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Micro-Turbine Altitude Simulator
100% Report

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This B.S. thesis is written in partial fulfillment of the requirements in EML 4905. The contents represent the opinion of the authors and not the Department of Mechanical and Materials Engineering.

Ethics Statement and Signatures

The work submitted in this B.S. thesis is solely prepared by a team consisting of Cesar Astudillo, Valeria Proaño, and Joseph Ruocco and it is original. Excerpts from others' work have been clearly identified, their work acknowledged within the text and listed in the list of references. All of the engineering drawings, computer programs, formulations, design work, prototype development and testing reported in this document are also original and prepared by the same team of students.

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List of Acronyms

Table 1 Acronyms

Acronym	***Description***
MC	Micro Turbine
CFD	Computational Fluid Dynamics
CB	Center Body
CINAS	Convergent Inlet Nozzle Altitude Simulator
MAIDROC	Multidisciplinary Analysis, Inverse Design, Robust Optimization and Control Laboratory

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Abstract

The design and construction of a system composed of a converging inlet nozzle, a variable iris aperture and a plenum chamber will aim to simulate different altitudes for performance studies of a micro-turbine on the current test bench at Florida International University. This study does not only aim for researching the emissions field, but also as an educational tool available for students interested in the turbo machinery industry. The design procedures are mainly analytical and computational-numerical; the analytical expressions in both procedures are made much more complicated by the presence of the iris mechanism, but the computational process is a great tool for the studies. The study of the behavior of a micro-turbine at different altitudes is a critical aspect of research to fully understand the effects and impact noxious gases have in our atmosphere. Developing a facility in Florida International University where extended research in bio-fuels can be performed on a micro-turbine can be the step stone for growth and innovation of the University in emission solutions.

1. Introduction

1.1 Problem Statement

Emission gases are a critical concern in the global energy crisis. The challenge of introducing green solutions to industrial applications is currently being targeted all around the world. Countries from the European Commission propose a target called Europe 2020. One of the statements in the proposed plan for the year 2020 mentions the three following goals: to reduce greenhouse gas emissions by 20% compared to 1990 levels, to increase the share of renewable in final energy consumption to 20%, and move towards a 20% increase in energy efficiency, and to increase to 30% the emissions reduction if the conditions are right [7].

Bio-fuels are very promising source of environmental friendly energy solutions. Advancement in energy technologies is only possible through the vast amount of research performed by scientists and engineers in order to achieve more efficient and affordable solutions that approach the hazardous emissions. Extended research and testing are important key components in the process of mechanical development of such technologies.

The Department of Mechanical and Materials Engineering at Florida International University currently owns a test bench for a MCT that is partially used for educational experiments. This test bench has a colossal potential for extended research in bio-fuels, as well as an educational tool. Atmospheric changes play an important role in the study of performance of MCT. For research studies at the University, an affordable and user friendly device for the MCT test bench needs to be designed and developed to address the

pressure changes found at different altitudes. Also, a manual and development of user friendly procedures can help future students and researchers to use this tool.

1.2 Motivation

Research and testing are important key components in the process of mechanical development of more efficient and affordable solutions that approach hazardous emissions in the world. Emission gases are a critical concern in global energy crisis. The challenge of introducing green solutions to industrial applications is currently being targeted all around the world.

MCT's are being introduced to bio-fuels, not only for ground turbo machinery, but also as small scale testing for large turbine engines for airplanes.

This altitude simulator test bench will not only aim to be a stepping stone for growth and innovation of the University in emission solutions, but also as an educational tool available for students interested in the turbo machinery industry. The testing console at Florida International University will enable the students to understand the behavior of turbo machinery in real life applications.

1.3 Literature Survey

1.3.1 Performance Characteristics of Turbines

Turbines are designed to transform energy from a flowing fluid into useful mechanical work. For gas-turbine engines the process of converting energy is governed

by the Brayton cycle. Most gas turbines operate on an open cycle meaning that ambient air conditions are directed into the compressor where the air properties are changed. The air is compressed therefore; its temperature is going to rise before it enters the combustion chamber. The high pressure air then combined with fuel at a constant pressure resulting in high temperature gases impacting the turbine wheel which is the part of the engine that captures the moment of the gases and transfers that energy to a shaft connected to the compressor. In order to maintain a constant mass flow rate the compressor has to maintain uniform continuous air flow regardless of air properties. For example, if the engine goes up in altitude the air properties are going to change and the engine will have to compensate for these changes. The gas turbine engine's compressor will have to rotate faster meaning more air going into the combustion chamber and more energy transfer to the turbine to compensate for the loss of air properties due to the change of atmospheric conditions [13]. To determine if the engine is producing efficient thrust efficiency is measured in various sections.

Efficiency is an important characteristic within turbo machinery. Mechanical energy losses occur between the turbine rotor and the output shaft as a result of the work done against friction at the bearings and other components. These losses translate into less power and less thrust therefore the efficiency of the engine is going to be affected. To be more precise, in jet engine theory overall propulsive efficiency refers to the ratio between cycle efficiency and propulsive efficiency and air characteristics have a direct effect on this calculation. Another important efficiency concerning jet engines is the compressor efficiency [14]. An axial compressor generates a flow and pressure increase

down the engine. It achieves this through the flow of air over successive rows of rotor blades and stator vanes. Both the blades and the vanes are similar to aircraft wing airfoils. If the flow separates over the airfoils badly the airfoil can be said to stall. Once stalled, the airfoil loses the ability to pump gas down the engine. There is then nothing to prevent the high pressure gas at the rear of the engine from flowing forwards to the lower pressure stages. This reverse flow is called a surge.

Factors affecting thrust

Thrust force depends on the inlet and outlet mass flow rates, fuel to air ratio. The inlet air mass flow rate influencing both the momentum thrust and momentum drag is dependent on several variables, including the flight speed, ambient temperature and pressure, humidity, altitude and rotational speed of the compressor. The pressure thrust term depends on the turbine inlet temperature, flight altitude and the nozzle outlet area and pressure. The momentum thrust is also dependent on the jet nozzle velocity [15].

The main concern is mass air flow: it depends on the air temperature and pressure as both together determines the density of the air entering the engine. Rise of temperature will decrease density and vice versa. Increase pressure density increases. In brief, the density affects the inlet air mass flow and it directly affects thrust. So, a 10,000 lb thrust engine might only generate 8000 lb of thrust in a hot day and in a cold day 12,000 of thrust. With change in altitude the ambient temperature and pressure vary with height above the sea level. It depends to some extent on the season and latitude. Refer to (ISA). It provides average values at middling latitudes. Temp decreases by about by about 3.2 K

per 500 m of altitude up to nearly 11,000 m (36089 ft). It can be concluded that the effect of altitude on thrust is really a function of density [15].

1.3.2 Computational Fluid Dynamics

It is the process of numerically solving problems related to fluid equations to calculate resultant flow fields on a variety of flow phenomena. It helps to predict the behavior of different conditions such as air velocities, pressures and temperatures[16].

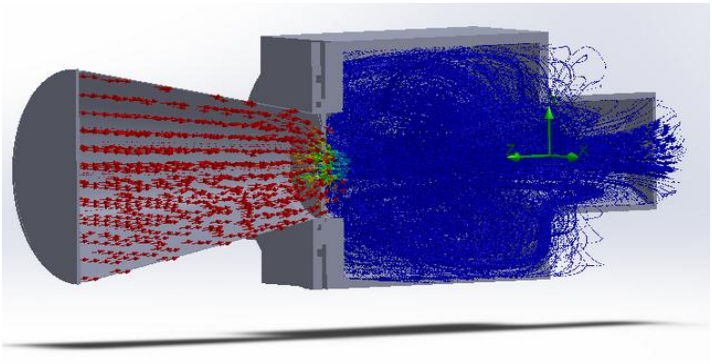

Figure 1 CFD sample

The following steps are the guidelines when establishing a CFD problem.

1. Formulate the Flow Problem
2. Model the Geometry and Flow Domain
3. Establish the Boundary and Initial Conditions
4. Generate the Grid
5. Establish the Simulation Strategy
6. Establish the Input Parameters and Files

7. Perform the Simulation
8. Monitor the Simulation for Completion
9. Post-process the Simulation to get the Results
10. Make Comparisons of the Results
11. Repeat the Process to Examine Sensitivities

Computational Fluid Design analysis does not replace the measurements completely but it is an indispensable tool in modern design and engineering and the amount of experimentation and the overall cost can be significantly reduced [16]. The results of a CFD simulation are never 100% reliable because the input data may involve too much guessing or imprecision.

1.3.3 Altitude Simulation

Altitude simulators are systems that allow the replication of the behavior of several air conditions done in a stationary test console. The idea of altitude simulation comes from the necessity of testing components as if they were on a completely different scenario than ground sea level or even normal flight conditions in a testing facility. It is for this reason, that many companies around the globe have used their scientific knowledge to develop testing consoles capable of modifying air conditions on an environment.

This idea has a wide range of applications for humans in different fields. One of the industries that constantly deals with altitude changes are the aerospace and propulsion industries. Here, engineers have to design aircrafts to serve different purposes, such as

military or commercial jets, but cannot afford the cost of building an aircraft to test real life flight conditions. This procedure not only would be less cost effective, but also it carries an enormous risk on the test pilot and crew. This is where altitude simulators play an essential role in technological development and well usage of resources. Aerospace and propulsion companies are widely known for using components like compressors, diffusers and nozzles to change the properties of air or a specific gas to achieve the desired conditions. Arnold Engineering Development Center operates eight active test cells models C-1 and C-2 for atmospheric inlet and altitude testing. Each of these cells can provide inlet temperatures up to 350°F and are capable of performing test on engines producing up to 100,000 lb of thrust. [1]

Other industries that benefit from the output provided by these systems are fluid mechanics and gas dynamics-based systems regarding vacuum technology. The system requires components such as a vacuum chamber where air or other gases are extracted to create low pressure conditions. A pump is required to suck the gas from the chamber and create the vacuum effect; this can be achieved by the usage of different type of pumps such as single or two stage rotary vanes [8].

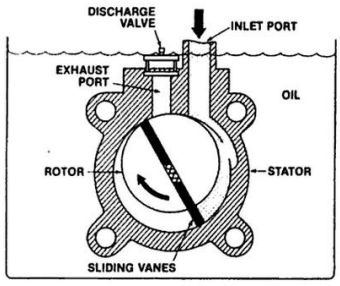

Figure 2 Sliding Vane Pump [11]

Nonetheless, not all applications involve testing of components, altitude simulators come in all geometries and sizes and are also used in human beings interest in performing activities such as cycling, running, track and field, triathlon, boxing, MMA, soccer, swimming, and specially mountaineering. Humans can wear a mask with an inhaling tube that creates the same oxygen composition as if you were climbing a mountain. This method uses the exhaled air and removes the carbon dioxide, leaving a remainder of low oxygen air. By mixing this with fresh air, a condition of low pressure air can be created.

1.3.4 Converging Nozzle

According to P. Balachandra, "a nozzle is a device employed in flow passage to gain velocity increase at the expense of pressure, that is the flow in the nozzle must be such that as it proceeds the velocity of flow has to increase and simultaneously the pressure has to decrease" [6]. A converging nozzle is a device that accelerates a flow with a favorable pressure gradient keeping wall boundary layers thin and minimizing the effects of friction.

Error! Reference source not found. presents the variation of ratios of static to total conditions through choked nozzle. Pressure (p), density (ρ), and temperature (T) ratios, decrease with the increase of the position ration through the length of the nozzle.

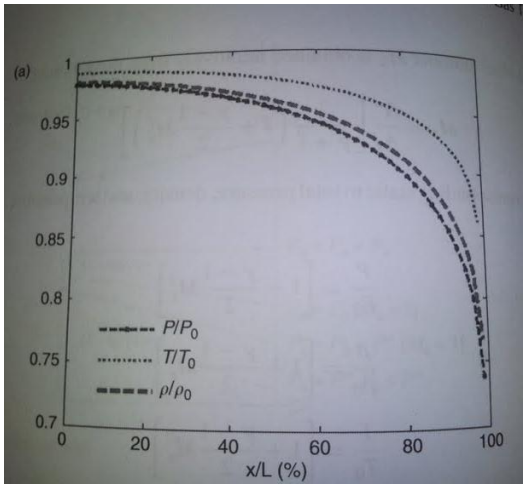

Figure 3 Behavior of Atmospheric Properties in a convert nozzle [9]

In **Error! Reference source not found.**, the relation between the exit and back pressure along the distance of the nozzle is presented [2]. There is a point where the flow in the nozzle reaches a critical pressure, which is when the maximum exit Mach number reaches one, shown in Regime I (IV). At this point a condition called “chocked flow” appears in the system and mass flow rate can no longer be increased. For ideal air conditions, this critical pressure ratio is 0.528 [3].

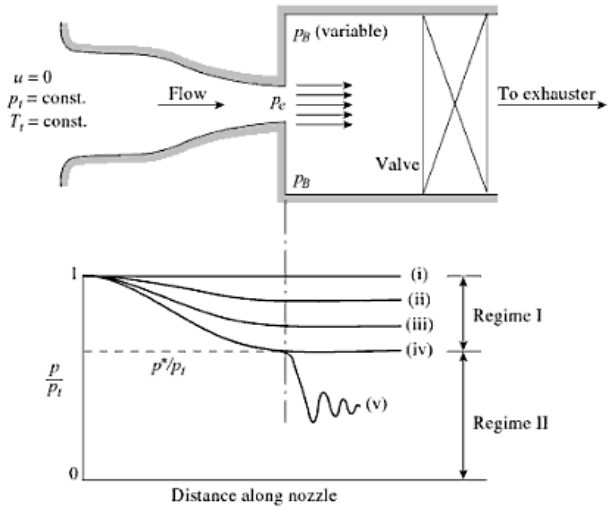

Figure 4 Converging Nozzle operating at various back pressures [10]

Isentropic flow is a good approximation for converging nozzles; therefore it will be used in our study. In order to have flow across a nozzle, pressure difference must be present. Properties of the gas change, as it flows through the nozzle. As back pressure is decreased, mass flow rate is increased.

1.3. 5 Center Body

The purpose of the CB is to provide a smooth contour to entrain atmospheric air into the inlet of the MCT, while minimizing total pressure and losses of mass flow. When designing the CB, the air flow path is used to provide guidance for the structural body shape. Even though in the proposed design incoming sonic flow is not encountered, certain basic concepts are overviewed from the CB design used for ramjet inlets [4].

Figure 5 Inlet Ramjet CB [4]

For a specific pressure gradient, the maximum airflow area is determined by the ratio between the positions of the CB relative to the duct length. During the design process, there would be a maximum and a minimum setting for the CB to operate inside the nozzle; these scenarios could be encountered in the following schemes. First, when the ratio between the positions of the CB relative to the duct length is 0.9, the result will be the mating of the inner surface of the nozzle and the outer surface of the CB resulting in possible airflow path blockage. At this position, the pressure will be at its highest. Inversely, if the ratio is 0.1, the outer surface of the CB will be the farthest apart from the inner surface of the nozzle resulting in inconsistent airflow path to the inlet of the MCT. However, the pressure will be at its minimum. These scenarios should be studied in depth during CFD analysis. The team established a maximum boundary for limitation purposes of the first scenario. Since the airflow area ratio must remain consistent at the downstream, it must remain smooth so that the entering air streamlines stay laminar and flow separation (turbulence) is kept as low as possible before the transition occurs between CINAS and the MCT.

1.3.6 Restriction Flow Meters for Internal Flows

Restriction flow devices are based on acceleration of a fluid stream through some form of a geometric aperture that in theory, the main purpose is that the change in velocity leads to a change in pressure [3]. Depending on the geometry, the restriction will give the gas different properties once the fluid enters the plenum chamber. A plenum chamber is an enclosed defined space in which plenum condition exists. The chamber retains the air's properties obtained with the geometric restrictions placed before it. In other words, the chamber acts a control volume device for the incoming air. Selecting the proper geometry for the flow meter depends in various factors ranging from cost and accuracy to how much head loss is produced by the shape of the restrictor. Some flow meters commonly used in the industry include the shape of a simple orifice a flow nozzle and venturi flow. Each of these devices changes the head loss according to its shape and the uncontrolled expansion downstream of the air can be control and reduce.

1.3. 7 Mechanical Iris

This mechanism acts as a variable valve that changes the geometry of a series of blades placed in a circular pattern that are actuated mechanically. Depending on the restriction the designer wants to achieve many geometrical shapes can be used. Some of the parameters required to construct an iris are the following: desired outside diameter, maximum and minimum aperture, number of blades and number of overlapping blades.

This mechanism is commonly used where flow regulation is critical. It permits the user to have direct control over the quantity of the substance.

2. Project Formulation

2.1 Project Objective

This design project aims to condition Florida International University micro-turbine test bench to serve not only as an educational tool for students interested in the turbo machinery industry as well as for research testing. Extended research in bio-fuels is important for the development of less harming solution understanding of the effects and impact have in our atmosphere. Designing and developing an altitude simulator for the test bench allows for growth in testing of micro-turbine performance at different altitudes. The design will incorporate three subsystems. The first sub-system consists of a converging nozzle capable of re-directing the incoming air flow and preventing vortex generation at the inlet of the system. The second sub-system consists of a mechanical iris that will serve as an airflow valve that will aim to achieve a pressure of 68kPA. The third sub-system is a plenum chamber that will enclose and maintain the pressure achieved by the mechanical iris component.

3. Design Alternatives

3.1 Design Alternative 1

This design alternative is based on the same principle of variation of area to achieve a desired pressure at the exit of the nozzle. The main difference between this design and all other alternatives is that in this scenario, the nozzle itself is not a rigid body; instead the nozzle has to be capable of expanding and contracting its cross sectional area as the desired exit pressure varies. For this design approach, the nozzle would not be a single component, but a junction of several overlapping metal sheets bended to a certain angle and paced in such a way that generates a conical shape. This conical shape has to increase and decrease its diameter by using a hand-driven mechanical system. The mechanism will be actuated by an axial mobile component that engages all metal sheets and pulls and pushes to obtain the desired exit diameter. This movement can be achieved with a fixed base that has a threaded hole, and a large threaded rod attached to the sheet mechanics. When the rod is screwed in, it would push the metal sheets resulting in a decrease of the outer diameter, the opposite will happen if the rod is unscrewed.

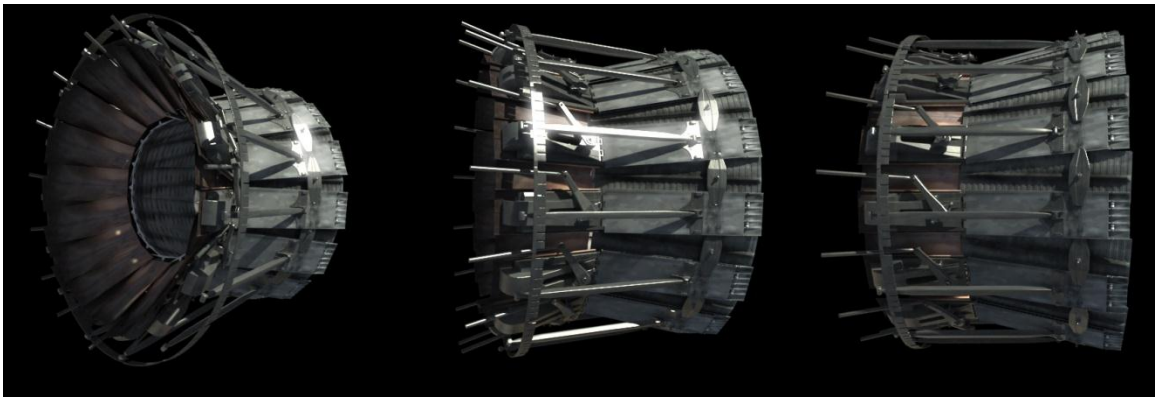

Figure 6 Variable Nozzle Conceptual Design 1 [5]

This mechanism can also be operated through the usage of an electrical control system. Rotary motors have to be used to replace the hand operation of screwing in and out the connection rod. Engaging and disengaging the rotary motor produces the desired expansion or contraction of the outer diameter of the nozzle. To operate the motor, electrical connections must be made between a control system such as an ECU and the actual motor. The control system is in charge of inputs and outputs. Inputs are specified by the user into a computer software who then sends and output signal that engages the motor to operate to specification.

3.2 Design Alternative 2

The second conceptual design consist of designing a small wind tunnel before the inlet of the MCT so that at the called test section of the wind tunnel, there will be a change in area achieved mechanically. The change in area will accelerate the air and it will lower the pressure according to the position desired to replicate atmospheric conditions at high altitudes. The inlet and outlet of the wind tunnel will contribute to

provide uniform flow of air so it remains laminar and no losses of pressure and velocity are obtained. The air exiting out of the tunnel must not be choked and it has to maintain uniformity before it enters the compressor to prevent compressor stalls and inefficiencies.

3.3 Design Alternative 3

This design approach modifies multiple nozzles so that each one will have specific characteristics to replicate changes of the incoming compressible fluid, such changes are pressure, velocity and density to be precise. Every time a change of pressure needs to be achieved interchange of customized nozzle needs to be done to obtain desired results. It is a simple conceptual design in theory but, it brings its challenges with every correction is made to each customized nozzle also, there will be inconsistency of flow work while performing the analysis because, every time that the user needs a change of pressure he/she will have to interrupt the flow of air while the turbine is running. This scenario becomes hazardous to the user and further modifications to the test bank will have to be performed in order to eliminate dangers.

3.4 Proposed Design

This design consists in producing pressure changes by accelerating the air flow and creating a restriction. The acceleration of the flow will be achieved by implementing changes in the cross sectional area through two components: a convergent nozzle and an inner body that will move along the axial axis of the nozzle through a mechanical mechanism. The nozzle itself will increase the speed of the airflow and contract in the

nozzle producing and initial drop in pressure. As the inner body is introduced into the nozzle, the passage of air will be blocked producing higher velocities and lower pressures. The air passage will be restricted until reaching the desired pressure.

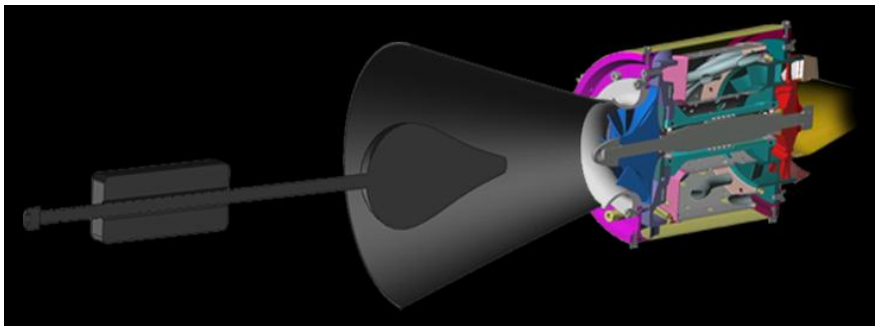

Figure 7 Converging Inlet Nozzle for Altitude Simulation Cross-Section View

3.5 Proposed Design Revised

The design of a system composed of a converging inlet nozzle, a variable iris aperture and a plenum chamber will aim to simulate different altitudes for performance studies of a micro-turbine on the current test bench at Florida International University. The first stage of the system consists of a converging inlet nozzle that will accelerate and re-direct the incoming air. In the absence of a nozzle in the system, vortex could be generated at the inlet of the system and sucked into the micro-turbine which could lead to compressor inefficiencies and overall malfunction of the turbo machinery instrument. A mechanical iris forms the second stage of the system that will provide a variable airflow entrance. Changing the area of the iris mechanism will result in the production of different pressure and different altitude simulation. This sub-systems consists of eight

triangular blades that when all together are linearly engaged, an octagonal area variation will be produced. A circular plate will serve as a base for the mechanism and will contain the linear rails for the blades to slide. One of the triangular blades will be the actuator of the mechanism and a lever will be added onto its design. The following image represents the assembled iris mechanism and all its components.

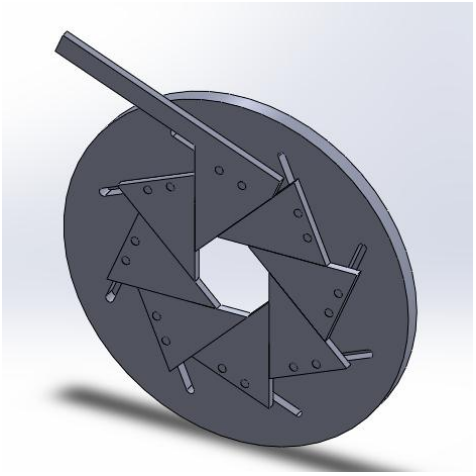

Figure 8 Mechanical Iris Design

The third component of the system consists of a plenum chamber that will serve as a pressurized housing or environment containing the low pressure air. Also, it allows the airflow to stabilize and become laminar. This component's inlet will be controlled by the mechanical iris and will exit directly to the inlet of the micro-turbine.

Through the development of a system boundary chart, the interaction of our components with the module and the important considerations are identified. Through the process of research, design and testing, more interactions or interfaces will be populated. This chart helps the design process to focus on specific considerations and identify earlier design failures that can occur.

First, the system is identified to have three components, a converging nozzle, an iris mechanism and a plenum chamber that is in our system boundary. Then, surroundings are examined; the components that will have any interaction with the system are identified: the test bench, the starter motor and the MCT. Finally the interactions and considerations with the surroundings are scrutinized. Here we find physical contact, crucial location interface and energy interaction with air.

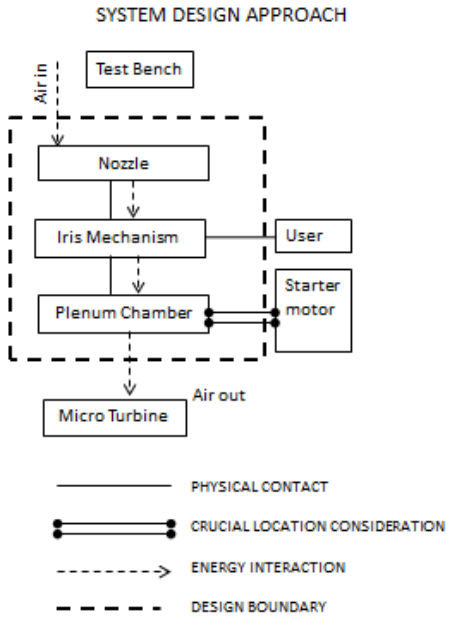

Figure 9 System Design Schematic

The following image shows a CAD assembly model of the three components and its physical interaction. Additionally, a cross sectional view is displayed to show the internal view of all components and a clear view of where the air will be flowing through.

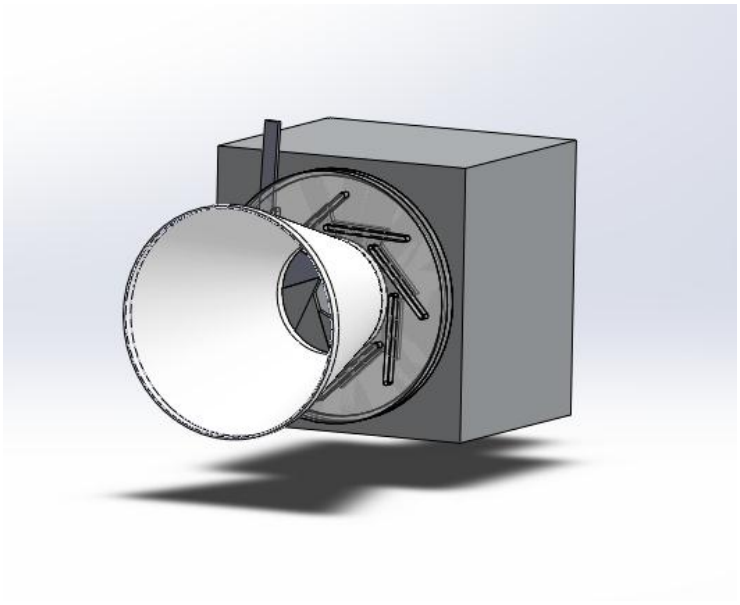

Figure 10 Proposed Design

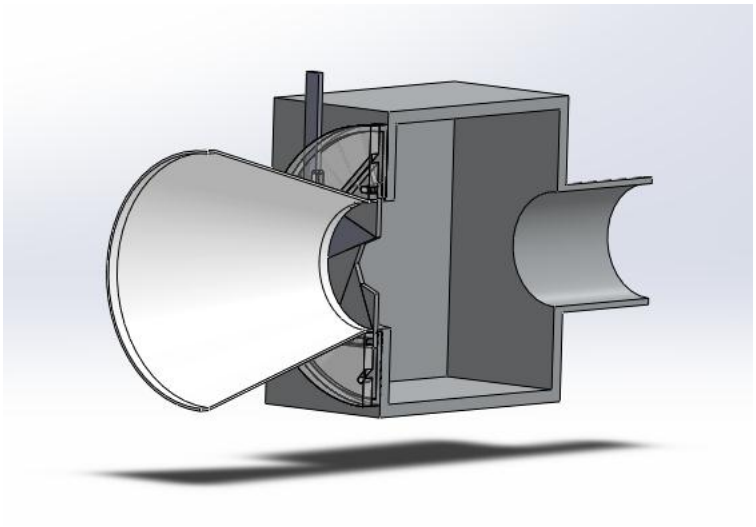

Figure 11 Cross Sectional View of Proposed Design

4. Project Management

4.1 Timeline Gantt Chart

Table 2 Gantt Chart

Date / Description	1/20/2012	2/9/2012	2/28/2012	3/19/2012	4/8/2012	4/28/2012	5/18/2012	6/7/2012	6/27/2012	7/17/2012	8/6/2012	8/26/2012	9/15/2012	10/5/2012	10/25/2012	11/14/2012	12/4/2012
Project Formulation																	
Design Alternatives																	
Project Constrains																	
Proposed Design																	
Design and Analysis																	
CAD Model																	
CFD Analysis																	
Revised design																	
Final CFD Analysis																	
Parts List/Cost Analysis																	
Prototype Construction																	
Prototype Test and Analysis																	
Final Report																	
Final Presentation																	

4.2 Breakdown of Responsibilities among Team Members

This project is distributed equally between team members. Equivalent distribution of the tasks allows for all team members to research, design and develop the proposed prototype, while providing an efficient project management. All team members are responsible to collaborate in the development of each individual task. Each team member is assigned few specific tasks to own, lead and be responsible for the completion of such,

while managing the other members support. This project management strategy serves as a reinforcement tool to develop leadership skills and soft skills among team members.

The following task distribution chart represents the description of each task, the distribution among the team members, as well as the time (hours) spent completing each task. The duration time of each task is based on an average of 15 hours a week per team member dedicated to the development of this project.

Table 3 Task Description

Task	Description	Task Distribution	Start Date	End Date	Duration (Hours)
1	Project Formulation	All	1/20/2012	2/9/2012	33
2	Design Alternatives	Joseph Ruocco	2/9/2012	3/8/2012	60
3	Project Constrains	Cesar Astudillo	1/20/2012	2/28/2012	130
4	Proposed Design	Valeria Proaño	2/28/2012	4/28/2012	130
5	Design and Analysis	All	2/28/2012	7/17/2012	300
6	CAD Model	Valeria Proaño	2/28/2012	8/6/2012	343
7	CFD Analysis	All	5/18/2012	8/26/2012	215
8	Revised Design	Joseph Ruocco	8/6/2012	9/15/2012	86
9	Final CFD Analysis	All	9/15/2012	10/5/2012	43
10	Parts List/Cost Analysis	Cesar Astudillo	6/27/2012	8/26/2012	130
11	Prototype Construction	All	8/26/2012	11/14/2012	172
12	Prototype Test and Analysis	All	9/15/2012	11/14/2012	130
13	Final Report	All	8/26/2012	12/4/2012	114
14	Final Presentation	All	1/20/2012	12/4/2012	319

5. Engineering Design and Analysis

5.1 Major Components

The major components of our design consist on a converging nozzle, an iris mechanism and a plenum chamber. The design is performed for a specific volumetric flow rate. Additionally, the system will contain a mount system, sealing joints, and a pitot tube for pressure measurements.

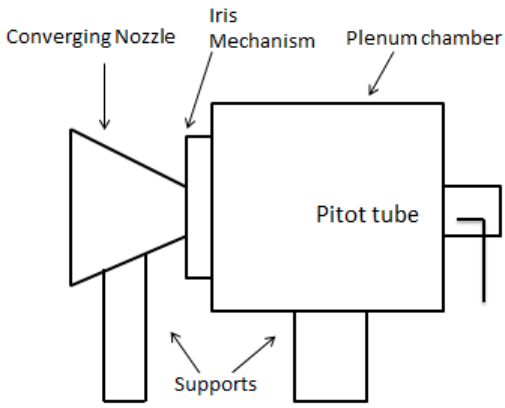

Figure 12 Prototype Schematic

5.1.1 Nozzle

The nozzle is the apparatus whose main purpose is to accelerate the air through a variation of inlet and outlet area. For this design it is also used to prevent vortices generation at the inlet of the system, by generating flow entrance to the iris chamber.

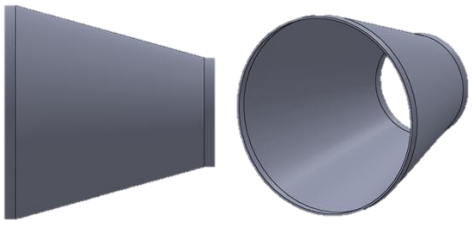

Figure 13 Propose Nozzle

5.1.2 Iris Mechanism

The Iris mechanism is a variable valve that regulates the inlet area producing a range of pressures that will simulate several flight altitudes.

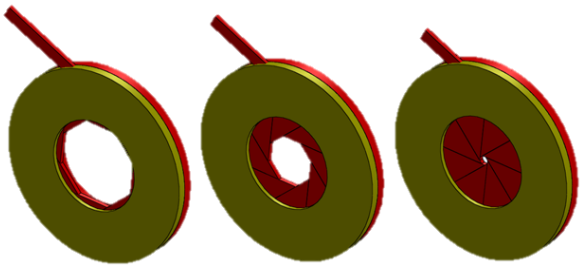

Figure 14 Proposed Iris Mechanism

5.1.3 Plenum Chamber

The plenum chamber is a pressurized housing that will contain the low pressure air that will be sucked by the micro-turbine.

