Scramjet Engine Optimization

ENME 5910: Advanced Fluids

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Abstract

The scramjet engine is one of the main components for both supersonic and hypersonic flight. Optimizations of the scramjet engine occurs to determine ways to produce longer flight duration (distance) or more thrust production (speed). This paper will focus on 5 different optimizations techniques including exergy optimization, combustion geometry optimization, Strut fuel injectors with afterburners optimization, fuel optimization, thermodynamic system optimization. From these five optimizations techniques three main facts were synonyms throughout the papers the more mixing that occurs the more combustion will take place, heating the fuel before entering the combustor will provide a higher combustion efficiency, and creating a high force is easy enough to produce, but the sacrifice is generally the specific impulse of the fuel.

Introduction

Propelling a vehicle at supersonic or hypersonic speeds is not a simple task, a scramjet engine (supersonic combustion ramjet engine) is the leading set up to make flights in these regimes possible. A scramjet engine is made up of four main parts the inlet, isolator, combustor, and nozzle. Where the main purpose is to take in supersonic/hypersonic air and slow the flow in the inlet using a diffuser, direct the flow axially in the isolator, cause a chemical reaction between the air and fuel in the combustor creating a large force that is accelerated out the back of scramjet engine as an exhaust/propellant at a diverging nozzle. Now that scramjet engines have been successfully designed the next course of action is to optimize the scramjet engine so that either the duration of flight can be increased or the force of the propellent can be increased. This paper details five different methods of increasing the force, time duration, or fuel amount/concentration in the scramjet engine including an exergy balance optimization, flame holder and combustor geometry optimization, strut fuel injector with after burning optimization, water injection in the combustion process optimization, and a Re-cooled scramjet engine optimization. The optimization of the scramjet engine can lead to further successes in sustained hypersonic flight, missile system enhancement, and even low orbital flight. Scramjet engines are the future of supersonic/hypersonic flight and must be understood and optimized to ensure a forward moving aeronautical future.

Scramjet engine Optimization

Exergy Balance optimization:

Meijun Zhu, Shuai Zhang, Yao Zheng preformed an exergy balance on a scramjet engine to minimize exergy destruction, which directly relates the entropy generated within the scramjet engine. Exergy can also be described as the quantity of lost work, so their analysis can be described as finding where work was being lost with in a scramjet engine and finding ways to minimize that loss. The figure to the right shows the model of the scramjet engine, in centimeters, that was used in their analysis. They decided to use the specific impulse and exergy efficiency as evaluation points to determine how their optimization effected the characteristics of the scramjet engine.

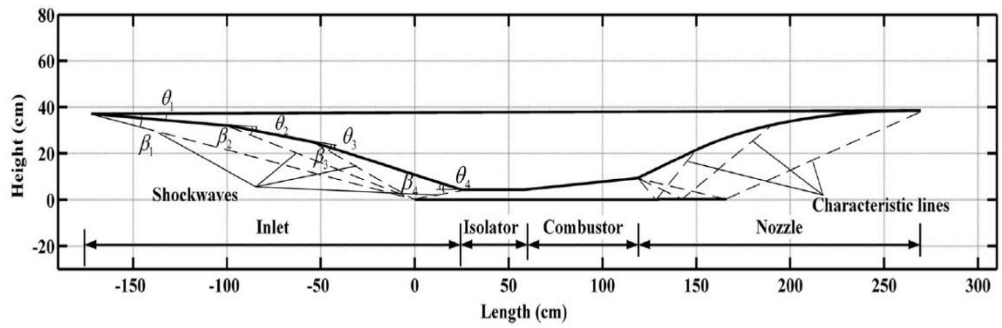

Figure 1 Scramjet engine model for exergy balance [5]

To start their analysis an exergy balance needed to be conducted to determine initially where the largest amounts of exergy destruction were occurring. They broke exergy down into three types as shown in figure 2, to the left, where they considered exergy transfer by mass, heat, and work. It should be noted that mass transfer exergy was only considered at the inlets and outlets of the scramjet engine where it has the highest values, similarly that work and heat transfers of exergy were only considered with in the combustor where loses due to heat and work where at its highest values. To determine these values, they kept the flight altitude, Mach number, angle of attack, mass flow rate, combustion efficiency, pressure efficiency, expansion efficiency, the fuel equivalency ratio,

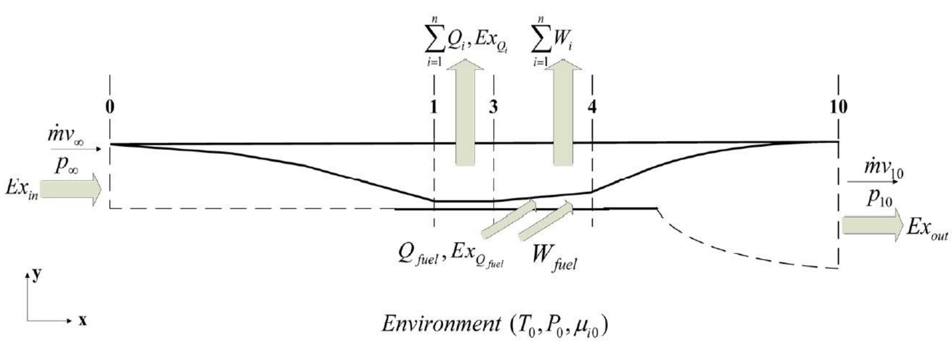

Figure 2 Exergy Free Body Diagram [5]

temperature, and type, and injection diameter constant. While altering the static temperature ratio, forebody high, the length of the combustor, axial velocity of fuel injection, fuel injection rate, pressure entering the nozzle. This led them to the finding that as the impulse of the scramjet engine increased the exergy efficiency of the scramjet engine decreased, and that almost all exergy destruction occurred in either the nozzle and or combustor [5]. They also determined that the highest impulse was related to the highest thrust and that the highest exergy efficiency related to the highest efficiency of the fuel energy [5]. A deeper look into fuel efficiency and utilization will be conducted later in this paper.

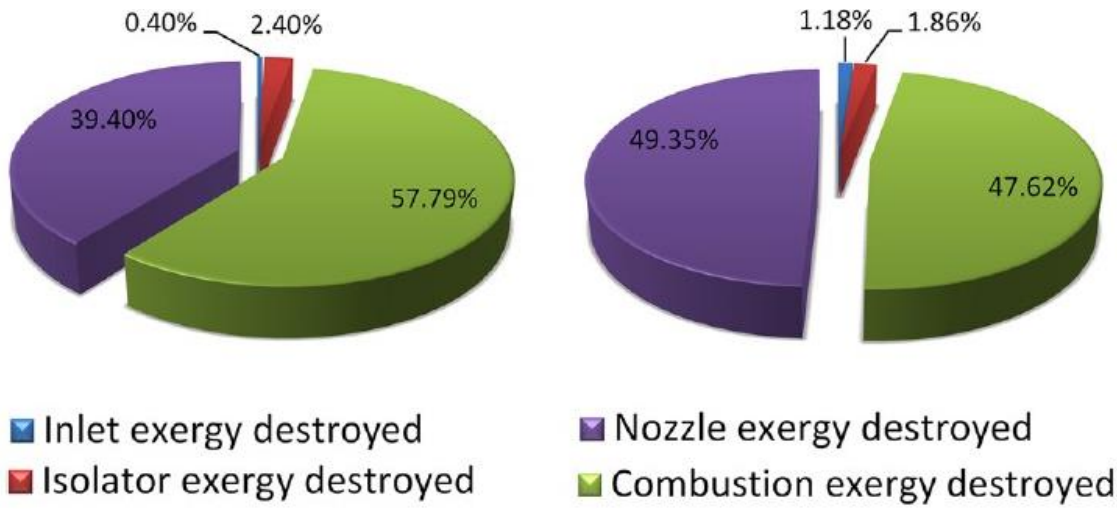

Figure 3 exergy destruction and impulse [5]

