

DESIGN, FABRICATION, AND CHARACTERIZATION OF AN ACTIVELY-CONTROLLED  
MACH 5 TO 8 WIND TUNNEL

A Dissertation Proposal

by

JACOB B. VAUGHN

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Chair of Committee, Edward White

Committee Members, Rodney Bowersox

Nathan Tichenor

Je Han

Head of Department, Ivett Leyva

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## NOMENCLATURE

### Acronyms

ACE	Actively Controlled Expansion
CFD	Computational Fluid Dynamics
FEA	Finite Element Analysis
BCDC	Bush Combat Development Complex
NAHL	National Aerothermochemistry and Hypersonics Laboratory
MDOE	Modern Design of Experiments
MW	Machine Works Inc.
FEDC	Fischer Engineering Design Center
PLC	Programmable Logic Controller
MATLAB	Matrix Laboratory

### Common Symbols

$M$	Mach number
$Re/m$	Unit Reynolds number
$P$	Pressure
$T$	Temperature

### Greek Symbols

$\rho$	Density
$\mu$	Dynamic viscosity

### Common Subscripts

0	Stagnation condition
<i>none</i>	Static condition
<i>set</i>	Set condition for PID reference

$\mu$

## Sutherland's constants

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## 1. INTRODUCTION & LITERATURE REVIEW

### 1.1 Introduction

In recent decades, the continual improvement in hypersonic aircraft aerodynamics has emphasized the need for advancements in wind tunnel ground testing capabilities [1]. The conventional approach, reliant on distinct nozzles for discrete Mach numbers, poses logistical challenges and limits the exploration of dynamic characteristics in evolving aircraft designs. Recognizing these limitations, there is a growing demand within the hypersonic community for a novel solution, namely a continuously variable Mach-number nozzle designed to seamlessly adapt to the evolving needs of hypersonic research.

This imperative shift towards innovation seeks to overcome the constraints of conventional wind tunnels by introducing a continuously variable Mach-number nozzle to provide researchers with a more similar representation of real-world scenarios. By dynamically adjusting the Mach number throughout the wind tunnel runs, the variable conditions experienced by hypersonic vehicles during different flight trajectories can be replicated. This capability enables the advancement of ground testing for a more comprehensive understanding of dynamic hypersonic phenomena.

The Actively Controlled Expansion (ACE) wind tunnel at Texas A&M University has served as a workhorse in hypersonic research for over a decade, but it is overdue for improvements to meet the growing demand of hypersonic flight research. Although the facility was initially designed to facilitate the continuous variation of Mach number, the mechanical implementation ultimately proved to be overly simplistic. Consequently, the nozzle predominantly maintained a fixed Mach 6 setting throughout the majority of the tunnel's operation, falling short of fully realizing its designated variable nature.

### 1.2 Research Outline and Objectives

In order to maintain the National Aerothermochemistry and Hypersonics Laboratory (NAHL) as a cutting-edge research facility, its current facilities are rapidly advancing in capability to en-

able better science. The objectives of this research aim to lay the foundation for variable Mach number wind tunnel control to meet the recent increased demand of dynamic hypersonic vehicle aerodynamics research.

The existing ACE facility will be upgraded to achieve true active control and to potentially produce low-disturbance flow for higher Reynolds numbers. Its successor, ACE2.0, will employ a feedback-control system with servo motors, linear actuators, and various instrumentation to enable the accurate and continuous variation of Mach number and Reynolds number. Once fabricated and calibrated, the ACE2.0 facility will be utilized to accomplish the following objectives:

1. Improved experimental control and efficiency
  - (a) Feedback-controlled active Mach number selection
  - (b) Constant/proportional Reynolds number control
2. Characterization of noise and uniformity throughout nozzle
  - (a) Uncertainty quantification
  - (b) Hysteresis investigation
3. Preliminary investigation of model flow characteristics hysteresis during Mach trajectory

These objectives will effectively demonstrate the capabilities and merit of the new ACE2.0 facility. The intent is to evaluate the performance of the facility while paving the groundwork for the next decade of dynamic hypersonic flight research. In addition, the standard operating procedures for ACE2.0 will be updated to reflect the best practices deduced throughout the completion of these objectives, and the resulting control procedures and interface will be straightforward and well documented for future student researches to easily learn and utilize, ensuring a seamless transition for future investigations. The documentation will not only enhance the accessibility of ACE2.0 for subsequent research endeavors but also contribute to the broader scientific community by providing a robust framework for effective wind tunnel control and dynamic hypersonic vehicle aerodynamics exploration.

