



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

INLET FLOW ANALYSIS OF A TRANSONIC COMPRESSOR

by

Patrick G. Giambruno

December 2023

Thesis Advisor:
Co-Advisor:
Second Reader:

Garth V. Hobson
Anthony J. Gannon
Walter C. Smith

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REPORT DOCUMENTATION PAGE			<i>Form Approved OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE December 2023	3. REPORT TYPE AND DATES COVERED Master's thesis		
4. TITLE AND SUBTITLE INLET FLOW ANALYSIS OF A TRANSONIC COMPRESSOR			5. FUNDING NUMBERS	
6. AUTHOR(S) Patrick G. Giambruno				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			12b. DISTRIBUTION CODE A	
13. ABSTRACT (maximum 200 words) The purpose of this study was to accurately determine the inlet flow field characteristics of a transonic compressor rig, as well as develop a method to provide accurate and reliable measurements of upstream throttle setting. In order to properly determine the flow field characteristics in the inlet region, probes were designed to be inserted into the casing of the compressor rig. These probes were designed to contain Kulite pressure transducers, as well as total pressure ports, in order to provide measurements of pressure and pressure unsteadiness. In addition, a computational fluid dynamics (CFD) model of the compressor inlet ducting was created to model the inlet flow at full open and near stall conditions. CFD results were compared to experimental results from prior research with hot film anemometry. In order to reliably and accurately provide throttle setting measurements, two optical encoders were installed and integrated into the transonic compressor rig, allowing for continuous, precise determination of the throttle setting.				
14. SUBJECT TERMS TCR, transonic compressor rig, pressure transducer, flow unsteadiness, computational fluid dynamics, CFD			15. NUMBER OF PAGES 103	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18

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INLET FLOW ANALYSIS OF A TRANSONIC COMPRESSOR

Patrick G. Giambruno
Ensign, United States Navy
BS, United States Naval Academy, 2022

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AEROSPACE ENGINEERING

from the

**NAVAL POSTGRADUATE SCHOOL
December 2023**

Approved by: Garth V. Hobson
Advisor

Anthony J. Gannon
Co-Advisor

Walter C. Smith
Second Reader

Brian S. Bingham
Chair, Department of Mechanical and Aerospace Engineering

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ABSTRACT

The purpose of this study was to accurately determine the inlet flow field characteristics of a transonic compressor rig, as well as develop a method to provide accurate and reliable measurements of upstream throttle setting. In order to properly determine the flow field characteristics in the inlet region, probes were designed to be inserted into the casing of the compressor rig. These probes were designed to contain Kulite pressure transducers, as well as total pressure ports, in order to provide measurements of pressure and pressure unsteadiness. In addition, a computational fluid dynamics (CFD) model of the compressor inlet ducting was created to model the inlet flow at full open and near stall conditions. CFD results were compared to experimental results from prior research with hot film anemometry. In order to reliably and accurately provide throttle setting measurements, two optical encoders were installed and integrated into the transonic compressor rig, allowing for continuous, precise determination of the throttle setting.

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List of Acronyms and Abbreviations

ANSYS	Analysis System
CFD	Computational Fluid Dynamics
CFX	Computational Fluid Flow
TCR	Transonic Compressor Rig
TPL	Turbopropulsion Laboratory
TKE	Turbulent Kinetic Energy

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Acknowledgments

Completion of this thesis would not be possible without many individuals. I would like to thank my advising team of Dr. Garth Hobson, Dr. Anthony Gannon, and Dr. Walter Smith for their enormous support and guidance this past year. My advisors offered support and answered any question, yet still pushed me to think critically and put my knowledge into practice. I thank them for the lessons I have learned in my time at NPS that will help me to succeed in future endeavors. I would also like to thank Mr. John Gibson and Mr. Landon Lindsay, who offered extensive help at the Turbo-Propulsion lab with the manufacturing and installation of parts for my thesis. Finally, I would like to thank my classmates, particularly Jack Spector and Taylor Adams, who provided feedback, insight, and motivation.

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CHAPTER 1: Introduction

1.1 Research Motivation

Most modern military aircraft are powered by gas turbine engines, which are designed to operate stably over a required flight envelope. An adequate “stall margin” is typically a requirement in the design of these aircraft and their engines. Outside of this stall margin, gas turbine engines are subject to a phenomenon known as compressor stall. A U.S. Navy aircraft undergoing a compressor stall can be seen in Figure 1.1.



Figure 1.1. F/A-18C Suffers Compressor Stall During Carrier Takeoff. Source: [1]

Compressor stall occurs when there is a reduction in mass flow through the engine, and the demand for airflow exceeds the airflow supplied by the compressor. This disruption in airflow leads to a sudden loss of pressure and a loud banging or popping noise. Compressor stalls can cause significant damage to the engine, as well as cause it to shut down. Aircraft

are more susceptible to compressor stall at high angles of attack and lower airspeeds, making takeoff and landing flight regimes of increased risk. This issue is further exaggerated in the context of Naval aircraft taking off from aircraft carriers, where the ingestion of steam from the catapult may cause flow distortion, increasing the risk of compressor stall [2], [3].

There are various features that can be implemented in gas turbine engines in order to help prevent the onset of compressor stalls, such as variable stator vanes, bleed valves, casing treatments, and re-circulation devices. The design of such devices requires an accurate determination of the flow characteristics present in the engine. In particular, it is critical to understand the mass flow through the engine, the pressure profile, the velocity profile, the turbulence intensity, and the existence of any shocks when in the transonic regime [2].

1.2 Literature Review

1.2.1 Prior Transonic Compressor Rig Research

Research on the Transonic Compressor Rig (TCR), located at the Naval Postgraduate School Turbo-Propulsion Laboratory (TPL), has been ongoing for years. The main objectives of the research have been centered around increasing the understanding of compressor stalls and developing casing treatments and other techniques to increase the stall margin.

Notable prior research has focused on the effects of inlet flow distortion [3] and inlet flow measurement during steam ingestion [4]. Papamarkos [3] included research on the relation of inlet flow conditions to compressor characteristics, as well as computational analysis of the inlet flow field. Payne [4] performed probe surveys of the inlet flow utilizing both hot wire sensors and Kulite pressure transducers during steam ingestion. Payne was able to successfully obtain measurements of the average turbulence intensity in the inlet of the compressor at speeds ranging from 70% to 95%. Further computational modeling of the upstream flow conditions was performed by Wallen [5]. Wallen also constructed a bell mouth attachment for the Transonic Compressor Rig based upon Computational Fluid Dynamics simulations in order to increase confidence in mass flow data. Research conducted by Hearn [6] focused on the measurement of the upstream flow field characteristics experimentally utilizing hot film anemometry. Hot wire sensor data was obtained at 85% and 70% power settings in full open, intermediate, and near stall conditions, allowing for a characterization of the

flow. These measurements were obtained at azimuthal angles of 0° , -30° , 30° , and 120° , as depicted in Figure 1.2.

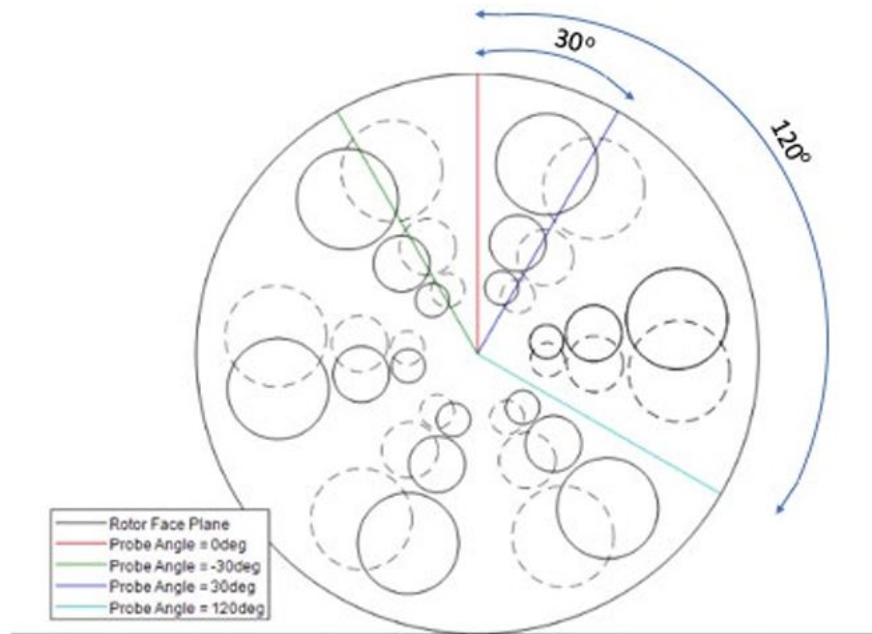


Figure 1.2. Hot Film Locations. Source: [6]

The hot wire sensors were able to yield accurate measurements at high frequencies and allowed for the computation of average turbulence intensity, flow field velocities, displacement thickness, momentum thickness, and shape factor. However, these sensors were only able to provide data of the flow in one dimension [6]. In addition, the hot wire sensors did not provide a long-term method of flow characterization due to their fragility.

1.2.2 Turbulence

One of the characteristics of a flow that is most critical to understand when investigating compressor stalls and their mitigation is turbulence. Turbulent flows are difficult to define, however, according to Tennekes and Lumley, they can be described by their irregularity, diffusivity, large Reynolds numbers, three-dimensional vorticity fluctuations, dissipation, and continuum [7]. These flows exhibit random, disordered, fluctuating motion and have several factors that contribute to their development.

Turbulence arises in originally laminar flows due to instability at high Reynolds numbers. However, turbulent flows are dissipative in nature and are not self-sustaining. These flows require a constant input of energy from their environment, and a common source of the energy required for the velocity fluctuations seen in turbulence is shear in the mean flow. If the turbulent flow occurs in an environment where shear or any other energy input mechanism is present, the Reynolds number will decrease, the turbulence will decay, and the flow will tend towards laminar again. This is most clearly demonstrated by turbulence induced by a grind in uniform flow within a wind tunnel [7].

There are multiple parameters used in fluid mechanics to characterize and quantify turbulence in flows. One such parameter is Turbulent Kinetic Energy, or TKE. Turbulent kinetic energy refers to the energy associated with the chaotic motion of fluid particles in a turbulent flow. Turbulent Kinetic Energy per unit mass can be calculated as

$$k = \frac{1}{2}(u'^2 + v'^2 + w'^2) \quad (1.1)$$

where u' , v' , and w' are the velocity component variances.

Another key parameter is turbulence intensity, which provides a measure of the relative strength of turbulence within a flow [7]. For isotropic flow, turbulence intensity can be calculated from turbulent kinetic energy by

$$TI = \frac{\sqrt{\frac{2}{3} \times k}}{U_{mean}} \quad (1.2)$$

where U_{mean} is the mean flow velocity.

1.2.3 Flow Field Measurement Techniques

When characterizing a flow field, key aspects to capture include the pressure profile, velocity profile, and turbulence profile. There are numerous methods that can be implemented in order to capture these characteristics in an engine. Many of the existing methods for obtaining these characteristics are dependent upon pressure-based measurements, which are commonly obtained in the aerospace industry using Pitot-static probes. These probes obtain two pressure measurements: total and static pressure. Utilizing Bernoulli's Principle,

the dynamic pressure can be obtained as the difference between the total and static pressures, and thus the flow velocity can be calculated. It is important to note that Bernoulli's Principle only applies to incompressible flows, and thus is only valid for low Mach numbers. In the case of compressible subsonic flows, isentropic relations can be utilized to solve for the velocity of the flow. In supersonic flows, a bow shock occurs ahead of the probe, causing the flow to be decelerated to subsonic speeds, before being isentropically stagnated. This shock must be accounted for in the determination of the velocity for these flows [6].

A technique previously utilized for flow characterization research on the TCR was constant temperature hot film anemometry, which was implemented by Hearn [6]. In this measurement technique, a hot wire containing a sensor is aligned perpendicular to the flow. A depiction of a hot wire probe can be seen in Figure 1.3.

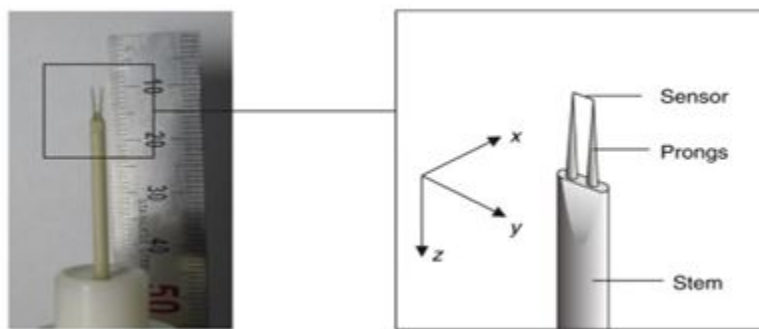


Figure 1.3. Hot Wire Probe

As the flow passes over the hot wire, convection transfers heat between the sensor and the flow. With increasing flow velocity, more convection occurs, lowering the temperature of the wire. In order to maintain the temperature of the wire, a current is applied. The change in the current applied to the wire can be recorded and used to measure the velocity of the flow. More sophisticated probes may contain multiple sensors at different angles in order to allow for the measurement of the velocity decomposed into its three directional components [6].

An alternative tool for sensing the flow field characteristics are pressure transducers, like those manufactured by Kulite Semiconductor Product, Inc, which can be seen in Figure 1.4.

Pressure transducers are electromechanical devices that measure the pressure of a fluid with a high degree of accuracy by measuring the force exerted on a surface and outputting an

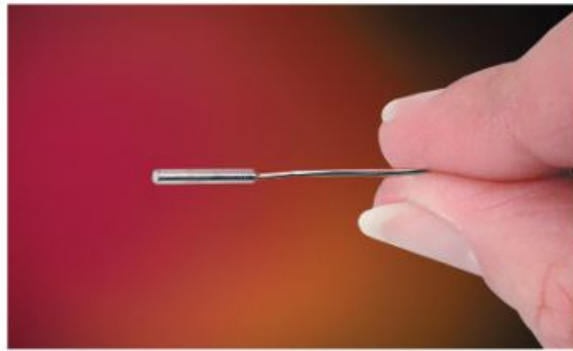


Figure 1.4. Kulite Pressure Transducer

electrical signal. The sensors found on Kulite pressure transducers are dielectrically isolated, silicon-on-insulator devices, consisting of a three-layer structure, atomically bonded together. A diagram depicting the sensor structure on a Kulite pressure transducer can be seen in Figure 1.5.

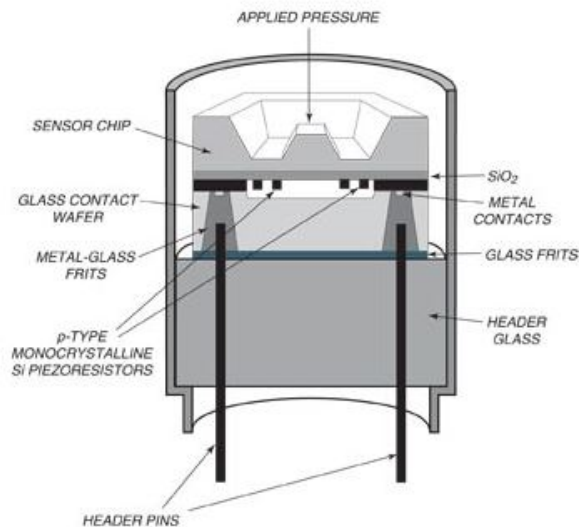


Figure 1.5. Kulite Sensor

The first layer of the Kulite comprises monocrystalline N-type silicon, micromachined into a diaphragm. The second layer is made of silicon dioxide, providing dielectric isolation between the N-type silicon diaphragm and the P-type silicon found on the third layer. This

dielectric isolation provides the device with a higher operational temperature capability. The third layer contains four strain gauges made of P-type silicon patterned into a Wheatstone bridge circuit. When pressure is applied to the diaphragm, two of the strain gauges are put into tension, increasing their resistance, and two are placed into compression, decreasing their resistance. The gauges in tension are located opposite each other on the Wheatstone bridge, as are the gauges in compression. The applied stress causes a resistance imbalance, maximizing the output of the bridge, and the magnitude of the imbalance is proportional to the magnitude of stress applied [8].

Kulite pressure transducers are capable of accurately measuring pressure ranges from a few millipascals to several thousand atmospheres, depending on the application requirements. The sensors have a high degree of accuracy, with a typical static error band of less than 0.1% of full scale. The sensors are highly reliable, with an estimated sensor mean time before failure of 3 million hours, and can operate continuously at operational temperatures exceeding 500°C. The sensors are small, lightweight, and highly tolerant to shock and vibration. Their small size and mass result in high natural frequencies, minimizing the effect of vibration or shocks. Their reliability, versatility, and accuracy make Kulite pressure transducers popular for pressure measurement in aerospace and turbomachinery applications [9].

Kulite pressure transducers were utilized in 2007 research conducted by Lafferty and Norris [10] on the AEDC Hypervelocity Wind Tunnel in order to better characterize the freestream disturbances known as “tunnel noise” in hypersonic flows. Two Kulite XT-140a pressure transducers were used for fluctuating Pitot pressure measurements in a dual-probe assembly. The frequency response of the Kulites was limited to 20KHz, per manufacturer specifications in the operational pressure range. Lafferty and Norris concluded that the probe configuration allowed for routine, accurate Pitot acoustic measurements during testing, and the measurements obtained could be used to understand tunnel noise and boundary-layer transition, and its relationship with unsteady flows. Kumar et al. [11] utilized Kulites in their 2021 research on the behavior of a transonic axial compressor when tested with a self-recirculating casing treatment. The Kulite pressure transducers were used to capture the unsteadiness in the flow, and rotating stall signatures. The Kulites were able to capture the differences in flow perturbations at choked flow and at stall flow for each casing treatment. Fotia, Hoke, and Schauer [12] used Kulites in their 2021 research focused on the unsteady pressure measurement of flow from a rotating detonation engine. This study was

of particular interest as it explored the response of Capillary Tube Attenuated Pressure measurement under these forced unsteady flow characteristics, mirroring the conditions seen by Kulite Pressure Transducers when placed in probes. Fotia, Hoke, and Schauer [12] state that precise pressure measurement relies upon “three considerations: the coupling of the fluid in the tube between the pressure input port and the transducer, the frequency response of the transducer, and the frequency response of the signal processing electronics”. Kulites were tested in different probe configurations containing capillary tubes of varying lengths and diameters. It was concluded that the pressure signal attenuation was highly dependent on the magnitude of the pressure fluctuations, relative to the mean static pressure, for tubing of 0.010" or larger inner diameter. The attenuation of pressure measurements in smaller tubing was found to be dependent on the static pressure solely. In order to properly account for the attenuation of pressure measurement in a tube, it is therefore important to know the arrangement's response to pressure fluctuations [12].

1.3 Thesis Objectives and Overview

The research conducted in this study had three primary objectives: the optimization of throttle operation and mass flow control, the measurement of inlet flow field characteristics utilizing Kulite pressure transducers and total pressure ports, and the computational modeling of the flow in the inlet ducting of the Transonic Compressor Rig.

In order to efficiently, reliably, and accurately determine the mass flow of air entering the TCR, the throttle position must be accurately measured and recorded. In addition, proper, precise knowledge of the throttle setting allows for repeatable flow characterization. The installation of 2 optical encoders provides a method to precisely and reliably determine the throttle position in order to better understand when compressor stall occurs and accurately characterize the flow.

Research conducted by Hearn [6] provided valuable data regarding the inlet flow field characteristics, however, the hot wire sensors utilized lacked durability and longevity. The installation of probes containing Kulite pressure transducers provides a more permanent method to accurately determine the characteristics of the flow entering the compressor, providing a foundation for future research on compressor stalls and mitigation techniques.

Computational fluid dynamics simulations were performed in order to investigate the disrup-

tion of flow as it passes through the throttle plate and the propagation of these characteristics through the compressor. A porous region was inserted in the flow in order to attempt to model the flow passing through screens located in the settling chamber. Computational results were compared to experimental data provided by Hearn [6] in order to determine the accuracy of the model created.