The results of their analysis can be seen in the figure above which shows the exergy destroyed by components on the right at optimal impulse (force over time) and on the left by optimal exergy efficiency [5]. This leads to the conclusion that the nozzle and combustor sections of the scramjet engine should be focused on to provide higher thrust or longer flight. These results can be observed in the figure to the right which involves a deeper analysis into the combustor, which shows that as the static temperature ratio between the incoming air entering the combustor and the fuel temperature is increased the specific impulse is increased. This is to be expected

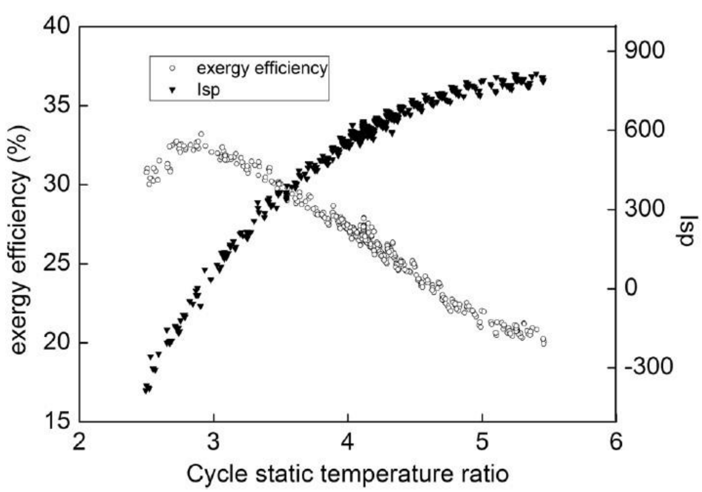

Figure 4 Exergy efficiency vs impulse vs temperature ratio [5]

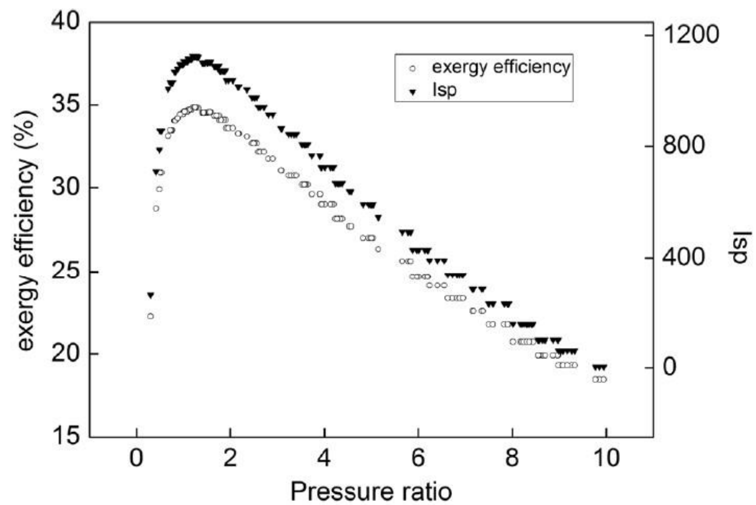

Figure 5 Exergy Efficiency vs impulse vs Pressure ratio [5]

because as the temperature of the combustion process becomes larger a more complete combustion process occurs between the fuel and the air [5]. The exergy efficiency decrease is explained by the increase in combustion causing an increase in the exhaust temperature that will cause the heat transferred exergy to increase [5]. The figure above shows how the exergy efficiency and impulse is decreased as pressure ratio between the incoming pressure at the nozzle and exit pressure of the nozzle increases from its maximum value of 1 or ideal to 10. These results confirm the understanding that if a desired altitude is known, then a scramjet engine nozzle should be designed to exhaust at a pressure equal the atmospheric conditions because that will provide the highest exergy efficiency and impulse. The figure below shows the results of the optimization in the geometry of the scramjet engine lengths between exergy efficient, impulse efficient, or pareto efficient, which refers to a situation were no parameter is optimized that would take away optimization from another parameter. Due to the pressure ratio causing both exergy efficiency

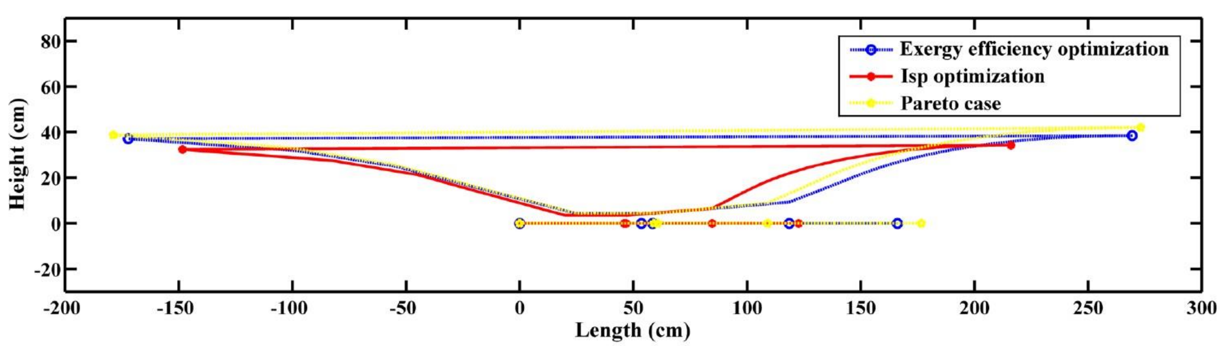

Figure 6 exergy, impulse, and Pareto geometries [5]

and impulse to decrease it was set at a pressure ratio 5 because that is the standard value [5]. It can be noticed that specific impulse efficiency model is shorter in length and thinner in width then the other two models which would allow for more mixing and more complete combustion process to occur due to less area in the combustor. Where the larger length exergy efficient model would provide less heat exergy loss in the combustor and less kinetic and enthalpy loses in the nozzle [5]. Where the Pareto model shows that there will always be a cost to completely optimize to a maximum impulse or exergy efficiency. In other studies, discussed in this paper, a deeper look into combustor geometry will be considered. The results determined by Meijun Zhu, Shuai Zhang, Yao Zheng show that a more compact scramjet engine will provide more impulse and therefore in this case more thrust, while a longer scramjet engine will provide longer flight duration due to minimized exergy loses. In the final remarks it was noted that if a high impulse is needed for the effectiveness of a mission that exergy efficiency may need to be sacrificed since one cannot be increased without lessening the other[5].