### 1.3 Literature Review

The literature review for this dissertation will be examined in four parts related to hypersonic variable Mach-number wind tunnels and according to the above objectives: (1) variable mach number nozzle design, (2) parameter control, (3) flow characterization and uncerntainty, and (4) hysteresis in hypersonic flows. This review will discuss articles that establish the most current knowledge base and techniques in the relevant areas of hypersonic wind tunnel research.

Variable Mach number nozzles have been explored in many configurations since the 1950s such as interchangeable fixed-block, plug-type, asymmetric sliding blocks, tilting plate, fully flexible, and hinged/flexure [2]. Each of these designs have varying degrees of flow quality, cost effectiveness, and experimental efficiency that must be considered. Only the fully flexible and flexure designs maximize experimental efficiency without sacrificing flow quality. Of these two, the flexure design minimizes costs by reducing mechanical complexity and supporting structure. Therefore, the flexure design is the optimal choice considering these criteria.

The flexure type nozzle was first proposed in 1955 by Rosen [3] and improved upon separately by Erdmann and Rom [4, 5] in order to minimize the mechanical complexity. This simple nozzle design operated by a single jack greatly reduces manufactring and controls costs and allows for greater flexibilty in active control to quickly and continuously vary the Mach number to model dynamic supersonic vehicle flight.

In the last decade, many variable mach number supersonic wind tunnels have been manufactured due to increased demand of hypersonic flight research. The majority of these are fully flexible or flexure nozzle designs with varying implementations of actuation and control [6–12]. All of these facilites were developed to study vehicle flight trajectory and the hysteresis phenomenon therein.

With the increased emergence of these variable mach number facilites, effective control schemes must be employed for the flow paramters  $M$ ,  $P_0$ ,  $T_0$ , and the resulting  $Re/m$  in order to vary each parameter independently and accurately model hypersonic flight conditions through various trajectories by maintaining flow similarity. This control problem, acknowledged as early as the 1980s,

prompted the development of diverse solutions implementing the various areas of control theory such as optimal control [13, 14], state feedback control, mathematical model prediction control, preprogrammed controllers [15], and PID control [16–18].

In recent years, researchers at numerous state-of-the-art variable Mach number facilities have embraced advanced intelligent control methods. Techniques such as fuzzy logic, genetic algorithms, neural networks, adaptive control or gain scheduling, and their combinations have been applied [19, 20], reflecting a contemporary shift towards leveraging intelligent algorithms to address the complexities and nonlinearity of hypersonic wind tunnel flow control. The methods that will be explored in this research are those of Hwang [14], Matsumoto [15], Ilić [17], and Shahrababaki [20] as they each introduce the different advantages and challenges of each control technique.

First, Hwang developed a robust LQG/LTR based controller enhanced by an anti-integrator windup and a modified Smith predictor to overcome unavoidable modeling errors, uncertainties, and time-delay effects. This controller demonstrated a faster stabilization and exhibited fewer oscillations in comparison to its PID counterpart. Given its superior performance, it presents an appealing prospect for implementation in ACE2.0, and a detailed exploration of this controller will be undertaken in a subsequent chapter.

Next, Matsumoto took a simplified approach by replacing an existing real-time PID controller with a preprogrammed controller to avoid input time delays. This was advantageous for his facility because the run time was not much longer than the time delay for the PID controller to stabilize. This is the most straightforward approach to obtain specific constant or dynamic trajectories of multiple input parameters, but it is not without its challenges. The controller must have a new program for each individual desired parameter set condition or path, and each program must be iterated to minimize errors. Additionally, considering the longer run times of ACE2.0, a PID controller has ample time to stabilize and can be implemented.

Then, Ilić implemented a cascade nonlinear feedforward-feedback PID controller as a combined system to enhance a standard single-loop PID. The system's setpoint reference tracking is improved by the feedforward-feedback architecture, and the disturbance rejection is improved by

the cascade architecture. With these two architectures combined in one multi-loop controller, large transient overshoots are eliminated, setpoint settling times are decreased, and the overall accuracy of the controlled parameters is maximized. Once again, the improved performance of this controller makes it another appealing prospect for ACE2.0, which will be discussed later.

Lastly, Shahrabaki utilized an artificial neural network and fuzzy logic to enhance a conventional PD controller to handle the complex nonlinearity of the variable mach number wind tunnel flow parameters. The advantages of fuzzy logic include its simplicity and adaptability of introducing new control rules to handle imprecise data, uncertainty, and unmodeled dynamics. The combined advantage that Shahrabaki explores pertains to the utilization of the neural network to develop the membership functions for the fuzzy logic controller. He designed and trained a feed-forward multilayer perceptron neural network according to the database from the mathematical model of the wind tunnel behavior in order to develop the optimal membership functions. This method will only be explored further for ACE2.0 if the methods of Hwang or Ilić do not yield sufficient performance.

