospace is headed. Scramjet engines fill the gap between highly efficient turbojets and the high speed of rocket engines. To fully understand what a SCRAMJET, or Supersonic Combustion Ramjet, is one must first know the definition of a ramjet. A ramjet is an air-breathing jet engine. It uses the forward motion of the engine to compress the incoming air, therefore it does not require a compressor. Figure 1 shows a diagram of the ramjet components. The interesting innovation of ramjet and scramjet engines is their independence from having to carry liquid oxygen onboard [6]. Before the creation of these engines, it was known that the farther or faster one wanted a rocket to go, the bigger the rocket had to be. That way it could accommodate the large amount of liquid oxygen needed to create thrust. In a ramjet and scramjet

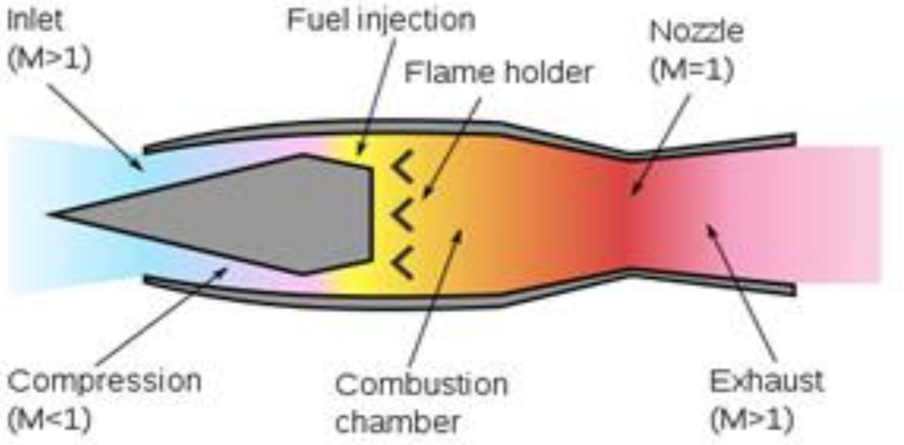

Figure 1- Ramjet diagram [1]

propulsion system, the oxygen needed for combustion is taken from the surrounding atmosphere instead of from an onboard tank. This allows the craft to be smaller, lighter and therefore faster. The difference between a ramjet and scramjet is the speed of the airflow at combustion. While a ramjet engine decreases the airflow to subsonic speeds before combustion, a scramjet engine keeps the airflow supersonic throughout the entire engine and so combustion takes place at supersonic speeds [8]. Supersonic flow generates a greater reaction which gives the scramjet the ability to efficiently operate at hypersonic speeds. Figure 2 shows a diagram of a scramjet engine.

Scramjets have many advantages as well as disadvantages. As mentioned earlier, an advantage of the engine is that it does not require a supply of oxidizer onboard. Another major advantage is that there is not any moving parts in the engine, which makes it easier to manufacture and maintain [4]. Although scramjets sound simple in theory and design, there are many challenges with actually implementing this system. The temperature on the aircraft is much higher than the air surrounding it which requires new materials to endure these temperatures. In addition, challenges occur in maintaining combustion in the supersonic flow; the fuel has to be injected, mixed, ignited, and burned all within fractions of a seconds. Viswanath compares this to “lighting a match in a tornado and keeping it alight at any costs [6],” which can be quite difficult to achieve.

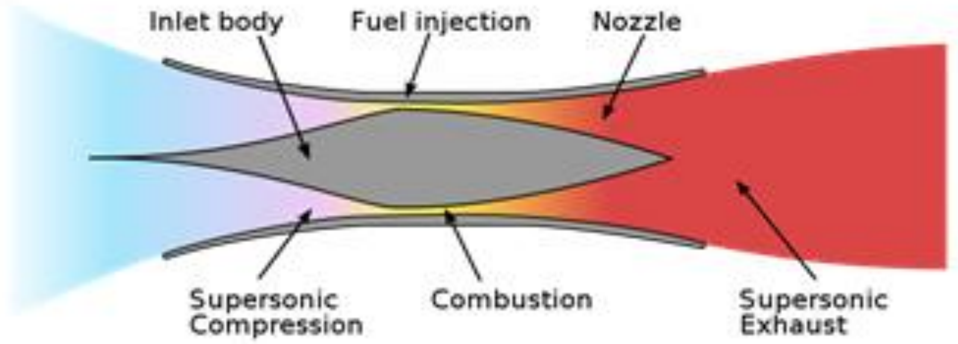

Figure 2- Scramjet diagram [1]

Furthermore, scramjets cannot produce thrust at zero velocity and so need a second propulsion system to help them reach an adequate operating flight Mach number [4]. Even with these challenges, scientist see it fit to keep developing and undergoing new testing. The reason being is that scramjet engines make flying at fifteen times the speed of sound a possibility, which is appealing for many different reasons: air travel and missiles being the prominent motives [9]. Although the ultimate goal is to make air travel faster, presently it is more logical to think that scramjet engine technology will be used for missiles or surveillance aircraft. As of now though, scientists are simply trying to get scramjet engines to fly and remain flying for a decent amount of time. There is a lot of development that still needs to occur to make flying people using a scramjet engine a feasible option. Because of this using the technology for missiles is a more reasonable assumption for the near future of scramjets. It is a race between countries to see who can perfect the engine first and have it to their advantage.

Scramjet type of technology can be dated back to before World War II, when Rene Lorin first thought of the idea of using ram pressure in propulsive machines [10]. These engines have come a long way since then. A scramjet engine was first tested in a lab in the 1960's, since then NASA achieved a record of Mach 9.6 using the X-43a experimental aircraft in 2004 [4]. The US Defense Advanced Research Project Agency (DARPA) combined efforts with the Australian Defense Science and Technology Organization (DSTO) and attained successful scramjet flight at Mach 10, using a rocket engine to boost the vehicle to hypersonic speeds in 2007 [11]. In 2009, NASA, using the X-51a, reached Mach 5 for 200 seconds, setting the longest scramjet flight [11]. Many programs have been created to improve the scramjet engine propulsive system, presently none have reached a long enough flight to consider scramjet technology to be used for common air travel anytime soon. It is more likely that the developments will result in new missile strategies.

The SR-71 is the fastest manned air-breathing supersonic jet plane. It was used by the U.S. military as a spy plane in the Cold War to fly fast and high away from danger. The SR-71 flew many missions at Mach 3 (more than 2000mph) and altitudes of 80,000 feet (15 miles). It could survey more than 100,000 square miles of the surface of the earth per hour [7]. Lockheed Martin Skunk Works designed the jet plane to use two engines to run in constant afterburner mode to attain the supersonic speeds. Titanium skin is used to protect the aluminum frame from the extreme heat of supersonic flight and the plane was covered in special black paint to absorb radar, and to radiate excess heat, this black paint gave the jet plane the official name of "Blackbird". The rising use of satellites for space surveillance and the increase danger of better air defenses caused the Air Force to discontinue the use of the Blackbird [7]. As mentioned, the Blackbird uses ramjet engine to reach Mach 3, it uses ramjet and turbojet technology combined in series. This plane designed almost 50 years ago is now giving birth to a new idea, the SR-72. This plane will be intended for unmanned flights at supersonic speeds reaching Mach 6 and will be used as a spy drone. The SR-72 will use a turbine-based combined cycle propulsion system which will combine both the turbine engine and ramjet engine combined in parallel, allowing the plane to go from static to five times the speed of sound [3]. The turbine engine will provide the thrust from takeoff to Mach 2 speeds, like it did for the SR-71. This will allow the plane to be at a suitable speed for the ramjet technology to be applied and increase the speed to hypersonic speeds, hopefully around Mach 6. The Lockheed Martin team is attempting to perfect the SR-72 by 2030 and this would be a game changer for a scramjet engine future. If the turbine-based combined cycle propulsion system is perfected this could solve the dilemma of scramjets not being able to start from standstill. Figure 3 demonstrates the SR-72 proposed propulsion system. Even though the SR-72 uses a ramjet engine instead of a scramjet one, it is a stepping stone for scramjet development.