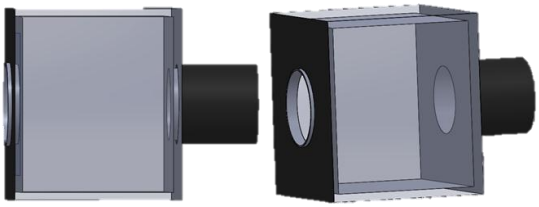

Figure 15 Proposed Plenum Chamber

5.1.4 Fastening Components

The mounting components are designed to sustain the loads produced by the mechanism and ensure its stability. A sealing joint is added to the system to fasten the exit of the plenum chamber to the inlet of the micro-turbine, and to avoid any air coming in to the system at the junction. A pitot tube is mainly for measurement of the pressure at the exit of the plenum chamber to record the pressure being simulated at the inlet of the nozzle.

The integration of these components in the micro-turbine test bench must ensure proper ergonomics and simple operation for the user.

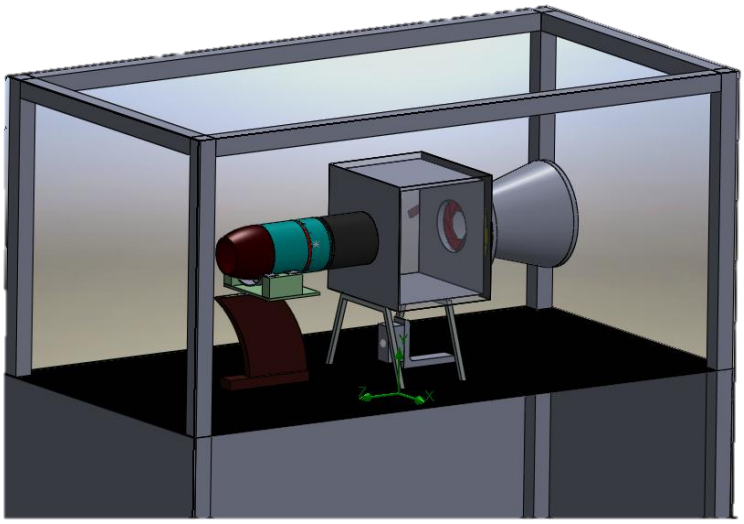

Figure 16 Proposed Design and Testing

5.2 Initial Design Flow Analysis

5.2.1 Boundary Conditions

Before studying the different characteristics of a plenum chamber, required conditions to be satisfied must be established. The plenum chamber will have both and inlet and an outlet orifice. The outlet orifice will be connected to the entrance of the MT and the inlet orifice will serve as the entrance for air to flow into the system. Since the altitude simulator will work as an add-on device for a specific MT, the volumetric flow rate is already defined. For this reason, the first boundary condition will be an outlet volumetric flow rate of 0.03 m^3/s. The air that will flow into the system will be suctioned from the surroundings presenting ambient conditions. The second boundary condition will be environmental pressure of 101325 PA at the plenum chamber inlet. Also, adiabatic and zero roughness characteristics will be used on all the internal walls of the chamber since the material selection will be performed on the following studies.

Additionally, al studies will be performed using air as the internal dynamic gas across the system and laminar and turbulent flow conditions will be taken into account in all simulations. The following image represents the physical boundary conditions on the CAD model.

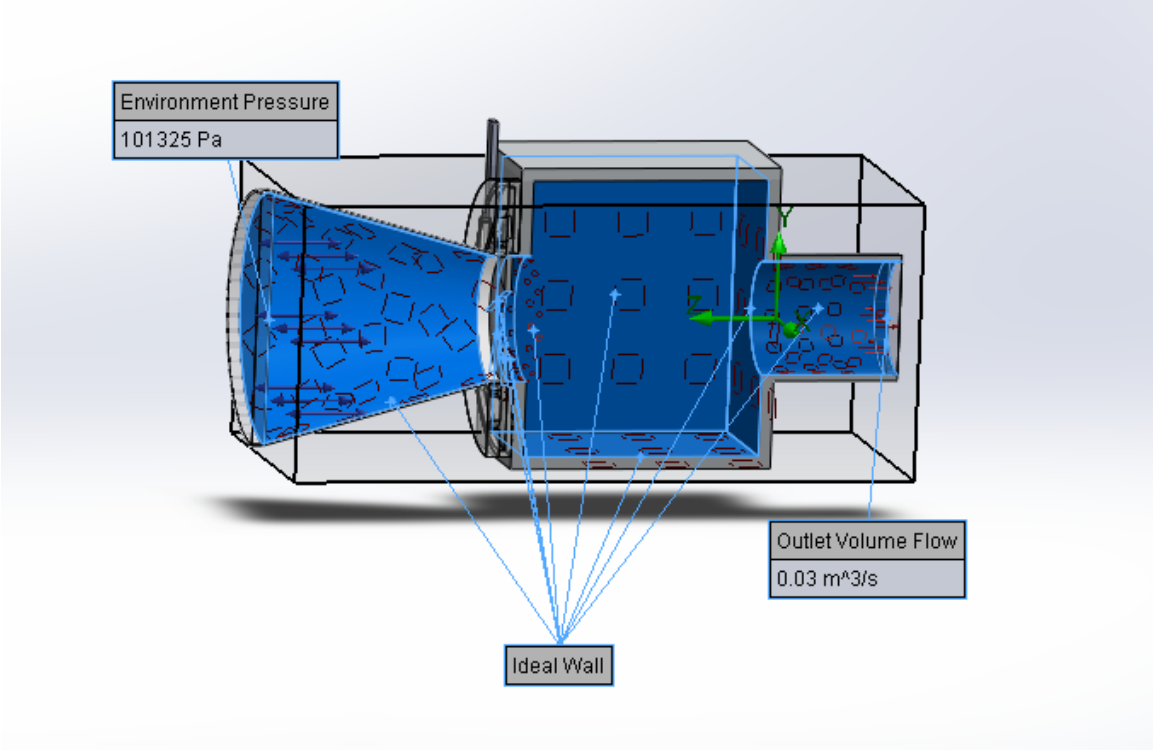

Figure 17 Plenum Chamber Boundary Conditions

5.2.2 Variable Characteristic Parameters

In order to understand and select the dimensions, holes size and additional components of a plenum chamber, studies will be perform to understand how the variation a single parameter will affect the system. The goal parameters to be studied are

the static and total pressure inside the plenum chamber. The parameters to be considered and varied are represented in the following table.

Table 4 Plenum Chamber Considered Parameters

Length	Width	Height	# of Holes	Di (inlet)	Area	Inlet Θ	Nozzle L	Nozzle D1	Nozzle D2	Do (outlet)	Tube length	Thickness

5.2.3 Analysis Air Flow across the Plenum Chamber

Study 1 Chamber with inlet of 1cm and 9cm outlet

For the first plenum chamber, initial dimensions were selected taking into consideration the available space for the add-on device on the MT test bench. A 20X20X20 box was designed with a 1cm diameter inlet and 9cm diameter Outlet. The following image represents the CFD results for this geometry.

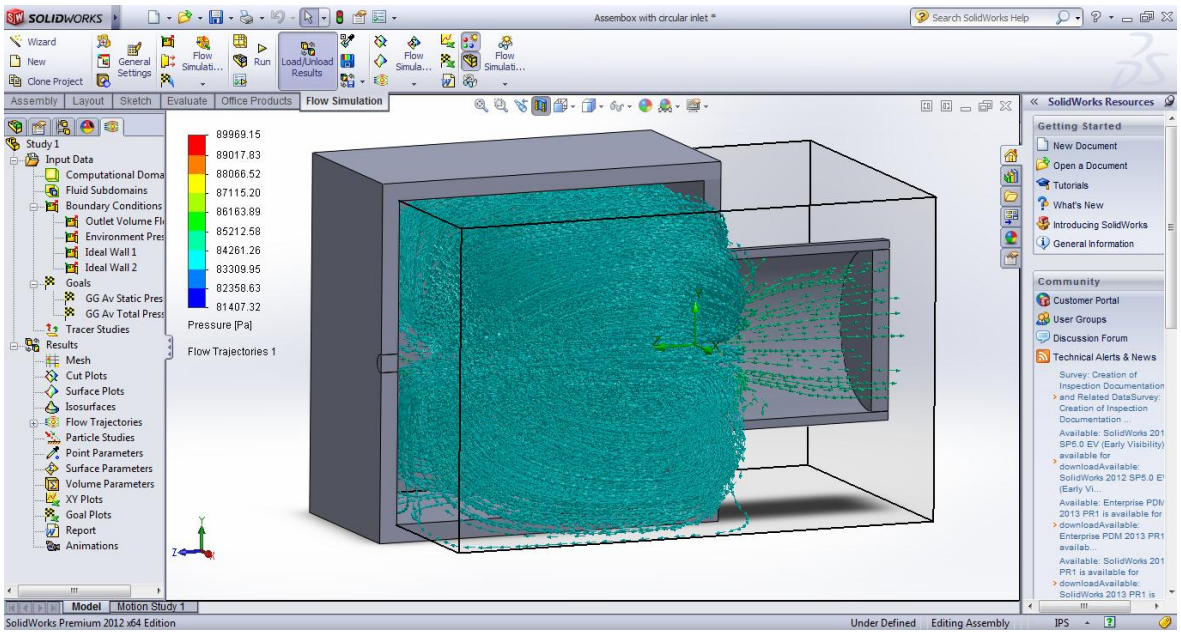

Figure 18 Plenum Chamber-Study 1

Study 2 Chamber length

For the second plenum chamber, the parameter to study was the length of the plenum chamber. A 40X20X20 box was designed with a 1cm diameter inlet and 9cm diameter Outlet. The following image represents the CFD results for this geometry.

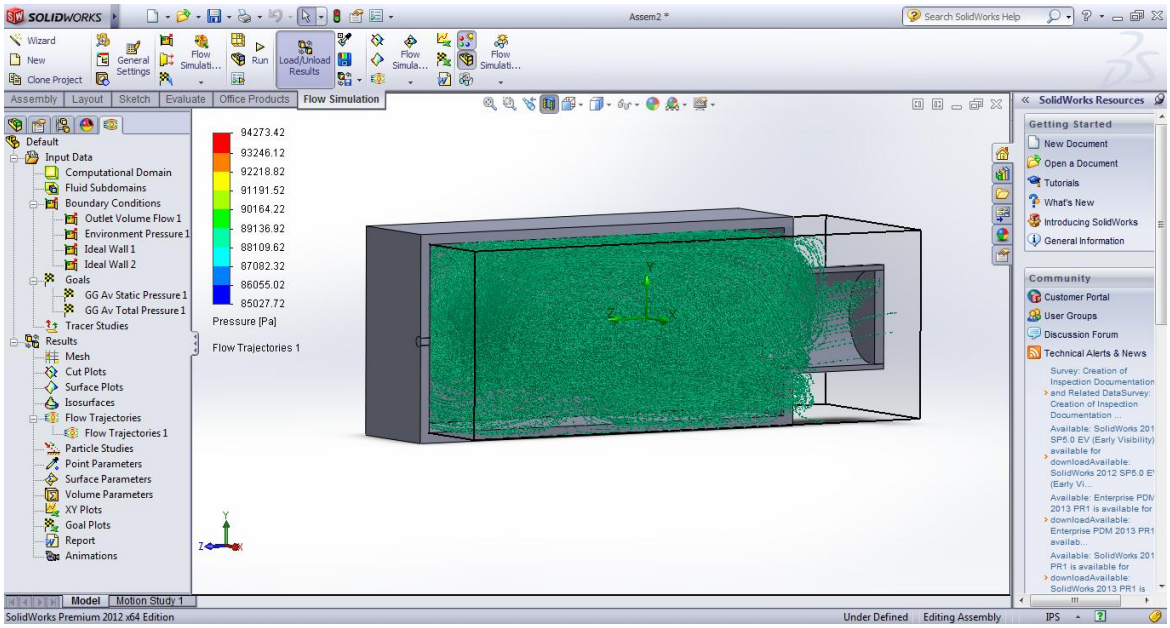

Figure 19 Plenum Chamber-Study 2

Study 3 Symmetric chamber with 1cm inlet 9cm outlet

For the third plenum chamber, the parameter to study was the width and height of the plenum chamber. A 40X40X40 box was designed with a 1cm diameter inlet and 9cm diameter Outlet. The following image represents the CFD results for this geometry.

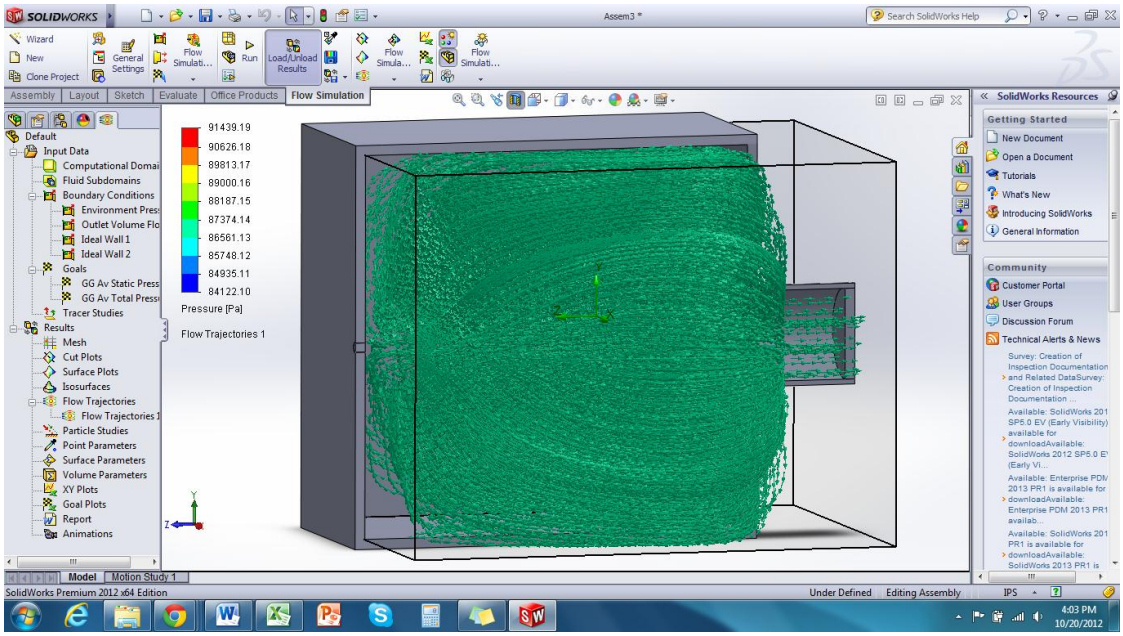

Figure 20 Plenum Chamber-Study 3

Study 4 Chamber with 10, .5 cm inlet holes and an outlet of 9cm

For the fourth plenum chamber, the parameter to study was number inlet holes of the plenum chamber. A 20X20X20 box was designed with 10, 0.5 cm diameter inlet holes and 9cm diameter Outlet. The following image represents the CFD results for this geometry.

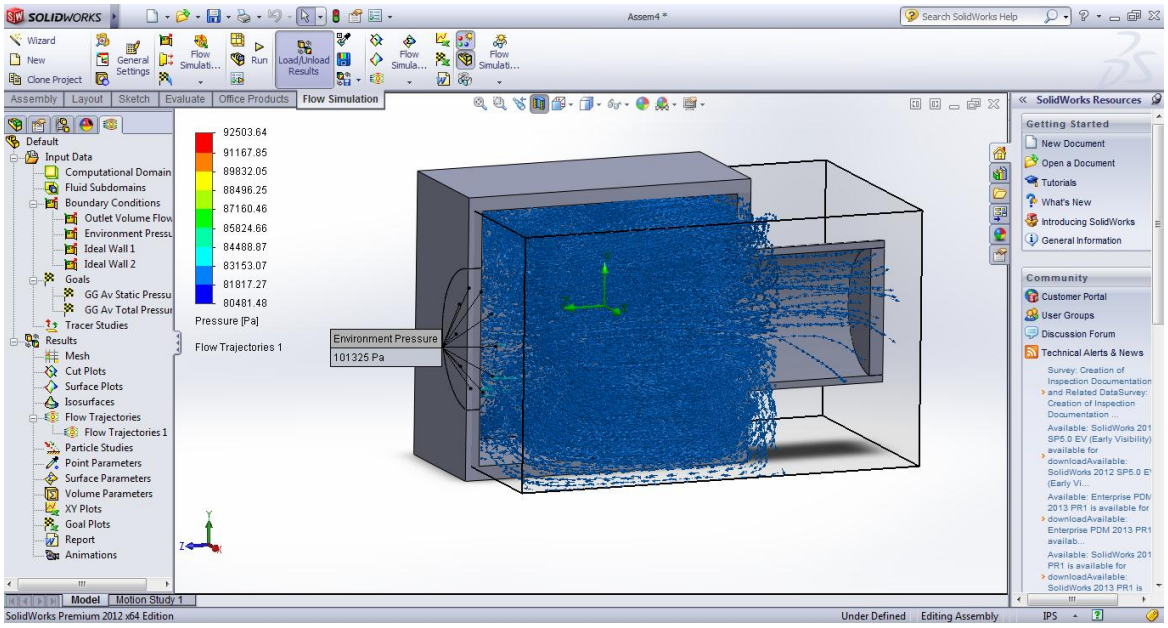

Figure 21 Plenum Chamber-Study 4

Study 5 Chamber with 10, .1 cm inlet holes and an outlet of 9cm

For the fifth plenum chamber, the parameter to study was number inlet holes and their diameter of the plenum chamber. A 20X20X20 box was designed with 10, 0.1 cm diameter inlet holes and 9cm diameter Outlet. The following image represents the CFD results for this geometry.

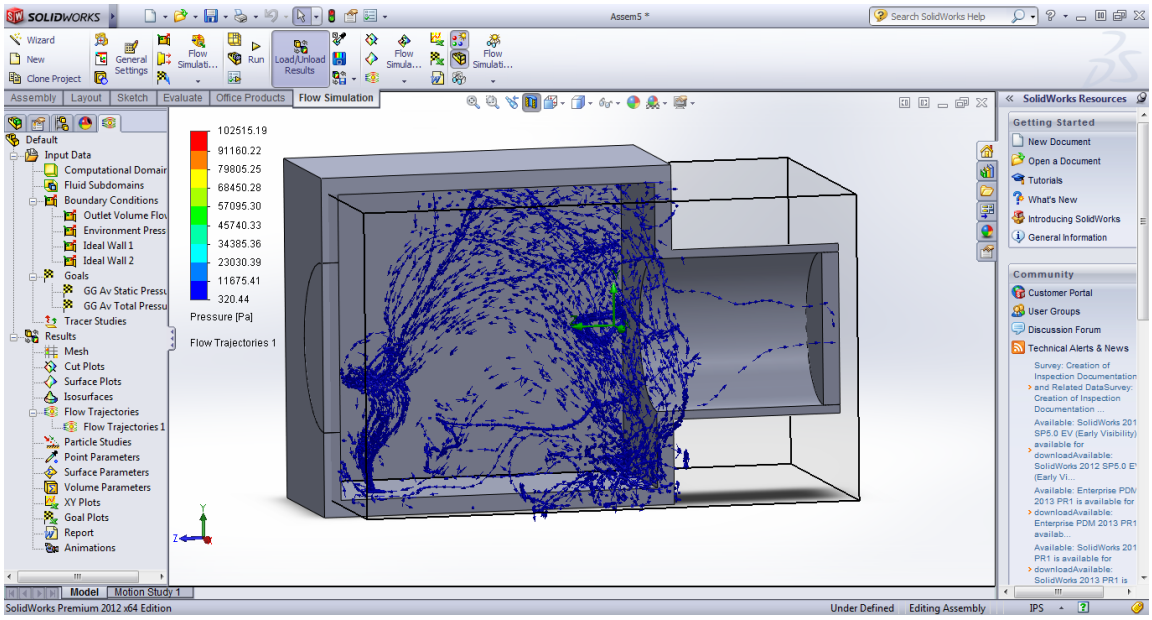

Figure 22 Plenum Chamber-Study 5

Study 6 Chamber with 5, .5 cm inlet holes and an outlet of 9cm

For the sixth plenum chamber, the parameter to study was number inlet holes and their diameter of the plenum chamber. A 20X20X20 box was designed with 5, 0.5 cm diameter inlet holes and 9cm diameter Outlet. The following image represents the CFD results for this geometry.

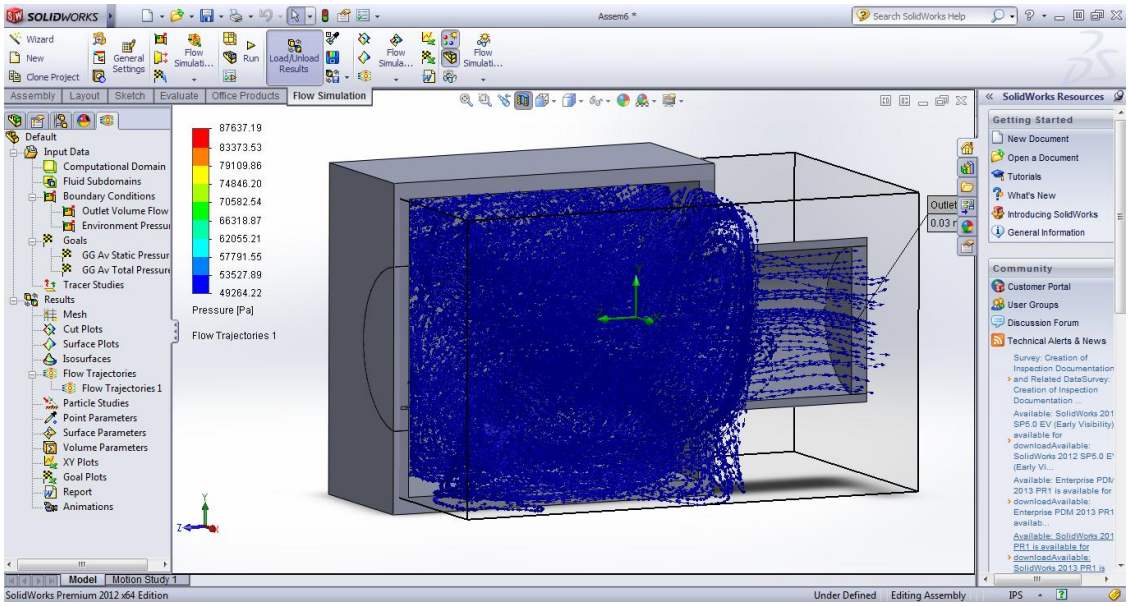

Figure 23 Plenum Chamber-Study 6

Study 7 Chamber with 5, .5 cm inlet holes with an angle and an outlet of 9cm

For the seventh plenum chamber, the parameter to study was angle of the inlet holes of the plenum chamber. A 20X20X20 box was designed with 5, 0.5 cm diameter inlet holes with 7 degrees inclination and 9cm diameter Outlet. The following image represents the CFD results for this geometry.

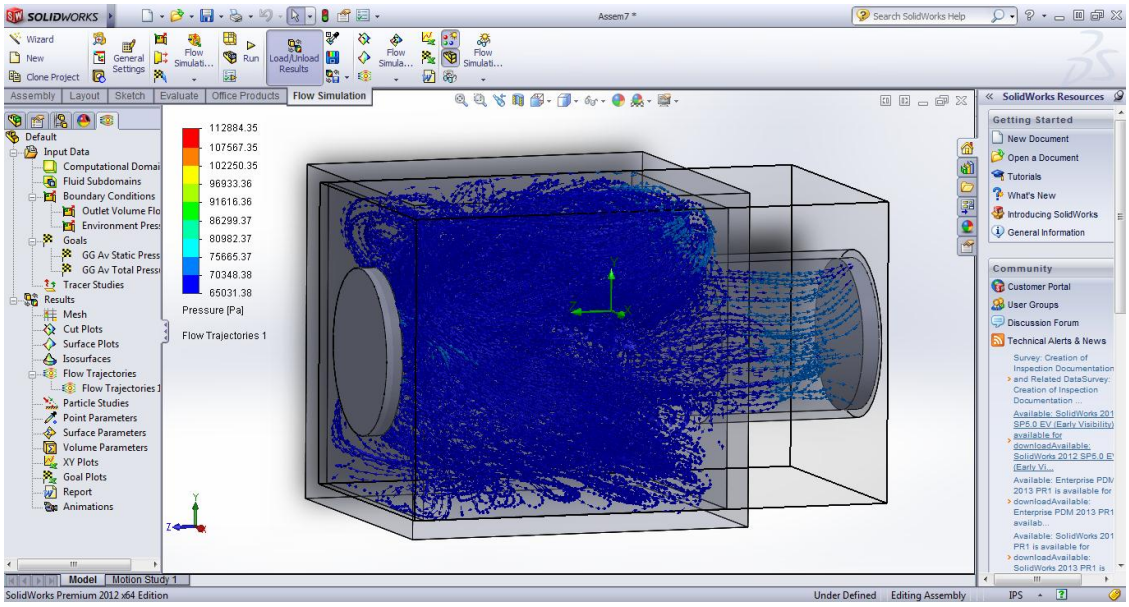

Figure 24 Plenum Chamber-Study 7

Study 8 Chamber with 10, .5 cm inlet holes with an angle and an outlet of 9cm

For the eighth plenum chamber, the parameter to study was angle of the inlet holes of the plenum chamber. A 20X20X20 box was designed with 10, 0.5 cm diameter inlet holes with 7 degrees inclination and 9cm diameter Outlet. The following image represents the CFD results for this geometry.

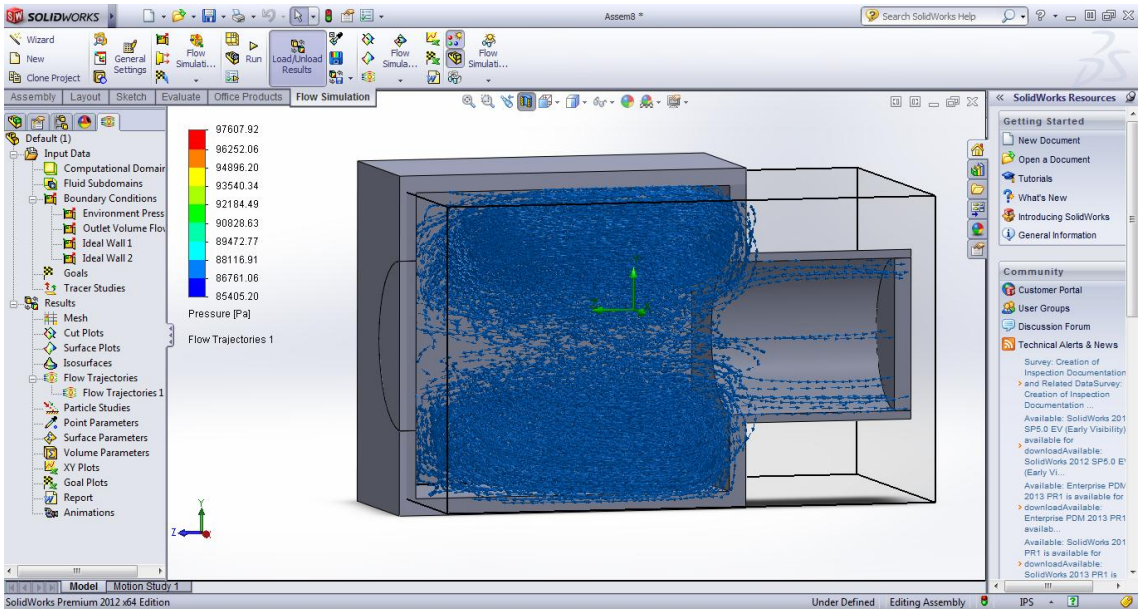

Figure 25 Plenum Chamber-Study 8

Study 9 Nozzle+ chamber with 10, .5 cm diameter inlet holes and an outlet 9 cm

For the ninth plenum chamber, the parameter to study was the addition of an inlet nozzle to the plenum chamber. A 20X20X20 box was designed with 10, 0.5 cm diameter inlet holes and 9cm diameter Outlet. The nozzle has a 20 cm inlet diameter and 10cm outlet diameter with a total length of 20cm. The following image represents the CFD results for this geometry.

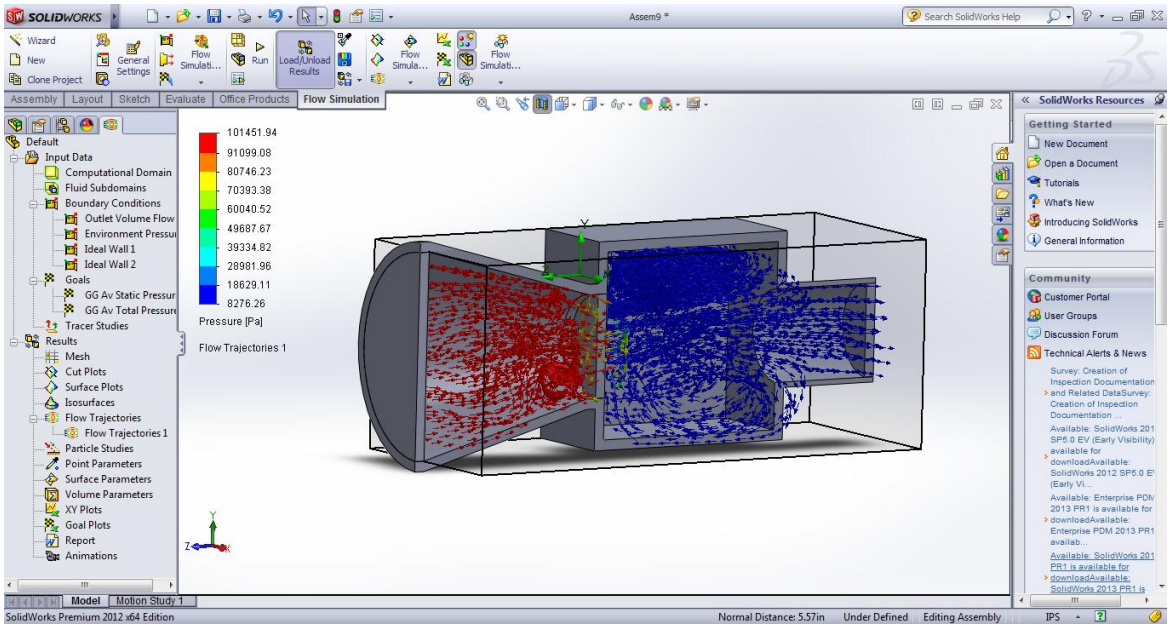

Figure 26 Plenum Chamber-Study 9

Study 10 Nozzle+ chamber +octagon opening, 1 cm diameter and an outlet 9 cm

For the tenth plenum chamber, the parameter to study was the variation of a circular restriction to a octagon with an inner diameter of 1cm. A 20X20X20 box was designed with 9cm diameter Outlet. The nozzle has a 20 cm inlet diameter and 10cm outlet diameter with a total length of 20cm. The following image represents the CFD results for this geometry.

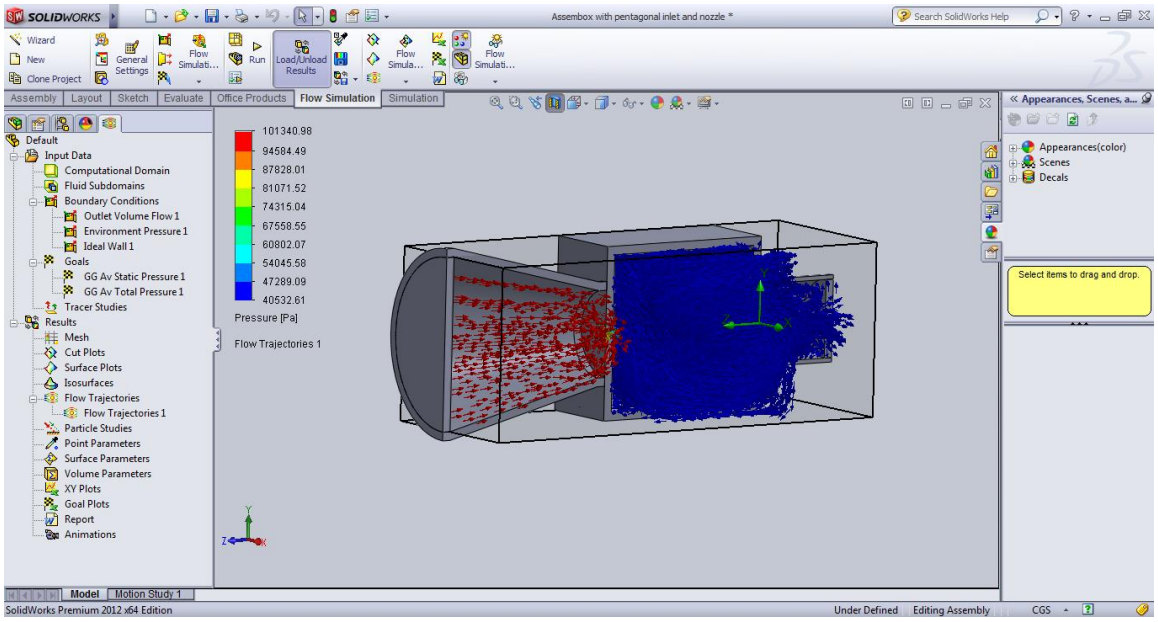

Figure 27 Plenum Chamber-Study 10

Study 11 Nozzle+ chamber with 9 cm inlet diameter and an outlet diameter 9 cm

For the eleventh plenum chamber, the parameter to study was the addition of an inlet nozzle to the plenum chamber. A 20X20X20 box was designed with 9cm diameter Outlet. The nozzle has a 20 cm inlet diameter and 10cm outlet diameter with a total length of 20cm. The following image represents the CFD results for this geometry.

