# Ramjet Fuel System

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# Ramjet Fuel System

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**A fuel system to be implemented into a ramjet for Cal Poly's supersonic wind tunnel was designed. The objective was to design, build, and test a fuel system for an experimental ramjet design. The fuel system is composed of a tank, filter, pump, pressure regulator, and check valve. The fuel type chosen was Jet-A, which gave an approximate combustion chamber temperature of 3,960 Rankine. A calculated fuel flow of 0.0334 and a pressure of 30psi inside the combustion, sized the components used in the system. The fuel system was tested and found to have a flow rate of 41.55 gallons per hour with the pressure regulator open and a flow rate of 22.75 gallons per hour with the pressure regulator closed. Future design considerations for the combustion chamber included the fuel injectors, flame holder, and igniter, as well as a testing procedure to determine the best location of components for optimum fuel:air mixing.**

## Nomenclature

$C_p$ = Heat Capacity (ft lbf/slug Rankine)
$h_{PR}$ = Heating Value of Jet-A fuel (ft lbf/slug)
$T$ = Temperature (Rankine)

Subscripts
*2* = combustion chamber inlet
*4* = combustion chamber exit

## I. Introduction

Ramjets are generally used for systems flying at supersonic conditions. Some aircraft have utilized this simple air breathing design, but there has been more applicable testing for the use of missiles. Spacecraft have also explored this engine design to help escape the Earth's, but would only be able to operate for an insignificant amount of time before the atmosphere becomes too thin to compress. Ramjets have no moving parts and are designed with only a few basic components to produce thrust; the diffuser, combustion chamber, and nozzle. Operated at supersonic speeds, ramjets use the forward motion of the system to compress high-speed fluid through the diffuser to a slower flow at a greater pressure. Fuel is injected and mixed with the air in the combustion chamber and burned to produce heat. The excited mixture is then directed through a nozzle where the flow accelerates back to supersonic velocities. At zero airspeed, ramjets cannot produce any thrust and therefore must be coupled with another form of propulsion to initially get an aircraft moving to supersonic speed. Ramjets are beneficial when designing missile systems that need sustained thrust over a longer period of time. Missiles fired from aircraft are already in high-speed flow and may take advantage of this small and simple engine design.

The target area of this project is a subsection of the combustion segment. The combustion section begins after the inlet and includes the components up to the start of the exit nozzle. This includes the fuel injection system, flame holder, and igniter and is used to add heat to the system by burning fuel with the compressed air from the inlet. As the air enters the combustion chamber, the fuel system pumps fuel into the flow creating a blend of fuel and air. An igniter lights the fuel and air, while a flame holder retains the combination just long enough to ensure complete burning before the mixture leaves the chamber. This project will focus on the fuel system for the combustion chamber of a Ramjet design for Cal Poly's supersonic wind tunnel.

## II. Preliminary Design

To begin the design process, design parameters had to be determined. The primary factor to consider was the type of fuel to burn in the combustion chamber. Temperature in the combustion chamber is mainly attributed to the energy output of the fuel to be used. When looking at different fuels, the main parameter to keep in mind was the temperature at which the fuel will heat the inside of the combustion chamber. When looking at different aircraft fuel types, most fuels were found to have similar ignition temperatures and heating values.[1] Other aircraft fuels researched came with performance enhancing properties, which were eliminated on the basis that this exceeds the needed performance for a ramjet operating in a test stand.[1] Based on historical data from a turbine experiment in Cal Poly's propulsion lab, values inside the combustion chamber were measured to be on the order of 3,960 Rankine. Since the turbine uses Jet-A fuel, we assumed the same properties for our combustion chamber and chose to use the same fuel.

The fuel injection system takes the fuel from a tank and pumps it out an injector nozzle into the ramjet flow. This is where the air and fuel begin to mix. Unlike a turbine, since there is nothing downstream of the fuel injection, the ramjet is optimally run at stoichiometric fuel:air ratios. Stoichiometric ratios occur when exactly enough fuel is added to the incoming air to completely burn off all of the fuel before exiting the engine. This is ideal as to not waste any fuel while getting the maximum amount of burn possible. Using the equation from Mattingly,[2] the fuel to air ratio was calculated by,

$$\frac{\quad}{\quad} \qquad (1)$$

where $C_p$ is the heat capacity of air, $h_{PR}$ is the heating value of the fuel, $T_2$ is the inlet temperature of the combustion chamber, and $T_4$ is the exit temperature of the combustion chamber. Assuming $T_2$=1,375 °R and $T_4$=3,960 °R, the fuel to air ratio is found to be f=0.0334. Because the inlet and exit temperatures where assumed, a wide array of values were input into Eq. 1 to see how the ratio fluctuates based on these temperatures. A contour plot of fuel to air ratio was generated to observe the results, Figure 1. As seen in Figure 1, the fuel to air ratio decreases if either inlet or exit combustion temperature decreases. The main limiting factor found was the pressure inside the combustion chamber, expected to be approximately 30psi. This is useful when designing the injection system to allow for a fuel pump that will handle this pressure. To produce adequate spraying at the injector, the force and pressure loss through the fuel lines had to be accounted for by increasing the pressure capability of the pump. A higher pump pressure would also allow future testing of increased fuel flow in the ramjet. Because Jet-A fuel, kerosene, and diesel fuel are closely related, a diesel pump would work to transfer the fuel from the tank to the injectors. The system could be designed with one pump or two pumps to obtain the right pressure. The benefit of having two pumps would be to have a low pressure pump to move the fuel closer to the engine where a second higher pressure pump would push the fuel into the flow. The disadvantage of this system is purchasing two separate pumps.