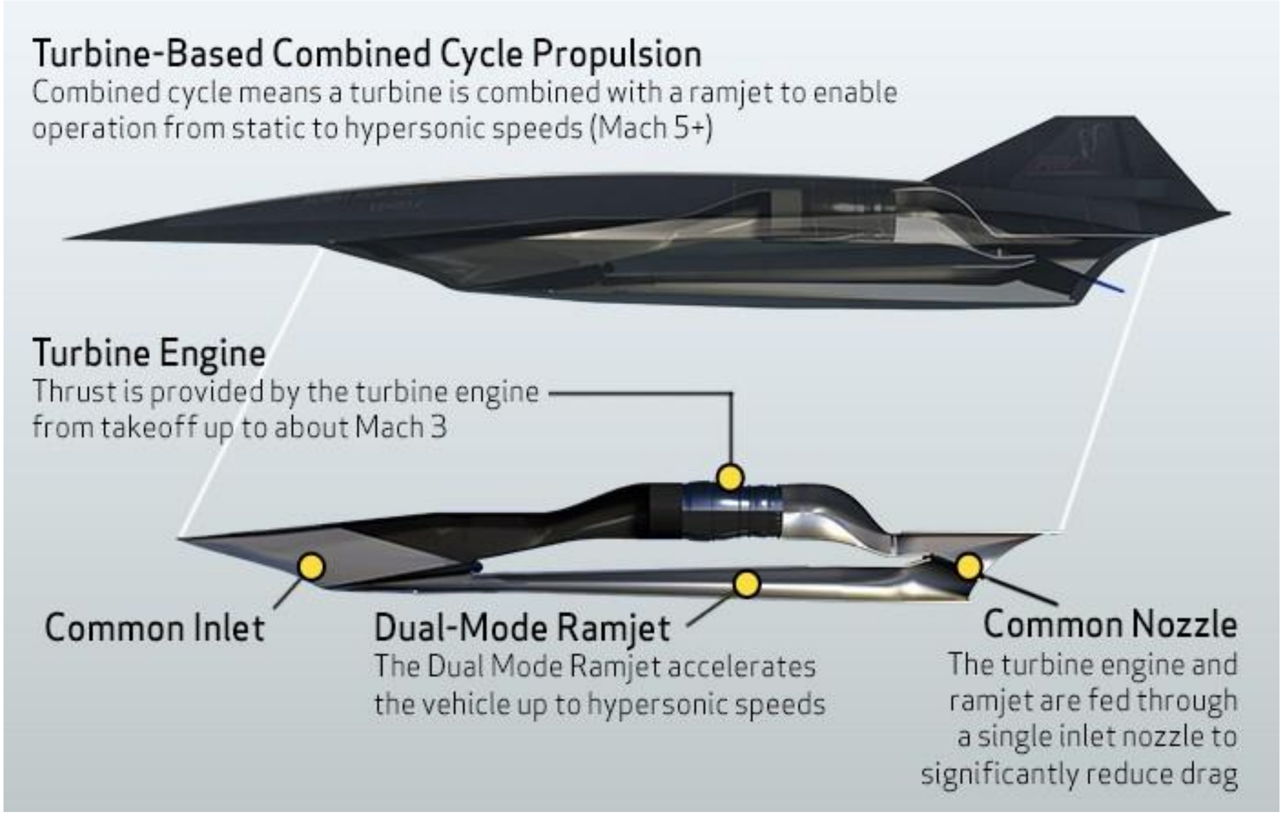

Figure 3- Turbine-Based Combined Cycle Propulsion system diagram [3].

STATEMENT OF THE PROBLEM

An important aspect to consider is the fuel option available for scramjet engines. This report will discuss the research done on two common fuels for jet engines and an experimental fuel being used. When fuel analysis is considered the main concern is the h_{pr} or lower heating value. This value defines the quantity of energy released in the combustion of the fuel and the remaining combustion products continue in gaseous form [6]. When analyzing fuels one wants to choose the fuel that burns the fastest and generates the most amount of thrust, this is where the lower heating value comes into play. The higher the value the more thrust per mass the fuel produces. Other traits to take under consideration are pollution, density, and weight. The fuel should be dense enough so that it does not require an immense amount to produce an adequate amount of energy, but low enough to not significantly weigh down the scramjet. The following will discuss the characteristics, advantages, and disadvantages of JP-7, JP-8, and hydrogen for use as fuels in scramjet engines. Table 1 provides a comparison of the fuels. Figure 4 provides a T-s diagram of the Brayton cycle that the scramjet and ramjet are based on. The diagram shows both the ideal scramjet and ideal ramjet for comparison.

Table 1- Comparison of fuels

Fuel	**JP-7 [12]**	**JP-8 [6]**	**Liquid Hydrogen [2]**
Hpr (kJ/kg)	43,500	43,190	119,600
Density (kg/m^3)	779-806	800	0.09
Flash Point (˚C)	60	38	-253

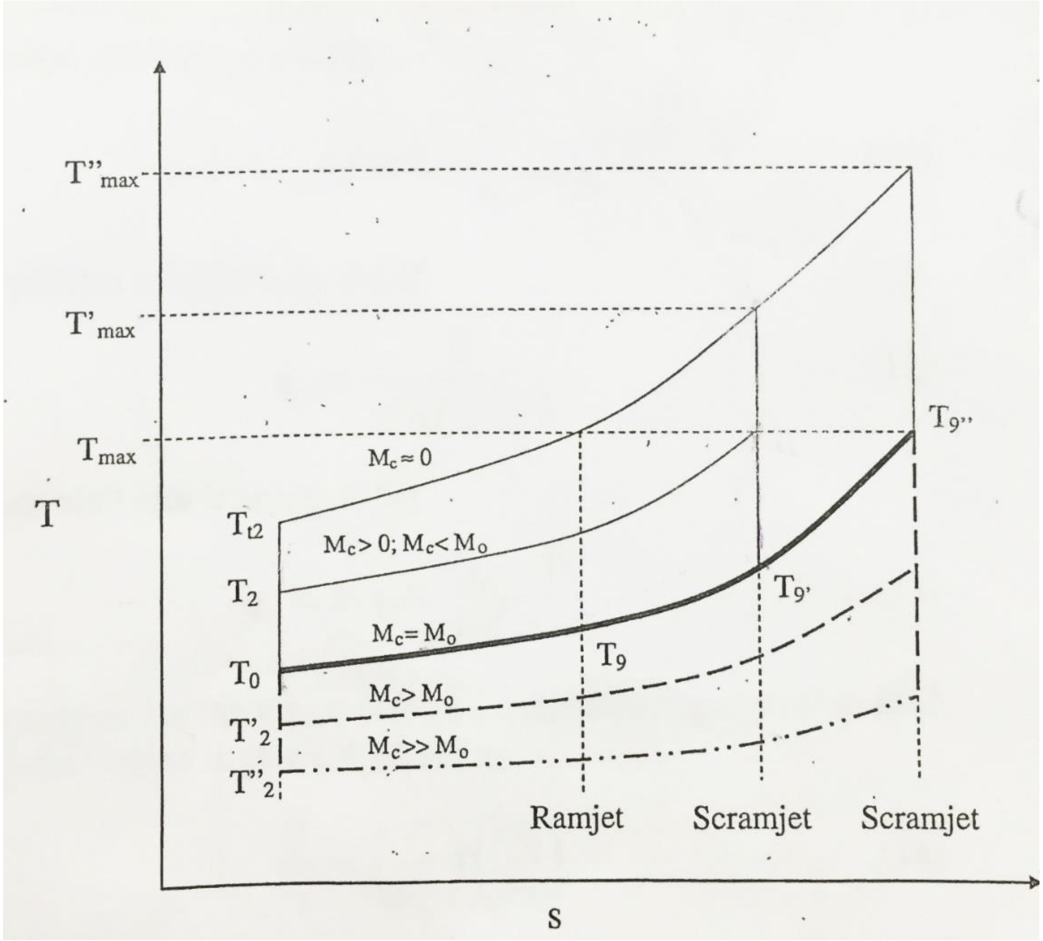

Figure 4- T-s diagram comparison for ideal ramjet and ideal scramjet [8].

The flow is shown as entering the inlet at T_0, it is not compressed to rest, like in ramjet, but is brought to supersonic speed at T_2. Combustion occurs at this point. Heat is added at constant pressure and T_{max} is achieved at the exit of the burner. Then the gas is isentropically expanded to T_9 in the exit nozzle; T_{max} is dependent on the engine's maximum material operating temperature [8]. The maximum temperature is not affected by the type of fuel chosen and so for the purpose of this report when analyzing fuels, a T_{max} of 1900 K is used.

The first fuel to be examined is JP-7 or Jet Propellant 7. JP- 7 was developed by the U.S. military to be used in supersonic jets. Many aircrafts, like Boeing X-51 and SR-71, have previously used this fuel because of its high flash point (the lowest temperature needed for fuel to combust) and thermal stability [12]. JP-7 is a mixture of hydrocarbons with an additive fluorocarbon for increased lubrication. It is produced from special blending stocks so that it can have a low concentration of benzene and toluene. An advantage of this fuel is that it can operate at a wide range of temperatures. Its low volatility makes it flash resistant in high temperatures. Also, it contains cesium which helps disguise the radar and infrared signatures of the exhaust cloud. JP -7 has a high enough density that a large volume of it is not required to acquire enough chemical energy for usage. The high flash point indicates this fuel is not very flammable allowing it to be less hazardous. This can also be a disadvantage because it requires triethylborane to be injected in order to initiate combustion and so this has to be available on board [12]. Another disadvantage to think about is the pollution that hydrocarbons emit. This type of fuel is not the cleanest to burn because it produces monoxide and carbon dioxide.

JP-8 is a kerosene-based, hydrocarbon fuel commonly used in military aircrafts. It is created with the addition of icing and corrosion inhibitors, lubricants, and antistatic agents. It contains less benzene than other jet fuels, however it has a stronger odor and oily feel to it.

Although JP-8 has a slight lower hpr value than JP-7, it has a much lower flash point which makes it highly flammable and therefore eliminates the need for additives to help it ignite. A disadvantage of this fuel is that it has problems during cold start and idling due to low compression. Also, just like JP-7, pollution is released upon combustion. Furthermore, hydrocarbon fuels come from fossil fuels which are being depleted and so this JP-8 will probably only be used for a few more years [6]. Consequently, scientist have decided to try a cleaner, renewable energy source for fuel.

