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Investigation into the Adaptation of a Steam Injector for Use on a Liquid Rocket Engine

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THESIS

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Abstract

This thesis investigated the properties of a steam injector to see if the concept might be suitable for use on a liquid rocket engine. A steam injector is a device developed in the 1850's and was used to inject feedwater into the boiler on a steam locomotive without any moving parts. The injectors used a small portion of the steam generated in the boiler to increase the pressure of the feedwater to a level higher than the pressure in the boiler. Previous experimenters claim that condensation of steam to water was necessary for an injector to work. This experiment tested injection without condensation using one of AFIT's wind tunnels. Compressed air was used to simulate steam and liquid ethanol was used in place of water. Pressure measurements were taken at points along the tunnel to determine the performance of the tunnel. Results show that this type of injection produces a small pressure rise compared to tests without liquid injection. However, the exit pressure is still lower than the initial pressure. Further testing is recommended to analyze various parameters such as high temperature flows and injector size.

Investigation Into the Adaptation of a Steam Injector for Use on a Liquid Rocket Engine

Chapter 1 - Introduction

1.1 Introduction

The technology used on rockets has changed very little since the 1950's. Chemical rockets with liquid propellants have always had only two means of delivering the propellants from the propellant tanks to the combustion chamber. The two options are a separate pressurant tank to push the propellants towards the combustion chamber or the use of turbopumps to suck the propellants out of their tanks. Both options have serious drawbacks.

Pressurant tanks, while simple to use and require no moving parts, add extra mass to the rocket, reducing its usefulness. Large rockets require a lot of propellant, so the pressurant tank needed to push all of that propellant would need to be huge, making the rocket extremely inefficient. Therefore, pressurant tanks are generally only used on small rockets.

Larger rockets usually have turbopumps to move the propellant. While the turbopumps are less massive than the pressurant tanks required for large rockets, turbopumps can be extremely complex with many moving parts [6]. A new option that combines low mass with simplicity that can be used on any size rocket is long overdue.

The steam injector may provide the ability to pump the propellants of a liquid rocket without adding as much mass as a pressurant tank and without the complexity of turbopumps. A steam injector is a device originally used to pump feedwater into boilers on locomotives without any moving or powered parts. Prior research [4], [9] claims that the condensation of steam into water is necessary for the successful operation of an injector. In a rocket engine application, the steam function would be performed by the products of combustion. These products may be at an extremely high temperature, which would make condensation difficult to achieve. Testing must be performed to measure the performance of an injector in which no condensation of the gaseous medium is present.

1.2 Problem Statement and Scope

Can the principles that make a steam injector work be applied to a liquid rocket engine? The objective of this research is to examine the properties of a steam injector type apparatus and to look at condensation as a limiting factor of injector performance. If someone can develop an injector that still functions properly without condensation, then the process of placing injector technology on a liquid rocket will be simplified. If, however, condensation is absolutely necessary, that process must expand to include developing a way to induce condensation in high temperature rocket exhaust. One thesis cannot possibly cover all of the factors that would preclude putting a steam injector system on board a liquid rocket. This thesis will limit itself to looking at the properties of the steam injector. Specifically, to determine if the working fluid, usually steam, must be hot and then undergo a phase change from gas to liquid in order for the injector to produce a pressure rise.

1.3 Thesis Overview

Chapter 2 presents the appropriate background information necessary to accomplish this research. A description of pressurant tanks and turbopumps and the disadvantages of each is given. Next a short history of the steam injector is given. This is followed by a description of recent interest in using steam injectors for non-locomotive applications. Finally, a section on the thermodynamic and fluid dynamic equations that govern the operation of a steam injector is given.

Chapter 3 describes the experimental set up used in this research. Also included are some recommendations of how to change the set up in order to more accurately simulate a real working injector and some of the aspects involved with using an injector in space.

Chapter 4 includes the results and a discussion of the analysis, while Chapter 5 presents conclusions. Chapter 5 also gives some recommendations for the direction that future research on this topic could take. Appendix A contains sample pressure plots from a baseline test run. Appendix B contains calculations for mass flow rate of ethanol and air.

Chapter 2 - Background Literature

2.1 Current Liquid Propellant Delivery Systems

2.1.1 Pressurant tank fed system

As mentioned in the introduction, one of the two options currently available for delivering liquid propellants from the propellant tanks to the combustion chamber is through the use of a separate pressurant gas stored in a pressurant tank. Figure 1 shows a schematic of an example pressurant-fed system.

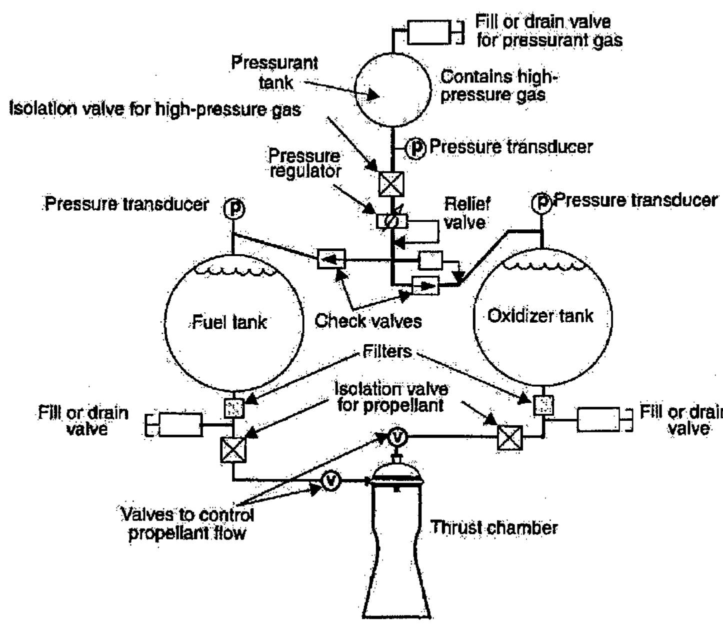

Figure 1. Pressurant fed system

Designers generally choose a non-combusting gas, such as helium or nitrogen, as the pressurant. The pressurant must be able to maintain the propellant tank pressures throughout the burn until all of the propellant is used up. That means that there must be enough pressurant stored at a high enough initial pressure that at the end of the burn the pressurant occupies the entire volume of both propellant tanks and the pressurant tank at the initial propellant pressure. In a case study example by Humble [6], the initial pressurant tank pressure is thirty times higher than the combustion chamber operating pressure. This results in a pressurant tank mass that is nearly equal to both propellant tank masses combined, not including the propellants. Granted this is just an example problem that assumes low risk options, but the final result is that the pressurant system adds a significant mass to the rocket.

2.1.2 Turbopump fed system

The other option currently used to move propellants from their tanks to the combustion chamber is turbopumps. Turbopumps are complicated pieces of machinery composed of many moving parts that increase the pressure of the flow going through them. In addition to being complicated pieces of hardware, another aspect of using a turbopump is that the pump must be powered in some manner, usually with a turbine. However, turning the turbine requires that the engine divert a portion of one or both of the propellants. There are three primary methods, or cycles, of using a turbine to power a pump that are currently used [6].

The simplest cycle is the expander cycle. In the expander cycle, the fuel, initially at a high pressure, runs along the nozzle to cool the nozzle and, in the process, is heated and vaporized. Then the vaporized fuel is run through the turbine, which then powers the fuel and oxidizer pumps. After going through the turbine, the fuel then travels to the combustion chamber where it reacts with the oxidizer.

The second cycle is the called the staged-combustion cycle. In the staged-combustion cycle the fuel is again heated by the nozzle. The fuel then goes to a warm gas generator, or a pre-combustion chamber. There the fuel reacts with a small amount of oxidizer (just enough to further warm the fuel vapor but not combust the entire flow of fuel). The warm gas then travels to the turbine to run the pumps then down to the combustion chamber to meet the rest of the oxidizer.

The final cycle is the gas-generator cycle. In the gas-generator cycle, a small portion of the fuel and oxidizer are diverted to a hot gas generator, which is just a small combustion chamber. After combustion, the hot gases turn the turbine and are then, usually, dumped overboard. This exhausting of the propellants that are used to turn the turbine, while just a small percentage of the total propellant flow, reduces the amount of total thrust that the rocket can generate. The rocket must, therefore, be designed with more propellant than is really needed to do the mission, which raises the cost.

Regardless of which cycle runs the turbine, the turbine must power a pump that raises the pressure of the propellant flow. In the liquid oxygen pump shown in Figure 2, the liquid oxygen enters the impeller through the inducer inlet. The impeller gradually raises the static pressure of the liquid until the pressure is high enough to prevent cavitation in the centrifugal pump. The flow then enters the centrifugal impeller, which imparts most of the total pressure rise. This pressure rise occurs by adding kinetic energy to the flow and diffusing part of the resultant velocity so that the flow emerges from the impeller with more velocity and more static pressure than it entered with. The rest of the velocity is diffused in the volute and diffuser. The final flow that emerges from the J2 liquid oxygen pump has a static pressure rise of 7.6 mega pascals, or about 1100 pounds per square inch [6].

2.2 Development of the Steam Injector

In the 1800's, most improvements to locomotives were made by men with little or no scientific training. Rather these men were practical minded engineers who developed improvements out of experience and trial and error. One notable exception, however, was Henri J. Giffard. Giffard was a French engineer who had graduated from the Ecole Centrale and went about his work using scientific principles. In 1850, Giffard proposed an idea for a steam injector based on Venturi's Law and other principles of fluid mechanics. He wanted the steam injector to pump feedwater for a steam-powered airship. Many engineers of the time did not understand the principles behind the injector and, therefore, considered the idea with skepticism. This skepticism was due, in part, to the fact that the injector seemed to do the impossible. Basically, the injector would take some steam, mix it with some water while the flows traveled through a series of converging and diverging nozzles, and end up with water that was at a higher pressure than the original steam. This higher pressure enabled the water to be forced into the boiler to renew the supply of water there. In May of 1858, Giffard produced a working injector and received a patent from the French government. However, most engineers did not show much interest in using the injector [12].

Then, an English engineering firm, Sharp, Stewart, and Company of Manchester, saw a sample injector and immediately recognized its usefulness on steam locomotives as a boiler feeding device. The injector possessed several advantages over the current pumps that were used to force feedwater into the boilers. First, the injector was small and compact. Second, the injector had no moving parts to break and it operated even when the locomotive was stationary. Third, it did not draw upon the locomotive's power or put any strain on any other components. Finally, the feedwater was heated by the steam so that the boiler was not strained by blasts of cold water. Sharp, Stewart, and Company fitted a locomotive of the St. Helens Railway with an injector in mid-1859 and within a year between twenty-five and thirty English locomotives were running with steam injectors. Only the relatively high cost of the injectors, about one hundred and fifteen dollars each, kept the injectors from becoming more widespread throughout England.

Giffard's injector crossed over to the United States in 1860 when William Sellers, a manufacturer from Philadelphia, went to visit the operations of Sharp, Stewart and Company. Sellers quickly saw the value of the injector and secured the rights to be the sole manufacturer of the injector in the United States. From that point, the popularity of the injector soared. The William Sellers and Company had a good reputation for manufacturing locomotive products such as machine tools, turn tables, and many other items. This reputation, combined with the recognized need for a better way to feed the boiler than a force pump, produced a favorable American market for the injector. William Sellers and Company, in their first year of producing the steam injector, sold nearly three thousand. In the time immediately following the introduction of the injector to American railroads, many master mechanics highly praised the simple operation of the injectors.

Unfortunately, the popularity of the steam injector did not last long. The early designs of the injector ended up being sensitive devices that needed to be handled with care. The rough environment of a locomotive caused some serious disorders when the injectors were not properly supervised and eventually some engine crews began to refuse to work on locomotives fitted with the injectors [12].

2.3 Non-locomotive Applications

Over the years, locomotive engineers started to develop alternatives to steam powered locomotives, such as electric trains. Steam injectors, while still used on some museum locomotives and hobby trains, gradually fell into disuse. Eventually, however, engineers in other fields realized that steam injectors could be useful tools.

2.3.1 Nuclear Power Plants

In particular, engineers in the nuclear power industry have become interested in using steam injectors as a safer and more reliable means of delivering feedwater to emergency core cooling systems. Most current safety systems consist of electrically activated pumps, motors and valves that force feedwater to a steam generator where the water picks up heat from the core, converts to steam, releases the heat in the cooling tower, and then condenses back into the storage tank [9]. These components have relatively low reliabilities, so in order to meet safety standards for cooling, many redundant systems are required. Using many systems greatly increases the complexity and cost of the safety measures.

The easiest and most useful place to insert a steam injector is in the steam generator feed system. This would make the steam generation system completely autonomous from the electricity produced by the generator. This set up would be effective in handling smaller emergencies such as the failure of a steam generator. If a steam generator were to cease functioning, then no new feedwater could be injected through the main feed system and no electricity would be produced. The water present in the generator would continue to act as a heat sink until all of the water changes to steam and the steam temperature equals the core temperature. However, since the steam injector does not use the electricity produced by the generator, an auxiliary feedwater system can still use the injector to get water to flow. A simple electrically opened valve that would close when the generator stopped working, and thus closes the main feed system, would force the water through the auxiliary feed system. This simple set-up, while not restoring steam generator function, ensures that the core will continue to be cooled.

The steam injector is also useful during other, more serious accidents. Popov and Stanev discuss the possibility of using a steam injector as part of an emergency core cooling system [9]. They suggest that a steam injector, possibly the same injector already attached to the steam generator, could supply water to supplement the primary core coolant in the case of a coolant leak. At this time, studies of using steam injectors for emergency core cooling have been limited to small ruptures with little loss of primary coolant. However, Popov and Stanev suggest that steam injectors could possibly be appropriate for use against significant ruptures. The serious loss of primary coolant could be handled by replacing water with a different working fluid that is able to transport more heat.

2.3.2 Water Heaters

Another alternative use for the steam injector that has been developed is simply as a liquid heater. In some industries such as dairy, metal treatment, and textiles, liquid heating is simply a part of the production process. In other industries, a fluid may be needed to promote a chemical reaction or circulation of fluid. Several companies, in particular Spirax Sarco, have incorporated steam injectors into these applications. The steam injector provides efficient circulation and heating of the fluid while limiting the noise produced. Steam injectors are compact, so they do not require much extra space and do not require continuous maintenance [11].

2.4 How a Steam Injector Works

One of the key tasks that needed to be accomplished before trying to simulate a steam injector was figuring out how the steam injector worked. At first glance, a steam injector appears to be a relatively simple device that uses a series of convergent-divergent nozzles to alter the velocity and pressures of the steam and water flows in such a way as to produce an exit pressure that is higher than the input pressure. This is about all of the explanations given by White [12] and, separately, Scarry [10] for the interior workings of the injector. Llewellyn Ludy [8], in his treatise on locomotives, simply states "a jet of steam imparts its energy to the water and thus forces it into the boiler against the boiler pressure." All three men based their discussions on the injector sold by William Sellers. Figure 2 shows a drawing of Sellers' injector of the early 1860's.

