Design of a high altitude simulation apparatus for the UAH solid fuel ramjet

Joseph Agnew

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DESIGN OF A HIGH ALTITUDE SIMULATION APPARATUS FOR THE UAH SOLID FUEL RAMJET

Joseph Agnew

A THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering in The Department of Mechanical and Aerospace Engineering to The Graduate School of The University of Alabama in Huntsville August 2023

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Abstract

DESIGN OF A HIGH ALTITUDE SIMULATION APPARATUS FOR THE UAH SOLID FUEL RAMJET

Joseph Agnew

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

Mechanical and Aerospace Engineering
The University of Alabama in Huntsville
August 2023

A modular high altitude simulation apparatus is designed and incorporated into the UAH connected-pipe flow facility for solid fuel ramjet studies. A literature review is conducted on solid fuel ramjets, high altitude simulation approaches, and parameters of gas ejectors. Next, a system-wide design process is detailed with validating calculations as well as high-level CFD simulations. Finally, a compilation of relevant test data is provided along with relevant analysis. The eductor system achieved 11 psia at 0.054 lbm/s of heated air flow rate, well short of the desired 8 psia at 0.062 lbm/s flow rate. Ejector efficiency was between 43 and 55 percent of anticipated values. This was likely caused by inefficiencies from viscous and shear interactions of gas entrainment which occurred at high temperature air flow conditions. Recommendations for future work are to remove losses from the system and upgrade ejector flow capacity to account for air temperature-related effects.
Acknowledgements

I would like to thank my advisor, Dr. Robert A. Frederick, for his continuing guidance and support during this start to my professional career. His sense of humor and technical knowledge make learning fun, and I would not be where I am today without him. I also want to thank the staff and the Propulsion Research Center, particularly Dr. David M. Lineberry, for his daily support, mentorship, and advice with everything from LabView to Spearfishing, and Tony Hall, for being a wealth of knowledge and advice for any project that comes around.

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<td>$T_{ex}$</td>
<td>Ejector exhaust temperature</td>
</tr>
<tr>
<td>$T_{mot}$</td>
<td>Ejector motive gas temperature</td>
</tr>
<tr>
<td>$T_{sec}$</td>
<td>Temperature of the secondary flow inlet of ejector</td>
</tr>
<tr>
<td>$\dot{m}_a$</td>
<td>Mass flow rate of air</td>
</tr>
<tr>
<td>$\dot{m}_{mot}$</td>
<td>Mass flow rate of the ejector motive gas</td>
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<tr>
<td>$\dot{m}_{sec}$</td>
<td>Mass flow rate of secondary ejector inlet gas</td>
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<tr>
<td>$\omega$</td>
<td>Ejector entrainment ratio</td>
</tr>
<tr>
<td>$p_{ed}$</td>
<td>Eductor Plenum Pressure</td>
</tr>
<tr>
<td>$p_{mot}$</td>
<td>Ejector motive gas pressure at ejector primary flow inlet</td>
</tr>
<tr>
<td>$I_{SP}$</td>
<td>Venturi throat which can entrain flow</td>
</tr>
<tr>
<td>$T_0$</td>
<td>Standard temperature equal to 237.15</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>Term for ejector efficiency, defined as the ratio of actual to theoretical entrainment ratio</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Dynamic viscosity</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>$p^*$</td>
<td>Pressure at nozzle throat</td>
</tr>
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</tr>
<tr>
<td>$ACFM$</td>
<td>Actual Cubic Feet per Minute</td>
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<td>Symbol</td>
<td>Description</td>
</tr>
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<td>------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Eductor</td>
<td>Test rig plenum which is drawn to vacuum and is physical attachment point for hardware and instrumentation</td>
</tr>
<tr>
<td>Ejector</td>
<td>Venturi throat which can entrain flow</td>
</tr>
<tr>
<td>SCFM</td>
<td>Standard Cubic Feet per Minute</td>
</tr>
<tr>
<td>$S$</td>
<td>Expanded random uncertainty</td>
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<td>$t$</td>
<td>T-table value for statistics</td>
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Chapter 1. Introduction

Ramjet research has increased dramatically in the past several years due to the need for hypersonic-capable engines as well as more efficient rocket propulsion in general. These hybrid motors provide ample opportunity for data collection on diverse, inert fuel formulations. The inert nature of the fuel being particularly advantageous, as safety procedures are significantly less strict than those dealing with volatile propellants.

Figure 1.1: Ramjet Engine Overall Geometry [1].

A standard solid fuel ramjet (SFRJ), pictured in Figure 1.1 consists of an air intake, igniter, flame holder, fuel grain, mixer plate, mixing chamber, and exhaust nozzle. The intake is specifically shaped to reduce the inlet air velocity from supersonic to subsonic in the combustion chamber, and so guides a series of oblique shocks into the intake passages. The igniter provides an initial spark of energy to ignite the fuel grain, which combusts with the inlet air oxygen. A physical 'step' is present between the inlet and the fuel grain to act as a flame holder, which encourages vortices in recirculation zones in order to encourage continual burning and 'smoldering' of the flame and prevent premature engine burnout. The mixing chamber provides more time for the fuel and air to mix downstream of the mixing plate and improve
combustion efficiency. This burning mixture is accelerated out the nozzle to produce thrust.

Ideally in a solid fuel regression rate study, one would put each formulation through a thorough range of conditions similar to the flight conditions of the desired final application. This includes a range of flow rates, pressures, temperatures, burn times, and ignition conditions for the end-use missile, aircraft, or rocket. Figure 1.1, shows the critical components of a SFRJ, and two of these in particular are most affected by altitude. The first is the air intake, which is designed to compress the air and increase both its temperature and pressure to heat the fuel and provide more favorable ignition conditions. The initial conditions of the air will determine its final state within the combustion chamber. Because the temperature and pressure of air can vary so dramatically with altitude, the inlet geometry can only be optimized for a small range of flight conditions.

The second altitude-related factor is the exit plane pressure of the exhaust nozzle. This exit plane pressure, is assumed to be equal to back pressure. Back pressure is defined as atmospheric static pressure of the vehicle environment, and changes with altitude and weather. Under non-choked conditions, the back pressure will drastically affect the pressure in the combustion chamber, and by association, the ignition conditions of the fuel grain. If the pressure due to air flow or combustion in the chamber is high enough to cause choking at the nozzle, then the back pressure will only affect thrust and nozzle performance. All three parameters, thrust, ignition performance, and nozzle dynamics, are of interest in fuel tests, but ignition, combustion efficiency, and lower pressure deflagration limit are of critical interest in fully characterizing a fuel concept.

In a standard connected-pipe test facility, i.e. one which connects inlet air directly to the combustor, implementation of fuel grain studies and variation of air properties, such as temperature and flow rate, are relatively simple to implement.
It is comparatively complicated to incorporate high-altitude simulation to vary back pressure and chamber pressure in an SFRJ. Varying these conditions would afford the ability to test fuel ignition and relight characteristics, but requires additional low pressure hardware. The required equipment can be challenging to implement on a test motor but significantly less expensive than an equivalent test run in-flight. Incorporating this high altitude back pressure system into small scale testing is also important as it would allow for quick turnaround time, repeatability, and lower operating costs. These advantages would ultimately lead to a higher quantity of tests run and a larger and more thorough dataset. A reduced back pressure system adds additional capability to fuel formulation testing by increasing the number of variables to change in the test matrix. With that, potential fuels can be better evaluated at the small scale, saving money on full size testing of the best candidates.

The current University of Alabama in Huntsville (UAH) Solid Fuel Ramjet (SFRJ) system uses a connected-pipe flow system to control operating parameters for small scale, two-inch outer diameter, ramjet grains. The facility can provide up to 0.1 lbm/s of heated air at 800 F. The small size, modular design, and aforementioned quick turnaround time, up to 20 tests per day, make this a logical candidate for implementing an evacuated-air test rig.

The goal of this project is to design a High Altitude Simulation Apparatus (HASA) which can reduce the chamber pressure of the ramjet to representative high altitude conditions. The HASA would be required to operate during the heated air flow preheat stage as well as during the ignition and combustion stage of testing. The preheat stage mimics the pre-start air-breathing stage of an in-flight SFRJ as it is boosted by a solid rocket motor, preparing the hybrid grain for ignition. The HASA will have to function at a variety of start, relight, and altitude conditions particularly through variation of flow rate and pressure.
A brief literature review will be presented to describe the rationale behind several preliminary design decisions, as well as overall UAH SFRJ facility description for context. This review of previous work and technical data will be followed by a component-specific and system-level design of the HASA, including how the requirements are met. The technical design will be followed by experimental results demonstrating the feasibility of the design. Finally, a conclusion will be provided with recommendations for future work and improvements on test capability.
Chapter 2. Literature Review

The first step to designing a test rig for analyzing ramjet characteristics is to understand the in-depth operation and governing principles of ramjets in general, and SFRJs in particular. This will provide the knowledge necessary to review compatible low back pressure, test facilities. The facility review will include a description of the benefits of high-altitude testing, the equipment used to do so, and the materials and consumables required.

2.1 Theory of Ramjet Operation

A solid fuel ramjet is a type of hybrid propulsion, and is defined as a motor which contains a solid fuel, obtains its oxidizer from its operating environment, and operates at supersonic conditions. Ramjets have been a topic of research in the worldwide propulsion community since the late 1940s, with the United States, Russia, China, and many others conducting extensive studies. They were initially proposed as a way to deliver additional thrust to early jet age aircraft and propel them at supersonic speeds and higher altitudes [2]. Modern ramjet applications include missiles, artillery, aircraft, and even undersea vehicles or weapons. Their purpose is to bridge a performance gap between traditional rocket engines and the turbojets or turbofans commonly used in airplanes.

As shown in Figure 2.1, the operating regime of a ramjet lies between that of an afterburning turbofan and a scramjet, or about Mach 2 to Mach 6 in terms of speed. The y-axis details the specific impulse, or \( I_{SP} \), which is a measure of the efficiency of the propulsion system at a particular speed. Below Mach 2, the inlet air does
not have enough energy to be a sufficient oxidizer source at required temperatures and pressures. Above Mach 6 the pressure recovery losses due to stepping down hypersonic air to subsonic are too great to maintain efficiency. Thus, a scramjet will be implemented which is similar to a ramjet in principle but maintains supersonic air in the combustor. Operating altitudes of ramjets range anywhere from sea level to 140,000 ft [2].

Figure 2.1: Specific Impulse vs Mach Number Range for Different Propulsion Systems [3].