This leads to the third fuel being analyzed in this report, liquid hydrogen. Liquid hydrogen has recently started being used as fuel for scramjets for many reasons. It has become very appealing since its hpr value is extremely high relative to the hydrocarbon fuels. Hydrogen is extremely flammable it takes a small amount of energy to ignite and has a wide flammability range (it can ignite when it occupies 4% to 74% content of the air by volume [6]). Also hydrogen mixes well with air, making it a more efficient combustion. It also has minimum pollution and its widely available [5]. Some disadvantages that are associated with hydrogen fuel is its very low density (0.09 kg/m^3). This is a positive when it comes to reducing weight, but a negative in the fact that it requires a large volume to store enough chemical energy for practical use [6]. The density can be increased by cooling or pressurizing the fuel until it becomes liquid, but even so it would require double the storage of JP-8 to store the same amount of energy. Comparing to the JP fuels, more energy can be stored in smaller volumes of hydrocarbon which results in aircrafts being able to fly longer when using denser fuels than hydrogen. The cost and safety issues related to manufacturing liquid hydrogen are a downside. Even with these restrictions hydrogen is still very tempting because it has a more than double the h_{pr} value of most other fuels, which means it can produce a lot more thrust per mass than any other fuel available at the moment [6].

ANALYSIS

The following will present the equations used to examine the scramjet engine and the fuels previously discussed. Six performance parameters will be used for the mathematical analysis of the engine, two of which will depend on the lower heating value of the fuel and the rest will give a general overlook of the scramjet. Also, the thrust flux and area ratio will be included for a thorough understanding. To begin, a few variables will need to be defined. The total freestream stagnation temperature divided by the total freestream static temperature is represented by the variable τ_r and can be calculated using Eq. (1) [8]

$$\tau_r = 1 + \left[\frac{(\gamma - 1)M_o^2}{2}\right] \qquad (1)$$

The total enthalpy leaving the burner over the total freestream enthalpy is represented by τ_λ and can be calculated using Eq. (2) [8]. Taking into consideration the combustion Mach number as it compares to the freestream Mach number, one can decide which version of the equation to use.

$$\tau_\lambda = \frac{T'_{max}}{T_o} \quad for\ M_c < M_o \qquad\qquad \tau_\lambda = \frac{T''_{max}}{T_o} \quad for\ M_c \geq M_o \qquad (2)$$

T'_{max} and T''_{max} can be calculated through Eqs. (3a) and (3b) [8]

$$T'_{max} = T_{max}\left[1 + \frac{(\gamma-1)}{2}M_c^2\right] \quad for\ M_c < M_o \qquad (3a)$$

$$T"_{max} = T_{max}\left[1 + \frac{(\gamma-1)}{2} M_o^2\right] \quad for\ M_c \geq M_o \tag{3b}$$

Various other variables will be used in the parametric analysis and are defined in the nomenclature The first two equations that are discussed are the ones that are fuel dependent. These equations involve the lower heating value (h_{pr}) and so can be used to compare fuels. The fuel-to-air ratio *f* is shown in Eq. (4) [8]

$$f = \frac{c_p T_0}{h_{pr}} (\tau_\lambda - \tau_r) \tag{4}$$

and the thrust-specific fuel consumption S is shown in Eq. (5) [8]

$$S = \frac{c_p T_o g_c (\tau_\lambda - \tau_r)}{a_o M_o h_{pr}\left(\sqrt{\frac{\tau_\lambda}{\tau_r}} - 1\right)} \tag{5}$$

The next few equations do not depend on the fuel chosen but provide a general understanding of scramjets. Equation (6) analyzes the specific thrust [8].

$$\frac{F}{\dot{m}_o} = \frac{a_o M_o}{g_c}\left[\sqrt{\frac{\tau_\lambda}{\tau_r}} - 1\right] \tag{6}$$

The thermal efficiency is given by Eq. (7) [8]

$$\eta_T = 1 - \frac{1}{\tau_r} \tag{7}$$

The propulsive efficiency is given by Eq. (8) [8]

$$\eta_P = \frac{2}{\sqrt{\frac{\tau_\lambda}{\tau_r}} + 1} \tag{8}$$

Overall efficiency is given by Eq. (9) [8]

$$\eta_o = \eta_T \eta_P = \frac{2(\tau_r - 1)}{\sqrt{\tau_\lambda \tau_r} + \tau_r} \tag{9}$$

The thrust flux is given by Eq. (10) [8]

$$\frac{F}{A_2} = \left(\frac{F}{\dot{m}_o}\right)\left(\frac{\dot{m}_o}{A_2}\right) \qquad (10)$$

This equation can be separated into three simpler equations for easier calculation. Equation (11) is the mass flux part which is separated into two more equations for simplicity, Eqs. (12) and (13) [8].

$$\frac{\dot{m}_o}{A_2} = g(\gamma, R)\left(\frac{A^*}{A}\right)\frac{P_0}{\sqrt{T_0}}{\tau_\lambda}^3 \qquad (11)$$

$$\frac{A^*}{A} = \left\{\frac{1}{M_2^2}\left[\frac{2}{(\gamma+1)}\left(1 + \frac{(\gamma-1)}{2}M_2^2\right)\right]^{\frac{\gamma+1}{\gamma-1}}\right\}^{\frac{-1}{2}} \qquad (12)$$

$$g(\gamma, R) = \sqrt{\frac{\gamma}{R}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \qquad (13)$$

The last equation that will be used for the analysis will be the area ratio, Eq. (14) [8].

$$\frac{A_4}{A_2} = \sqrt{\frac{\tau_\lambda}{\tau_r}} \qquad (14)$$

RESULTS

The following figures illustrate the results from the parametric equations presented in the prior section. The performance parameters are presented as a function of the combustion Mach number (M_c) and are plotted against the freestream Mach number (M_o). The values for $T_o = 217$ K, $P_o = 19{,}403$ Pa, $T_{max} = 1900$ K, $c_p = 1.004$ kJ/(kg K), $\gamma = 1.4$ are used for all the equations. The h_{pr} will depend on the fuel being analyzed. For JP-7, $h_{pr} = 43{,}500$ kJ/kg for JP-8, $h_{pr} = 43{,}190$ kJ/kg and for hydrogen, $h_{pr} = 119{,}600$ kJ/kg. The solid lines represent when $M_c < M_o$, while the dashed lines represent when $M_c > M_o$. Where the solid line intersects when the dashed line corresponds to when $M_c = M_o$. The solid line shows the most likely operating circumstances for the ideal scramjet. The dashed line shows the theoretically possibilities for the ideal scramjet. Figures 5-10 demonstrate the performance parameters that are independent of fuel choice. The last two figures shown in this section corresponds to the comparison of the fuels based in their fuel to air ratio and thrust specific-fuel consumption values.

Figure 5 shows the thermal efficiency (total net workout over the heat added) as a function of the flight Mach number M_o. The thermal efficiency is the energy contained in the fuel. It can be seen that as the flight Mach number (M_o) increases the thermal efficiency also increases. An ideal scramjet can operate at higher values than the ramjet, the thermal efficiency theoretically can surpass 90%. As seen from figure 5, there is only one line plotted because the thermal efficiency

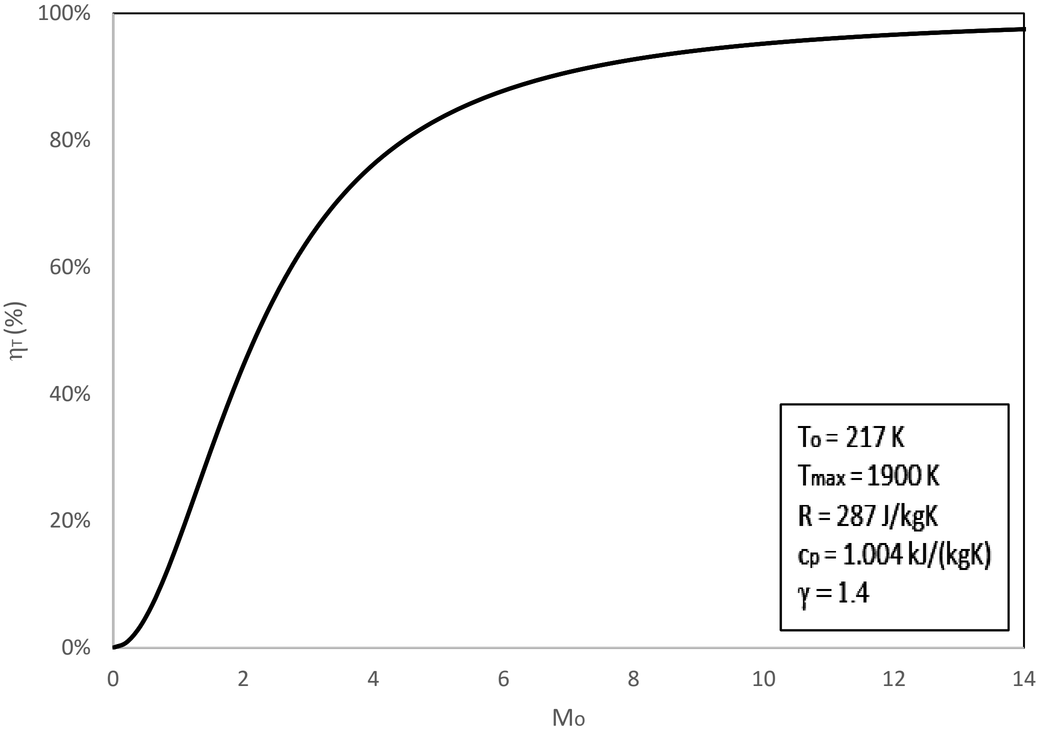

Figure 5- Ideal scramjet thermal efficiency (η_T) versus free-stream Mach number (M_o).

is independent of combustion Mach number (M_c). Figure 6 illustrates the propulsive efficiency as a function of M_o, using M_c as a parameter. It can be seen that the propulsive efficiency increases with increasing flight Mach number but only when $M_c < M_o$ (solid line). The figure shows that when Mc > Mo (dashed line) the propulsive efficiency is constant. The higher the combustion Mach number is the higher the flight Mach number has to be to achieve the same propulsive efficiency as a lower Mach number. The propulsive efficiency is the amount of work, out if the total network, that actually propels the aircraft. This can replace the energy lost to gravity, drag, and acceleration. Figure 7 demonstrates the overall efficiency as a function of M_o. The overall efficiency is the amount of work actually propelling the aircraft over the total energy in the fuel. The overall efficiency increases with increasing flight Mach number. The scramjet operates overall more efficiently as M_o increases.