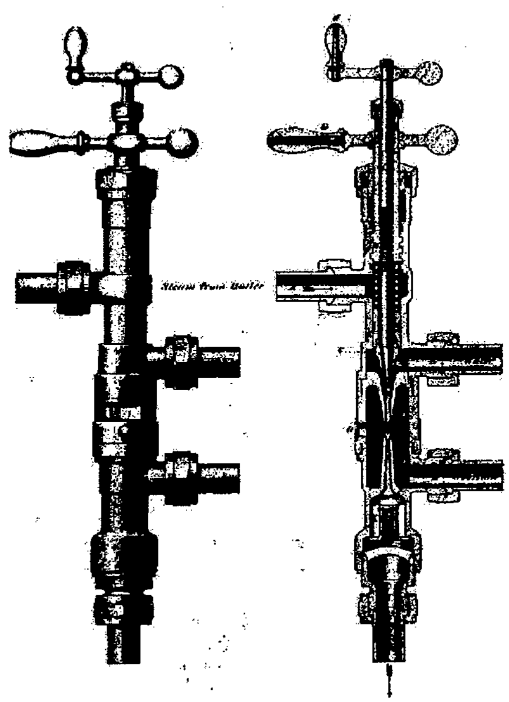

Figure 2. Sellers' injector

Figure 3 shows how steam enters the injector from the boiler and is accelerated through a nozzle. Then the steam picks up the water and enters a mixing region. Here, the steam transfers its momentum and heat to the water. The steam-water mixture then passes through another converging-diverging nozzle to decelerate the flow and convert its dynamic pressure into a static pressure that is higher than the original steam pressure. However, understanding of nozzles shows that simple nozzles cannot accomplish this pressure rise. In a perfect world with no viscous forces and other irreversibilities, the best any nozzle can do is provide an exit total pressure that is equal to the input total pressure. Since this is not a perfect world, there will always be some total pressure losses due to friction when a fluid flows and the exit pressure out of a nozzle will always be lower than the input pressure. In a well designed nozzle, the loss may be extremely small, but there will be a loss. Since the nozzles cannot account for the pressure rise, some other mechanism must be present that does. This mechanism must be involved with the mixing of the water and steam.

Deberne proposes that this mechanism is a shock wave that forms because of the condensation of the steam into water. Figure 3 shows a representation of Deberne's injector.

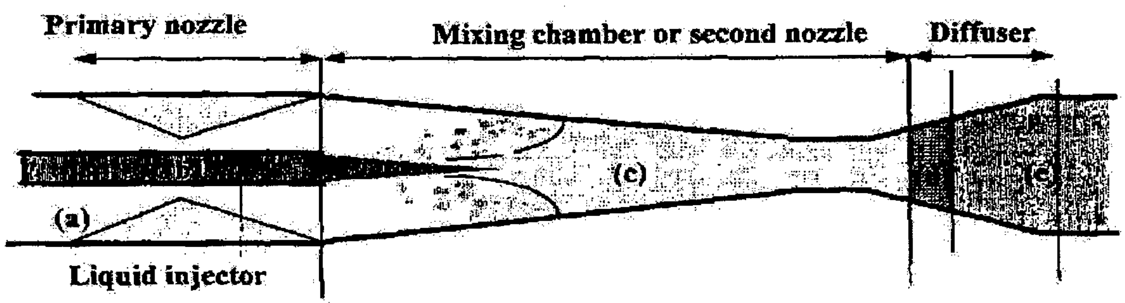

Figure 3. Deberne's injector [4]

Deberne used a slightly different set-up for his injector than the traditional injectors designed by Giffard and then sold by Sellers [12]. Deberne uses a central water pipe surrounded by an annular steam nozzle. The steam nozzle accelerates the steam to supersonic velocities, which correspond to a low static pressure. This static pressure is lower than the water pressure so the water is pulled through its pipe from where ever it is being stored. The water enters and mixes with the steam in the mixing chamber. This mixture then enters a diffuser where the condensation of the steam onto the water droplets causes a shock wave to form in the flow. On the other side of the shock wave, region d in Figure 3, the flow travels through the rest of the diffuser and then exits. [4]

The most important parts of the injector is the mixing region and the front portion of the diffuser. As the injected water flows through the mixing region, the stream of water diffuses. At the end of the mixing region, the water has spread out into many tiny droplets. This diffusion into droplets greatly increases the effective surface area of the injected water. The increased surface area promotes rapid condensation of the steam onto the droplets. According to Deberne, the condensation of the steam sets up a standing shock wave at the entrance to the diffuser and that this shock wave is the mechanism which causes the majority of the static pressure rise. In his book, James John also mentions that condensation of water can lead to a shock wave. However, he mentions that fact as something to be avoided, as the shock wave can alter the measurements made in the tunnel [7]. Deberne claims to use this shock wave to his advantage. The diffuser then further decelerates the now water only flow, which also increases the static pressure. At the end of the diffuser, the static pressure of the water is now higher than the static pressure inside the boiler and the water can enter the boiler and replenish the water there.

Popov and Stanev also claim that condensation of water plays an important part in the successful operation of a steam injector. However, Popov and Stanev designed their injector so that the condensation shock wave is in the mixing chamber. Figure 4 shows the basic configuration of their injector.

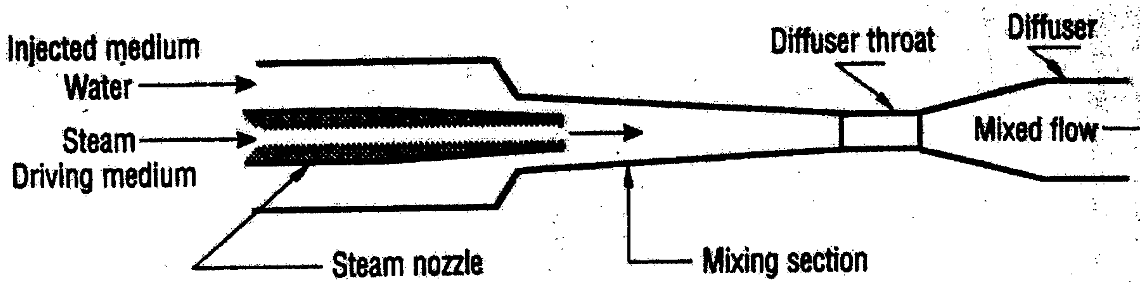

Figure 4. Popov and Stanev's injector [9]

As the figure shows, Popov and Stanev also used an annular arrangement for the steam and water inlets. However, they placed the steam inlet on the inside of the outer water annulus. The rest of their design is essentially the same as Deberne. The steam is accelerated in the steam injector so that it can pull the water into the mixing section. An exchange of temperature and momentum leads to condensation of steam onto the water and a shock wave. The flow then travels through the diffuser for further conversion of kinetic energy into static pressure. Popov and Stanev mention several other factors that affect the performance of their injector. One factor is the ratio of liquid mass flow rate and steam mass flow rate, or entrainment ratio. According to them, the higher the entrainment ratio is, the higher the final pressure will be. Another important factor is the pressure of the driving medium, in this case steam. The steam pressure is also directly proportional to the final pressure, so higher operating pressures will generate higher final pressures.

2.5 Governing Equations

2.5.1 Isentropic flow

The actual operation of the components of a steam injector is governed by several concepts. One important concept is that of isentropic flow of a calorically perfect fluid through a variable-area channel. A perfect gas is a gas which obeys the perfect gas law:

$$P = \rho RT \tag{1}$$

where P is the pressure, ρ is the density, T is the temperature, and R is the gas constant, which, for a perfect gas, is defined as:

$$R = \frac{\overline{R}}{MW} \tag{2}$$

where $\overline{R}$ is the universal gas constant and MW is the molecular weight of the gas in question.

An isentropic flow is one in which there is no heat exchange and the process is completely reversible. A reversible process is one in which the properties of the flow can change during the process and then be changed back to the original properties without any change to the system or the environment. A calorically perfect fluid is one in which the amount of heat added to the fluid to generate a degree rise in temperature, also known as the specific heat, is constant. There are actually two different specific heats, a constant volume, c_v, and a constant pressure, c_p, specific heat. The constant volume specific heat, c_v, is defined as being :

$$c_v = \left(\frac{\partial e}{\partial T}\right)_v \tag{3}$$

where e is the specific internal energy of the fluid and T is temperature.

The constant pressure specific heat is defined as being:

$$c_p = \left(\frac{\partial h}{\partial T}\right)_p \tag{4}$$

where h is the specific enthalpy of the fluid.

In a perfect gas, the specific heats are related to the gas constant by:

$$c_p - c_v = R \tag{5}$$

An important identity taken from the specific heats is the ratio of specific heat, or γ. The ratio of specific heats is found using:

$$\gamma = \frac{c_p}{c_v} \tag{6}$$

In many applications, the ratio of specific heats is assumed to be a constant. This is usually a fairly good assumption if the temperature range in question is small, as the ratio of specific heats is nearly constant over a small range of temperatures.

In real life, there is no such thing as an isentropic flow. However, assuming that a flow is isentropic greatly simplifies the calculations for computing the properties of the flow, and, usually, does not produce an enormous amount of error into the problem. By assuming an insentropic flow, some of the properties of the flow, pressure, temperature, and density, can be related to each other using only the ratio of specific heats. For calorically perfect flow, these three isentropic relationships are:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \quad (7)$$

$$\frac{T_2}{T_1} = \left(\frac{\rho_2}{\rho_1}\right)^{\gamma-1} \quad (8)$$

$$\frac{P_2}{P_1} = \left(\frac{\rho_2}{\rho_1}\right)^{\gamma} \quad (9)$$

When dealing with compressible flow, it is often useful to find the stagnation, or total, properties. A stagnation property is defined as the value that property would take if the flow were isentropically brought to rest at that point in the flow. Two of the more important stagnation properties are stagnation temperature and stagnation pressure. These two properties are found to be:

$$T_t = T\left(1+\frac{\gamma-1}{2}M^2\right) \quad (10)$$

$$P_t = P\left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{\gamma}{\gamma-1}} \quad (11)$$

where T, P, and M are the temperature, pressure, and Mach number at a point in the flow.

Mach number relates the velocity of the flow to the speed of sound and is defined as:

$$M = \frac{U}{a} \quad (12)$$

where U is the velocity and a is the speed of sound.

The speed of sound in a medium changes as the properties of the medium change. The speed of sound can be calculated as:

$$a = \sqrt{\gamma RT} \quad (13)$$

Mach number and the ratio of specific heats are also related to other properties in a flow. One of the more important of these properties is the ratio between the local area and the area where the Mach number is one. The area ratio is found using the equation:

$$\frac{A}{A^*} = \frac{1}{M}\left[\frac{2}{\gamma+1}\left(1+\frac{\gamma-2}{2}M^2\right)\right]^{\frac{\gamma+1}{2\gamma-2}} \tag{14}$$

2.5.2 Shock waves

Another important aspect of compressible flow which has important equations is that of shock waves. A shock is a discontinuous location in a flow. Fluid entering the shock is supersonic and has a certain set of properties. The fluid leaving the shock is subsonic and has a different set of properties. A shock wave represents an irreversible process in which the static pressure rises suddenly, the total pressure drops, and the velocity decreases. The simplest type of shock wave is a normal shock wave, which stands perpendicular to the flow. This project assumes all shock waves are normal so the equations for oblique shocks are not included here.

In a normal shock, there is no direction change, area change, or work done on the flow. With these conditions, the conservation of mass, energy, and momentum equations reduce to:

$$\rho_1 U_1 = \rho_2 U_2 \tag{15}$$

$$T_{01} = T_{02} \tag{16}$$

$$p_1 - p_2 = \rho_1 U_1 (U_2 - U_1) \tag{17}$$

where subscripts 1 and 2 represent properties before and after the shock respectively.

By combining these three equations with the equations for Mach number and the ideal gas law and performing a lot of simplifying algebra, three new equations are generated that describe the effect of normal shock waves on fluid properties. These three equations are:

$$\frac{p_2}{p_1} = \frac{2\gamma}{\gamma+1}M_1^2 - \frac{\gamma-1}{\gamma+1} \tag{18}$$

$$\frac{p_{02}}{p_{01}} = \frac{\left[\frac{\left(\frac{\gamma+1}{2}M_1^2\right)}{\left(1+\frac{\gamma+1}{2}M_1^2\right)}\right]^{\frac{\gamma}{\gamma-1}}}{\left(\frac{2\gamma}{\gamma+1}M_1^2 - \frac{\gamma-1}{\gamma+1}\right)^{\frac{1}{\gamma-1}}} \tag{19}$$

$$\frac{T_2}{T_1} = \frac{\left(1+\frac{\gamma-1}{2}M_1^2\right)\left(\frac{2\gamma}{\gamma-1}M_1^2 - 1\right)}{\frac{(\gamma+1)^2}{2(\gamma-1)}M_1^2} \tag{20}$$

2.5.3 Gas mixtures

Applying all of the equations presented so far is relatively simple for single gases. However, when dealing with a mixture of gases, additional steps must be taken prior to applying the isentropic and shock wave equations. The additional steps are required to find an effective ratio of specific heats for the mixture. The first step in this process is to find the mass flow rates for each of the component fluids. Mass flow rate is calculated using the equation:

$$\dot{m} = \rho U A \tag{21}$$

When using a supersonic wind tunnel, the most convenient place to apply the mass flow rate equation is at the nozzle throat. The throat is a convenient location for several reasons. The first reason is that the throat dictates the mass flow rate for the rest of the wind tunnel. The second reason is that the area of the throat should be a known quantity. The third reason is that for choked flow the velocity at the throat will be the speed of sound, which simplifies finding the velocity. The speed of sound can be found using equation 13. At the throat, the flow is an air only flow, so the ratio of specific heats used in equation 13 is for air. The temperature can be found using equation 10, since the Mach number must be one and the total temperature is just room temperature. The only remaining variable needed to find the mass flow rate is the density of the air at the throat. The density can be found using the perfect gas law, equation 1. The temperature at the throat was computed above to find the speed of sound and the gas constant for air is already known. Pressure can be found using equation 11, since the total pressure is set by the user and, therefore, known.. After finding the density, the mass flow rate for air can easily be computed.