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CHAPTER 2: Experimental Equipment

2.1 Transonic Compressor Rig

The Transonic Compressor Rig was operated from a room outside of the test cell. The compressor test rig was driven by two opposed rotor air turbines, which are supplied by a 12-stage Allis-Chalmers axial compressor. This setup provides a continuous flow of air at pressures up to 300 kPa at a mass flow rate of 5 kg/s. The pressurized air from the Allis-Chalmers compressor is fed through a motor-driven valve to the turbine drive unit, which powers the test compressor [3]. The test compressor first draws atmospheric air through a bellmouth attachment created by Wallen [5] before it enters the intake plenum chamber. Flow then proceeds through an electrically driven throttle before entering the inlet ducting. The flow proceeds from the inlet ducting and into the test compressor before being directed back out to the atmosphere. A diagram of the Transonic Compressor Rig can be seen in Figure 2.1.

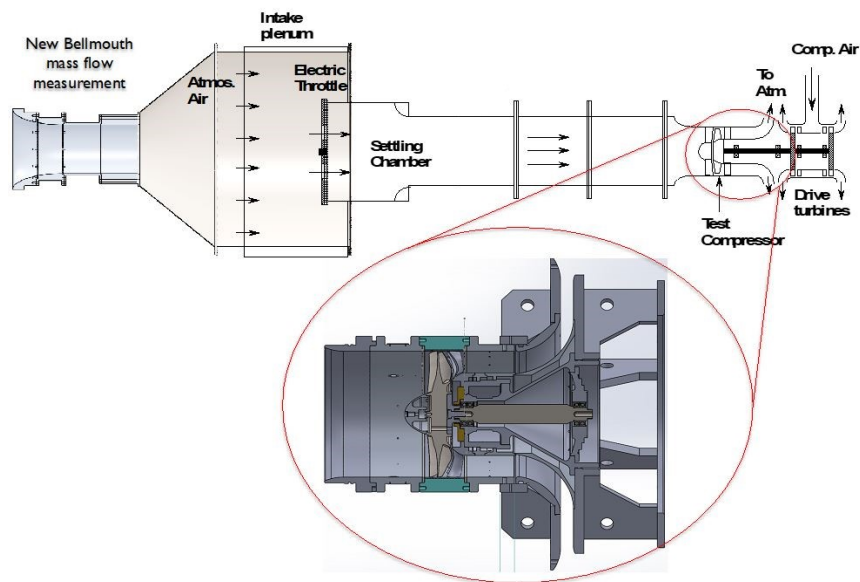


Figure 2.1. TCR Schematic Diagram

2.1.1 TCR Throttle

The TCR throttle is made up of two cylindrical plates, each with a matching configuration of 6 sets of three holes. The rotation of the upstream plate is driven by an electric motor. The rotation of the plate controls the mass flow of air entering the test compressor and is graduated with 12 positions. The throttle plate can be rotated anywhere within these settings, however, the operating range of the compressor is typically between 1 and 6.3. Increasing throttle settings correlate to a smaller opening between the throttle plates, and thus, less airflow permitted into the TCR. The position of the throttle can be viewed from the TCR control room [5]. The TCR throttle section can be seen detached from the rest of the rig in Figure 2.2, alongside a diagram displaying its rotation.

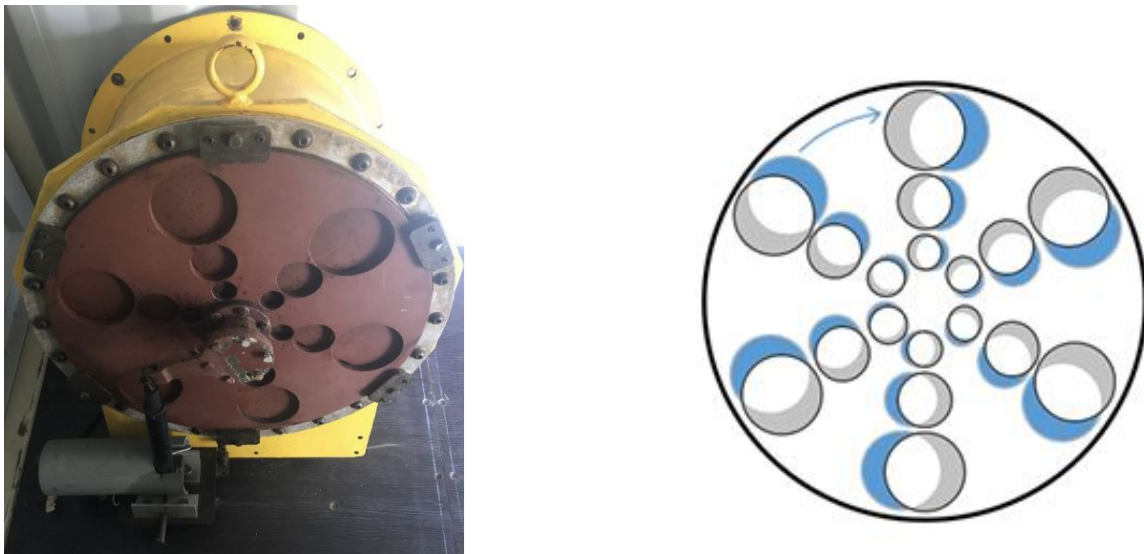


Figure 2.2. TCR Throttle

2.1.2 TCR Inlet Section

Behind the rotating-plate throttle is a settling chamber, 1 meter in diameter and 2.88 meters long. This settling chamber necks down to a pipe, 0.46 meters in diameter and 5 meters long. This once again smoothly necks down to a 0.279-meter diameter compressor section [3]. Within the settling chamber exists a honeycomb-like flow screen that filters and aligns the air entering the inlet ducting. At the end of the inlet ducting section is a casing that allows for instrumentation and measurement of flow characteristics. This casing was where Hearn performed hot film measurements in order to characterize the flow [6].

2.2 Optical Encoders and Mounts

2.2.1 Renishaw Optical Encoders

Two Renishaw RL26BBT050B99A RESOLUTE™ linear and partial arc absolute optical encoders were installed on the rig. One optical encoder was installed along the outer edge of the throttle face in order to measure its angular displacement, and the other was installed on the center operating rod of the motor that drives the throttle face, measuring its linear displacement. The Solidworks model of the assembly of both optical encoders and their mounts at various throttle settings can be seen in Figure 2.3.

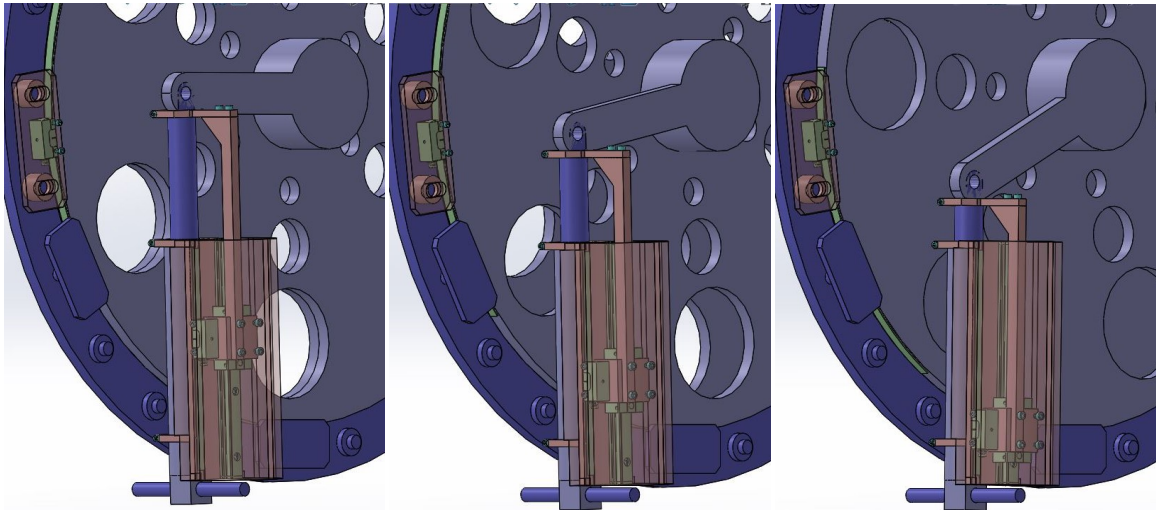


Figure 2.3. Throttle Assembly with Optical Encoders

A similar model of Renishaw optical encoder readhead to those utilized can be seen in Figure 2.4.

The encoders utilize optical principles in order to provide accurate and reliable feedback of position, and are suitable for use in many applications including manufacturing, robotics, and turbomachinery. The encoder system consists of a single-tracked scale, which operates as a target for the sensor, and a readhead containing the sensor system. The sensor utilizes a light source to illuminate the scale and measure its absolute position, acting similar to a miniature digital camera, with no need for a set zero or homing operation [13].

These optical encoders allow for efficient, reliable, and accurate measurement of the throttle



Figure 2.4. Renishaw Optical Encoder Readhead

setting. The encoders measure their absolute position with a 50nm resolution and are capable of operating across a temperature range from 0°C to 80°C. They are designed to be highly resistant to shock and vibrations, as well as environmental factors such as dirt, dust, and moisture [13].

The optical encoders were connected to an E201-9S USB Interface in order to integrate them into the operating system of the TCR. The E201 can be seen in Figure 2.5.



Figure 2.5. Renishaw E201 USB Interface

The interface contained a DB9 connector female end and a micro USB port. This interface allowed for simple interaction with the SSI/BiSS encoders through ASCII commands over a USB connection [14]. All commands given to the encoders, and all processing of the data provided by them, were performed within a MATLAB script.

2.2.2 Optical Encoder Test Rig

A simple three-part rig was developed in order to test the operation of the optical encoders and develop the associated MATLAB script. This three-part design consisted of a track, a slider, and an adjustable mount. The track was a simple flat base with a dovetailed guide

slot for the slider and a groove to place the scale for the encoder system. The slider mated into the slot in the base and had 4 top holes for the attachment of the encoder mount. The optical encoder readhead was attached to the side of the mount, and its ride height above the scale could be adjusted through the screws affixing the mount to the slider. The Solidworks model of the test rig, with the optical encoder readhead attached, can be seen in Figure 2.6.

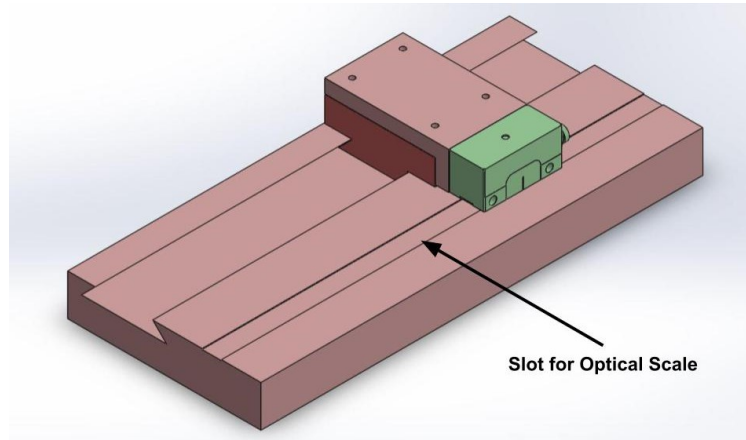


Figure 2.6. Test Rig (Red) with Readhead Affixed (Green)

All parts for the test rig were 3-D printed from PLA on the 3D printer located at the TPL.

2.2.3 Linear Displacement Mount Design

The mount that contains the optical encoder that measured the linear displacement of the control rod was designed to be affixed to the rod itself. The scale was designed to be placed on a base plate affixed to the fixed actuator of the rod, and the readhead was to be mounted to an arm connected to the inner moving piston rod.

The design for this linear displacement mount was an evolution of the design used in the test rig. The base plate consisted of a groove to attach the scale via adhesive, however, forwent the dovetail slot seen on the test rig. The dovetail slot and slider were replaced with a steel guide rail and a Maintenance-Free Ball Bearing Carriage obtained from McMaster-Carr. The steel guide rail was affixed to the base plate, and the mounting bracket with the optical encoder readhead was affixed to the carriage. The base plate was attached to the outer barrel of the control rod with 2 clips, and the carriage was attached to the piston rod via an arm and clip. A fairing was designed to wrap around the entirety of the linear displacement mount to

minimize disturbance of flow entering the TCR. The Solidworks model of the linear mount, with each part labeled, can be seen in Figure 2.7. The fairing has been removed to allow visibility of all other parts.

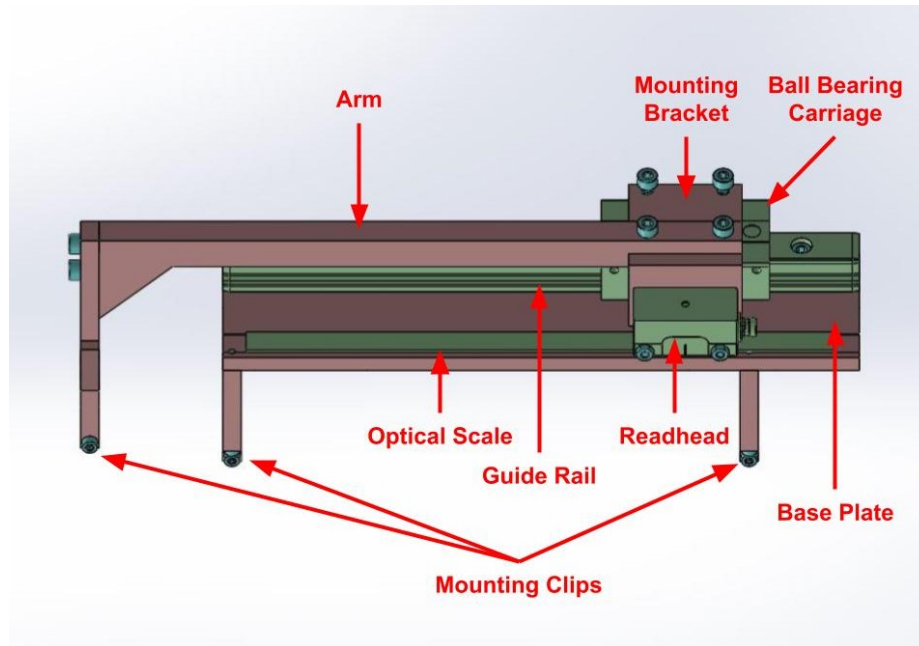


Figure 2.7. Linear Optical Encoder Mount

The base plate of the mount, as well as the arm connecting the carriage to its clip, were machined from stainless steel. The engineering draws for these parts are depicted in Appendix A. Two temporary mounting clips were 3-D printed from PLA, and will be replaced with 3-D printed titanium clips in future work. One other clip and the mounting bracket were 3-D printed from titanium on the EOS M100 3-D metal powder printer. The fairing was 3-D printed from polycarbonate.

2.2.4 Angular Displacement Mount Design

The mount that contains the optical encoder that measured the angular displacement of the throttle face was designed to be affixed to the outer casing of the throttle section of the Transonic Compressor Rig. The angular displacement mount consisted of a single mounting plate to which the readhead was attached and two spacers. The readhead was installed between the mounting plate and the casing of the throttle, and the mounting plate

was affixed to the casing with bolts in preexisting locations. The scale was attached to the outer edge of the throttle face via an adhesive. The Solidworks model of the angular mount installed on the throttle face can be seen in Figure 2.8.

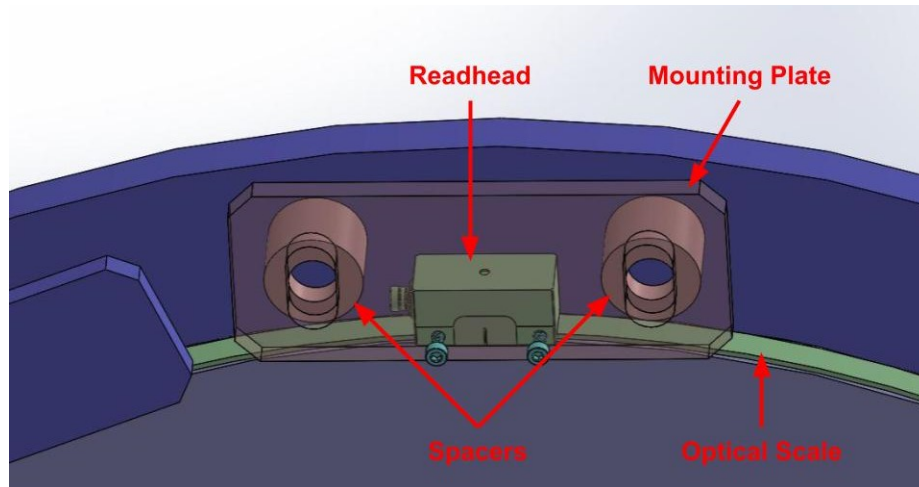


Figure 2.8. Angular Optical Encoder Mount

A temporary mounting plate and spacers were temporarily 3-D printed from PLA, and will be replaced with metal parts in future work.

2.2.5 Plug Design

In his research, Wallen developed a bell mouth attachment and intake plenum chamber to be fitted to the inlet of the TCR. This design allowed for optimum efficiency and accurate measurement of pressure differentials and mass flow rates, however, it must remain sealed in order to provide these benefits. In order to connect instrumentation to the throttle plate, there must be an air-tight hole in the intake plenum. A one-inch hole was created in the plenum to allow the throttle plate to be instrumented. In order to maintain a seal in the plenum chamber, an airtight plug was developed in order to allow for the wiring of the optical encoders. This plug consisted of a 25mm bolt split in half, with two holes to allow for the wires of each optical encoder to pass through. A nut would be placed on each end of the plug in order to create an airtight seal. The wires were affixed within the plug via Silicon glue. The Solidworks model of the plug can be seen in Figure 2.9.

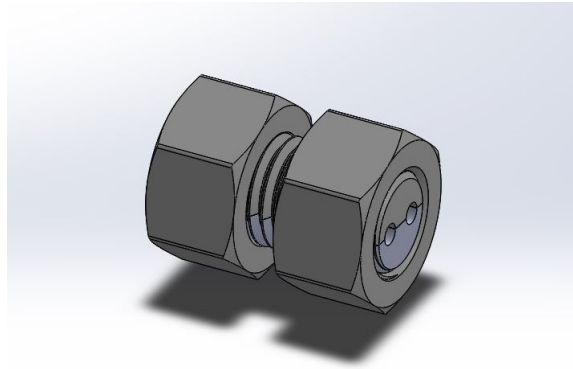


Figure 2.9. Airtight Plug

2.2.6 Software Development

The MATLAB script used to communicate with the optical encoders was developed using the test rig. A schematic of the experimental setup utilized for communications with the optical encoder when developing this script is depicted in Figure 2.10.

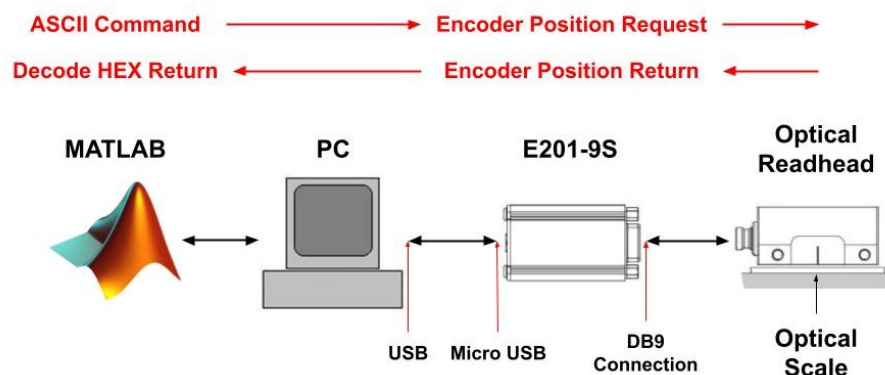


Figure 2.10. Communication Setup

The script communicates to the E201-9S encoder interface through a PC serial port via a USB connection. In the script, communication is first established with the E201-9S, then two locations on the strip are defined as 0% and 100%, correlating to the location the readhead would be along the scale at 0% and 100% throttle during operation of the TCR. Communications are then performed with the encoder in a loop for a specific amount of time. Every 0.05 seconds, the script will write a request to the encoder for its position,

clear any old position data, read the new return, decode the return into a position, and store the position in an array. The return from the optical encoder consists of 16 Hex character string. In order to decode this return into a position, the Hex character string is converted to a binary vector. The 32 bits correlating to the position of the encoder are extracted and converted to decimal [15]. A simple calculation is performed to determine what percentage this decimal value is equivalent to. The Test MATLAB script can be seen in Appendix B.