Flame holder optimization

Obula Reddy Kummithaa, Krishna Murari Pandeyb, and Rajat Guptab conducted an analysis with hydrogen as their fuel and using computational fluid dynamics and measured optimization of the combustor of a scramjet engine in terms of mixing and combustion efficiencies. Where the top image in figure 7 is a standard passive fuel injected combustor system. Passive injection (transverse) refers to fuel being injected upstream of the combustion process; the second figure introduces the wave bottom of the combustor which is meant to increase temperature and pressure in the combustor by decreasing the velocity causing a reduction in ignition delay and increase the chance of early combustion; the third image adds an angled top to the combustor to direct the flow and to encourage mixing; while the fourth image uses both the direct and passive fuel injection [2]. Where direct injection

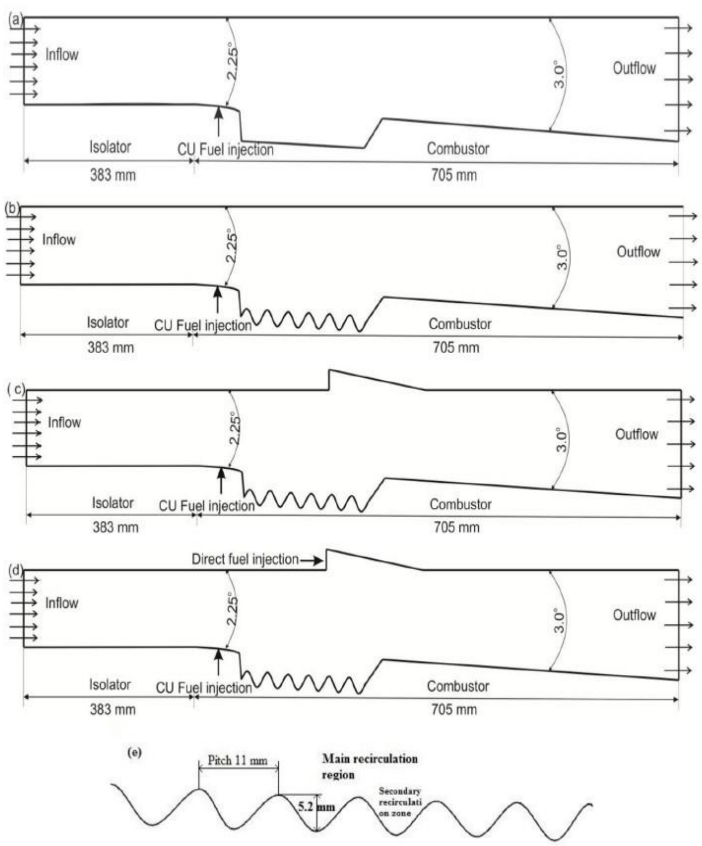

Figure 7 combustor alterations [2]

(parallel) is not premixed and is injected from the wall of the combustor [2]. The figure to the right shows how the four different model effected the overall mixing within the combustor. Where at the top image, the only mixing is occurring at the bottom where the combustor's depth changes. The introduction to the wave bottom in image two provides a larger circulation region due to the wave bottom, this can be seen by there being more change in the density contour in the second image then in the first. The third image provides a secondary mixing region which is due to the second converging section added to the top of the combustor, but because there is nothing directing the flow a very wavy density gradient and tight recirculation region can be observed. While the finale image in figure 8 shows the effects of the direct injection being added to the combustor, and the density gradient becoming more directed, but the two mixing regions are maintained.

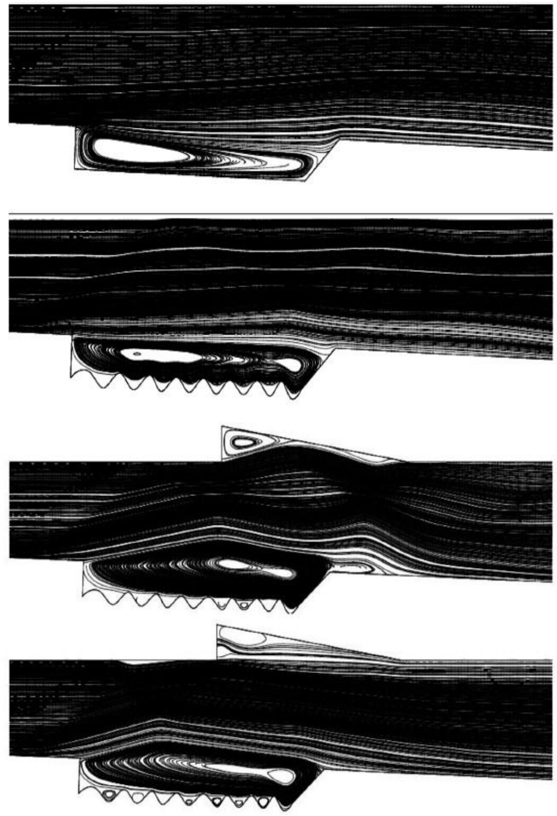

Figure 8 density contours [2]

Where an overview of the flow velocity from the start of the combustor to the end of the combustor can be viewed in figure 9. The velocity is compared to the height of the combustor to help in the visualization of the alterations to the combustors that were shown in figure 7. From figure 9 it can be observed that the wave bottom and the converging nozzle with direct

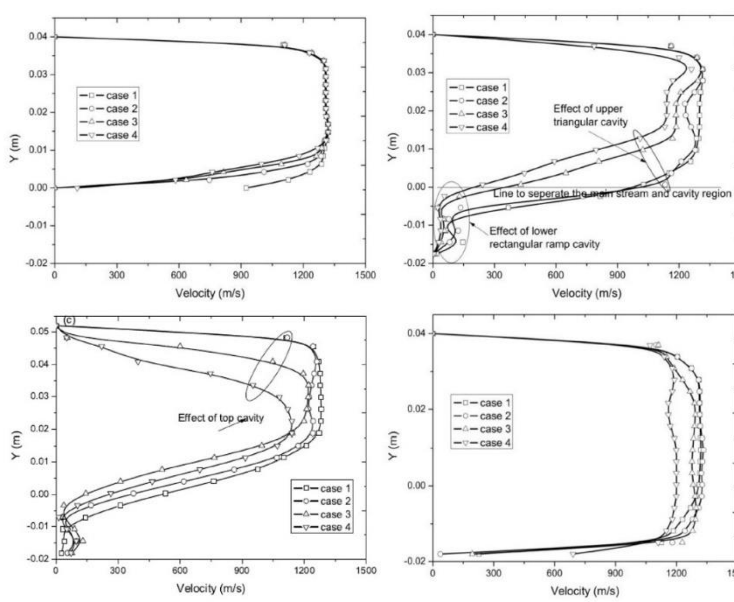

Figure 9 velocity within the combustor [2]

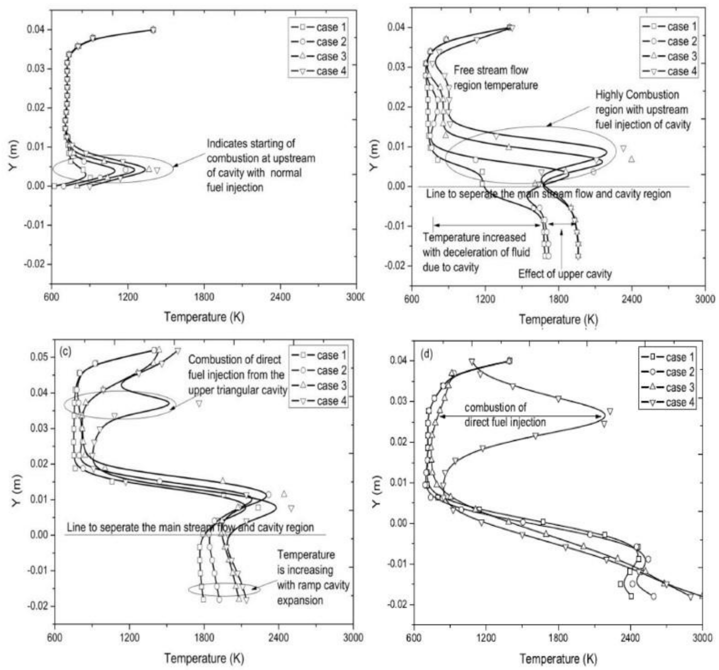

Figure 10 temperature within the combustor [2]

fuel injection caused the velocity within the combustor to decrease, thus allowing more time for mixing and complete combustion to occur. As expected, the temperature acted inversely to the change in velocity, at the point of direct injection the temperature increases even further. The increase temperature allows for a more complete reactions to occur. It should be noted that the effects of the direct fuel injection or wave bottom do not affect the tempeture at the outlet of the combustor which can be seen on the bottom right image of figure 10, where temperature with and without direct injector or with or without wavy bottom are all close temperature values at the combustor exit [2]. When compared to the analysis that was completed in the exergy balance study these results are favorable because this means there will not be a much larger exergy lose due to heat transfer at the exit of the combustor. The figure to the right shows the production of H2O as a mass fraction within the combustion process. The figure shows that throughout the combustion process that more H2O is produced when the direct fuel injection and wave bottom are used in the combustor [2]. The value in the bottom right shows a higher mass fraction in the first two models compared to the third and fourth models because most of the combustion has already been completed for the third and fourth model by the time it reaches the end of the combustor [2]. From the data determined from figure 9,10, and 11 enough