Finding the mass flow rate of the injected fluid, ethanol in this experiment, must be done in a different manner. In the experiment for this project, the ethanol was poured into a graduated cylinder so that the starting volume of ethanol was known. During the wind tunnel run, the time that the ethanol was injected into the flow was kept by a stop-watch. After the run was over, the final volume of ethanol was measured. Knowing the volume of ethanol used and the time that it was used in, the volume flow rate of ethanol is found by simply dividing the amount of ethanol by the time. Next, use the definition of density to find the mass flow rate of ethanol. The definition of density is:

$$\rho = \frac{m}{V} \tag{22}$$

where m is mass and V is volume. Multiply the volume flow rate, which is volume per unit of time, by the density, and the result is mass per unit time, which is mass flow rate.

After the mass flow rate of air and the mass flow rate of ethanol are found, the two rates are added in order to find the total mass flow rate. Knowing the total mass flow rate, the percentage of the total that each component comprises needs to be found. The accurate computation of the ratio of specific heats for a two phase mixture is beyond the scope of this research. The analysis instead incorporated a simple mass averaged value. This is accomplished using the equation:

$$\gamma_{mix} = \frac{\gamma_{air}\dot{m}_{air}}{\dot{m}_{total}} + \frac{\gamma_{eth}\dot{m}_{eth}}{\dot{m}_{total}} \tag{23}$$

2.5.4 Measuring pressure

When measuring pressure, care must be taken to specify what kind of pressure is involved. There are two types of pressure that experimenters concern themselves with, static pressure and total, or stagnation, pressure. Static pressure is the pressure that would be felt by an object travelling at the flow velocity. Total pressure is the pressure of the flow if it is isentropically brought to a stop. Isentropic deceleration can be simulated using pitot tubes. When a pitot tube is measuring the total pressure of a subsonic flow, the total pressure measured is the true total pressure of the flow, as would be calculated from equation 11. However, if the pitot tube is measuring the total pressure of a supersonic flow, the total pressure measured is not the true total pressure. The reason for the difference is that the pitot tube, which is pointing straight back into the flow, acts as a barrier to the supersonic flow and a detached normal shock wave forms at the mouth of the pitot tube. This means that the total pressure measured by the pitot tube is actually the total pressure that has been affected by a shock wave according to equation 19. If the freestream Mach number of the flow is known, then equation 19 can be used to calculate the total pressure before the shock wave.

Chapter 3 - Experimental Set-up

The set-up used in this experiment is designed to mimic the operation of a steam injector, but on a larger scale and using compressed air as the working medium, not steam. Due to time and monetary constraints, as many in-house parts were used as possible. AFIT already possessed the wind tunnel infrastructure necessary to supply the compressed air and accelerate that air to supersonic velocities. The wind tunnel used in this experiment is not a continuously running, supersonic tunnel. A vacuum system is used to generate a back pressure low enough for the tunnel to achieve supersonic velocities. However, the vacuum tanks fill up as the tunnel runs and the back pressure will rise until the system is unable to maintain supersonic flow, called unstarting. When the vacuum tanks reach atmospheric pressure, a large relief valve opens to prevent any pressurization of the vacuum tanks higher than atmospheric. Since the vacuum tanks fill up, supersonic flow time is limited to around thirty seconds. The final experimental set-up evolved through several different set-ups as more experience and understanding of the tunnel properties was gained . Most of the alterations performed on the set-up were part of a goal to create a continuously running wind tunnel that was not limited by the vacuum tanks. Continuously running wind tunnels generally are closed loop tunnels which recirculate the air from the test section back through the compressor, to be used again. An open loop, continuously running, supersonic wind tunnel which exhausts the compressed air into the atmosphere is a novel idea and would be an extremely beneficial side effect of this thesis. Such a tunnel would provide the means to better investigate the operation of a steam injector apparatus and provide AFIT with a capability that could be used in future applications that required supersonic velocities and long run times. A description of the compressed air supply system, the properties of the various sections of the tunnel, and descriptions of each set-up used are included.

3.1 Compressed Air Supply System

The supplied air comes from two Ingersoll-Rand SSR compressors. These compressors, shown in Figure 5, are capable of compressing one hundred and thirty-four cubic feet of air per minute up to two hundred pounds per square inch (psi)

Figure 5. Air compressors

The compressors send the compressed air into a large tank. From the tank, the air travels through two Ingersoll-Rank HRM compressed air driers. After exiting the driers, the air goes through a regulator, which reduces the pressure of the air to one hundred and twenty-five psi. Next, the air travels through an air filter, then to a valve. This valve, shown in Figure 6, is a regulated valve and sets the inlet pressure that the user specifies between zero and thirty psi gage.

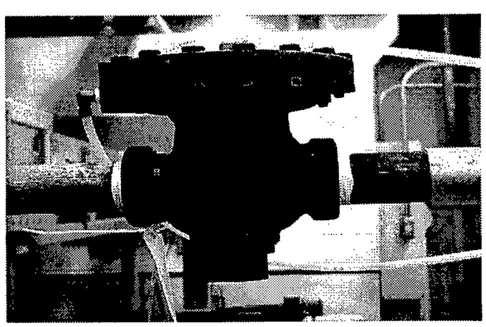

Figure 6. Valve

This pressure is set on a regulator that controls the valve shown in Figure 6. After exiting the regulator, the air flows through the supply plenum and into the user's convergent/divergent nozzle, which is designed to accelerate the air up to Mach three. After exiting the nozzle, the supersonic flow then travels through the constant area test section where the flow may or may not pick up the injected fluid, depending on the test. The path that the flow takes after leaving the mixing section is also dependent on the test set-up being run.

The operation of the tunnel is controlled by two switches. One switch controls the vacuum valve. When this switch is activated, the valve that separates the evacuated tanks and the wind tunnel opens. This causes the tunnel to become evacuated all of the way back to the regulated valve depicted in Figure 6. The second switch controls the air flow. When this switch is activated, the valve that closes the path of the compressed air is opened. This allows air pressurized at one hundred and twenty-five psi to move up to the regulated valve. This valve operates by trying to make the pressure behind it equal to the pressure set by the user on the pressure regulator. When the valve senses the high pressure on one side and the vacuum on the other side, it will open to allow air of the set pressure through. The valve will remain open as long as the pressure behind it is not equal to the set pressure, but will close if the pressures ever equalize. This serves as a safety measure to try to prevent drastic overpressurization of the test section of the tunnel. If some circumstance were to go extremely wrong, such as the user forgets to open the vacuum valve and there are no other relief valves present, then all of the tunnel from the vacuum pump back to the regulated valve will experience a sudden and, possibly, dangerous pressurization. However, as soon as that pressure rises to the level set by the user, then the regulated valve will close to prevent further pressurization. To make this safety precaution actually worthwhile, all of the components on the tunnel from the regulated valve up to the vacuum valve must be constructed of materials strong enough to safely withstand the set pressure.

3.2 Description of Components Within the Experiment

3.2.1 Description of the nozzle

The nozzle is needed to accelerate the air to supersonic velocities in order to drop the static pressure of the flow. The nozzle has a symmetric converging section with a non-symmetric diverging section. The inlet area of the nozzle is fifteen square inches, the throat area is 1.475 square inches, and the exit area is 6.25 square inches. Two pressure measurements are taken from the nozzle. One measurement is a total pressure measurement using a pitot tube. The pitot tube is located in the converging part of the nozzle and is pointed towards the opening of the nozzle. This total pressure measurement is needed to find the true initial total pressure of the flow. As mentioned above, the user may set the pressure that is delivered by the large regulated valve. The regulating mechanism, however, is not extremely accurate and so a measurement must be taken in order to know the total pressure. The second pressure measurement is a static pressure reading taken at the nozzle throat. A picture of the nozzle is shown in Figure 7.

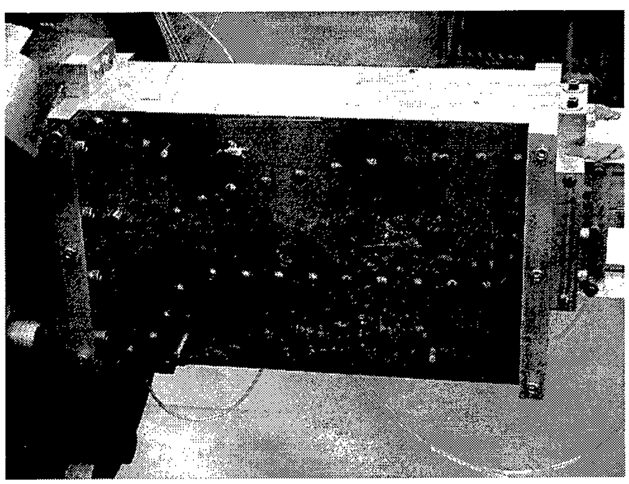

Figure 7. Nozzle

The compressed air enters the nozzle with a certain amount of total pressure which is set by the user. By knowing the geometry of the nozzle and employing the equations for isentropic flow in a changing area channel, the properties of the flow, such as total pressure, static pressure, velocity, and temperature, can be determined. The isentropic flow equations show certain trends for the flow properties in converging and diverging portions of a nozzle based on whether the flow is subsonic or supersonic. The diagram in Figure 8 shows the changing properties in subsonic flow through a nozzle. As shown, during subsonic flow in a converging nozzle, Mach number will increase (but cannot increase higher than Mach one), true velocity will increase, static pressure will decrease, static temperature will decrease, and density will decrease. For subsonic flow in a diverging diffuser, Mach number will decrease, true velocity will decrease, static pressure will increase, static temperature will increase, and density will increase. Figure 9 shows how properties change for supersonic flow inside a nozzle. For supersonic flow in a converging nozzle, Mach number will decrease, true velocity will decrease, static pressure will increase, static temperature will increase, and density will increase. For supersonic flow in a diverging nozzle, Mach number will increase, true velocity will increase, static pressure will decrease, static temperature will decrease, and density will decrease. The converging-diverging nozzle in this experiment uses these trends by having a subsonic converging section and a supersonic diverging section. This combination increases Mach number and velocity while decreasing static pressure, temperature, and density.

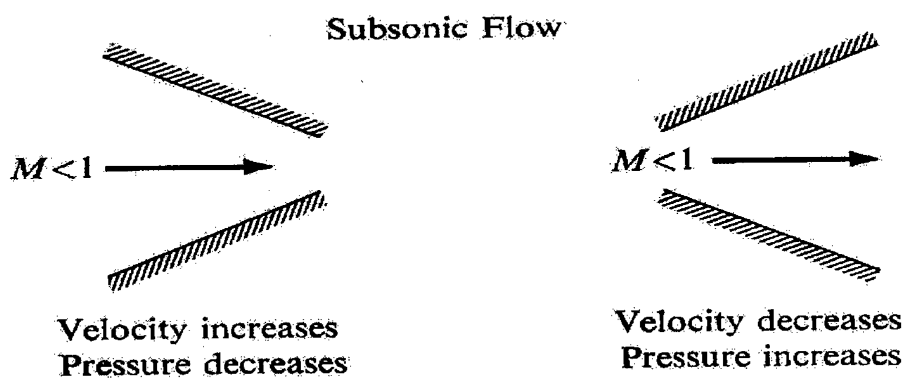

Figure 8. Properties of subsonic flow in a nozzle

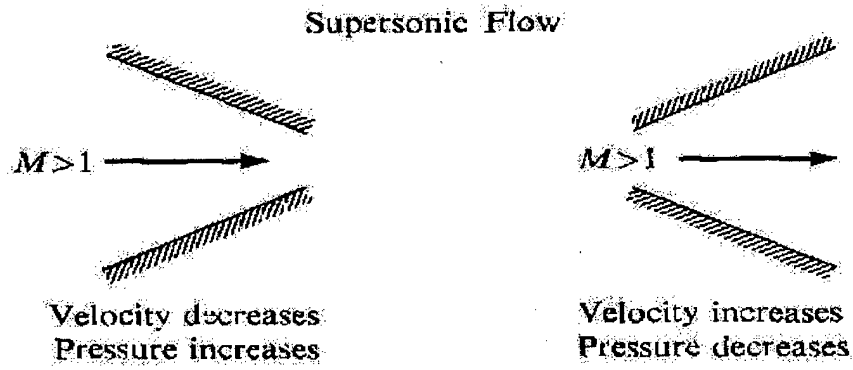

Figure 9. Properties of supersonic flow in a nozzle

For this experiment, an interesting property to know is the static pressure at the nozzle exit. To find the static pressure at the exit, the Mach number at the exit must first be found. The Mach number can be found by using equation 14. The quantity $\frac{A}{A^*}$ is known from the actual geometry of the nozzle. That value is equal to 4.237. Equation 14 then can be solved iteratively for the Mach number. For this nozzle, the area ratio of 4.237 corresponds to a Mach number of three. Knowing the Mach number and the total pressure, measured with the pitot tube, the static pressure at the nozzle exit is then found using equation 11. For the injection of fluid to occur, this static pressure must be lower than the static pressure of the ethanol.

3.2.2 Description of the injection/mixing section

The mixing section, shown Figure 10, is where the injection of the ethanol occurs and mixing of ethanol and air begins.

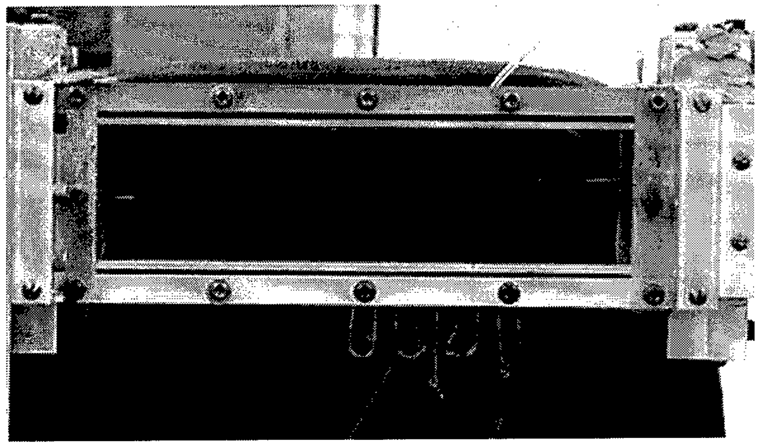

Figure 10. Mixing Section

The mixing section has a cross-section identical to that of the nozzle exit. The area of the mixing section is 6.25 square inches and is thirteen inches long. In the front part of the mixing section, a small tube enters from the bottom of the section, as seen in Figure 10. The tube then bends ninety degrees so that the exit of the tube is directed downstream. This is the injection tube through which the ethanol travels on its way from the graduated cylinder to the flow. At the back part of the mixing section is another pitot tube to measure total pressure. This pitot tube was initially placed there in the first attempt to measure the effect of injection on pressure. In the first attempt, it was hoped that the mixing section would be long enough for thorough mixing of ethanol and air to occur. Unfortunately, the section was not long enough for the ethanol stream to sufficiently break up and mix so the pitot tube at the end of the mixing section did not register any useful data. At the end of the mixing section, the ethanol was still confined to a steady stream. That stream had spread to several times as large as the stream that emerged from the injection tube, but was no where near to filling the entire area of the mixing section. The pitot tube did was used in the final experimental setup. However, its use was not to measure data that would be analyzed for pressure change, but as an indication of when the wind tunnel unstarted and became subsonic.