Additionally, with parameter control introduced in a hypersonic wind tunnel, the uncertainty of the various flow parameters can be quantified more effectively. The primary references for the uncertainty quantification in this research will be the NASA report by Stephens [21] and Hubbard, Chair of AIAA Wind Tunnel Measurement Uncertainty Committee on Standards, and the dissertation by Curriston in 2024 [22]. The methodology in this report combines the techniques of the prevalent literature on the subject from the last few decades, and Curriston demonstrates this methodology in essentially a case study for reference.

Now, considering flow characterization in literature, the primary references will be the recent AIAA articles by Chou [23] and Duan [24] on hypersonic wind tunnel freestream disturbance measurements as they clearly provide the latest measurement processes and procedures and reference over 50 publications on relevant topics from the last couple decades. In addition to these two references, a decade of NAHL experience and best practices will guide the characterization of ACE2.0 upon its fabrication and initial shakedown.

Finally, the review of hypersonic flow hysteresis in literature yielded many publications discussing the phenomenon primarily in shock interactions and inlet start/unstart processes. The inlet literature will not be referenced directly in this work, but it will undoubtedly be invaluable for future research in ACE2.0. Focusing on the shock interactiions, both numerical and experimental data is presented throughout this literature. Hysteresis has been reported in hypersonic wind tunnel experiments as early as the 1950s [25, 26]. The test conditions that produced hysteresis were usually avoided in experiments until the 1990s when the phenomona began to be studied directly [6, 27, 28]. Recent literature reveals numerical investigations easily reproduced shock interaction hysteresis, while experimental investigations proved more difficult to reproduce the hysteresis due to the freestream noise in conventional facilities [7]. Nevertheless, hysteresis was successfully observed experimentally in low-noise (quiet) wind tunnels [29–31]. Methodolgies from all of this lierature will be studied in order to attempt to reproduce shock interaction hysteresis in ACE2.0. Additionally, the data gathered by Wirth [32] in the existing ACE facility will serve as the primary reference for the exploration of surface heat flux hysteresis of a fin-cone model.

Something about modern design of experiemtns (MDOE) here with reference to DeLoach.

## 2. DESIGN AND FABRICATION OF ACE2.0

### 2.1 Background and Motivation

The existing ACE (Actively Controlled Expansion) tunnel was designed and manufactured between 2009 and 2010 and began operating in 2010 [33–35]. The nozzle is 40 inches long from the throat to the test-section entrance. The test section is 14 inches wide and 9 inches tall. The last 4 inches of the nozzle is a thin flexure portion that allows the the throat height to be varied from 0.04 to 0.36 inches, meaning the test-section Mach number can be varied from Mach 5 to 8.

#### 2.1.1 ACE Turbulent Transition

Below a unit Reynolds number of  $Re/m = U/\nu \approx 3 \times 10^6 m^{-1}$  the RMS pressure fluctuations in the test section are less than 1%, and above this unit Reynolds number the pressure fluctuation levels significantly increase. It was desired to increase the unit Reynolds number at which laminar flow can be maintained, so the mechanism causing this transition had to be determined. The hypothesis and supporting data regarding the pressure fluctuation levels increase and how it might be delayed to higher unit Reynolds numbers is summarized below.

##### 2.1.1.1 *Evaluation of Suspect Transition Mechanisms*

There are five primary suspects for this transition:

1. A known manufacturing surface discontinuity at the throat
2. Sidewall mushroom vortices
3. Görtler vortices
4. Freestream turbulence in the incoming flow and/or upstream boundary layer
5. Wall roughness or waviness