In addition, a ramjet combustor, compared to that of a liquid rocket or turbojet, is relatively easy to manufacture, making it a great choice alongside solid rockets for disposable applications such as self-propelled artillery rounds or missiles. One contributing factor to this high efficiency is that the oxidizer is pulled directly from the atmosphere. Ramjets have significantly higher specific impulse than conventional rockets, leading to superior range [4]. On the down-side, ramjets are limited to operation in atmosphere, due to the need for oxidizer from the atmosphere. To summarize, ramjets demonstrate simplicity, reliability, and good range performance as compared to other propulsion solutions.
Ramjets can take on several different forms, but are generally separated into two categories, Solid Fuel Ramjets (SFRJs) and Liquid Fuel Ramjets (LFRJs). Liquid and solid fuels generally have approximately the same specific heating values per mass of fuel, but solid fuel is often chosen due to its higher volumetric power density, and hence higher total energy available in a limited vehicle volume. This can be about 15 percent more fuel mass than a similar liquid fuel engine concept [1]. In addition, the associated hardware requirements of an SFRJ are significantly fewer and less complicated than that of liquid fuel concepts. SFRJs afford a much lower cost solution compared to liquid fuel ramjets due to their inherent simplicity and reduced maintenance requirement over their life span. Metal additives in solid propellants improve specific impulse to the liquid fuel regime and can increase combustion efficiency to a threshold, depending on concentration.

SFRJs do have their disadvantages, primarily the inability to adapt to a wide operating envelope. By this is meant that one can design the engine for peak performance at a set altitude and speed range, such as the boost phase of a mission, but this generally results in lower efficiency at other mission segments, such as the cruise phase [5]. Consider an example mission where a ramjet-powered vehicle is deployed from an aircraft at 10,000 ft, boosts to 20,000 ft, and then cruises for 20 miles. An SFRJ designed for a high-efficiency boost phase, a quick and efficient change in altitude, will have the inlet scoop and nozzle parabolically optimized for the range of altitudes being covered, i.e. it will reach maximum thrust and efficiency around 15,000 ft. The fuel grain may have its geometry modified to allow for a thrust curve with more starting impulse. In contrast, an SFRJ optimized for the cruise phase will have its nozzle area ratio optimized for a back pressure indicative of 20,000 ft, and the fuel grain itself will be optimized more toward a slow, fuel efficient burn to maximize range.
Shown in Figure 2.2 below are a few indicative SFRJ configurations intended to provide additional efficiency under different operating conditions. Pictured in Figure 2.2a shows a typical layout for an SFRJ incorporated into a missile. The front section functions as the inlet to compress the air and route it through the fuel grain. The other configuration in Figure 2.2b shows alternative geometries which are intended to improve overall performance. The first option includes a mixing vane to facilitate fuel and air combustion in the mixing chamber. The second configuration in the figure shows a bypass inlet which can inject air directly into the mixing chamber to increase oxidizer to fuel (O/F) ratio and improve combustion efficiency.

Ramjet combustion efficiency depends on several inter-dependent factors: inlet air temperature, flight Mach number, and environment air temperature and density. Performance efficiency for ramjet combustion processes is performed using the Brayton cycle as a basis, as shown in Figure 2.3 [6]. Compression occurs in the air intake, followed by ignition and combustion in the chamber, expansion out of the nozzle, and pressure recovery back to atmospheric conditions.

Other factors are important as well, such as characteristic length, $L^*$, shown in equation 2.1, which describes the combustion efficiency contribution of a particular geometry of combustion chamber:

$$L^* = \frac{V_{tot}}{A_t}. \quad (2.1)$$

$V_{tot}$ corresponds to the total volume of the combustor, and $A_t$ corresponds to the throat area of the nozzle. Characteristic length is essentially a measure of residence time of the fuel and air in the combustion chamber before it is exhausted through the nozzle. $L^*$ is proportional to the combustor volume and nozzle throat area, and changed to this relationship will directly affect $c^*$, or combustion efficiency. In calculating air mass flux in a ramjet, the air density is heavily dependent on the altitude of the vehicle, and so is considered a dependent variable. Similar to a typical
Figure 2.2: Ramjet Common Configuration and Modification for Performance [1].
ramjet, a solid-fuel gas generator is used as the flame holding device, running fuel-rich to minimize inlet air effects on combustion at varying speeds and altitudes.

Figure 2.3: Pressure-Volume Graph of a Brayton Cycle.

Figure 2.4: Ramjet Detailed Geometry and Burn Characteristics [1].

Figure 2.4 details the unique geometric elements of the SFRJ combustor. The solid fuel grain is generally cylindrical and comprised of a binder, such as HTPB (hydroxyl-terminated polybutadiene), and a hydrocarbon fuel, such as PMMA (polymethyl methacrylate). Frequently these are also mixed with metallic powders in order to increase impulse, thrust, or other performance factors. Such powders include boron...
and aluminum in particular. The mixing plate and mixing chamber both serve to improve mixing efficiency of the fuel and oxygen as they pass through the engine at high speeds. Bypass air ports can be incorporated in order to improve O/F ratio in the mixing chamber and improve combustion efficiency, $c^*$.

The authors of [7] describe how chamber geometry and size can drastically effect combustion efficiency and droplet size in a liquid fuel engine, due to the complicated vortices and associated aerodynamic contributing effects. Li, et al. [8] describe this effect in SFRJ combustors specifically, and found that combustion flame temperature tends to increase with chamber length, due to a larger burning surface area, and that the total heat flux through the chamber increases under this condition also. The mixing plate is located between the mixing chamber and the fuel grain, and acts similarly to the flame holder. It encourages vortices to form in the mixing chamber, which improves mixing efficiency much better than otherwise would be the case if the flow was uninterrupted. These products are then exhausted through the nozzle and accelerated to supersonic speeds, preserving total pressure across the entire engine. The SFRJ will also self-throttle for different operating conditions, as the fuel regression rate is proportional to mass flux and injected air temperature. In essence, higher air throughput causes more fuel to be stripped from the grain, which maintains a balanced oxidizer to fuel ratio during combustion, regardless of speed.

In order to test an SFRJ system, one needs a source of through-put air to simulate the air-breathing nature of the engine. This can be accomplished in two ways, a connected-pipe or a free-flow facility [9]. In literature, free flow facilities (such as wind tunnels), are used to validate airfoils, inlet geometries, and other aerodynamic effects, due to their larger available test section. Connected-pipe applications are related more to direct examination of engine and fuel performance from a combustion perspective, as the combustion chamber is isolated from other possible performance variables. When this is the only data that are important for a test, using significant
Figure 2.5: Example UAH SFRJ Test Firing with 6” Combustion Chamber and 12” Mixing Chamber.

amounts of air for a free-flow test is costly and more complicated. With this in mind, UAH possesses a connected-pipe facility which serves as an SFRJ test bed, shown in Figure 2.5. This study will use the approach taken with this SFRJ facility to develop high altitude simulation capability which will work in tandem with current hardware. This new testing variable will then serve as an additional source of data to analyze ignition and combustion characteristics of fuels in future test programs [9].

2.2 High Altitude Simulation Importance and Approaches

Given the wide operating envelope of SFRJ systems, there is a need to obtain data at varying initial conditions, to see how the fuel or engine geometry would perform. This is common across the entire engine industry, from high altitude rockets to turbines, low-pressure testing is critical to full characterization of the device’s capabilities. There are various methods that have been explored which can achieve low pressure conditions, and the choice thereof is determined by application and size and
pricing constraints. In this program, the end-goal was to develop hardware to be used to study the relationship between the fuel grain ignition characteristics and equivalent atmospheric pressure. This mimics the anticipated ramjet operating condition of air flow into the ram scoop, undergoing compression, ignition, and exhaust through the nozzle while at high altitude. The test apparatus must be able to provide adequate air flow while also maintaining desired vacuum conditions. Secondarily, there was interest in observing nozzle exit plane characteristics during the test, which requires maintaining a vacuum in the diffuser as the fuel is burning. With this in mind, the following comparison can be used to help down-select appropriate test hardware.

There are four options to achieve vacuum conditions downstream of the SFRJ nozzle [10]:

(a) self-pumping (supersonic ejector)

(b) self-pumping + gas extraction

(c) gas extraction

(d) vacuum chamber

The self-pumping approach in Figure 2.6a involves wind tunnel design and shock theory, and essentially turns the entire exhaust diffuser system into an 'ejector'. Combustion gases are accelerated through the nozzle to supersonic speeds and forced out of a secondary nozzle. The secondary nozzle creates a normal shock which thermodynamically isolates the diffuser from ambient pressure, negating back-flow into the diffuser. This one-way flow also creates a vacuum differential on the chamber containing the engine, thereby termed self-pumping. This method is useful when a relatively low vacuum and high mass flow rate are needed, as in the case of a full scale liquid rocket engine test. This poses a few issues, however, as it does not allow for easy throttling of the vacuum pressures in the plenum, or adaptation to many test
conditions. Plenum pressure, chamber pressure, and air flow rate can significantly affect the position and reflection angle of recovery shocks in the diffuser, making it impossible to design a secondary throat diffuser for more than a small range of test conditions [11].

![Diagram of Self-Pumping Ejector Facility](image1)

(a) Self-Pumping Ejector Facility.

![Diagram of Self-Pumping Plus Gas Extraction Combined Design](image2)

(b) Self-Pumping Plus Gas Extraction Combined Design.

![Diagram of Gas Extraction Method](image3)

(c) Gas Extraction Method.

![Diagram of Vacuum Chamber Design](image4)

(d) Vacuum Chamber Design.

**Figure 2.6:** Diagrams of Common Simulated High Altitude Test Facility Concepts.

Gas extraction, which is shown in Figure 2.6c, involves the use of a vacuum pump or ejector element to pull air out of the cell before or during testing. The choice of hardware is dependent on the required pumping rate and vacuum level. This can be paired with the self-pumping system for better performance, such as in Figure 2.6b. The combination of these two methods allows for more efficient use of resources due to the nature of the self-pumping approach. During combustion, an isentropic shock will form in the secondary throat of the diffuser, which will thermodynamically isolate the vacuum pressure in the plenum from the atmosphere. This means that the
ejectors can be used pre-test to pump the plenum down to vacuum levels, and then are not needed once the engine fires and the shock is formed.

Gas extraction is useful for a blend of higher vacuum levels and still relatively high flow rates, more so on the level of jet turbines or missile rocket motors. Finally, the vacuum chamber approach, such as that in Figure 2.6d, involves a large chamber which is pumped down pre-test, with no active flow ongoing during the test. This is primarily used when very high vacuum is required and small thrusters and mass flow rates, relative to the size of the vacuum chamber, are tested. Due to the nature of the testing be performed, i.e., a pretest pumpdown with active subsonic mass flow through the system, an active gas extraction system is needed. Post-ignition, self-pumping can be used to some advantage by means of the supersonic flow exiting the nozzle, but this was not incorporated into the design.

Table 2.1: Comparison Between Ejector and Mechanical Exhausting for High Altitude Testing.