2.3 Probes

2.3.1 Location in the Flow

In order to characterize the flow entering the inlet of the test compressor, instrumented probes were designed to be inserted through the inlet casing and into the flow. The location of the casing where the probes were designed to be inserted is depicted in Figure 2.11.

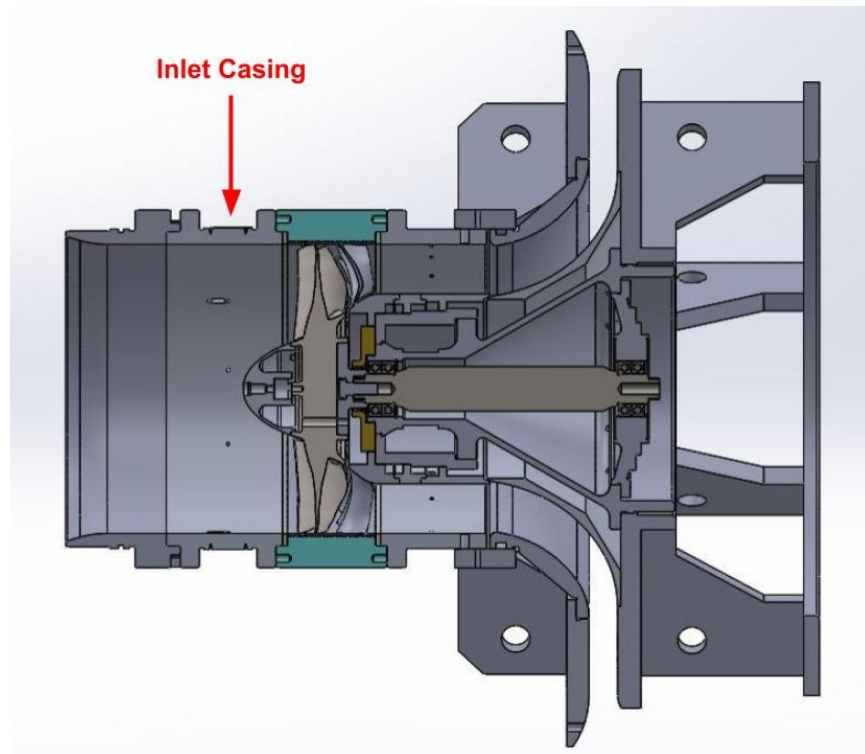


Figure 2.11. Inlet Casing

The probes were designed to be installed at the same axial distance along the length of the

compressor as the hot film probes utilized by Hearn, at azimuthal angles of 0°, 120°, and 240°. A Solidworks image of a probe inserted into the inlet casing can be seen in Figure 2.12.

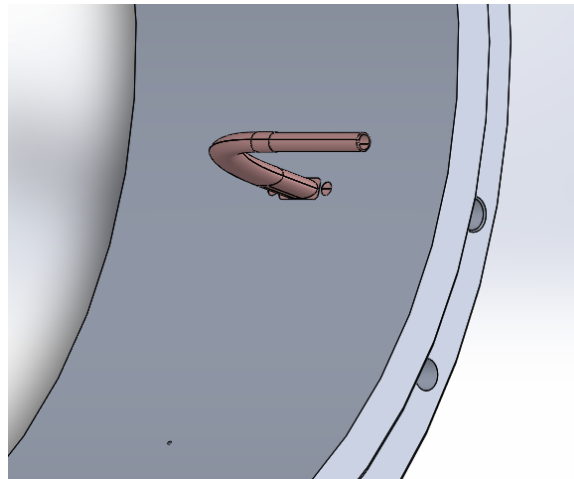


Figure 2.12. Probe in Inlet Casing

2.3.2 Probe Design

In order to insert the Kulite pressure transducers and total pressure ports into the flow, probes had to be designed that would contain the instrumentation and properly stagnate the flow. These probes were modeled after the designs commonly found on aircraft Pitot tubes, and each contains a single Kulite XCE-062 series pressure transducer and two total pressure ports. A diagram of the XCE-062 pressure transducer is in Figure 2.13.

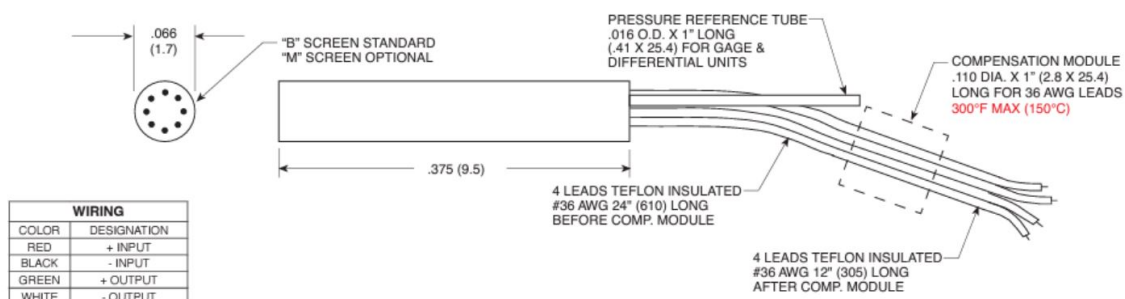


Figure 2.13. Kulite XCE-062 Diagram

This Kulite model is capable of a temperature range of -65°F To 525°F, and is designed for use in turbine engine probes and wind tunnel applications. The XCE-062 is well suited for use in user-designed probes and pressure rakes due to its rugged design and excellent performance in static and dynamic pressure measurements [16].

The probe is constructed of two halves 3-D printed from titanium on the EOS M100 3-D metal powder printer. The halves are sealed together using a silicon adhesive and are inserted into the probe via slots in the inlet casing. The Solidworks model of the probe can be seen in Figure 2.14. Note the Kulite pressure transducer, depicted in red.

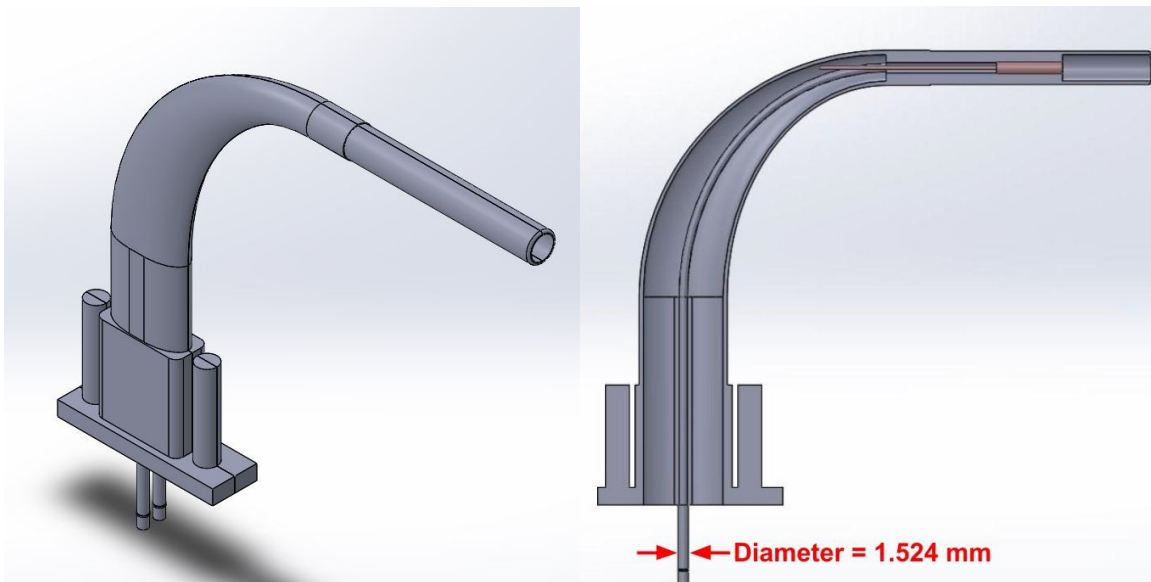


Figure 2.14. Probe (Left) and Cutaway View (Right)

A front view of the probes, depicting the location of the Kulite pressure transducer and total pressure ports can be seen in Figure 2.15.

The probes featured an easily customizable design in order to explore the effects of different parameters. The height of the probe can be easily adjusted via a parameter in Solidworks in order to change the depth in the flow at which the pressure transducer and total pressure ports are located. The length of the recess can also be adjusted via a parameter in order to explore the effects the length of the recess has on the attenuation of pressure measurements [12]. Based upon the designed recess length of 0.0127m and the radius of the recess at 1.905mm, it is expected that any pressure attenuation will be dependent upon the magnitude of pressure

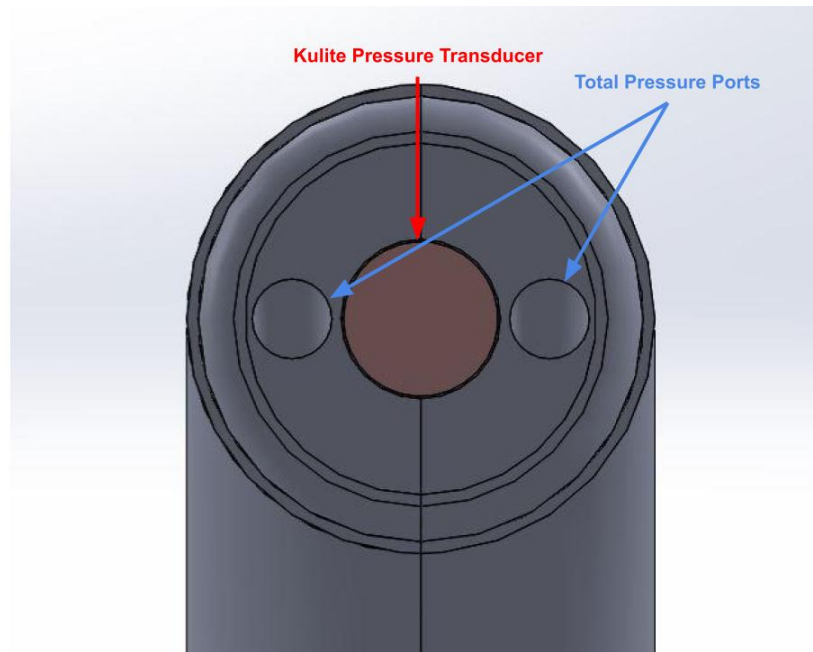


Figure 2.15. Front of Probe

fluctuations relative to the mean static pressure. Pressure attenuation will likely be less significant in the probe when compared to the tubes tested by Fotia, Hoke, and Schauer due to the larger recess radius in the probe than in the capillary tubes tested [12].

The total pressure port allows for the measurement of total pressure and low-frequency pressure unsteadiness. The Kulite pressure transducer also allows for the measurement of total pressure, but also high-frequency pressure unsteadiness. The measurement of total pressure, combined with the measurement of static pressure from static pressure ports located in the casing, allows for the determination of flow velocity and construction of velocity profile by varying the depth at which measurements are obtained. Based on the frequency of pressure unsteadiness measured, an estimation of the turbulence intensity can be made. These measurements allow for a characterization of the flow in the inlet.

CHAPTER 3: Data Collection and Analysis

3.1 Optical Encoder Integration

3.1.1 Optical Encoder Installation

The entirety of each optical encoder mount was preassembled before being installed into the TCR. In order to install the optical encoders, the bellmouth attachment and intake plenum were removed, allowing access to the throttle face. Before mounting the optical scale for the angular encoder the surface of the throttle face had to be prepped. A wire brush and a Dremel tool with a metal sanding disk bit were used to remove excessive rust from the throttle face. An epoxy spray paint was applied to the edge after sanding, creating a smooth surface where the scale would be applied. The throttle face after being prepared for the installation of the angular optical scale can be seen in Figure 3.1.



Figure 3.1. Throttle with Prepared Surface

After the surface was prepared, the scale for the angular optical encoder was attached to the edge of the throttle disk using the adhesive tape on the scale. The mounting plate with the angular optical encoder attached was affixed to the casing through the preexisting holes. Longer bolts were utilized to allow for room for the spacers and mounting plate. The angular optical encoder assembly installed on the TCR can be seen in Figure 3.2.

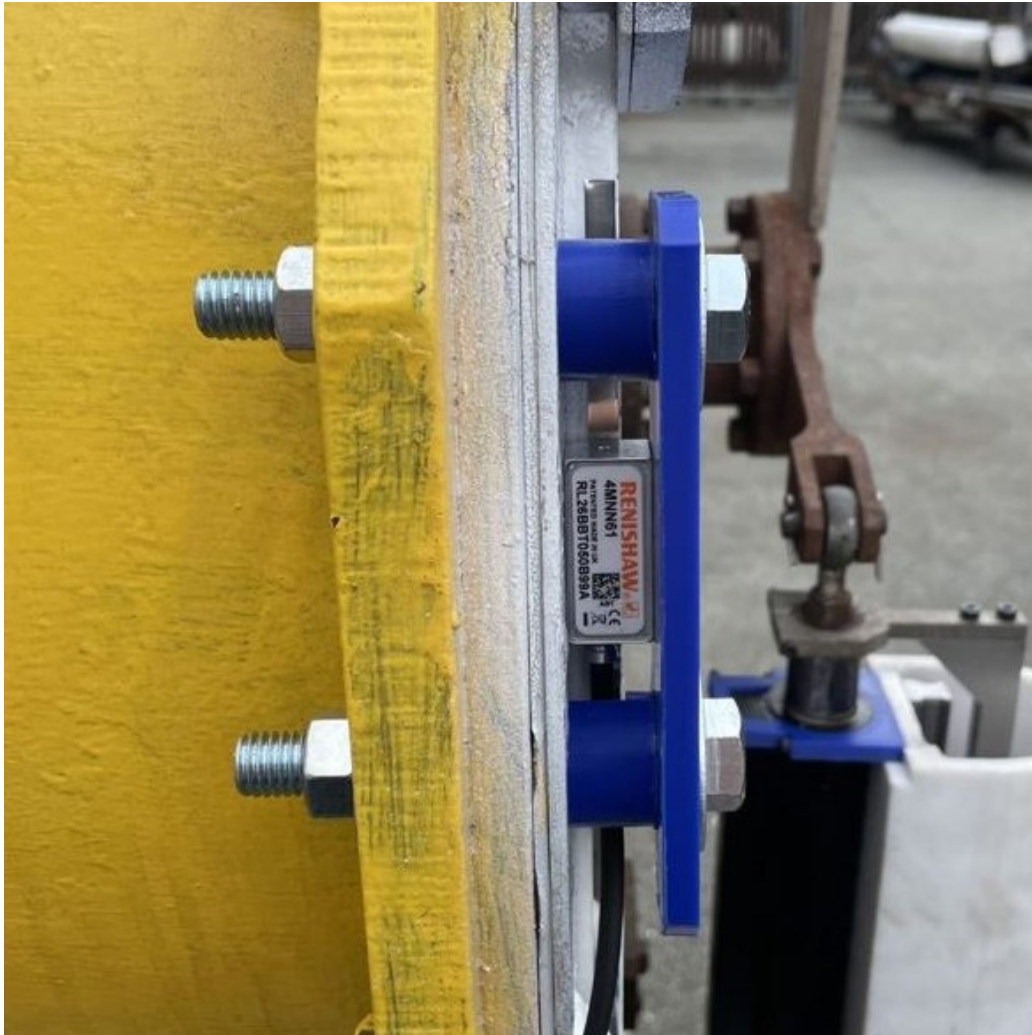


Figure 3.2. Angular Optical Encoder

The electric motor was removed from the rig to install the linear optical encoder mount assembly. The clips that support the baseplate were attached prior to attaching the mounting clip that supports the carriage and arm. After attaching the linear optical encoder assembly

to the electrical motor, the motor was reinserted into the rig. The throttle of the TCR with both the angular and linear optical encoder assemblies installed can be seen in Figure 3.3.

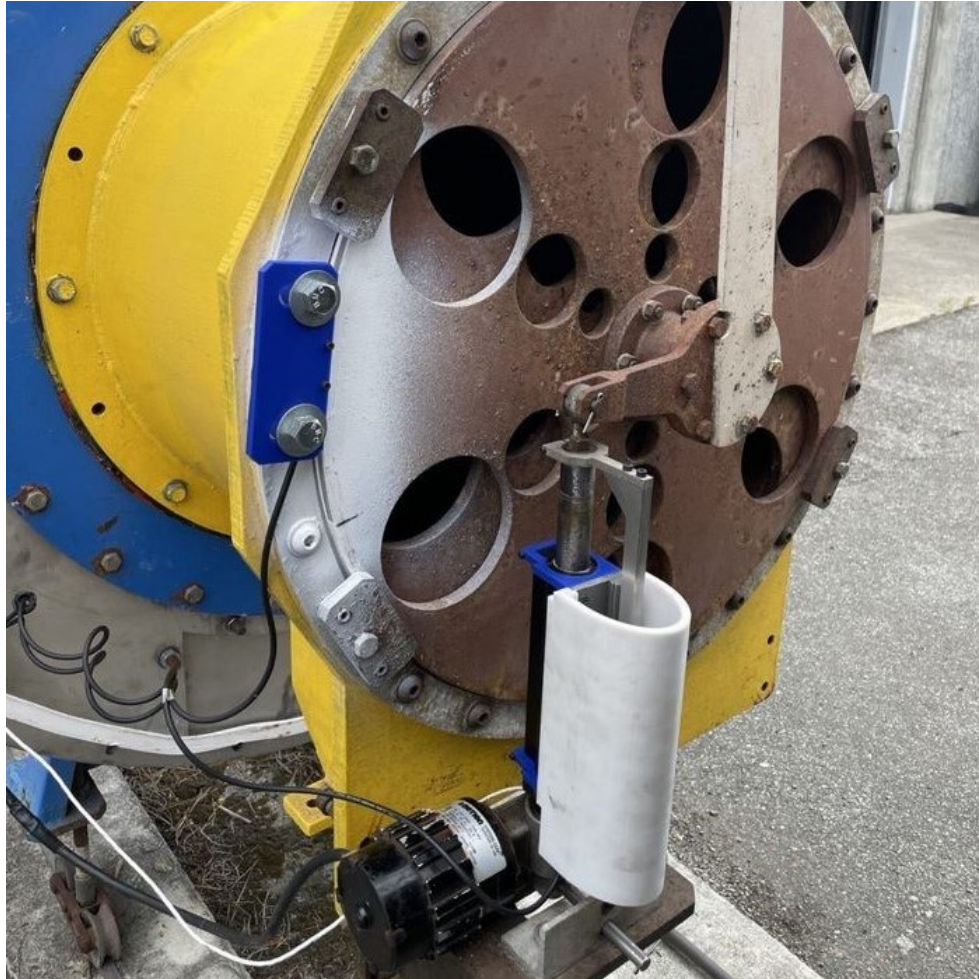


Figure 3.3. Optical Encoders installed in TCR

After installing both of the optical encoder assemblies to the throttle of the TCR, the male DB9 connector end of the optical encoders was fed through the 2 nuts and the hole in the casing of the intake plenum section. One nut was placed on each side of the casing, and the two halves of the split bolt were inserted into the hole in the casing. The two nuts were tightened down, providing the airtight seal in the intake plenum section necessary for proper operation. The optical encoder wires can be seen inserted through the airtight port in the intake plenum in Figure 3.4.



Figure 3.4. Airtight Connection

3.1.2 Optical Encoder Calibration

Once the two optical encoders were installed on the throttle of the TCR, they had to be calibrated in order to provide an accurate measurement of the throttle setting. To calibrate the optical encoders, the throttle was actuated to the full open, or "0," position, and the position output was requested from each optical encoder. The 32 position bits were converted to decimal and recorded for both the angular and linear optical encoders. This same process was repeated at the full closed, or "11," position. The test script from Subsection 2.2.6 was modified for each optical encoder, changing the "pos0" and "pos1" values to the decimal output from each optical encoder at the "0" and "11" position, respectively. Both the angular and linear optical encoder MATLAB scripts can be found in Appendix C.