3.2.3 Description of the diffuser

The diffuser, shown in Figure 11, serves a different purpose in the different set-ups. Therefore, a detailed description of the properties within the diffuser accompanies the section for each set-up. This section will limit itself to a general description of the diffuser.

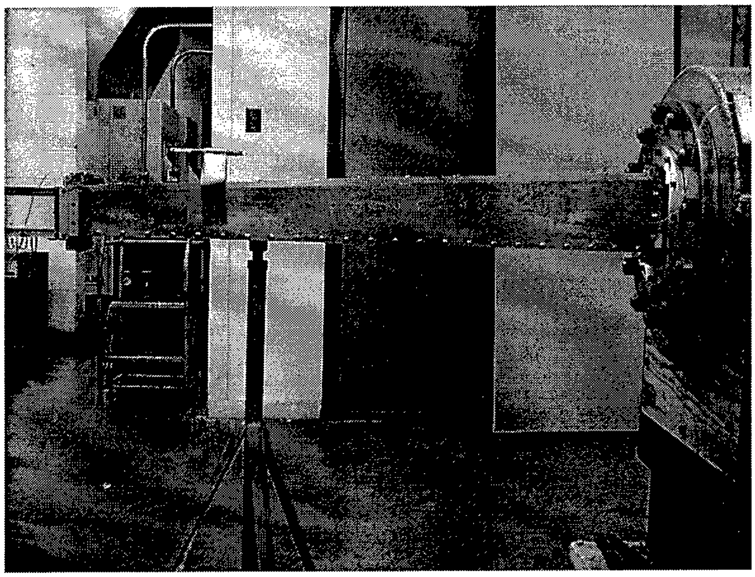

Figure 11. Diffuser

The diffuser is approximately forty-eight inches long and can be separated into two regions. The first region has a constant cross-sectional area equal to that of the mixing region, or 6.25 square inches, and is approximately twenty-five inches long. The second region is about twenty-three inches long and has a cross-sectional area that increases towards the back end. The area starts out at the same area as the mixing section and the first region of the diffuser, or 6.25 square inches. The area then doubles to 12.5 square inches at the exit of the diffuser.

3.2.4 Description of the exit plenum

The exit plenum is a cylindrical tank constructed of aluminum 2024. Like the diffuser, the purpose of the tank varied with each experimental set-up. Figure 12 shows the tank in its final configuration.

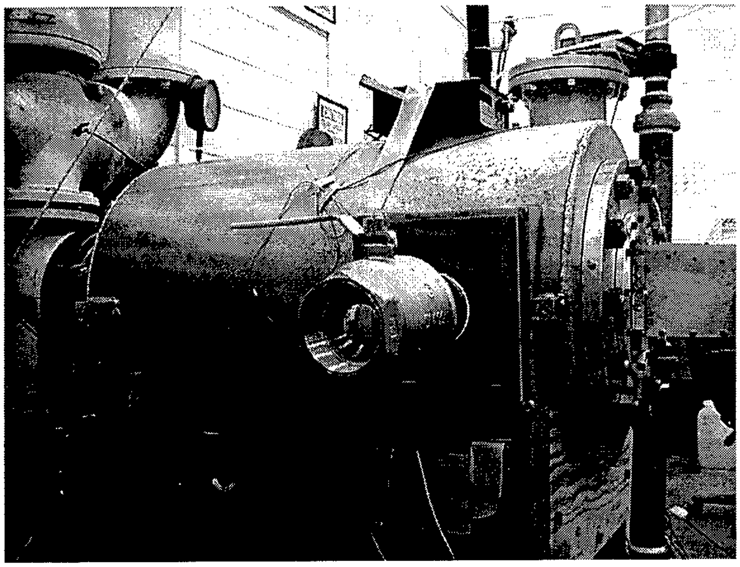

Figure 12. Exit plenum

The tank has a seventy-seven inch outer circumference, which corresponds to a twenty-four and a half inch outer diameter. The aluminum is one quarter inch thick, which means that the inner diameter of the tank is twenty-four inches. The tank is forty inches long and has a volume of 18100 cubic inches, or 10.5 cubic feet. The tank has two windows which protrude from the sides. The windows are two rectangular openings that were originally filled with thick glass on one side and thick plexiglass on the other. For safety purposes, the glass and plexiglass plates were replaced with two aluminum plates that could withstand higher pressures. Since the possibility existed for the tank to become pressurized, a calculation needed to be performed to ensure that the pressure inside the tank would not exceed the strength of the aluminum. As mentioned above, the tank is an aluminum cylinder. A cylindrical pressure vessel experiences two distinct stresses. Those stresses are longitudinal, meaning the stress against the two circular ends of the cylinder, and hoop stress [2]. Hoop stress is the stress caused by the pressurized medium inside the cylinder pushing against the side wall and trying to expand the radius of the cylinder. Hoop stress is twice as large as longitudinal stress in a cylindrical pressure vessel and causes a failure in the form of a fracture that points at the ends of the cylinder. Since hoop stress is twice as large as longitudinal stress, the aluminum tank must be able to withstand any foreseeable hoop stress that could be placed on it. The hoop stress is calculated using the equation:

$$\sigma_h = \frac{pr}{t} \tag{24}$$

where p is the static pressure inside the cylinder, r is the radius, and t is the thickness [2].

Using this equation and knowing that the yield strength of aluminum 2024 is 47000 pounds per square inch [2], the pressure needed to exceed the yield strength is calculated to be about 980 pounds per square inch. Since the pressure inside the tank can never reach that level with the safety shut off of the regulated valve, the tank can be deemed as safe to use in the tunnel.

3.2.5 Recording Data

The data in this experiment was primarily in the form of pressure measurements taken at the points indicated in the component descriptions above. Several total pressure measurements and several static pressure measurements were made. Examples of this data is shown in Appendix A. The method used to measure static pressure in this experiment was with a small hole drilled perpendicular to the edge of the wall. This hole was then connected to a pressure transducer through a small plastic tube. The transducers used in this experiment were Endevco Piezoresistive Pressure Transducers. Even though each transducer was calibrated prior to use, there was still some error associated with them. The transducers were calibrated to be accurate to a tenth of a pound per square inch. However, the actual error in the transducers would have to be determined after the test runs were completed and the data analyzed. The total pressure was measured using pitot tubes, as described in Chapter 2. These pitot tubes also connected to pressure transducers through the thin plastic tubing. The transducers for both static and total pressure were connected to an Endevco model 4428A tranducer readout box. Each transducer was connected to a separate readout. The readout boxes displayed the measured pressure, then converted the transducer data from pressures, measured in pounds per square inch, to a corresponding voltage. The boxes used in this experiment converted the pressure readings to a voltage in the range of zero to five volts. The voltage was then sent to the data acquisition and recording system.

The system used in this experiment is the Nicolet Multipro Data Acquisition System. The data from the transducers is input into the Multipro Pedestal Data Acquisition Unit, shown in Figure 13.

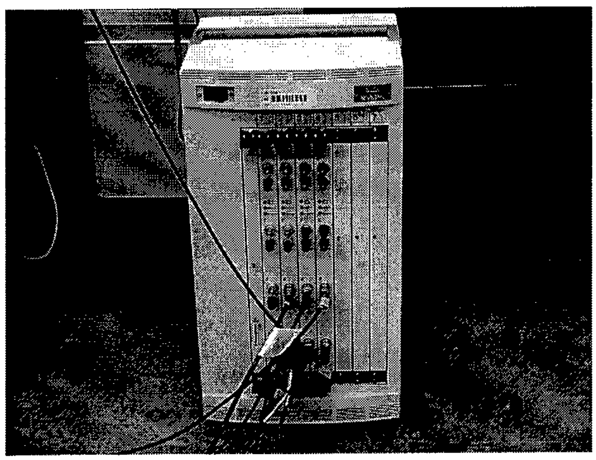

Figure 13. Data Aquisition Unit

The Pedestal Data Acquisition Unit, DAU, used in this experiment has four digitizer boards installed. Each board can accept four different inputs, for a total of sixteen possible data inputs into the system. The DAU then sends the data to the computer where the Nicolet Windows software is installed. Within Nicolet Windows, the user sets up the properties of each channel of data collection. Within each enabled channel, the user may determine the range of voltages to read from the incoming data, how often to sample the data, how many data points to take, what incoming voltage should trigger data collection, and how to convert the incoming voltage to usable units. By the final set-up of this experiment, seven different pressure readings were being taken. That meant that seven channels of data collection needed to be set-up.

Rather than have separate triggers for each channel, all seven channels were set-up to begin recording data when the first channel triggered. The first channel was the static pressure of the input plenum. The channel trigger was set to trip when the voltage coming into channel one reached 0.16 psig. This corresponds to a pressure of 1.6 psig, or 1.6 psi higher than atmospheric pressure since the pressure transducers were all set to measure zero at atmospheric pressure. At that input pressure, all seven channels began recording data and continued recording for forty-five seconds. This time limit was based on the available supersonic flow time being limited to about thirty seconds due to filling of the vacuum tanks. Each channel took a data point every three milliseconds, corresponding to a sample rate of 333 hertz. At this sample rate, each channel took 15000 data points each run. This configuration was used for two primary reasons. First, it kept the number of data points taken to a manageable number. Second, taking a data point every three milliseconds ensured that any rapid changes in the state of the flow were captured. This is important when dealing with shock waves as they can move extremely quickly at times and a fast sampling rate is needed to accurately detect any changes. After the forty-five seconds had elapsed, Nicolet plotted the data that it had just received. This gave the user the ability to obtain an immediate feel for what occurred during the run. The plots for all active channels could be viewed on the same screen, providing the ability to easily compare and contrast what each channel recorded, or each plot may be viewed separately.

3.3 First Test Configuration

The goal of the first test set-up was to directly measure the influence of the liquid injection by means of a total pressure pitot located at the exit of the mixing section. For this set-up, the compressed air would travel through the nozzle and be accelerated to supersonic speeds. The flow would then enter the mixing section and pick up the liquid. Next, the flow would exit the mixing section and enter the diffuser. Finally, the flow would travel through the diffuser to the vacuum tanks. Unfortunately, the injected fluid did not have time to adequately mix with the compressed air when the mix reached the pitot tube at the exit of the mixing section. As mentioned above, the liquid was still confined to an all liquid cone of spray, so the pitot tube was not measuring the pressure of thoroughly mixed flow. The design needed to be modified to allow a longer mixing time. Also, the idea for the continuously running tunnel emerged at this point. This meant that the next design needed to be continuously running while allowing adequate mixing room and a means of measuring any effect on the pressure. Since this design showed very clearly that it could not accomplish the goals of the research, it was not used any further and contributed no results.

3.4 Second Test Configuration

The second test set-up incorporated the exit plenum into the system for the attempt to make the tunnel run continuously. The plenum was inserted between the diffuser and the vacuum valve A considerable amount of time was spent pondering the idea of an open loop, continuously running, supersonic wind tunnel that exhausted the flow into the atmosphere. The theory that developed over time was that the tunnel would need to be started with the vacuum system to achieve supersonic velocities. The tunnel should run normally and allow the back pressure to slowly build in the vacuum tanks and the exit plenum. A large relief valve would need to be installed somewhere on the plenum. This valve should be closed during start up and while the tunnel is running with the vacuum system on. After the tunnel ramps up to supersonic, two actions must occur at nearly the same time. First, someone must close the vacuum valve using its control switch. Second, someone else must open the relief valve on the exit plenum. If everything is designed and operated correctly, then the tunnel will continue to run at supersonic velocities, but the air will exit through the plenum tank instead of going to the vacuum tanks. Then, the tunnel should operate as long as the compressors are able to supply high pressure air. In support of this idea, a three inch, manually operated valve was installed in one of the windows of the tank. This location was chosen because the windows were the only locations on the plenum into which a pipe could be threaded securely and the other window was blocked by some of the air supply infrastructure.

Another idea proposed during this period of testing was an alternative method of measuring the effect of fluid injection on the total pressure. This idea was to use the exit plenum to measure the total pressure. If the plenum possesses a large enough volume, then velocity inside of the plenum will be near to zero. Even with the relief valve open and air flowing out of it, a large plenum should manifest most of the total pressure inside of it as static pressure. Therefore, a static pressure transducer was installed on the plenum. Two separate methods for using the plenum to measure the change in pressure were developed. The plan for implementing both of these ideas assumed a continuously running wind tunnel. For the first method, if the tunnel was started and switched off of the vacuum system with zero injection allowed, the static pressure reading from the plenum should represent the total pressure of the air only flow. Once the tunnel had achieved steady state in this configuration, the valve controlling the flow of liquid was opened and injection commenced. The static pressure inside of the plenum should change to reflect any changes in total pressure brought about by the injection.

The second method of using the exit plenum to determine any change in pressure required two separate runs. In the first run, the tunnel would be started and then switched off of the vacuum system with no injection occurring, as in the previous method. Next, however, no fluid is injected. Rather, the exit valve is slowly closed to gradually raise the pressure inside the plenum. Eventually, the pressure inside the plenum will become high enough to cause the tunnel to unstart. Next comes the second run. In this run, the tunnel is started followed by ethanol injection. After the injection has started, the tunnel is switched off of the vacuum system. The exit valve is then slowly closed, as it was in the first run, until the tunnel unstarts. If the injection of liquid into the flow had any change on the pressure of the flow, then the pressure inside of the plenum should be different for the run with injection than for the run without injection.

Extensive effort went into this phase of the experiment and many tests were run. These tests led to several minor changes to the set-up during this phase as understanding of the properties of the system continued to grow. One of these changes was the replacement of the three inch valve with a four inch ball valve. Part of the flow area of the three inch valve was blocked. The blockage was significant enough as to cause some concern over flow choking inside the valve. The four inch ball valve provided a large flow area that was free from obstructions.

3.5 Final Test Configuration

The final experimental configuration did not differ much from the second configuration. The major design difference was a return to the idea of directly measuring the changes in total pressure by means of a pitot tube. The difference in this idea from the first configuration was the primary location of interest. In order to ensure that full mixing of the air and ethanol had occurred at the location of the pitot tube, the new tube was moved further back in the set-up to the exit of the diffuser. Another change was to increase the supply pressure up to about 30 psig. Figure 14 shows the final experimental set-up used.