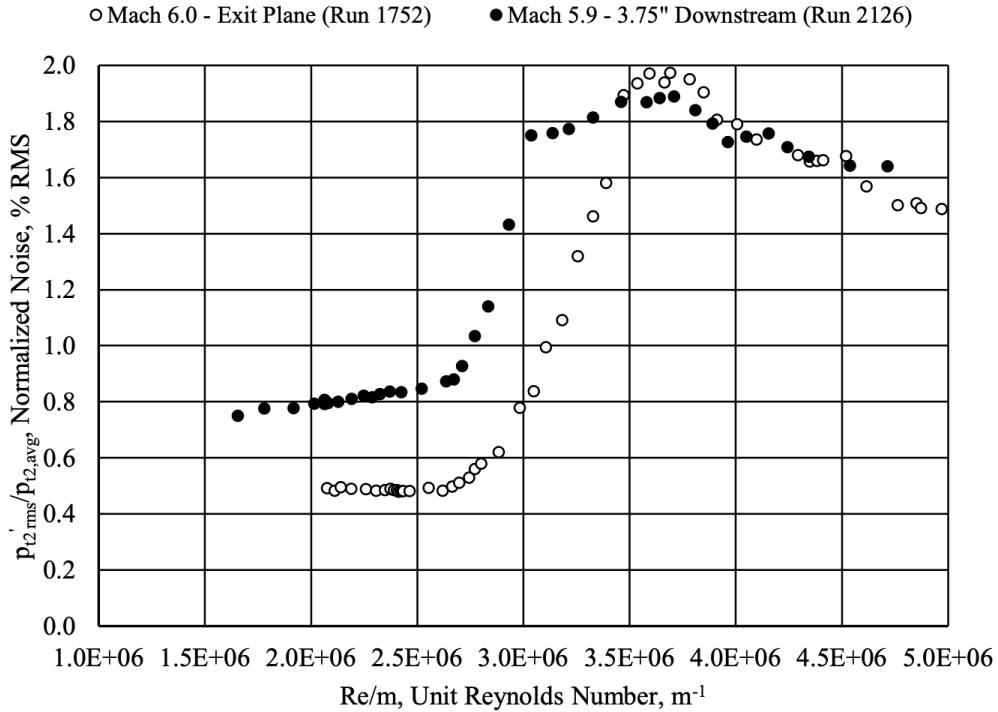
This following evaluates each of these possibilities and concludes that the primary culprit is the surface discontinuity at the throat. This conclusion is supported by pitot surveys, method-of-characteristics line tracing, and CFD simulations. Sidewall mushroom vortices and Görtler vortices would lead to transition too far downstream from the throat to be responsible for the pressure fluctuation levels increase. Items 4 and 5 are potential causes of poor flow quality in all supersonic tunnels and are included for completeness. The specific mechanism by which these would cause transition is not known. While they are not the primary suspects for the pressure fluctuation levels increase, improving these conditions will be addressed in the redesign intended to extend laminar flow to higher Reynolds numbers.

#### *ACE Nozzle Noise Surveys*

Three recent pitot surveys have been conducted in the ACE tunnel. The first by Mai (2014) revealed transition occurring around a unit Reynolds number of  $3 \times 10^6 m^{-1}$ , as shown in Figure 2.1. The same result was found by Neel (2019) shown in Figure 2.2 that transition occurs at this unit Reynolds number 6 inches upstream of the test section entrance. A final pitot survey in ACE by Wirth (2022) was conducted to determine whether the pressure fluctuation levels increase occurred at different  $Re/m$  values at positions farther upstream in the nozzle. He found pressure fluctuation levels increase at  $Re' \approx 3 \times 10^6 m^{-1}$  at a measurement location 17 inches upstream of the test section entrance. His results in Figure 2.3 align perfectly with Mai and Neel and clearly establish that the Reynolds number at which pressure fluctuation levels increase is unrelated to location in the nozzle. This suggests that transition is not moving upstream through the nozzle as Reynolds number is increased.

#### *Mach Line Tracing*

The origin of the noise measured farthest upstream of the nozzle exit was determined by tracing characteristics from the measurement location at the centerline upstream to the wall. Both the side view and top view of this can be seen in Figure 2.6.



**Figure 55. ACE tunnel freestream flow noise at nozzle exit plane and 95 mm (3.75 in.) downstream.**

Figure 2.1: ACE freestream pressure fluctuations at nozzle exit (2014) [36]

### *Suspect Mechanism Conclusions*

The above results reveal the pressure fluctuation levels increase but not the transition mechanism. The two primary suspects that can be eliminated using the data above are the sidewall mushroom vortices and Görtler vortices.

Sidewall mushroom vortices arise from the pressure distribution in the nozzle and the low momentum flow in the sidewall boundary layers. The flow at the centerline expands to the test section pressure ahead of the top and bottom curved walls. The flow at the top and bottom lags behind the centerline flow with a higher pressure to create a vertical pressure gradient that introduces a secondary vertical flow in the sidewall boundary layers that flows from the corners to the centerline [38]. CFD simulations show the sidewall mushroom vortices beginning to form approximately