During operation, the script determined throttle position as a linear interpolation between the outputs from the "0" and "11" positions. In order to verify the accuracy of the optical encoder outputs, the throttle setting was adjusted until the indicator reached different throttle indices. Angular and linear optical encoder outputs were recorded at throttle indices of 0, 2, 4, 6, 8, 10, and 11. This procedure was repeated twice, once throttling up from 0 to 11, and once down from 11 to 0. Also recorded was the measurement from the linear displacement sensor in the electric motor for comparison.

While performing the calibration of the optical encoder systems, an error occurred where an erroneous position return would remain cached in the MATLAB script, and could not be cleared. The procedure that worked to remedy this error is described in Appendix D.

3.2 Computational Fluid Dynamics Setup

In addition to the design and integration of the optical encoder mounts and probes, research was conducted to perform computational fluid dynamics simulations of the transonic compressor rig inlet ducting. These simulations were built upon prior research conducted by Wallen [5], continuing based on recommendations and updating the geometry to reflect the current state of the rig. Namely, the inlet flow nozzle that was present in the simulations performed by Wallen was removed. The main focus of these simulations was to compare CFD results to the experimental hot film velocity and turbulence profiles obtained by Hearn [6] in the full open and near stall conditions at 85% power. In addition, a goal was to study the disruption of the flow as it passed through the throttle plates, and how these disruptions propagated down the length of the inlet ducting. A porous section was implemented to model the flow screen located in the settling chamber, in an effort to construct an accurate model of the flow in the inlet ducting of the TCR.

3.2.1 Solidworks Modeling

A 60° slice, representing one 6th of the transonic compressor rig, was modeled in SolidWorks. This slice contained one singular set of the 3 holes present on the throttle of the transonic compressor rig, used to throttle the rig by controlling the mass flow of air into the inlet. The fluid domain extended from the throttle to the location of the test compressor. The model of the domain was split into four separate parts of equal volume in order to more effectively utilize computational resources. The fluid domain and its four parts can be seen in Figure 3.5.

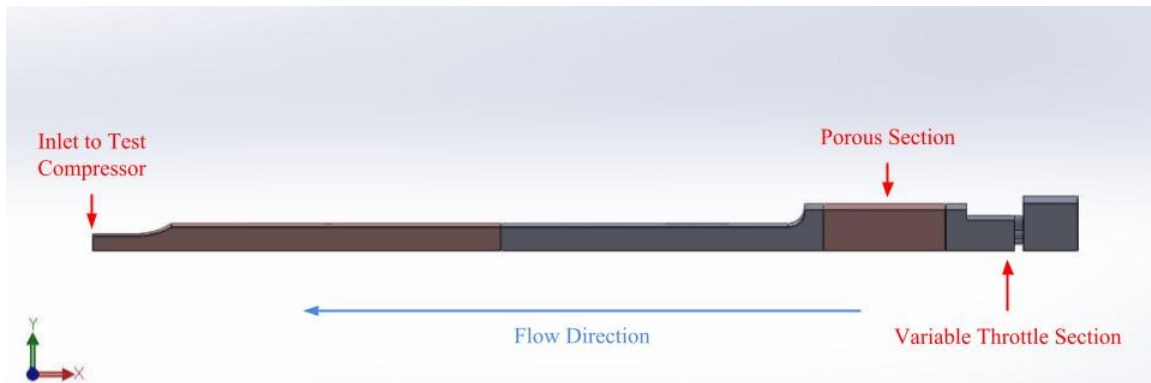


Figure 3.5. CFD Domain

The throttle face of the rig could be rotated in the Solidworks model of the first part of the assembly in order to model different throttle settings. This is depicted in Figure 3.6.

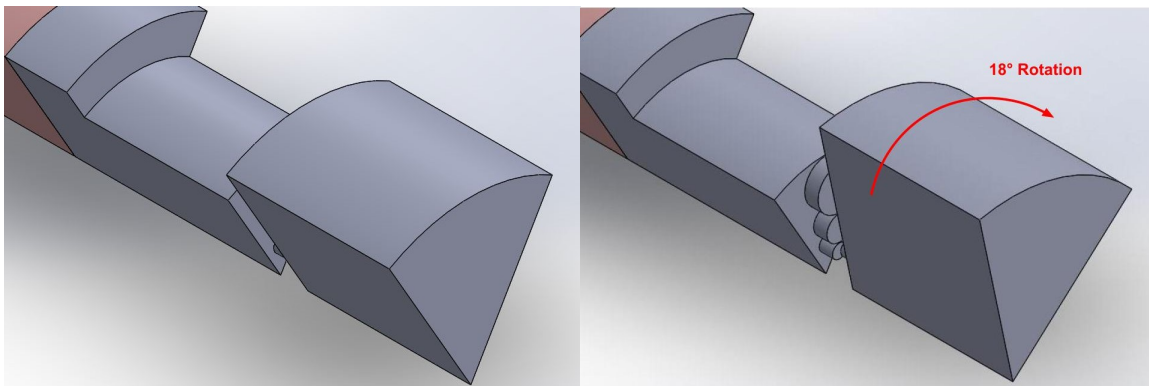


Figure 3.6. Rotation of Throttle Face

This study modeled two different throttle settings: a full open condition, as seen on the right in Figure 3.6, and a near stall condition, depicted on the left. In the near stall condition, the throttle was 75% closed, which required an 18° rotation of the throttle face.

3.2.2 Meshing and Setup

Once modeled, the two separate geometries were imported into ANSYS. An initial coarse mesh of approximately 1,800,000 elements was created in order to gain preliminary results before mesh refinement. The mesh was refined to approximately 9,600,000 elements for each geometry, in order to ensure mesh independence. The same settings were applied to each geometry when meshing, and the full details of each mesh can be seen in Appendix E. Mesh control matching was implemented between each individual part in the assembly to properly model the interface between each part.

Once meshed, each geometry was set up in ANSYS CFX. The upper boundary of the region was modeled as a no-slip wall, as were each of the faces of the throttle interface region. Air, Ideal Gas was selected as the fluid, with the total energy heat transfer option and Shear Stress Transport turbulence model implemented. The reference pressure and temperature were set to 1 atm and 286 K, respectively, as to properly model the atmospheric conditions surrounding the TCR. When the inlet of the fluid domain was modeled as an inlet, multiple errors occurred preventing solutions from being obtained. In order to resolve this, the inlet was modeled as an opening with a relative pressure of 0 KPa and a medium turbulence intensity of 5%. The outlet was modeled as an outlet with a relative pressure of -21.403 KPa in the full open condition, and -31.952 KPa in the near stall condition. These outlet pressures correlated to the 79.922 KPa and 69.373 KPa pressures experienced in the rig, relative to 0 atm, in each test condition. These pressures matched those seen in the experimental results of Hearn [6] when operating at 85% speed.

Due to this model being a 60° slice of the entire TCR inlet duct, rotational periodicity was implemented between the left and right side faces of the geometry in order to model the domain as a fraction of the whole region.

3.2.3 Porosity Setup

Following the initial results for each geometry, a porous section was implemented in the second part of the domain. The porous region in ANSYS CFX pre can be seen in Figure 3.7.

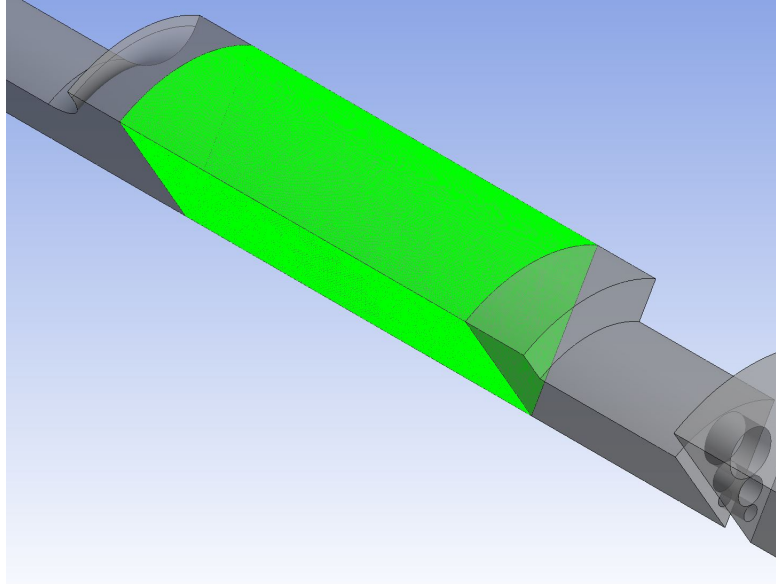


Figure 3.7. Porous Region

This porous region was implemented in order to simulate the flow screens located in the settling chamber section of the TCR, as actually modeling the screen would be extremely computationally intensive. When implementing the porous region, a porosity value from 0 to 1 was prescribed. A porosity of 1 correlated to a completely open free stream with no solid, and a porosity of 0 correlated to a solid wall in the domain. The directional loss model was utilized, as this porous region was modeling the flow through a honeycomb-like flow screen, and the momentum losses were not equal in each direction. The directions of the momentum losses caused by the flow screen were specified in Cartesian coordinates as [0,1,1]. This setup ensured that the flow exiting the porous region would be purely axial. A permeability coefficient had to be prescribed for the region, which controlled how the fluid was permitted to flow through the porous media and in turn how much momentum loss the media would induce. The equations to determine momentum loss in this directional loss model were

$$S_{M,x'} = -\frac{\mu}{K_{perm}^S} U_{x'} \quad (3.1)$$

$$S_{M,y'} = -\frac{\mu}{K_{perm}^T} U_{y'} \quad (3.2)$$

$$S_{M,z'} = -\frac{\mu}{K_{perm}^T} U_{z'} \quad (3.3)$$

where K_{perm}^S was the streamwise permeability and K_{perm}^T was the transverse permeability. An iterative process, consisting of varying the permeability and porosity of this region, was utilized to control the flow in this region until the computational results matched those seen in the experimental results of Hearn [6]. The final values of the volume porosity and permeability that yielded results most similar to those seen in data from Hearn were 0.6 and $4.5e - 7m^2$, respectively. The full porosity settings can be seen in Appendix F.

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CHAPTER 4:

Results

4.1 Optical Encoder Calibration Results

The results from the calibration process of the optical encoders are tabulated in Table 4.1.

Table 4.1. Encoder Calibration Raw Results

Throttle Index	Ang. Position First Trial	Ang. Position Second Trial	Lin. Position First Trial	Lin. Position Second Trial	Motor Sensor
0	51204088	50914750	166565931	166565931	14.34
2	89831227	90257215	147741900	146985767	11.87
4	130365298	131203637	128778803	128363505	9.42
6	168579253	167937525	109930623	109547197	7.00
8	207631996	210413053	91712225	89953585	4.44
10	246542002	247887994	72942182	72311212	2.16
11	266175031	266175031	64117516	64117516	1.08

The position data for each optical encoder consists of 32 bits, recorded in decimal format. By linearly interpolating each position return between the 0 and 11 values, each return can be expressed between 0 and 11. These values can be seen compared to the marked throttle indices in Table 4.2.

Table 4.2. Encoder Calibration Reduced Results

Throttle Index	Ang. Position First Trial	Ang. Position Second Trial	Lin. Position First Trial	Lin. Position Second Trial	Motor Sensor
0	0.0000	-0.0148	0.0000	0.0000	0.0000
2	1.9765	1.9983	2.0212	2.1023	2.0490
4	4.0507	4.0936	4.0572	4.1018	4.0814
6	6.0061	5.9732	6.0810	6.1222	6.0890
8	8.0044	8.1467	8.0371	8.2260	8.2127
10	9.9954	10.0643	10.0525	10.1202	10.1041
11	11.0000	11.0000	11.0000	11.0000	11.0000

4.2 Computational Fluid Dynamics Results

The velocity along the X-Y plane is depicted for the full open condition with and without the porous media implemented in Figures 4.1 and 4.2, respectively.

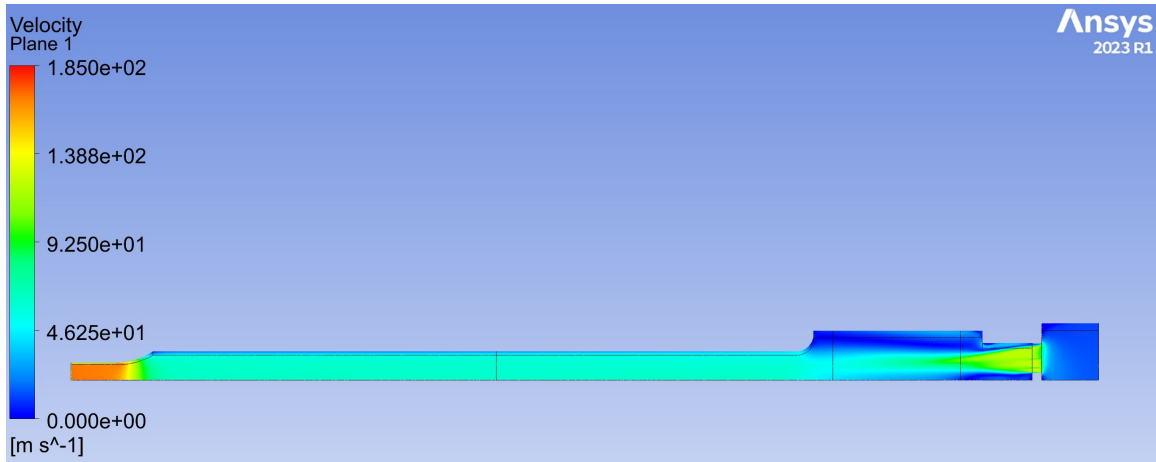


Figure 4.1. Full Open Velocity, No Porous Media

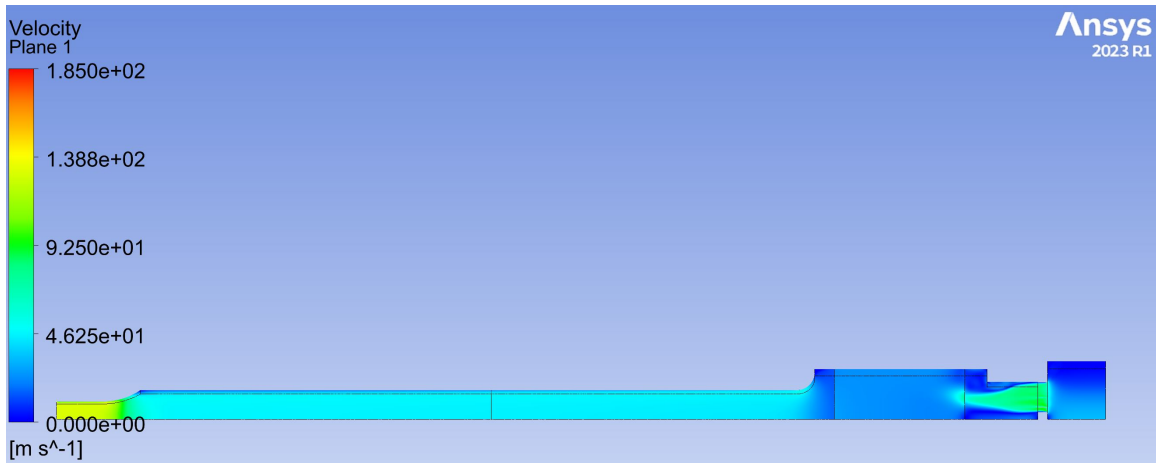


Figure 4.2. Full Open Velocity, Porous Media

The maximum velocity occurred at the exit both with and without the implementation of the porous media, however, the maximum velocity achieved without the porous media was greater than with the porous media. The maximum velocity at the exit was approximately

170.0 m/s without the porous media and 131.6 m/s with the porous media. The most significant difference visible between the two simulations, other than the momentum loss induced by the porous media, was the flow dispersion caused by the porous media in the settling chamber. Without the porous media, there was a region of high velocity directly following the throttle face, and a region of low velocity along the outer rim of the settling chamber, with little to no mixing between these regions. The porous media, when implemented, "smoothed out" the velocity profile in the settling chamber. The high-velocity region induced by the throttle jets was dissipated, yielding an even velocity profile axially.

The pressure along the X-Y plane in the full open condition, with and without the porous media, can be seen in Figures 4.3 and 4.4.



Figure 4.3. Full Open Pressure, No Porous Media

The lowest pressure in both simulations was the prescribed outlet pressure, and the highest pressure was in the corners of the throttle inlet region. The average pressure along the length of the inlet ducting was greater without the porous media than with it due to the higher average velocity, and thus higher dynamic pressure. When the porous media was not implemented, there was a large pressure drop following the throttle, however, the pressure remained rather consistent along the length of the inlet ducting before dropping again in the final contraction at the exit to the test compressor region. When the porous media was implemented, there was still a pressure drop following the throttle, however, this was followed by a gradual pressure drop in the porous media. Following the porous media,

pressures remained consistent along the length of the ducting before dropping at the exit contraction.

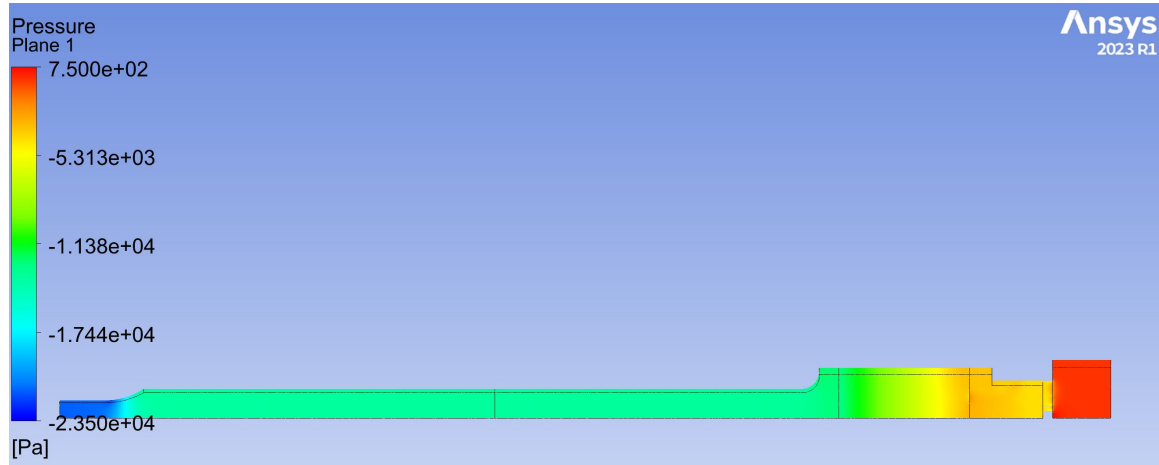


Figure 4.4. Full Open Pressure, Porous Media

The velocity along the X-Y plane in the near stall condition with and without the porous media is depicted in Figures 4.5 and 4.6, respectively.