<table>
<thead>
<tr>
<th>Pros</th>
<th>Mechanical Exhausters</th>
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<tbody>
<tr>
<td>Ejectors</td>
<td>Mechanical Exhausters</td>
</tr>
<tr>
<td>Steam, water, air, nitrogen, oil</td>
<td>Pump (turbine, impeller, etc.)</td>
</tr>
<tr>
<td>Inexpensive</td>
<td>Long operating duration</td>
</tr>
<tr>
<td>Efficient</td>
<td>Low vacuum capability</td>
</tr>
<tr>
<td>Multipurpose (impurity scrubber applications)</td>
<td>Good for low flow rates</td>
</tr>
<tr>
<td>Cons</td>
<td></td>
</tr>
<tr>
<td>High flow rate capability</td>
<td>Large power requirements</td>
</tr>
<tr>
<td>High amounts of motive fluid required</td>
<td>High maintainance</td>
</tr>
<tr>
<td>Less vacuum capability than mechanical pump</td>
<td>Less Reliable</td>
</tr>
</tbody>
</table>

Table 2.1 lists the two primary methods for gas extraction, using mechanical pumps or supersonic ejectors. As indicated, the best choice is dependent on the required evacuation level, pumping rate, and available facilities. For an SFRJ, a high evacuation rate and medium-level vacuum level is required. In addition, low cost and low maintenance are both highly appealing, even at the expense of large quantities
of motive gas, the fluid used to drive an ejector pump, required. Hence the ejector method provides the best solution for this project. The self-pumping method is also able to be integrated in combination with the ejector concept and will provide a steady state vacuum once the engine is firing, thereby taking over from the ejectors and allowing for a higher maximum flow rate of air and fuel combined [12]. Both of these systems are noted for ease of purging impurities, as detailed in [13] and [14], and minimal cleaning maintenance [15]. This is an especially important factor in quick-turnaround testing when high amounts of boron and aluminum particulates become lodged in the downstream system [6]. Thus a combined self-pumping and ejector system was chosen.

With this conclusion in mind, the next step was to look at relevant current and future testing requirements as well as test facility capabilities around the country to determine a sufficient range of operation. According to [10], there were several rocket altitude test facilities in the country as of 1987, with varying applications in solid, liquid, and cryogenic propulsion. Only a few of these are capable of testing engines in the thrust range of 100 lbf or less. In addition, most facilities invested in equipment to attain simulated altitudes of 80,000 ft or higher, as in [16]. This makes them very expensive to reserve for testing, as there is significant infrastructure to maintain even for small scales. For the UAH facility, a 20,000 ft simulated test altitude was targeted as sufficient for characterizing a back-pressure-related trend in ignition studies. This would be achieved at a maximum mass flow rate of 0.062 lbm/s of heated air. This meant that ejector and diffuser configurations could be scaled down and acquired at much lower cost than a typical large scale facility upgrade might be. Occasionally a higher altitude than normally specified is required for a test, so designs were incorporated which would allow for expansion of the ejector manifold and capability in the future [17].
A very similar facility design is detailed in [18], where the test facility is brought down to pressure with ambient temperature air using air jet ejectors, and then the air is chilled with liquid nitrogen to altitude-level temperatures. This air is supplied by way of a pneumatic pressure regulator and sonic choke to maintain consistent flow rate. A coriolis meter provides mass flow data. 100 psig air at 1.667 lb/sec flow rate can maintain the necessary conditions to simulate about 35,000 ft altitude. This proof-of-concept provides a good estimate for the flow rate and expected altitude performance of the UAH eductor system, which will incorporate 100 psig air at a lower flow rate to achieve the desired 20,000 ft altitude.

In the case of the SFRJ program, hot air is desired, as the inlet air will be heated entering the ramjet after having been compressed and reduced to subsonic velocities in the ram scoop. The rest of the experiment configuration is useful, however and bears resemblance to the current UAH SFRJ facility.

Further down-selection is possible when examining budget and facility constraints which limit solutions to a few options. Air and nitrogen are the only motive fluids currently available in bulk at the UAH connected-pipe facility. Thus, despite steam being an unequivocally better option in terms of performance, the cost of implementing a high volume boiler system at the UAH far outweighs this performance gain for the purposes of this experiment [9]. Since gas ejectors are required by default, attaining the desired performance will be a function of ejector venturi size and quantity [19]. There is of course a point of diminishing returns relative to this project, as too large or too many ejectors will use up more air, resulting in fewer possible tests for the current capacity of bulk tanks. The combustion products of the engine will also be of a gaseous nature, apart from impurities, making the gas-gas style ejector and associated equations the tool of choice [20].
2.3 Gas-fed Ejector Pumps

Ejectors are the preferred choice for providing vacuum pumping to the test rig due to the prior review of concepts, and so it is important to gain a more in-depth understanding of their form and function. This will guide the selection of a style and quantity of ejector, as well as material considerations and whether off-the-shelf or custom elements are required. Figure 2.7 shows a single stage ejector and its principle operating parameters. Motive fluid such as air, steam, or oil is accelerated through the ejector motive flow nozzle, which creates a vacuum draw on the secondary fluid inlet, drawing in the gas and accelerating as a mixed fluid through the diffuser and the outlet port [21].

![Diagram of a Typical Single Stage Ejector Element](image)

**Figure 2.7:** Diagram of a Typical Single Stage Ejector Element [22].

Ejector pumps, as stated previously, were chosen for their potent combination of high flow rate and good vacuum level capabilities. Ejector performance is based on density and flow rate of the driving fluid or gas, the ejector throat diameter [23], and the incorporation of ejector staging [21]. The first three are all inherently connected and are a large contributor to efficiency and flow rate capability. Ejector staging is performed when additional entrainment efficiency, or low vacuum pressures are required. Staging can increase the experiment hardware and consumables cost
substantially, but provides significant performance improvements, and will be covered in more detail later in the section.

Ejector efficiency from a quantitative standpoint is defined using three governing equations. [24] These are pressure ratio in equation 2.2, flow ratio in equation 2.3, and mixing tube-to-nozzle diameter ratio. These are outlined in detail below:

\[
N = \frac{P_{ex} - P_{sec}}{P_{mot} - P_{ex}}, \tag{2.2}
\]

where \( N \) is the non-dimensional pressure ratio term. All pressure terms in the equation are total pressures.

Flow ratio is given two different ways depending on the application: mass flow ratio and volumetric flow ratio, both of which are listed here:

\[
M = \frac{\dot{Q}_2}{\dot{Q}_1}, \tag{2.3}
\]

\[
\omega = \frac{\dot{m}_2}{\dot{m}_1}, \tag{2.4}
\]

where \( V_1 \) is the volumetric flow rate of the motive gas at the primary inlet, and \( V_2 \) is the flow rate of the secondary flow inlet gas at the secondary inlet. The mass flow rates of the same number also correspond to these parts of the ejector geometry.

Finally, the critical area ratio term:

\[
T = \frac{A_2}{A_t}, \tag{2.5}
\]

where \( A_2 \) is the area of the mixing section of the ejector and \( A_t \) is the area of the throat of the primary flow nozzle.

The design process for manufacturing custom ejectors or sizing off-the-shelf options is well documented and based on the venturi equation and basic fluid dynam-
ics. The governing principle upon which the venturi equation is based is the Bernoulli equation, relating pressure, mass flow rate, and density of a given fluid or gas, and is used for calculating pressure drop and vacuum capability in cases of venturis and Pitot tubes, to name a few. In designing one of these elements, the primary focus is on controlling the length of the diffuser section, and intended pressure drop and circulation rate across the element [25].

![Figure 2.8: Example Diagram of a Two-Stage Ejector Setup [26].](image)

Ejectors can also incorporate staging elements into their geometry to improve performance. It involves connecting two or more ejectors together, outlet-to-secondary-inlet, with a manifold feeding the primary flow inlet, as shown in Figure 2.8. The first ejector operates as normal, passes the entrained and mixed flow onto the second, which pulls it through the secondary inlet with its own primary flow supply, then exhausts this mixture through the outlet. This can be sequenced several times, depending on requirements, resulting in six stage ejectors being feasible, as shown in Table 2.2 [27]. More stages than this are possible, but standard performance values are not readily available. At high staging extremes, flow rate tends to be traded for vacuum capability, but this can be rectified. Consulting with an engineer at Fox Valve provided industry-standard information about ejector performance which helped guide the ensuing design choices. Ejector performance is heavily influenced by the temperature of the gas it is required to entrain. This influenced the decision to
Table 2.2: Expected Ejector Performance Characteristics Based on Motive Fluid and Staging.

<table>
<thead>
<tr>
<th>Ejector Stages</th>
<th>mm Hg</th>
<th>High Alt [ft]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Steam as motive fl.)</td>
<td>High Range</td>
<td>Low Range</td>
</tr>
<tr>
<td>1</td>
<td>30</td>
<td>760</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>130</td>
</tr>
<tr>
<td>3</td>
<td>0.8</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>0.075</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>0.01</td>
<td>0.4</td>
</tr>
<tr>
<td>6</td>
<td>0.003</td>
<td>0.1</td>
</tr>
<tr>
<td>(Air as motive fl.)</td>
<td>207</td>
<td>32,000</td>
</tr>
<tr>
<td>2</td>
<td>52</td>
<td>60,000</td>
</tr>
</tbody>
</table>

test a single stage, off-the-shelf alternative first, and then design a custom part based on system-specific performance data. As such, the off-the-shelf single stage ejectors from Vaccon proved to be a good solution.

During a typical engine test, the ejectors will experience 4000 F combustion gases for the duration of the burn sequence, which can vary from 5 to 30 seconds, if they remain activated through an engine firing. This will necessitate gaining data on the anticipated heat transfer between mixed inlet streams, or primary and secondary flows [28], and the venturi throat to determine if the aluminum element will be compromised during a test. If the secondary stream temperature is too high for the aluminum elements, the anticipated temperatures will be incorporated into the next ejector design [29], with higher flow capacity and temperature-resistant materials [30].

A final facet of ejector system design is the ability to manifold multiple ejectors together. This is an easy way to keep the vacuum performance identical while improving the mass flow rate capability by a quantized amount. For the purposes of
this setup, working with what is available, a group of 4 ejectors linked to a manifold result in the appropriate mass flow rate at desired conditions. An ejector manifold is often easier and less expensive than a larger, single ejector of equivalent flow rate. This is due to the component costs of larger fittings, tubing, and associated hardware.

Conclusions from the literature study determined that a single-stage, gas-gas ejector system coupled with the UAH connected-pipe flow facility would provide the best results for the given testing conditions. These require a 0.062 lbm/s mass flow rate of 800 °F heated air to be evacuated, such that a vacuum condition equivalent to a 20,000 ft altitude could be maintained. The single-stage system provides sufficient performance capabilities and high flow rates for the aforementioned set points, while the connected-pipe facility allows for intricate analysis of combustion-specific performance of SFRJ fuel grains.
Chapter 3. Materials and Methods

With the preliminary system specs selected, the design process could begin. The general methodology was to size the system to meet the test campaign requirements and then to perform checkout tests. Since a modular high altitude simulation device for an air-breathing SFRJ was not readily found in literature, a prototype test and further refinement would be necessary, as similarly performed in [31]. It should be noted that the terms ‘plenum’ and ‘eductor’ are frequently used interchangeably. In this particular application, the entire plenum assembly could be quantified as an air eductor or ejector. Due to the use of genuine air ejectors in the project, the eductor assembly is used for clarity to describe the test rig as a whole.