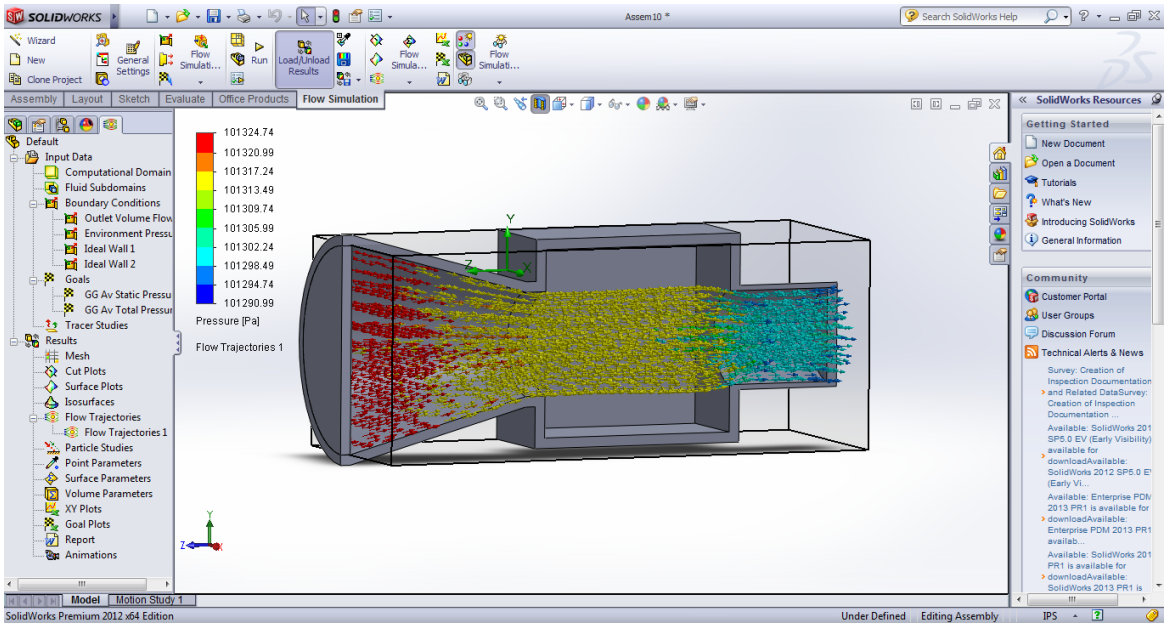

Figure 28 Plenum Chamber-Study 11

Study 12 Nozzle+ chamber with 1 cm inlet diameter and an outlet 9 cm

For the twelfth plenum chamber, the parameter to study was the addition of an inlet nozzle to the plenum chamber. A 20X20X20 box was designed with 9cm diameter Outlet. The nozzle has a 20 cm inlet diameter and 10cm outlet diameter with a total length of 20cm. a restriction with a hole of a 1cm is placed at the end of the nozzle. The following image represents the CFD results for this geometry.

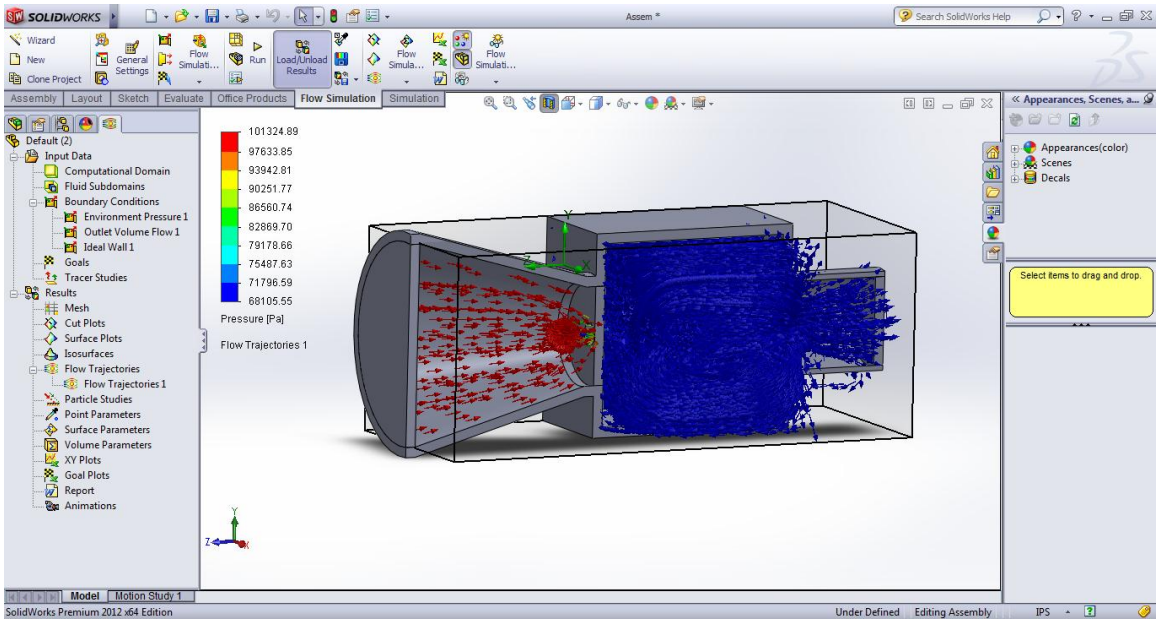

Figure 29 Plenum Chamber-Study 12

Study 13 Nozzle length 24.5 cm + chamber with 1 cm inlet diameter and an outlet 9 cm

For the thirteenth plenum chamber, the parameter to study was the addition of an inlet nozzle to the plenum chamber. A 20X20X20 box was designed with 9cm diameter Outlet. The nozzle has a 20 cm inlet diameter and 10cm outlet diameter with a total length of 24.5cm. a restriction with a hole of a 1cm is placed at the end of the nozzle. The following image represents the CFD results for this geometry.

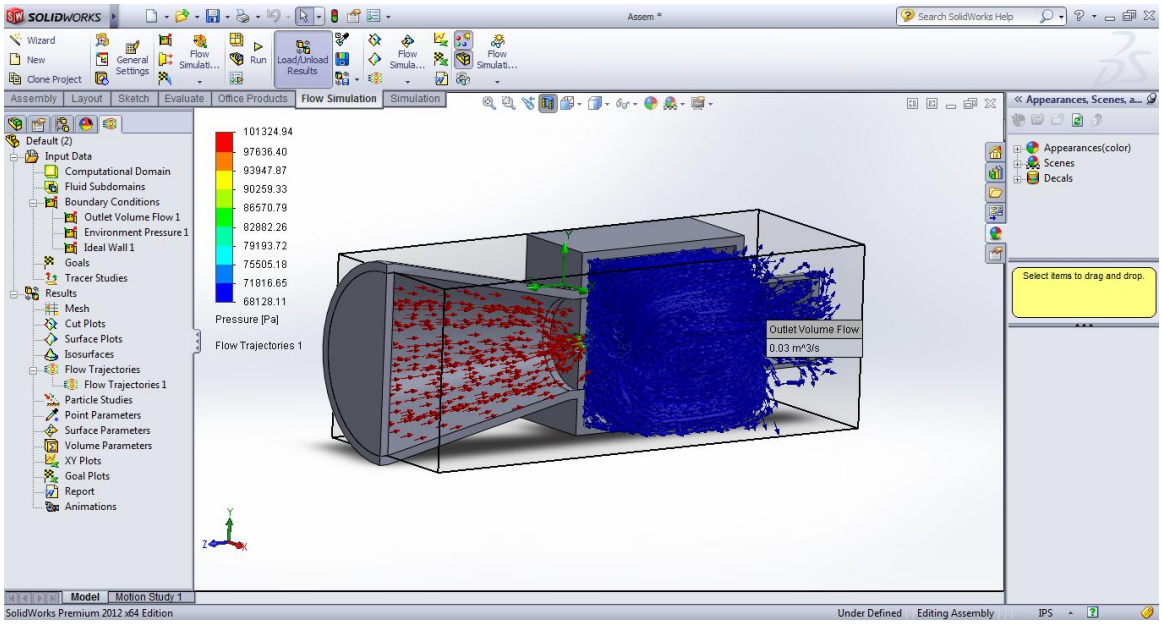

Figure 30 Plenum Chamber-Study 13

5.2.4 CFD Results

Computational fluid dynamics is a crucial method for this project since 3D flow calculations are very extend. Utilizing SolidWorks software, it is easier to understand how the variation of one single parameter affects the entire system. With these results, selection of the optimum dimensions for the plenum chamber was possible and the addition of new features was also studied. The following table represents a list of all the case studies analyzed above and all the parameters that were taken into consideration. All dimensions are in centimeters and degrees.

Table 5 Plenum Chamber Parameters Variation

Plenum Chamber													
Study	**L**	**W**	**H**	**# of Holes**	**D (inlet)**	**A1**	**Inlet Θ**	**Nozzle L**	**Nozzle d1**	**Nozzle d2**	**D (outlet)**	**Tube length**	**Thickness**
1	20	20	20	1	1	0.79	0	-	-	-	9	10	1
2	40	20	20	1	1	0.79	0	-	-	-	9	10	1
3	40	40	40	1	1	0.79	0	-	-	-	9	10	1
4	20	20	20	10	0.5	1.96	0	-	-	-	9	10	1
5	20	20	20	10	0.1	0.08	0	-	-	-	9	10	1
6	20	20	20	5	0.5	0.98	0	-	-	-	9	10	1
7	20	20	20	5	0.5	0.98	7	-	-	-	9	10	1
8	20	20	20	10	0.5	1.96	7	-	-	-	9	10	1
9	20	20	20	10	0.5	1.96	0	20	20	10	9	10	1
10	20	20	20	Octagon	1	0.83	0	20	20	10	9	10	1
11	20	20	20	1	10	78.5	0	20	20	10	9	10	1
12	20	20	20	1	1	0.79	0	20	20	10	9	10	1
13	20	20	20	1	1	0.79	0	25.4	20	10	9	10	1

For the case studies showed on the table above, an exit pressure was obtained. The following table represents the exit air pressure that will be at the outlet of the plenum chamber and the inlet of the MT.

Table 6 Plenum Chamber Exit Pressure

Study	Exit Pressure (Pa)
1	84261
2	88109
3	86561
4	81817
5	320
6	49264
7	65031
8	86761
9	8276
10	40050
11	101291
12	68105
13	68128

5.3 Final Design Flow Analysis

The numerical evaluation of the airflow through the altitude simulator device is carried out using commercial software Solid works 2012. From the steady state experimental volume flow rate is determined at the outlet of the altitude simulator where it interfaces with the micro turbine. The entrance is directly in contact to the atmosphere, with an environmental pressure, and ideal wall through the device is used for simplicity. An initial analysis is performed to the device to determine that the pressure drop across the device is greater than the required to simulate 10,000ft or 68000Pa with a specific aperture of the iris mechanism that is greater than the minimum.

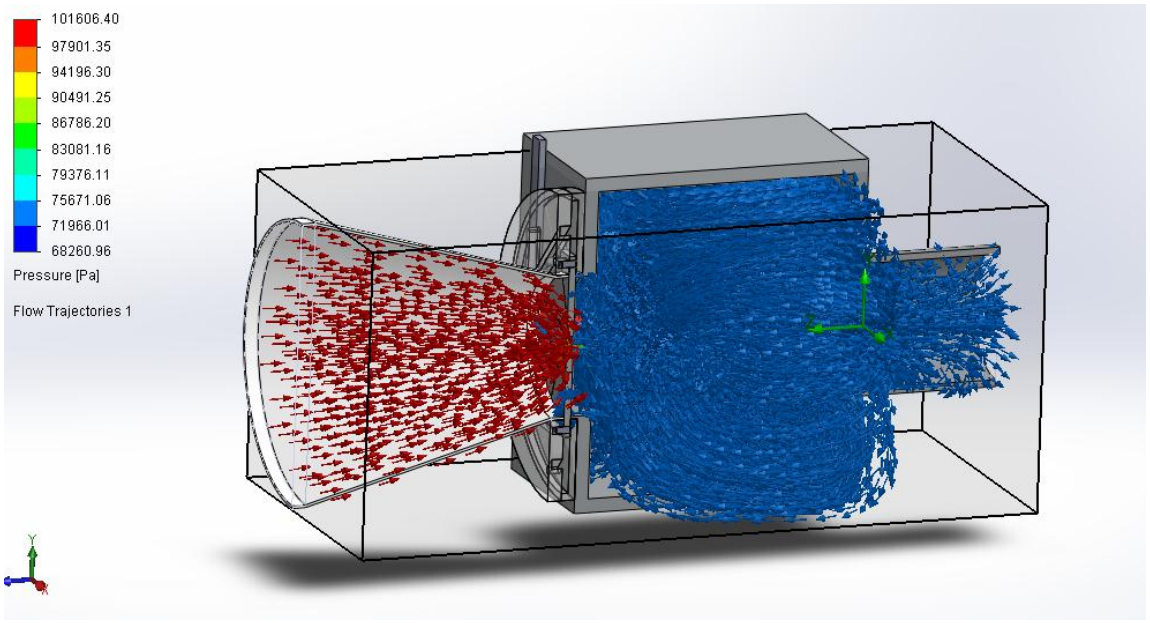

Figure 31 Desired Pressure Drop

Through Solid Works Flow Simulation it is determined that our system is capable to drop the pressure from 101KPa to 68KPa.

Flow analysis of varying inlet area is presented below. Changes of one millimeter to the diameter of the opening of the mechanical iris are presented to estimate the drop in pressure produced by the design.

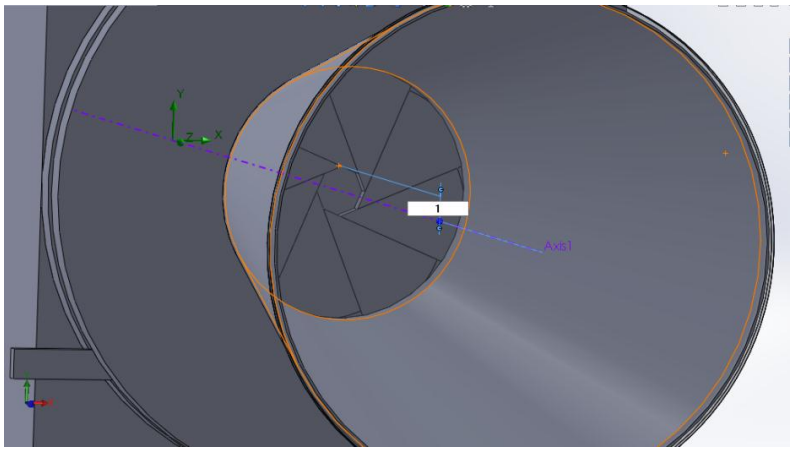

Figure 32 Geometry Variation of the Inlet

The desired maximum pressure drop was achieved with a radial opening of 1cm, achieving 68737Pa of pressure at the outlet of the CINAS.

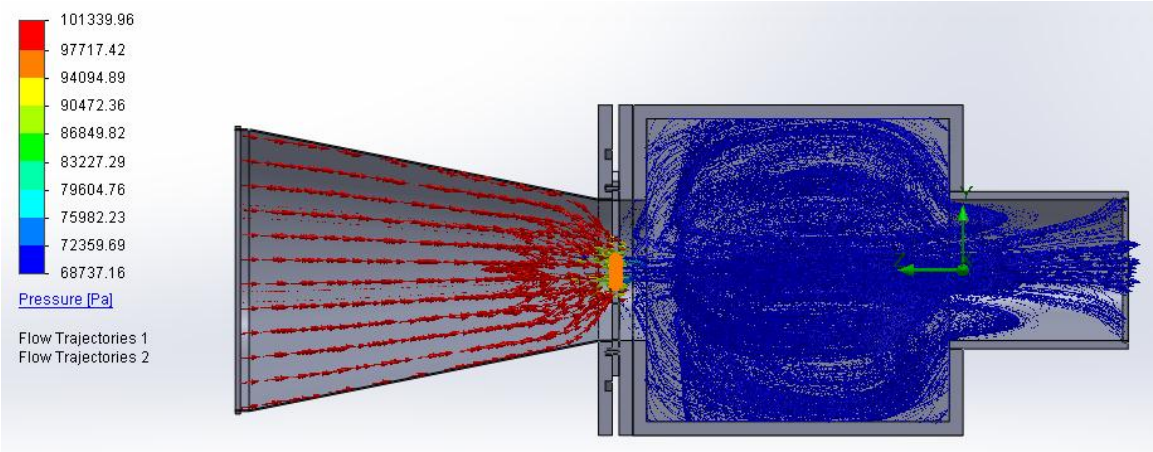

Figure 33 1.0 cm opening

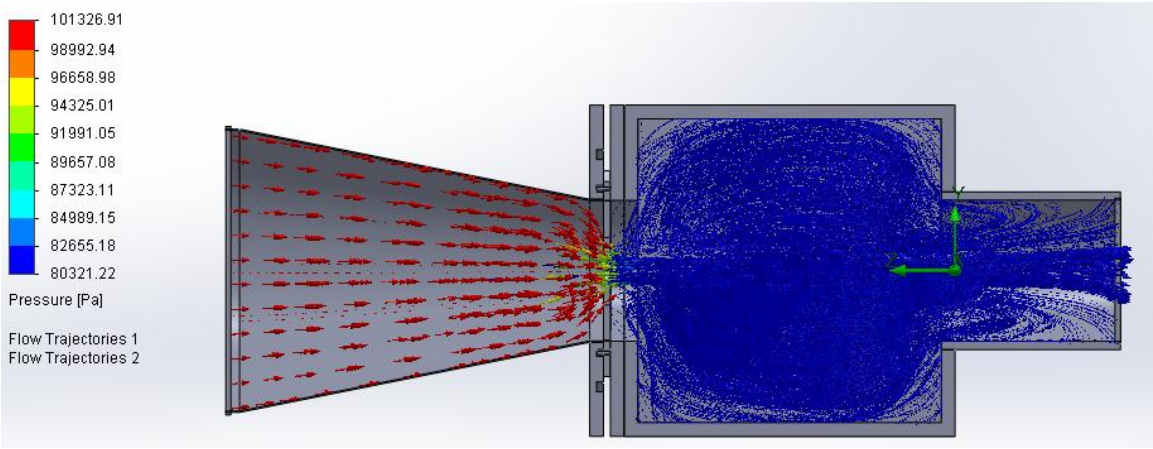

Figure 34 1.10 cm opening

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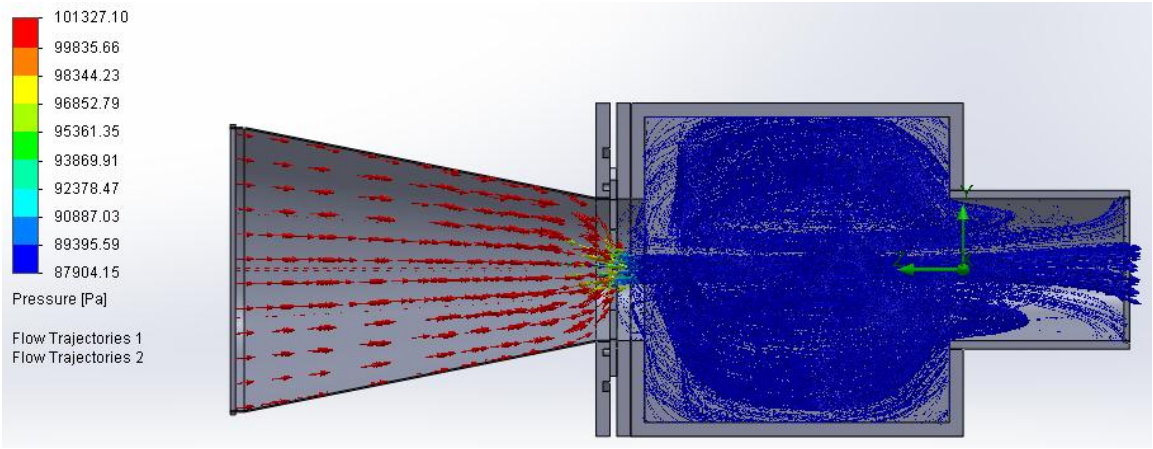


Figure 35 1.20 cm opening

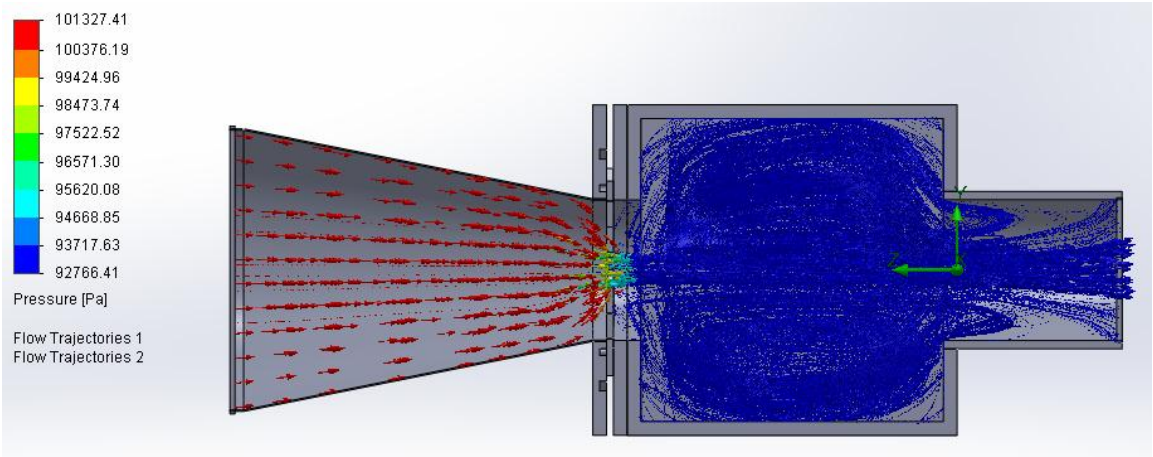


Figure 36 1.30 cm opening

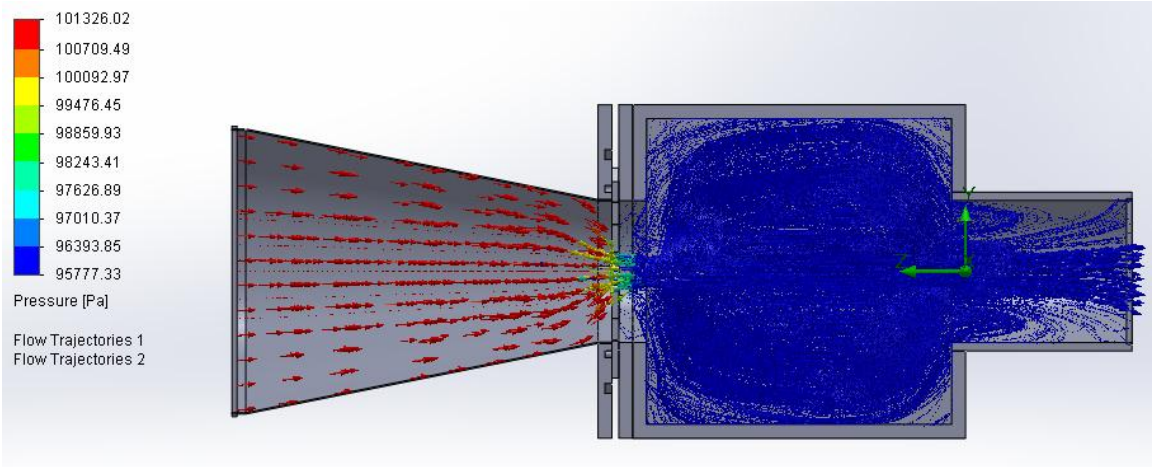


Figure 37 1.40 cm opening

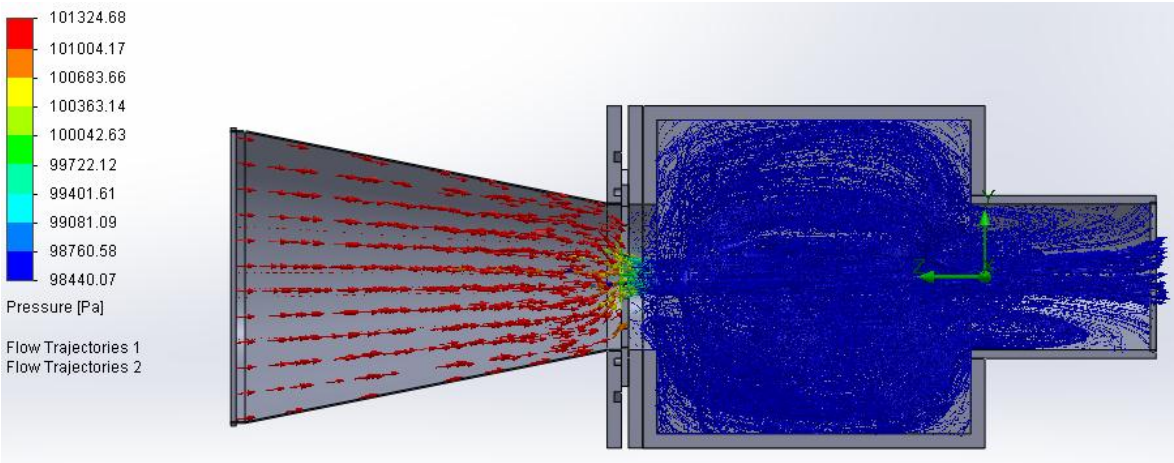


Figure 38 1.50 cm opening

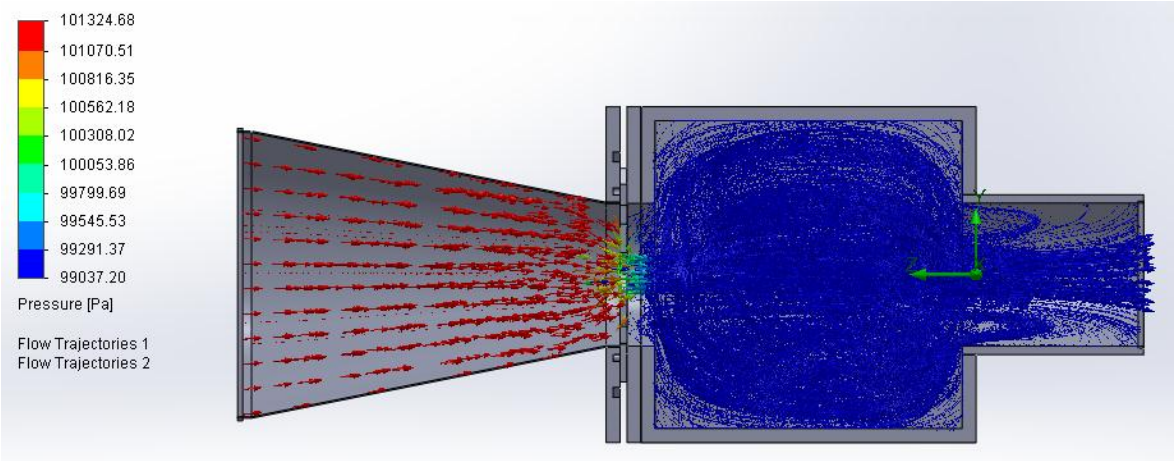


Figure 39 1.60 cm opening

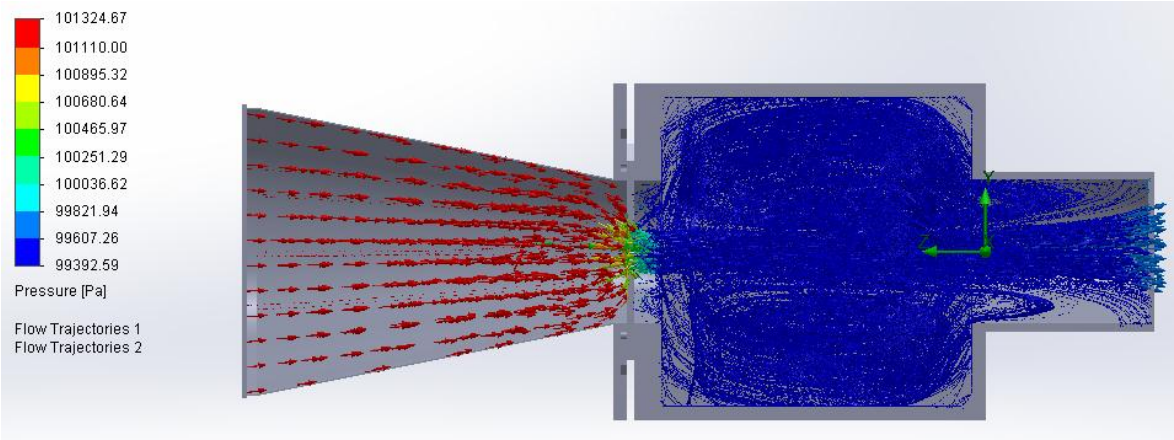


Figure 40 1.70 cm opening

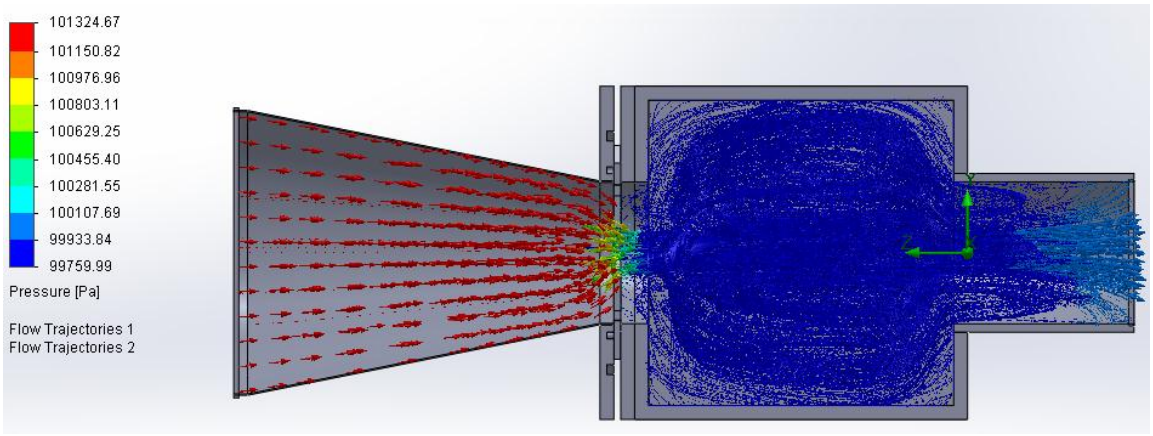


Figure 41 1.80 cm opening

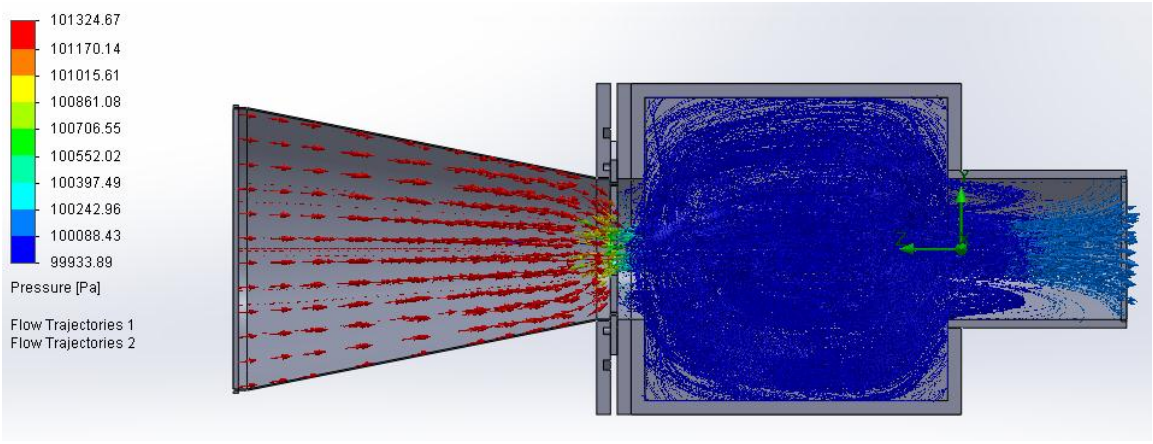


Figure 42 1.90 cm opening

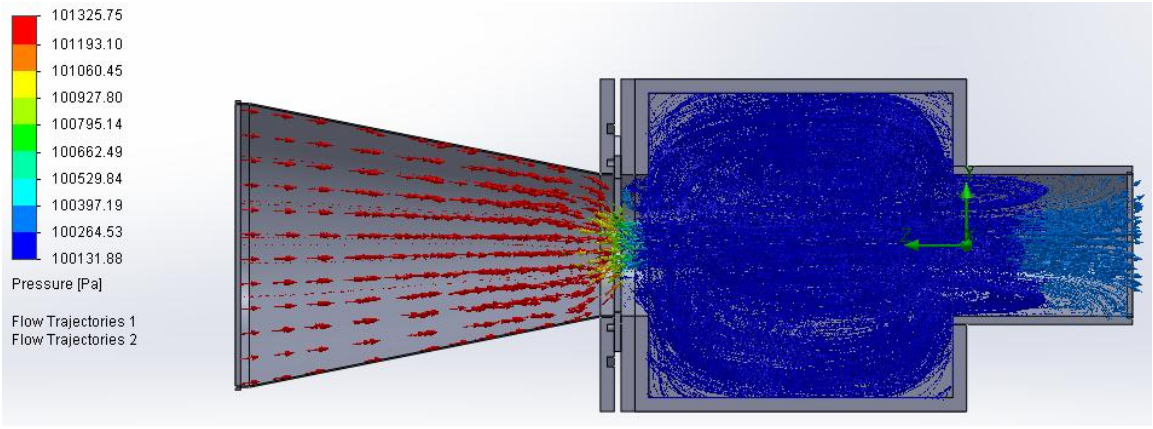


Figure 43 2.0 cm opening

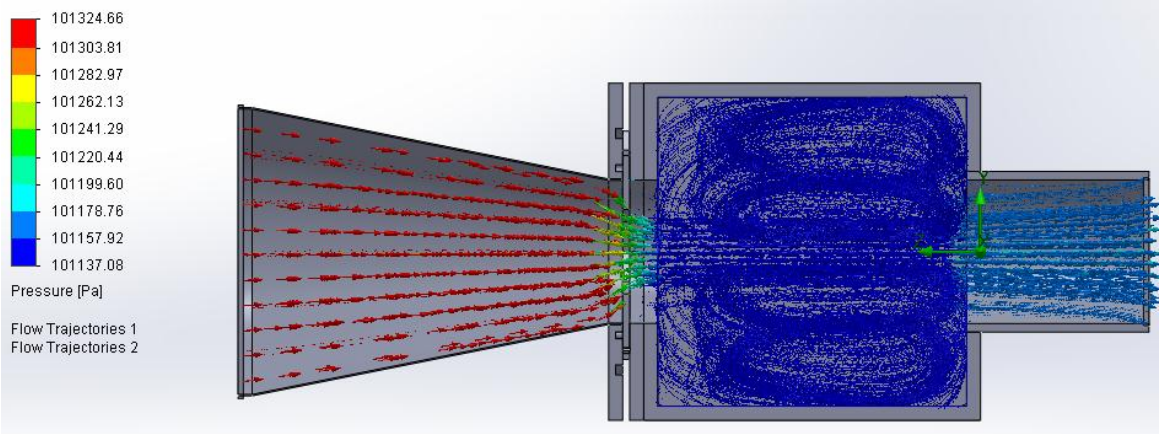


Figure 44 3.0 cm opening

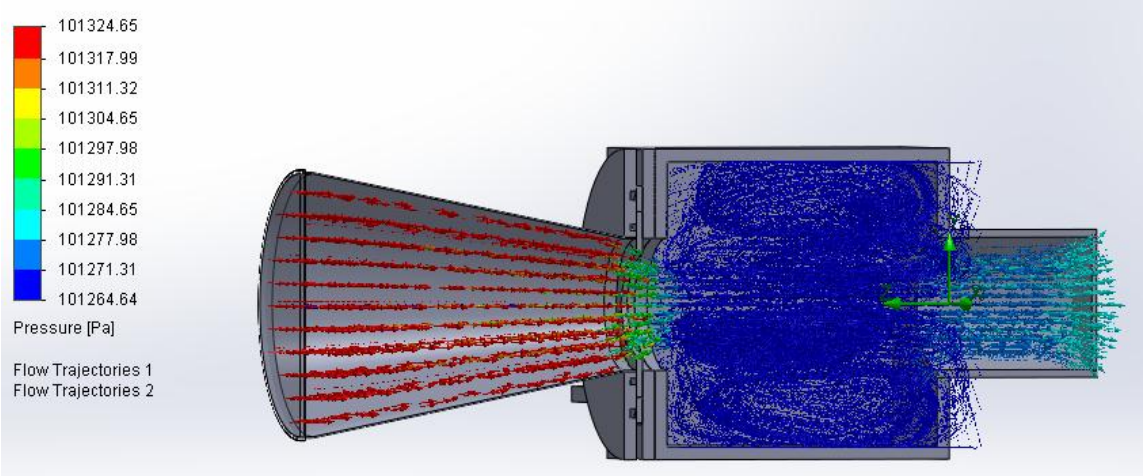


Figure 45 4.0 cm opening

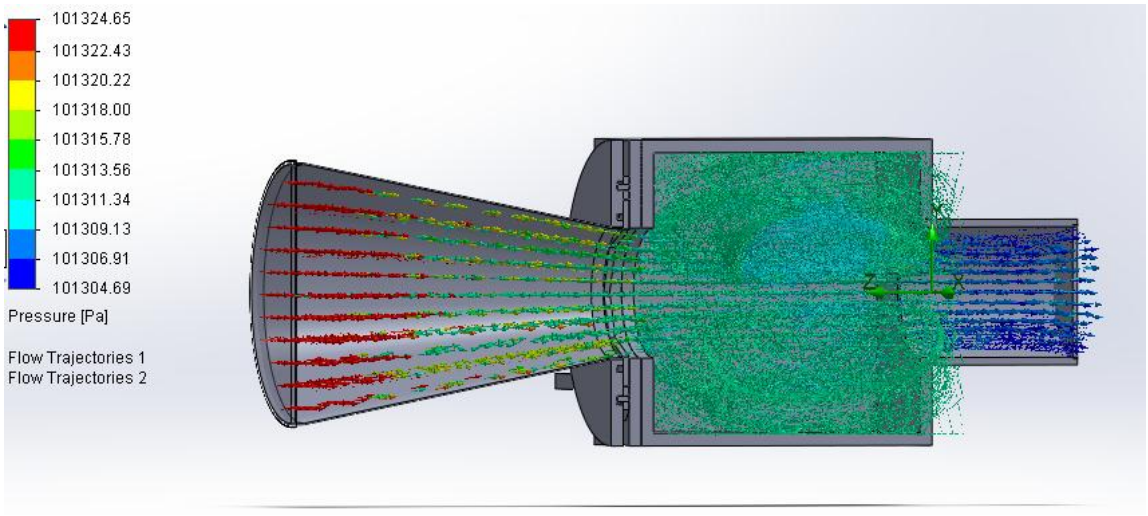


Figure 46 5.0 cm opening

The following tables represent the diameter and area opening of the iris mechanism and the corresponding CFD results. With the values obtained from these studies, pressure at the exit of the system can be recorded which corresponds to the pressure that will be entering the MT. With these values of pressure, altitude can be calculated and a relation area to altitude is obtained.