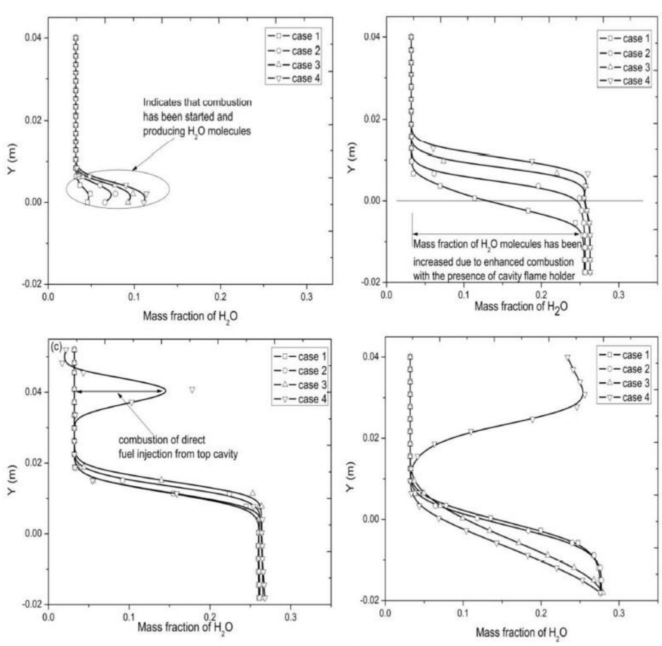

Figure 11 H2O mass fraction concentration within combustor [2]

information was understood to compare the four methods mixing and combustion efficiencies. The results showed the fourth case provided the highest mixing efficiency which can be seen in figure 12. The highest mixing efficiency occurred in case 4 because it had a secondary mixing region when compared to cases 1 and 2, as well as the flow being directed when compared to case 3, which had more wavy flow as shown in figure 8. It should be noted from figure 12 that the largest changes in mixing efficiency occurred when the wave bottom was added between models 1 and 2 and when the direct injection was added between models 3 and 4 [2]. Figure 13 shows the combustion efficiency follows the same trend as the mixing efficiency where case 4 has the highest efficiency. Similarly, to the discussion about figure 12 the wave bottom and direct fuel injection are what make case 4 the most efficient. Due to the velocity slowing down due to the wave bottom, a higher tempeture and pressure occurs within the combustor thus creating a more complete combustion process.

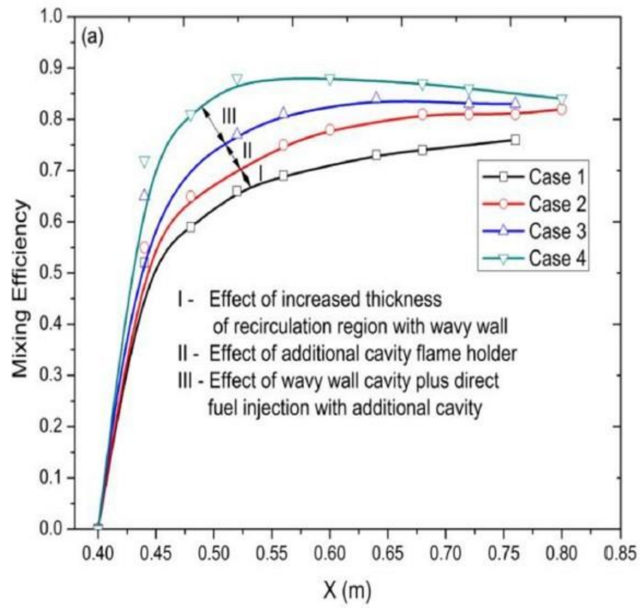

Figure 12 Mixing efficiency within the combustor [2]

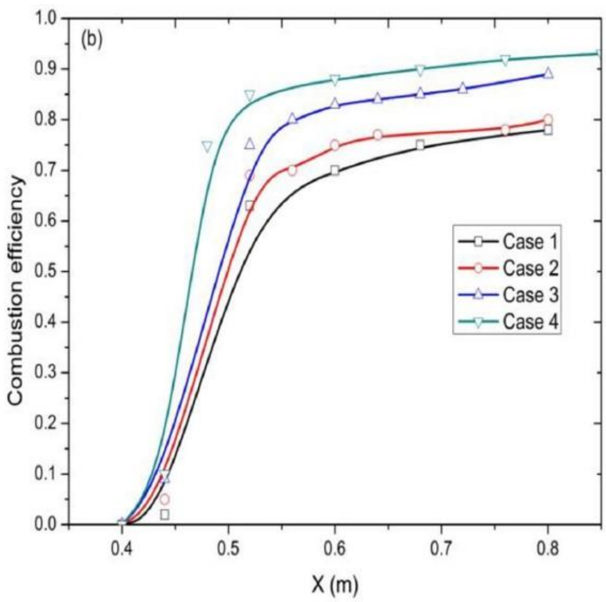

Figure 13 Combustion efficiency within combustor [2]

In closing, the information derived by Obula Reddy Kummithaa, Krishna Murari Pandeyb, and Rajat Guptab determined that as the velocity is slowed in the combustor, the temperature rises and then by then adding the wave bottom geometry the flow heavily mixes and allows for a more full combustion process to be completed [2].

Strut Fuel injectors with Afterburner

The introduction of Strut injection wedge and afterburner was considered by M.J. Candon and H. Ogawa**.** Where similiary to Obula Reddy Kummithaa, Krishna Murari Pandeyb, and Rajat Guptab they created a secondary mixing region to enhance the combustion process, unlike the study done above, they focused on mixing in the nozzle and not in the combustor. The strut fuel injectors purpose is to add more oxygen in to the flow to cause more reaction to occur between a seconday source of oxygen and the leftover hydrogen in the nozzle, this can be seen in the figure

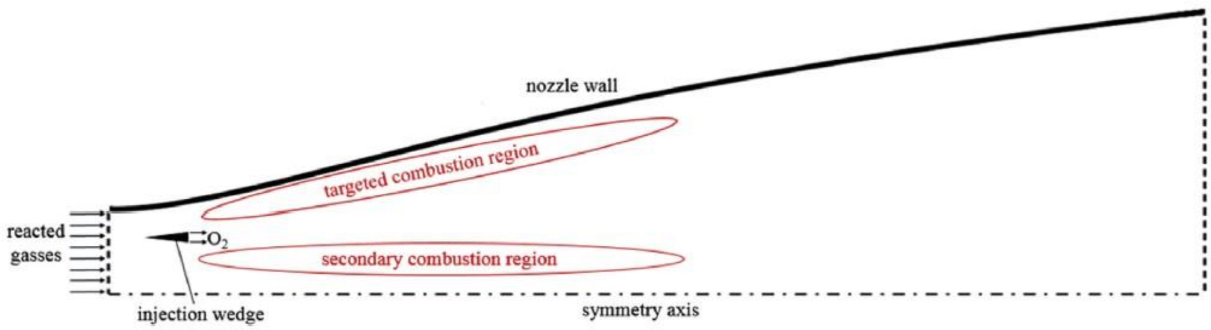

Figure 14 Strut Fuel Injector with Afterburner model [1]

shown above. To complete their anaylsis they held the mass flow rate of the fuel injected constant while changing the position of the strut fuel injector in the x and y directions, the pressure of the fuel jet, and the angle of attack of the injection wedge. They considered flow properties with chemical reactions frozen and with combustion proccesses occuring to verify if the combution processes was causing the change in properties or the change in flow direction caused by the wedge was changing the properties. When the combustion process was being considerd they used the Evans and Schexnayder flame model that considers 12 species and 25 chemical reactions [1]. Where they determined the scramjet engine to be optomized by the max amout of thrust produced at the exit of the nozzle. They found that the pressure of the fuel injection and the angle of attack of the wedge had the largest effect on the thrust at the eixt of the nozzle [1]. The large change in between pressure of