3.1 Design and Integration of Ejector System

The requirements for the high altitude simulation test rig consist of: 0.062 lbm/s mass flow rate of air pre-test, 20,000 ft altitude or about 6.75 psia plenum (or eductor) pressure, air or nitrogen ejectors, and all in a modular system to fit on the existing SFRJ test cart. The components should be sturdy enough to hold up to potential equipment failure for safety purposes. The most likely source of failure in this type of test is over-pressurization, either due to clogged orifices or a regulator failure, and must be accounted for to avoid hardware failure. In addition, there are often exotic combustion products which will contaminate the eductor itself and could potentially make their way into the ejectors. These include, but are not limited to, Hydrochloric Acid (HCl), Hydroflouric Acid (HF) and Hydrogen Cyanide, all of which require the use of compatible materials, such as stainless steel for structural
components and silicon for sealing purposes. The extreme combustion temperatures that the system might potentially see, 4000 F maximum, also necessitated a stainless steel structure.

**Table 3.1:** Ejector Specifications and Flow Rate Calculations.

<table>
<thead>
<tr>
<th>UAH SFRJ EDUCTOR SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ejector Model</td>
</tr>
<tr>
<td>Vacuum flow @ 9&quot;hg (-4.4 psig)</td>
</tr>
<tr>
<td>Ejector Quantity</td>
</tr>
<tr>
<td>Total Flow Capacity @ 9&quot; hg</td>
</tr>
<tr>
<td>Mass flow Rate of Engine (air)</td>
</tr>
<tr>
<td>Mass flow Rate of Engine (air + fuel)</td>
</tr>
<tr>
<td>Equivalent flow rate of ramjet air</td>
</tr>
<tr>
<td>Equivalent flow rate of ramjet air + fuel</td>
</tr>
<tr>
<td>Maximum Achievable vacuum (theory)</td>
</tr>
<tr>
<td>Maximum Achievable Vacuum (air-fuel)</td>
</tr>
</tbody>
</table>

The required mass flow condition can be converted to Standard Cubic Feet per Minute (SCFM), the standard unit for most ejector systems, using the values shown in Table 3.1. With this relationship provided by the manufacturer, the vacuum flow requirements are readily obtained. Running ram-air only at the expected flow rate of 0.062 lbm/s yields about 12.4 SCFM per ejector. This is calculated by multiplying by 60 to convert from seconds to minutes and then dividing by standard density of air to obtain a total flow rate. One-fourth of this is the per-ejector flow requirement. Using the performance data for the off-the-shelf ejectors shown in Table 3.2, one can obtain the anticipated vacuum values directly or by interpolation of the data. The interpolation for 12.4 SCFM for an ejector corresponds to 8 psia of vacuum flow rate. The maximum experimental flow rate of ram-air plus the propellant at 0.1 lbm/s total yields approximately 80 SCFM corresponding to 12 psia during a hot fire test. Properties of anticipated combustion products are relatively well-estimated by properties of air or nitrogen, except for specific gravity.

With these data in mind, an eductor-specific schematic was devised which details the chosen components and locations of relevant instrumentation, as shown in
Figure 3.1, the decision was made to use an existing 3/4” nitrogen line and associated high-flow regulator for a four-ejector manifold and branch from there for increased performance. Nitrogen was chosen as a way to increase possible run times by using a separate group of high pressure bulk tanks rather than branching off of the needed supply for the throughput air. Additionally, using parts in-hand, it is considerably cheaper to route 3/4” tubing than 1” tubing, which requires a pneumatic bender.

**Figure 3.1**: Parts and Instrumentation Diagram (P&ID) Guide for the Outlined Eductor Module.

### 3.2 UAH Connected-Pipe Flow Facility Hardware

The UAH Flow Facility is comprised of several components, including, but not limited to, a heated air supply, igniter propellant lines, and nitrogen feed system. The schematic in Figure A.4 provides a general layout of the existing hardware and how it interacts with the engine on the test cart. As mentioned previously [32], the direct-
connect approach allows for more detailed manipulation of combustion conditions, ideal for fuel formulation testing [33].

Figure 3.2 shows additional images which illustrate the equipment noted in the schematic. The bulk air tanks in Figure 3.2b are set up to run as tandems, two at 2500 psi, and two at 300 psi. The high pressure pair are used for SFRJ tests. The heater in 3.2c was acquired from TUTCO and is rated at 50kW on a 480V supply. It is capable of heating 0.1 lbm/s of air to 900 F, and is maximum rated for 1200 F at lower flow rates, comparable to the system specs used at Glenn Research Center for similar testing [33]. The H2/O2 torch igniter from 3.2d is the PRC workhorse for most ignition tasks, using an automotive spark plug to light a fuel-rich mixture which impinges directly on the fuel grain for a test duration between 5 and 30 seconds. Finally, the ramjet motor itself, in 3.2e is manufactured from carbon steel, with SS 304 adapting components, and can be configured based on the test requirements. It can be set up with any combination of a 6” or 12” mixing chamber and 6” or 12” combustion chamber. These elements are held together in compression by four threaded rods, which are torqued to a specified setting before each firing. Not pictured, but also important is the way mass flow is regulated. This is done by swapping the orifice in the air feed line, which is located in between the heater and the SFRJ motor. This allows for the pneumatic regulator to control higher or lower flow rates when using the 0.180”, 0.255”, or 0.390” option [34].
Figure 3.2: UAH SFRJ Connected Pipe Test Facility Major Components.
3.3 Experiment-Specific Hardware

The hardware design phase involved two additional factors. First, designing the eductor system to be user-friendly and fit on the test cart, while maintaining system performance requirements. The second was incorporating high-temperature C-type thermocouples into the system in order to accurately measure combustion temperatures. Both of these processes are described in the following sections.

3.3.1 Eductor Design and Modeling

Several considerations are made when designing a low back pressure eductor. Primary among these are aerodynamic geometry, structural integrity, ease of access, and materials compatibility. The primary geometries used in the eductor design are those of the Constant Area Exhaust Diffuser (CAED), and the Secondary Throat Exhaust Diffuser (STED). The qualifying reasons for choosing one over the other are primarily size and complexity concerns, but due to the unique nature of the experiment, the need for pre-ignition pump-down, both designs are plausible solutions. Figure 3.3 illustrates the different anticipated effects in each of these designs.

As illustrated in Figure 3.3a, The CAED is the simplistic design, and relies on having a long enough tube that a normal shock will eventually form. This is advantageous for quick setup, without the need for reducing unions, but requires more space in the test area. The CAED or constant area exhaust diffuser is considered the simplest of the designs from a geometrical perspective. It is a long, straight cylindrical tube, sometimes with a flared end for the exhaust to recover to ambient pressure. It suffers however from needing a higher starting pressure to build the necessary shocks within the tube. The starting pressure and position of the shock is determined by the area ratio of the diffuser to the nozzle throat. A ‘started’ diffuser means that it is choked from the supersonic flow out of the nozzle, which indicates the vacuum section
of the chamber is isolated from atmosphere across this boundary. In addition, it means that there is a train of oblique shocks reflecting down the length of the diffuser tube which result in an overall isolation of the system from atmosphere. The location of these shocks in both geometries is determined primarily by the impingement location of the nozzle exit flow on the diffuser wall. One of the main governing parameters of this starting pressure for a CAED is the diffuser $L/D$ ratio, as well as the diffuser area ratio, an example graph of which is included below in Figure 3.4. The minimum position for these generators is at a $L/D$ of 1.34 from the entrance. This creates the possibility of ’starting’ an ejector system with a $L/D$ as low as 2.62 with a high enough starting pressure [35]. This will also help avoid premature unchoking of the diffuser section during a hot fire [36].

The STED, shown in Figure 3.3b, incorporates supersonic theory to take the accelerated nozzle flow and compress it to sonic speeds within the secondary throat. It is more compact than the CAED and requires a lower starting pressure, but takes
much more time on the front end to design, as the complex mach relationships are difficult to tune exactly. The STED also requires fine tuning if one desires to run at more than one operating condition, and so would require a long secondary throat or the ability to adjust the size and ramp angle of the secondary throat to account for throttling. An STED has the advantage of a lower average starting pressure, as shown in Figure 3.4 since the flow is choked in a secondary throat and not in the ‘subsonic diffuser’ section of the CAED [37]. The STED flow evolution is detailed as starting choked at the diffuser inlet, being ‘swallowed’ by the secondary throat, and ending up on the subsonic diffuser, before being re-swallowed back into the throat to maintain a steady state [38].

For ease of manufacture, the CAED design was chosen. If needed, it could later be adapted with an insert to an STED if required. The eductor could also be lengthened or shortened as needed for adaptation to tests with different operating parameters, making it a useful modular approach. The chart in Figure 3.4 details
useful relationships to keep in mind to ensure the CAED is properly sized. The inlet-nozzle throat area ratio was maximized as much as possible within space constraints due to the wide variation of nozzles used during tests. This culminated with a 6” eductor diameter, which was compatible with SFRJ nozzles up to 0.8” diameter, and could be reduced with spacers for smaller nozzles if needed. Time was taken to deliberate over details such as pressure and temperature sensor mounting points, interfacing with current hardware, and ease of access for back-to-back tests were also considered.

This culminated in the design shown in Figure 3.5, and the ensuing fabricated hardware. The eductor module is comprised of an SS 304 6” diameter pipe section, 16” in length, supported on either side by SS 304 flanges. These mount to steel right angle brackets, which sit on linear bearings, which, in turn, sit on a linear rail. This allows for the relatively heavy module to be easily pulled apart and pushed back into place in between tests. The aft flange attaches to a machined flange which supports the blow-off door. This door was fabricated from aluminum and is secured loosely in place with tape. This allows for it to self-seal against the rear o-ring when a vacuum is pulled, and be pushed off its sealing point when there is positive pressure within the eductor. This affords high flow rate capacity during a burn without concern of overpressure in the eductor [11]. The front end flange supports another unique flange, which, together with the re-machined SFRJ aft end, act as the coupler between the two modules. Pressure taps and ejector ports were added orthogonal to the cylindrical eductor at regular intervals. All steel-steel joints are sealed with a high-temperature silicon o-ring, except for the flange joints, which are sealed with high temperature vermiculite. The flanged design proved to be a cheap and effective way of adapting off-the-shelf hardware to suit the present need, and reusable, high-temperature gaskets. The mounting rails are kept lubricated and allow for easy shifting of the eductor post-test to replace the fuel grain and reconnect.
Figure 3.5: Fabricated Exhaust Eductor System.
It was also necessary to ensure the assembly was structurally sound, not only for the aforementioned fail-safe in case of over-pressurization, but also for possible starting and stopping loads. At high pressure differentials there can be a backflow, essentially air hammer [39], when the ejectors are stopped suddenly. This is mitigated by gradual pressure decrease, operating at low pressure, or simply making the system sturdy. Flanges for optional optical windows, as seen in [40], were added along the nozzle exit plane for analyzing the exhaust products and flow separation [41]. Finally, the thermocouple and pressure tap locations were chosen for a range of useful information, spaced about 5 inches apart along the centerline of the eductor [42].