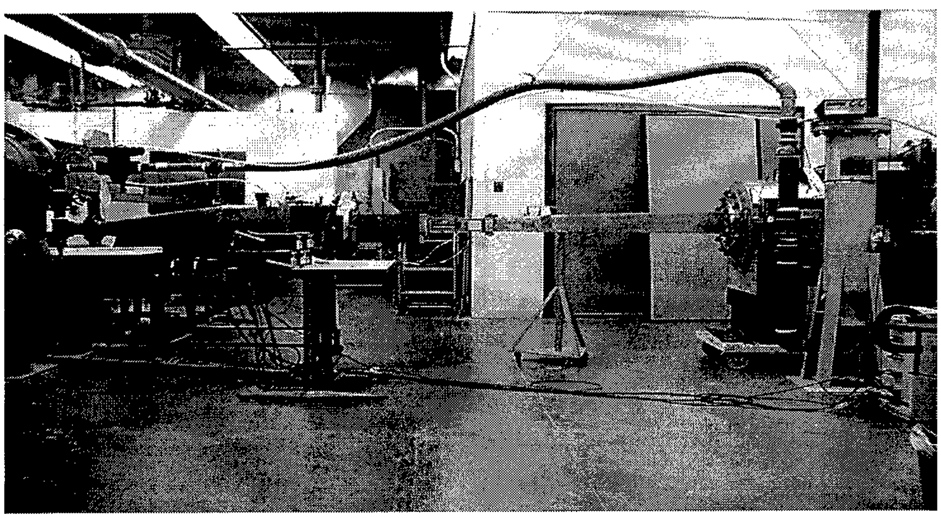

Figure 14. Final Set-up

Experience from the second configuration led to the abandonment of the idea of using the exit plenum to measure total pressure changes. This experience resulted in an understanding of the system's limitations. These limitations were beginning to lower the expectations of success in developing the continuously running wind tunnel. Since the idea of using the exit plenum to measure total pressure changes relied upon the operation of a continuously running tunnel, an alternative pressure measurement method was deemed prudent. Also, some questions were raised as to the actual capability of the plenum to still the flow and generate an accurate total pressure measurement. If the flow retained too much velocity inside of the plenum, then the static pressure reading would not accurately reflect the total pressure.

Experience also led to an understanding of the importance of the diffuser, both as part of the injector and as a component of a continuously operating wind tunnel. As the air and ethanol exited the mixing section, the flow entered the first region of the diffuser. This region essentially served as an extension to the mixing section and tripled the length of tunnel for the ethanol to mix with the air. This thorough mixing was necessary for a complete exchange of momentum to occur from the high speed air to the low speed ethanol. This exchange of momentum resulted in a multiphase flow where the air and ethanol droplets have the same velocity. This velocity was lower than the velocity that the flow initially achieved after exiting the nozzle. There are two reasons for the decrease in velocity. First, the mass flow rate was set by the nozzle throat and the air that entered the mixing region had a velocity that contributed to maintaining that constant mass flow rate. When the ethanol entered the mixing region, it contributed its own mass flow rate. Since the total mass flow rate must be constant, the mass flow rate of the air must decrease by the amount that the ethanol mass flow rate adds. The decrease in the air's component of the mass flow rate resulted in a decrease in the velocity of the air. The second reason for a decrease in flow velocity was the exchange of momentum between air and ethanol. Since the mixing of air and ethanol resulted in the combining of two separate mass flow rates into a single mass flow rate, the exchange of momentum was modelled as a perfectly plastic collision between the air and ethanol. The momentum of a single mass was found as the product of mass multiplied by linear velocity. A perfect collision between two masses can be characterized by the equation:

$$m_1 u_1 + m_2 u_2 = (m_1 + m_2)\, u_{final} \tag{25}$$

The set-up used had a considerable amount of air at high velocity hitting a small amount of ethanol with relatively little velocity. The combination of these two mass flows into one mass flow resulted in a decrease in velocity for the air and an increase in velocity for the ethanol. As the flow exited the first region of the diffuser and entered the second region, this momentum exchange was complete.

The second region of the diffuser did the actual work of changing the pressure and velocity of the flow. A pitot tube was positioned at the exit of the diffuser in order to measure the total pressure of the completely mixed and diffused flow. Chapter two mentioned that the purpose of the diffuser was to further decelerate the flow and raise the static pressure. However, the section on nozzle properties in Chapter three explained that for supersonic flow, a diffuser actually decreased static pressure and increased velocity. So why does the setup include a diffuser that does the opposite of what it was intended to do? The answer is that the flow in the diffuser was not supersonic for the entire test run. As mentioned previously the tunnel experienced increases in back pressure. As the pressure in the vacuum tanks rose, that increase in pressure moved from the tanks, through the piping system and exit plenum, towards the exit of the diffuser.

As the pressure behind the diffuser started to rise, compression waves began to form that raised the static pressure of the flow to that of the back pressure. The back pressure continued to increase and the compression waves became stronger and stronger until they coalesced into a standing normal shock wave at the diffuser exit. This shock wave was of sufficient strength to raise the static pressure of the flow to the level of the back pressure. If the back pressure increased even more, the shock wave was not strong enough to make the static pressure equal to the back pressure. To compensate, the shock wave began to travel backwards through the diffuser. For each level of back pressure, the shock wave had a certain position in the diffuser such that the increase in static pressure due to the shock wave and the increase in static pressure from the portion of the diffuser that remained was just enough to raise the static pressure of the flow to that of the back pressure.

As the shock wave moved further down the diffuser, the wave eventually reached the point where the area of the diffuser stopped decreasing and remained constant. At that point, the shock wave raced through the tunnel and became lodged in the nozzle. When that happened, the tunnel was said to have unstarted and the flow through the tunnel was completely subsonic.

To develop a continuous tunnel, something must prevent the shock wave from leaving the diffuser and reaching the mixing region. In essence, the shock wave must be "captured" in the diffuser. A diffuser with an adjustable throat will most likely be required to accomplish this feat. The diffuser used in this experiment already had an adjustable throat from a previous user. The roof of the diffuser was actually made of two separate pieces of aluminum joined by a hinge. By operating a butterfly valve that pushed a rod down onto the hinge, a section of the roof would lower and make a converging-diverging nozzle in the diffuser. The throat of this nozzle was located about seven inches from the interface between the mixing section and the first region of the diffuser. The variable throat could reduce the area at that point to half of the original 6.25 square inches. A technique was theorized for capturing a shock wave using the variability feature of the diffuser. First, the tunnel would be started as usual, with the adjustable throat wide open. Second, someone would turn the butterfly valve and reduce the area of the new throat. After the throat has been lowered, the tunnel would need to be taken off of the vacuum system in the method developed for the second phase of testing. If the diffuser has performed properly, then the shock wave that forms because of the increase in back pressure will not unstart the tunnel.

3.6 Recommended Changes to Test Configuration

AFIT already owned the majority of the equipment used in this thesis. This significantly reduced the amount of time spent designing and building a unique test apparatus. Unfortunately, this also limited the testing capabilities of the experiment. Some major changes are necessary to create a test set-up that more accurately mimics the operational environment a steam injector would experience in space applications. The first major change is the size of the configuration.

The wind tunnel used in this thesis was more than six feet long, just from the entrance of the nozzle to the diffuser exit. The supply plenum and exit plenum add around ten more feet. An operational system could not be anywhere near that size. The larger set-up may be easier to work with, but the extra size adds significant pressure losses due to friction. The next step in this experimental process should include a test apparatus scaled down by at least fifty percent.

Another significant change needed is in the pressure that can be supplied in the test. The compressed air in the present system could not be supplied at higher than about thirty-two psig. This limitation is probably due to two ninety degree corners in the compressed air delivery piping between the regulated pressure control valve and the inlet plenum. The minimum combustion chamber pressure for liquid rocket engines used in space is around one hundred psi and can go as high as two thousand psi [6]. Therefore, the supply pressure possible for the tests must be at least one hundred psi to accurately represent an operational system. The higher supply pressure will definitely increase the chances for successfully capturing a shock wave in the diffuser since the back pressure will also need to get higher before the system will unstart.

The mass flow rate of the air and liquid is also a factor that should be analyzed. This experiment used an extremely tiny tube as an injector in order to limit the impact of the tube on the flow. A large tube may have caused sufficient turbulence in the flow as to prevent smooth starting of the tunnel. However, the small tube limited the mass flow rate of the ethanol. The ethanol ended up only having a mass flow rate of .0016 kilograms per second, or .00353 pound mass per second. This meant that the mass flow rate of the ethanol was considerably smaller than the mass flow rate of the air, which was .678 kilograms per second, or 1.49 pound mass per second. The mass flow rate calculations are found in Appendix B. Popov and Stanev used water mass flow rates that ranged from ten to fifty times larger than the steam mass flow rates [9]. Deberne also used water mass flow rates that were much larger than the steam mass flow rates [4]. A different method of delivering the liquid into the tunnel must be developed that would allow for much larger liquid mass flow rates while not impacting the starting of the air or steam.

Another issue that must be considered is the vacuum system. The vacuum system used in this experiment reduced the back pressure to ten millimeters of mercury on the vacuum gage. That corresponded to about two tenths of a psi. Improvement in the vacuum system may require more time and effort than is reasonable, so, any future work should at least consider that the vacuum system in place at AFIT does not create a true vacuum. Future work must also consider that operating in space will grant the injector system free access to a true vacuum and that there will be no residual back pressure to affect performance.

The operating temperature of the tunnel is yet another area of concern. In the current configuration, the user must accept the ambient total temperature anywhere conditions in the tunnel. Whatever the temperature of the air is coming from the large tank is the total temperature that the experimenter must live with. In a rocket application, the exhaust gases from the combustion chamber that will feed back to pick up the propellants will be at extremely high temperatures. A good estimate of the flame temperature in a liquid rocket is three thousand degrees Kelvin. While heating the compressed air up to three thousand Kelvin may be unreasonable, the system must contain the ability to heat the air some. The system should be able to heat the air to at least the boiling point of water, or three hundred seventy-three kelvin. With the air at that temperature or higher, water may be introduced into the flow to create steam. In a liquid oxygen and liquid hydrogen rocket, the major exhaust product is steam. Other species exist in the exit flow because the high temperatures lead to dissociation, but as the flow becomes directed and cools, recombination will cause steam to be the only significant exhaust product. That steam would still have a temperature high enough that condensation of that steam would take an extremely large temperature drop. Even the cryogenic fuels that are picked up by the flow would likely evaporate before the steam condensed because those propellants are much closer to their vaporization temperatures than the exhaust is to its condensing temperature. However, the ability to have steam in the test would allow for more direct testing of condensing versus non-condensing injectors while creating more accurate operating temperatures.

A final change that is necessary is that the diffuser should have a truly adjustable throat. The adjustable throat that was present in the diffuser had some serious design flaws. Whoever had built the variable throat had fitted the hinge extremely tight against the sides of the diffuser to limit the amount of air that could slip around. Unfortunately, the bend observed earlier was causing the hinge to gouge into the sides of the diffuser as it was raised and lowered. The hinge was made of thin aluminum and was originally attached to the roof pieces by three tiny aluminum screws on each piece. On one of the pieces, however, all three screw heads had been ripped off, so the hinge was no longer attached to that roof piece. Some force must have been present on the hinge to cause the damage observed and at first examination, that force was a mystery. The answer to that mystery lay in the method used to mount the movable roof pieces to the sides of the diffuser. The non-hinged end of both pieces were fitted to small metal rods that connected the roof piece to the diffuser side. These rods served as pivot points and allowed the hinged end of each roof piece to swivel up and down. The roof pieces were sized and fitted so that when the hinge had not been lowered at all and was perfectly straight, no stresses would be placed on the hinge. Unfortunately, however, the pivot rods were held stationary in a single hole and not allowed to slide down the length of the diffuser. When the butterfly valve pushed down on the hinge, the roof pieces would pivot down. This, however, lengthened the path between the two pivot points and the roof pieces would not be long enough to reach the entire new path. Since the pivot points were stationary, the hinge pulled at the pivots and the pivots pulled at the hinge. The metal of the pivot rods proved to be stronger than the tiny aluminum screws in the hinge and sheared the screw heads off, leaving the rest of the screws still in the aluminum of the roof pieces. The most serious problem is the method of anchoring the pivot rods. If one or both of the roof pieces had pivot points that were not anchored in a single hole, but rather anchored in a groove that allowed that pivot to slide towards the hinge, then the stress between the hinge and the pivot rods would be eliminated.

Any variable throat in the future should be able to be operated without fear of the damage described above. The throat should raise and lower smoothly, without exposing any corners or edges to the flow. Also, the throat should be able to reduce the area of the diffuser nearly down to the area of the nozzle throat. The diffuser area should not be the same as the nozzle area because that would cause choking in the flow. However, if the area can be reduced to nearly the nozzle area, then the shock wave would have the greatest chance of being captured since the backpressure would have to keep increasing to move the shock wave into the smaller area. This is important because in an operational system the back pressure is formed in the combustion chamber. The whole purpose of the injector is to increase the pressure of the feedback gases and injected propellants to a pressure that is higher than is in the combustion chamber. The variable throat will need to get as small as it can to block a shock wave formed by that high of a pressure. The diffuser used in this experiment could reduce the area of the diffuser by about half, but was still more than twice the area of the nozzle throat. If that diffuser had been designed with pivots that could slide along grooves as suggested above, then the area could safely be reduced all of the way to zero, if so desired.

Chapter 4 - Experimental Results and Analysis

After collecting all of the pressure data from the wind tunnel runs, that data needed to be analyzed to determine what effect, if any, the liquid injection had on the pressure of the flow. As mentioned in the previous chapter, the first experimental configuration was completely inadequate as a means of measuring pressure changes. The only information drawn from the first set-up was that the mixing section needed to be long. This is not new information, however. Both Popov [9] and Deberne [4] show long mixing sections in their designs to allow for adequate mixing. The first configuration used in this experiment merely reinforced that lesson. Much more data was acquired, and much more was learned, during the second and third phases of the experiment.

4.1 Results From the Second Set-Up

The experiments run using the second configuration were devoted, primarily, to developing the continuous tunnel. With that goal in mind, no ethanol injection runs were conducted during this stage of testing. The results obtained during this phase of testing, while extremely frustrating and disappointing, led to the development of the theory of shock wave capture tested with the next configuration.