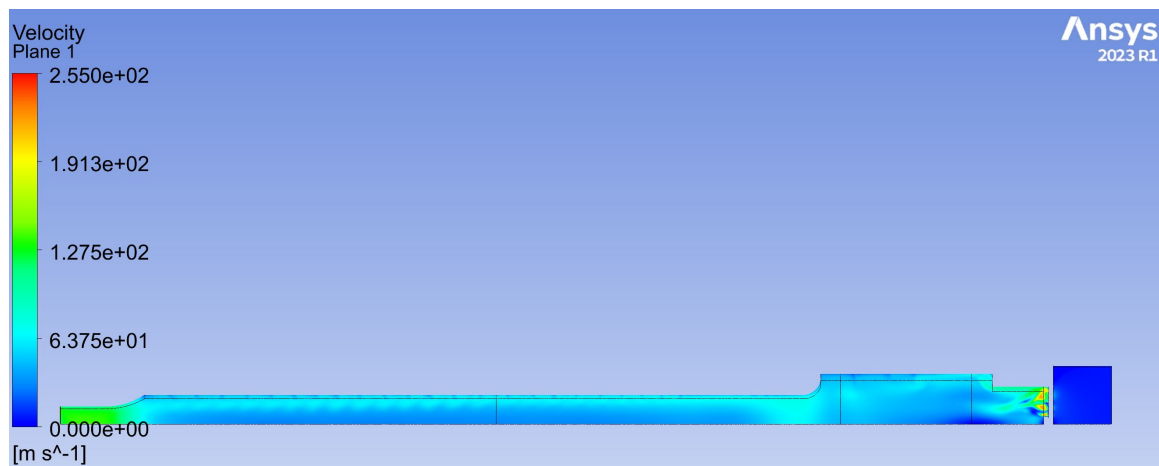


Figure 4.5. Near Stall Velocity, No Porous Media

The maximum velocity reached both with and without the porous media was in the throttle region, due to the smaller gap in the throttle holes. The maximum exit velocity without the porous media was approximately 130.7 m/s and was approximately 101.3 m/s with the

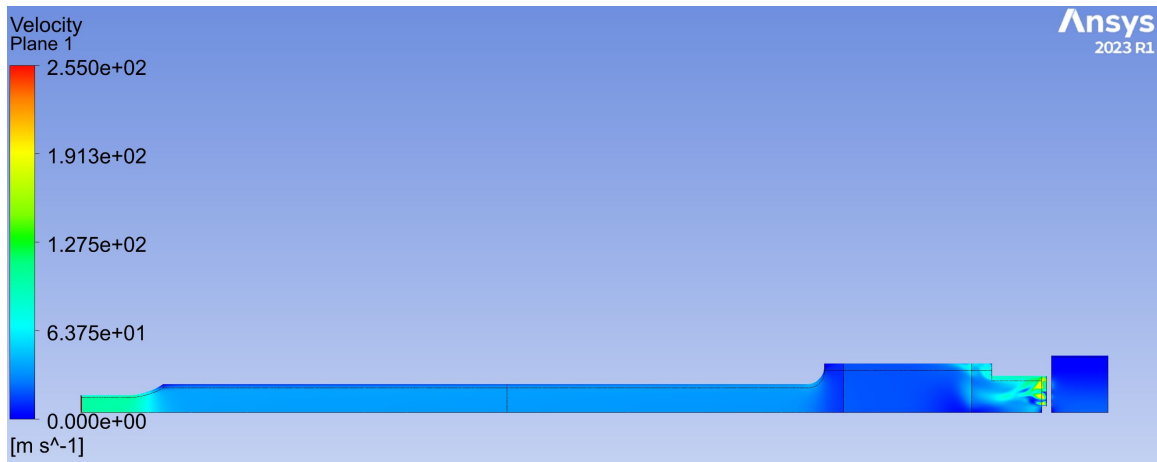


Figure 4.6. Near Stall Velocity, Porous Media

porous media. Without the porous media implemented, the uneven velocity profile induced by the throttle persisted down the length of the ducting before smoothing out in the exit contraction. The uneven velocity profile was more pronounced in the near stall condition than in the full open condition, with a region of high velocity down the entire length of the duct following the settling chamber near the wall, and a region of lower velocity in the center of the duct. The porous media, similar to in the full open condition, dissipated the effects of the throttle and created an even velocity profile down the length of the ducting.

The effects of the throttle on the velocity in the inlet ducting in the near stall condition could be more clearly seen when looking at velocity vectors in the X-Z plane, as depicted in Figure 4.7 without the porous media and in Figure 4.8 with the porous media.

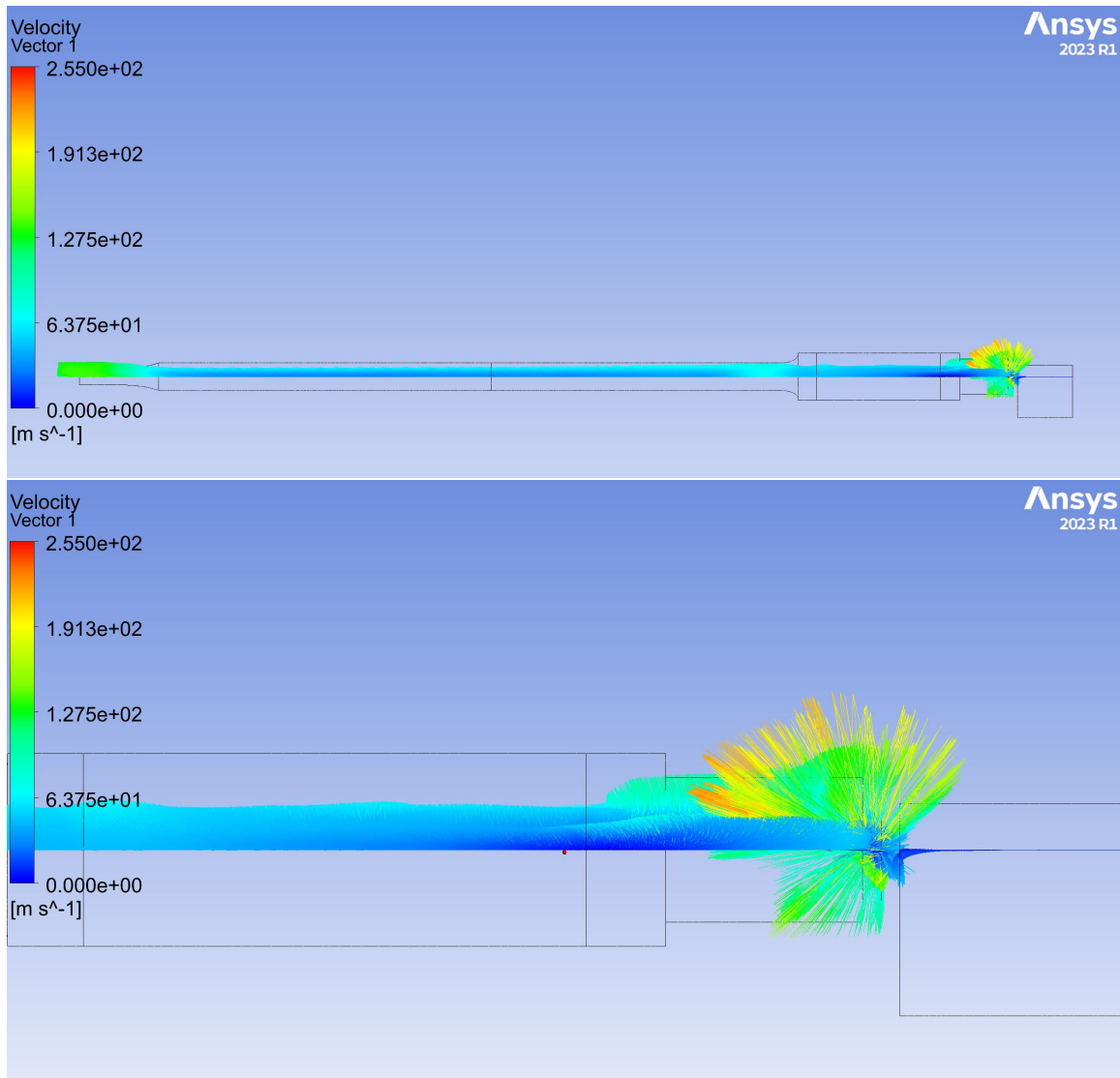


Figure 4.7. Near Stall Velocity Vectors, No Porous Media

The throttle region induced a significant clockwise angular velocity component in the near stall condition, which persisted down the length of the entire inlet ducting without the porous media. This angular velocity component was responsible for the increased velocity seen along the wall in Figure 4.5.

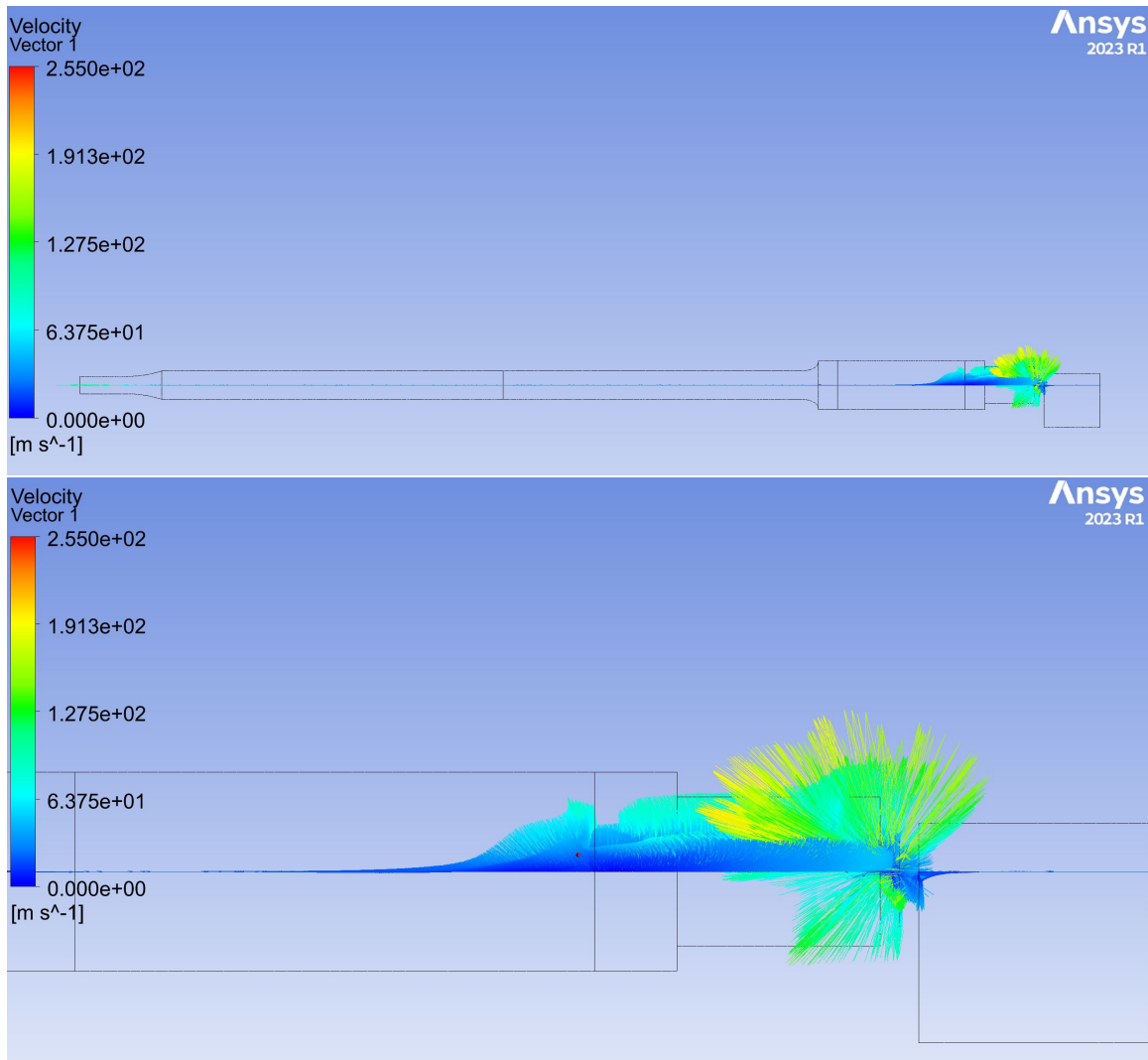


Figure 4.8. Near Stall Velocity Vectors, Porous Media

The same angular velocity component was induced by the throttle when the porous media was implemented, however, the media dissipated the angular velocity component. At the exit of the porous media region, the velocity in the inlet was purely axial.

The pressure along the X-Y plane in the near stall condition, with and without the porous media, can be seen in Figures 4.9 and 4.10.

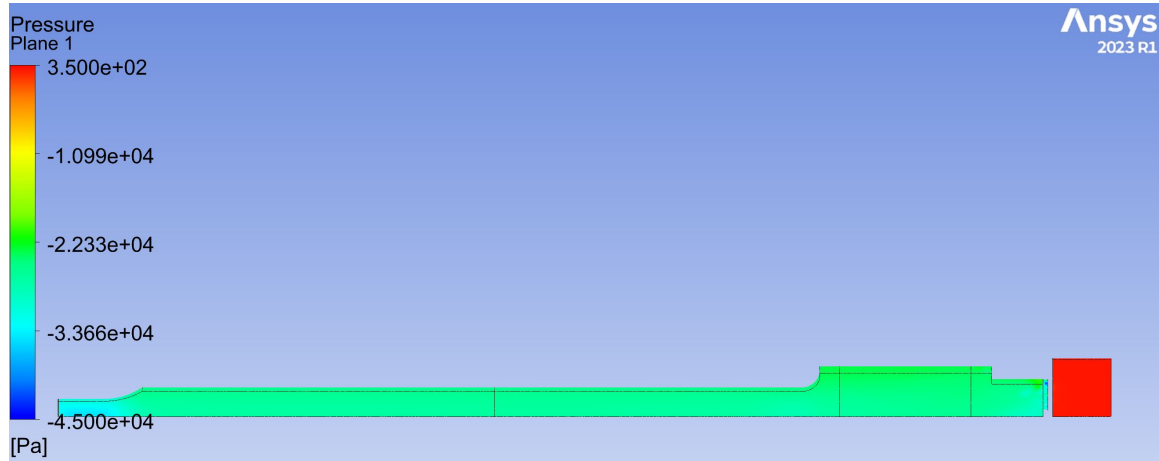


Figure 4.9. Full Open Pressure, No Porous Media

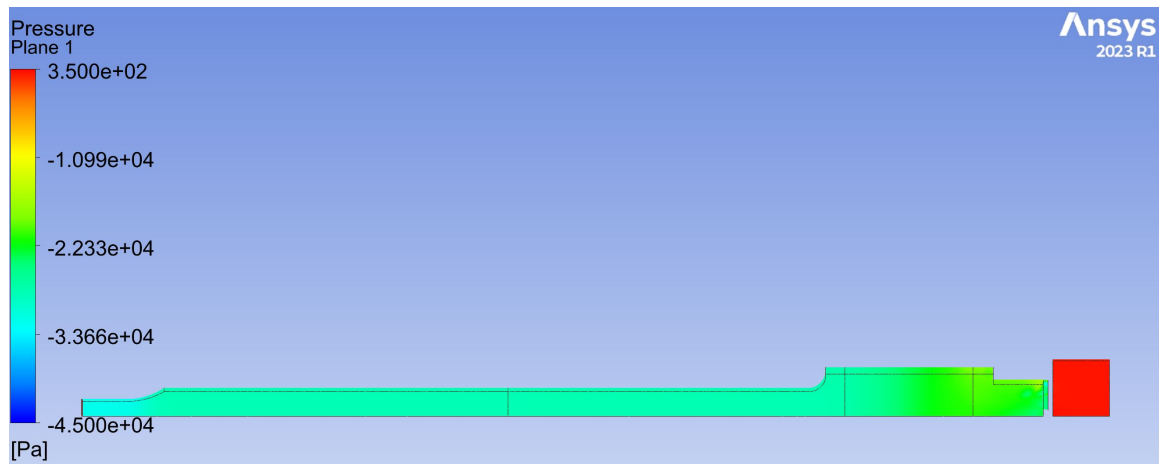


Figure 4.10. Full Open Pressure, Porous Media

The same trends seen in the full open condition pressure were exhibited in the near stall condition pressure. There was a pressure drop immediately following the throttle region, and a small pressure drop in the porous media when implemented. The simulation without the porous media exhibited a region of slightly higher pressure near the wall due to the increased dynamic pressure caused by the angular velocity component. The pressure profile was more even axially when the porous media was implemented.

4.3 Comparison with Experimental Results

The computational fluid dynamics results were compared with the experimental data from Hearn [6] at 85% power in both the full open and near stall conditions. The experimental data can be seen tabulated in Appendix G. The CFD velocity profiles at the exit of the inlet ducting for both the simulations with and without the porous region can be seen compared to Hearn's experimental data in Figure 4.11. Comparisons were plotted in both the full open and near stall conditions.

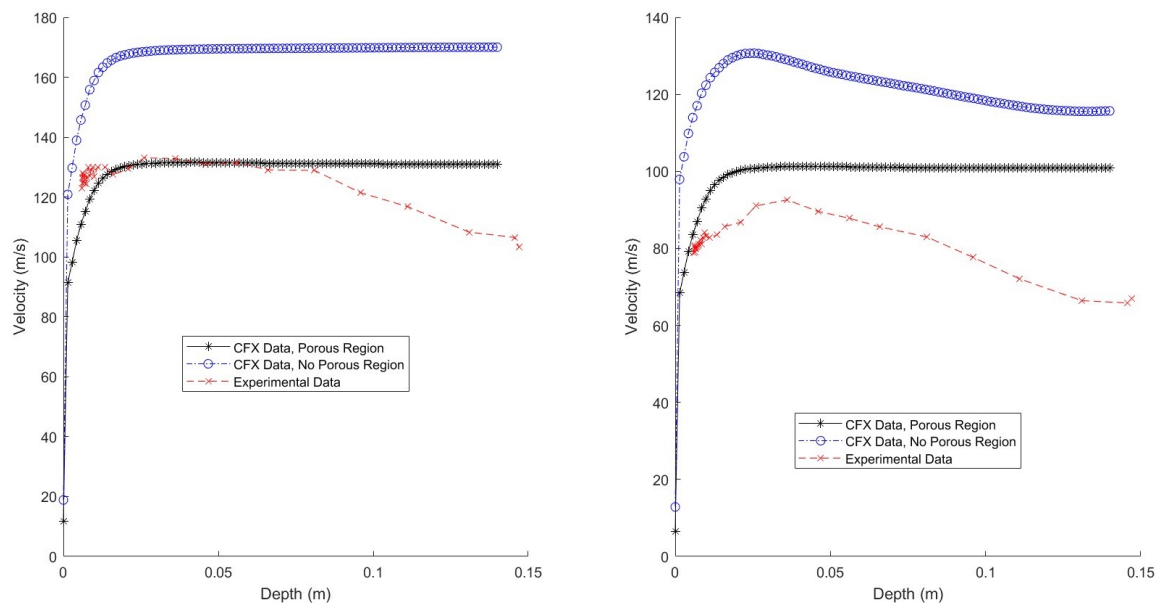


Figure 4.11. Inlet Exit Velocity Profiles at Full Open (Left) and Near Stall (Right) Conditions

In the full open condition, the maximum experimental velocity was approximately 133.1 m/s,

which occurred at a depth of 0.026 m into the flow. Velocities remained around this maximum value from 0.008 m from the wall to 0.081 m from the wall before decreasing. The maximum velocity in the CFX data was approximately 170.0 m/s without the porous region implemented and 131.6 m/s with it implemented. Both with and without the porous region, velocities remained at this maximum velocity from 0.02 m from the wall to the center of the flow. There was a 27.8% error when compared to experimental exit velocity for the simulation without a porous region and a -1.13% error for the simulation with a porous region. The reduction in velocity near the center of the flow seen in the experimental data but seen in neither CFD simulation was caused by the bluff body drag of the center hub of the test compressor.

In the near stall condition, the maximum experimental velocity was approximately 92.6 m/s and occurred 0.036 m from the wall. Velocities decreased with increasing depth beyond this point. In the CFD simulation without a porous media, the maximum velocity was 130.7 m/s at a depth of 0.025 m from the wall. As depth increased beyond this point, velocity decreased. When the porous media was inserted, the maximum velocity was approximately 101.3 m/s, and this velocity was consistent from a depth of 0.022m to the center of the region. There was a 41.12 % error when compared to the experimental data for the simulation without a porous media and a 9.38% error for the simulation with a porous media. The experimental data once again showed a reduction in velocity near the center of the flow due to the bluff body from the compressor hub, similar to the full open condition. The CFD simulation without a porous media also showed this reduction in exit velocity near the center of the region, however, this was due to the angular velocity induced by the throttle as discussed in 4.2.

The exit turbulence intensity profiles for the CFD simulations with and without the porous media were plotted against the experimental data in both the full open and near stall conditions in Figure 4.12.