Figure 3.6: Cut-away of Eductor Assembly Showing Transducer and Thermocouple Locations.

Figure 3.6 shows the names and locations of relevant transducers and thermocouples as referenced later in the presented data. The three collinear locations on the top of the eductor are primarily for combustion tests and redundancy during non-combustion tests. The K-type was chosen as a backup for the C-types, since these had not been used before by the facility. During combustion, these would give a better idea of any shocks that form within the eductor, as there will be more dramatic pressure and temperature gradients. The motive gas sensors provide a more accurate representation of the pressure and temperature going into one side of the ejector.
manifold. The exhaust TC is meant to provide an understanding of final temperature of the gases after mixing in the ejector eductor. Relevant to the ejector setup, a 3/4” nitrogen line feeds into a tee, which is then stepped down to two separate 1/2” tees which feed the four ejectors.

### 3.3.2 Thermocouples

Measuring the temperatures of combustion products of the SFRJ has proven to be a challenging effort, as most standard thermocouples (TCs) are not designed for the high-temperature environment. This led to a desire to incorporate exotic material TCs into the exhaust system. C-Type thermocouples were chosen, as their tungsten-rhenium alloy is rated to 4200 F. These were installed with matching extension-grade wire and routed to the appropriate card in the Data Acquisition computer (DAQ).

The C-type TCs are nonstandard, unlike the more available K, T, and J types, required incorporation, through a custom thermocouple cold junction, into the system DAQ. Omega provides a handbook containing the necessary calibration equation, shown in equation 3.1,

\[ EMF = A \times T + B \times T^2 + C \times T^3 + D \times T^4 + E \times T^5 + K, \]  

and the associated coefficients, shown in table 3.7. These were input to the DAQ and rearranged to solve for temperature, such that the input reference voltage could be converted. TCs require a cold junction reference temperature in order to provide an accurate reference signal, so a system was rigged up where a K-type TC provided ambient DAQ cabinet temperature, converted it to a voltage, referenced this to an

<table>
<thead>
<tr>
<th>Coefficients for W5Re/W26Re</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
</tr>
<tr>
<td>7.19E-03</td>
</tr>
</tbody>
</table>

**Figure 3.7:** Polynomial Fit Coefficients for C-Type Thermocouple.
equivalent C type voltage and temperature, and then added this to the in-situ C-type voltage to obtain the corrected temperature. This was then read and compared to the in-line K-type TC to verify proper function and that the low-end temperatures were within error margin.

3.4 Modeling and Simulation of System

With the eductor design defined, a simulation study could be performed to ensure it would be within anticipated performance parameters. In particular, it was necessary to determine the evacuation rate of the ejectors relative to the air flow rate and ensure the blow-off door would stay under vacuum until after ignition. A computational fluid dynamics (CFD) simulation was put together in ANSYS Fluent to estimate the expected performance of the eductor module configuration. The geometry as pictured in Figure 3.8 was dynamically meshed with tetrahedral points, with small nodes around points of interest such as the nozzle and larger nodes elsewhere.

Table 3.3 shows the prevailing boundary conditions for each test of the fluid simulation. The primary change between tests are the conditions at the nozzle inlet.
to test for a distinguishable difference between a mass flow and pressure bounding condition, as well as gas temperatures.

**Table 3.3**: Test Boundary Conditions for Ansys Fluent Simulations.

<table>
<thead>
<tr>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nozzle Inlet</strong></td>
<td><strong>Nozzle Inlet</strong></td>
<td><strong>Nozzle Inlet</strong></td>
<td><strong>Nozzle Inlet</strong></td>
</tr>
<tr>
<td>Temperature</td>
<td>Pressure</td>
<td>Temperature</td>
<td>Mass Flow</td>
</tr>
<tr>
<td>800 F</td>
<td>80 psig</td>
<td>4000 F</td>
<td>0.1 lbm/s</td>
</tr>
<tr>
<td><strong>Wall</strong></td>
<td><strong>Nozzle Inlet</strong></td>
<td><strong>Nozzle Inlet</strong></td>
<td><strong>Nozzle Inlet</strong></td>
</tr>
<tr>
<td>Wall</td>
<td>Pressure</td>
<td>Temperature</td>
<td>Mass Flow</td>
</tr>
<tr>
<td>N/A</td>
<td>N/A</td>
<td>800 F</td>
<td>0.1 lbm/s</td>
</tr>
<tr>
<td><strong>Ejector Outlet</strong></td>
<td><strong>Ejector Outlet</strong></td>
<td><strong>Ejector Outlet</strong></td>
<td><strong>Ejector Outlet</strong></td>
</tr>
<tr>
<td>Pressure</td>
<td>Pressure</td>
<td>Temperature</td>
<td>Mass Flow</td>
</tr>
<tr>
<td>1 psig</td>
<td>1 psig</td>
<td>800 F</td>
<td>0.1 lbm/s</td>
</tr>
</tbody>
</table>

Figure 3.9 shows several simulations of initial values. The eductor is pictured as a transparent object, such that only the internal streamlines are visible within the wireframe. The left-most side of the pictured eductor in Figure 3.9 is the SFRJ nozzle, the combustion-chamber side of which was the experiment-specific setpoint. For Figures 3.9a and 3.9b, the initial condition was a constant mass flow rate of 0.1 lbm/s. Figures 3.9c and 3.9d show the initial conditions of the combustion chamber side of the eductor set to 80 and 100 psia. The four protrusions are the eductor tubes, which were set to 6 psia. Finally, the right-most side, the blow-off door, was set to atmospheric pressure. Air temperature was also varied between 800 F and 4000 F to simulate pre- and post-ignition air flow.

The graphs in Figure 3.9 indicate the eductor performing as intended. The air enters the nozzle and is accelerated to Mach 1, and then further to Mach 2-3, then very quickly decelerated in the eductor to subsonic speeds. This is ideal for
Figure 3.9: Ansys Simulated Tests of Eductor Geometry to Determine Exhaust Conditions at Blow-Off Door.

the purposes of this experiment, as rapid slowing of the gas will ensure the door stays on for the maximum amount of time and will help ensure the ejectors can keep up with the through-put air. This would also preserve the appropriate nozzle flow characteristics, over/under expansion, detachment, etc., for further data collection and imaging [4]. The reader may refer to Appendix B for more information.

3.5 Testing Matrix and Approach

In order to qualify the test hardware for future experiments, a test matrix was composed which could fully characterize the capabilities of the system. This involves
cold flows of air over a variety of mass flow rates, and then if working properly, a follow-up matrix of hot flow and then test firings. The eductor shock dynamics are quite complicated, and although performance can be predicted within a degree of uncertainty, the true performance is based on so many variables that checkout testing is necessary. Several vacuum transient conditions would be tested in this circumstance, with both hot and cold flows of varying mass flow rates.

The first is where the ejectors are activated before the diverter valve is switched from exhaust to the engine. This would allow for the pressure in the eductor and combustion chamber to reach an equilibrium vacuum pressure before the test, setting a maximum threshold with zero flow rate. Then the valve would be switched to flow through the engine, and pressure would be recorded throughout this process to measure transient conditions. This gives an idea of how the ejector system will handle the sudden mass flow spike, as well as how the system will choke with reduced back pressure conditions initially. This will also simulate, in the hot fire scenario, a high altitude ‘starting’ condition, as none of the usual choke points will be choked and the combustion chamber will be at simulated ‘ambient’ conditions. As mentioned in [43], it is important that the system reach a steady state during a test, as transient and steady state performance is vastly different in ejectors.

Another condition to be tested in a nominal way involved turning on the ejectors after the engine has started, and pumping the eductor down to a low pressure condition during air flow. This will give some indication of how easily the ejectors can ‘overtake’ and produce vacuum conditions in an active flow scenario.

In addition to these test criteria, it will also be necessary, from a eductor choking perspective, to test the vacuum conditions with the ejectors on during the full test and with them switched off during combustion. The latter condition will ensure that the eductor is truly thermodynamically isolated from the ambient pressure and can maintain vacuum conditions without the need to be constantly supplemented by
the ejectors. This is not necessary for the success of the test program but is the ideal and simplest condition to maintain for long duration experiments.

With this in mind, a comprehensive test matrix was developed that would thoroughly flesh out the design’s performance. This involved three phases of testing. First, vacuum pressure tests with no ram air flow, which recorded the steady state vacuum level achieved by the ejectors for a given muscle pressure. The second phase will introduce different ram air flow rates and combine those with different muscle pressures to record the steady state vacuum pressure. And finally, these tests were repeated at different test points with different temperatures of heated air. Upon the successful completion of the heated air tests, the system could be cleared in the future to run through a live hot-fire to see what vacuum level would be obtained and any changes which may occur during combustion.
Chapter 4. Results and Discussion

Characterization of ejector performance within the UAH system requires analysis of three main variables and their relative effects: inlet air flow rate, air temperature, and motive gas pressure. The first two of these are commonly varied set-points during fuel formulation testing, making it imperative that the Eductor assembly functions at such conditions. Motive pressure is an ejector-specific variable, and intended to provide a way to adjust back pressure during tests, as well as combustion chamber pressure during the preheat stage of a test.

4.1 Uncertainty Analysis

Effective presentation of the test data required application of uncertainty principles to all of the temperature and pressure data. This would lend some clarity to how much the results can be trusted relative to the both random and systematic uncertainty factors. Table 4.1 details the accuracy values found in the datasheet for each sensor, and the range in which they can be applied.

Table 4.1: Rated Accuracy Values for Critical Measuring Equipment.