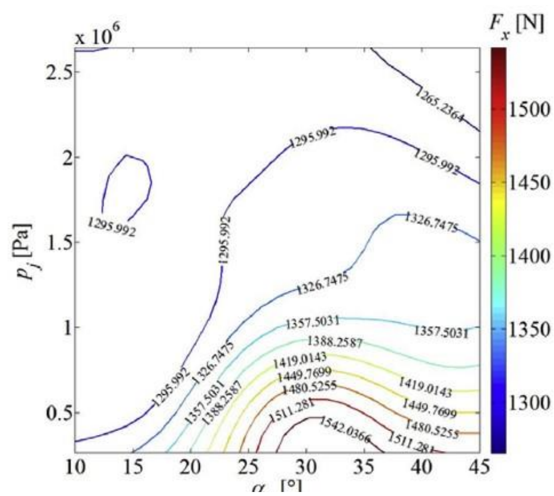

Figure 15 Jet Pressure Vs. Wedge angle with respect to Force [1]

jet and angle of wedge with respect to the force can be seen in the figure 15. There research also showed that as the pressure was lowered and the wedge of the angle was increased to around 32.5 degrees that the highest force was produced at the exit of the nozzle. Secondarly, the x and y postions of the injection wedge were compared to determine if they contribuated to a large change in force. M.J. Candon, H. Ogawa found that the position alone of the wedge did not cause the force at the exit of the nozzle to change extremly. From the understanding that position didn't directly effect the force exiting the nozzle they verified that the position did not indirectly change the force by comparing the position of the wedge to the angle of the wedge and pressure of the fuel injection, to determine that they were not greatly changed by change in position. From figure 17 and 18 it was determined the optimal position in both the streamwise, and radial locations could be determined by using the corresponding position from the optimal pressure of jet and angle of wedge plots. The optimal values of the analysis are as follow pressure of jet 285990 pa, streamwise location .0068 m, radial location .012 m, and angle of wedge 32.6 degrees these four components created the highest thrust 2075 newtons with afterburning and 1481.55 newtons without afterburning.

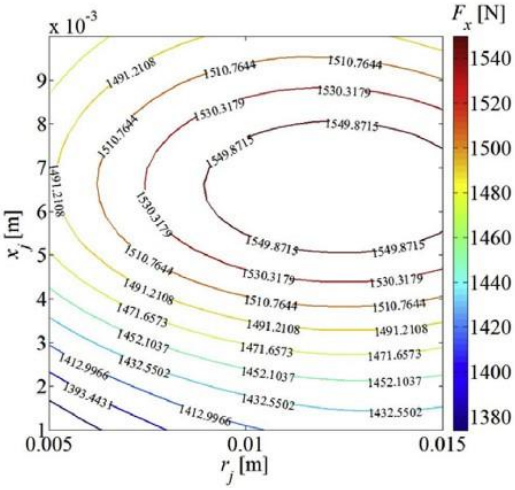

Figure 16 x (streamline) vs y (radial) with respect to force [1]

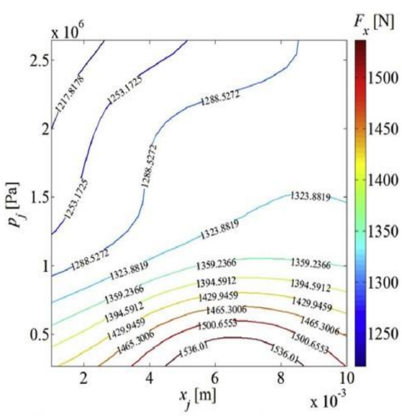

Figure 17 Jet Pressure Vs. x (streamwise) with respect to force [1]

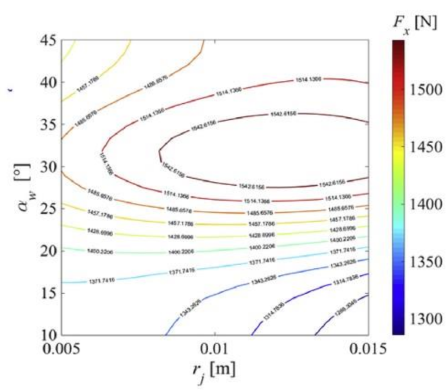

Figure 18 Wedge angle vs y (radial) with respect to force [1]

They then determined how the afterburning/combustion processes affected thrust at the exit of the nozzle. They compared three cases with and without the combustion process occurring, the optimal case that was determined through discussion above, a maximum pressure case, and the minimum angle of attack for the injection wedge case. M.J. Candon, H. Ogawa verified the three results by measuring the mass fraction of the hydrogen at exit of the nozzle which is shown in figure 19 below. The results of this experiment showed that the effect of changing fuel pressure only effected .2 percent more hydrogen to be burned when comparing afterburning occurring and not occurring at high pressure, thus determined as an inverse effect to combustion. The wedge angle of 10 degrees led to 35.5 percent more hydrogen to be burned when afterburner was used then when it was not used. The optimal design caused 35.2 percent more hydrogen to be burned when afterburner was used then when it was not used [1]. From these results they determined that the minimum wedge case increased the thrust by 45.2 percent when after burners were used, while the optimum only increased the thrust force by 28.6 percent when afterburners were used, thus determining that the change in thrust is not as significant as thought to altering the combustion because a 16.6 percent difference in thrust led to only a .3 percent change in combustion [3].

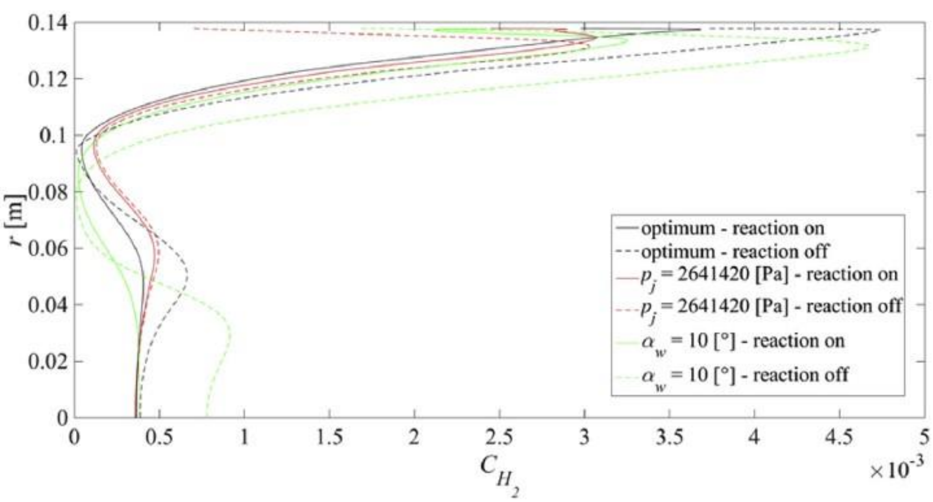

Figure 19 Y (radial) location at exit of nozzle vs mass fraction of H2 [1]

M.J. Candon, H. Ogawa determined that as the net thrust increases to a limit that the percentage of combustion is increased, but after the limit is surpassed the amount of thrust being produced does not contribute to more combustion taking place, but similarly to the studies found above that as more mixing occurs (which happens at low fuel pressures) that combustion will increases [1].