Presented in figure 8 is the specific thrust as a function of M_o, at different Mach numbers. As the combustion Mach number increases, the maximum specific thrust peak increases also. As the freestream Mach number increases the specific thrust decreases. Specific thrust is important because it indicates the force per unit mass of air in the engine. Having a higher combustion Mach number can be seen as correlating with a higher specific thrust which means that the engine is producing more thrust for the same amount of airflow.

Figure 9 is showing the thrust flux as a function of M_o at different M_c values. The thrust flux gives a better indication than the specific thrust of the M_o at which the scramjet thrust achieves a maximum value. The thrust flux can be useful in deciding what combustion Mach number to use. The best option is to find the lowest combustion Mach number that still produces enough thrust. The lower the combustion number, the slower the airflow is in the combustion chamber and therefore the fuel has more time to ignite. The figure shows the rapid progression of increasing

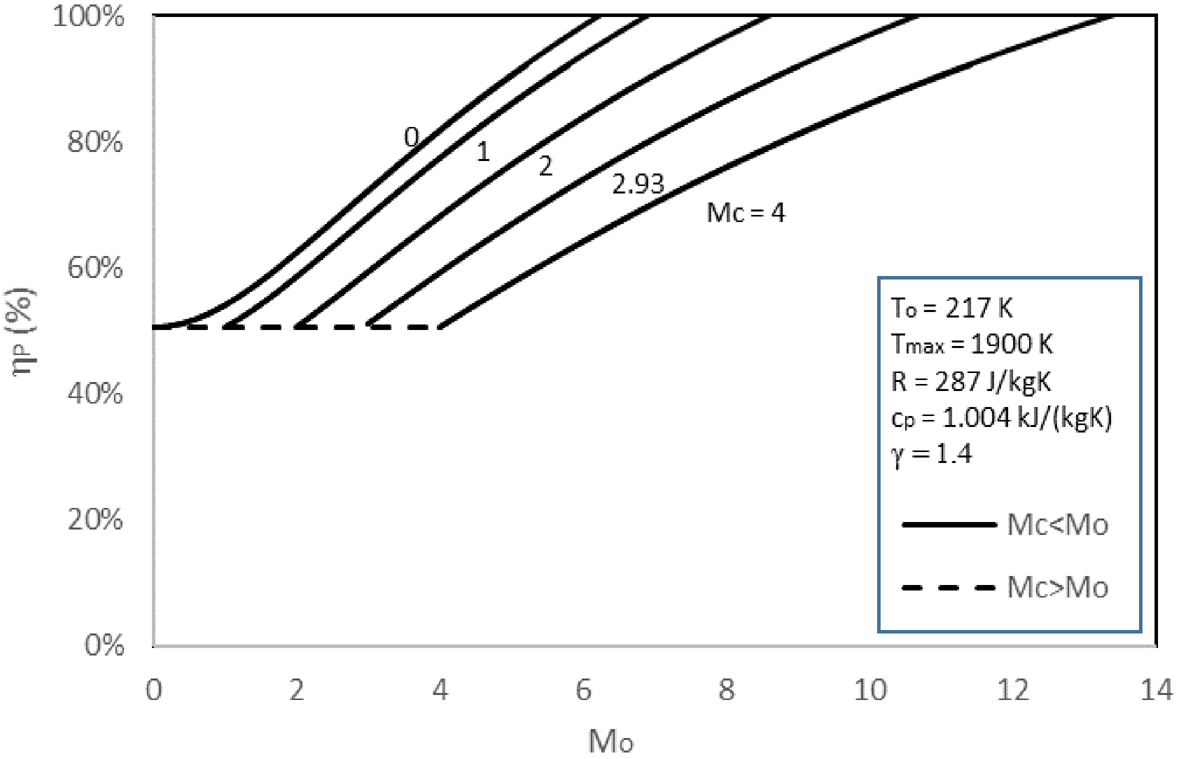

Figure 6- Ideal scramjet propulsive efficiency (η_P) versus free-stream Mach number (M_o).

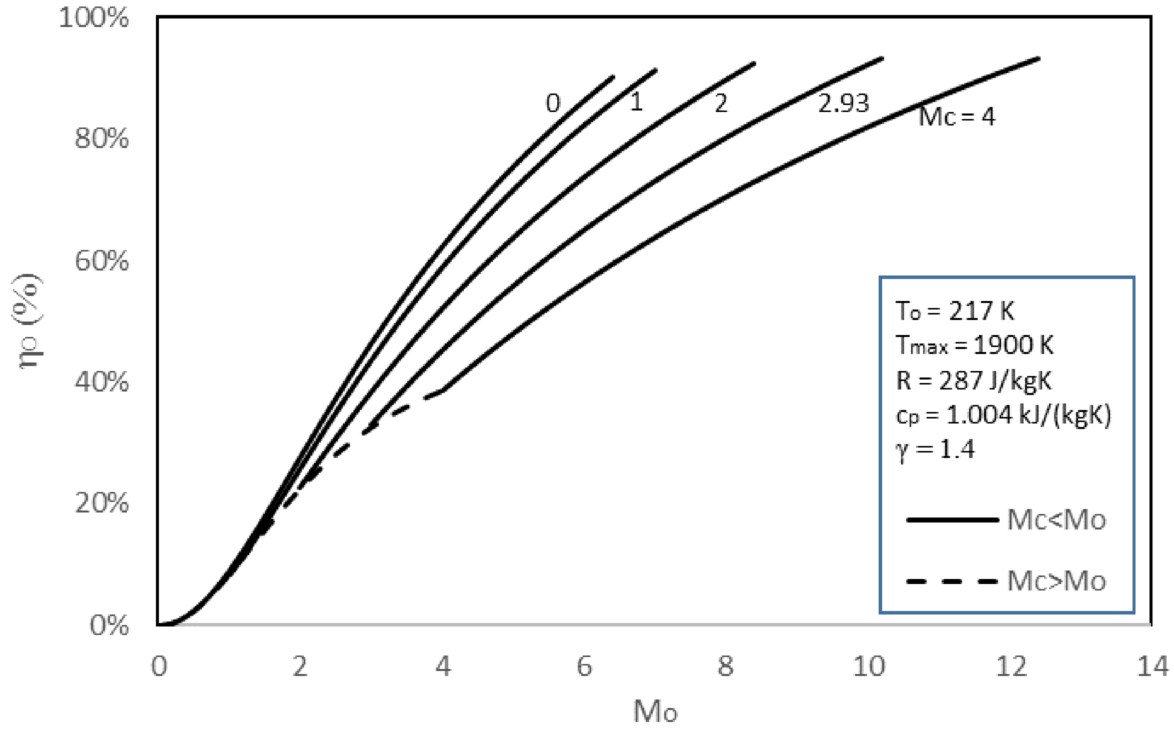

Figure 7- Ideal scramjet overall efficiency (η_o) versus free-stream Mach number (M_o).