<table>
<thead>
<tr>
<th>Physical Parameter</th>
<th>Location</th>
<th>Manufacturer</th>
<th>Sensor Type</th>
<th>Range</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>Eductor aft, ejector secondary/exhaust</td>
<td>Omega</td>
<td>K-Type Thermocouple</td>
<td>-326 to 2300 F</td>
<td>4 F or 0.5%</td>
</tr>
<tr>
<td>T</td>
<td>Eductor front/mid</td>
<td>Omega</td>
<td>C-Type Thermocouple</td>
<td>32 to 4200 F</td>
<td>4.5C to 425</td>
</tr>
<tr>
<td>P</td>
<td>Sonic nozzle</td>
<td>GE</td>
<td>Transducer</td>
<td>0 to 1500 psig</td>
<td>1% to Full Scale</td>
</tr>
<tr>
<td>P</td>
<td>Ejector motive</td>
<td>Omega</td>
<td>Transducer</td>
<td>0 to 150 psig</td>
<td>p/m 0.25%</td>
</tr>
<tr>
<td>P</td>
<td>Eductor front/mid/aft</td>
<td>Omega</td>
<td>Transducer</td>
<td>0 to 50 psia</td>
<td>p/m 0.25%</td>
</tr>
<tr>
<td>m</td>
<td>Air feed line</td>
<td>Emerson</td>
<td>Coriolis Meter</td>
<td>8 to 155 SCFM</td>
<td>0.10% of Rate</td>
</tr>
</tbody>
</table>
Mass flow accuracy of the coriolis flow meter, as shown in Figure A.2 was so high that the error bars are not visible behind each point on the plot. It should be noted that there is a minimum range for the coriolis meter, but the test parameters never dropped below that threshold value. This high accuracy was also present with the 0-50 psia and 0-150 psig transducers. The accuracy of these instruments is a fractional value of their range, and this range significantly smaller than the head end 0-1500 psig transducer. Primary contributors to systematic uncertainty were the sonic nozzle transducer, which rated for 0-1500 psig, and the C-type thermocouples, which have a 41 °F bounding condition at low temperatures. The seemingly large range of error for a C-Type thermocouple is more apparent when a system parameter value is calculated using front eductor temperature. The plot in Figure 4.8 does not show C-type uncertainty for the sake of graphical clarity and not busying the plot unnecessarily. Comparison with the K-type thermocouple in the aft position on the eductor should provide instrumentation redundancy to verify the C-type thermocouple value being recorded is within tolerances.

Random uncertainty was estimated for the time-averaged mean values of each test. Data were recorded with the data acquisition system (DAQ) at approximately 100 hz over the course of 10-15 seconds. This provided 1000+ measurements to incorporate into a mean value, the uncertainty of which was calculated using equation 4.1. In which

\[ S = t \frac{\sigma}{\sqrt{n - 1}}, \]  

where \( S \) is the expanded random uncertainty, \( t \) is a coverage factor given by the t-table, assuming infinite samples, \( \sigma \) is standard deviation, and \( n \) is number of data-points. In this particular case, relative to the systematic uncertainty of the individual sensors, this value was on the order of 1 ten-thousandth of the systematic value. Random uncertainty was still included in the uncertainty bars as part of the lump sum
of total estimated error, but was relatively negligible due to its magnitude. The uncer-
ainty results themselves will be presented along with their respective data in the
following sections.

4.2 Ejector-only Threshold Tests

Tests were conducted first with no air flow, to characterize the vacuum potential of the 4-Ejector manifold at different motive pressure set-points. These targets were predetermined by manufacturer specifications, shown in 3.2, on the ejectors themselves, and these targets are shown in Figure 4.2. The difference between the regulator setting and the resulting motive pressure at the ejector is believed to be due to system losses from the many tube fittings and overall length of tubing between the physical regulator and the Ejector. Table 4.2 was used to attain a desired motive pressure set-point with the manual regulator before a test and reduce time required to reset after a test.

Table 4.2: Motive Pressure Regulator Set-Points Compared to Actual Motive Pressure.

<table>
<thead>
<tr>
<th>Ejector Checkout</th>
<th>Motive Pressure Regulator SP [psig]</th>
<th>Resulting Motive Pressure SP [psig]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>130</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td>140</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>100</td>
</tr>
</tbody>
</table>

The other aspect of ejector-only tests was to characterize maximum vacuum level, or minimum eductor pressure, for a given motive pressure set-point. This minimum pressure could then serve as a threshold value for determining expected vacuum
levels once air flow is introduced, as a cold or heated flow condition will always result in a higher pressure than a no-flow condition. Figure 4.1 shows the test points for this no-flow condition and the resulting eductor pressures achieved. Comparing this plot with the manufacturer data from 3.2, it is seen that the curve shape and overall pressures are within the anticipated performance range. Maximum effectiveness lies between 80 and 100 psig motive pressure, and further increase in pressure has little to no effect on flow entrainment. In this dataset, as with the succeeding cold and heated flow tests, the system was allowed to reach steady state for several seconds, to ensure a consistent, accurate reading and reduce random uncertainty.

![Figure 4.1: Eductor Absolute Pressure vs Motive Gas Pressure.](image)

4.3 Ejector Tests with Air Flow

The second tests run were those with cold air flow of varying flow rates. These were also run at various motive gas pressures to compare with previous data and
determine the relative performance of each set-point for a given mass flow. The chosen values are given in Table 4.3, and were based on the maximum performing range of the ejectors as well as typical flow rates expected in an SFRJ test.

Table 4.3: Set-Point Ranges for Cold Air Flow Characterization.

<table>
<thead>
<tr>
<th>Motive Pressure SP</th>
<th>95 psig</th>
<th>120 psig</th>
<th>135 psig</th>
<th>150 psig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp SP</td>
<td>60 F</td>
<td>.03-.057</td>
<td>.03-.065</td>
<td>.03-.104</td>
</tr>
</tbody>
</table>

![Figure 4.2: Eductor Pressure vs. Time for a Typical Test Run with Air Flow.](image)

The plot in Figure 4.2 shows eductor pressure along the ejector secondary flow inlet plane over the course of a typical test run. Exact timings are test-dependent, but the general sequence of test events is consistent across all tests. A mass flow test point is chosen and, if required, heated to the desired steady-state condition. This is routed to the exhaust side of the 3-way valve during the pre-test heat. The heater requires a maximum milliamp set-point, corresponding to temperature, and ramp
rate entered into LabView, which is automatically relayed to the heater. Once steady state has been achieved, data collection is initiated, and the test is run manually. The ejectors are switched on as shown at 2.5 seconds into the sequence, allowing them to reach a steady state vacuum level. Once confirmation of appropriate vacuum pressure is made, the 3-way valve is switched from bypass to routing air through the engine, which in this example occurs at 10 seconds. This condition is allowed to reach steady state and maintains this for a comparatively lengthy time period, about 25 seconds. Then, at 35 seconds, the 3-way valve is swapped back to the bypass condition and the eductor is allowed to return to a steady state vacuum. This verifies that the blow off door is still secure and nothing occurred during the test to change the operating capability of the ejectors. The ejectors are switched off at 40 seconds and air continues to run through the bypass for as long as required to assist in heater cooldown procedures. Note that the datapoints for all the ensuing flow tests of cold and heated air are displayed as time-averaged value taken over generally a 10-20 second span, as shown in Figure 4.2. This is shown as an absolute pressure, as indicated by the 0-50 psi absolute pressure transducer.

### 4.3.1 Cold Air Flow Tests

The data in Figure 4.3 indicate that the ejectors were able to maintain vacuum with active flow coming into the eductor plenum, meaning they could continuously pull out the pre-test air and maintain a pressure differential at various settings. The plot shows 95, 120, 135, and 150 psig set-points at the regulator, which roughly equates to a 30 to 50 psi drop at the ejector inlet (60, 80, 90, 100 psig at the inlet). Observed is that the slope of the linear fit of the data can be adjusted with more or less muscle pressure, but the intersecting ‘apex’ indicates a maximum performance ceiling for a size or quantity of ejectors. This indicates that the steady state eductor pressure can be decreased for an increased motive pressure, but there is a point of
diminishing returns governed by the maximum mass flow rate of the ejector array. The value at 100 psig motive pressure indicates the maximum performance of the ejectors, and the other set-points illuminate the linear relationship between mass flow through the ejector and entrained flow through the secondary port of the ejector.

Figure 4.3: Eductor Pressure vs Mass Flow Rate at Varied Muscle Pressures During Cold Flow.

Also of interest for sake of logistics is the approximate time constant of the system during a test and if this varied to any large degree over different test points. This could potentially affect test sequence timing if ejector recovery time is extremely long or varies to a large degree.

Figure 4.4 shows the datapoints used to calculate the time constant, \( \tau \). A value on the initial slope of 10 percent of the steady state was acquired, along with its time stamp. Next a value was chosen that was 63 percent higher than this or 73 percent of maximum, along with its time stamp. These were then put into an exponential time fit equation, as shown in equation 4.2

\[
p_{cd} = p_{\text{min}} + p_{\text{max}} \left(1 - e^{-\frac{t}{\tau}}\right), \tag{4.2}
\]
where $p_{ed}$ is the eductor pressure for a particular time, $t$, $p_{min}$ is the steady state no-flow eductor pressure, and $p_{max}$ is the steady state eductor pressure during air flow. Figure 4.5 shows the obtained graph of $\tau$ vs mass flow rate of air. It should be noted that the final two datapoints correspond to a condition where the eductor pressure recovered to atmospheric, meaning the ejectors were not evacuating the inlet air at a high enough rate to alter the readings. This will bias the final two datapoints towards being a shorter time constant. A non-atmospheric pressure recovery will reach maximum pressure within 5 times the time constant value. However, a test which recovers to the atmospheric threshold will follow the exponential curve up to atmospheric and then flatline, artificially lowering the recovery time.

No major trend was observed for time constant as a function of mass flow, other than a vague trend upwards. The time constant is so small, however, that slight variations between set-points make very little difference in sequence timing. The
small system recovery time constant indicates that the ejectors are able to evacuate the eductor quickly enough that transient and recovery affects will be negligible.

4.3.2 Heated Air Flow Tests

Finally, heated flow tests at varying temperatures, flow rates, and muscle pressures were performed to complete the dataset. Table 4.4 shows the planned test conditions, which repeat several of the cold flow set-points and gain a better understanding of how ejector performance varies with inlet air temperature.

**Table 4.4:** Test Set-Point Ranges for Heated Air Flow Characterization.

<table>
<thead>
<tr>
<th>Temp SP</th>
<th>Motive Pressure SP</th>
<th>Flow Rate SP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>125 psig</td>
<td>150 psig</td>
</tr>
<tr>
<td>400 F</td>
<td>.025-.034</td>
<td>.025-.051</td>
</tr>
<tr>
<td>500 F</td>
<td>.026-.051</td>
<td>.026-.051</td>
</tr>
<tr>
<td>600 F</td>
<td>.026-.053</td>
<td>.026-.053</td>
</tr>
</tbody>
</table>
Each mass flow set-point corresponds to an particular mA value on the ER3000, which equates to a predetermined downstream pressure, maintained by the regulator PID controller. This pressure equates to a desired mass flow rate, depending on the orifice installed in the system. The x-axis separation of these points is indicative of the variation of equivalent flow rate of air as the temperature rises or falls. For a given ejector muscle pressure, secondary air temperature, \textit{i.e.} the temperature of air routed through the engine and entrained by the ejectors, affects only the relationship between regulator set-point and mass flow rate. The ‘gap’ in the data between the 0.045 and 0.05 \textit{lbm/s} conditions is due to a missing dataset rather than any anomalous behavior.