Water injection

Yuefei Xiong, Jiang Qin, Kunlin Cheng, Youyin Wang investigated the effects of adding water to the fuel before the combustion process which acts as both a coolant and enhancement to the thrust, as shown below in figure 20 [4]. The scramjet engine was optimized with respect to thrust and impulse of the fuel. [4].

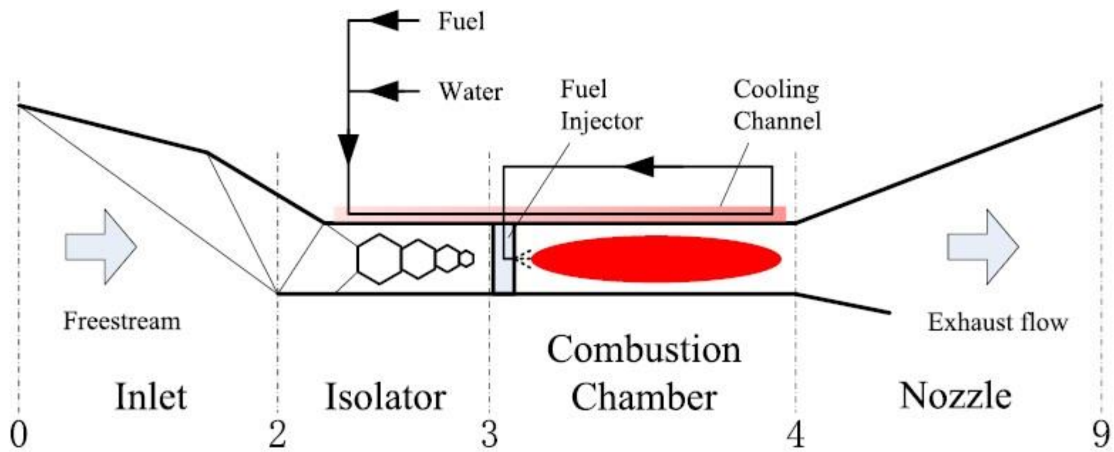

Figure 20 Water injection model [4]

Figure 21 shows how the total thrust was affected as the water was passively added to the fuel

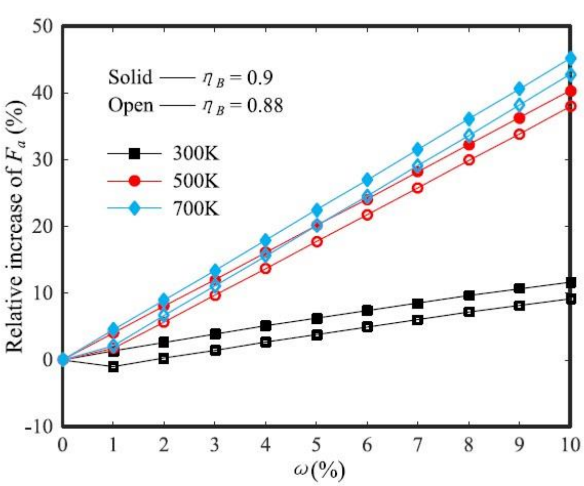

Figure 21 Percent in thrust force vs percent water addition [4]

before the combustion chamber. From the figure to the left, it can be observed that as the water percentage increases at any temperature the relative thrust force percentage also increases [4]. The large gap that occurs between the 300 kelvins models and the 500 and 700 kelvins model is due to the fact that at 300 kelvins water is still in a liquid state and provides an adverse effects for producing thrust [4]. Their research also shows that as the temperature of the fuel is raised the overall force is increased.

These results can also be obtained by raising combustion efficiency which is denoted by n_b and means that more complete combustion is taken place within the combustor [4]. A second test was conducted to determine how the impulse would change with respect to temperature and combustion efficiency as the water percentage was steadily increased. Figure 22 shows that as water percentage is increased the total impulse of the fuel is decreased. In the same manner, as temperature and combustion efficiency are decreased the specific impulse of the fuel also decreases. The authors continue their study to show, in figure 23, that as the water percentage in the fuel is increased that the upper limit of thrust is increased further before reaching an anisotropic limit. Similar results are depicted in figure 24 that show as the water percentage is increased the Mach number and the overall fuel equivalence ratio also increase. It is important to note that as the thermal choking limits are reached the circles in figure 24 become hollowed instead of solid [4]. This shows that at higher Mach numbers the addition of water can provide a higher equivalence ratio before reaching their thermal chocking limits.

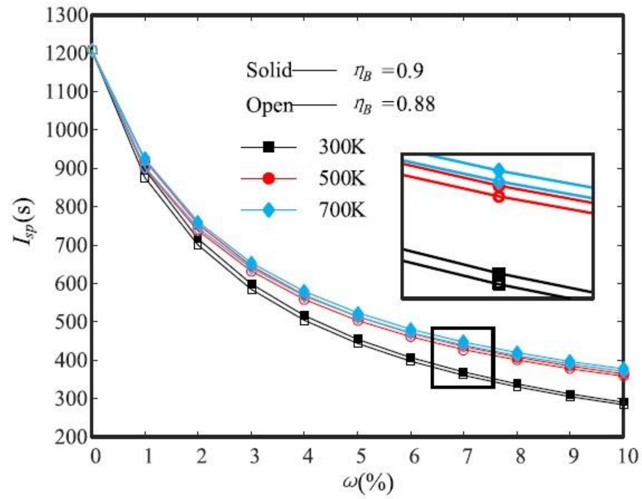

Figure 22 Fuel impulse vs water percentage [4]

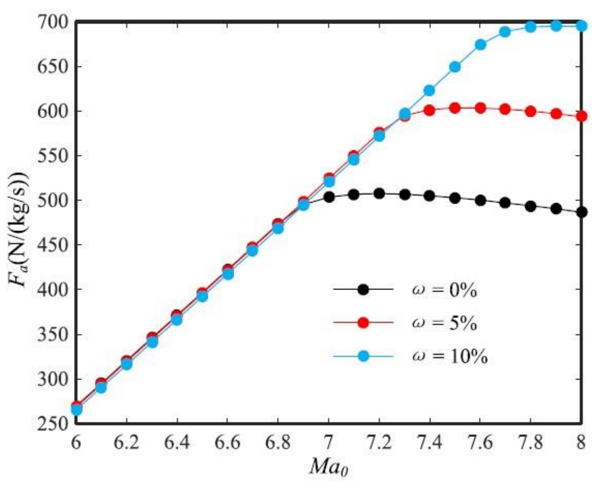

Figure 23 Force vs Mach number [4]

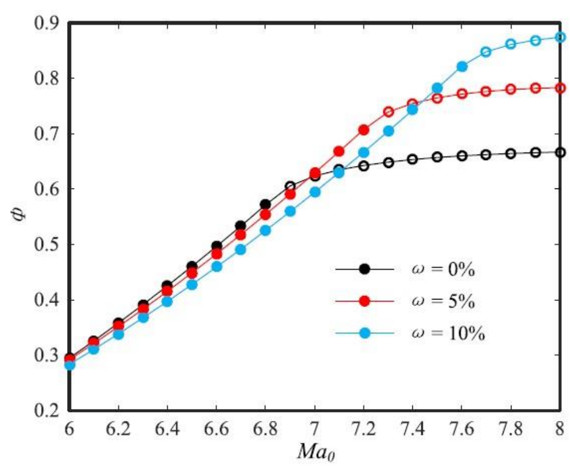

Figure 24 Equivalence ratio vs Mach number [4]