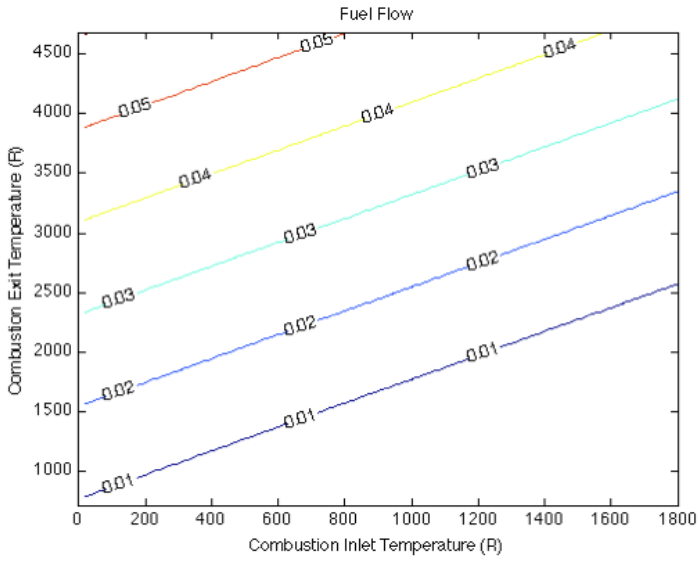


**Figure 1. Fuel to air ratio with varying combustion inlet and exit temperatures.**

The pressure capabilities limited the regulator to specific pressure limits. The other components also had to be chosen to withstand the maximum pressure capability of the system.

## III. Apparatus

The fuel system is laid out starting with the fuel tank and then the filter, to catch any particles that may have been picked up inside the tank. From the filter, the fuel is sent through the fuel pump and then the pressure regulator. The check valve will be located after the regulator with the fuel travelling from here to the injectors in the combustion chamber. Once in the flow, the flame holder will produce turbulence allowing the fuel:air combination to stay in the combustion chamber long enough for it to be ignited. Shielded spark plugs will be used to combust the mixture before being sped back to Mach speeds through the nozzle.

With a chamber pressure determined to be 30psi, the fuel system must be able to overcome this pressure and inject fuel into the flow. This pressure is directly correlated with the fuel pump and the output pressure it can provide. Since Jet-A fuel is similar to diesel fuel, high-pressure automotive pumps were looked at to keep the price of the fuel system lower. A MSD In-Line Hi-Pressure Fuel Pump, capable of 43 gallons per hour with a pressure rating of 85psi, was chosen. The higher pressure was chosen to overcome the pressure needed at the injector, coupled with the chamber pressure. A pressure regulator will manage the amount of fuel and pressure seen at the injectors. For testing purposes, the regulator will allow a variation in pressure to determine the best flow for the fuel and air to mix effectively. The regulator chosen was an AEM 25-302BK high volume adjustable fuel pressure regulator. A check valve installed after the regulator was used in case the ramjet malfunctions. Check valves only allow the flow of fuel into the engine, prohibiting any substance from reversing back to the pump or fuel tank. The check valve chosen is a Metro Machine Check Valve, capable of operating up to 3,000psi. A basic inline fuel filter was placed after the fuel tank to prevent any foreign objects before entering the pump. A clear fuel inline filter was chosen so that it may be visually inspected for any build up and replaced when needed. The fuel tank holds 6 gallons and is made of stainless steel. It will be housed outside the supersonic wind tunnel in case anything was to happen to the fuel inside. Injector grade fuel lines were chosen for its high-pressure capability to link the different components together.

The main components of the fuel system are laid out on a sheet of aluminum for easy maintenance and lab viewing purposes. These components include the fuel filter, fuel pump, pressure regulator, and check valve. The aluminum plate will be mounted with piping to the fuel tank as well as the injectors in the combustion chamber. The hoses will disconnect from the fuel system to move the ramjet to allow other propulsion lab testing in future classes. The fuel system configuration can be seen in Figure 2.