The tunnel was never able to sustain a continuous supersonic flow. In every test run, the tunnel unstarted as soon as the vacuum valve was closed and the exit valve was opened. A lack of experience with wind tunnels caused the results to be a little misleading initially, however. When the tunnel was started, the pitot tube in the mixing section measured a total pressure that was 4.3 psi below atmospheric pressure. The low reading is the result of the shock wave at the opening of the tube. After the exit valve was opened, the total pressure increased to 2.3 psi above atmospheric. This pressure was still well below the total pressure input into the system, which was about 14.9 psig. Since the measured pressure was still well below the input pressure, the pitot must have been measuring behind a shock wave. An erroneous conclusion was drawn from the fact that the pitot tube was clearly behind a shock wave. The erroneous conclusion was that the tunnel was still supersonic and the shock wave affecting the pitot was the one attached to its opening. Further analysis of the data and consulting with Lt. Col. Little revealed the error. The error arose from simply analyzing one line of pressure. The truth was revealed when all of the lines of data were analyzed with respect to each other. The key to discovering the truth was in the static pressure measurements of the mixing section. When the tunnel was started, the static pressure in the mixing section was predictably lower than atmospheric. The measured static pressure was about -11.9 psig. This is a clear indication of supersonic flow. After the exit valve was opened, however, the static pressure increased to about 1.4 psig, which is above atmospheric pressure. With the tunnel configured the way it was, that static pressure could not occur with supersonic flow. This result is confirmed by using equation 11. Inserting the measured pressures into the equation and solving for the Mach number yields a Mach number of 0.24. The earlier conclusion that the total pressure was being measured after a shock wave was correct. Unfortunately, the assumed location of the shock wave was not correct. When the exit valve was opened, the increase in backpressure resulted in the formation of a shock wave that moved all of the way through the tunnel and become lodged either in the nozzle throat or in the air supply system somewhere. Figures 15 through 19 show the data from one of the runs on this configuration.

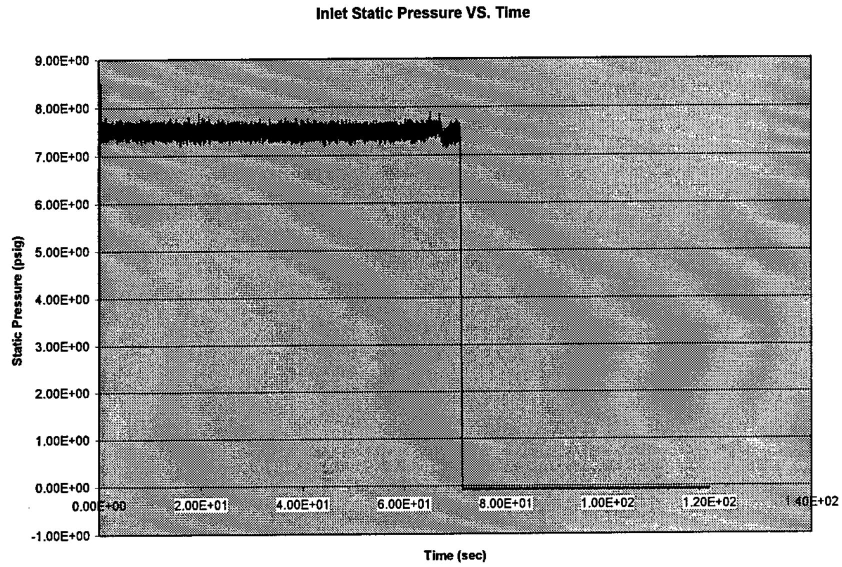

Figure 15. Inlet Plenum Static Pressure

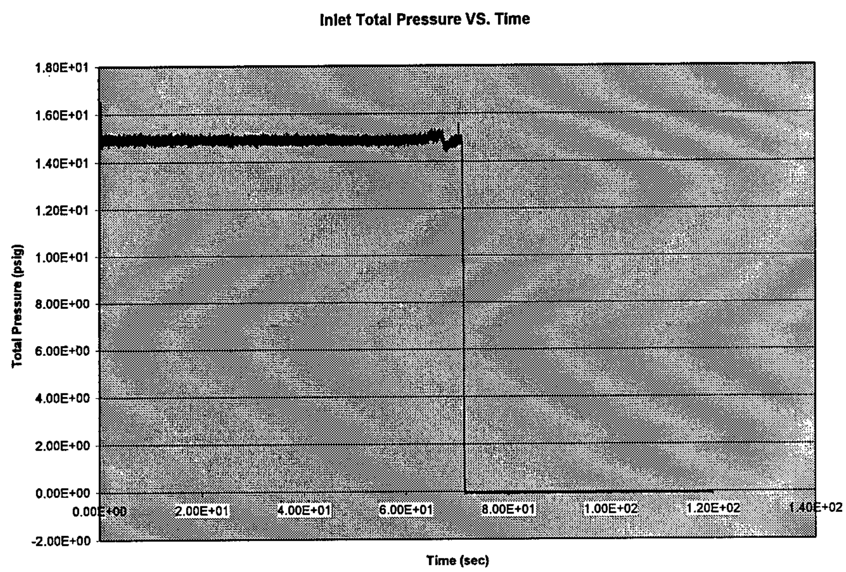

Figure 16. Inlet Total Pressure

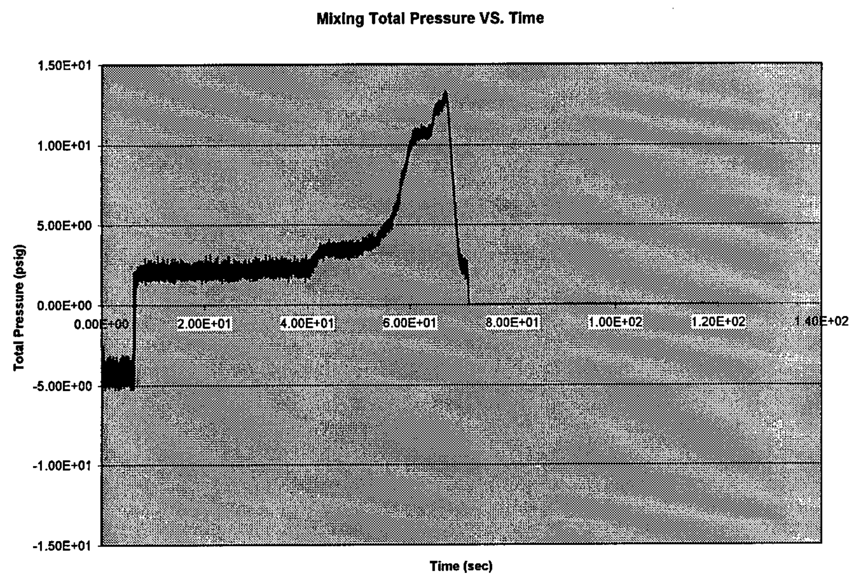

Figure 17. Mixing Section Static Pressure

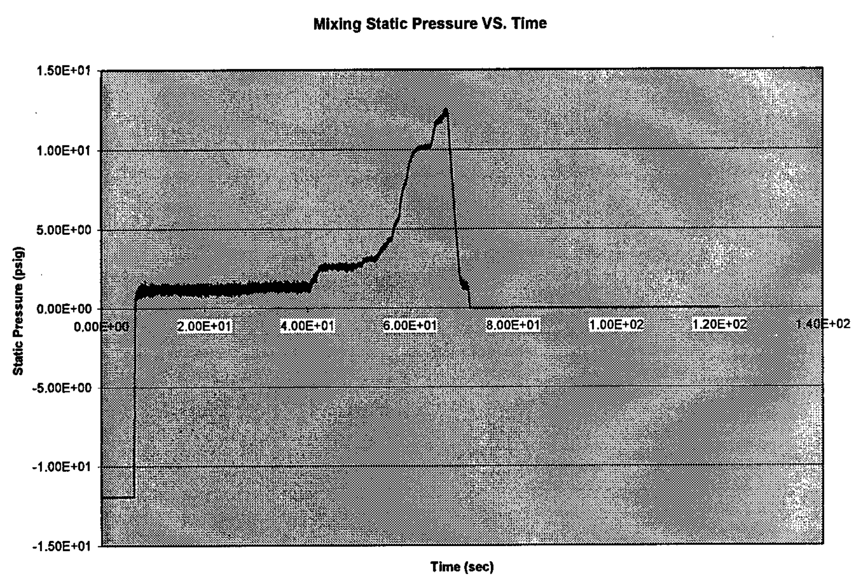

Figure 18. Mixing Section Total Pressure

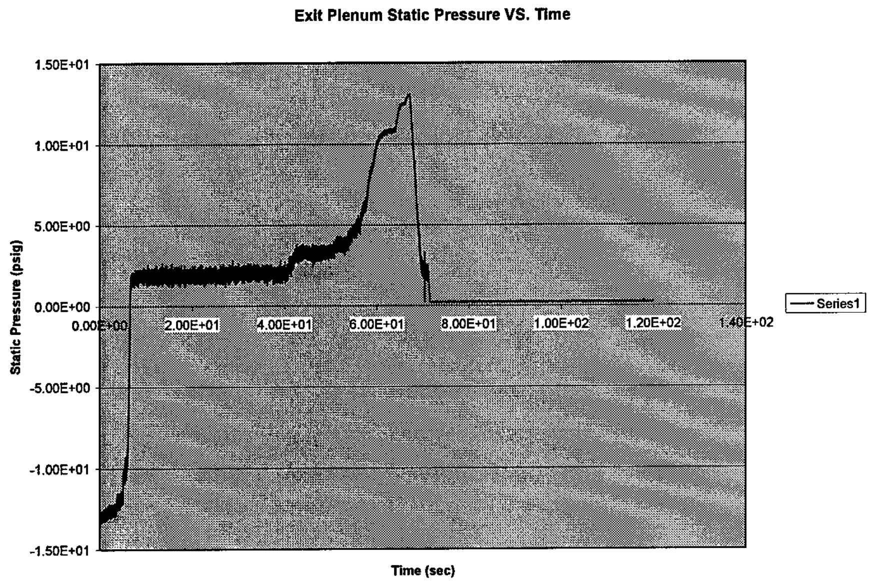

Figure 19. Exit Plenum Static Pressure

4.2 Results From the Final Set-Up

Testing on the final configuration consisted of two different series of tests. The goal of the first series of tests was to attempt to capture the shock wave, as described in Chapter 3. Also mentioned in Chapter 3 was that the supply pressure was increased to about 30 psig. The higher pressure gave the tunnel a higher inlet to back pressure ratio. This pressure ratio is important because the unstarting of a wind tunnel occurs at a specific inlet to back pressure ratio. Increasing the initial ratio increases the back pressure that must be obtained for unstart to occur. The desired result was for the increase in supply pressure, combined with the adjustable diffuser throat, to raise that critical back pressure to above atmospheric. With the critical back pressure higher than atmospheric pressure, the shock wave should not be able to move past the diffuser throat and unstart the tunnel.

The first test used an adjustable throat that was lowered only a small amount. In the next few tests, the throat was lowered a little more each time. After several tests, however, the variable throat began to feel strange when it was being raised and lowered. Looking down the throat showed that the hinge connecting the two roof pieces of the diffuser was bent. Completely dismantling the diffuser revealed the problems discussed at the end of Chapter 3.

The damage to the hinge and roof pieces seriously hindered the ability to run tests, so some repairs were in order. Running without the adjustable roof pieces in place was not an option because that would drastically alter the geometry of the diffuser. Since the hinge was bent, reusing it was impossible. Luckily, the base model shop had a similar sized hinge that they donated to the project. The new hinge was actually made out of titanium and, therefore, much stronger than the original hinge. To help prevent a repeat of the damage to the screws, stainless steel screws were used in place of the old aluminum ones, further increasing the hinge's strength. Since further use of the adjustable throat would likely result in either a repeat of the failure in the hinge or in a failure of the pivot rods, a decision was made to not operate the variable throat in the future. This conclusion resulted in an alteration in the focus of the testing. Further testing did not include any effort to establish the continuous running capability for the wind tunnel. Instead, the effort was limited to measuring the pressure change from the injection with the pitot tube at the diffuser exit. This is the second type of test performed with the final test configuration.

The second series of tests began by taking data on a baseline run with no fluid injection. The wind tunnel ran until the backpressure became high enough to cause the tunnel to unstart. Subsequent tests included ethanol injection and were also run until the tunnel unstarted. At the time when the tunnel unstarted, the shock wave in the diffuser has already moved past the diffuser exit pitot tube, leaving subsonic flow in that part of the diffuser. Since the flow is subsonic, the total pressure measured by the pitot tube is the true total pressure. The total pressure from the injection flows can then be compared to the total pressure of the baseline case to see if any change occurred. Figures 20 through 26 show the data from one of the runs from this series of tests.