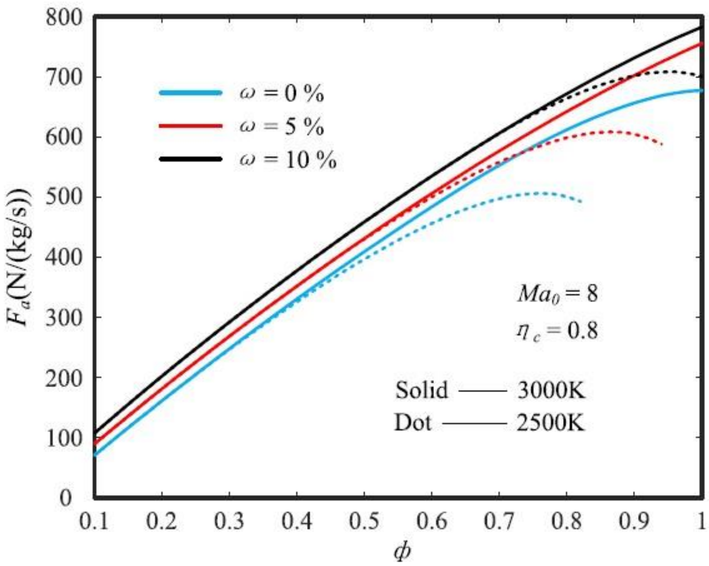

Figure 25 Force vs equivalence ratio [4]

Further research was conducted to determine how maximum temperature in the combustor with water addition effected overall thrust force. From the figure to the left it can be determined that as the temperature decreases the thrust force decreases significantly [4]. This result follows the same logic as other studies above that a decrease in temperature causes less combustion to take place, less combustion taking place can lead to less thrust exiting the nozzle.

The current study by Yuefei Xiong, Jiang Qin, Kunlin Cheng, Youyin Wang determined that thrust can be increased by adding water to the fuel passively before the combustor by sacrificing specific impulse of the fuel, and that adding water is beneficial to flights only at high Mach numbers because of the increase of the upper limit of the equivalence ratio and the thrust force [4].

Re-Cooled Cycle

The Re-cooled cycle as shown below, in figure 26, was produced by the research conducted by Jiang Qin, Weixing Zhou, WenBao, DarenYu. This research focuses on optimizing the amount of fuel that needs to be held on board a supersonic aircraft, and to increase the overall fuel heat sink [3]. In current designs more fuel is necessary then for flight because as the fuel is circulated before being combusted it is absorbing heat transferred from the scramjet engine. The amount of heat that is being transferred out of the scramjet engine is too great for only the fuel for flight to absorb, so extra fuel is placed inside the aircraft just as a source of heat absorption which is then wasted when the flight is over. In previous models this is necessary because if the fuel reaches its critical temperature and heat transfer is still occurring thermal expansion and pressure forces can occur which can cause adverse effects to the scramjet engine [3]. Where the Re-cooled system requires less extra excess fuel for flight by including a turbine and generator to cool the fluid before entering a second cooling passage that absorbs more heat transferred from the scramjet engine before the fuel enters the combustor. The sole purpose of the turbine is not to preform work but instead to decrease the temperature of the fuel [3]. A secondary use of the turbine is to provide power to a generator that can be used to power secondary systems [3].

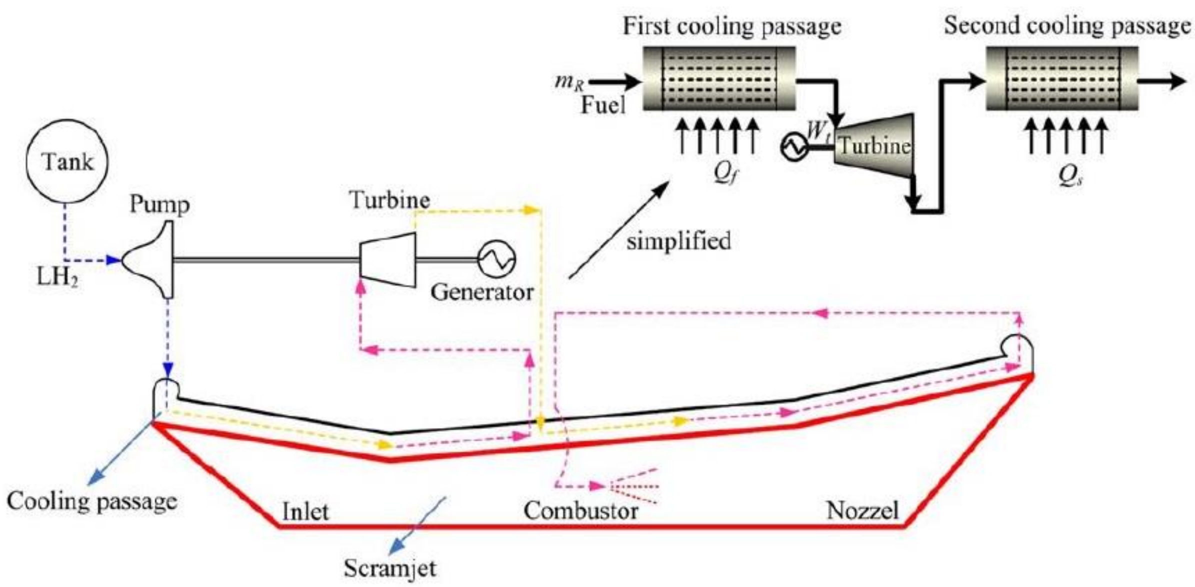

Figure 26 Re-Cooled cycle model [3]

To determine the effectiveness of the Re-cooled cycle the authors varied the pressure from 1-20 MPA at the entrance of the first cooling passage with a limit at 1 MPA at end of the second cooling passage which was determined from the pump and the necessary pressure exiting the second passage to adequately spray fuel within the combustor ,the temperature in the secondary pass was ranged from 800 to 1000 kelvin because the material it was designed from is nickel 201 has a maximum structural temp of 1100 kelvins, and the Mach number of the fuel was set .25 which corresponds to a velocity of 250 meters per second. Where y is defined as a length factor between the first and second passage, as y increases the second passage gets longer [3].

Where a fuel flow reduction ratio was produced from comparison of mass flow rates and the heat transfer rates from the first and second passages which were derived from a first law analysis as shown in figure 27. Where figure 27 shows, “that as long as Qs does not equal 0 that the Re-cooled cycle will reduce the fuel flow for cooling, which is equivalent to the indirect increase In fuel heat sink”[3].

$$\varphi = \frac{m_r - m_R}{m_r} = \frac{Q_s}{Q_f + Q_s}$$

Figure 27 Reduction ratio of Fuel flow [5]

Figure 28 shows that as the pressure ratio increases the fuel flow reduction ratio increases, this is because an increase in the pressure ratio leads a to a decrease in m_R[3]. In other words, this means that initial system is providing more cooling so the Re-cooled system would need to be