Table 7 Final Design Analysis (SI)

Diameter (cm)	Area Opening (cm^2)	Average Pressure (Pa)	Altitude (m)
1.00	2.83	68737.16	3153.77
1.10	3.42	80321.22	1915.88
1.20	4.07	87904.15	1181.89
1.30	4.78	92766.41	737.83
1.40	5.54	95777.33	472.20
1.50	6.36	98440.07	242.86
1.60	7.24	99037.20	192.12
1.70	8.17	99392.59	162.06

1.80	9.16	99756.99	131.31
1.90	10.21	99933.89	116.40
2.00	11.31	100131.88	99.76
3.00	25.46	101137.00	15.67
4.00	45.25	101264.64	5.03
5.00	70.71	101304.69	1.68

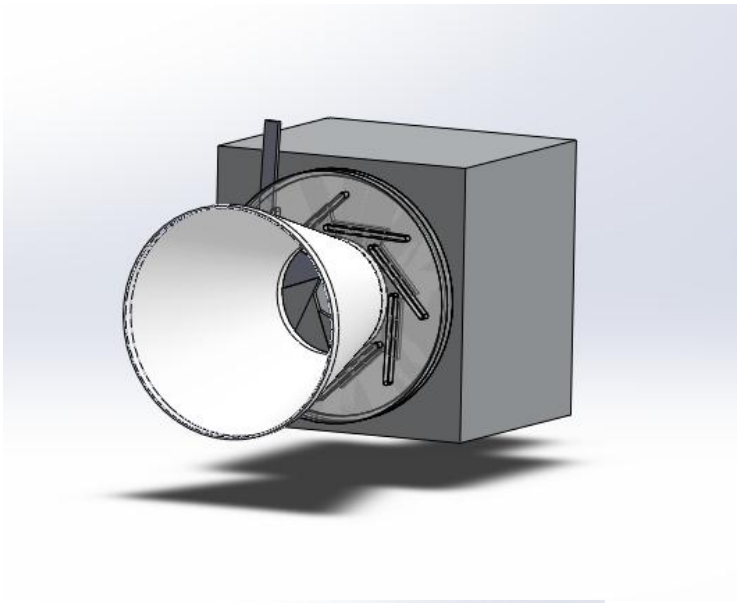
Table 8 Final Design Analysis (US)

Diameter (in)	Area Opening (in^2)	Average Pressure (psi)	Altitude (ft)
0.39	0.44	9.97	10347.00
0.43	0.53	11.65	6285.70
0.47	0.63	12.75	3877.60
0.51	0.74	13.45	2420.70
0.55	0.86	13.89	1549.20
0.59	0.99	14.28	796.80
0.63	1.12	14.36	630.30
0.67	1.27	14.42	531.70
0.71	1.42	14.47	430.80
0.75	1.58	14.49	381.90
0.79	1.75	14.52	327.30
1.18	3.95	14.67	51.40
1.57	7.01	14.69	16.50
1.97	10.96	14.69	5.50

5.4 Final Design Stress Analysis

5.4.1 Iris Stress Analysis

Structural analysis of the iris mechanism shows stress analysis of the blades by the differential pressure. Acrylic was chosen as the material for the manufacturing of the device. Results show a FOS greater than 3.0, therefore there will be no failure.



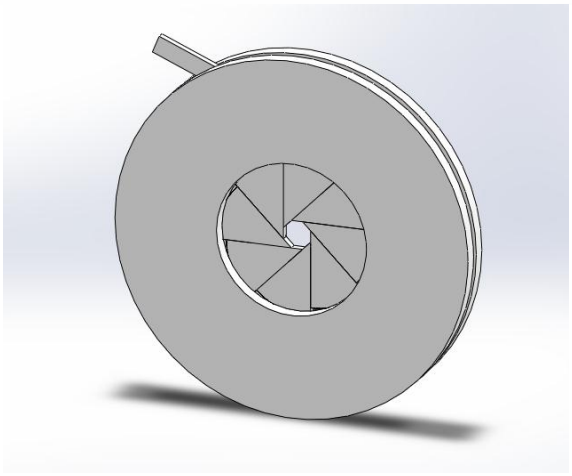


Figure 47 Mechanical Iris made of Acrylic

Iris Stress Analysis Results

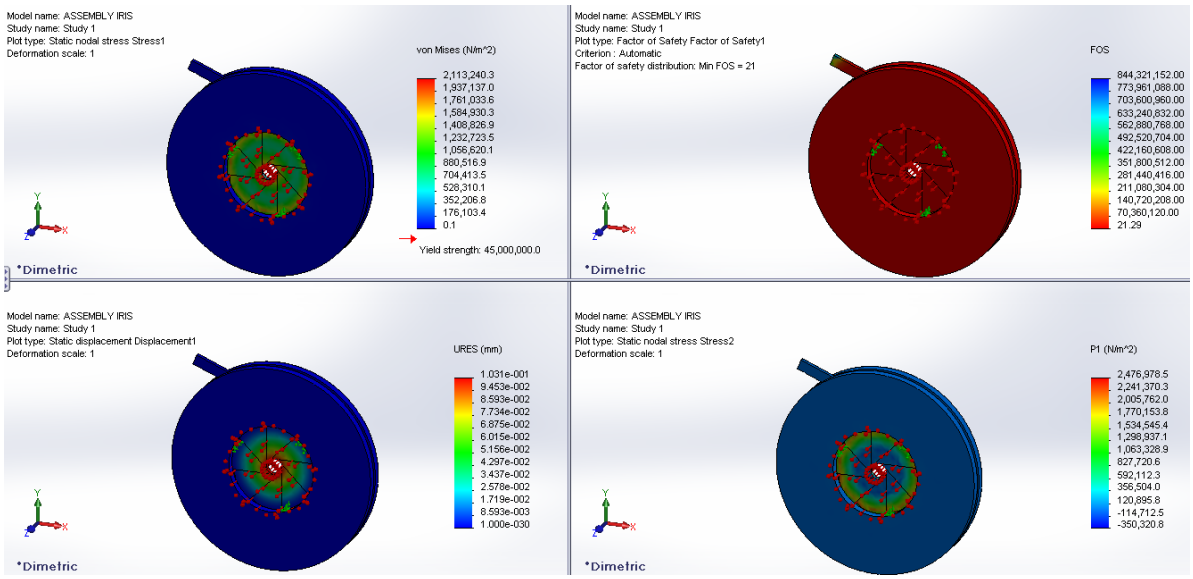


Figure 48 Iris Results Von Misses, Principal Stress, Displacement and Safety Factor

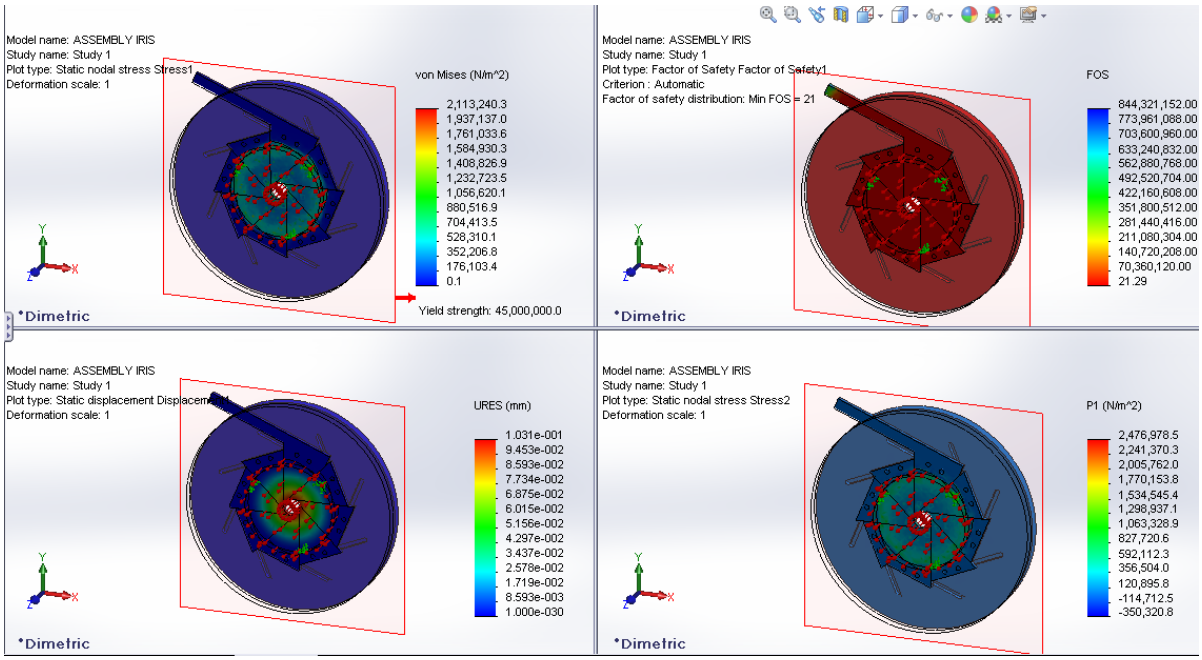


Figure 49 Iris Section Clip Results Von Misses, Principal Stress, Displacement and Safety Factor

5.4.2 Plenum Chamber Stress Analysis

A vacuum test of the plenum chamber is performed to determine the material for the prototype build. Acrylic was the material chosen for this component manufacturing. The FOS is greater than 3.0, therefore there will be no failure of the material chosen.

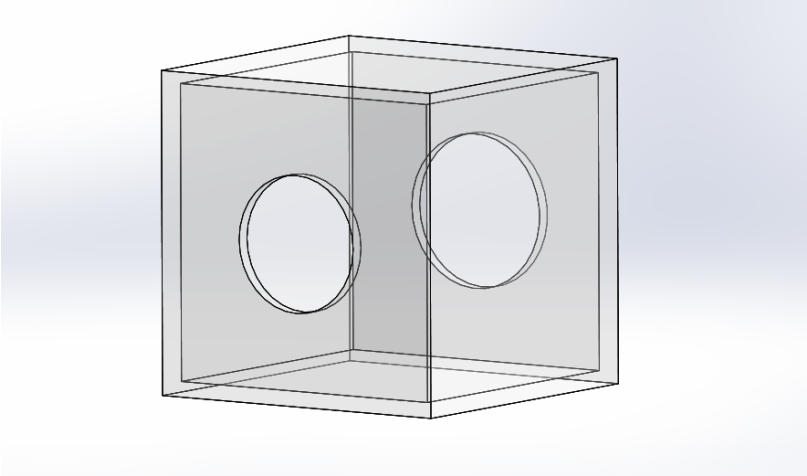


Figure 50 Plenum Chamber made with Acrylic

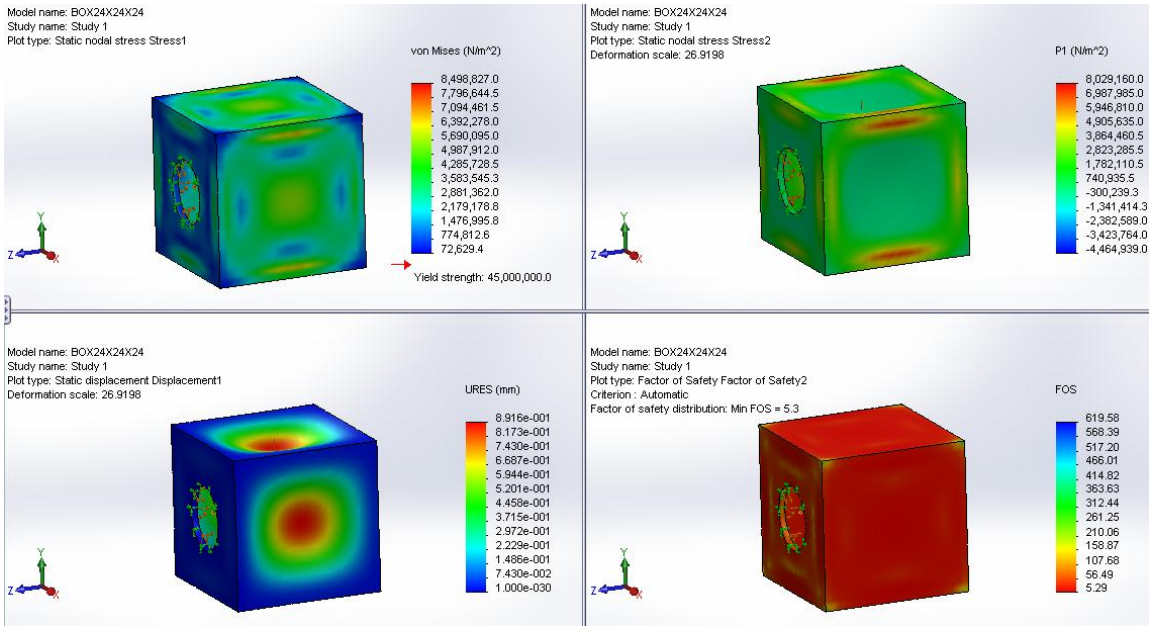


Figure 51 Plenum Chamber Results Von Misses, Principal Stress, Displacement and Safety Factor

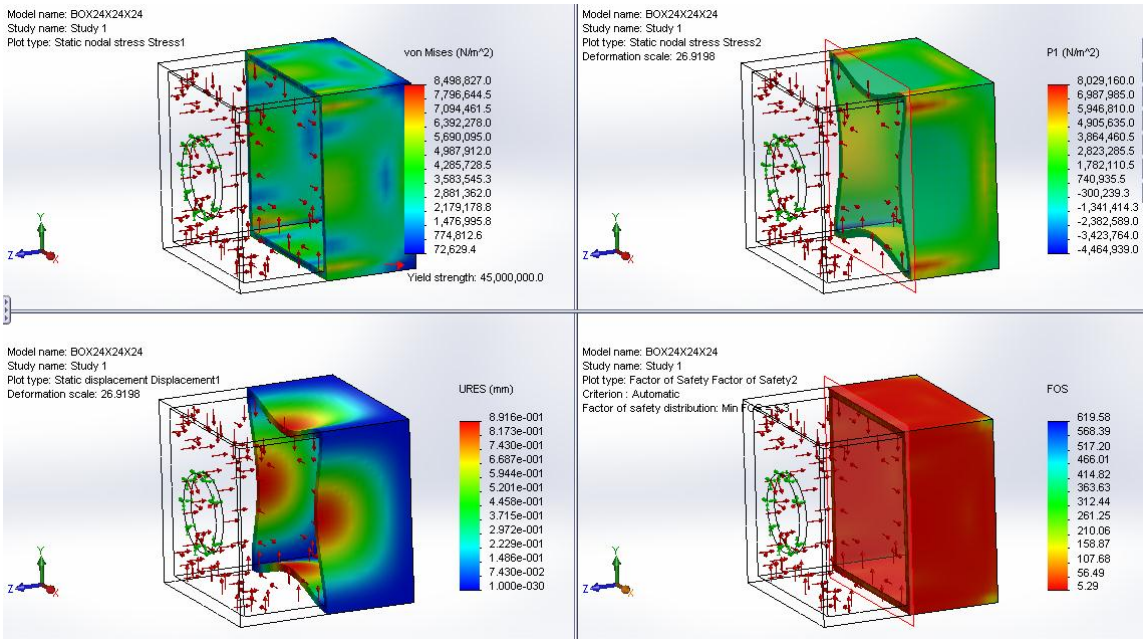


Figure 52 Plenum Chamber Section Clip Results Von Misses, Principal Stress, Displacement and Safety Factor

5.4.3 Fastening components

CINAS must be able to interact with the micro-turbine test bench efficiently and it has to be as ergonomic proficient to provide a safe and comfortable environment for the operation of the micro-turbine.

In our design, the structural analysis consists on the use of different mechanical concepts to ensure that the design considerations and objectives are achieved. Computer simulations are conducted to analyze the structure's deformation, internal forces, stresses, support reactions and stability. These results are compared to the theoretical analysis and

are used to verify the structure's functionality, often saving physical tests. Structural analysis is thus a key part of the engineering design for our prototype since it will confirm material selection and critical components design for support.

6. Cost Analysis

The team used the most reliable and cost effective way of putting the prototype together. Since the beginning of our design the team had no restrictions on how expensive or cheap the design was going to be but, ergonomics played an important role since the team was working with a defined test-bench and everything had to interact efficiently and safely. The cost analysis includes parts that were manufactured at the machine shop at FIU and parts that require specialized equipment. A rough estimate of man hours and material cost are included in the following table.

Table 9 Cost Analysis

Part	Quantity	Description	Unit Price	Total Price	Figure
Aluminum Pipe Reducers	2	Master Flow 8 in. to 6 in. and 6in. To 4in. Round Reducer	$7.22	$14.44	
Plenum Chamber	1	Thickness of 1 in. and .5 in acrylic sheets	$60.00	$60.00	
Silicone	2	GE Silicone II 2.8 oz. Window and Door Caulk Clear	$4.00	$8.00	
PVC Extension	1	DURA 4 in. Schedule 40 PVC Coupling SxS	$4.00	$4.00	
Rubber Reducer	1	Diameter 4 in. to 3 in.	$4.00	$4.00	
Mechanical Iris	1	Diameter 4 in. Aperture, Maximum 2.5 in.	$165.00	$165.00	
Thrust Bracket	1	CNC bolt holes and exact length of the bracket	$0.00	$0.00	
Fastening Components	1	Screws, washers, bolts	$10.00	$10.00	
TOTAL				$265.44	

The only parts that required specialized equipment for manufacturing purposes were the plenum chamber which it was performed by a specialized acrylic company and cost is presented in the above table. A CNC modification to the thrust bracket was

performed at no cost thanks to the help of Professor Zicarelli. Each member of the team dedicated 15 weekly hours to conduct research, analysis and group meetings as well as time in the prototype construction, testing and evaluation.

7. Prototype Construction

7.1 Description of Prototype

The team designed an altitude simulator apparatus that was used to simulate flight conditions. The design of the device was based on the inlet dimensions and performance curves of a Wren MW54 MK3 micro-turbine. Florida International University owns a micro-turbine test bench that was enhanced by the integration of the altitude simulator prototype. With this integration, testing capabilities were expanded. The design incorporates three subsystems. The first sub-system consists of a converging nozzle that will provide direction to the flow and the most important feature of the nozzle is that it will prevent the generation of vortices at the inlet of the second sub-system. Since the nozzle acts as a guide path of the air flow the geometry was choose considering the space constraint given by the test-bench. The nozzle will be constructed from thin aluminum sheets conically shaped. Since the purpose of the apparatus is to produce a reduction in pressure, a converging nozzle was used to fit the application. Since the micro-turbine is mounted on a test bench, the team was limited by the free space left on the test bench and had to develop not only a nozzle geometry that would fit into the bench, but also a mounting system for the nozzle to stand by its self. Integration of the designed nozzle to

the micro-turbine was done by designing a static mounting component that would produce an exact connection between both components together.

The second sub-system consists of a mechanical iris that varies its shape depending on the amount of air flow the user desires to achieve. The manufacturing of the iris is not very complex on the other hand; this device provides an excellent solution to address pressure loss. This mechanical iris produces a variation of area at the outlet of the converging nozzle to create a range of altitudes which it leads to our third sub-system. The third sub-system consists of a plenum chamber that would act as defined space to trap the air properties achieved by the previous sub-systems before the air enters the micro-turbine. The plenum chamber will be constructed using Plexiglas or aluminum depending on the amount of vacuum exerted by the micro-turbine.

7.2 Manufacturing

After analyzing what material best suited the prototype the team has decided to use Poly(methyl methacrylate) mostly known as an acrylic vs. standard sheets of metals like aluminum. Even thou, metals are more resistance and are capable of withstand more loads compared to polymers, the properties of acrylic meets and exceeds the design specifications. Some of the advantages of using acrylic for the prototype are that this polymer is light in weight yet strong at impact and it is a material that can be worked in a similar manner as a metal but it requires special attention when working with close tolerances.

7.2.1 Mechanical Properties

The mechanical properties of polymers are established with many of the same parameters that are used for metals [17]. For polymeric materials, the widely method of the simple stress-strain test is used to distinguish between its mechanical parameters. The mechanical characteristics of polymers, for the most part, are highly sensitive to the rate of deformation, the temperature and the chemical nature of the environment [17]. For Poly(methyl methacrylate) the main concern is temperature because it significantly affects its properties. By increasing the temperature the material will have a decrease in its elastic modulus and its tensile strength will be reduced. As an illustration on how temperature affects this specific polymer, Figure 53 will show the influence of temperature on the stress-strain characteristics of acrylic and Figure 54 will present room temperature mechanical characteristics of some polymers.

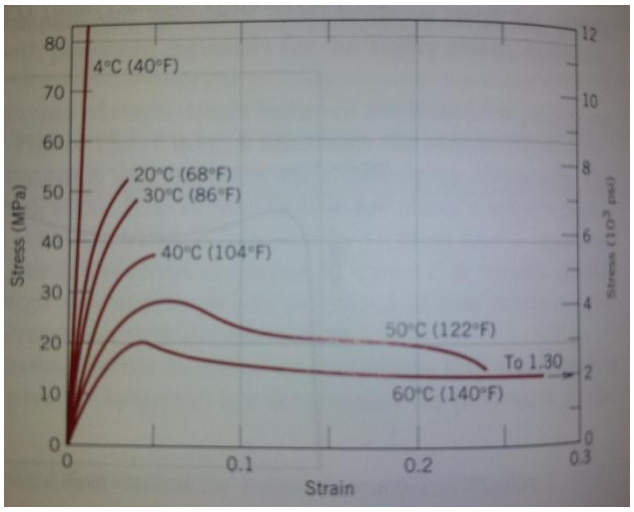


Figure 53 Temperature Influence on the stress-strain curve Poly (methyl methacrylate)

DATA TABLE FOR: Polymers: Commodity Polymers: PMMA

Mechanical Properties

Quantity	Value	Unit
Young's modulus	1800 - 3100	MPa
Shear modulus	1700 - 1700	MPa
Tensile strength	48 - 76	MPa
Elongation	2 - 10	%
Compressive strength	83 - 124	MPa
Fatigue	11 - 12	MPa
Bending strength	120 - 148	MPa
Impact strength	0.16 - 0.27	J/cm

Physical Properties

Quantity	Value	Unit
Thermal expansion	50 - 90	e-6/K
Thermal conductivity	0.167 - 0.25	W/m.K
Specific heat	1466 - 1466	J/kg.K
Glass temperature	105 - 105	°C
Service temperature	-40 - 90	°C
Density	1170 - 1200	kg/m³
Resistivity	1e+19 - 0	Ohm.mm²/m
Breakdown potential	16 - 30	kV/mm
Dielectric loss factor	0.04 - 0.06	
Friction coefficient	0.54 - 0.54	
Refraction index	1.492 - 1.492	
Shrinkage	0.3 - 0.8	%
Water absorption	0.3 - 0.4	%

Figure 54 Mechanical Properties of Poly (methyl methacrylate)

For the design of CINAS, temperature becomes an important factor when actual manufacturing is in progress. On the other hand, temperature is not a main concern when CINAS interacts with the micro-turbine because, temperature variation for CINAS will only depend on environmental conditions and its location within the test stand protects it from higher temperatures produce at the aft section of the turbine so, changes in temperature can be said to be negligible when load, stress and displacement calculations are conducted.

7.2.2 Acrylic handling

As mentioned earlier, temperature becomes a critical factor when actual work is done to the acrylic. The tools used to cut and shape acrylic becomes a source of heat and possible deformation of the material can occur while manufacturing is in progress. Some of the preferred tools used to shape acrylic are carbide-type blades, water jets, laser jets and CNR machines [18]. Acrylic should be cut at a steady pace to prevent chipping and melting. When drilling holes, special attention to the speed of the drill and the location of

the holes should be consider because these two factors will minimize damage to the piece. Allow the drill bit to cool down in between cuts or use coolant throughout the operation and as a general rule to prevent cracks near the edge, drill holes 1.5 times away from the diameter of the hole measured from the center [18]. The quality of the finish product will depend on the quality of the tools used and the procedures utilized while handling acrylic.

7.2.3 Plenum Chamber Construction

After determining the correct shape of the plenum chamber and running simulations to confirm that the structure will withstand the different conditions exerted to the system it was decided that manufacturing was going to be perform professionally. Acrylines a company specialized in acrylics PVC and polycarbonate located in Miami, FL was the company that manufactured the chamber. The following technical drawings were provided in detail to the company.

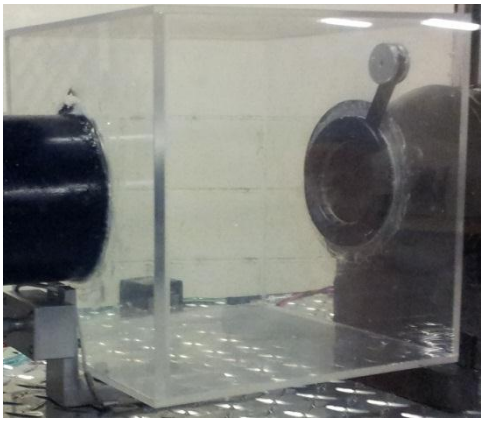


Figure 55 Assembled plenum chamber

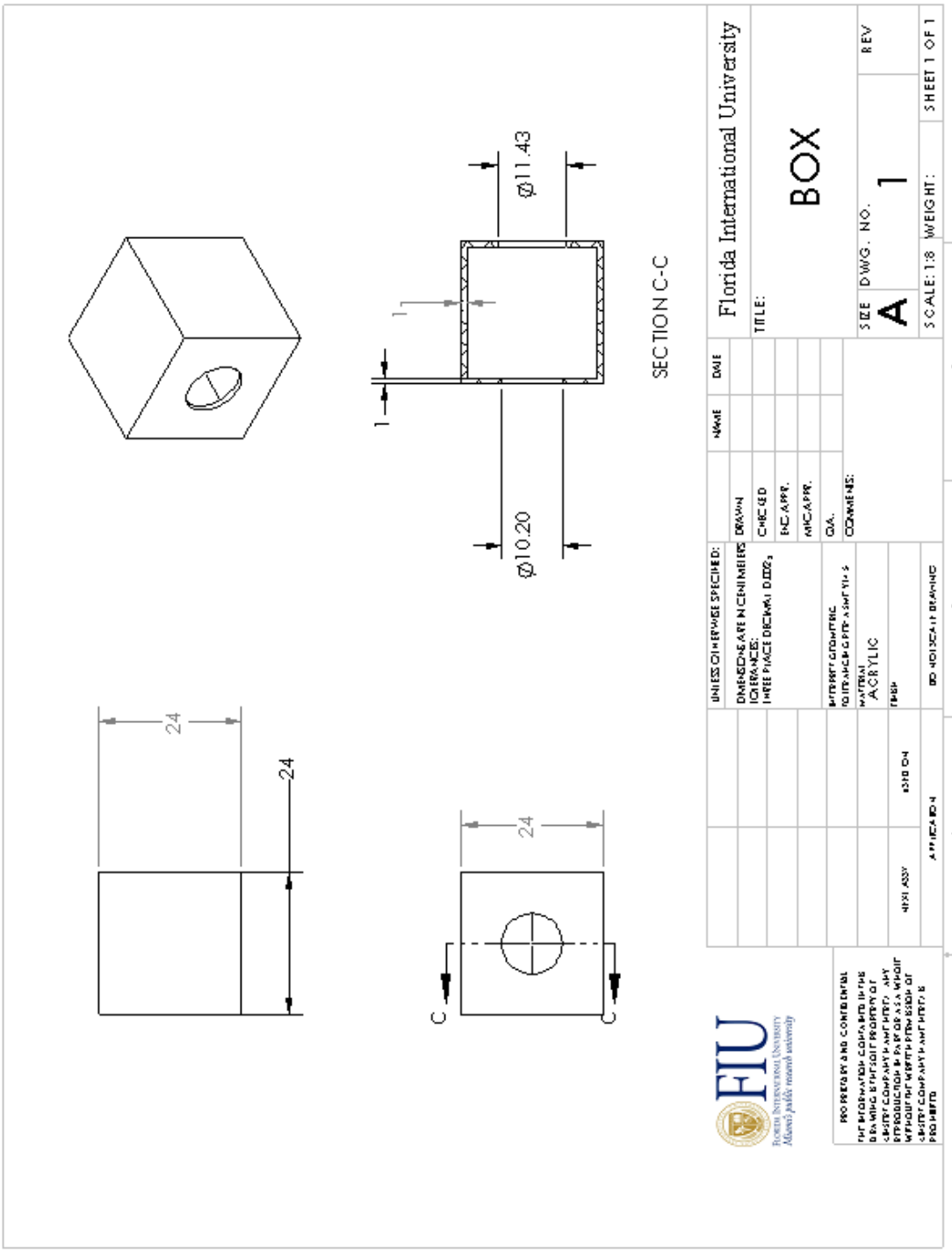


Figure 56 Technical drawing of the plenum chamber

7.2.4 Nozzle Construction

After considering various designs for the nozzle the team came up with a simple yet innovative idea to replicate the CAD model of the nozzle. Integration of two reduction pipes and proper modification of the nozzle permitted the team to replicate the nozzle with similar characteristics used in the CAD model. The following pictures illustrate some of the modifications made to the nozzle and how the construction was performed.

Figure 57 Filling the nozzle with resin

Figure 58 Partial dryness of the resin

The resin used inside of the custom nozzle allowed the designed to have a lower friction coefficient and minimize surface roughness by covering imperfections by creating an even surface profile inside the nozzle as shown in figure 58 to address the issues mentioned before.

7.2.5 Proposed Test-bench

As mentioned in previous chapters of the report, the MME Dept. currently owns a micro-turbine test stand that is used for teaching propulsion concepts. CINAS was design to interact with the micro-turbine and most of the characteristics from the micro-turbine were used to design the prototype. The test stand was modified to interact with CINAS in the most ergonomic way possible to reduce cost and to maintain full mobility of the system. The first modification was the placement of the thrust sensor. The prototype location conflicted with the bracket that holds the sensor. The bracket was moved several inches forward placing the sensor close to the micro-turbine. The bracket was cut short 5 inches from its original size and the case that encloses the sensor was rotated 90 degrees and new attaching holes were made using the CNC machine located in the FIU manufacturing shop.

Figure 59 Original bracket

Figure 60 CNC machine at FIU OU building

Figure 61 CNC machine in Progress

Figure 62 Modification of the bracket

Figure 63 Bracket Modification

Figure 64 Final set up of the bracket

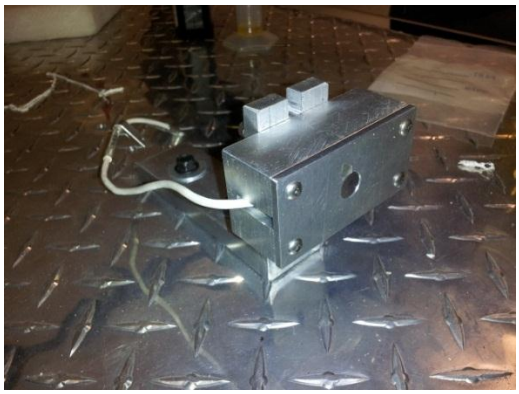


Figure 65 Final assembly of the thrust sensor

This modification did not change the instrumentation that records the thrust of the micro-turbine and allowed CINAS to perfectly interact with the micro-turbine. The second modification to the turbine was the implementation of a connector that could adapt to CINAS without restricting the air flow of the compressor and the electrical and fuel cables to be in their correct positions.