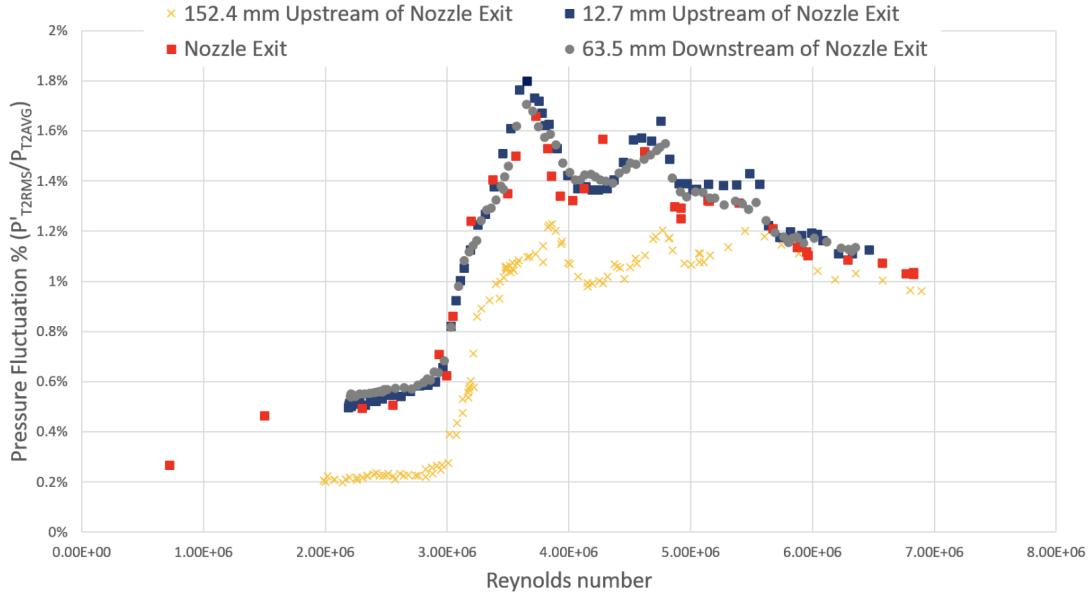


Figure 5.1: Freestream pitot pressure fluctuation levels. ACE tunnel.

Figure 2.2: ACE freestream pressure fluctuations at various locations (2019) [37]

24 inches upstream of the nozzle exit shown in Figures 2.4 and 2.5. Tracing the characteristics from 17 inches upstream of the test section entrance, Figure 2.6 shows the origin to be upstream of the throat where sidewall mushroom vortices are not relevant.

Görtler vortices are counter-rotating streamwise vortices that occur in boundary layers on concave surfaces [39]. To estimate where these may lead to transition, a CFD basic state simulation and N-factor analysis was performed by Kocian (2022). However, tracing the characteristics from 17 inches upstream of the test section entrance, Figure 2.6 shows the measured noise originates at the end of the straight section of the nozzle where Görtler is not relevant.

While both sidewall vortices and Görtler vortices can play some role in transition in planar nozzles, they are no longer considered suspects for the pressure fluctuation levels increase at unit Reynolds numbers above  $3 \times 10^6 m^{-1}$ .

The combination of pitot surveys and characteristic tracing eliminates the possibility of sidewall mushroom vortices or Görtler vortices because these instabilities would lead to transition downstream of the characteristic wall origins found by tracing from the measurement location to