![Figure 4.6: Eductor Pressure vs Air Mass Flow Rate at Varied Air Temperatures for $P_{mot} = 83, 100$psig.](image)

These heated air flow tests validated consistent ejector performance compared to that of the cold flow set-points. The temperature of the air appeared to have no effect on the flow entrainment and resulting pressure of the eductor. This is likely due to the orifice that defines constant mass flow rate being downstream of the heater, and regulating the ‘absolute’ flow rate of heated air, rather than the flow of the cold
air. In short, secondary air temperature appears to have no effect on the ejector vacuum capacity for a given flow rate, for the range of temperatures tested.

### 4.4 Chamber Pressure vs. Eductor Pressure

Because one of the desired test parameters for the eductor design is low pressure ignition of an SFRJ fuel grain, it was also useful to look at the pressure data within the combustion chamber. These data were then compared to the eductor pressure to find any correlations present that might be used to interpret the data. Since there is a nozzle between the two, there is a chance for choking of the flow once back pressure is reduced to a threshold value, impacting the starting pressure surrounding the fuel grain.

As shown in Figure 4.7, there is divergence between the eductor and head end combustor mean pressures. The desired outcome would be a chamber pressure indicative of the mass flow being forced through it, as well as the pressure drop to recover to the high altitude atmospheric condition. What appears to be the case is that there is a reduction of pressure due to the ejector vacuum draw, and this is less effective as mass flow is increased, hence the divergence of pressures. The condition will eventually reach a threshold where the motor nozzle becomes choked due to the pressure differential between chamber pressure and eductor pressure, and further reduction of the latter set-point will have no affect. Also of note, the chamber pressure appears to be a function of air temperature, while the eductor pressure is not, for these temperatures. This could potentially be due to the heat soaking of the eductor, cooler gas in the eductor due to nozzle expansion which limits the heating effects, or another factor as yet unidentified.
Figure 4.7: Mean Eductor and Head End Pressures for Varying Temperatures and Ejector Set-Points.

4.5 Ejector Flow Mixing Final Temperature

A final selection of data to analyze is that of the initial and final temperatures of gases entering and exiting the ejectors, and whether or not this will dramatically impact future design of high-temperature ejectors for the experiment. Shown in Figure 4.8 are the associated system temperatures of the eductor as well as the inlet
and outlet streams of the ejectors. These system temperatures are displayed from the point that air flow is switch from exhaust to engine throughput, by means of the 3-way valve, to the moment where the air flow is switched back from engine to exhaust. This captures all of the time during which the ejectors and eductor are exposed to heated air.

**Figure 4.8:** Eductor and Ejector System Temperatures at Varying Temperatures Relative to Time (Beginning from Ejector Valve Actuation).
For reference, the eductor aft, motive, inlet, and exhaust thermocouples are all K-type, and the eductor front and middle thermocouple are C-type. It is observed that the temperature of the eductor decreases from back to front. This is likely because the exit cone of the hot air impinges more directly towards the back of the eductor, which improves heat transfer greatly. In addition, the extraction of air by the ejectors could result in a cooler recirculation zone, adjacent to the nozzle exit, which is less affected by convective heat transfer. The system temperatures never reached steady state over the course of the displayed 15 second tests, which could signify substantial heat absorption by the eductor body.

It is interesting to note that the ejector exhaust temperatures, $T_{ex}$, were largely similar for a given flow rate between the two heated air set-points. These exhaust temperatures are very similar to that of the motive gas, which could infer that the larger mass flow of motive gas tends to affect temperature more than that of the ejector secondary inlet flow. Unexpected is the low temperature of the ejector inlet, $T_{sec}$, i.e. the temperature of the air moving from the eductor, through the ejector port, into the ejector inlet. The secondary flow temperature reaches sub-zero temperatures in Fahrenheit, despite the high temperature air flow into the eductor. This implies rapid cooling of exhaust gas once it has expanded into the eductor, and further cooling once sucked into the ejector lines. This is corroborated by the observation of condensation and even ice buildup on the ejectors themselves and their connected hardware. It is theorized that multiple effects are the cause of this phenomena, specifically the cooling properties of the motive gas, given by $T_{mot}$, the expansion of air as it enters the eductor and ejector ports, and the thermal soaking of the eductor, drawing heat away from the air as it passes through the system. Due to the decreased temperatures occurring in the ejector secondary inlet ports, the thermal soaking and expansion cooling seem most likely, but all three are possible culprits.
4.6 Analysis

In order to fully comprehend the abundance of data available from testing, it was necessary to analyze a few specific relationships to interpret the results. One of the more important relationships to look at was that of the SFRJ combustion chamber nozzle, i.e. that which separates the mixing chamber and the eductor. It is important that the flow through this nozzle remains unchoked for as long as possible, such that the starting chamber pressure for the fuel grain can be lowered as well as the back pressure, allowing for more variation in test conditions. This relationship is primarily governed by the mass flow set-point pre-test, but can be adjusted slight by the back pressure relationship until the choked flow threshold is reached. The graph of pressure ratios in Figure 4.9 shows the pressure ratio between the test chamber pressure, $P_{ch}$ and eductor pressure, $P_{ed}$. This is shown for both $p_{mot}$ set-points, and the full range of temperatures. Plotted alongside the test-specific pressure ratio is the theoretical maximum pressure ratio for a choked flow condition

$$\frac{p^*}{p_0} = \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma - 1}}.$$  \hspace{1cm} (4.3)

Assuming air with $\gamma = 1.4$, equation 4.3 becomes

$$p^* = 0.528p_0,$$  \hspace{1cm} (4.4)

or to rearrange and solve for $p_0$

$$p_0 = 1.894p^*,$$  \hspace{1cm} (4.5)

where $p^*$ refers to nozzle throat pressure, and $p_0$ refers to nozzle inlet pressure. Figure 4.9 shows the ratio between chamber pressure, denoted as $P_1$, and eductor pressure, represented as $P_2$, at two motive set-points. This will not correlate perfectly to
equation 4.3 as the eductor pressure and nozzle throat pressure are not identical, but the eductor front transducer is the closest in proximity to provide an accurate estimation. Any discrepancy between nozzle throat pressure and eductor pressure is likely due to losses along the nozzle cone and in the transition to the eductor plenum. Observed is a vaguely non-linear trend, likely fit by a 2nd order polynomial between pressure ratio and mass flow rate.

Figure 4.9: Pressure Ratio Across SFRJ Nozzle at $P_{mot} = 83psig, 100psig$ and Varied Temperature and Flow Rate Set Points.

There also appears to be a slight change in the slope of the lower motive pressure data which occurs around the aforementioned pressure ratio of 1.894, which would indicate a transition region from a pressure differential and mass flow dependent flow to a mass flow-only dependent condition. Air temperature also appears to affect the shape of the curve and the location of this transition region. More data are required to postulate on this further.

Figure 4.10 shows the pressure differential, as opposed to the ratio, between eductor and chamber pressure. Both datasets, at different motive set-points, appear to be linear, with the slope relatively similar and the intercepts shifting with motive set-point. This would indicate a linear relationship between eductor pressure and air...
flow rate. Based on previous analysis, both chamber pressure and eductor pressure are linear with mass flow of air, so the difference between the two is also linear.

![Figure 4.10: Pressure Differential Across Nozzle for Heated Flow Tests at $P_{\text{mot}} = 83\text{psig, 100psig.}$](image)

With the preceding graphs of pressure ratio and differential in mind, a comparison could be made between these tested values and the theoretical nozzle relationship values. Figures 4.11 and 4.12 show a comparison between the pressure of the eductor during a heated flow test vs what the theoretical pressure at the nozzle throat should be according to equation 4.3. These two parameters, nozzle throat and eductor pressure are assumed to be similar for the sake of comparison, but in reality there are nozzle exit losses which result in some variation between the two. The plot for 83 psig of motive pressure shows the eductor values lie above the choked flow condition at low flow rates, and gradually overtake them at around 0.03 lbm/s, eventually diverging as flow rate increases. This is shifted to the left in the ensuing plot of the 100 psig condition, where the pressure matches up at the low flow condition and proceeds to diverge from there. Values above the threshold indicated by the filled-in shapes are potentially unchoked at that flow condition. This is because the ratio between chamber pressure and eductor pressure is higher than 1.894. Below this threshold,
it is theorized that the flow condition becomes choked, and further decrease in back pressure will not affect chamber pressure as dramatically, if at all. This is reminiscent of the earlier conclusion from the pressure ratio graph in Figure 4.9, where there may be a slight shift in the data fit right at this choking condition.

**Figure 4.11**: Theoretical $P_2$ from Nozzle Theory vs Test Pressures at Varying Flow Rates and Air Temperatures at $P_{mot} = 83$.

**Figure 4.12**: Theoretical $P_2$ from Nozzle Theory vs Test Pressures at Varying Flow Rates and Air Temperatures at $P_{mot} = 100$. 
The final point of analysis to characterize system performance and thresholds was that of ejector entrainment ratio, or $\omega$. This is defined as

$$\omega = \frac{\dot{m}_{sec}}{\dot{m}_{mot}}.$$  

(4.6)

where $\dot{m}_{sec}$ refers to the secondary flow rate through the ejector inlet, which is assumed to be one fourth of the air flow through the combustor, when vacuum is achieved. $\dot{m}_{mot}$ refers to the mass flow of the motive gas, which is taken from the manufacturer tables. Entrainment ratio is essentially a measure of ejector efficiency, as it compares the mass flow rate of the motive gas to the flow rate of gas through the secondary inlet, or 'entrained' flow. Figure 4.13 shows the effects of increasing air flow rate, temperature, and motive pressure on ejector efficiency. As is clear from the plot, entrainment ratio appears unaffected by changes in air flow temperature for the set-points tested here. This is likely due to the previously-discussed normalization which occurs at the sonic orifice. The measured flow in the system is the absolute flow rate of heated air, rather than of air at STP.

![Figure 4.13: Entrainment Ratio vs Mass Flow Rate of Heated Air at Different Set Points.](image-url)
Figure 4.14 shows the same y-axis as the previous Figure but plotted against eductor pressure. This illuminates a slight difference between pressure and mass flow relationships. An increase in motive pressure for the same mass flow rate of air will lower the entrainment ratio and increase the level of vacuum achieved by the ejector. In other words, more vacuum draw by the ejectors will ultimately result in poor efficiency, as it requires more motive gas flow rate to draw out less secondary flow at such vacuum conditions. This means that higher altitude conditions must be incorporated into the design of an ejector to ensure that the system can provide the necessary motive flow rate to run at very low entrainment efficiency.