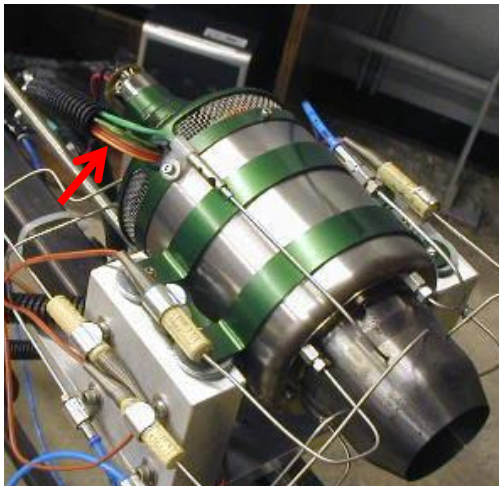


Figure 66 Electrical and fuel connections of the micro-turbine

The challenge to this modification was to find a mean of perfectly sealing the outer part of the micro-turbine allowing enough space for the cables and lines to be outside the connector. A reducer seal utilized in conventional piping was the perfect solution to the problem. The reducer allowed perfect sealing with a slight modification on the side and at the end to ensure a hermetic connection.

Figure 67 Seal connection (front view)

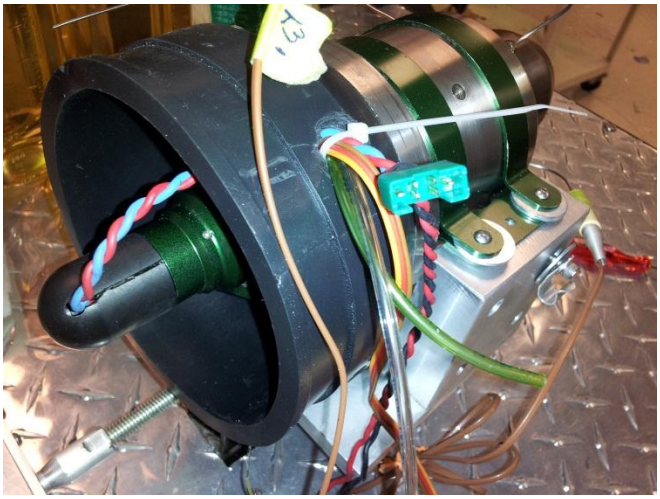


Figure 68 Seal connection (Side view)

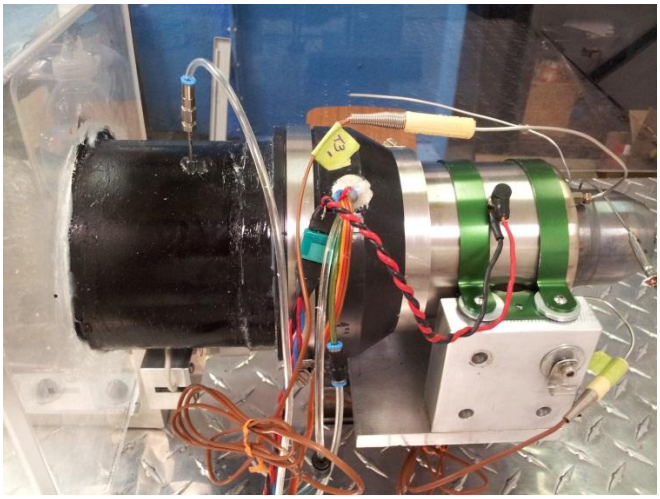


Figure 69 Seal connection to CINAS

The third modification was the installation of a Pitot tube to measure the pressure entering the turbine. Using the existing software and instrumentation a new sensor was placed between the micro-turbine and CINAS to record the pressures.

Figure 70 Pitot tube placement

The third modification was the addition of two supports one for the nozzle and the other for the plenum chamber. These supports help the system to be structurally stable and provide additional strength to the system. Some additional upgrades to the test stand included an extra fuel tank to increase the capacity of the existing tank to have an extend range of operation while testing also, a set of new wheels were installed to increase the mobility of the bench either inside or outside of the lab. A CAD model of the test bench is presented below as well as the finished test bench.

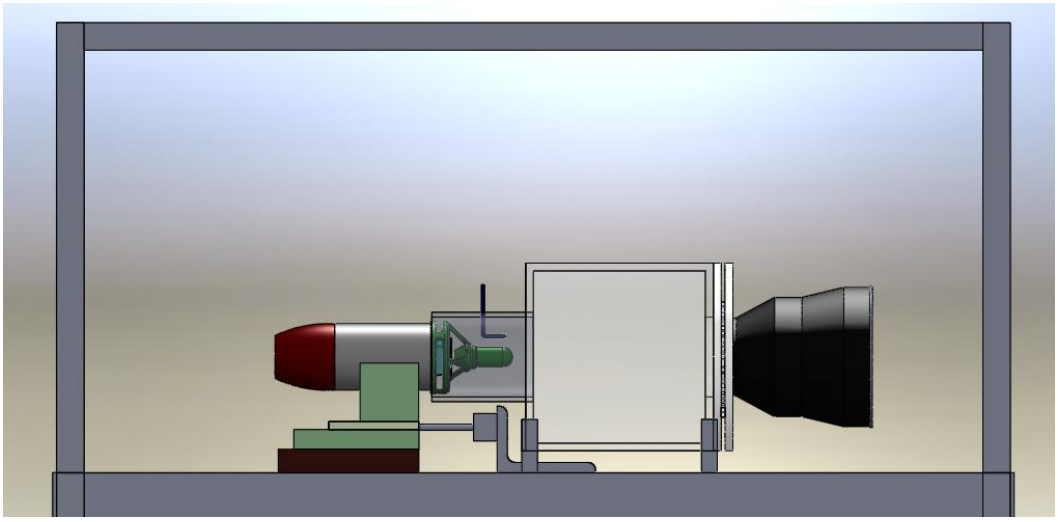


Figure 71 Proposed test bench CAD model

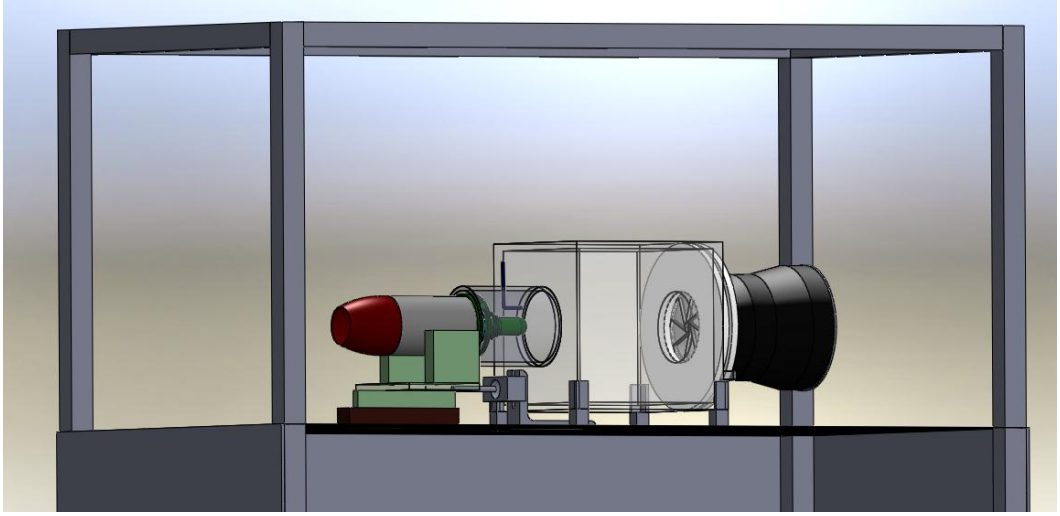


Figure 72 Isometric view of the test stand

7.2.6 Optional Test-bench

Due to time constraints and continuous maintenance to the micro-turbine test bench, an alternative way to test the prototype was implemented as a second option to compare results. An electric compressor fan was utilized to replicate the same volumetric flow rate as the micro-turbine to create the difference in air pressure at the outlet of CINAS. The main goal of the alternative device is to have a way of comparison between the testing systems. This device operates on a single speed, therefore as head increases volumetric flow decreases; not allowing having a constant volumetric flow rate through the experiment, yet it does allow proving the concept of the design to simulate altitude.

This test bench serves to manufacture the adaptation of the altitude simulator to the micro-turbine. A reduction pipe was used to connect the exit of the pvc of the altitude simulator to the inlet of the compressor fan and sealed using high strength liquid silicone. Additionally a hose clamp was used to secure the pipe to the compressor fan to ensure that the system contains no air leaks.

7.2.6.1 Evaluation of Optional Test-Bench

CFD analysis was performed using the specified volumetric flow rate of the compressor fan. This specific component was selected due to its similarity to the actual proposed testing component. In order to obtained accurate results, modification had to be made to the CAD model and a radial aperture variation of the iris mechanism was perform to study the relation between area and pressure drop. The following images show the results obtained from the CFD analysis.