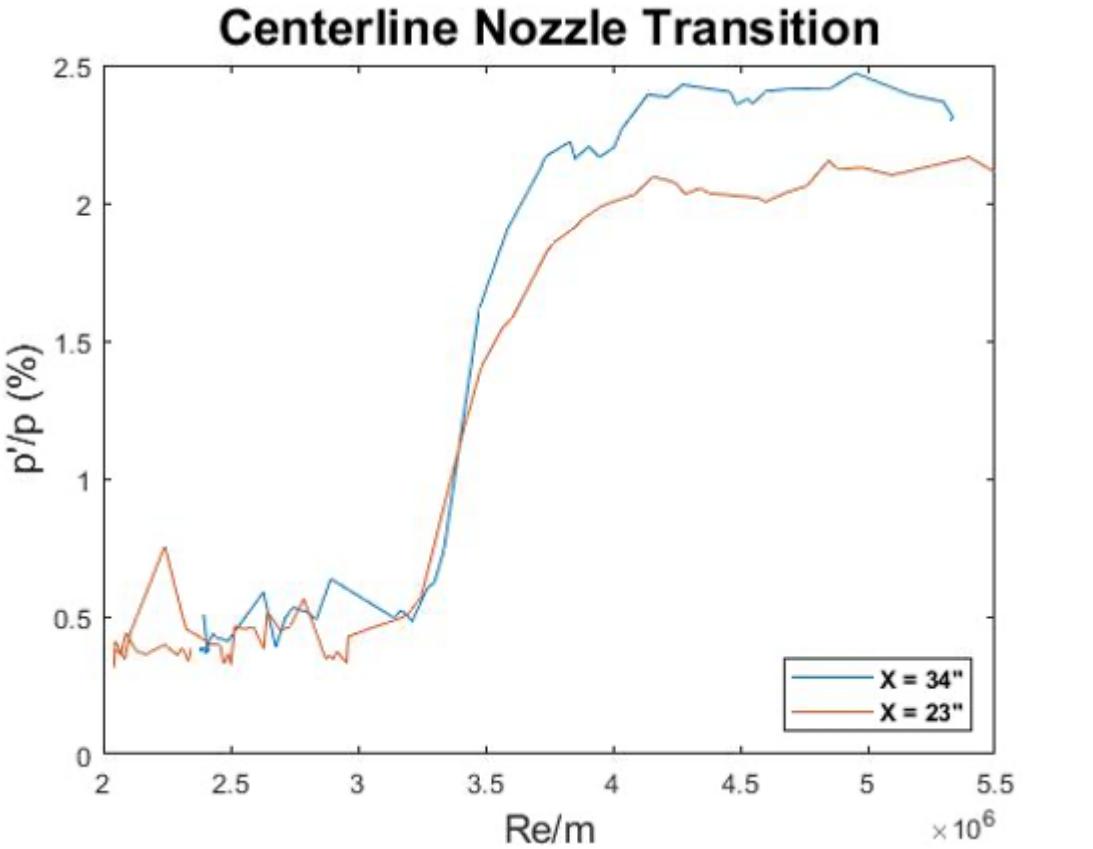


Figure 2.3: ACE freestream pressure fluctuations at 6 in. and 17 in. upstream of nozzle exit (2022)

the wall intersection. This leaves the surface discontinuity at the throat as the primary culprit for the pressure fluctuation levels increase. The remaining suspect mechanisms are still important to note and address in the redesign of the ACE tunnel.

The following improvements are recommended to obtain laminar flow for some value above  $Re' \approx 3 \times 10^6 m^{-1}$ :

1. Second-derivative-smooth subsonic-to-supersonic throat transition (eliminate discontinuity)
2. Continuous curvature with analytical functions (eliminate waviness and discontinuities)
3. Mirror polishing as much as possible (eliminate roughness/waviness)
4. Improved settling chamber performance