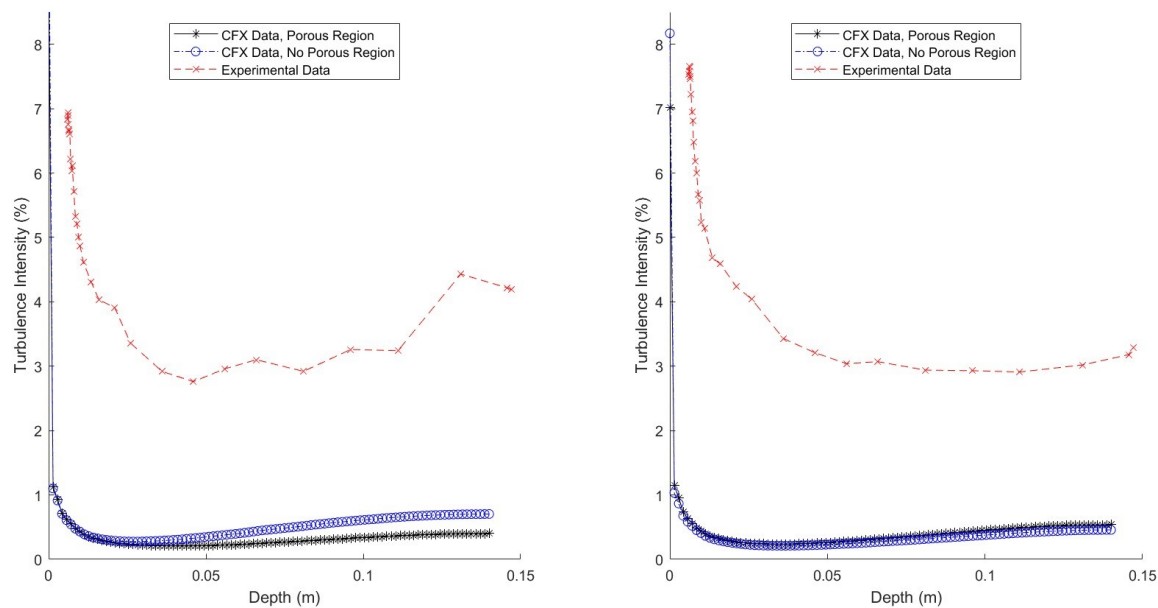


Figure 4.12. Inlet Exit Turbulence Intensity Profiles at Full Open (Left) and Near Stall (Right) Conditions

In the full open condition, the experimental turbulence intensity remained around 3% in the middle of the flow regime, increasing to approximately 4.2% in the center of the flow. In the CFD simulation without a porous media, the turbulence intensity ranged from 0.277% 0.027 m from the wall to 0.704% in the center of the region. When the porous media was inserted, the turbulence intensity ranged from 0.208% 0.042 m from the wall to 0.400% in the center. In the near stall condition, the experimental turbulence intensity was approximately 3% from a depth of 0.046 m to the center of the flow. The CFD simulation without a porous media showed a range of 0.211% at 0.033m to 0.457% in the center. When the porous media was inserted, the turbulence intensity ranged from 0.238% at 0.033m to 0.538% in the center.

In both the full open and near stall conditions, the computational fluid dynamic simulations yielded turbulence intensities approximately 2.5% lower than the experimental data. The porous media had little impact on the exit turbulence intensity. In an effort to better simulate the turbulence intensities seen in the experimental data, simulations were run with higher turbulence intensities of 10 and 15%. These simulations were performed in the full open

condition, however, these results showed little to no difference when compared to simulations with a medium inlet turbulence intensity of 5%. Further work is required in this area to better simulate the turbulence profiles seen at the exit of the inlet ducting in the TCR.

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CHAPTER 5:

Conclusions and Recommendations

The installation of the two optical encoders provided a method for the accurate determination of throttle setting and inlet conditions. The encoders can be fully integrated into the transonic compressor rig control system and give it a fine degree of throttle control not previously possible. This will allow for precise characterization of flow based on initial conditions, facilitating future research. In future work, the temporary parts 3-D printed from PLA will be replaced with parts constructed from metal.

The installation of the probes will allow for permanent, accurate measurement of pressure and pressure unsteadiness. These probes, when used in conjunction with the present static pressure ports, will allow for the determination of velocity at the exit of the inlet ducting. The Kulite and total pressure port configuration will allow for the measurement of both high-frequency and low-frequency pressure unsteadiness, allowing for estimations of turbulence intensity. The modifiable design of these probes will allow for measurement at different depths in the flow in order to construct a profile of velocity and turbulence intensity. Therefore, it is recommended to print multiple configurations of these probes, measuring the pressure and pressure unsteadiness at various depths and azimuthal angles in order to construct a map of the flow field characteristics at the exit of the inlet.

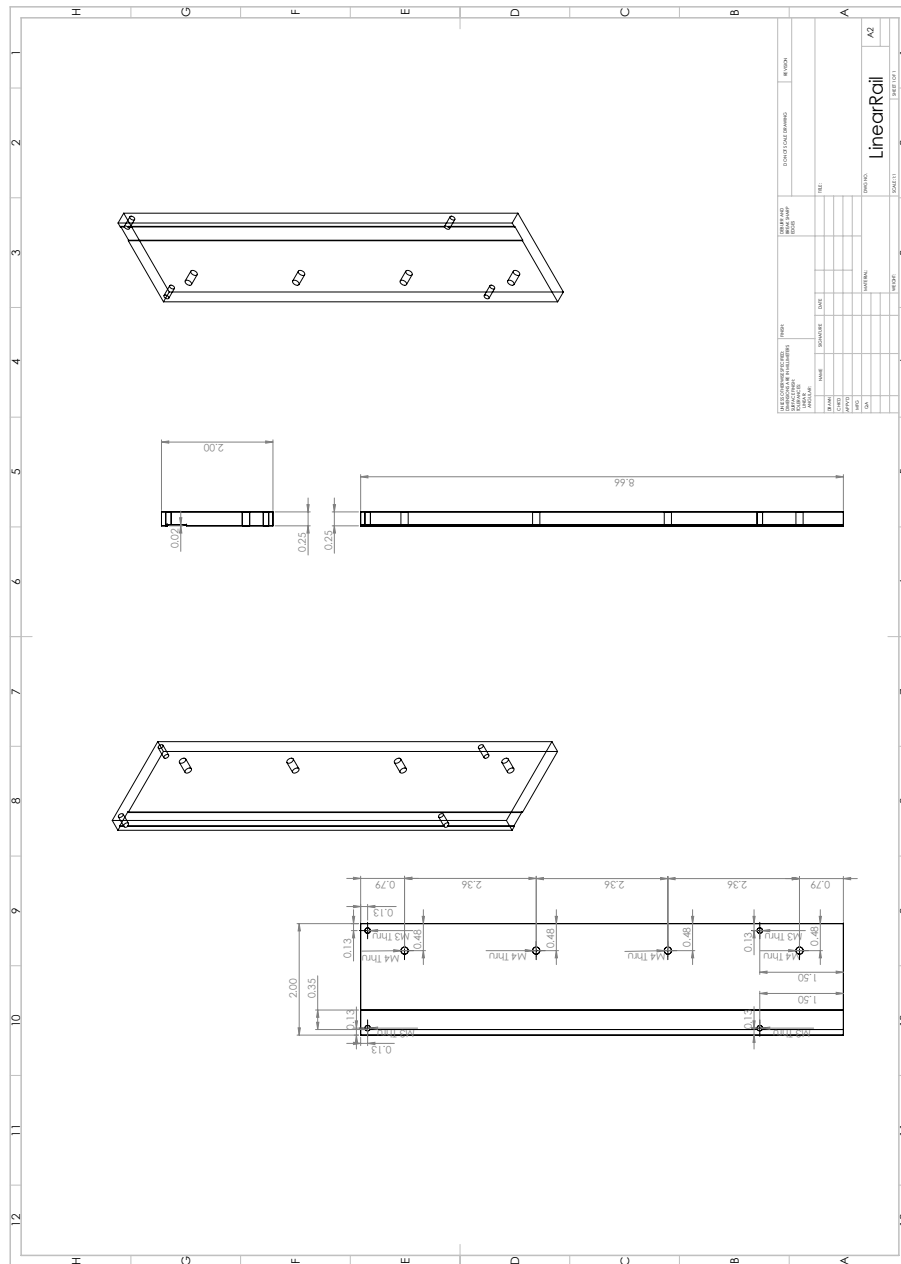
The combination of the optical encoders and probes offers a reliable method of determining the mass flow in the inlet and characterizing the flow field velocity and turbulence. This will allow for future research on casing treatments and recirculation devices that can help to treat compressor stalls and increase the stall margin on the transonic compressor rig.

From the computational fluid dynamics simulations, it can be concluded that the porous media provides an accurate model to determine the exit velocity of the inlet ducting. The porous media models the honeycomb flow screen located in the settling chamber, and disperses the flow accurately. The results from the computational simulations show that the flow jets induced by the throttle are dissipated by the flow screen, and the flow is purely axial by the time it reaches the exit of the inlet ducting. Computational results suggest an even velocity profile at the exit of the inlet ducting, however, this does not match experimental

results. This disparity was most likely due to the lack of a model of the compressor hub in the computational simulation.

Therefore, in future simulations, it is recommended that the compressor hub is modeled in future computational simulations with the porous region. This will likely yield a model that accurately predicts the velocity profile at the exit of the inlet ducting. The computational simulations did a poor job of predicting the turbulence profile at the exit of the inlet ducting, even when the inlet turbulence intensity was prescribed at 10 and 15%. Therefore, in order to better model the turbulence in the inlet ducting it is recommended to perform a large eddy simulation.

APPENDIX A: Engineering Drawings



APPENDIX B:

Optical Encoder Test MATLAB Script

The following MATLAB script was developed while testing the optical encoders with the test rig. This script was adapted for use with both the angular and linear optical encoder systems installed on the TCR.

1	<code>%% Optical Encoder Test</code>	
2	<code>% ENS Giamb Bruno</code>	
3	<code>% For use with Renishaw RL26BBT050B99A RESOLUTE™ linear and partial arc</code>	
4	<code>% optical encoder, connected to PC USB port via E201-9S USB Encoder Interface</code>	
5	<code>clear</code>	
6	<code>clc</code>	
7	<code>%% Establish Connection</code>	
8	<code>ComPort='COM8';</code>	
9	<code>BaudRate=9600;</code>	
10	<code>Encoder=serialport(ComPort,BaudRate);</code>	
11	<code>%% Boundaries of Strip</code>	
12	<code>pos0=57589667;</code>	<code>% '0%' Location</code>
13	<code>pos1=219549872;</code>	<code>% '100%' Location</code>
14	<code>%% Loop to Find Location for N Seconds</code>	
15	<code>N=10;</code>	<code>% Run Time (sec)</code>
16	<code>t0 = clock;</code>	<code>% Initialize Timed Loop</code>
17	<code>i=1;</code>	
18	<code>I=0;</code>	
19	<code>per=0;</code>	
20	<code>while etime(clock, t0) < N</code>	
21	<code> i=i+1;</code>	
22	<code> I=[I, i];</code>	
23	<code> pause(0.05);</code>	<code>% Pause 0.05 sec</code>
24	<code>%% Communicate with Encoder</code>	
25	<code>writeline(Encoder, '4')</code>	<code>% Encoder Position Request</code>
26	<code>clear str</code>	
27	<code>str=read(Encoder,16+7,"char");</code>	<code>% Encoder Position Return (16 Hex Character String, 7 Hex Character CR)</code>
28	<code>%% Decode BISS Information</code>	
29	<code>bin=hexToBinaryVector(str(1:16));</code>	<code>% Convert Hex String to Binary Vector</code>
30	<code>bin_reduced=bin(3:64);</code>	<code>% Discard First 2 Bits</code>
31	<code>startbit=find(bin_reduced,1,'first');</code>	<code>% Start Bit</code>
32	<code>cdsbit=startbit+1;</code>	<code>% CDS Bit</code>
33	<code>pos=bin_reduced((startbit+2):(startbit+2+31));</code>	<code>% 32 Position Bits</code>
34	<code>status=bin_reduced((startbit+33+1):(startbit+33+2));</code>	<code>% 2 Status Bits</code>
35	<code>crc=bin_reduced((startbit+35+1):(startbit+35+5));</code>	<code>% 6 CRC Bits</code>
36	<code>pos_dec=bin2dec(num2str(pos));</code>	<code>% Convert Binary Position to Decimal</code>
37	<code>percent=(pos_dec-pos0)/(pos1-pos0)*100;</code>	<code>% Calculate Location Along Strip as Percentage</code>
38	<code>disp(percent)</code>	<code>% Display Location as Percentage</code>
39	<code>per=[per, percent];</code>	
40	<code>end</code>	
41	<code>figure(1)</code>	
42	<code>plot((1:N)/length(I),per)</code>	
43	<code>ylim([1 100])</code>	
44	<code>title('Percentage over Time')</code>	
45	<code>xlabel('Time (sec)')</code>	
46	<code>ylabel('Percentage')</code>	

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APPENDIX C:

Optical Encoder MATLAB Scripts

The following MATLAB scripts were adapted from the script in Appendix B, and were the scripts that drove the function of the angular and linear optical encoder systems.

1	<code>%% Angular Optical Encoder</code>	
2	<code>% ENS Giambruno</code>	
3	<code>% For use with Renishaw RL26BBT050B99A RESOLUTE™ partial arc</code>	
4	<code>% optical encoder, connected to PC USB port via E201-9S USB Encoder Interface</code>	
5	<code>clear</code>	
6	<code>clc</code>	
7	<code>%% Establish Connection</code>	
8	<code>ComPort='COM8';</code>	
9	<code>BaudRate=9600;</code>	
10	<code>Encoder=serialport(ComPort,BaudRate);</code>	
11	<code>%% Boundaries of Strip</code>	
12	<code>pos0=51204088;</code>	<code>% '0' Location</code>
13	<code>pos1=266175031;</code>	<code>% '11' Location</code>
14	<code>%% Loop to Find Location for N Seconds</code>	
15	<code>N=9999999;</code>	<code>% Run Time (sec)</code>
16	<code>t0 = clock;</code>	<code>% Initialize Timed Loop</code>
17	<code>i=1;</code>	
18	<code>I=0;</code>	
19	<code>ind=0;</code>	
20	<code>while etime(clock, t0) < N</code>	
21	<code> i=i+1;</code>	
22	<code> I=[I, i];</code>	
23	<code> pause(0.05);</code>	<code>% Pause 0.05 sec</code>
24	<code>%% Communicate with Encoder</code>	
25	<code>writeline(Encoder, '4')</code>	<code>% Encoder Postion Request</code>
26	<code>clear str</code>	
27	<code>str=read(Encoder,16+7,"char");</code>	<code>% Encoder Postion Return (16 Hex Character String, 7 Hex Character CR)</code>
28	<code>%% Decode BISS Information</code>	
29	<code>bin=hexToBinaryVector(str(1:16));</code>	<code>% Convert Hex String to Binary Vector</code>
30	<code>bin_reduced=bin(3:64);</code>	<code>% Discard First 2 Bits</code>
31	<code>startbit=find(bin_reduced,1,'first');</code>	<code>% Start Bit</code>
32	<code>cdsbit=startbit+1;</code>	<code>% CDS Bit</code>
33	<code>pos=bin_reduced((startbit+2):(startbit+2+31));</code>	<code>% 32 Position Bits</code>
34	<code>status=bin_reduced((startbit+33+1):(startbit+33+2));</code>	<code>% 2 Status Bits</code>
35	<code>crc=bin_reduced((startbit+35+1):(startbit+35+5));</code>	<code>% 6 CRC Bits</code>
36	<code>pos_dec=bin2dec(num2str(pos));</code>	<code>% Convert Binary Position to Decimal</code>
37	<code>index=(pos_dec-pos0)/(pos1-pos0)*11;</code>	<code>% Calculate Location Along Strip as Index</code>
38	<code>disp(index)</code>	<code>% Display Location as Index</code>
39	<code>ind=[ind, index];</code>	
40	<code>end</code>	

Figure C.1. Angular Optical Encoder MATLAB Script

1	%% Linear Optical Encoder	
2	% ENS Giamb Bruno	
3	% For use with Renishaw RL26B8T050B99A RESOLUTE™ linear	
4	% optical encoder, connected to PC USB port via E201-9S USB Encoder Interface	
5	clear	
6	clc	
7	%% Establish Connection	
8	ComPort='COM8';	
9	BaudRate=9600;	
10	Encoder=serialport(ComPort,BaudRate);	
11	%% Boundaries of Strip	
12	pos0=166565931;	% '0' Location
13	pos1=64117516;	% '11' Location
14	%% Loop to Find Location for N Seconds	
15	N=99999999;	% Run Time (sec)
16	t0 = clock;	% Initialize Timed Loop
17	i=1;	
18	I=0;	
19	ind=0;	
20	while etime(clock, t0) < N	
21	i=i+1;	
22	I=[I, i];	
23	pause(0.05);	% Pause 0.05 sec
24	%% Communicate with Encoder	
25	writeline(Encoder, '4')	% Encoder Position Request
26	clear str	
27	str=read(Encoder,16+7,"char");	% Encoder Position Return (16 Hex Character String, 7 Hex Character CR)
28	%% Decode BISS Information	
29	bin=hexToBinaryVector(str(1:16));	% Convert Hex String to Binary Vector
30	bin_reduced=bin(3:64);	% Discard First 2 Bits
31	startbit=find(bin_reduced,1,'first');	% Start Bit
32	cdsbit=startbit+1;	% CDS Bit
33	pos=bin_reduced((startbit+2):(startbit+2+31));	% 32 Position Bits
34	status=bin_reduced((startbit+33+1):(startbit+33+2));	% 2 Status Bits
35	crc=bin_reduced((startbit+35+1):(startbit+35+5));	% 6 CRC Bits
36	pos_dec=bin2dec(num2str(pos));	% Convert Binary Position to Decimal
37	index=(pos_dec-pos0)/(pos1-pos0)*11;	% Calculate Location Along Strip as Index
38	disp(index)	% Display Location as Index
39	ind=[ind, index];	
40	end	

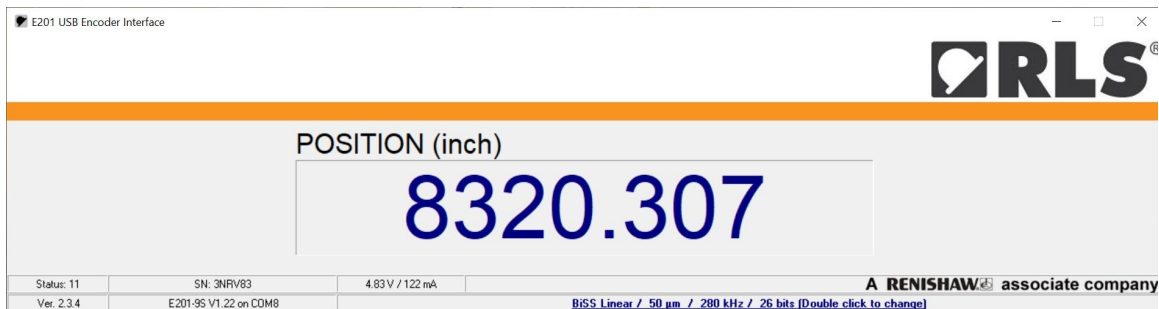
Figure C.2. Linear Optical Encoder MATLAB Script

APPENDIX D:

Optical Encoder MATLAB Script Application Note

In the event that an erroneous position value, or no position value, is returned by one of the optical encoders, the following procedure should be utilized to "reset" the system and return it to proper operation.

1. Verify the proper script is being utilized.
i.e. Angular script with angular encoder, linear script with linear encoder.
2. Execute the "clear" function in MATLAB and attempt to run the script again.
3. Close MATLAB and open the Renishaw E201 software.
4. Double click on the E201 settings (Bottom Right).



5. Verify the following settings.

E201 Settings

Encoder Type
☒ Linear ☐ Rotary ☐ Distance Coded Ref Marks

Encoder Interface
☐ SSI ☒ BiSS

BiSS Frequency
280 kHz

Resolution
µm: 50 Position Data (Bits): 26

SSI / BiSS Mode Settings
Status Bits: 2 CRC Bits: 6
☒ Show Encoder Status
☐ Show Status Colors
☐ Active Status LOW

Distance Coded Reference Marks Settings
☒ Nominal Increment (Periods) Counts Per Period: 2
1000
☐ Basic Increment K (mm) Periode Length (mm): 2
2000
☒ Show Reference Marks

Display Units
Linear: ☐ mm ☒ inch ☐ µm ☐ mil
Rotary: ☒ Counts ☐ D° M' S" ☐ Degrees

Direction
☐ Invert Direction

E201 Interface Status
☒ Show E201 Status Info

OK Cancel

Ver. 2.3.4.3 / E201-9S V1.22

6. Verify all connections between PC, E201, and optical encoder. Check the status lights on the E201 hardware. Both the "Encoder" and "USB" lights should be green.
7. Actuate the throttle and ensure the position value changes within the E201 software.
8. If the position value does not change in the E201 software, verify the status of the optical encoder, as the issue may be due to the ride height of the sensor over the scale being out of tolerance. A light on top of the readhead indicates the ride height status. A blue status light is ideal, green and orange lights are acceptable. The sensor will still operate with a red light, albeit unreliably.
9. If the position value does change in the E201 software, close the software and open the MATLAB script. When closing the E201 software, the "USB" status light on the E201 will turn red. Once the MATLAB script is executed, this light should return to green.