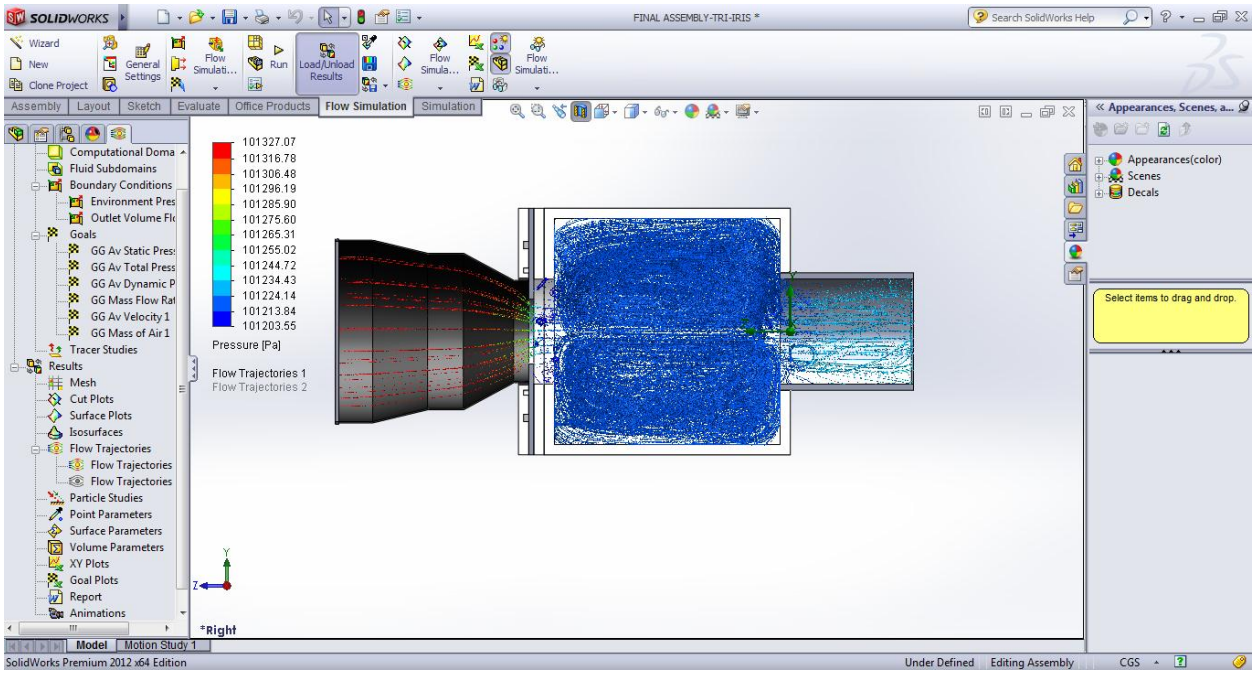


Figure 73 Optional Test-Bench Apperture Size 6.3cm

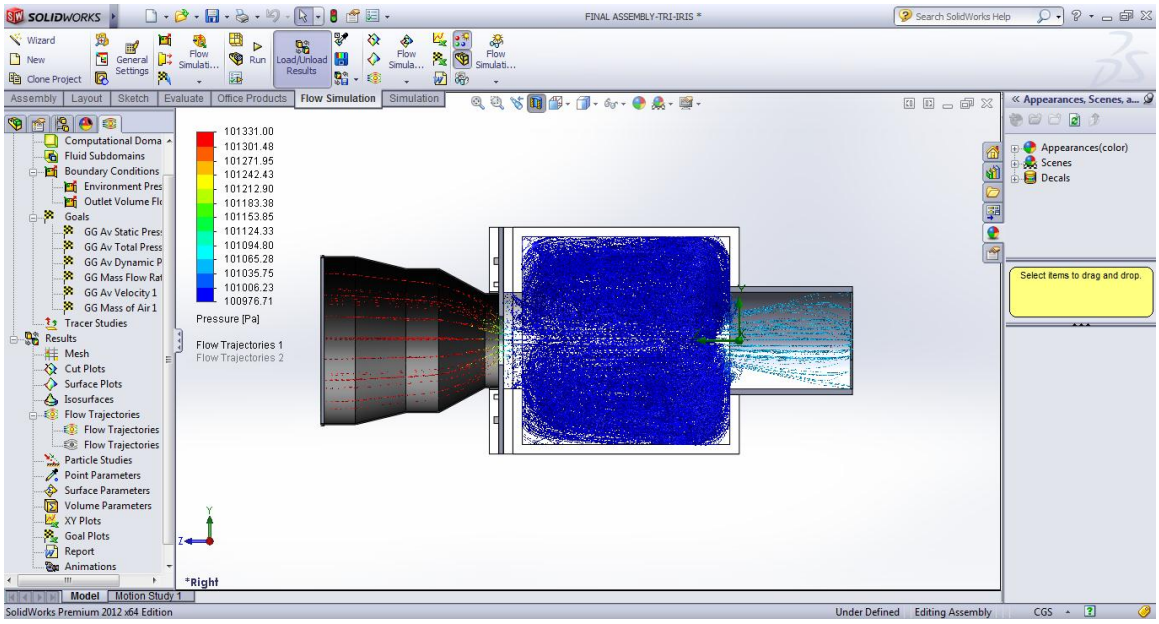


Figure 74 Optional Test-Bench Apperture Size 5.1cm

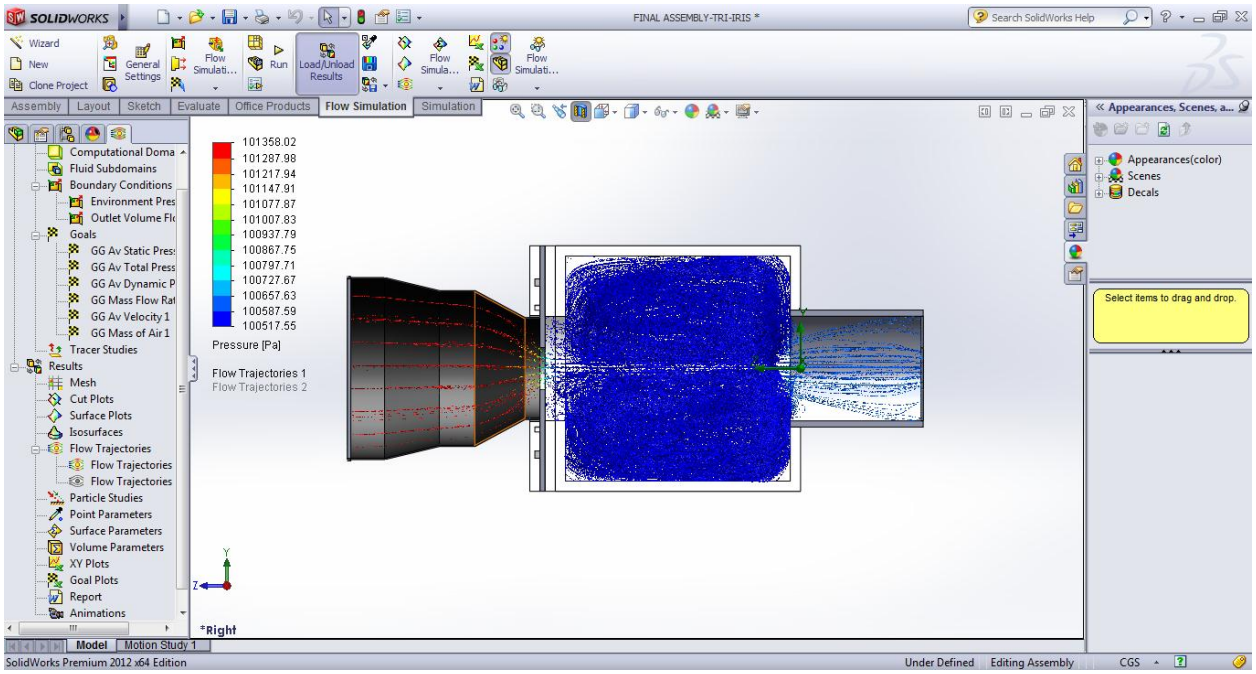


Figure 75 Optional Test-Bench Apperture Size 4.1cm

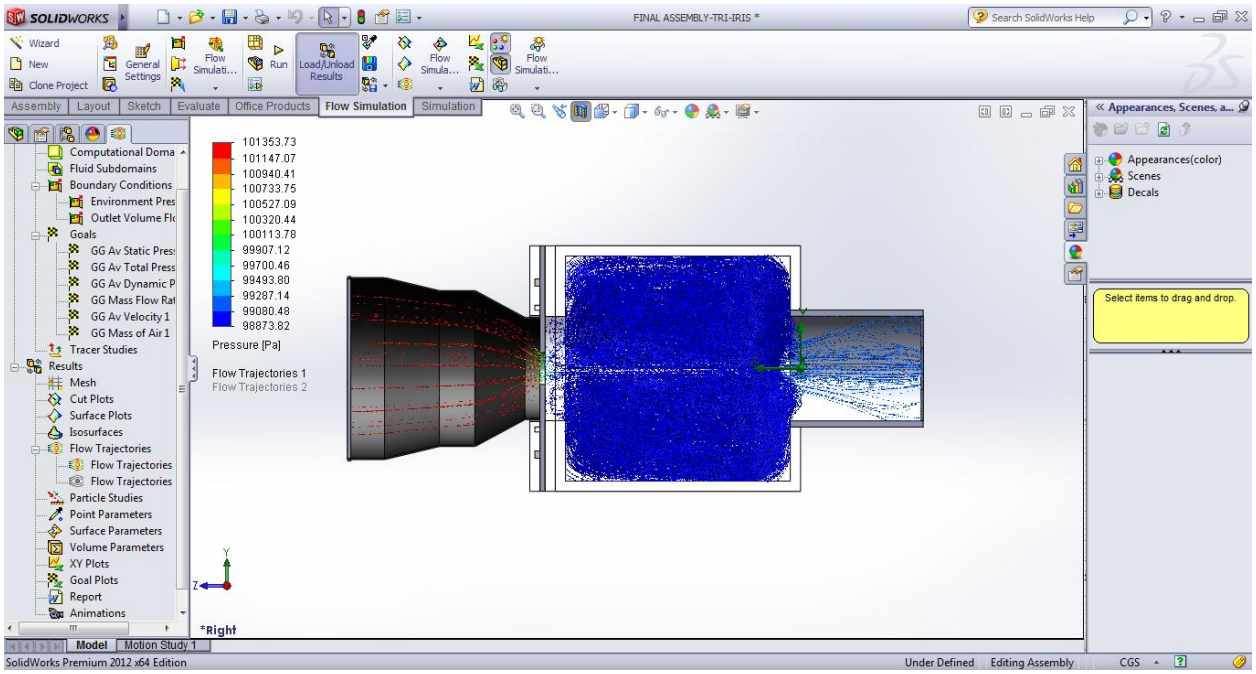


Figure 76 Optional Test-Bench Apperture Size 3.0cm

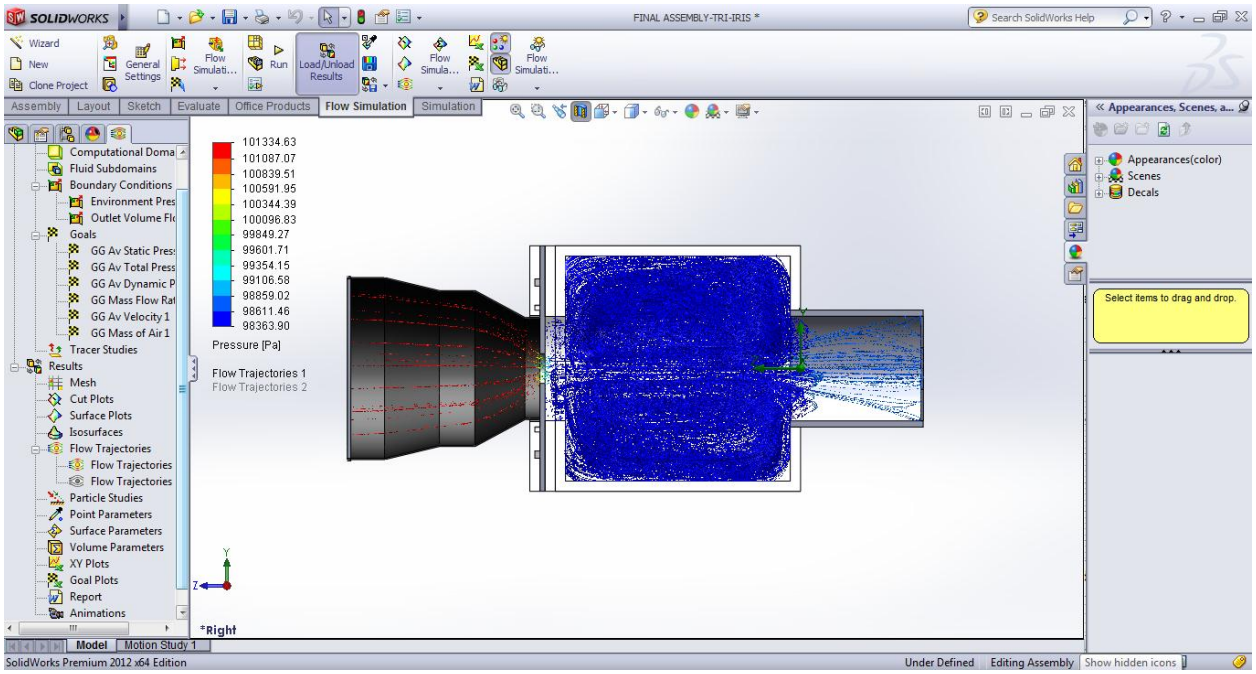


Figure 77 Optional Test-Bench Apperture Size 2.9cm

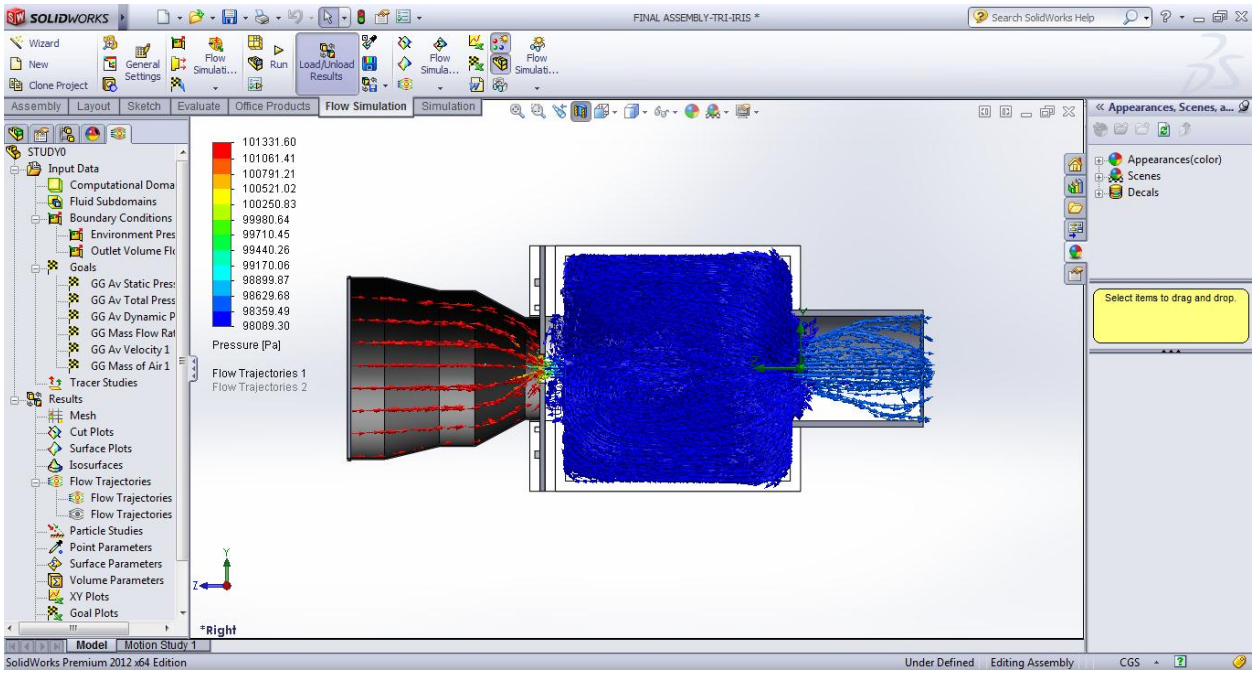


Figure 78 Optional Test-Bench Apperture Size 2.8 cm

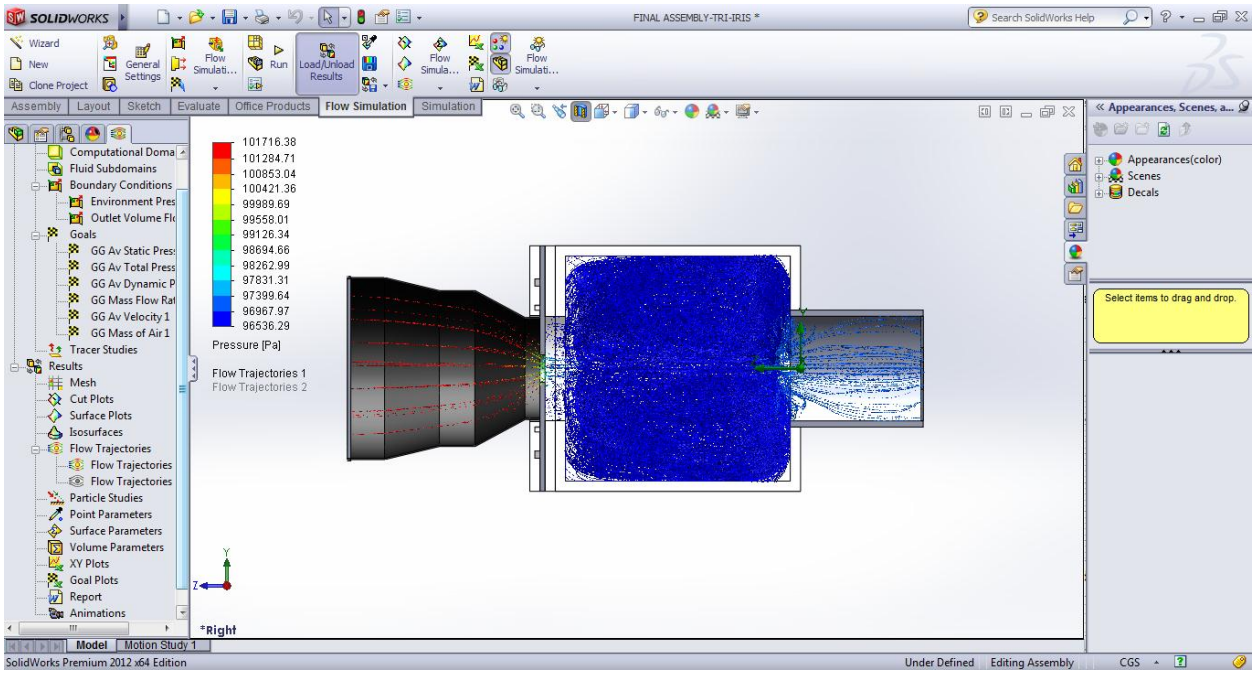


Figure 79 Optional Test-Bench Apperture Size 2.7 cm

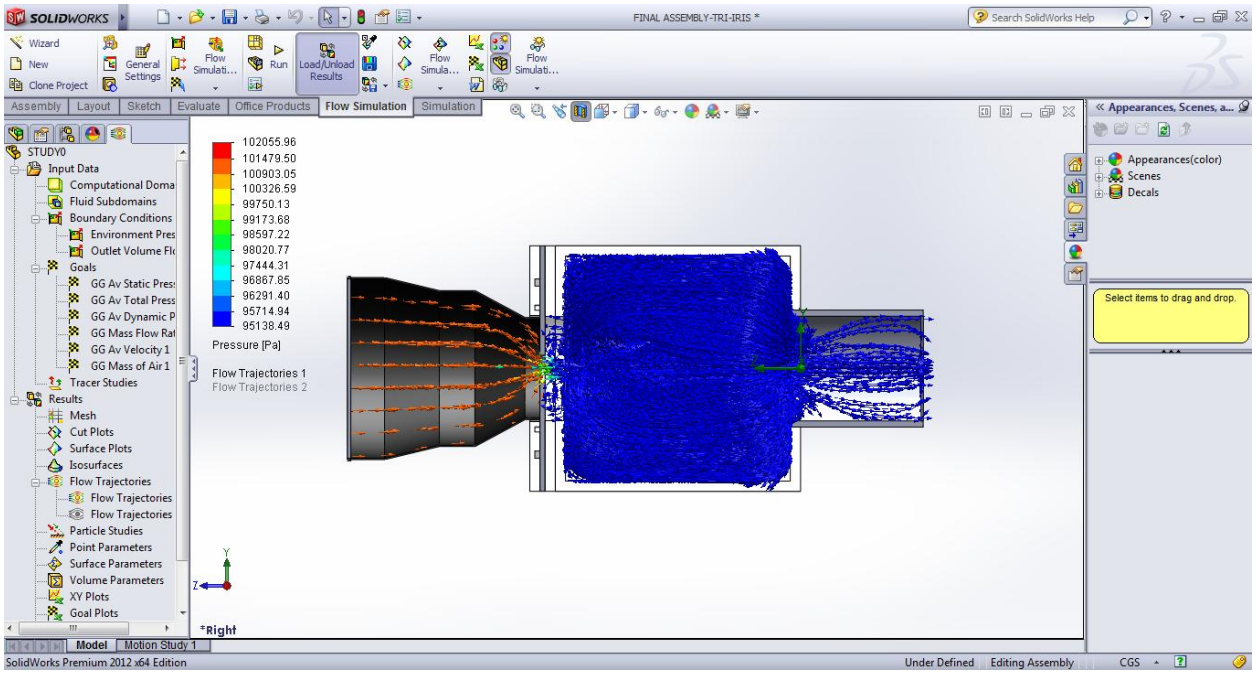


Figure 80 Optional Test-Bench Apperture Size 2.6 cm

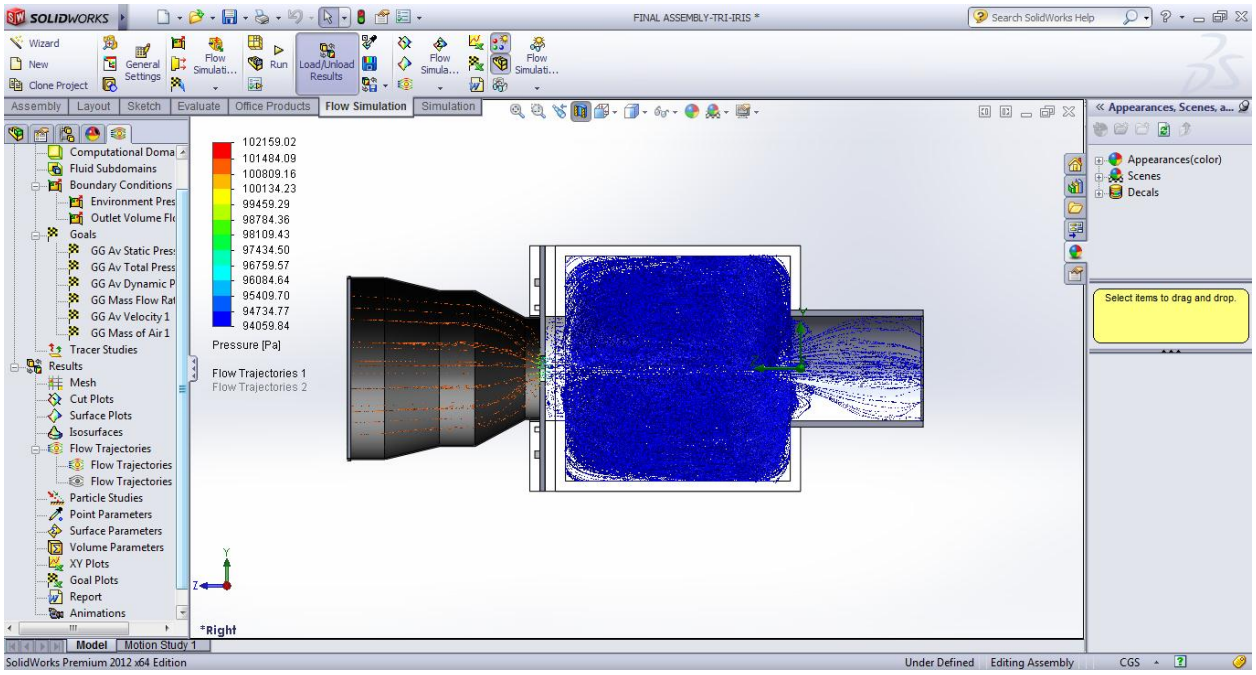


Figure 81 Optional Test-Bench Apperture Size 2.5cm

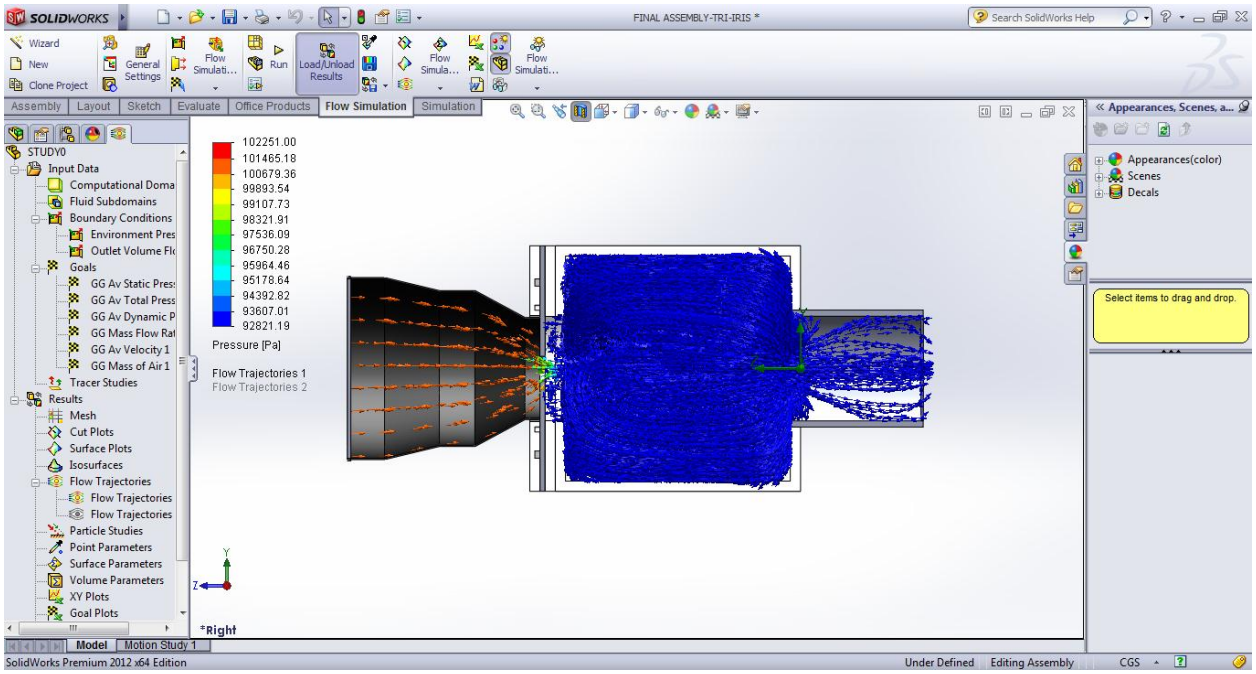


Figure 82 Optional Test-Bench Apperture Size 2.4cm

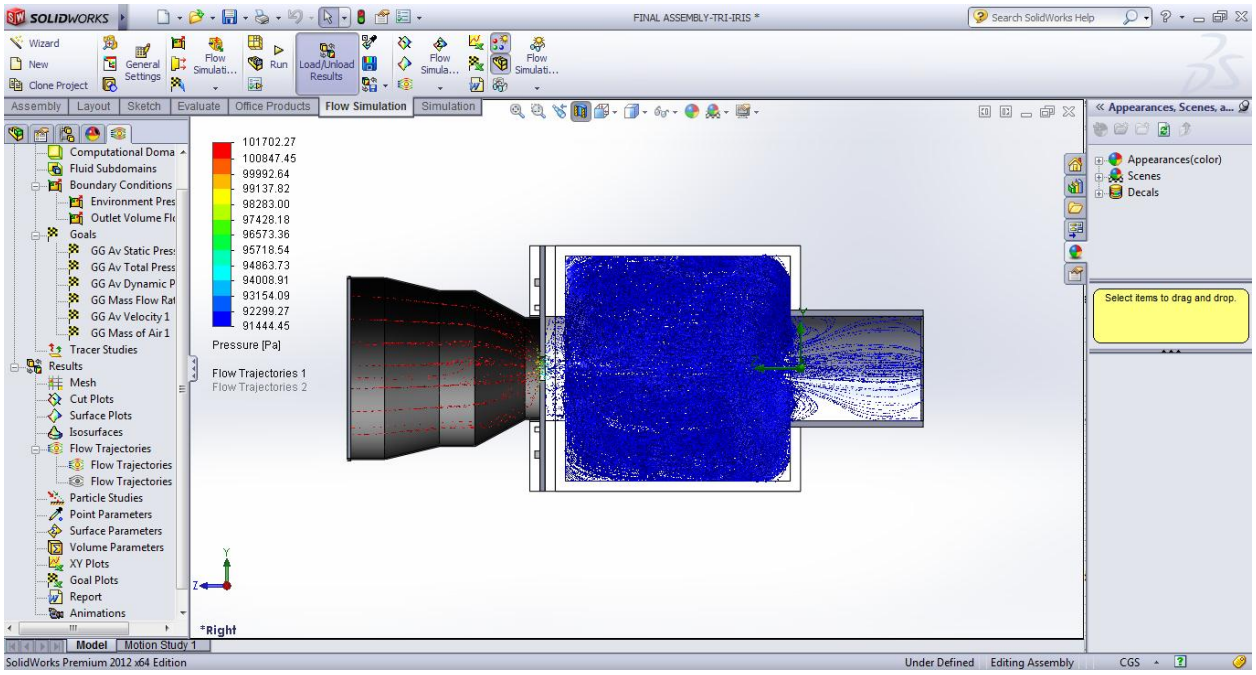


Figure 83 Optional Test-Bench Apperture Size 2.3cm

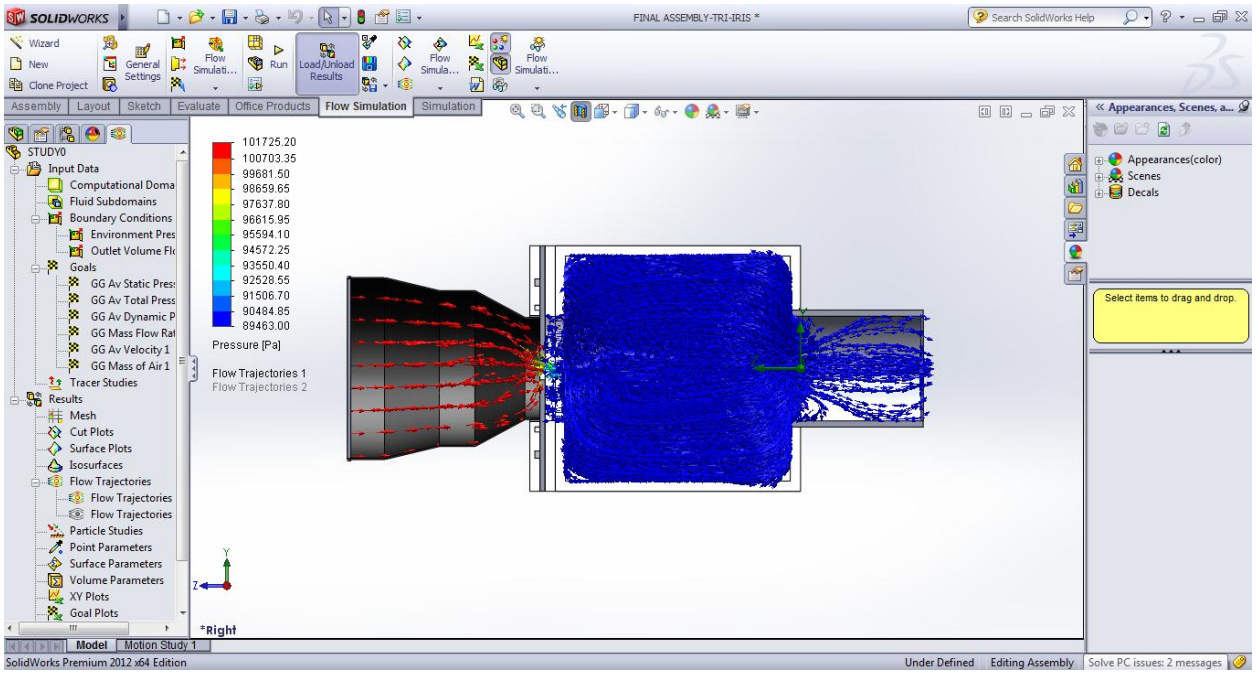


Figure 84 Optional Test-Bench Apperture Size 2.2cm

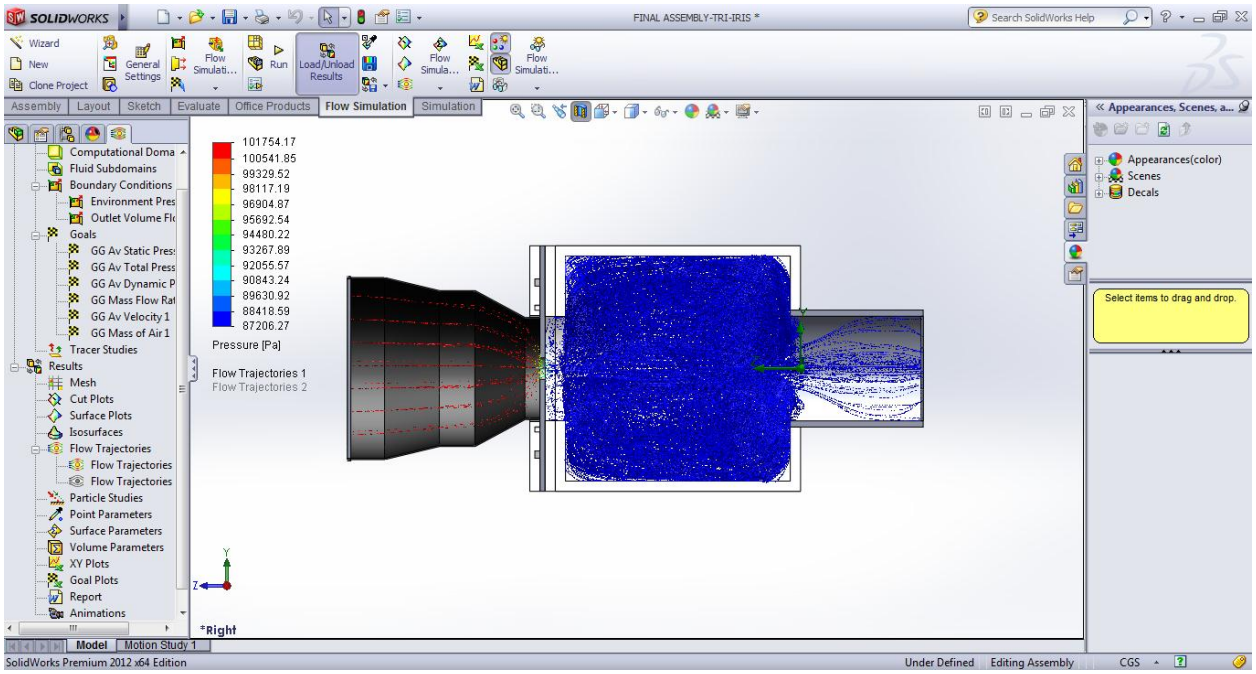


Figure 85 Optional Test-Bench Apperture Size 2.1cm

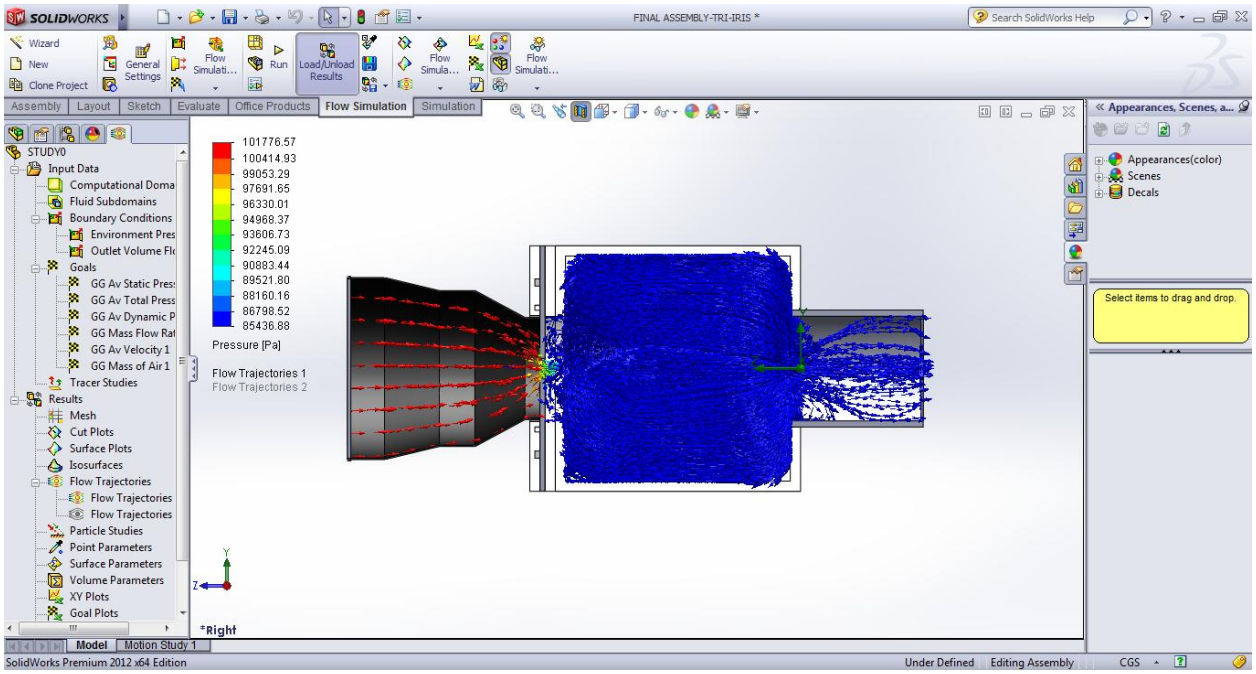


Figure 86 Optional Test-Bench Apperture Size 2.0cm

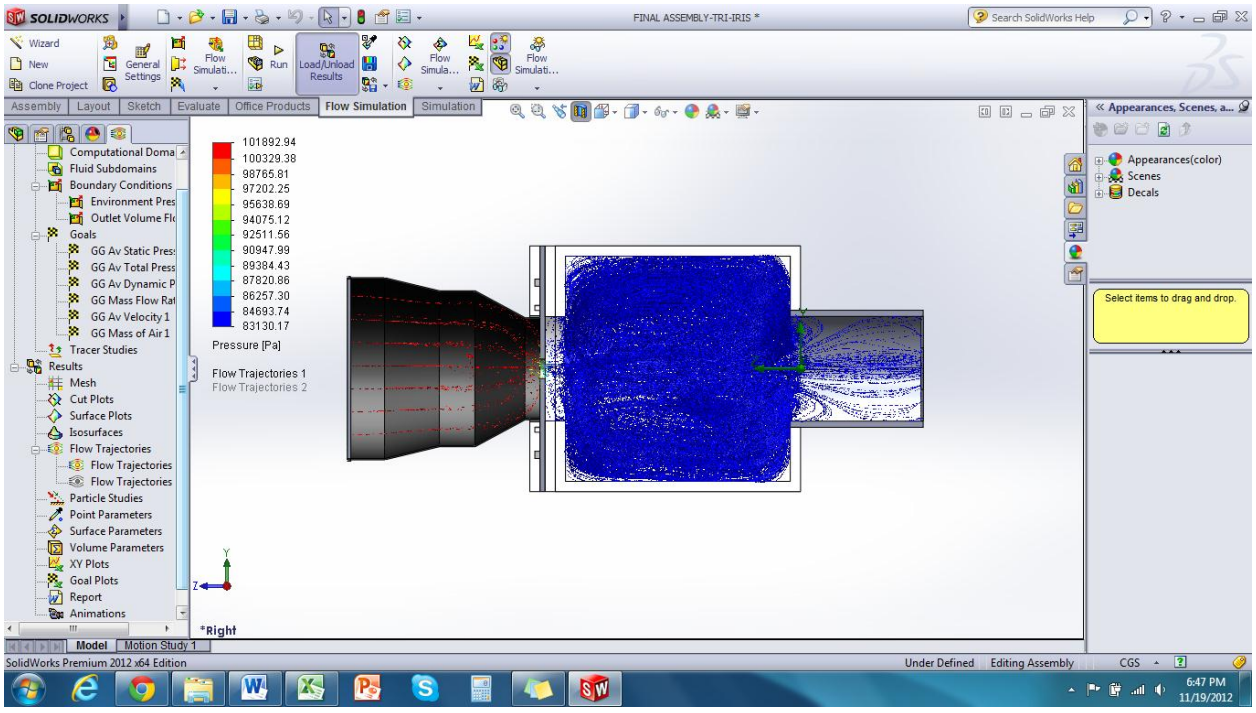


Figure 87 Optional Test-Bench Apperture Size 1.9cm

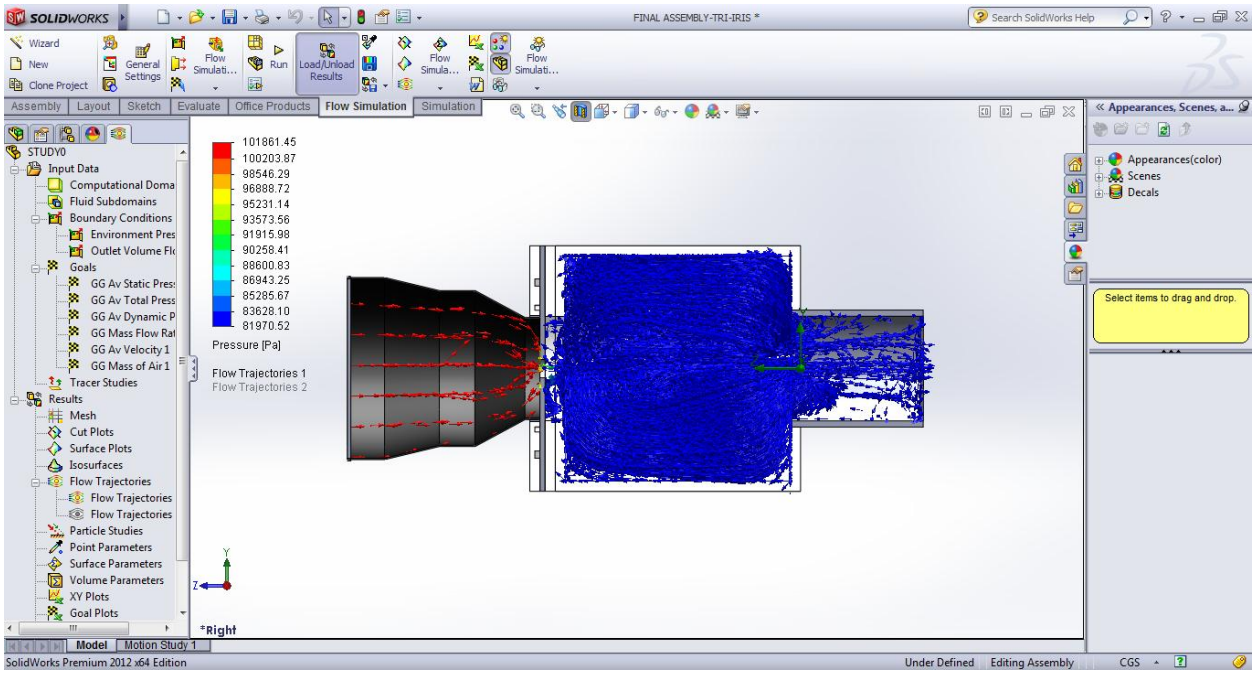


Figure 88 Optional Test-Bench Apperture Size 1.8cm

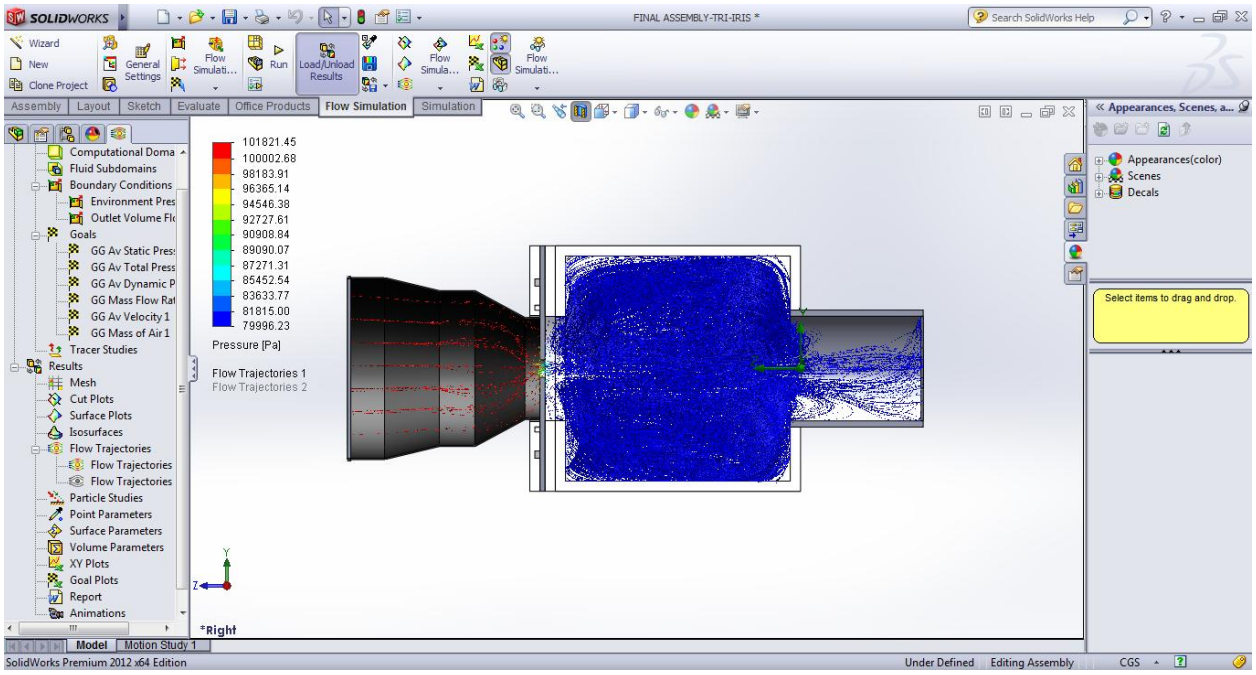


Figure 89 Optional Test-Bench Apperture Size 1.7cm

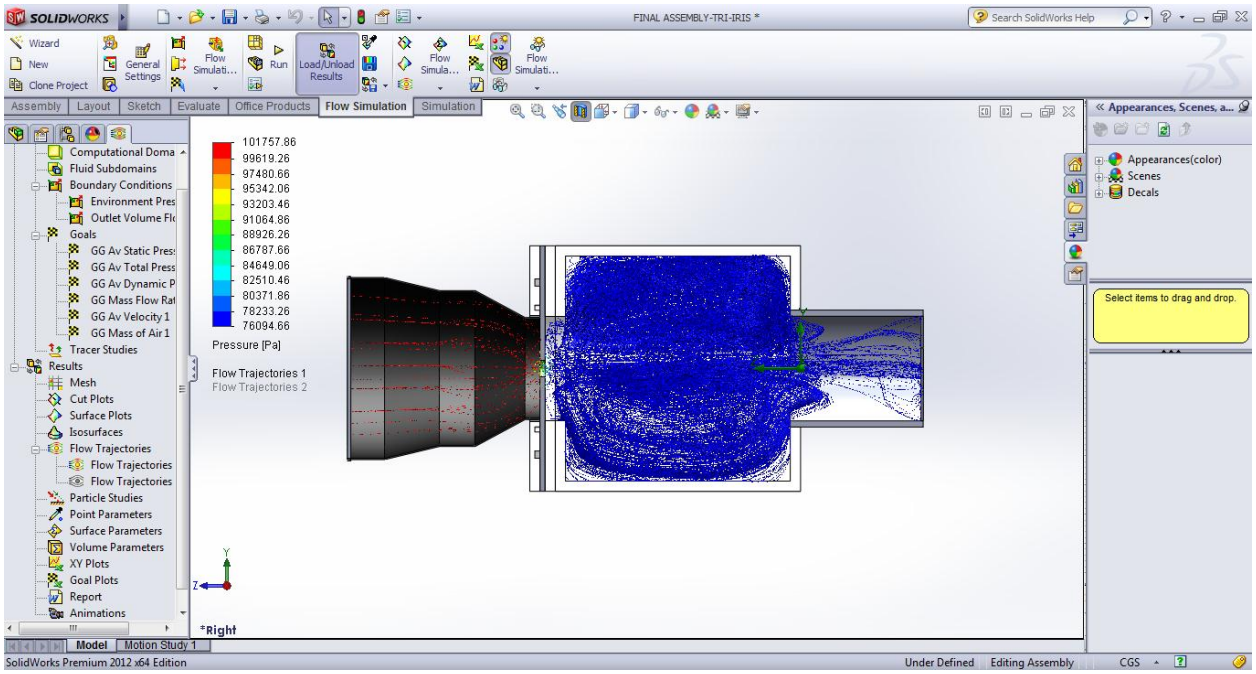


Figure 90 Optional Test-Bench Apperture Size 1.6cm

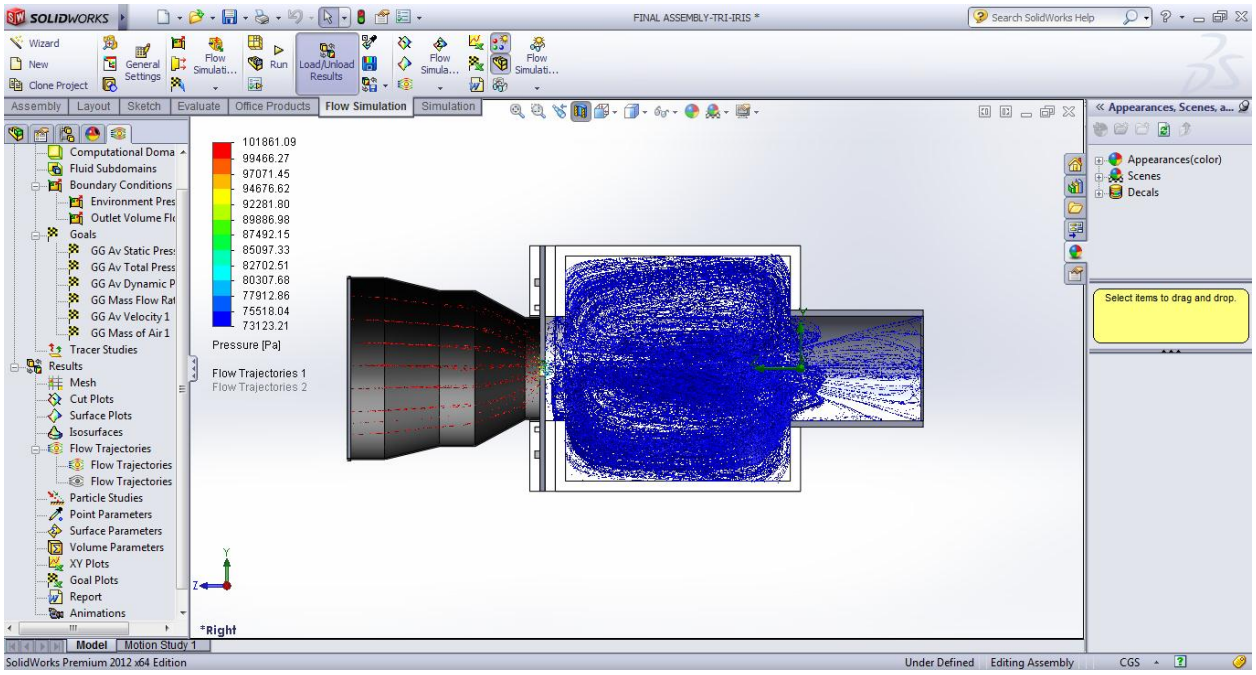


Figure 91 Optional Test-Bench Apperture Size 1.5cm

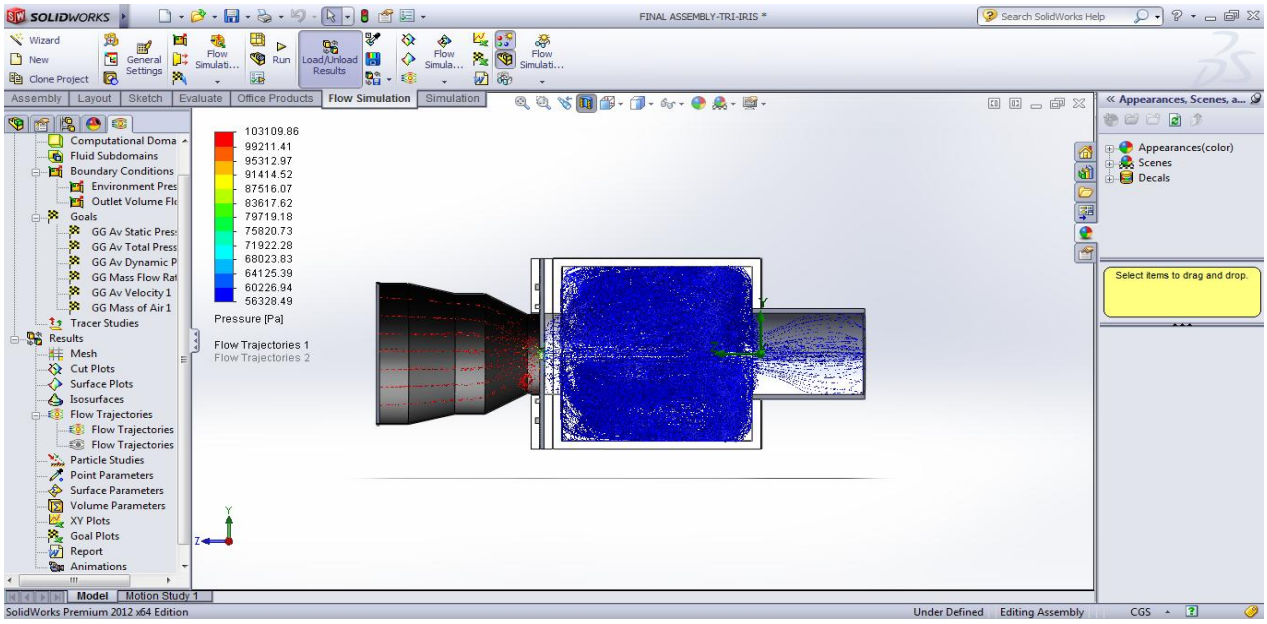


Figure 92 Optional Test-Bench Apperture Size 1.4cm

Table 10 Optional Test-Bench Altitude Analysis (SI)

Diameter (cm)	Area Opening (cm^2)	Average Pressure (Pa)	Altitude (m)
1.4	5.5	60226	4175.97
1.5	6.4	75518	2410.36
1.6	7.2	78233	2127.84
1.7	8.2	81815	1766.96
1.8	9.2	83628	1589.17
1.9	10.2	84693	1486.20
2.0	11.3	86798	1285.68
2.1	12.5	88412	1134.59
2.2	13.7	90484	943.87
2.3	15.0	92299	779.68
2.4	16.3	93607	662.97
2.5	17.7	94734	563.45
2.6	19.1	95714	477.71
2.7	20.6	96967	369.11
2.8	22.2	98359	249.78
2.9	23.8	98611	228.33
3.0	25.5	99080	188.49
3.3	30.8	99439	158.13

3.5	34.6	99798	127.83
3.7	38.7	100018	109.33
3.9	43.0	100885	36.67
4.1	47.5	100517	64.10
4.3	52.3	100670	54.65
4.5	57.3	100789	44.68
4.7	62.5	100841	40.36
4.9	67.9	100907	34.84
5.1	73.6	100976	29.08
5.3	79.5	101048	23.07
5.5	85.6	101087	19.81
5.7	91.9	101130	16.25
5.9	98.5	101152	14.42
6.1	105.2	101175	12.50
6.3	112.3	101205	10.00

Table 11 Optional Test-Bench Altitude Analysis (US)

Diameter (in)	Area Opening (in^2)	Average Pressure (Pa)	Altitude (ft)
0.6	0.86	8.74	13700.7
0.6	0.99	10.95	7908
0.6	1.12	11.35	6981.1
0.7	1.27	11.87	5797.1
0.7	1.42	12.13	5213.8
0.7	1.58	12.28	4876
0.8	1.75	12.59	4218.1
0.8	1.93	12.82	3722.4
0.9	2.12	13.12	3096.7
0.9	2.32	13.39	2558
0.9	2.53	13.58	2175.1
1.0	2.74	13.74	1848.6
1.0	2.96	13.88	1567.3
1.1	3.20	14.06	1211
1.1	3.44	14.27	819.5
1.1	3.69	14.30	749.1
1.2	3.95	14.37	618.4
1.3	4.77	14.42	518.8
1.4	5.37	14.47	419.4

1.5	6.00	14.51	358.7
1.5	6.67	14.63	120.3
1.6	7.37	14.58	210.3
1.7	8.11	14.60	179.3
1.8	8.88	14.62	146.6
1.9	9.68	14.63	132.4
1.9	10.53	14.64	114.3
2.0	11.40	14.65	95.4
2.1	12.31	14.66	75.7
2.2	13.26	14.66	65
2.2	14.24	14.67	53.3
2.3	15.26	14.67	47.3
2.4	16.31	14.67	41
2.5	17.40	14.68	32.8

The following graphs represent the changes in pressure and altitude produced by changing the exit orifice or iris mechanism at the exit of the nozzle. This diameter is reduced from the fully open position of 6.3cm or 2.48 in to 1.4cm or 0.6in. As the area of the iris is reduced, a pressure drop is produced reaching values as low as 60226 Pascal's or 8.74 psi which corresponds to an altitude of 4175 meters or 13700 feet's.