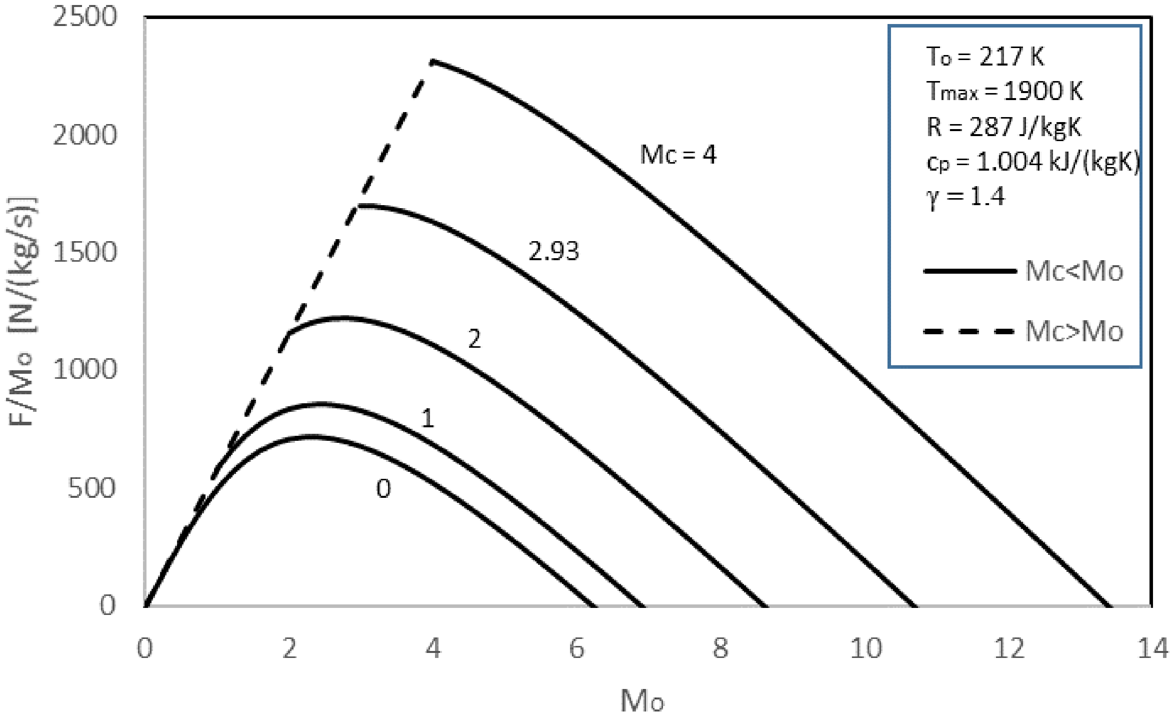

Figure 8- Ideal scramjet specific thrust (F/ $\dot{m}_o$) versus free-stream Mach number (Mo).

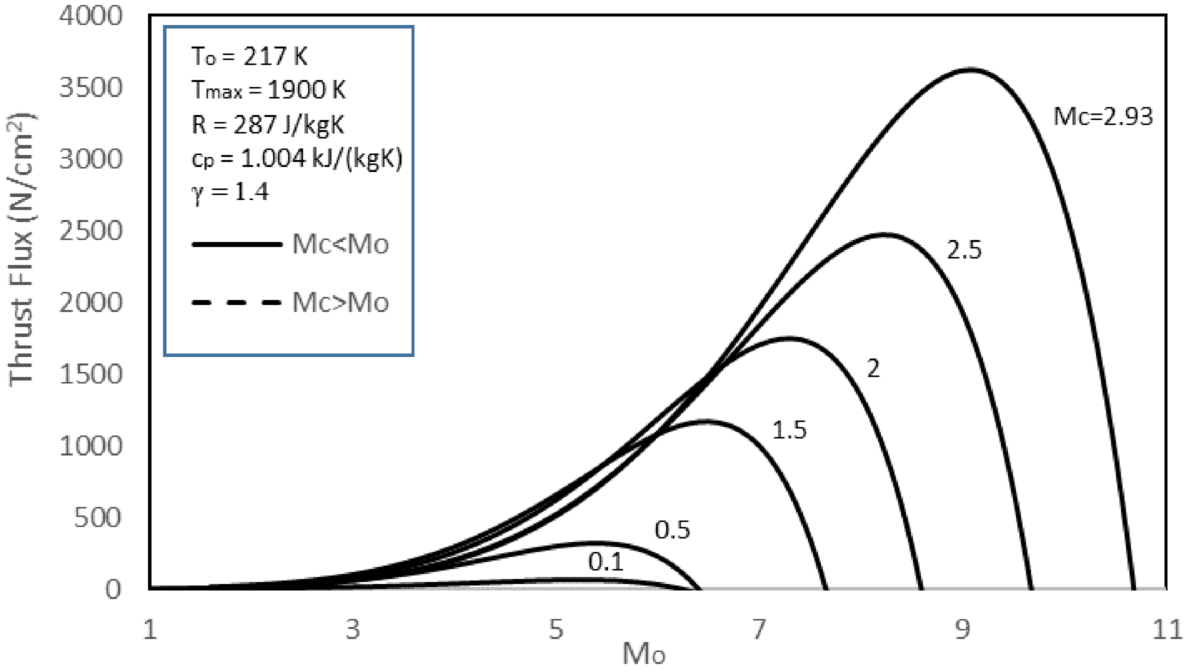

Figure 9- Ideal scramjet thrust flux versus free-stream Mach number (Mo).

thrust flux values as combustion Mach number increases. Figure 10 shows the combustion chamber area ratio as a function of M_o at different M_c. As the freestream Mach number increases and $M_c < M_o$, the area ratio decreases. When $M_c > M_o$ the area ratio stays constant. Having an area ratio greater than 1 means that the exit area is bigger than the entrance area resulting in a divergent nozzle. Knowing the desired flight Mach number and combustion Mach number, one use figure 10 and find the area ratio needed to achieve this.

The next two figures (figs. 11 and 12) show a comparison of the fuels at the same combustion Mach number of $M_c = 4$. For a more comprehensive analysis of each fuel, at different combustion Mach numbers, Appendix provides figures 13-18 with this information for fuel-to-air ratio and thrust-specific fuel consumption. Figure 11 shows fuel-to-air ratio as a function of freestream flight Mach number. This figure shows the trends for all three fuels for ease of comparison. It can be seen that the fuel-to-air ratio, regardless of the fuel chosen, will increase with increasing M_o when $M_c > M_o$ but will decrease with increasing M_o when $M_c < M_o$. Another thing notice is that the higher the h_{pr} value of the fuel is, the lower the range of the fuel-to-air ratio will be. The fuel-to-air ratio is important because it gives the information of how much fuel is needed per air mass to operate the jet engine. A lower fuel-to-air ratio means less fuel is required for the engine to work which makes the engine more efficient. In figure 11 one can see that hydrogen has the lowest fuel-to-air ratio which is accurate because that corresponds to the higher h_{pr} value from the three fuels selected. JP-7 and JP-8 have almost the same fuel-to-air ratio range and are almost double the values of hydrogen.

Figure 12 demonstrates the thrust-specific fuel consumption (S) as a function of M_o, using M_c as a parameter. All three fuels are depicted at $M_c = 4$ for comparison. Liquid Hydrogen is seen as having the lowest S range. JP-7 and JP-8 have very similar S ranges. When $M_c > M_o$, it is seen

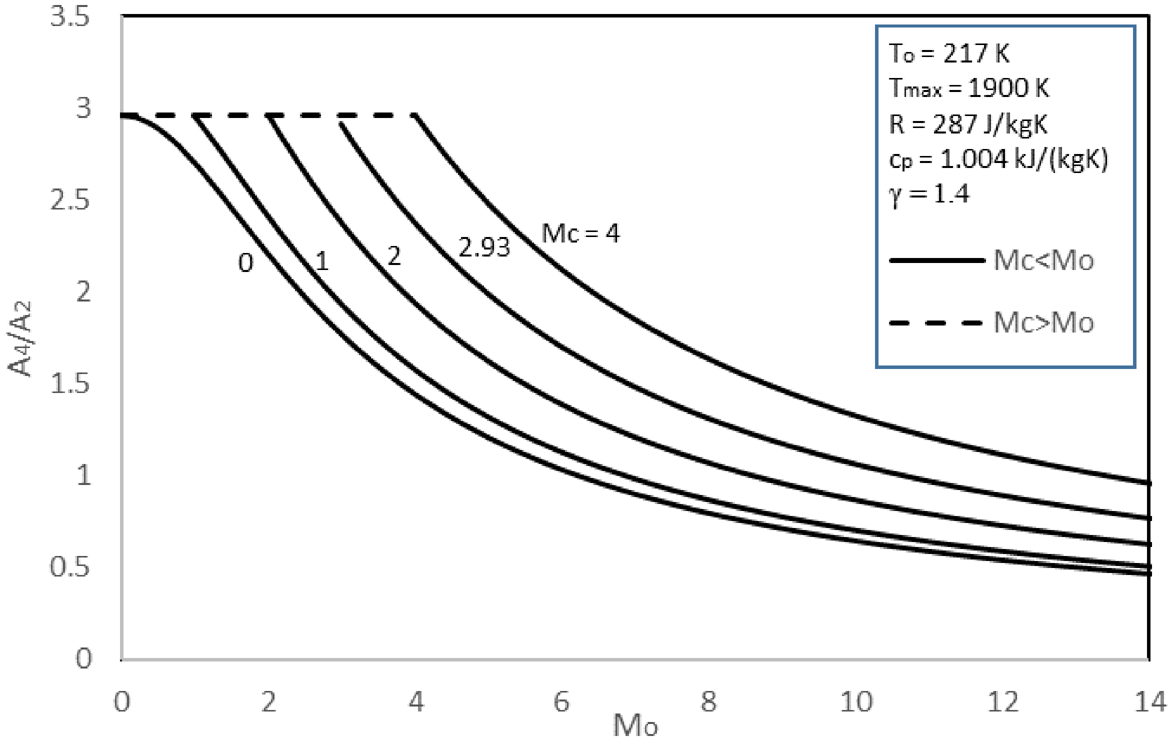

Figure 10- Ideal scramjet area ratio versus free-stream Mach number (M_0).