APPENDIX E: Mesh Settings

The following mesh settings were utilized while performing the Computational Fluid Dynamics analysis of the TCR inlet ducting.

Details of "Mesh"	
Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	CFD
Solver Preference	CFX
Element Order	Linear
☐ Element Size	5.e-003 m
Sizing	
Use Adaptive Sizing	No
☐ Growth Rate	Default (1.2)
☐ Max Size	Default (1.e-002 m)
Mesh Defeaturing	Yes
☐ Defeature Size	Default (2.5e-005 m)
Capture Curvature	Yes
☐ Curvature Minimum	Default (5.e-005 m)
☐ Curvature Normal	10.0°
Capture Proximity	No
Bounding Box Diameter	8.3024 m
Average Surface Area	0.21177 m ²
Minimum Edge Length	2.54e-002 m
Quality	
Check Mesh Quality	Yes, Errors
☐ Target Skewness	Default (0.9)
Smoothing	Medium
Mesh Metric	None
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
☐ Transition Ratio	0.77
☐ Maximum Layers	5
☐ Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced	No
Advanced	
Number of CPUs	4
Straight Sided Elements	
Rigid Body Behavior	Dimensionally Reduced
Triangle Surface	Program Controlled
Topology Check	Yes
Pinch Tolerance	Default (4.5e-005 m)
Generate Pinch	No
Statistics	
☐ Nodes	2428970
☐ Elements	9591460
Show Detailed Statistics	No

Details of "Patch Conforming Method" - Method	
Scope	
Scoping Method	Geometry Selection
Geometry	4 Bodies
Definition	
Suppressed	No
Method	Tetrahedrons
Algorithm	Patch Conforming
Element Order	Use Global Setting

Details of "Inflation" - Inflation	
Scope	
Scoping Method	Geometry Selection
Geometry	4 Bodies
Definition	
Suppressed	No
Boundary Scoping Method	Geometry Selection
Boundary	17 Faces
Inflation Option	First Layer Thickness
☐ First Layer Height	1.e-005 m
☐ Maximum Layers	8
☐ Growth Rate	1.2
Inflation Algorithm	Pre

Details of "Contact Match 1_2"	
Scope	
Scoping Method	Geometry Selection
Primary Geometry	1 Face
Secondary Geometry	1 Face
Primary Bodies	TCRFluidDomain_1_FullOpen_Giambruno
Secondary Bodies	TCRFluidDomain_2_Giambruno
Definition	
Scope Mode	Manual
Tolerance Type	Slider
Tolerance Slider	0.
Tolerance Value	2.0756e-002 m
Suppressed	No

Details of "Contact Match 2_3"	
Scope	
Scoping Method	Geometry Selection
Primary Geometry	1 Face
Secondary Geometry	1 Face
Primary Bodies	TCRFluidDomain_2_Giambruno
Secondary Bodies	TCRFluidDomain_3_Giambruno
Definition	
Scope Mode	Manual
Tolerance Type	Slider
Tolerance Slider	0.
Tolerance Value	2.0756e-002 m
Suppressed	No

Details of "Contact Match 3_4"	
Scope	
Scoping Method	Geometry Selection
Primary Geometry	1 Face
Secondary Geometry	1 Face
Primary Bodies	TCRFluidDomain_3_Giambruno
Secondary Bodies	TCRFluidDomain_4_Giambruno
Definition	
Scope Mode	Manual
Tolerance Type	Slider
Tolerance Slider	0.
Tolerance Value	2.0756e-002 m
Suppressed	No

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APPENDIX F: Porosity Settings

The following porosity settings were implemented into the porous section of the Computational Fluid Dynamics model. Included is the .ccl file for the full open, porous model, and the settings utilized in CFX.

State file created: 2023/07/05 16:05:35
Build 23.1 2022-11-25T14:31:12.124816

LIBRARY:

CEL:

EXPRESSIONS:

MassFlowMon = (massFlow()@Inlet)+(massFlow()@Outlet)

END

END

MATERIAL GROUP: Air Data

Group Description = Ideal gas and constant property air. Constant \
properties are for dry air at STP (0 C, 1 atm) and 25 C, 1 atm.

END

MATERIAL GROUP: CHT Solids

Group Description = Pure solid substances that can be used for conjugate \
heat transfer.

END

MATERIAL GROUP: Calorically Perfect Ideal Gases

Group Description = Ideal gases with constant specific heat capacity. \
Specific heat is evaluated at STP.

END

MATERIAL GROUP: Constant Property Gases

Group Description = Gaseous substances with constant properties. \
Properties are calculated at STP (0C and 1 atm). Can be combined with \
NASA SP-273 materials for combustion modelling.

END

MATERIAL GROUP: Constant Property Liquids

Group Description = Liquid substances with constant properties.

END

MATERIAL GROUP: Dry Peng Robinson

Group Description = Materials with properties specified using the built \
in Peng Robinson equation of state. Suitable for dry real gas modelling.

END

MATERIAL GROUP: Dry Redlich Kwong

Group Description = Materials with properties specified using the built \
in Redlich Kwong equation of state. Suitable for dry real gas modelling.

END

MATERIAL GROUP: Dry Soave Redlich Kwong

Group Description = Materials with properties specified using the built \
in Soave Redlich Kwong equation of state. Suitable for dry real gas \
modelling.

END

MATERIAL GROUP: Dry Steam

Group Description = Materials with properties specified using the IAPWS \
equation of state. Suitable for dry steam modelling.

END

MATERIAL GROUP: Gas Phase Combustion

Group Description = Ideal gas materials which can be use for gas phase \
combustion. Ideal gas specific heat coefficients are specified using \
the NASA SP-273 format.

END

MATERIAL GROUP: IAPWS IF97

Group Description = Liquid, vapour and binary mixture materials which use \
the IAPWS IF-97 equation of state. Materials are suitable for \
compressible liquids, phase change calculations and dry steam flows.

END

MATERIAL GROUP: Interphase Mass Transfer

Group Description = Materials with reference properties suitable for \
performing either Eulerian or Lagrangian multiphase mass transfer \
problems. Examples include cavitation, evaporation or condensation.

END

MATERIAL GROUP: Liquid Phase Combustion

Group Description = Liquid and homogenous binary mixture materials which \
can be included with Gas Phase Combustion materials if combustion \

```

        modelling also requires phase change (eg: evaporation) for certain \
        components.
END
MATERIAL GROUP: Particle Solids
    Group Description = Pure solid substances that can be used for particle \
    tracking
END
MATERIAL GROUP: Peng Robinson Dry Hydrocarbons
    Group Description = Common hydrocarbons which use the Peng Robinson \
    equation of state. Suitable for dry real gas models.
END
MATERIAL GROUP: Peng Robinson Dry Refrigerants
    Group Description = Common refrigerants which use the Peng Robinson \
    equation of state. Suitable for dry real gas models.
END
MATERIAL GROUP: Peng Robinson Dry Steam
    Group Description = Water materials which use the Peng Robinson equation \
    of state. Suitable for dry steam modelling.
END
MATERIAL GROUP: Peng Robinson Wet Hydrocarbons
    Group Description = Common hydrocarbons which use the Peng Robinson \
    equation of state. Suitable for condensing real gas models.
END
MATERIAL GROUP: Peng Robinson Wet Refrigerants
    Group Description = Common refrigerants which use the Peng Robinson \
    equation of state. Suitable for condensing real gas models.
END
MATERIAL GROUP: Peng Robinson Wet Steam
    Group Description = Water materials which use the Peng Robinson equation \
    of state. Suitable for condensing steam modelling.
END
MATERIAL GROUP: Real Gas Combustion
    Group Description = Real gas materials which can be use for gas phase \
    combustion. Ideal gas specific heat coefficients are specified using \
    the NASA SP-273 format.
END
MATERIAL GROUP: Redlich Kwong Dry Hydrocarbons
    Group Description = Common hydrocarbons which use the Redlich Kwong \
    equation of state. Suitable for dry real gas models.
END
MATERIAL GROUP: Redlich Kwong Dry Refrigerants
    Group Description = Common refrigerants which use the Redlich Kwong \
    equation of state. Suitable for dry real gas models.
END
MATERIAL GROUP: Redlich Kwong Dry Steam
    Group Description = Water materials which use the Redlich Kwong equation \
    of state. Suitable for dry steam modelling.
END
MATERIAL GROUP: Redlich Kwong Wet Hydrocarbons
    Group Description = Common hydrocarbons which use the Redlich Kwong \
    equation of state. Suitable for condensing real gas models.
END
MATERIAL GROUP: Redlich Kwong Wet Refrigerants
    Group Description = Common refrigerants which use the Redlich Kwong \
    equation of state. Suitable for condensing real gas models.
END
MATERIAL GROUP: Redlich Kwong Wet Steam
    Group Description = Water materials which use the Redlich Kwong equation \
    of state. Suitable for condensing steam modelling.
END
MATERIAL GROUP: Soave Redlich Kwong Dry Hydrocarbons
    Group Description = Common hydrocarbons which use the Soave Redlich Kwong \
    equation of state. Suitable for dry real gas models.
END

```

```

MATERIAL GROUP: Soave Redlich Kwong Dry Refrigerants
  Group Description = Common refrigerants which use the Soave Redlich Kwong \
    equation of state. Suitable for dry real gas models.
END
MATERIAL GROUP: Soave Redlich Kwong Dry Steam
  Group Description = Water materials which use the Soave Redlich Kwong \
    equation of state. Suitable for dry steam modelling.
END
MATERIAL GROUP: Soave Redlich Kwong Wet Hydrocarbons
  Group Description = Common hydrocarbons which use the Soave Redlich Kwong \
    equation of state. Suitable for condensing real gas models.
END
MATERIAL GROUP: Soave Redlich Kwong Wet Refrigerants
  Group Description = Common refrigerants which use the Soave Redlich Kwong \
    equation of state. Suitable for condensing real gas models.
END
MATERIAL GROUP: Soave Redlich Kwong Wet Steam
  Group Description = Water materials which use the Soave Redlich Kwong \
    equation of state. Suitable for condensing steam modelling.
END
MATERIAL GROUP: Soot
  Group Description = Solid substances that can be used when performing \
    soot modelling
END
MATERIAL GROUP: User
  Group Description = Materials that are defined by the user
END
MATERIAL GROUP: Water Data
  Group Description = Liquid and vapour water materials with constant \
    properties. Can be combined with NASA SP-273 materials for combustion \
    modelling.
END
MATERIAL GROUP: Wet Peng Robinson
  Group Description = Materials with properties specified using the built \
    in Peng Robinson equation of state. Suitable for wet real gas modelling.
END
MATERIAL GROUP: Wet Redlich Kwong
  Group Description = Materials with properties specified using the built \
    in Redlich Kwong equation of state. Suitable for wet real gas modelling.
END
MATERIAL GROUP: Wet Soave Redlich Kwong
  Group Description = Materials with properties specified using the built \
    in Soave Redlich Kwong equation of state. Suitable for wet real gas \
    modelling.
END
MATERIAL GROUP: Wet Steam
  Group Description = Materials with properties specified using the IAPWS \
    equation of state. Suitable for wet steam modelling.
END
MATERIAL: Air Ideal Gas
  Material Description = Air Ideal Gas (constant Cp)
  Material Group = Air Data, Calorically Perfect Ideal Gases
  Option = Pure Substance
  Thermodynamic State = Gas
  PROPERTIES:
    Option = General Material
  EQUATION OF STATE:
    Molar Mass = 28.96 [kg kmol-1]
    Option = Ideal Gas
  END
  SPECIFIC HEAT CAPACITY:
    Option = Value
    Specific Heat Capacity = 1.0044E+03 [J kg-1 K-1]
    Specific Heat Type = Constant Pressure

```

```

END
REFERENCE STATE:
  Option = Specified Point
  Reference Pressure = 1 [atm]
  Reference Specific Enthalpy = 0. [J/kg]
  Reference Specific Entropy = 0. [J/kg/K]
  Reference Temperature = 25 [C]
END
DYNAMIC VISCOSITY:
  Dynamic Viscosity = 1.831E-05 [kg m^-1 s^-1]
  Option = Value
END
THERMAL CONDUCTIVITY:
  Option = Value
  Thermal Conductivity = 2.61E-2 [W m^-1 K^-1]
END
ABSORPTION COEFFICIENT:
  Absorption Coefficient = 0.01 [m^-1]
  Option = Value
END
SCATTERING COEFFICIENT:
  Option = Value
  Scattering Coefficient = 0.0 [m^-1]
END
REFRACTIVE INDEX:
  Option = Value
  Refractive Index = 1.0 [m m^-1]
END
END
MATERIAL: Air at 25 C
Material Description = Air at 25 C and 1 atm (dry)
Material Group = Air Data, Constant Property Gases
Option = Pure Substance
Thermodynamic State = Gas
PROPERTIES:
  Option = General Material
EQUATION OF STATE:
  Density = 1.185 [kg m^-3]
  Molar Mass = 28.96 [kg kmol^-1]
  Option = Value
END
SPECIFIC HEAT CAPACITY:
  Option = Value
  Specific Heat Capacity = 1.0044E+03 [J kg^-1 K^-1]
  Specific Heat Type = Constant Pressure
END
REFERENCE STATE:
  Option = Specified Point
  Reference Pressure = 1 [atm]
  Reference Specific Enthalpy = 0. [J/kg]
  Reference Specific Entropy = 0. [J/kg/K]
  Reference Temperature = 25 [C]
END
DYNAMIC VISCOSITY:
  Dynamic Viscosity = 1.831E-05 [kg m^-1 s^-1]
  Option = Value
END
THERMAL CONDUCTIVITY:
  Option = Value
  Thermal Conductivity = 2.61E-02 [W m^-1 K^-1]
END
ABSORPTION COEFFICIENT:
  Absorption Coefficient = 0.01 [m^-1]

```

```

    Option = Value
END
SCATTERING COEFFICIENT:
    Option = Value
    Scattering Coefficient = 0.0 [m^-1]
END
REFRACTIVE INDEX:
    Option = Value
    Refractive Index = 1.0 [m m^-1]
END
THERMAL EXPANSIVITY:
    Option = Value
    Thermal Expansivity = 0.003356 [K^-1]
END
END
MATERIAL: Aluminium
    Material Group = CHT Solids, Particle Solids
    Option = Pure Substance
    Thermodynamic State = Solid
    PROPERTIES:
        Option = General Material
        EQUATION OF STATE:
            Density = 2702 [kg m^-3]
            Molar Mass = 26.98 [kg kmol^-1]
            Option = Value
        END
        SPECIFIC HEAT CAPACITY:
            Option = Value
            Specific Heat Capacity = 9.03E+02 [J kg^-1 K^-1]
        END
        REFERENCE STATE:
            Option = Specified Point
            Reference Specific Enthalpy = 0 [J/kg]
            Reference Specific Entropy = 0 [J/kg/K]
            Reference Temperature = 25 [C]
        END
        THERMAL CONDUCTIVITY:
            Option = Value
            Thermal Conductivity = 237 [W m^-1 K^-1]
        END
    END
END
MATERIAL: Copper
    Material Group = CHT Solids, Particle Solids
    Option = Pure Substance
    Thermodynamic State = Solid
    PROPERTIES:
        Option = General Material
        EQUATION OF STATE:
            Density = 8933 [kg m^-3]
            Molar Mass = 63.55 [kg kmol^-1]
            Option = Value
        END
        SPECIFIC HEAT CAPACITY:
            Option = Value
            Specific Heat Capacity = 3.85E+02 [J kg^-1 K^-1]
        END
        REFERENCE STATE:
            Option = Specified Point
            Reference Specific Enthalpy = 0 [J/kg]
            Reference Specific Entropy = 0 [J/kg/K]
            Reference Temperature = 25 [C]
        END
    END

```

```

THERMAL CONDUCTIVITY:
  Option = Value
  Thermal Conductivity = 401.0 [W m^-1 K^-1]
END
END
MATERIAL: Soot
  Material Group = Soot
  Option = Pure Substance
  Thermodynamic State = Solid
  PROPERTIES:
    Option = General Material
    EQUATION OF STATE:
      Density = 2000 [kg m^-3]
      Molar Mass = 12 [kg kmol^-1]
      Option = Value
    END
    REFERENCE STATE:
      Option = Automatic
    END
    ABSORPTION COEFFICIENT:
      Absorption Coefficient = 0 [m^-1]
      Option = Value
    END
  END
END
MATERIAL: Steel
  Material Group = CHT Solids, Particle Solids
  Option = Pure Substance
  Thermodynamic State = Solid
  PROPERTIES:
    Option = General Material
    EQUATION OF STATE:
      Density = 7854 [kg m^-3]
      Molar Mass = 55.85 [kg kmol^-1]
      Option = Value
    END
    SPECIFIC HEAT CAPACITY:
      Option = Value
      Specific Heat Capacity = 4.34E+02 [J kg^-1 K^-1]
    END
    REFERENCE STATE:
      Option = Specified Point
      Reference Specific Enthalpy = 0 [J/kg]
      Reference Specific Entropy = 0 [J/kg/K]
      Reference Temperature = 25 [C]
    END
    THERMAL CONDUCTIVITY:
      Option = Value
      Thermal Conductivity = 60.5 [W m^-1 K^-1]
    END
  END
END
MATERIAL: Water
  Material Description = Water (liquid)
  Material Group = Water Data, Constant Property Liquids
  Option = Pure Substance
  Thermodynamic State = Liquid
  PROPERTIES:
    Option = General Material
    EQUATION OF STATE:
      Density = 997.0 [kg m^-3]
      Molar Mass = 18.02 [kg kmol^-1]
      Option = Value

```

```

END
SPECIFIC HEAT CAPACITY:
  Option = Value
  Specific Heat Capacity = 4181.7 [J kg-1 K-1]
  Specific Heat Type = Constant Pressure
END
REFERENCE STATE:
  Option = Specified Point
  Reference Pressure = 1 [atm]
  Reference Specific Enthalpy = 0.0 [J/kg]
  Reference Specific Entropy = 0.0 [J/kg/K]
  Reference Temperature = 25 [C]
END
DYNAMIC VISCOSITY:
  Dynamic Viscosity = 8.899E-4 [kg m-1 s-1]
  Option = Value
END
THERMAL CONDUCTIVITY:
  Option = Value
  Thermal Conductivity = 0.6069 [W m-1 K-1]
END
ABSORPTION COEFFICIENT:
  Absorption Coefficient = 1.0 [m-1]
  Option = Value
END
SCATTERING COEFFICIENT:
  Option = Value
  Scattering Coefficient = 0.0 [m-1]
END
REFRACTIVE INDEX:
  Option = Value
  Refractive Index = 1.0 [m m-1]
END
THERMAL EXPANSIVITY:
  Option = Value
  Thermal Expansivity = 2.57E-04 [K-1]
END
END
MATERIAL: Water Ideal Gas
  Material Description = Water Vapour Ideal Gas (100 C and 1 atm)
  Material Group = Calorically Perfect Ideal Gases, Water Data
  Option = Pure Substance
  Thermodynamic State = Gas
PROPERTIES:
  Option = General Material
EQUATION OF STATE:
  Molar Mass = 18.02 [kg kmol-1]
  Option = Ideal Gas
END
SPECIFIC HEAT CAPACITY:
  Option = Value
  Specific Heat Capacity = 2080.1 [J kg-1 K-1]
  Specific Heat Type = Constant Pressure
END
REFERENCE STATE:
  Option = Specified Point
  Reference Pressure = 1.014 [bar]
  Reference Specific Enthalpy = 0. [J/kg]
  Reference Specific Entropy = 0. [J/kg/K]
  Reference Temperature = 100 [C]
END
DYNAMIC VISCOSITY:
  Dynamic Viscosity = 9.4E-06 [kg m-1 s-1]