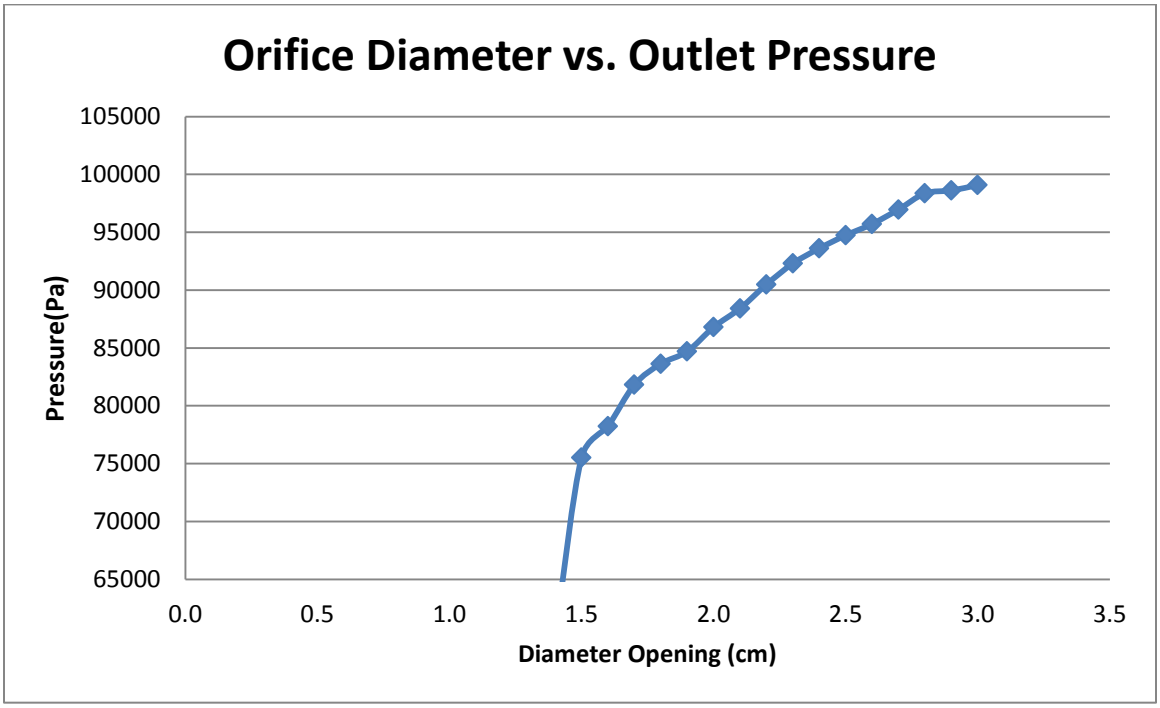


Figure 93 Optional Test-Bench Orifice Diameter vs. Outlet Pressure

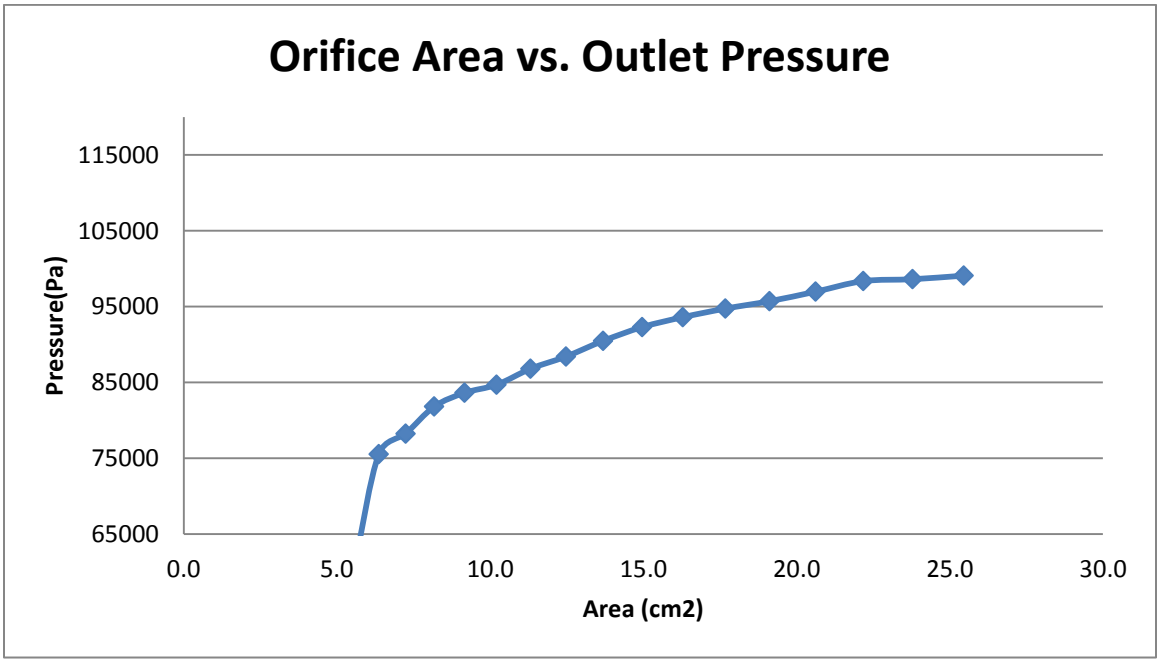


Figure 94 Optional Test-Bench Orifice Area vs. Outlet Pressure

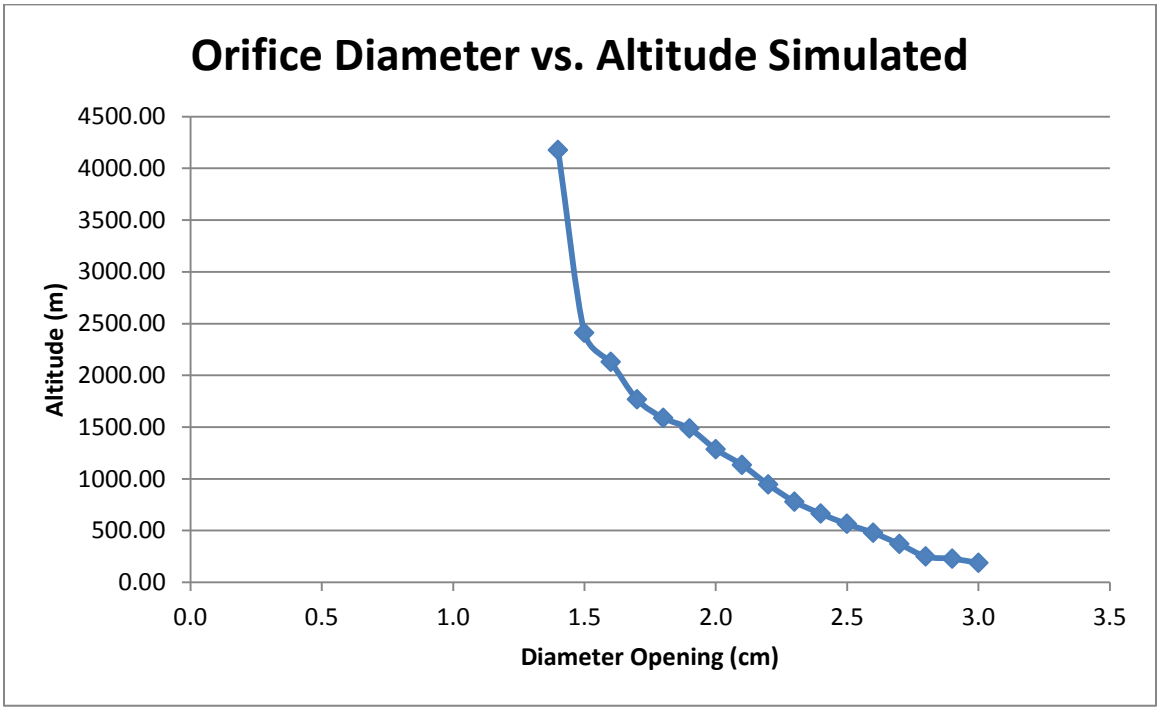


Figure 95 Optional Test-Bench Orifice Diameter vs. Altitude Simulated

8. Testing and Evaluation

8.1 Overview

Testing and evaluation of the designed product is important to verify the analysis done on each component as well as the effectiveness of the design. The system is tested using Computational fluid dynamics (CFD) using several CAD software's such as Solidworks. This testing will be done with the volumetric flow rate that the micro-turbine is able to generate given by the manufacturer. Once the prototype is built, it is tested with a Wren MK3-MW54 micro-turbine that generates the mass flow rate used for the design at 60000 RPM's. A pitot tube will be inserted at the exit of the plenum chamber, to

measure the exit pressure of the system and into the micro-turbine. An error analysis can be calculated from theoretical pressure achieved in the analytical and computational analysis and the actual pressure achieved measured with the pitot tube. Additionally, an optional testing is proposed with a device that produces a constant volumetric flow rate of 0.296 m^3/s.

After numerous design revisions of CINAS the final design was tested using the compressor fan and the micro-turbine test bench. Both tests are compared against the theoretical results obtained in CFD and statistical data will be presented to analyze the results.

8.2 Proposed Testing

After making the proper adjustments between the micro-turbine and CINAS, initial testing was conducted to obtain real life results. The micro-turbine had to undergone numerous inspections and maintenance in order to have a reliable working device to ensure that the system would work accordingly to plan.

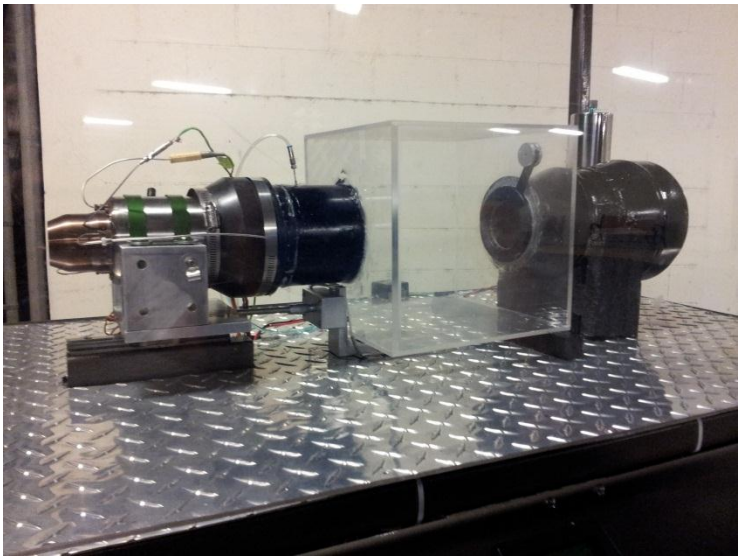


Figure 96 Final set up of CINAS (front view)

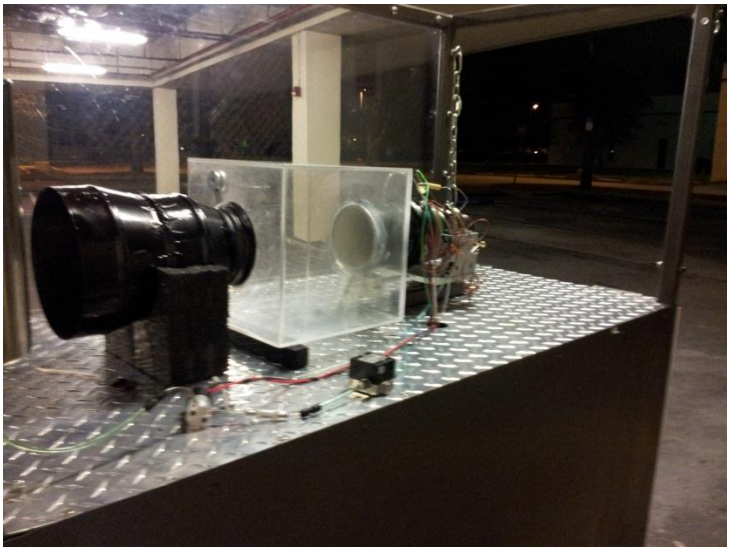


Figure 97 Final set up of CINAS (back view)

The following charts and graphs will present the data obtained from the test.

Table 12 Proposed Testing Altitude Analysis (SI)

Diameter (cm)	Tick Mark	Area (cm^2)	Time (sec)	RPM	Ave. Pressure (Pa)	Altitude (m)
6.3	0.5	31.17	210	123000	99999.62	110.83
6.2	1	30.19	227	123000	99991.26	111.68
6	2	28.27	255	123000	99992.53	111.86
5.8	3	26.42	280	123000	99954.68	115.03
5.6	4	24.63	295	123000	99816.87	125.97
5.4	5	22.90	320	123000	99609.56	143.68
5.2	6	21.24	340	123000	99609.56	144.54
5	7	19.63	360	123000	99205.10	177.49
4.8	8	18.10	115	123000	98433.25	243.72
4.6	9	16.62	130	123000	97854.66	293.25
4.4	10	15.21	150	123000	97161.60	352.47
4.2	11	13.85	305	130000	96305.54	425.90
4	12	12.57	330	138000	94279.64	603.44
3.8	13	11.34	30	141000	93284.73	692.02
3.6	14	10.18	325	144000	92146.79	793.06
3.4	15	9.08	105	151000	91774.21	827.26

Table 13 Proposed Testing Altitude Analysis (US)

Diameter (in)	Tick Mark	Area (in^2)	Time (sec)	RPM	Ave. Pressure (psi)	Altitude (ft)
2.48	0.5	4.83	210	123000	14.50	363.60
2.44	1	4.68	227	123000	14.50	366.40
2.36	2	4.38	255	123000	14.50	367.00
2.28	3	4.10	280	123000	14.50	377.40
2.20	4	3.82	295	123000	14.48	413.30
2.13	5	3.55	320	123000	14.45	471.40
2.05	6	3.29	340	123000	14.45	474.20
1.97	7	3.04	360	123000	14.39	582.30
1.89	8	2.80	115	123000	14.28	799.60
1.81	9	2.58	130	123000	14.19	962.10
1.73	10	2.36	150	123000	14.09	1156.40
1.65	11	2.15	305	130000	13.97	1397.30

1.57	12	1.95	330	138000	13.67	1979.80
1.50	13	1.76	30	141000	13.53	2270.40
1.42	14	1.58	325	144000	13.36	2601.90
1.34	15	1.41	105	151000	13.31	2714.10

The following graphs represent the changes in pressure and altitude produced by changing the exit orifice or iris mechanism at the exit of the nozzle. This diameter is reduced from the fully open position of 6.3cm or 2.48 in to 3.4cm or 1.34in. As the area of the iris is reduced, a pressure drop is produced reaching values as low as 91774 Pascal's or 13.31 psi which corresponds to an altitude of 827.2 meters or 2714.1 feet's.

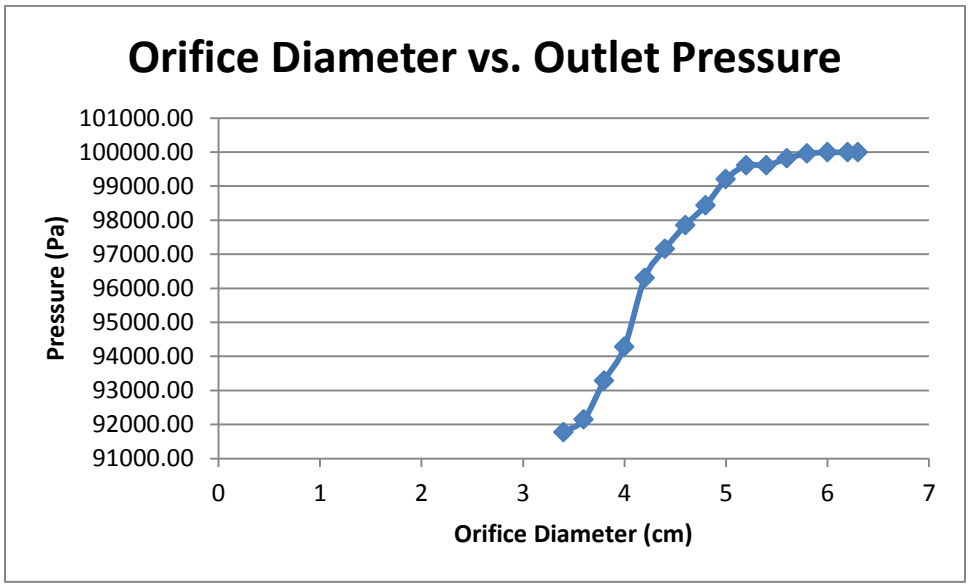


Figure 98 Proposed Testing Orifice Diameter vs. Outlet Pressure

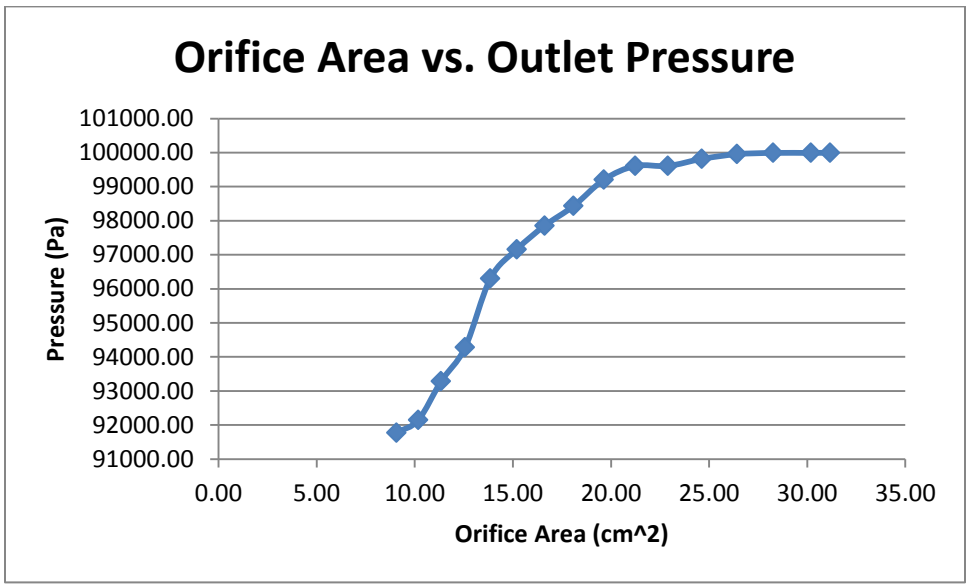


Figure 99 Proposed Testing Orifice Area vs. Outlet Pressure

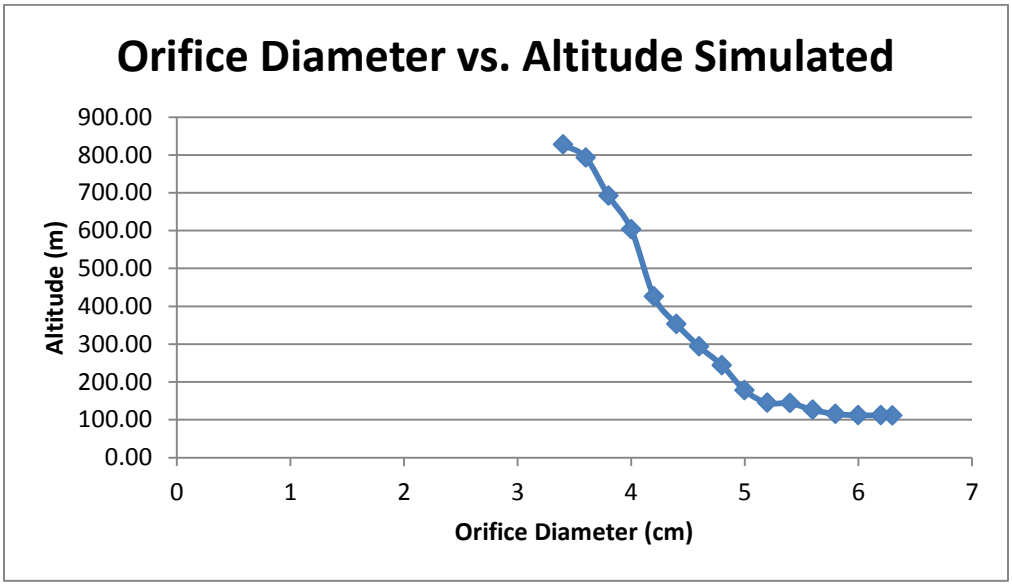


Figure 100 Proposed Testing Orifice Diameter vs. Altitude Simulated

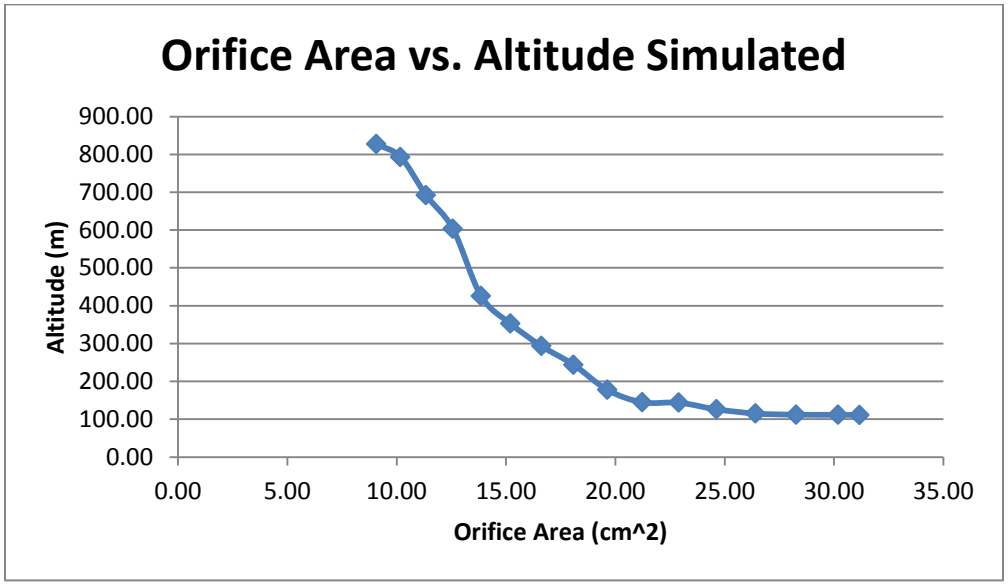


Figure 101 Proposed Testing Orifice Area vs. Altitude Simulated

8.3 Optional Testing

As an alternative way of testing our prototype, as mentioned earlier, an external compressor fan was used. This system gave us an idea on how the prototype was going to react to the changes of pressure before the real test was going to be conducted. The device provided us with a similar volumetric flow rate.

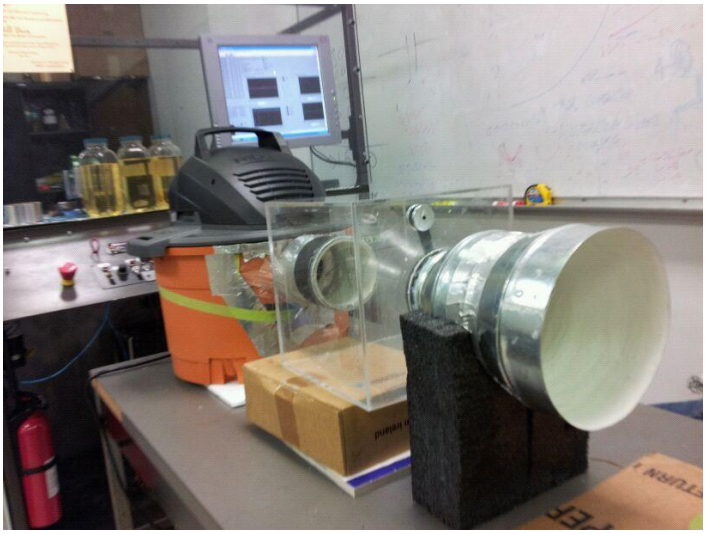


Figure 102 Alternative device used to test CINAS

The following charts and graphs will explain the data obtained thru the experiment.

Table 14 Optional Design Trial 1 (SI & US)

Trial 1 SI					
Diameter (cm)	**Tick Mark**	**Area (cm^2)**	**Time (sec)**	**Ave. Pressure (Pa)**	**Altitude (m)**
6.30	0.5	31.17	-	-	-
6.20	1	30.19	-	-	-
6.00	2	28.27	-	-	-
5.80	3	26.42	-	-	-
5.60	4	24.63	-	-	-
5.40	5	22.90	-	-	-
5.20	6	21.24	-	-	-
5.00	7	19.63	40	99947.02	115.03
4.80	8	18.10	70	99871.48	121.77
4.60	9	16.62	100	99867.73	121.77

4.40	10	15.21	130	99857.51	122.62
4.20	11	13.85	160	99742.95	132.74
4.00	12	12.57	190	99693.09	136.95
3.80	13	11.34	220	99605.50	143.68
3.60	14	10.18	250	99520.46	151.27
3.40	15	9.08	280	99345.23	165.66
3.20	16	8.04	310	99100.59	186.81
3.00	17	7.07	350	98823.75	210.56
2.90	17.5	6.61	380	98709.83	219.91
2.80	18	6.16	410	98502.37	237.77
2.70	18.5	5.73	440	98275.50	256.52
2.60	19	5.31	470	98187.19	264.20
2.50	19.5	4.91	500	97785.85	298.40
2.40	20	4.52	530	97501.29	323.24
2.30	20.5	4.15	560	97186.09	349.88
2.20	21	3.80	590	97078.99	359.36
2.10	21.5	3.46	620	96775.00	385.24
2.00	22	3.14	650	96335.26	423.31
1.90	22.5	2.84	680	95897.09	461.53
1.80	23	2.54	710	95761.58	473.69
1.70	23.5	2.27	740	95224.66	520.84
1.60	24	2.01	770	94842.86	554.16
1.50	24.5	1.77	800	94563.91	578.75
1.40	25	1.54	830	94023.96	626.39
1.30	25.5	1.33	860	93387.56	682.23
1.20	26	1.13	890	93609.10	662.70
1.10	26.5	0.95	920	93287.40	691.13

1.00	27	0.79	950	92819.35	733.01
0.90	27.5	0.64	980	92634.31	750.02
0.80	28	0.50	1010	92376.46	772.39
0.70	28.5	0.38	1040	92170.10	791.26
0.60	29	0.28	1070	91749.64	829.06
0.50	29.5	0.20	1100	91480.95	853.44
0.40	30	0.13	1130	91134.73	885.11
0.30	30.5	0.07	1170	90950.00	901.45
0.20	31	0.03	1220	90904.00	905.99
0.10	31.5	0.01	1250	90795	915.98
0.00	32	0.00	1280	90632	930.55

Trial 1 US

Diameter (in)	**Tick Mark**	**Area (in^2)**	**Time (sec)**	**Ave. Pressure (psi)**	**Altitude (ft)**
2.48	0.5	4.83	-	-	-
2.44	1	4.68	-	-	-
2.36	2	4.38	-	-	-
2.28	3	4.10	-	-	-
2.20	4	3.82	-	-	-
2.13	5	3.55	-	-	-
2.05	6	3.29	-	-	-
1.97	7	3.04	40	14.50	377.40
1.89	8	2.80	70	14.49	399.50
1.81	9	2.58	100	14.48	399.50

1.73	10	2.36	130	14.48	402.30
1.65	11	2.15	160	14.47	435.50
1.57	12	1.95	190	14.46	449.30
1.50	13	1.76	220	14.45	471.40
1.42	14	1.58	250	14.43	496.30
1.34	15	1.41	280	14.41	543.50
1.26	16	1.25	310	14.37	612.90
1.18	17	1.10	350	14.33	690.80
1.14	17.5	1.02	380	14.32	721.50
1.10	18	0.95	410	14.29	780.10
1.06	18.5	0.89	440	14.25	841.60
1.02	19	0.82	470	14.24	866.80
0.98	19.5	0.76	500	14.18	979.00
0.94	20	0.70	530	14.14	1060.50
0.91	20.5	0.64	560	14.10	1147.90
0.87	21	0.59	590	14.08	1179.00
0.83	21.5	0.54	620	14.04	1263.90
0.79	22	0.49	650	13.97	1388.80
0.75	22.5	0.44	680	13.91	1514.20
0.71	23	0.39	710	13.89	1554.10
0.67	23.5	0.35	740	13.81	1708.80
0.63	24	0.31	770	13.76	1818.10
0.59	24.5	0.27	800	13.72	1898.80
0.55	25	0.24	830	13.64	2055.10
0.51	25.5	0.21	860	13.54	2238.30
0.47	26	0.18	890	13.58	2174.20
0.43	26.5	0.15	920	13.53	2267.50

0.39	27	0.12	950	13.46	2404.90
0.35	27.5	0.10	980	13.44	2460.70
0.31	28	0.08	1010	13.40	2534.10
0.28	28.5	0.06	1040	13.37	2596.00
0.24	29	0.04	1070	13.31	2720.00
0.20	29.5	0.03	1100	13.27	2800.00
0.16	30	0.02	1130	13.22	2903.90
0.12	30.5	0.01	1170	13.19	2957.50
0.08	31	0.00	1220	13.18	2972.40
0.04	31.5	0.00	1250	13.17	3005.2
0.00	32	0.00	1280	13.15	3053

Table 15 Optional Test Trial 2 (SI & US)

Trial 2					
Diameter (cm)	**Tick Mark**	**Area (cm^2)**	**Time (sec)**	**Ave. Pressure (Pa)**	**Altitude (m)**
6.3	0.5	31.17	-	-	-
6.2	1	30.19	-	-	-
6	2	28.27	-	-	-
5.8	3	26.42	-	-	-
5.6	4	24.63	-	-	-
5.4	5	22.90	-	-	-
5.2	6	21.24	-	-	-
5	7	19.63	40	99644.18	141.15288
4.8	8	18.10	70	99587.41	145.3896
4.6	9	16.62	100	99683.80	137.80008
4.4	10	15.21	130	99542.22	149.59584

4.2	11	13.85	160	99477.40	154.65552
4	12	12.57	190	99383.49	163.09848
3.8	13	11.34	220	99213.78	177.48504
3.6	14	10.18	250	99006.96	194.43192
3.4	15	9.08	280	98820.82	210.55584
3.2	16	8.04	310	98709.28	219.9132
3	17	7.07	350	98650.98	225.00336
2.9	17.5	6.61	380	98335.34	251.39904
2.8	18	6.16	410	98171.50	265.90752
2.7	18.5	5.73	440	97930.31	286.39008
2.6	19	5.31	470	97566.55	317.23584
2.5	19.5	4.91	500	97412.31	330.98232
2.4	20	4.52	530	97281.24	342.138
2.3	20.5	4.15	560	97089.39	358.50576
2.2	21	3.80	590	96644.33	397.33728
2.1	21.5	3.46	620	96349.26	422.4528
2	22	3.14	650	96084.43	445.86144
1.9	22.5	2.84	680	95754.99	474.5736
1.8	23	2.54	710	95313.02	512.9784
1.7	23.5	2.27	740	94857.94	552.38904
1.6	24	2.01	770	94515.24	582.28992
1.5	24.5	1.77	800	94052.90	623.74272
1.4	25	1.54	830	93847.75	641.42112
1.3	25.5	1.33	860	93484.69	674.24808
1.2	26	1.13	890	93227.78	696.468
1.1	26.5	0.95	920	92809.12	733.92792
1	27	0.79	950	92538.91	758.06808

0.9	27.5	0.64	980	92405.40	769.71144
0.8	28	0.50	1010	92098.41	795.74136
0.7	28.5	0.38	1040	92015.84	804.73296
0.6	29	0.28	1070	91432.01	857.95104
0.5	29.5	0.20	1100	91514.15	850.72728
0.4	30	0.13	1130	91285.61	870.63072
0.3	30.5	0.07	1170	91150.75	883.3104
0.2	31	0.03	1220	91014	895.99008
0.1	31.5	0.01	1250	90899	906.90192
0	32	0.00	1280	90720	922.35528
Trial 2					
Diameter (in)	**Tick Mark**	**Area (in^2)**	**Time (sec)**	**Ave. Pressure (psi)**	**Altitude (ft)**
2.48	0.5	4.83	-	-	-
2.44	1	4.68	-	-	-
2.36	2	4.38	-	-	-
2.28	3	4.10	-	-	-
2.20	4	3.82	-	-	-
2.13	5	3.55	-	-	-
2.05	6	3.29	-	-	-
1.97	7	3.04	40	14.45	463.1
1.89	8	2.80	70	14.44	477
1.81	9	2.58	100	14.46	452.1
1.73	10	2.36	130	14.44	490.8
1.65	11	2.15	160	14.43	507.4
1.57	12	1.95	190	14.41	535.1

1.50	13	1.76	220	14.39	582.3
1.42	14	1.58	250	14.36	637.9
1.34	15	1.41	280	14.33	690.8
1.26	16	1.25	310	14.32	721.5
1.18	17	1.10	350	14.31	738.2
1.14	17.5	1.02	380	14.26	824.8
1.10	18	0.95	410	14.24	872.4
1.06	18.5	0.89	440	14.20	939.6
1.02	19	0.82	470	14.15	1040.8
0.98	19.5	0.76	500	14.13	1085.9
0.94	20	0.70	530	14.11	1122.5
0.91	20.5	0.64	560	14.08	1176.2
0.87	21	0.59	590	14.02	1303.6
0.83	21.5	0.54	620	13.97	1386
0.79	22	0.49	650	13.94	1462.8
0.75	22.5	0.44	680	13.89	1557
0.71	23	0.39	710	13.82	1683
0.67	23.5	0.35	740	13.76	1812.3
0.63	24	0.31	770	13.71	1910.4
0.59	24.5	0.27	800	13.64	2046.4
0.55	25	0.24	830	13.61	2104.4
0.51	25.5	0.21	860	13.56	2212.1
0.47	26	0.18	890	13.52	2285
0.43	26.5	0.15	920	13.46	2407.9
0.39	27	0.12	950	13.42	2487.1
0.35	27.5	0.10	980	13.40	2525.3
0.31	28	0.08	1010	13.36	2610.7

0.28	28.5	0.06	1040	13.35	2640.2
0.24	29	0.04	1070	13.26	2814.8
0.20	29.5	0.03	1100	13.27	2791.1
0.16	30	0.02	1130	13.24	2856.4
0.12	30.5	0.01	1170	13.22	2898
0.08	31	0.00	1220	13.20	2939.6
0.04	31.5	0.00	1250	13.18	2975.4
0.00	32	0.00	1280	13.16	3026.1

The following graphs represent the changes in pressure and altitude produced by changing the exit orifice or iris mechanism at the exit of the nozzle. This diameter is reduced from the fully open position of 6.3cm or 2.48 in to the fully closed position. As the area of the iris is reduced, a pressure drop is produced reaching values as low as 90632 Pascal's or 13.15 psi which corresponds to an altitude of 930.55 meters or 3053 feet's.