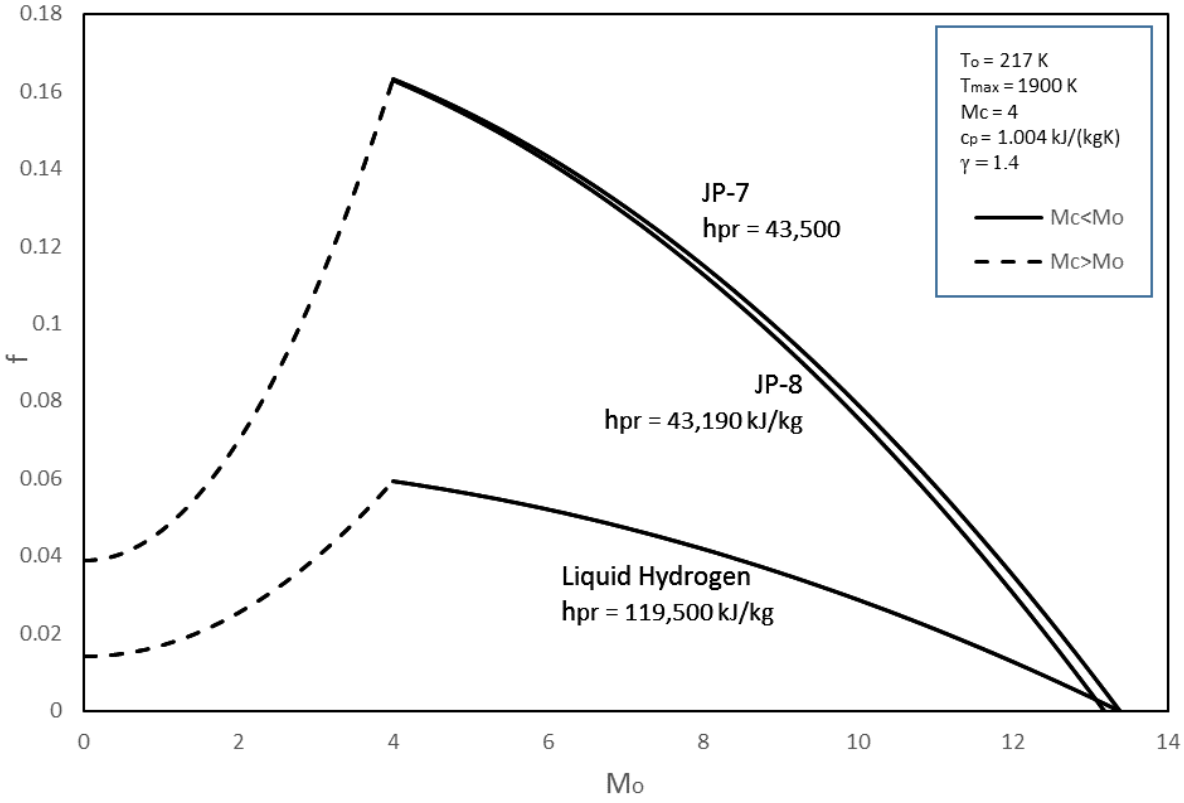

Figure 11- Ideal scramjet fuel to air ratio (f) versus free-stream Mach number (M_o) at M_c=4.

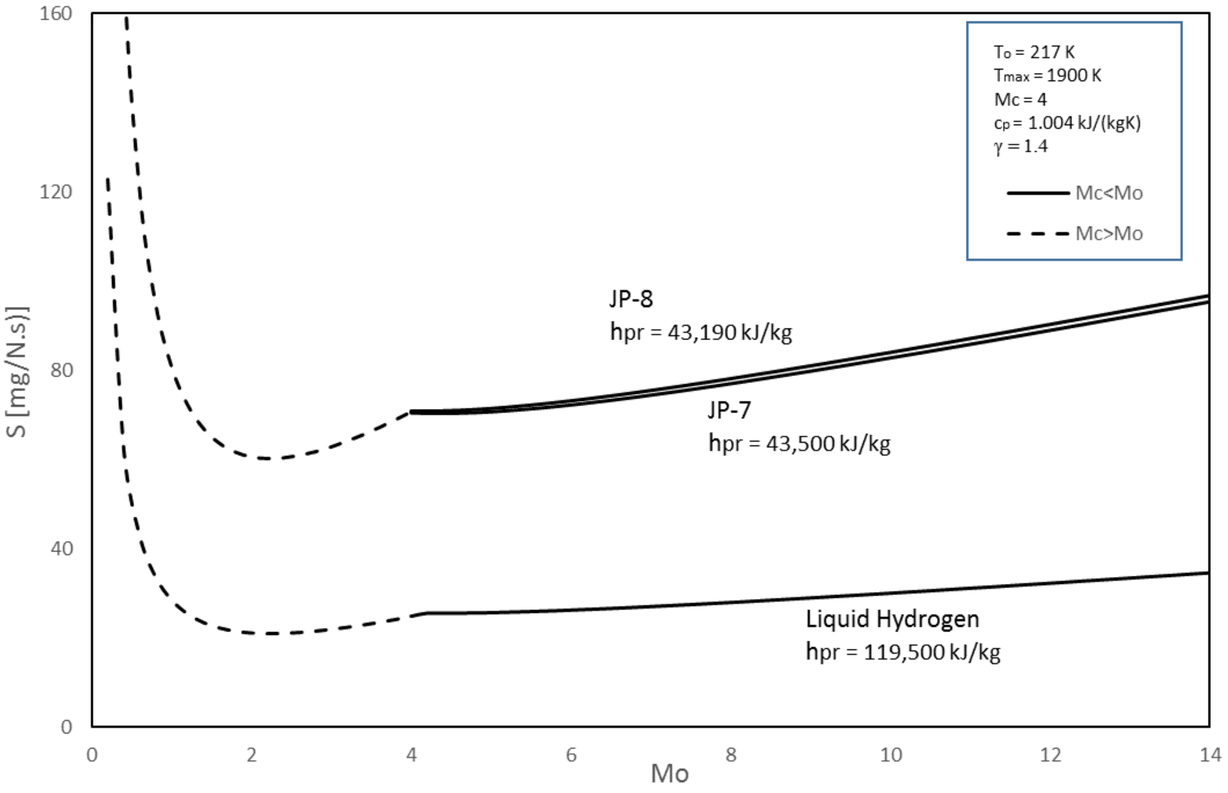

Figure 12- Ideal scramjet thrust-specific fuel consumption (S) versus free-stream Mach number (M_o) at M_c=4.

that S drastically decreases and then start to increase at about a flight Mach number of 4 where it reaches $M_c<M_o$ and then the trend starts to slightly increase with increasing flight Mach number. This is one area where the scramjet is not as efficient as the ramjet. The scramjet has to run at a higher S than a ramjet. The thrust-specific fuel consumption is the fuel efficiency of an engine with respect to thrust. S lets one know the amount of fuel consumed. A high S means that a lot of fuel is consumed to provide the thrust needed. The lower the S the more efficient the fuel is and so less is required to operate the engine for a specified amount of time. Hydrogen is shown to have a lower S than JP-7 and JP-8, it would require lesser amounts of hydrogen fuel than the JP fuels to power the engine the same amount of time.

CONCLUSION

The analysis of a scramjet through the performance parametric equations has been expressed. A focus on three fuels: hydrogen, JP-7, and JP-8 has been presented. The advantages, disadvantages and efficiencies of the fuels were shown and discussed to give a better understanding. Also, various combustion Mach numbers have been compared and the trends were examined. As a fuel, hydrogen surpassed the rest of the choices for many reasons. Its super high h_{pr} value allows it to burn the fastest and provide a lot of thrust. As seen from the figures hydrogen has a lower fuel to air ratio, meaning it requires less fuel to produce thrust but not only that it has a low thrust specific value which means it burns less fuel per hour. Also as stated earlier, hydrogen reduces much of the pollution that could be emitted from engines. It is widely available and safe. It requires a large volume to store enough chemical energy to be useful. JP-7 and JP-8 are not as efficient as hydrogen but still efficient enough to be considered. Their density is much larger and so not as much volume is needed, which allows the aircraft to fly longer. As a recommendation for a future analysis, a wider range of fuel choices should be researched.JP-7 and JP-8 were two similar to see any advantage over the other, while as hydrogen was very different and proved to be the better fuel choice by a landslide. Its only negative being the expense of having to manufacture it while the hydrocarbon fuels are much cheaper to use. This report hopefully provides understanding of what to look for when deciding on the best fuel option.