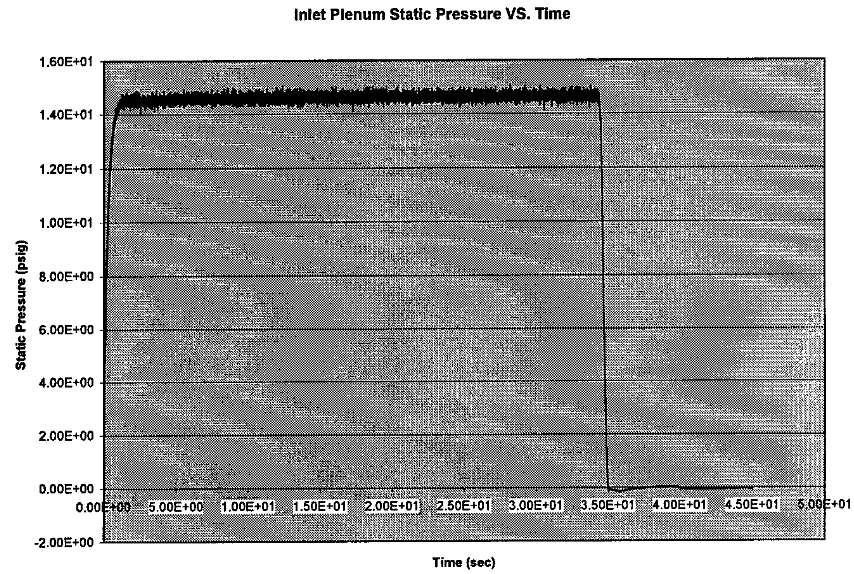

Figure 20. Inlet Plenum Static Pressure

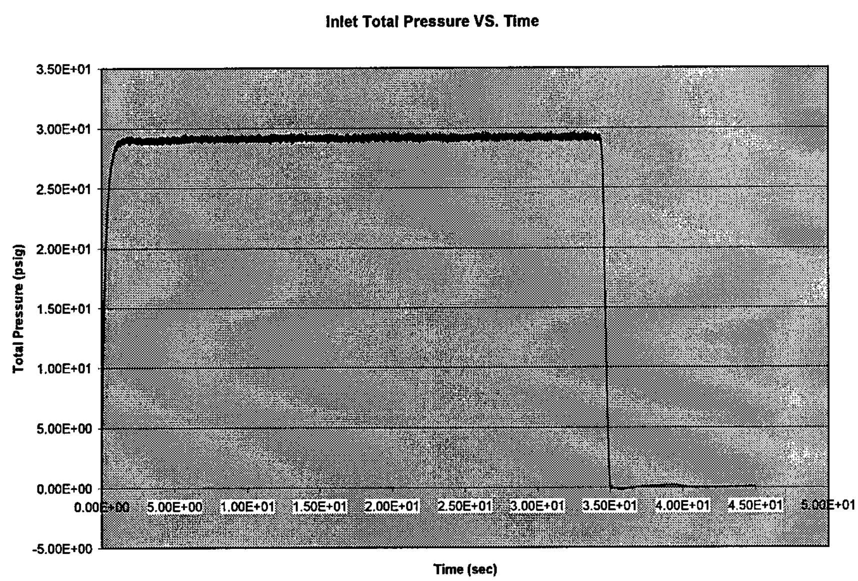

Figure 21. Inlet Total Pressure

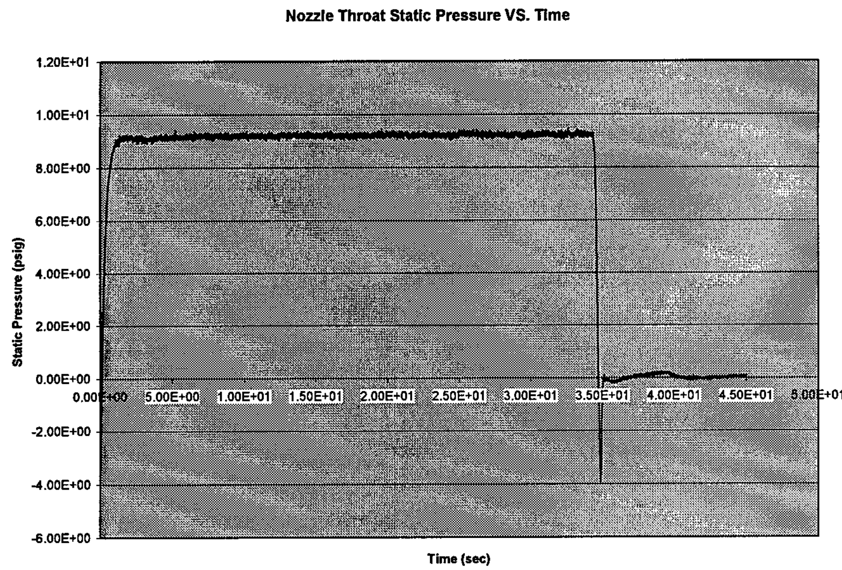

Figure 22. Nozzle Throat Static Pressure

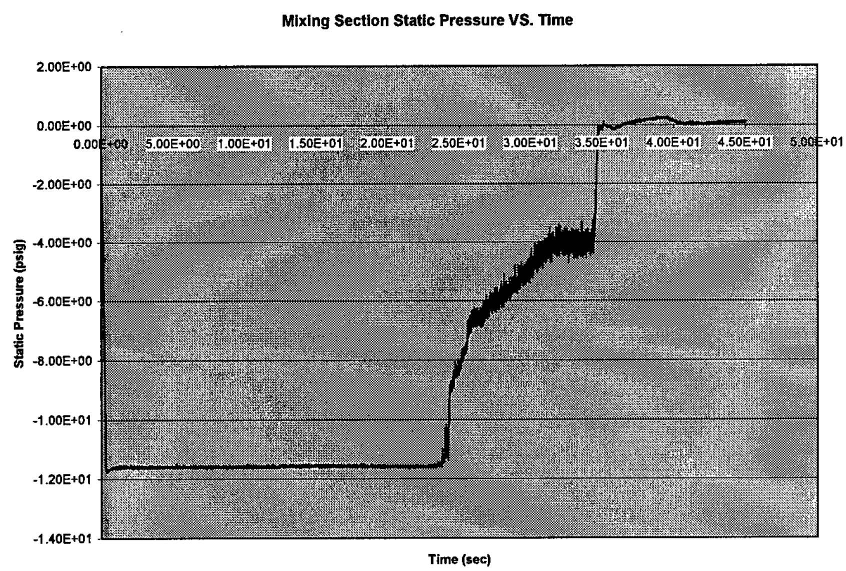

Figure 23. Mixing Section Static Pressure

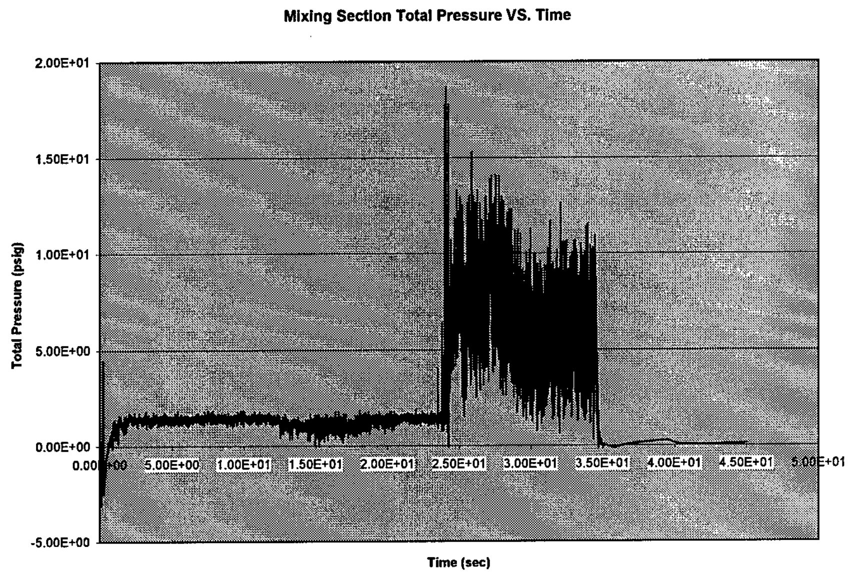

Figure 24. Mixing Section Total Pressure

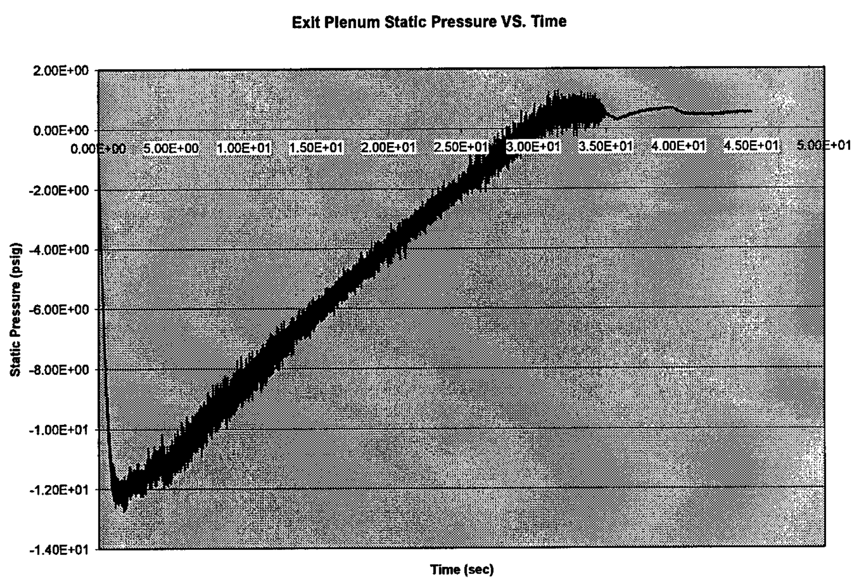

Figure 25. Exit Plenum Static Pressure

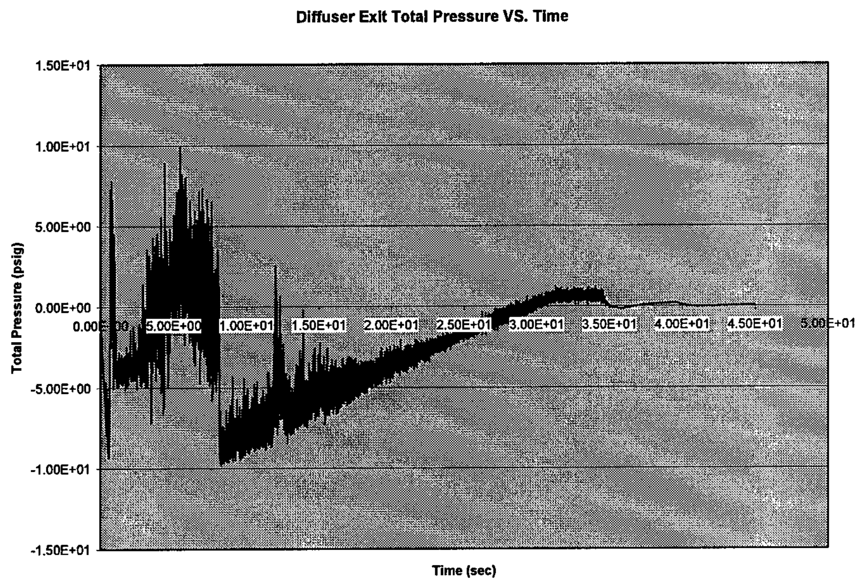

Figure 26. Diffuser Exit Total Pressure

Looking at the plots of the pressure data from a run helps to understand what is happening during the run. At the beginning of the run, the inlet pressures quickly rise up to a plateau and the mixing region static pressure quickly reaches a steady value that is much lower than atmospheric pressure. This is a good indication that the tunnel is supersonic. The exit plenum static pressure starts out low, because of the vacuum, and gets steadily higher during the run as the vacuum tanks fill up behind it. The exit total pressure quickly becomes erratic as the rising backpressure causes compression waves to begin forming around the exit. These compression waves affect the reading of the pitot tube. Then, the total pressure has a sharp decrease and smooths out some as the compression waves coalesce into a normal shock wave and the shock wave moves in front of the pitot tube. The point at which the tunnel unstarts is very clear on Figures 23 and 24 as the mixing region total pressure experiences a sharp increase and the mixing region static pressure increases quickly. At the end of the data, the tunnel was shut off and all of the pressure readings returned to atmospheric.

Table 1 shows the total pressure at the diffuser exit and the plenum static pressure at unstart in the baseline runs while Table 2 shows the total pressure at the diffuser exit and the plenum static pressure at unstart in the injection test runs. Nicolet displays pressures out to the thousandths of a psi. However, the transducers are only accurate to a tenth of a psi, so the data listed below is limited to three significant digits.

Table 1. Baseline diffuser exit total and exit plenum static pressures at unstart

Baseline Run	**Exit Total Pressure at Unstart (psia)**	**Tank Static Pressure at Unstart (psia)**
Baseline 1	12.1	11.9
Baseline 2	12.2	12.1
Baseline 3	12.5	12.6
Baseline 4	12.3	12.2
Baseline 5	12.3	12.2
Baseline Average	12.3	12.2

Table 2. Injection run diffuser exit total and exit plenum static pressures at unstart

Test Run	**Exit Total Pressure at Unstart (psia)**	**Tank Static Pressure at Unstart (psia)**
Test 1	12.9	12.6
Test 2	12.9	12.3
Test 3	13.0	12.5
Test 4	12.9	12.5
Test 5	12.9	12.0
Test 6	12.9	12.5
Test 7	12.7	12.3
Test Average	12.9	12.4

Comparing the two tables indicates that the tests run with ethanol injection have a small increase in the total pressure at the exit of the diffuser. The average increase in total pressure for the tests was 4.88 percent. This is not a large increase, but it is consistent throughout the tests and is not a chance occurrence during one test. The results also show that the static pressure inside the exit plenum is closer to the total pressure of the flow for the air only flows. One item to note about the data is that the numbers do not represent one hundred percent accurate knowledge of the pressures. Looking again at the Figures 16-20 and 21-27, the resulting data is not smooth. Rather, most of the channels of data have some error range associated with them. A close look at the data within Nicolet Windows, which allows you to zoom in on the plot, shows that the error bands are around .5 psi just prior to unstart. This means that the data in the Tables 1 and 2 is accurate plus/minus .25 psi.

Chapter 5 - Conclusions and Recommendations

The research conducted during this thesis attempted to find out whether injecting a liquid into a flow of air would have any effect on the pressure of the flow when there was no condensation occurring from gaseous to liquid state. Several conclusions and recommendations came from the analysis done on the experimental results.

The conclusion drawn directly from the data is that the injection of ethanol into the compressed air stream did cause a small increase in the total pressure of the system compared to the tunnel running with no fluid injection. However, compared to the pressure rises generated by other experimenters, in which the injector exit pressure is actually higher than the injector initial pressure, the pressure rises in this thesis are drastically smaller. The diffuser exit total pressure in air only tests was about twenty-eight percent of the input pressure. The average diffuser exit total pressure for the injection runs conducted for this thesis is just over twenty-nine percent of the input pressure. The final pressure in Deberne's paper ranged between two hundred percent up to three hundred percent of the input pressure [4]. The final pressure in Popov's experiments averaged around one hundred and seventy percent of the input pressure [9]. Final pressures greater than one hundred percent of the input pressure are necessary for the injector function. If an injector on a liquid rocket did not produce a pressure higher than the combustion chamber, the propellants could not flow into the combustion chamber, stopping any further combustion. With that limitation in mind, this experiment seems to indicate that an injector with no condensation of the feedback gases into liquid will not be able to perform its primary function of injecting liquid propellants into the combustion chamber.

If anyone continues the investigation into putting a steam injector type apparatus on a liquid rocket, some effort should be made to upgrade the test configuration, as recommended at the end of Chapter 3. With an upgraded testing capability, follow up research should attempt to produce an injector that actually generates the injector exit pressure rise. Another area that requires study is the problem of getting the extremely high temperature exhaust gases of a rocket engine to condense when the gases come in contact with the liquid propellants. Someone needs to do some thermodynamic investigation to discover the temperature that the exhaust would need to be lowered to so that condensation is possible and how to achieve that temperature drop.

This thesis showed that putting a steam injector on board a liquid rocket will not be an easy task. A large amount of research and testing remains to be done. However, the benefits that would come from such an effort could possibly far outweigh the cost of the research. Future studies should be conducted to ensure that liquid rocket builders are not restricted to two methods of propellant delivery but have a third option that removes the complexity of turbopumps and the large extra mass of a pressurant tank.