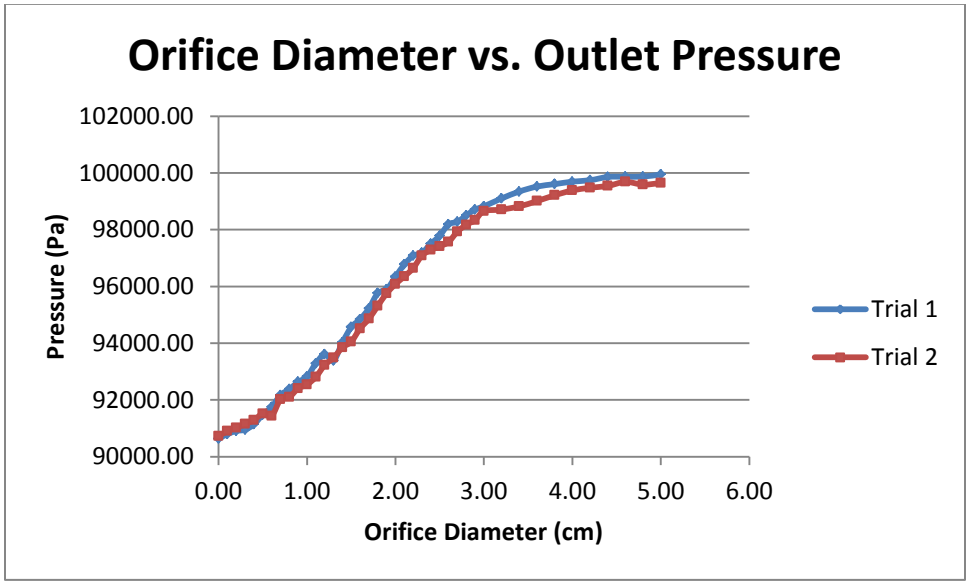


Figure 103 Optional Test Orifice Diameter vs. Outlet Pressure

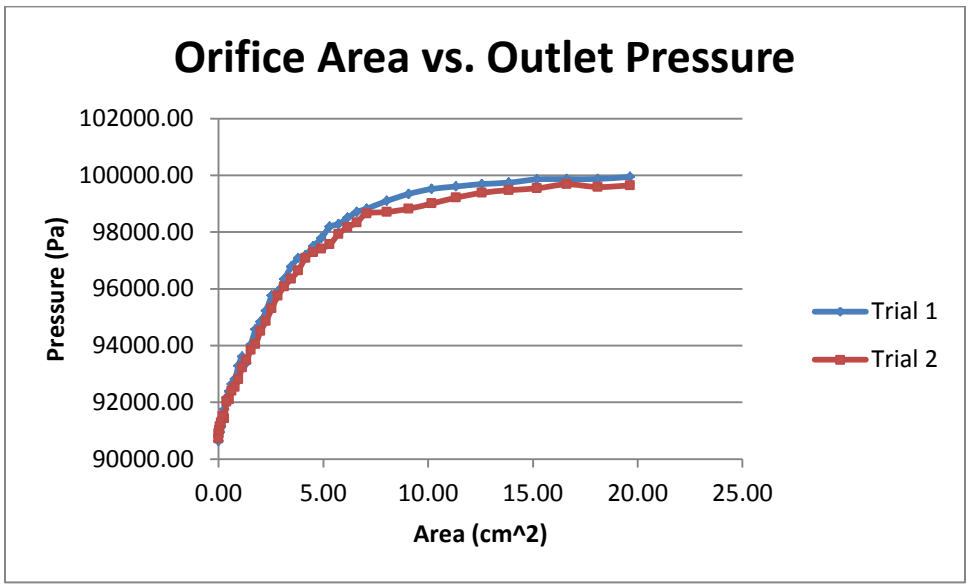


Figure 104 Optional Test Orifice Area vs. Outlet Pressure

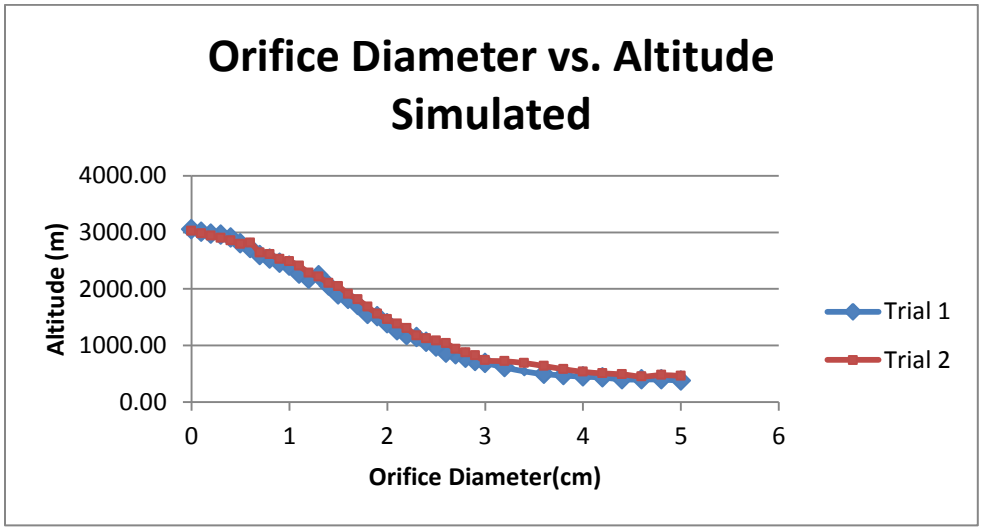


Figure 105 Optional Test Orifice Diameter vs. Altitude Simulated

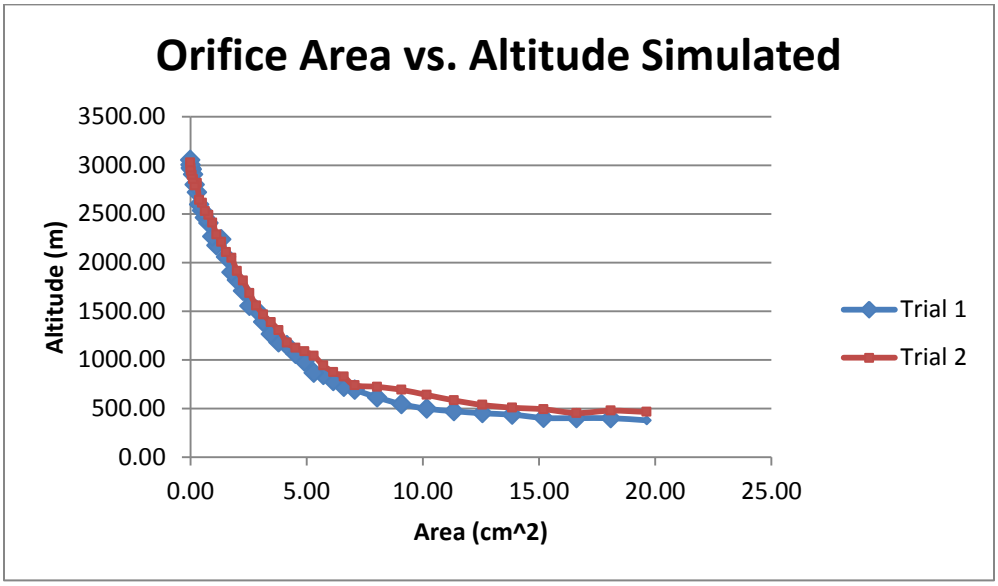


Figure 106 Optional Test Orifice Area vs. Altitude Simulated

Two trials were performed for this experiment allowing for the calculation of the standard deviation between both studies. The following table shows how experiments with the exact boundary conditions can produce different outputs. The average standard deviation for this experiment was of 17.94 which could have been produced by several factors such as: displacement of Pitot tube that captures the pressure measurements, air leakage in the system preventing the fluid from dropping the expected pressure, interaction of an external force or vibration with the system producing inaccuracy on data acquisition, etc.

Table 16 Test Error Analysis

Testing Error Analysis			
Altitude 1 (m)	**Altitude 2 (m)**	**Average**	**Standard Deviation**
115.03	141.15	128.09	18.47
121.77	145.39	133.58	16.70
121.77	137.80	129.78	11.34

122.62	149.60	136.11	19.07
132.74	154.66	143.70	15.50
136.95	163.10	150.02	18.49
143.68	177.49	160.58	23.90
151.27	194.43	172.85	30.52
165.66	210.56	188.11	31.75
186.81	219.91	203.36	23.41
210.56	225.00	217.78	10.22
219.91	251.40	235.66	22.26
237.77	265.91	251.84	19.89
256.52	286.39	271.45	21.12
264.20	317.24	290.72	37.50
298.40	330.98	314.69	23.04
323.24	342.14	332.69	13.36
349.88	358.51	354.19	6.10
359.36	397.34	378.35	26.85
385.24	422.45	403.84	26.32
423.31	445.86	434.58	15.95
461.53	474.57	468.05	9.22
473.69	512.98	493.33	27.78
520.84	552.39	536.62	22.31
554.16	582.29	568.22	19.89
578.75	623.74	601.25	31.81
626.39	641.42	633.91	10.63
682.23	674.25	678.24	5.65
662.70	696.47	679.58	23.88
691.13	733.93	712.53	30.26
733.01	758.07	745.54	17.72
750.02	769.71	759.87	13.92
772.39	795.74	784.07	16.51
791.26	804.73	798.00	9.53
829.06	857.95	843.50	20.43
853.44	850.73	852.08	1.92
885.11	870.63	877.87	10.24
901.45	883.31	892.38	12.82
905.99	895.99	900.99	7.07
915.98	906.90	911.44	6.42
930.55	922.36	926.45	5.80
		Average	**17.94**

9. Conclusion

9.1 Conclusion and Discussion

The team is aware of the critical concern of emission gases in global energy crisis. This test bench has a colossal potential for extended research in bio fuels. Research and testing are key components in the process of mechanical development of innovative components. This also aims to be an educational tool available for students to understand the importance of changes of performance of turbo machinery at different altitudes. The study of the behavior of a micro-turbine at different altitudes is a critical aspect of research to fully understand the effects and impact noxious gases have in our atmosphere.

The design procedures are mainly analytical and computational-numerical; the analytical expressions in both procedures are made much more complicated by the presence of a mechanical iris, but the computational process is a great tool for the studies. The final design concept consists in the integration of a fixed inlet nozzle design with an iris mechanism and a plenum chamber to simulate 10,000 ft. of altitude. Mounts are designed to support the mechanism design. A rubber seal is added to join the plenum chamber to the micro-turbine to prevent external gases from entering the system at the junction. A pitot tube is also added to the design at the constant area of the end of the plenum chamber to measure the pressure at the entrance of the micro-turbine.

Our system design approach consist in setting a boundary of our design and defining crucial location considerations with test bench load cell and starter motor, as

well as energy considerations with air. Developing a plan for project management allows each member of the team to be exposed to own a task, lead and be responsible of the completion of such.

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11. Appendices

Appendix A. Raw Design Calculations and Analysis

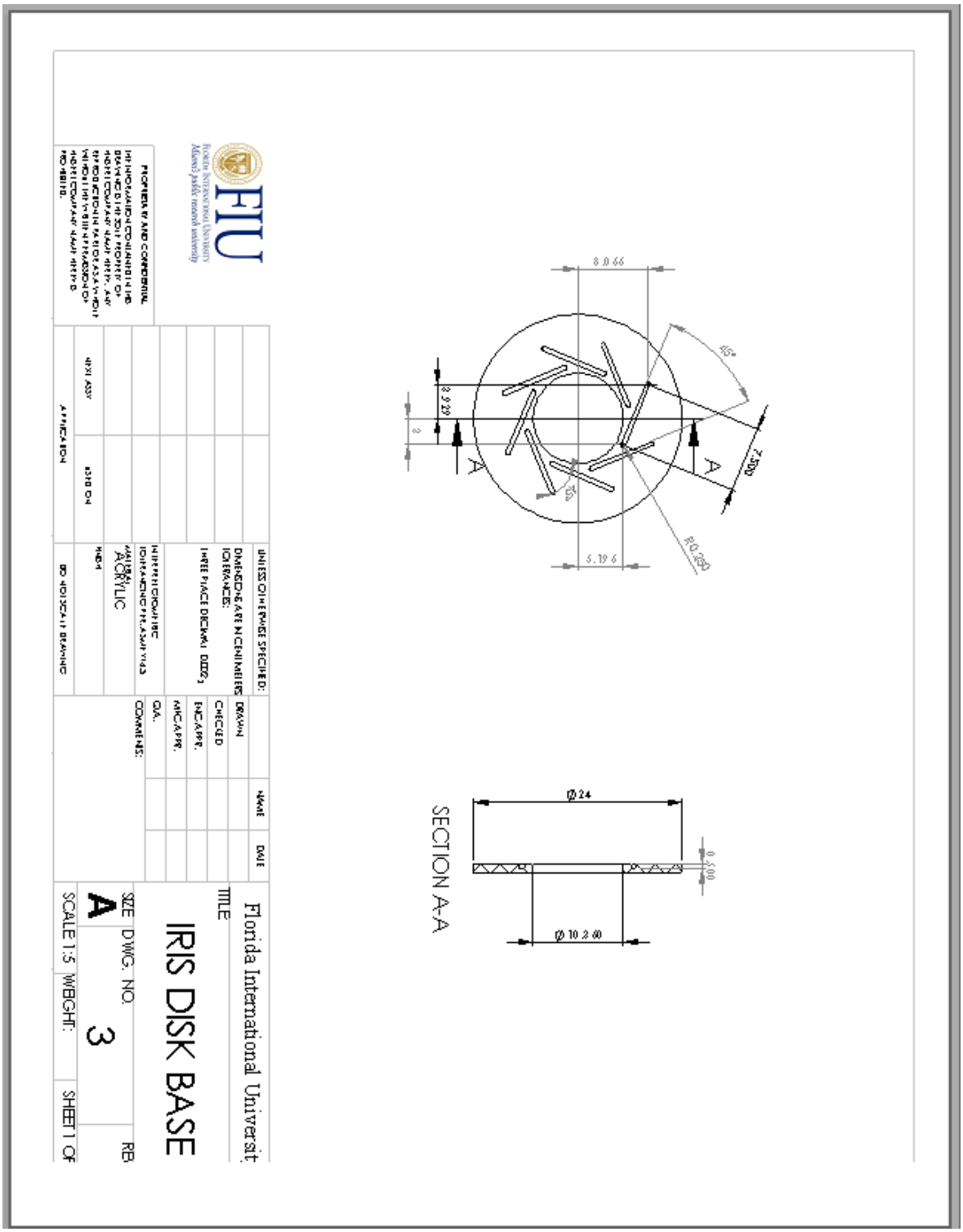
Table 17 Known Parameters for Raw Calculations of Nozzle Design

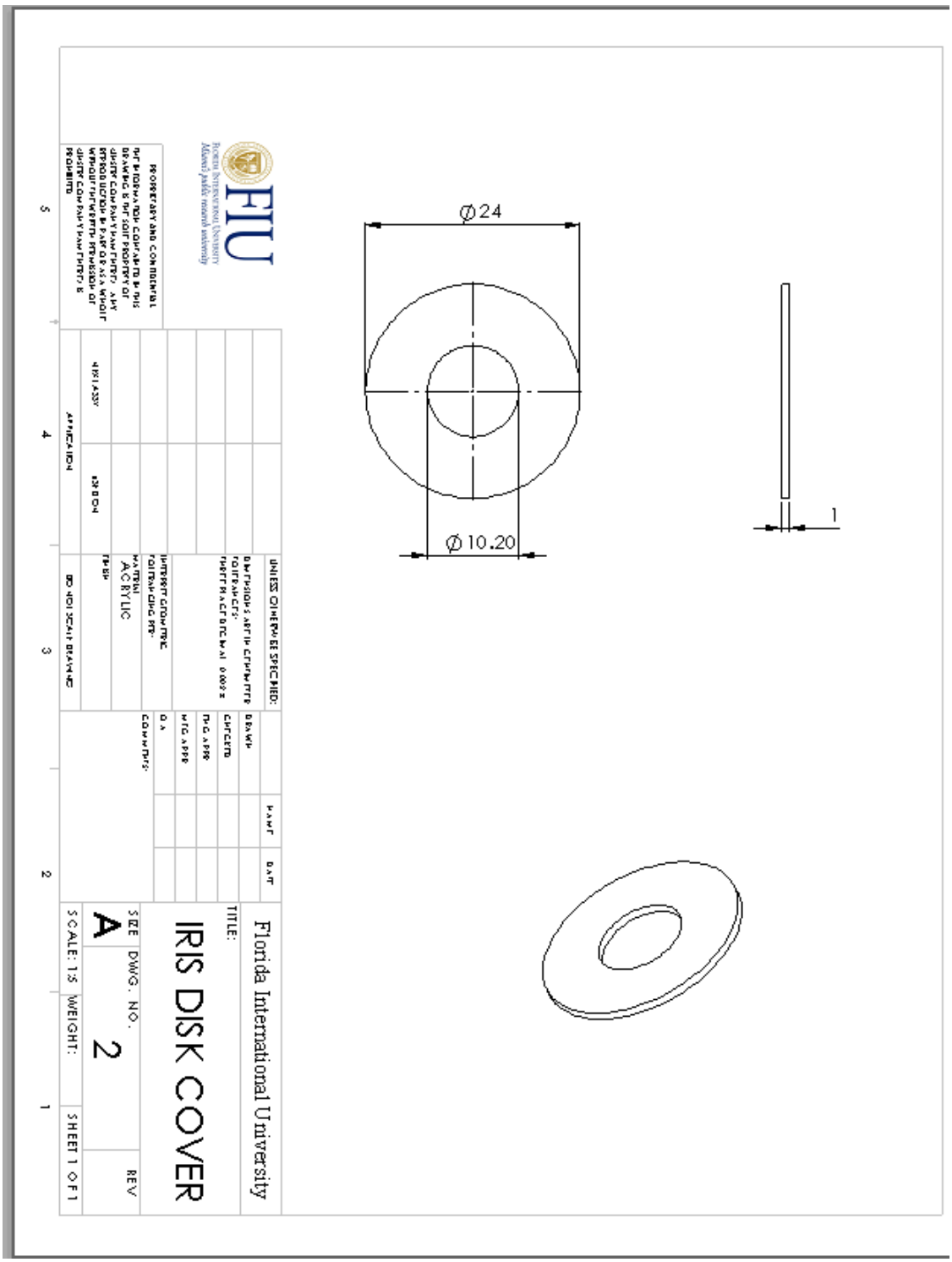
KNOWN			
Pressure of Air at Inlet	Po	101500	Pa
Pressure of Air at Exit	Pe	68000	Pa
Heat Capacity Ratio	k	1.4	
Specific Gas Constant	R	287	J/kg.K
Temperature at Inlet	To	277	K
Temperature at Exit	Te	277	K
Volumetric Flow Rate of MCT at 120 RPM	Qe	0.03	m^3/s
Mass Flow Rate of MCT at 60000 RPM	ṁt	0.0380	kg/s
Exit Diameter	de	0.04	m
Exit Area	Ae	0.001	m^2
Inlet Air Density	ρo	1.220	kg/m^3
Inlet Air Velocity	Vo	80	m/s

Table 18 Calculated Characteristics for Raw Analysis of Nozzle

CALCULATED						
	Quasi-one-dimensional Isentropic Compressible Flow Mach Equations			Continuity Equations		
Pressure Ratio	Pe/Po	0.670				
Mach of Air at Exit	Me	0.779				
Velocity of Air at Exit	Ve1	259.8	m/s	Ve2	295.7	m/s
Density of Air at Exit	ρe1	0.916	m^3/s	ρe1	0.855	m^3/s
Mass Flow at Exit	ṁe1	0.299	kg/s	ṁe1	0.318	kg/s
Inlet Area	Ao1	0.003	m^2	Ao2	0.003	m^2
Inlet Diameter	do1	0.062	m	do2	0.064	m

Appendix B: Proposed design-Technical Drawings

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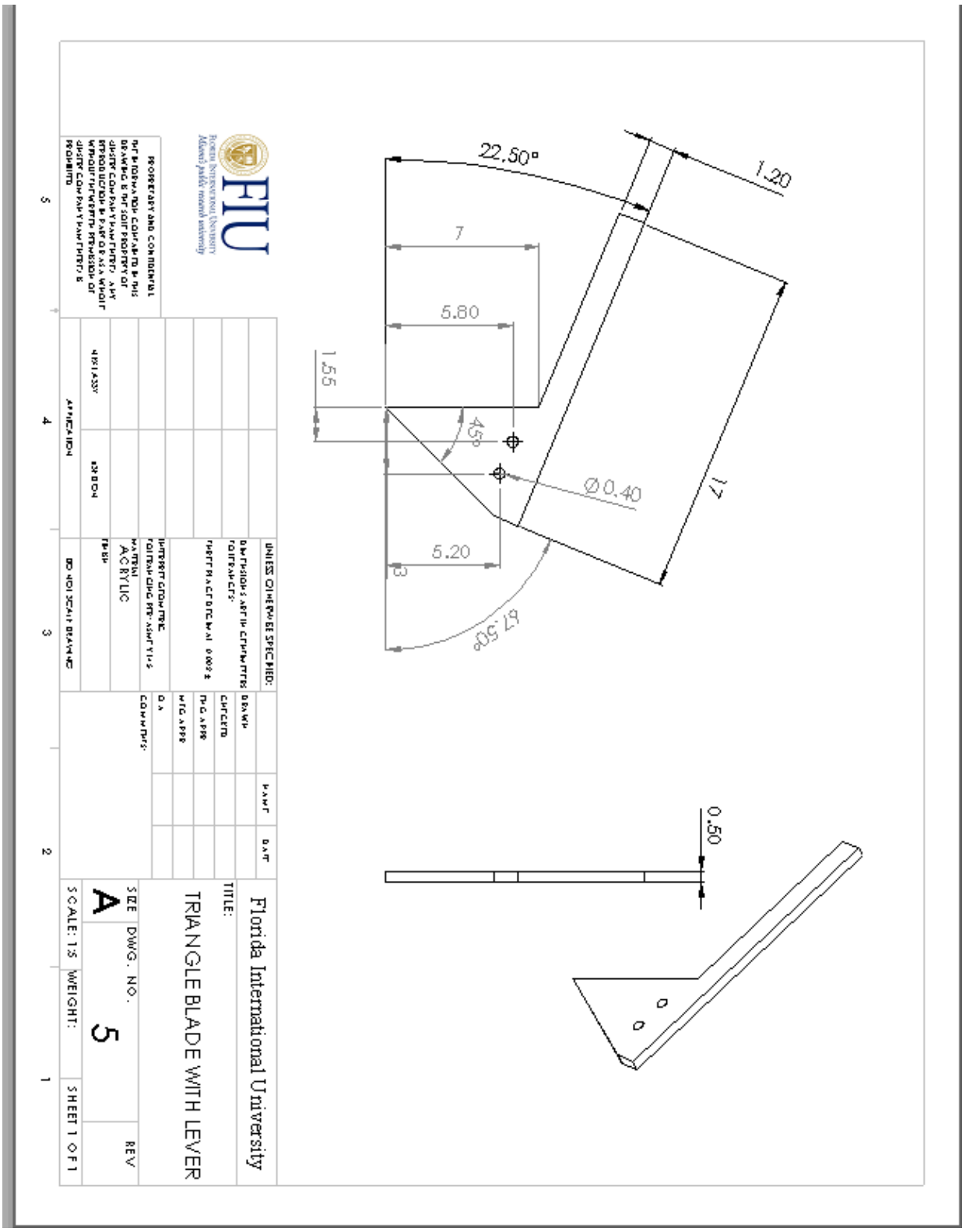
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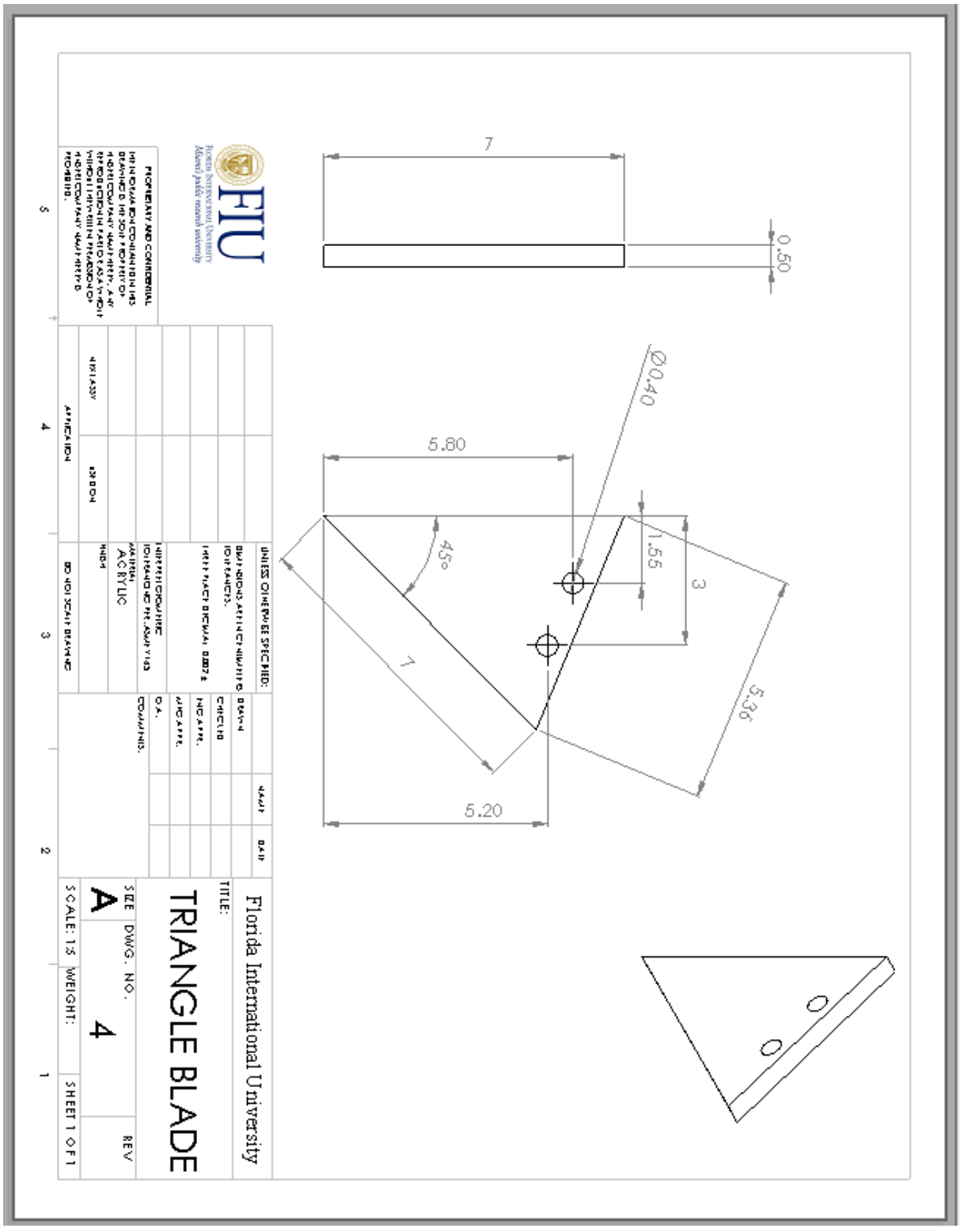
DWG. NO.
5
REV
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1
MATERIAL
ACRYLIC
FINISH
DO NOT SCALE DRAWING
UNLESS OTHERWISE SPECIFIED:
PROPRIETARY AND CONFIDENTIAL


7
0.50
Ø0.40
5.80
1.55
3
45°
7
5.36
5.20
0
0
FIU
Florida International University
TITLE:
TRIANGLE BLADE
SIZE
A
DWG. NO.
4
REV
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
MATERIAL
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PROPRIETARY AND CONFIDENTIAL

Appendix C Operational Manual

START UP PROCEDURE

Before you start operating a machine as powerful as a turbo jet, make sure you take into account all safety factors, follow these steps, and remember that this is not a toy. Not following these instructions could cause serious damage to the people operating the turbine and spectators. Wrong usage of the turbine and irresponsible actions could end up in a disastrous situation. If any malfunction is detected while operating the turbine, stop its operation immediately and let it cool down before trying to fix any problems. Remember, you are working with a machine that could heat up to 900ºC and is power by flammable fuels.

The Turbine has been modified to operate with automatic start rather than manual from its original design. Even though the test stand can support both set ups, we recommend the Auto-Start up to eliminate problems at the star up. One of the problems we encountered was that at the initiation the rpm's needed to be steadier; compression varied too much. The rpm's where difficult to maintain steady and would go either too low or too high. At the ramp up, it was more of a guess to hold the starter motor to establish the correct speed so that the turbine could idle at 45000 rpm without any lagging or flames. With the Auto-Mode the turbine computer knows exactly the amount of rpm's to reach its initial compression and the sequence is very smooth from there on.

PROPANE ENGINE WARM-UP

1) The propane tank has a BBQ valve. It must be on medium-high position and the propane switch is set on the off position.

2) Fuel Tank Valve is in the off position.
3) Check for any leaks on fuel and propane lines. It is very important that the valve on the fuel tank remains close until reaching the fuel ramp. When inspecting propane lines you will not see the leaks, instead you will smell the propane. Make sure all of the electrical systems are connected properly.
    - The ECU must display 0 POWER, ambient temperature and depending on the position of the throttle the ECU status, for example:

    STICK LOW

    BAD GLOW PLUG

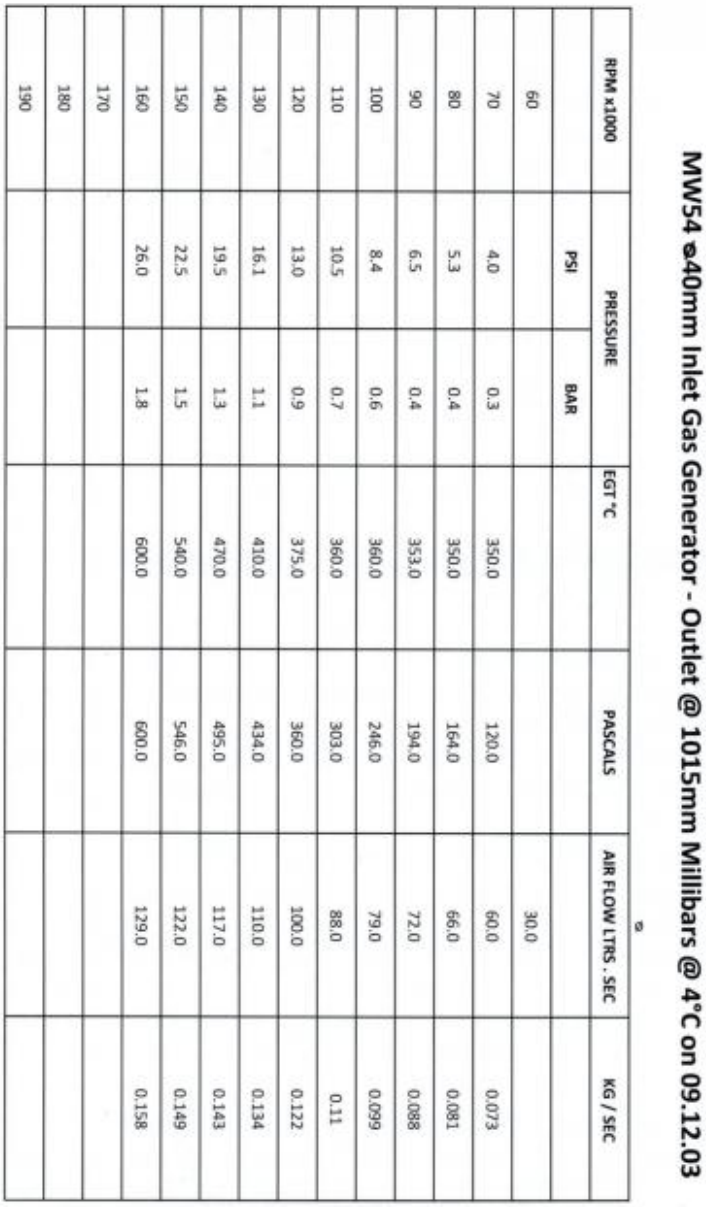
    READY

    Since the starter motor and the glow plug are connected to the same source both elements interact in a sequence. (The specifications to this step are found in the ECU set up). The throttle knob controls the pulses that are sent to the motor and it controls the acceleration of the turbine.
4) To initiate the start-up sequence, turn the knob all the way to its full position (clockwise) and then turn it back (counterclockwise) to its idle position. (The adjustment of such positions corresponds to a different set of steps that are presented ECU set up). You will know it's the exact position when the display shows GLOWPLUG TEST.
5) Flick the Propane switch to its ON position.
6) After step 5, you will hear the starter motor rotate in a sequence. At this stage, the propane will try to ignite in order to heat up the combustion chamber to 100° Celsius.

7) After the engine warms up to 100° C and PreHeating is displayed in status OPEN THE FUEL VALVE.
8) Finally, turn off the propane switch when the display shows 30000 rpm. At this moment, the starter motor and the glow plug will shut down automatically.

FUEL INITIATION

9) When the engine reaches 100ºC you will see the ECU status display "FuelRamp" and Power will now show some value. The ECU will activate right away the FUEL RAMP and the fuel pump will initiate. Fuel Ramp means that the engine is now ready to make the transition from propane to Jet-Fuel. At this moment fuel is now being injected to the combustion chamber to complete the startup cycle.
10) After the starter motor and propane are shut down only jet fuel will be injected to the engine. At this point, the turbine should be self-sustained and it should stabilize to its idle setting(45000 rpm)
11) When the turbine is in such process, flames might come out of the exhaust. Some of these flames are normal but, if excessive flaming is encountered shut the engine down wait at least 5 minutes and restart the whole process again.
12) When the engine sets at 45000 let it sit in that stage for a couple of seconds.
13) You are now in control of the turbine increase the power of turbine as desired but don't make rapid changes. The throttle response is quick and the turbine might stall causing it to shut down.



MW54 ø40mm Inlet Gas Generator - Outlet @ 1015mm Millibars @ 4°C on 09.12.03

RPM x1000	PRESSURE		EGT °C	PASCALS	AIR FLOW LTRS . SEC	KG / SEC
	PSI	BAR				
60					30.0	
70	4.0	0.3	350.0	120.0	60.0	0.073
80	5.3	0.4	350.0	164.0	66.0	0.081
90	6.5	0.4	353.0	194.0	72.0	0.088
100	8.4	0.6	360.0	246.0	79.0	0.099
110	10.5	0.7	360.0	303.0	88.0	0.11
120	13.0	0.9	375.0	360.0	100.0	0.122
130	16.1	1.1	410.0	434.0	110.0	0.134
140	19.5	1.3	470.0	495.0	117.0	0.143
150	22.5	1.5	540.0	546.0	122.0	0.149
160	26.0	1.8	600.0	600.0	129.0	0.158
170						
180						
190						

Figure 107 Micro-Turbine Manufacturer Performance Curves

Appendix C Warning Labels

There are some hazards involved during the operation of the micro-turbine that the operator should be aware before, during and after using the test bench. At all moments, the operator should be alert of any indication of a possible threat to him/herself and any other person around the test stand. Some of the precautions that the operator should consider are the following

Hearing protection

Eye protection

Hazards of flammable liquids: Propane and Jet fuel

Awareness of the fire extinguisher at all times

Maintain a restricted area behind the exhaust minimum of 10 feet/ 3 meters

Figure 108 Different warning and precautionary labels