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APPENDIX A

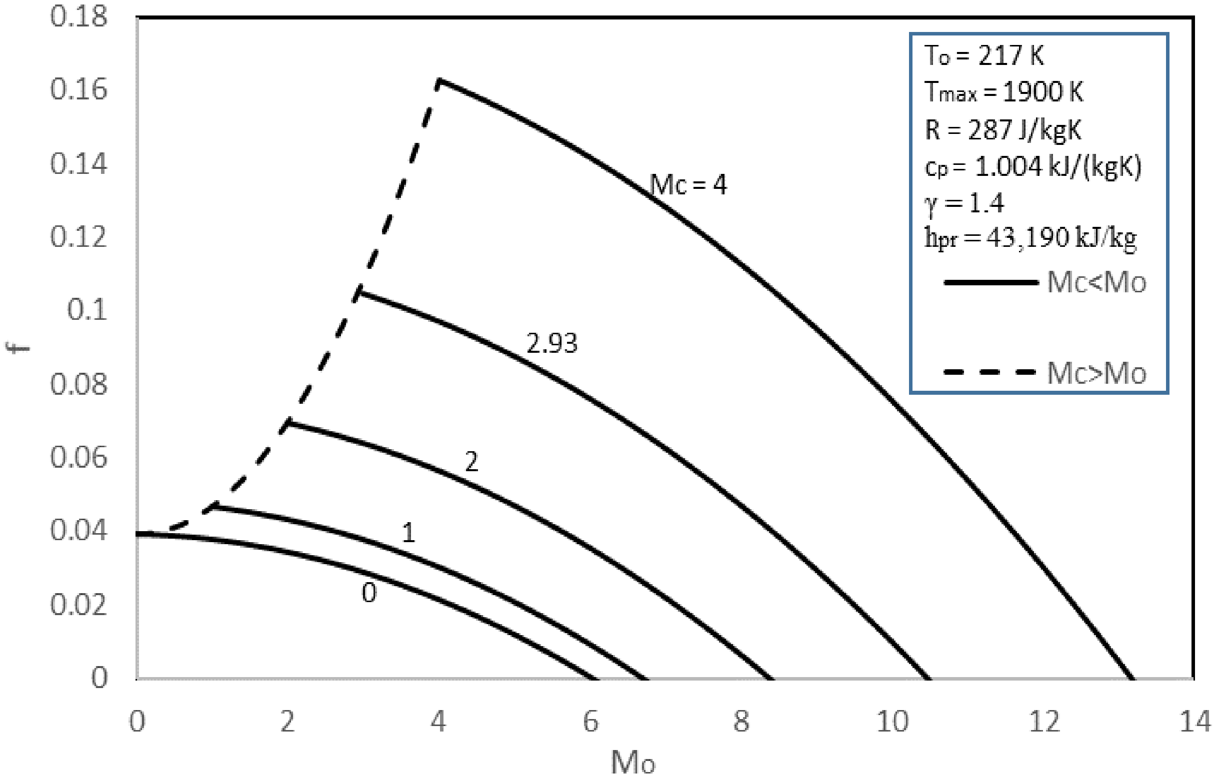

Figure 13- Ideal scramjet fuel to air ratio (f) versus free-stream Mach number (M_o) for JP-8 fuel.

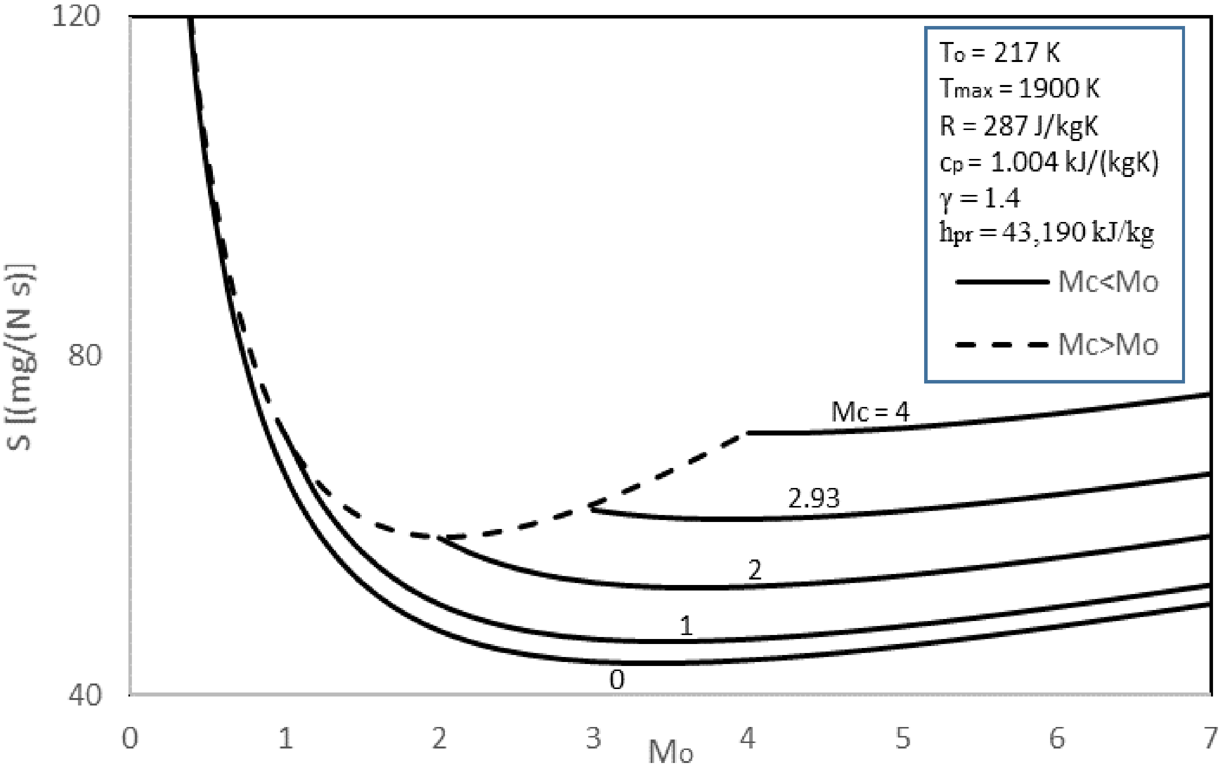

Figure 14- Ideal scramjet thrust-specific fuel consumption (S) versus free-stream Mach number (M_o) for JP-8 fuel.

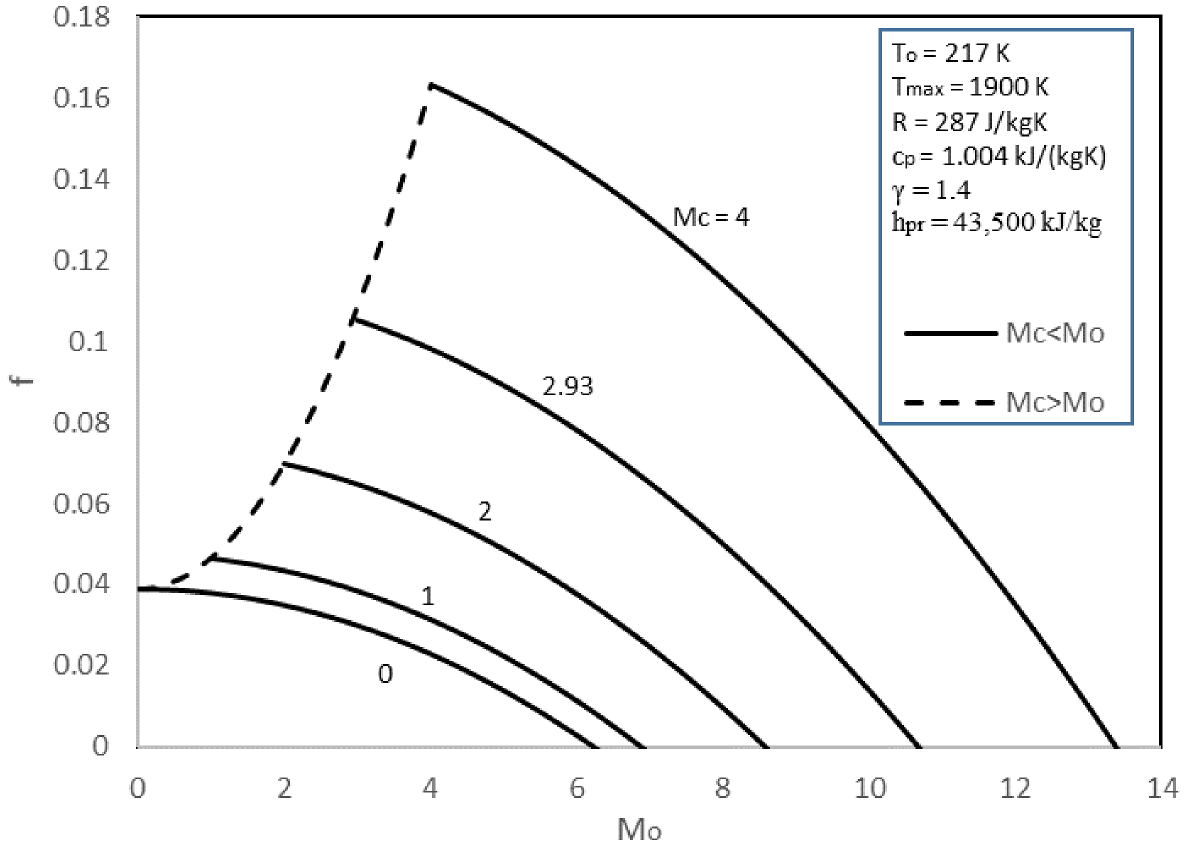

Figure 15- Ideal scramjet fuel to air ratio (f) versus free-stream Mach number (M_o) for JP-7 fuel.