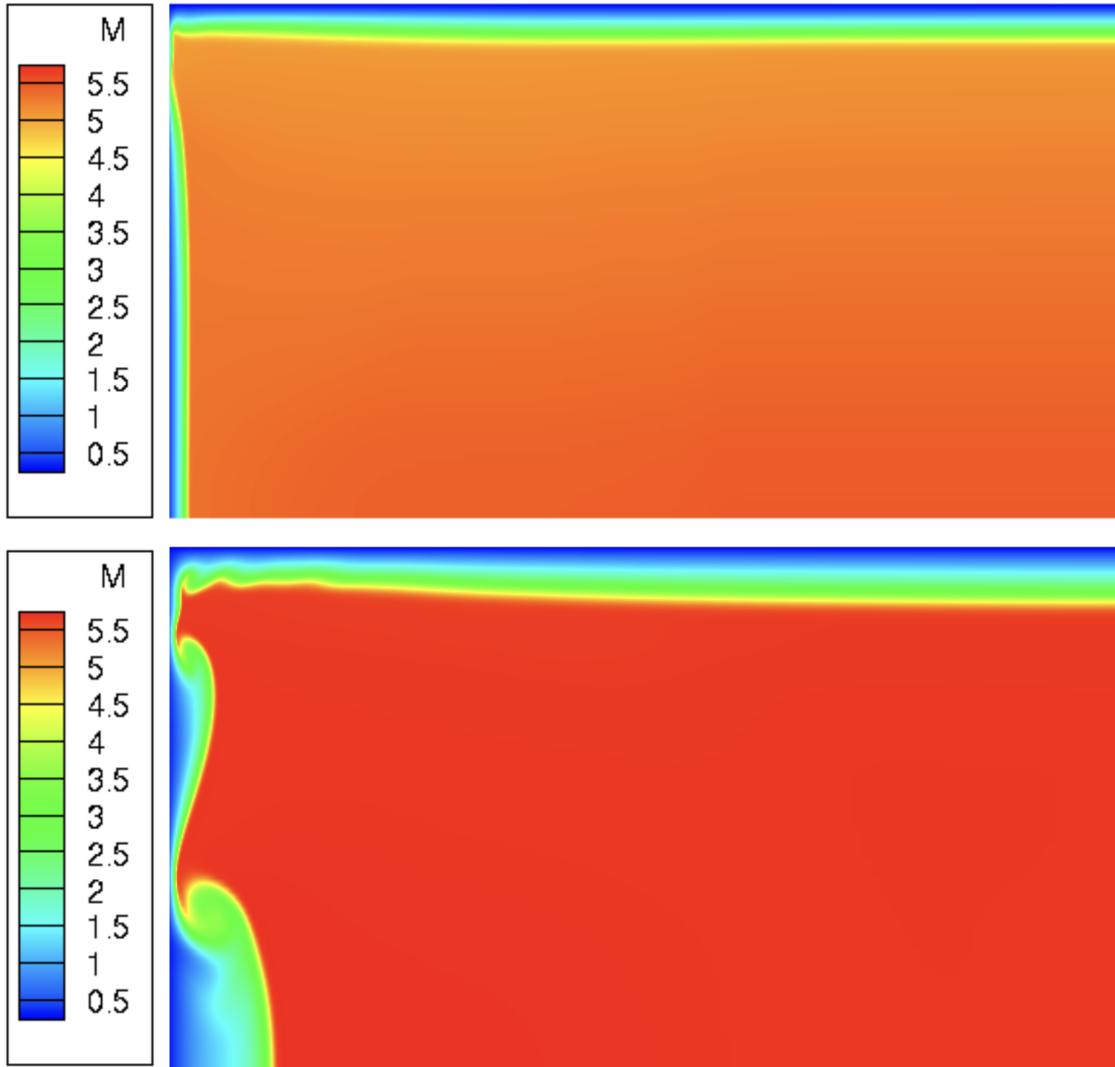


Figure 2.4: Mushroom vortex formation at sidewalls

## 5. Subsonic boundary layer suction/bleed

### 2.1.2 Active Control Capability

Despite the intention of the ACE design, the mechanical realization does not allow for active control. In fact, changing the Mach number at all is far from a simple process.

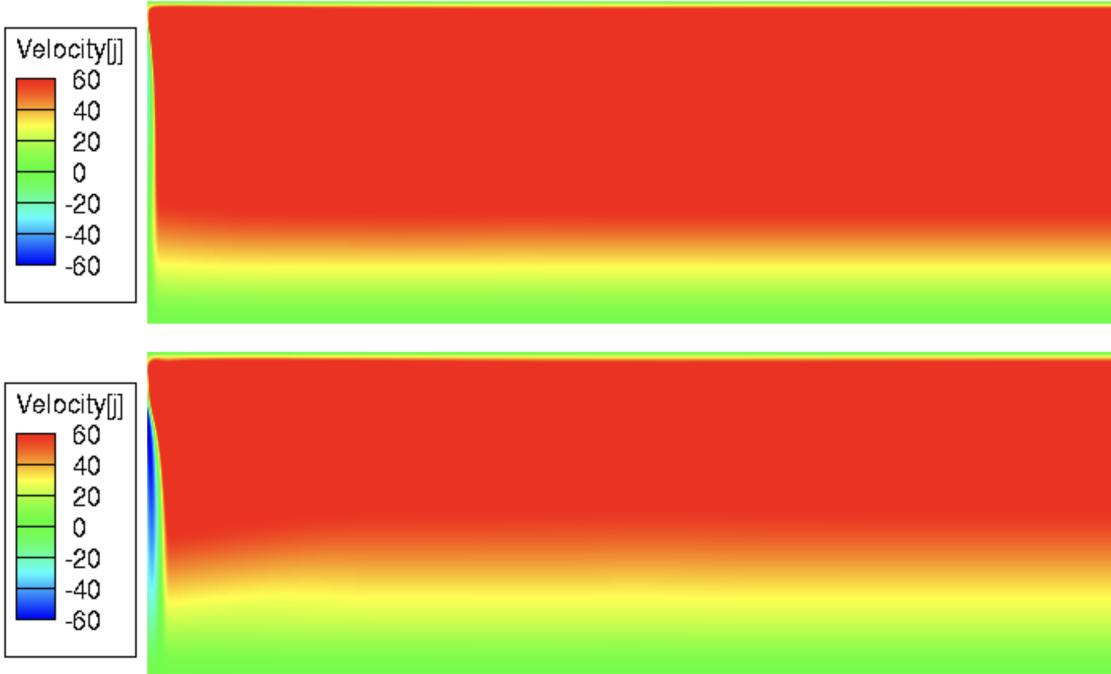


Figure 2.5: Vertical velocity

## 2.2 ACE2.0 Design

Following the above conclusions and recommendations, the most likely reason the pressure fluctuations increase is laminar-to-turbulent transition due to a surface discontinuity at the throat. This conclusion is supported by pitot surveys, CFD, and method of characteristics line tracing described above. To correct this, the nozzle will be redesigned and remanufactured to meet specific requirements that will ensure the best performance and potentially expand the laminar Reynolds number range. The decision to remanufacture the nozzle presents an opportunity to revise the nozzle and settling chamber design to achieve true active controllability, properly embodying ACE2.0 name.