![Figure 4.14: Entrainment Ratio vs Eductor Pressure at Different Set Points.](image)

The manufacturer datasheet in Appendix A shows data for entrainment ratio as a function of both motive pressure and level of vacuum of the secondary flow rate. This was taken and fit to a polynomial curve to acquire a theoretical flow condition for each datapoint. This comparison is shown in Figure 4.16. Note that all flow rates are compared as absolute values of Standard Cubic Feet per Minute (SCFM), corresponding to the equation
\[ \dot{m}_{SCFM} = \frac{\dot{m}_{air}}{\rho_{air, stp}}, \]  

(4.7)

where \( \dot{m}_a \) is the flow rate of air through the combustor and \( \rho_{air, stp} \) is the density of air at standard temperature and pressure. This shows a reduction in entrainment ratio of nearly 50 percent of the theoretical maximum for all flow conditions. This is best illustrated by the following comparison in equation 4.8 using an efficiency term, \( \epsilon \), rather than entrainment ratio. Ejector entrainment efficiency is defined here as

\[ \epsilon = \frac{\omega_{actual}}{\omega_{advertised}}, \]  

(4.8)

where \( \omega_{actual} \) is the entrainment ratio from the test results and \( \omega_{advertised} \) is taken from the manufacturer data. Figure 4.15 illustrates this relationship more clearly, plotting the efficiency term relative to mass flow rate for all heated air conditions. Ejector efficiency is improved at a higher motive pressure, and varies between 0.43 and 0.55, meaning about an average 50 percent decrease in efficiency overall.

![Figure 4.15: Graph of Ejector Efficiency, \( \epsilon \) vs Heated Air Mass Flow Rate for \( p_{mot} = 83, 100 \) psig.](image)

Figure 4.15: Graph of Ejector Efficiency, \( \epsilon \) vs Heated Air Mass Flow Rate for \( p_{mot} = 83, 100 \) psig.
The culprits for this efficiency reduction could likely be related to temperature, or perhaps conversion errors or misinterpretations about the applicability of the ejector performance datasheet, as well as limitations on the flow entrainment properties. These properties include the relative viscosities and densities of the gases, as well as the ability of the ejector secondary flow ports to accommodate the mass flow required. On this last point, a simple modification could be done to enlarge these ports and observe the resulting effects.

Figure 4.16: Ejector Entrainment Ratio Compared with Theoretical Performance for 100 psig Motive Pressure.

The next plot, Figure 4.17 shows the same test condition as 4.16 except using Actual Cubic Feet per Minute (ACFM) instead of SCFM, based on equation 4.9 as follows

$$\dot{m}_{ACFM} = \dot{m}_{SCFM} \frac{T_0}{T} \frac{P}{P_0},$$

(4.9)

where $T_0$ and $p_0$ are standard reference temperature and pressure respectively, $T$ is the actual temperature of the air, and $P$ is the actual pressure of the air. This indicates a more substantial, temperature-related difference between the various test points. The adjusted values also demonstrate the cold flow data to be more in line with the
theoretical manufacturer values. From there, the entrainment ratio is significantly reduced with increased temperature. This raises the question of whether the manufacturer actually specified flow rate in $ACFM$ or invalid assumptions were made when converting with reference pressure and temperature for their test data.

![Graph](image)

**Figure 4.17:** Ejector Entrainment Ratio Compared with Theoretical Performance for 100 psig Motive Pressure ($ACFM$).

It was theorized that the major contributing factors to the reduced experimental ejector entrainment ratio, $\omega$, shown in 4.17 were primarily tied to temperature, which affects the viscous interaction between entrained gases. Correction factors were produced to change the calculated values of secondary flow rate to account for dynamic viscosity, $\mu_{sec}$, and density, $\rho_{sec}$. These were normalized relative to the cold flow conditions. This led to the plot of adjusted values in Figure 4.18.

These show much better agreement with the theoretical values, and indicate that the manufacturer performance data, while provided in $SCFM$, are not inherently valid for air at different conditions. The data discrepancy is possibly due to the viscous and sheer forces between an entrained and motive gas, which is critically dependent on the temperatures of both gases. This is consistent with the information garnered from ejector manufacturers, who will often stipulate that flow values are
only accurate for a particular range of operation. As a result, temperature correction factors must be established which can guide the choice of equipment or factor into customized hardware. It is also possible that, if the ejector performance is sensitive to the properties of the entrained gas, particulates and other impurities from combustion could play a role in reducing efficiency further. For most flow conditions, it appears that a motive flow rate of five times the intended entrainment flow rate will reach the required conditions. This threshold, coupled with temperature correction, will guide the future work on the experiment and allow for effective hardware updates.

**Figure 4.18:** Ejector Entrainment Ratio as a Function of Eductor Pressure Corrected with $\mu_{sec}$ and $\rho_{sec}$. 
Chapter 5. Conclusion and Future Work

A modular test rig was designed to meet experiment requirements of the UAH connected-pipe facility and typical SFRJ fuel characterization studies. Factors were taken into account such as materials compatibility, size, cost, and performance which could affect major design refinement. Critical performance requirements included $0.062 \text{ lbm/s}$ of 800 °F throughput air while maintaining 8 psia back pressure at the nozzle exit plane. This hardware was validated through eductor relationship calculations, comparison with literature and industry, as well as flow simulations before fabrication.

The high altitude simulation apparatus (HASA) consists of an eductor plenum, four radially-connected ejector elements connected to a nitrogen manifold, blow-off door, linear rail mounting system, and pressure and temperature instrumentation. This assembly was put through ejector-only, cold flow, and heated flow tests to determine its operating limits.

Test results illuminate a peak vacuum-capable flow rate of about $0.05 \text{ lbm/s}$ at peak ejector flow rate. Without through-put air flow, minimum vacuum pressures are about $1.8 \text{ psia}$ at maximum ejector motive pressure. It was noted that the ejector performance did not match up as expected to the manufacturer specifications, with efficiency of the ejectors calculated to be between 43 and 55 percent of the advertised expected values. This large loss in performance led to detailed analysis of the ejector entrainment ratio and possible explanations for the discrepancy. Correction factors were established which postulated the discrepancy was a function of air temperature in the secondary flow ports, which affected the ability of the motive gas to entrain the
secondary flow. By association, this directly affects gas viscosity and density, which were the subject of the correction. It was also observed that the entrainment ratio calculated from actual flow rate rather than standardized flow rate matched more readily with the manufacturer data. It is plausible, when also compared to industry standards, that there must be established a temperature correction factor for an ejector system, as the published values are only considered valid at STP conditions.

Eductor temperatures were observed to be far below test set-point values, with ejector secondary flow temperatures reaching sub-zero Fahrenheit temperatures. Eductor thermocouples exposed to the 600 °F flow only experienced 200 °F conditions, indicating major heat loss in the system. It is theorized that gas expansion, heat transfer to the eductor plenum, and cooling from the motive gas all contribute to these reduced temperatures, even at a 600 °F condition. More work is needed to determine if these conclusions will hold at anticipated exhaust temperatures of the SFRJ fuel, or if the additional heat will overcome the mitigating factors at play.

Recommended future work would involve further characterization of ejector performance during a nominal SFRJ hot-fire test. This would involve conducting checkout tests using the igniter during active air flow and ejector operation to study the effects of the additional mass flow on the eductor plenum pressure. This would also afford more reference data for ejector performance at increased temperatures and with additional particulate matter and impurities in the entrained flow. This could be analyzed for its effects on entrainment ratio and overall efficiency. After this, a formal test of an SFRJ fuel grain could be performed with ejectors activated during the entire sequence. This would provide data on the anticipated exhaust temperatures of the mixed gas exhausted by the ejector and illuminate the need or lack thereof for ejectors manufactured from metal with a higher temperature resistance. A modification to the ejector secondary flow ports to accommodate higher flow rates would also give clarity on the operating limits of the eductor system and if any choking or tube losses caused
reduced entrainment also. Finally, designing new, higher capacity ejectors would be necessary to meet and exceed the flow rate expectations outlined in the project requirements.
References


Appendix A. Ejector Specifications
### Performance Data for iS Series Pumps

**S** is for “Hi” vacuum levels up to 26”Hg (948mbar) for applications involving non-porous materials (metal, plastic, glass, etc.)

#### Model # | Air Consumption 5CFM | Imperial - Vacuum Flow (L/min) vs. Vacuum Level (Hg) | Metric - Vacuum Flow (L/min) vs. Vacuum Level (mbar)
| --- | --- | --- | ---
| JS-200 | 7.80 | 5.40 4.70 3.85 3.35 3.00 2.60 2.10 1.60 1.20 0.60 | 70.00 65.00 59.50 54.00 45.30 34.00 21.00 10.00 4.00 0.00
| JS-250 | 12.50 | 9.00 8.50 7.85 7.00 6.50 5.30 3.90 2.50 1.80 0.90 | 125.00 115.00 105.00 95.00 85.00 65.00 45.00 30.00 15.00 7.50
| JS-300 | 22.00 | 17.00 14.00 12.70 12.00 10.00 7.40 4.90 2.70 1.30 0.00 | 220.00 205.00 195.00 185.00 175.00 155.00 125.00 95.00 65.00 35.00
| JS-350 | 28.00 | 22.00 18.70 15.50 14.50 11.80 8.10 5.70 4.50 2.25 0.00 | 280.00 258.00 235.00 215.00 185.00 155.00 125.00 95.00 65.00 35.00

#### Model # | Evacuation Time in Seconds based on 1 Cubic Foot Volume
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>JS-200</td>
<td>0.00 1.20 2.10 3.40 5.20 7.70 11.10 20.00 33.50 62.60 98.10</td>
</tr>
<tr>
<td>JS-250</td>
<td>0.00 0.75 1.30 2.70 3.50 5.60 9.10 17.40 30.10 56.00 76.00</td>
</tr>
<tr>
<td>JS-300</td>
<td>0.00 0.00 0.80 1.20 2.00 2.80 3.90 5.90 11.10 32.70 50.00</td>
</tr>
<tr>
<td>JS-350</td>
<td>0.00 0.00 0.00 1.20 1.90 2.30 3.40 5.30 8.80 26.00 44.00</td>
</tr>
</tbody>
</table>

**Note 1:** Standard operating pressure for Vaccon pumps is 80 PSI (5.5 bar). Pumps can be factory modified to run at other operating pressures i.e. 60 PSI (4 bar) etc.

**Note 2:** Evacuation speed is linear with volume; a two cu. ft. volume will take twice as long to evacuate as a one cu. ft. volume.

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**Figure A.1:** Vaccon Datasheet for JS-350 Model Ejectors
Figure A.2: Test Range and Accuracy for Emerson Coriolis Flow Meter
Figure A.3: Parts and Identification (P&ID) Guide for the Outlined Eductor Module
Figure A.4: UAH Heated Air Supply Facility P&ID Diagram