```

```

    Option = Value
END
THERMAL CONDUCTIVITY:
    Option = Value
    Thermal Conductivity = 193E-04 [W m^-1 K^-1]
END
ABSORPTION COEFFICIENT:
    Absorption Coefficient = 1.0 [m^-1]
    Option = Value
END
SCATTERING COEFFICIENT:
    Option = Value
    Scattering Coefficient = 0.0 [m^-1]
END
REFRACTIVE INDEX:
    Option = Value
    Refractive Index = 1.0 [m m^-1]
END
END
END
FLOW: Flow Analysis 1
SOLUTION UNITS:
    Angle Units = [rad]
    Length Units = [m]
    Mass Units = [kg]
    Solid Angle Units = [sr]
    Temperature Units = [K]
    Time Units = [s]
END
ANALYSIS TYPE:
    Option = Steady State
EXTERNAL SOLVER COUPLING:
    Option = None
END
END
DOMAIN: Default Domain
    Coord Frame = Coord 0
    Domain Type = Fluid
    Location = B452, B471, B488
BOUNDARY: Default Fluid Fluid Interface Side 1
    Boundary Type = INTERFACE
    Location = F333.471
    BOUNDARY CONDITIONS:
        HEAT TRANSFER:
            Option = Conservative Interface Flux
        END
        MASS AND MOMENTUM:
            Option = Conservative Interface Flux
        END
        TURBULENCE:
            Option = Conservative Interface Flux
        END
    END
END
BOUNDARY: Default Fluid Fluid Interface Side 2
    Boundary Type = INTERFACE
    Location = F450.452
    BOUNDARY CONDITIONS:
        HEAT TRANSFER:
            Option = Conservative Interface Flux
        END
        MASS AND MOMENTUM:
            Option = Conservative Interface Flux

```

```

END
TURBULENCE:
    Option = Conservative Interface Flux
END
END
BOUNDARY: Default Fluid Porous Interface Side 1
    Boundary Type = INTERFACE
    Location = F470.471,F504.488
    BOUNDARY CONDITIONS:
        HEAT TRANSFER:
            Option = Conservative Interface Flux
        END
        MASS AND MOMENTUM:
            Option = Conservative Interface Flux
        END
        TURBULENCE:
            Option = Conservative Interface Flux
        END
    END
END
BOUNDARY: Inlet
    Boundary Type = OPENING
    Location = Inlet
    BOUNDARY CONDITIONS:
        FLOW DIRECTION:
            Option = Normal to Boundary Condition
        END
        FLOW REGIME:
            Option = Subsonic
        END
        HEAT TRANSFER:
            Option = Static Temperature
            Static Temperature = 285 [K]
        END
        MASS AND MOMENTUM:
            Option = Static Pressure and Direction
            Relative Pressure = 0 [Pa]
        END
        TURBULENCE:
            Eddy Length Scale = 0.06 [m]
            Fractional Intensity = 0.15
            Option = Intensity and Length Scale
        END
    END
END
BOUNDARY: Outlet
    Boundary Type = OUTLET
    Location = Outlet
    BOUNDARY CONDITIONS:
        FLOW REGIME:
            Option = Subsonic
        END
        MASS AND MOMENTUM:
            Option = Average Static Pressure
            Pressure Profile Blend = 0.05
            Relative Pressure = -21.403 [kPa]
        END
        PRESSURE AVERAGING:
            Option = Average Over Whole Outlet
        END
    END
END
BOUNDARY: RotInt Side 1

```

```

Boundary Type = INTERFACE
Location = F337.471,F446.452,F503.488,F507.488
BOUNDARY CONDITIONS:
  HEAT TRANSFER:
    Option = Conservative Interface Flux
  END
  MASS AND MOMENTUM:
    Option = Conservative Interface Flux
  END
  TURBULENCE:
    Option = Conservative Interface Flux
  END
END
END
BOUNDARY: RotInt Side 2
Boundary Type = INTERFACE
Location = F336.471,F414.488,F420.488,F447.452
BOUNDARY CONDITIONS:
  HEAT TRANSFER:
    Option = Conservative Interface Flux
  END
  MASS AND MOMENTUM:
    Option = Conservative Interface Flux
  END
  TURBULENCE:
    Option = Conservative Interface Flux
  END
END
END
BOUNDARY: Throttle
Boundary Type = WALL
Location = ThrottleInterface
BOUNDARY CONDITIONS:
  HEAT TRANSFER:
    Option = Adiabatic
  END
  MASS AND MOMENTUM:
    Option = No Slip Wall
  END
  WALL ROUGHNESS:
    Option = Smooth Wall
  END
END
END
BOUNDARY: wall
Boundary Type = WALL
Location = \
  F295.452,F335.471,F415.488,F421.488,F449.452,F451.452,F467.471,F468.47\
  1,F469.471,F505.488,F506.488
BOUNDARY CONDITIONS:
  HEAT TRANSFER:
    Option = Adiabatic
  END
  MASS AND MOMENTUM:
    Option = No Slip Wall
  END
  WALL ROUGHNESS:
    Option = Smooth Wall
  END
END
END
DOMAIN MODELS:
  BUOYANCY MODEL:
    Option = Non Buoyant

```

```

END
DOMAIN MOTION:
    Option = Stationary
END
MESH DEFORMATION:
    Option = None
END
REFERENCE PRESSURE:
    Reference Pressure = 1 [atm]
END
END
FLUID DEFINITION: Fluid 1
    Material = Air Ideal Gas
    Option = Material Library
MORPHOLOGY:
    Option = Continuous Fluid
END
END
FLUID MODELS:
    COMBUSTION MODEL:
        Option = None
    END
    HEAT TRANSFER MODEL:
        Include Viscous Work Term = True
        Option = Total Energy
    END
    THERMAL RADIATION MODEL:
        Option = None
    END
    TURBULENCE MODEL:
        Option = SST
    END
    TURBULENT WALL FUNCTIONS:
        High Speed Model = Off
        Option = Automatic
    END
END
END
DOMAIN: PorousRegion
    Coord Frame = Coord 0
    Domain Type = Porous
    Location = PorousSection
BOUNDARY: Default Fluid Porous Interface Side 2
    Boundary Type = INTERFACE
    Location = F357.486,F485.486
BOUNDARY CONDITIONS:
    HEAT TRANSFER:
        Option = Conservative Interface Flux
    END
    MASS AND MOMENTUM:
        Option = Conservative Interface Flux
    END
    TURBULENCE:
        Option = Conservative Interface Flux
    END
END
SOLID: Screen
    BOUNDARY CONDITIONS:
        HEAT TRANSFER:
            Option = Adiabatic
        END
    END
END
END
END

```

```

BOUNDARY: RotInt2 Side 1
  Boundary Type = INTERFACE
  Location = F482.486
  BOUNDARY CONDITIONS:
    HEAT TRANSFER:
      Option = Conservative Interface Flux
    END
    MASS AND MOMENTUM:
      Option = Conservative Interface Flux
    END
    TURBULENCE:
      Option = Conservative Interface Flux
    END
  END
  SOLID: Screen
  BOUNDARY CONDITIONS:
    HEAT TRANSFER:
      Option = Conservative Interface Flux
    END
  END
END
BOUNDARY: RotInt2 Side 2
  Boundary Type = INTERFACE
  Location = F483.486
  BOUNDARY CONDITIONS:
    HEAT TRANSFER:
      Option = Conservative Interface Flux
    END
    MASS AND MOMENTUM:
      Option = Conservative Interface Flux
    END
    TURBULENCE:
      Option = Conservative Interface Flux
    END
  END
  SOLID: Screen
  BOUNDARY CONDITIONS:
    HEAT TRANSFER:
      Option = Conservative Interface Flux
    END
  END
END
BOUNDARY: wall2
  Boundary Type = WALL
  Location = F484.486
  BOUNDARY CONDITIONS:
    HEAT TRANSFER:
      Option = Adiabatic
    END
    MASS AND MOMENTUM:
      Option = No Slip Wall
    END
    WALL ROUGHNESS:
      Option = Smooth Wall
    END
  END
  SOLID: Screen
  BOUNDARY CONDITIONS:
    HEAT TRANSFER:
      Option = Adiabatic
    END
  END
END

```

```

END
END
DOMAIN MODELS:
  BUOYANCY MODEL:
    Option = Non Buoyant
  END
  DOMAIN MOTION:
    Option = Stationary
  END
  MESH DEFORMATION:
    Option = None
  END
  REFERENCE PRESSURE:
    Reference Pressure = 1 [atm]
  END
END
FLUID DEFINITION: Fluid 1
  Material = Air Ideal Gas
  Option = Material Library
  MORPHOLOGY:
    Option = Continuous Fluid
  END
END
FLUID MODELS:
  COMBUSTION MODEL:
    Option = None
  END
  HEAT TRANSFER MODEL:
    Include Viscous Work Term = True
    Option = Total Energy
  END
  THERMAL RADIATION MODEL:
    Option = None
  END
  TURBULENCE MODEL:
    Option = SST
  END
  TURBULENT WALL FUNCTIONS:
    High Speed Model = Off
    Option = Automatic
  END
END
POROSITY MODELS:
  AREA POROSITY:
    Option = Isotropic
  END
  FLUID SOLID AREA DENSITY:
    Interfacial Area Density = 0.001 [m-1]
    Option = Interfacial Area Density
  END
  FLUID SOLID HEAT TRANSFER:
    Heat Transfer Coefficient = 1 [W m-2 K-1]
    Option = Heat Transfer Coefficient
  END
  LOSS MODEL:
    Loss Velocity Type = Superficial
    Option = Directional Loss
  DIRECTIONAL LOSS MODEL:
    STREAMWISE DIRECTION:
      Option = Cartesian Components
      Unit Vector X Component = 0
      Unit Vector Y Component = 1
      Unit Vector Z Component = 1
    END
  END

```

```

        STREAMWISE LOSS:
            Option = Permeability and Loss Coefficient
            Permeability = 4.5e-7 [m^2]
        END
        TRANSVERSE LOSS:
            Option = Streamwise Coefficient Multiplier
            Streamwise Coefficient Multiplier = 10
        END
    END
END
VOLUME POROSITY:
    Option = Value
    Volume Porosity = 0.6
END
END
SOLID DEFINITION: Screen
    Material = Aluminium
    Option = Material Library
MORPHOLOGY:
    Option = Continuous Solid
END
END
SOLID MODELS:
    HEAT TRANSFER MODEL:
        Option = Thermal Energy
    END
    THERMAL RADIATION MODEL:
        Option = None
    END
END
END
DOMAIN INTERFACE: Default Fluid Fluid Interface
    Boundary List1 = Default Fluid Fluid Interface Side 1
    Boundary List2 = Default Fluid Fluid Interface Side 2
    Interface Type = Fluid Fluid
INTERFACE MODELS:
    Option = General Connection
    FRAME CHANGE:
        Option = None
    END
    MASS AND MOMENTUM:
        Option = Conservative Interface Flux
    MOMENTUM INTERFACE MODEL:
        Option = None
    END
    END
    PITCH CHANGE:
        Option = None
    END
END
MESH CONNECTION:
    Option = Automatic
END
END
DOMAIN INTERFACE: Default Fluid Porous Interface
    Boundary List1 = Default Fluid Porous Interface Side 1
    Boundary List2 = Default Fluid Porous Interface Side 2
    Interface Type = Fluid Porous
INTERFACE MODELS:
    Option = General Connection
    FRAME CHANGE:
        Option = None
    END
    MASS AND MOMENTUM:

```

```

        Option = Conservative Interface Flux
    MOMENTUM INTERFACE MODEL:
        Option = None
    END
END
PITCH CHANGE:
    Option = None
END
END
MESH CONNECTION:
    Option = GGI
END
SOLID INTERFACE MODELS:
    HEAT TRANSFER:
        Option = Side Dependent
    END
END
END
DOMAIN INTERFACE: RotInt
    Boundary List1 = RotInt Side 1
    Boundary List2 = RotInt Side 2
    Interface Type = Fluid Fluid
    INTERFACE MODELS:
        Option = Rotational Periodicity
    AXIS DEFINITION:
        Option = Coordinate Axis
        Rotation Axis = Coord 0.1
    END
END
MESH CONNECTION:
    Option = Automatic
END
END
DOMAIN INTERFACE: RotInt2
    Boundary List1 = RotInt2 Side 1
    Boundary List2 = RotInt2 Side 2
    Interface Type = Porous Porous
    INTERFACE MODELS:
        Option = Rotational Periodicity
    AXIS DEFINITION:
        Option = Coordinate Axis
        Rotation Axis = Coord 0.1
    END
END
MESH CONNECTION:
    Option = GGI
END
SOLID INTERFACE MODELS:
    HEAT TRANSFER:
        Option = Conservative Interface Flux
    HEAT TRANSFER INTERFACE MODEL:
        Option = None
    END
END
END
OUTPUT CONTROL:
    MONITOR OBJECTS:
        MONITOR BALANCES:
            Option = Full
        END
        MONITOR FORCES:
            Option = Full
        END
    END

```

```

MONITOR PARTICLES:
  Option = Full
END
MONITOR POINT: MDot
  Coord Frame = Coord 0
  Expression Value = MassFlowMon
  Option = Expression
END
MONITOR RESIDUALS:
  Option = Full
END
MONITOR TOTALS:
  Option = Full
END
END
RESULTS:
  File Compression Level = Default
  Option = Standard
END
END
SOLVER CONTROL:
  Turbulence Numerics = First Order
ADVECTION SCHEME:
  Option = High Resolution
END
CONVERGENCE CONTROL:
  Length Scale Option = Conservative
  Maximum Number of Iterations = 2000
  Minimum Number of Iterations = 200
  Solid Timescale Control = Auto Timescale
  Timescale Control = Auto Timescale
  Timescale Factor = 1.0
END
CONVERGENCE CRITERIA:
  Residual Target = 1.E-4
  Residual Type = RMS
END
DYNAMIC MODEL CONTROL:
  Global Dynamic Model Control = On
END
INTERRUPT CONTROL:
  Option = Any Interrupt
CONVERGENCE CONDITIONS:
  Option = Default Conditions
END
END
END
COMMAND FILE:
  Version = 23.1
END

```

Outline
Domain: PorousRegion

Details of **PorousRegion** in **Flow Analysis 1**

Basic Settings
Fluid Models
Solid Models
Porosity Settings
Initialization

Location and Type

Location
PorousSection

Domain Type
Porous Domain

Coordinate Frame
Coord 0

Fluid and Particle Definitions...

Fluid 1

Fluid 1

Option
Material Library

Material
Air Ideal Gas

Morphology

Option
Continuous Fluid

☐ Minimum Volume Fraction

Solid Definitions...

Screen

Screen

Option
Material Library

Material
Aluminium

Morphology

Option
Continuous Solid

Domain Models

Pressure

Reference Pressure
1 [atm]

Buoyancy Model

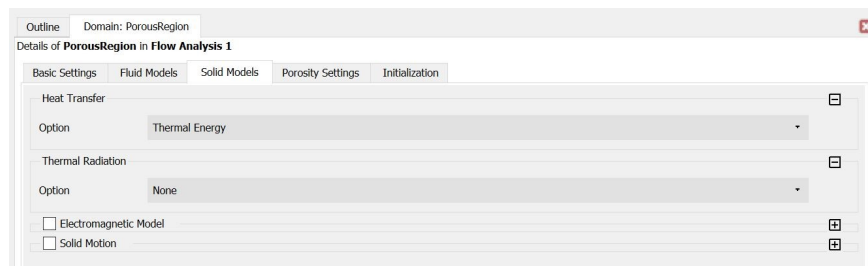
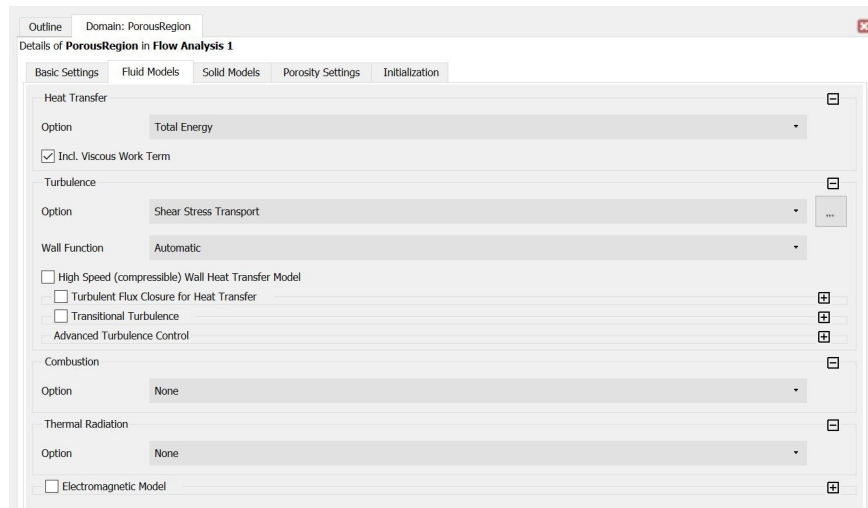
Option
Non Buoyant

Domain Motion

Option
Stationary

Mesh Deformation

Option
None



Outline
Domain: PorousRegion

Details of **PorousRegion** in **Flow Analysis 1**

Basic Settings
Fluid Models
Solid Models
Porosity Settings
Initialization

Area Porosity

OptionIsotropic

Volume Porosity

OptionValue

Volume Porosity0.6

Loss Model

OptionDirectional Loss

Loss Velocity TypeSuperficial

Directional Loss

Streamwise Direction

OptionCartesian Components

X Component0

Y Component1

Z Component1

Streamwise Loss

OptionPermeability and Loss Coeff.

☒ Permeability

Permeability4.5e-7 [m^2]

☐ Resistance Loss Coefficient

Transverse Loss

OptionStreamwise Coeff. Multiplier

Multiplier10

Fluid Solid Area Density

OptionInterfacial Area Density

Interfacial Area Den.0.001 [m^-1]

Fluid Solid Heat Transfer

OptionHeat Transfer Coefficient

Heat Trans. Coeff.1 [W m^-2 K^-1]

APPENDIX G:

Experimental Hot Film Data

Table G.1. Results for 85% Power Choked at 0°

Position (mm)	Umean (m/s)	Turbulence Intensity (%)
6.0	123.01	6.83
6.1	126.51	6.94
6.2	128.09	6.89
6.3	124.64	6.76
6.4	126.33	6.65
6.5	127.75	6.67
6.75	127.24	6.61
7.0	124.56	6.22
7.25	124.46	6.03
7.5	126.56	6.11
8.0	129.94	5.72
8.5	127.18	5.32
9.0	129.10	5.21
9.5	130.01	5.01
10.0	126.74	4.87
11.0	129.92	4.62
13.5	129.98	4.31
16.0	127.43	4.03
21.0	129.46	3.91
26.0	133.06	3.36
36.0	132.89	2.92
46.0	130.98	2.76
56.0	131.46	2.96
66.0	129.08	3.10
81.0	128.89	2.92
96.0	121.42	3.26
111.0	116.82	3.24
131.0	108.27	4.43
145.6	106.50	4.22
147	103.26	4.19

Table G.2. Results for 85% Power Near Stall at 0°

Position (mm)	Umean (m/s)	Turbulence Intensity (%)
6.0	78.94	7.53
6.1	80.51	7.66
6.2	80.51	7.58
6.3	79.02	7.65
6.4	80.75	7.50
6.5	80.05	7.46
6.75	80.05	7.22
7.0	80.27	6.95
7.25	80.83	6.81
7.5	81.08	6.48
8.0	82.28	6.18
8.5	81.16	6.00
9.0	82.90	5.67
9.5	84.12	5.58
10.0	83.17	5.23
11.0	82.74	5.14
13.5	83.50	4.68
16.0	85.71	4.59
21.0	86.75	4.24
26.0	91.03	4.04
36.0	92.60	3.43
46.0	89.61	3.21
56.0	87.85	3.04
66.0	85.57	3.07
81.0	82.98	2.94
96.0	77.66	2.93
111.0	72.06	2.91
131.0	66.42	3.02
145.6	65.85	3.18
147	66.93	3.29

List of References

- [1] D. Cenciotti, “Compressor stalls,” The Aviationist, September 24, 2010 [Online]. Available: <https://theaviationist.com/2010/09/24/compressor-stalls/>
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