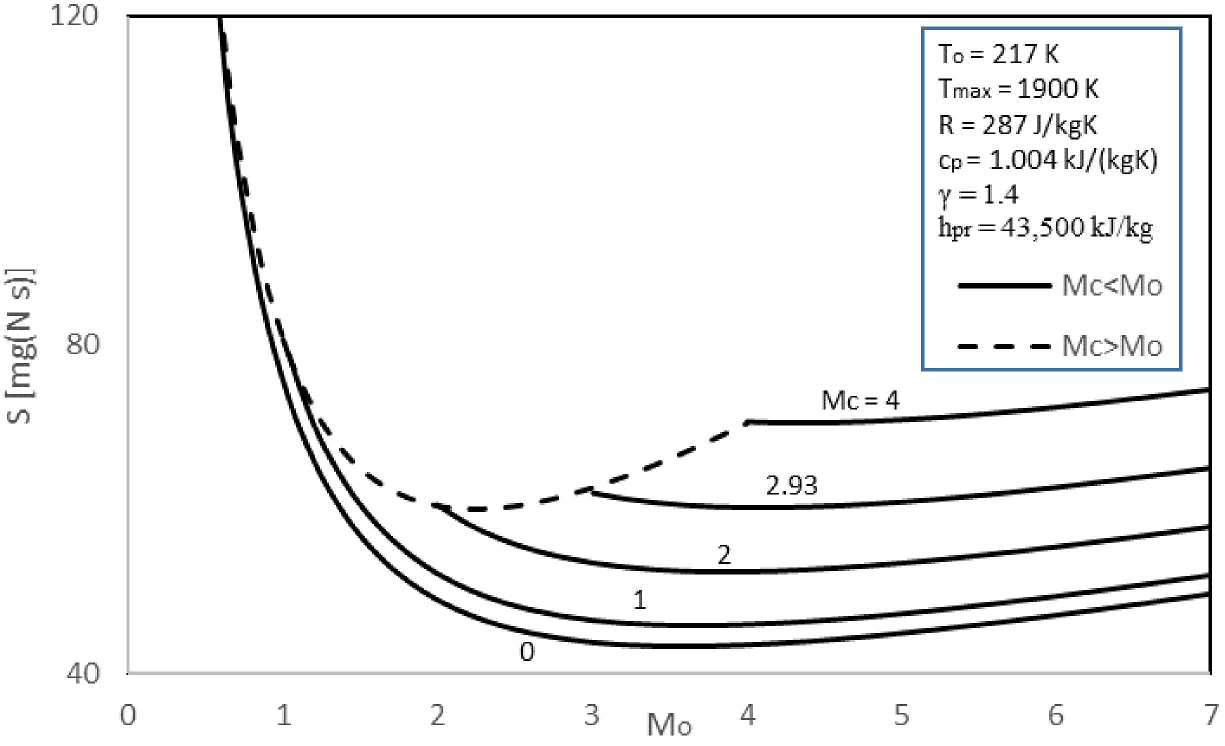

Figure 16- Ideal scramjet thrust-specific fuel consumption (S) versus free-stream Mach number (M_o) for JP-7 fuel.

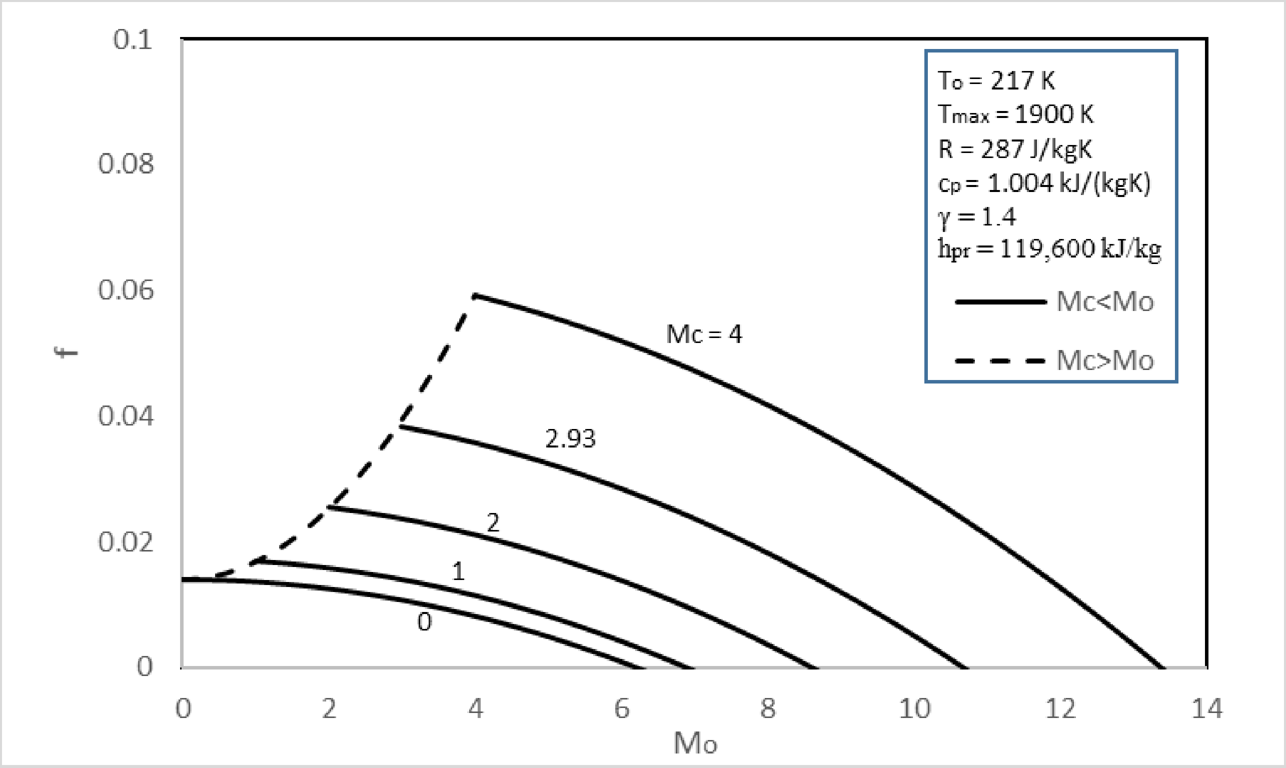

Figure 17- Ideal scramjet fuel to air ratio (f) versus free-stream Mach number (M_o) for Hydrogen fuel.

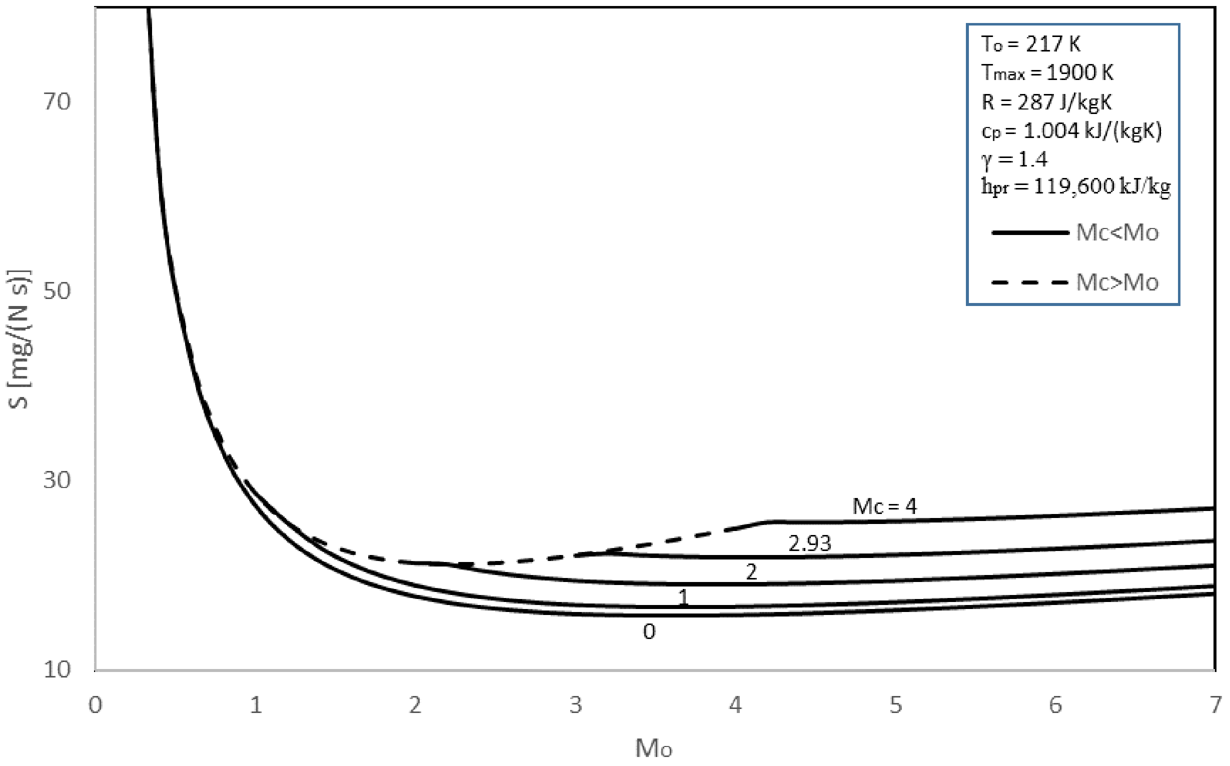

Figure 18- Ideal scramjet thrust-specific fuel consumption (S) versus free-stream Mach number (M_o) for Hydrogen fuel.