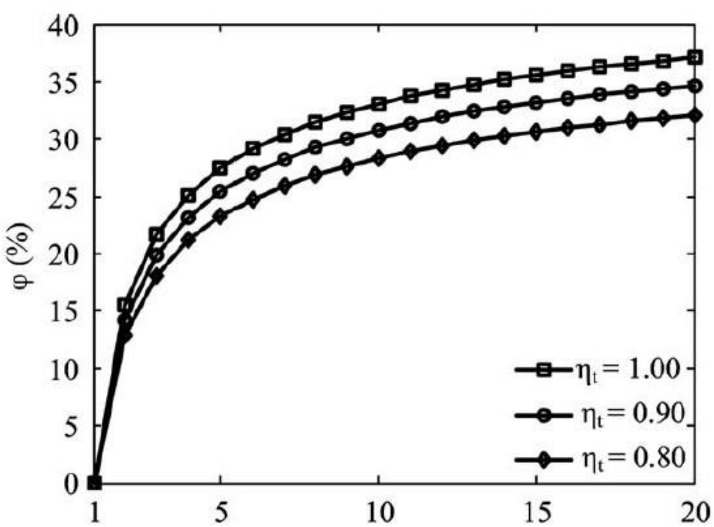

Figure 28 Fuel Flow reduction ratio percentage vs expansion ratio [3]

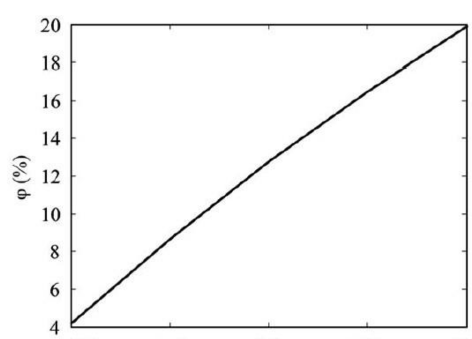

Figure 29 Fuel Reduction Ratio vs Secondary pass Temperature [3]

used less, which from figure 27 can also be determined as less heat transfer occurs in the second cooling passage. This figure also shows that the fuel reduction percentage increases as the turbine efficiency increases. This is expected because as the turbine efficiency is increased the fuel leaving the turbine would leave at a cooler temperature meaning more heat transfer could take place between the scramjet engine and second cooling passage. In a similar fashion, figure 29 shows that as the temperature in the second cooling passage increases the fuel reduction ratio also increases. This occurs because if the second cooling passage is reaching the maximum temperature experimentally allowed, that means that greatest amount of heat transfer is taking place, thus preforming optimally, meaning the amount of fuel required in the system can be decreased if the temperature of the fluid entering the combustor is less the 1000 degrees kelvin. Though the fuel reduction ratio increases as the pressure ratio increases it is important to note that as the pressure ratio gets bigger that rate at which the fuel reduction ratio increases gets smaller [3]. In fact, after a pressure ratio of around 5 adverse effects can start to take place in the turbine with little to no effect on the fuel reduction ratio [3]. From the determination that a pressure ratio of 5 or greater can cause adverse effects on a turbine, allow conclusions to be made from figure 32 to determine that the effective length ratio between the first and second cooling passage is .77, meaning that when designing the Re-cooled system the second pass should be 77 percent of the length as the first cooling pass.

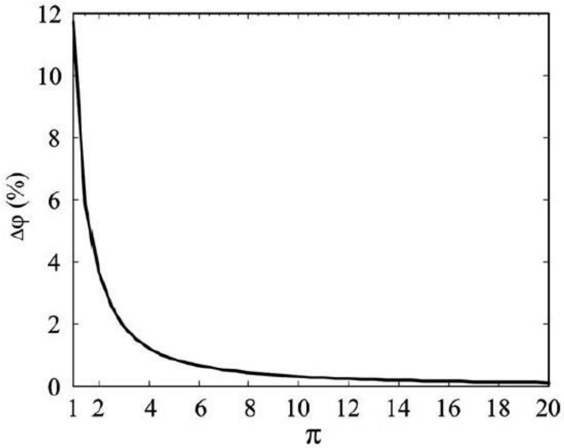

Figure 30 change in Fuel reduction ratio vs expansion ratio [3]

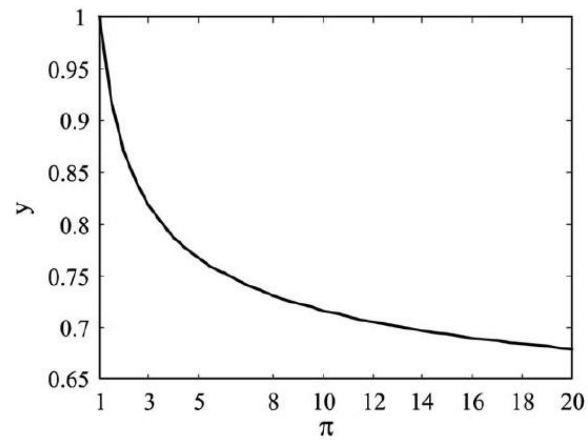

Figure 31 Length ratio vs expansion ratio [3]

From the research discussed above, Re-cooled system decreases the amount of fuel that must be carried onboard an aircraft with a scramjet engine, as well as the second passage provides more active cooling to prevent thermal expansion or pressure forces to have adverse effects on the scramjet engine.

Conclusion

Many scramjet engine optimization techniques have been discussed in detail above.

1) An exergy balance was conducted on a scramjet engine and found that almost all exergy lost occurred in the nozzle and the combustor due heat, kinetic, and enthalpy loses. It was also determined by Meijun Zhu, Shuai Zhang, Yao Zheng that exergy efficiency and specific fuel impulses were inverses of one another and that depending on the mission exergy efficiency may need to be sacrificed for the necessity of the mission.

2) Obula Reddy Kummithaa, Krishna Murari Pandeyb, and Rajat Guptab determined that changing the combustors geometry to add a wavy bottom, a converging top section, and a combination of transverse and parallel injection preformed optimally when considering combustion and mixing efficiency. The model described above worked the best because the wavy bottom decreased the velocity and increased the bottom recirculation region, where a second recirculation was formed at the top of the combustor due to the addition of the converging top, and direct flow injection helped with mixing and directing the fuel air mixture in to the streamwise direction creating axial thrust into the nozzle.

3) Similarly, to Obula Reddy Kummithaa, Krishna Murari Pandeyb, and Rajat Guptab, M.J. Candon, H. Ogawa created a secondary mixing section. Dissimilarly, this secondary mixing section was found in the nozzle instead of the combustor. M.J. Candon, H. Ogawa placed a wedge into the nozzle of scramjet engine that disbursed oxygen with an afterburner to increase thrust. They determined that at a low pressure and an angle 35.2 produced optimal thrust conditions. They found that a low-pressure of fuel injection allowed time for mixing to occur and a wedge angle the created two mixing regions was key for the afterburner to produce the most thrust. They also determined that the change in thrust may not cause a large change in combustion, but a change in fuel injection pressure will cause a change in combustion.

4) Where in the fourth article that was reviewed, water was added to the fuel passively before the combustion chamber. Yuefei Xiong, Jiang Qin, Kunlin Cheng, Youyin Wang determined that thrust can be increased by adding water to the fuel passively before the combustor by sacrificing specific impulse of the fuel. They also determined that adding water to the combustor is beneficial to flights only at high Mach numbers because of the increase of the upper limit of the equivalence ratio and the thrust force.

5) A Re-cooled system was considered onboard an aircraft with a scramjet engine. The Re-cooled system has a turbine that is used not initially to produce work, but to reduce the temperature of the fuel to allow for a secondary pass of active cooling before it enters the combustor. The turbine can then be used to power a generator which can be used to power subsystems on the aircraft. It was observed that as the reduction ratio of fuel flow was increased due temperature in the second passage or increase in expansion ratio that less fuel was required to be carried by the plane.

All five articles discussed many important topics but a couple conclusions where synonymous between the articles. The more mixing that occurs the more combustion will take place, heating the fuel before entering the combustor will provide a higher combustion efficiency, and high force is easy enough to produce but the sacrifice is generally the specific impulse of the fuel.

Conflict of interest

The author declares that there is not a conflict of interest in the paper if it were to be published.

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