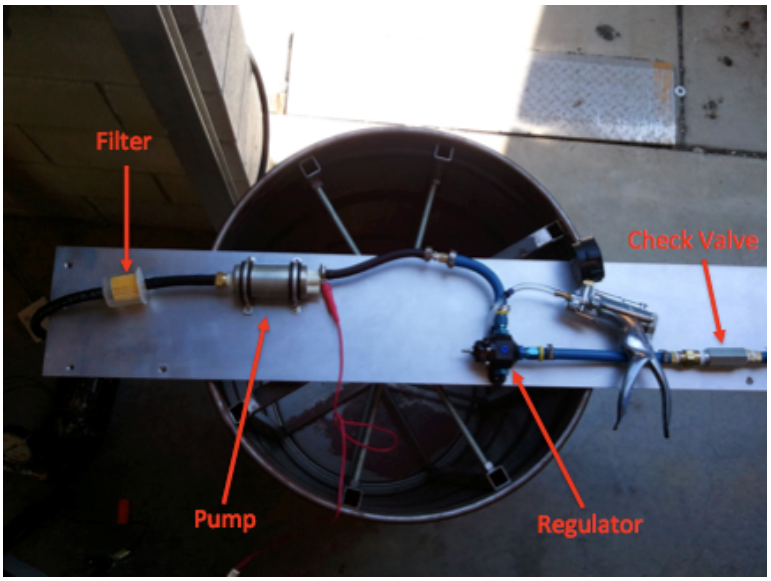


**Figure 2. Ramjet fuel system layout.**

After the components were mounted, the system was tested to see all the components performed. The test included adding Jet-A fuel to the gas tank and pumping fuel through the system back into the tank. This test was to make sure the system worked with the fittings and hose before implementing it with the ramjet in the supersonic wind tunnel. A test was performed to evaluate the fuel system and determine the flow rate capabilities with the pressure regulator, as seen in Table 1. The test proved that the system was able to output a flow rate of 41.55 gallons

per hour with the pressure regulator fully open and a flow rate of 22.75 gallons per hour with the pressure regulator almost closed. This verifies that the pressure regulator was able to alter the flow of fuel, allowing the ramjet design process to continue.

**Table 1. Fuel System Test.**

| Regulator Position | Volume Pumped | Time | Gallons per Hour |
|---|---|---|---|
| Open | 0.5 quarts | 10.83 sec | 41.55 |
| Closed | 0.5 quarts | 19.78 sec | 22.75 |

## IV. Future Work

Future plans for the fuel system include the design and testing of the fuel injectors and flame holder. The design of the fuel injectors involves testing various diameter outlet holes to optimize the spraying of fuel into the flow. Another consideration is the direction of the injector holes to the free stream flow and how different angles may cause better fuel to air mixing.

With the fuel injected into the flow, a downstream flame holder helps integrate the fuel and air to its stoichiometric ratio. Flame holders create eddies in the flow causing turbulence and increased mixing. An eddy is caused when a fluid passes a stationary object, resulting in a slight upstream current and churning fluid. Behind the object, opposite of the flow, the fluid is not moving. As the flow passes the object some of the velocity turns inward into the calm fluid behind, causing a slight reversal of current and a swirling motion in the fluid. This phenomenon is used to hold the fuel and air in the combustion chamber longer and cause disorder in the flow to allow increased mixing. The design of the flame holder must combine the fuel and air to its stoichiometric relation while not increasing the drag of the system. After the flow has been mixed, an igniter is used to light the fuel before being blow out the exit nozzle. A shielded spark plug may be used downstream in the combustion chamber to ensure proper ignition of the flow.

The mixing properties of the fuel and air will be tested by varying the distance between the injector, flame holder, and igniter. To find the best mixing of the fuel and air, the combustion system will be tested without chamber sidewalls in open-air conditions with the super sonic wind tunnel set to the designed Mach number inside the combustion chamber. This will allow the distance between each element of the combustion process to be varied easily to find the closest result to stoichiometric mixing. The ideal mixing is a stoichiometric relationship, but the test will be performed visually to inspect the best combination that produces the maximum amount of flame with minimal fuel expelled from the nozzle. Multiple tests will have to be run using trial and error to determine the best results. After the best relationship is found, the fuel system may be implemented with the walls of the combustion chamber.

The next part of the design would be the walls to incorporate the combustion system. The casing around the combustor must withstand the temperatures produced within the chamber itself. Table 2 shows different materials and their temperature properties. The main casing will be made out of metal with interchangeable plates to move or add different components to the design for future testing. Sidewalls made of quartz or some other clear material would allow for visualization of the fuel and air mixing along with the actual ignition of the flow.

**Table 2. Different materials with temperature properties.**

| **Material** | **METALS** | | | | | | **Quartz** | |
|---|---|---|---|---|---|---|---|---|
| **Type** | Inconel | Incoloy | Aluminum | Carbon Steel | Titanium | Stainless Steel | Tridymite | Cristobalite |
| **Temperature (Rankine)** | 3000 – 3060 | 3000 – 3060 | 1680 | 3060 – 3260 | 5860 | 3210 | 2163 | 2210 |

## References

[1]"Jet Fuel D-1655 Specifications," *Experimental Aviation Association*, URL: http://www.eaa.org/autofuel/jetfuel/d1655_specs.asp [cited 4 June 2012].

[2]Mattingly, J.D., *Elements of Propulsion, Gas Turbines and Rockets*, AIAA Education Series, AIAA, 2006.