APPENDIX A - Pressure Plots

A.1 Sample Baseline Run Data

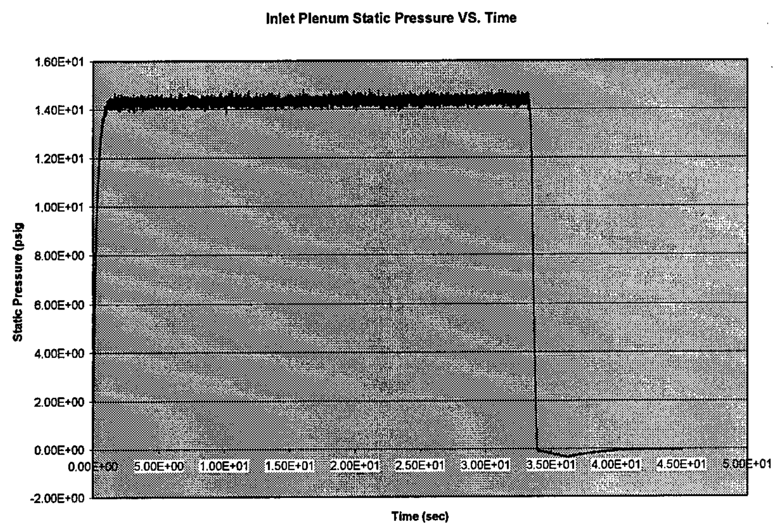

Figure 27. BL1 Inlet Plenum Static Pressure

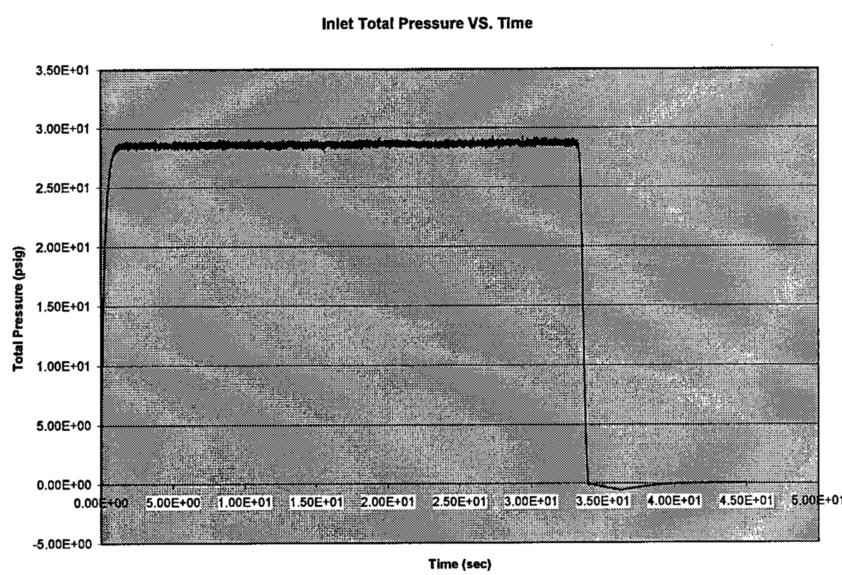

Figure 28. BL1 Inlet Total Pressure

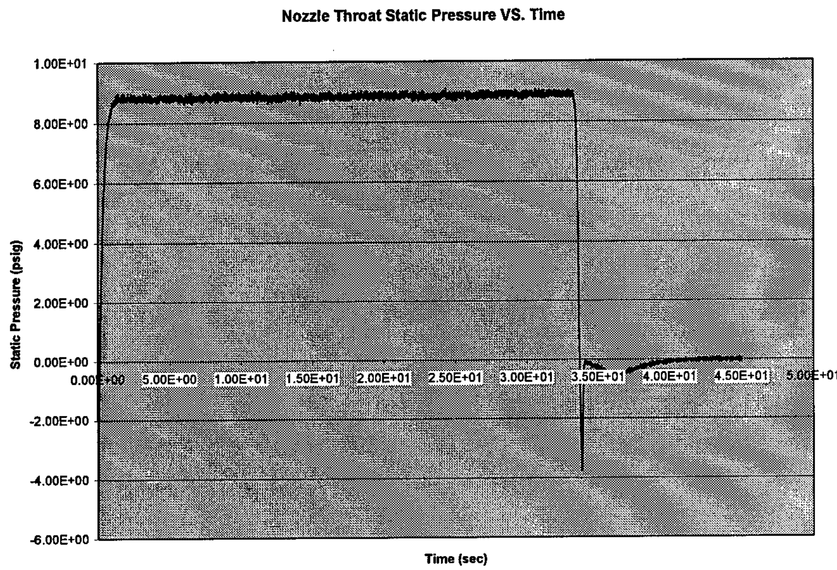

Figure 29. BL1 Nozzle Throat Static Pressure

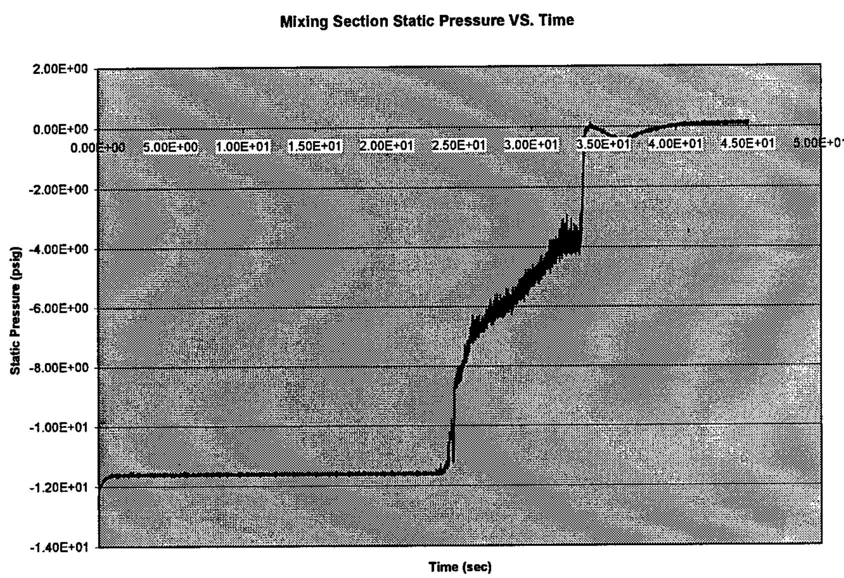

Figure 30. BL1 Mixing Section Static Pressure

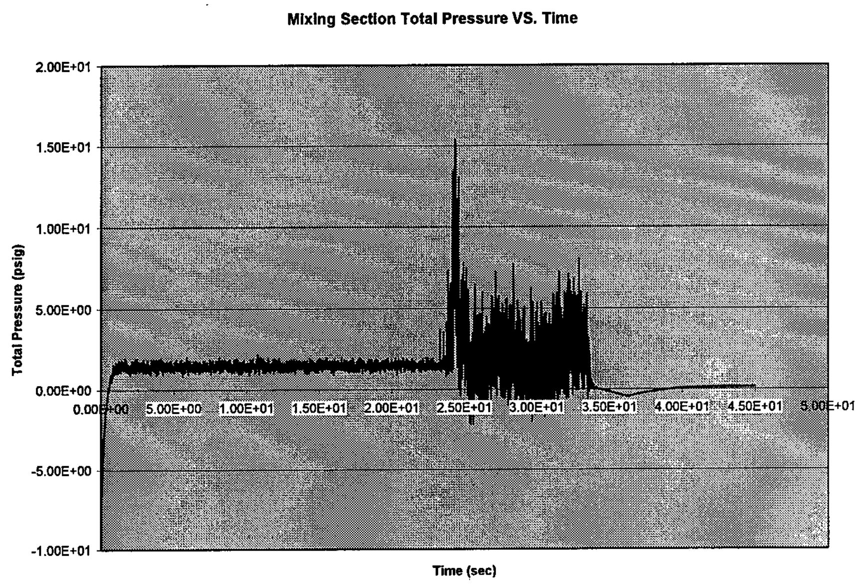

Figure 31. BL1 Mixing Section Total Pressure

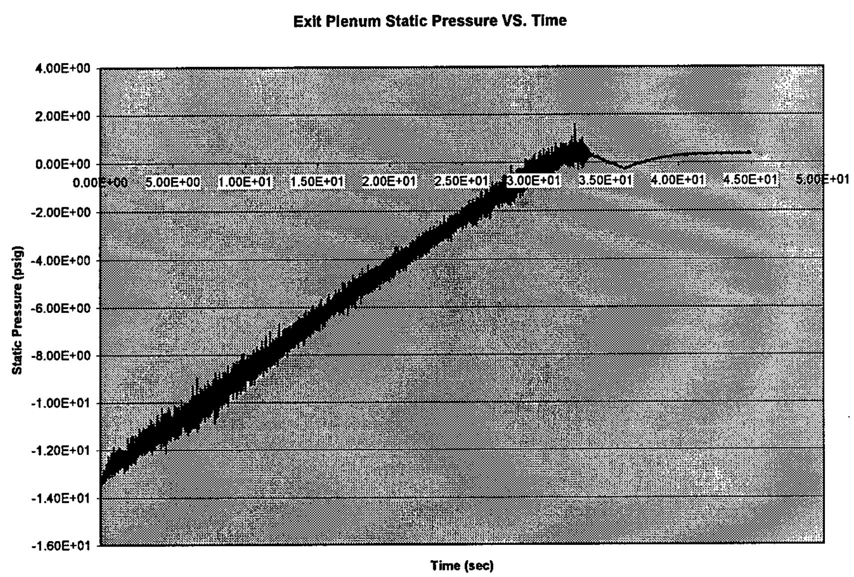

Figure 32. BL1 Exit Plenum Static Pressure

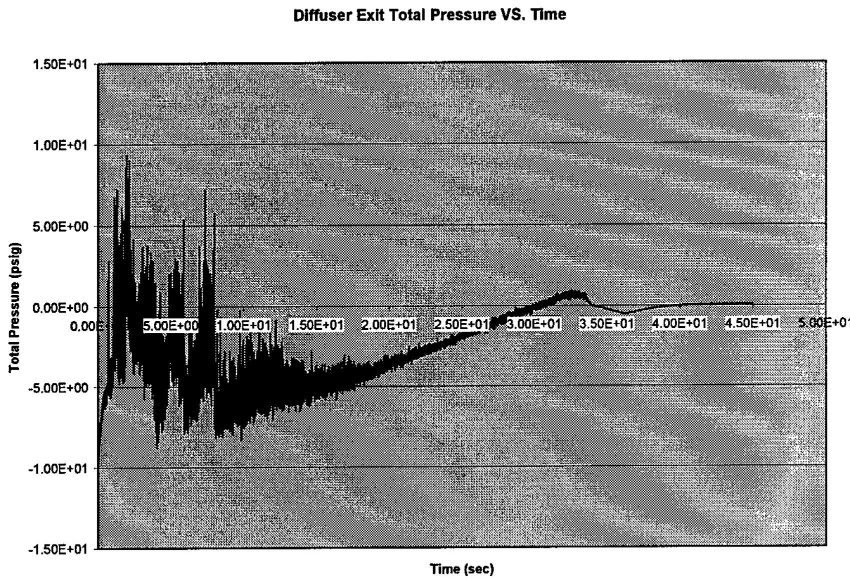

Figure 33. BL1 Diffuser Exit Total Pressure

APPENDIX B - Mass Flow Calculations

The calculations in this appendix were found following the method described in Chapter 2.

B.1 Ethanol Mass Flow Rate

Calculating the mass flow of the ethanol was relatively simple since the volume of ethanol injected and the time during which that injection occurred were measured.

$$V_{ave} = 55mL \tag{26}$$

$$t_{ave} = 25.8\,\text{sec} \tag{27}$$

$$\dot{V} = \frac{V_{ave}}{t_{ave}} = 2.1\frac{mL}{\text{sec}} \tag{28}$$

Next convert volume flow rate into cubic meters per second.

$$\dot{V} = \dot{V}\frac{1L}{1000mL}\frac{.001m^3}{1L} = 2.1 \times 10^{-6}\frac{m^3}{\text{sec}} \tag{29}$$

Next use density [3]to find mass flow rate.

$$\rho = 783\frac{kg}{m^3} \tag{30}$$

$$\dot{m}_{eth} \tag{31}$$

B.2 Air Mass Flow Rate

The mass flow rate for the air was found at the nozzle throat. From Chapter 2:

$$\dot{m}_{air} = \rho U A \tag{32}$$

The area at the nozzle throat was a known constant. Also known were the gas constant for air [3], the room temperature (total temperature of the flow), total pressure of the flow in the nozzle (set by user in the experiments), and an assumed constant ratio of specific heats for air. These values were:

$$
\begin{aligned}
Area &= A = 1.48in^2 = 9.55 \times 10^{-4}m^2 && (33)\\
\gamma_{air} &= 1.401 && (34)\\
R_{air} &= 287\frac{J}{kg \cdot K} && (35)\\
T_{tot} &= 70^{\circ}F = 294K && (36)\\
P_t &= 43.7psia = 301000Pa && (37)
\end{aligned}
$$

The first step was the find the velocity of the air at the throat. Since the throat was choked, that velocity was just the speed of sound, which was found using:

$$a = \sqrt{\gamma_{air} \cdot R_{air} \cdot T} \tag{38}$$

The static temperature at the throat with a velocity of Mach 1 was found with equation 10 to be:

$$T = 245K \tag{39}$$

That made the velocity:

$$a = 314\frac{m}{\text{sec}} \tag{40}$$

Next, the density was found using equation 1, the perfect gas law. To use equation 1, the static pressure at the throat was first found using equation 11. The static pressure was found to be:

$$P_s = 159000Pa \tag{41}$$

That made the density equal to:

$$\rho = \frac{P_s}{R_{air} \cdot T} = 2.26\frac{kg}{m^3} \tag{42}$$

Which made the mass flow rate of the air equal to:

$$\dot{m}_{air} = .678\frac{kg}{\text{sec}} = 1.49\frac{lbm}{\text{sec}} \tag{43}$$

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14. ABSTRACT
This thesis investigated the properties of a steam injector to see if the concept might be suitable for use on a liquid rocket engine. A steam injector is a device developed in the 1850's to inject feedwater into the boiler on a steam locomotive without any moving parts. The injectors used a small portion of the steam generated in the boiler to increase the pressure of the feedwater to a level higher than the pressure in the boiler. Previous experiments claim that condensation of steam to water was necessary for an injector to work. This experiment tested injection without condensation using one of AFIT's wind tunnels. Compressed air was used to simulate steam and liquid ethanol was used in place of water. Pressure measurements were taken at points along the tunnel to determine the performance of the tunnel. Results show that this type of injection produces a small pressure rise compared to tests without liquid injection. However, the exit pressure is still lower than the initial pressure. Further testing is recommended to analyze various parameters such as high temperature flows and injector size.

15. SUBJECT TERMS
Fluid Flow, Shock Waves, Liquid Propellant Injection

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