The rest of the chapter details the planned improvements to the ACE tunnel and specific design requirements that will achieve those improvements. In addition to a new nozzle, the settling chamber will also be redesigned to improve the uniformity and turbulence of the incoming flow into the nozzle. These improvements are to achieve the goal of increasing the unit Reynolds number at

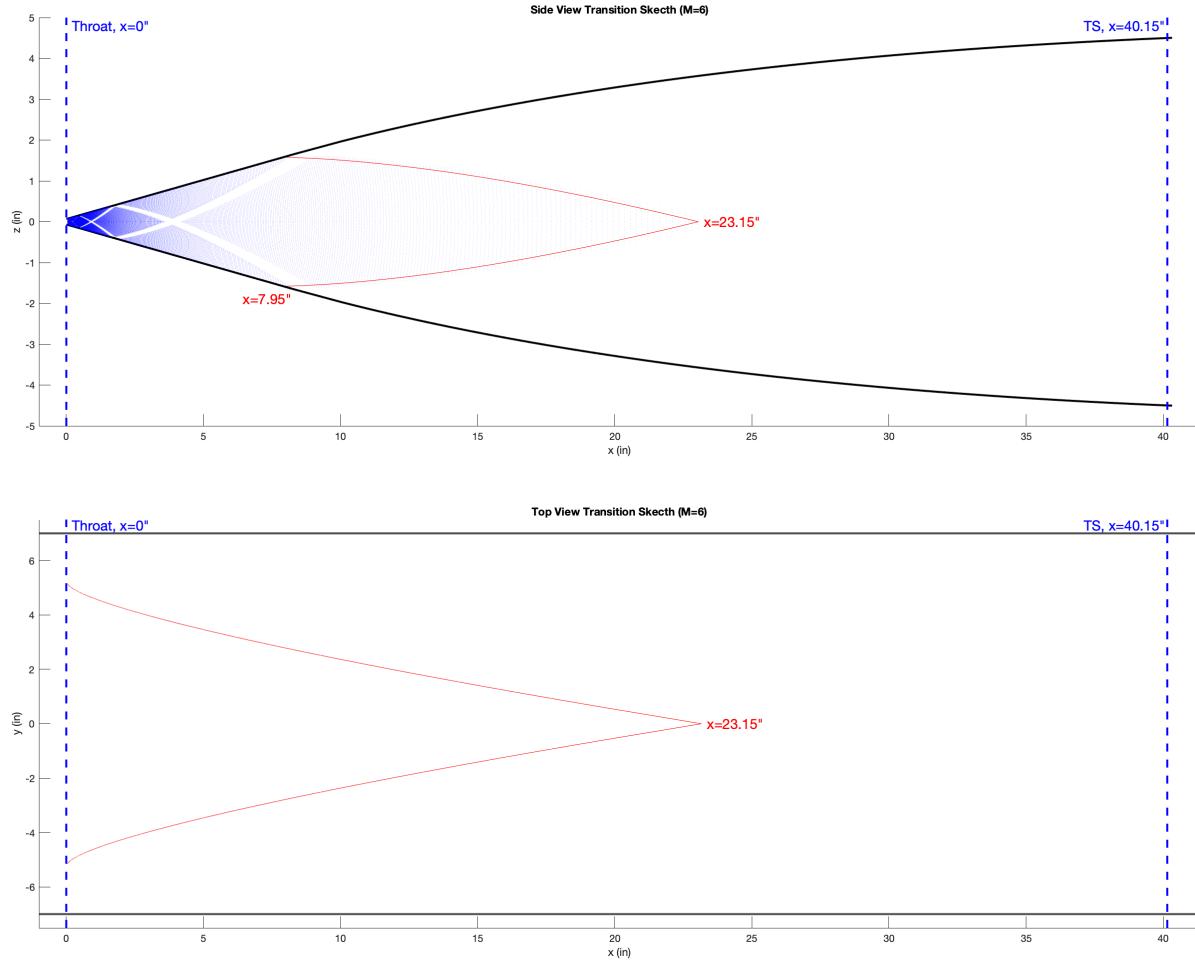


Figure 2.6: Mach lines for noise measured at 17" upstream on nozzle exit.

which laminar nozzle flow is maintained.

### 2.2.1 Design Requirements

ACE2.0 will maintain many characteristics while improving some, so many requirements are the same as the original ACE design. The new tunnel will still produce uniform Mach 5 to 8 flow in the 9 inches by 14 inches test section, withstand a total temperature of 530 Kelvin, and maintain a minimum engineering factor of safety of 1.5 when operating at a total pressure of 200 psia.

### *Nozzle Requirements*

The current ACE nozzle successfully produces uniform Mach 5 to 8 flow in its core. In order to maintain this good performance and not introduce unknown parameters, the new nozzle will retain a very similar contour with slight improvements. The requirements that remain the same are that the nozzle must produce uniform flow for the entire Mach range, achieve maximum height deflection without damage, and prevent leaks up to a pressure of 200 psia.

The improvements to the nozzle and associated requirements will be a contour with continuous 1st and 2nd derivatives that is specified by analytical functions that will eliminate discontinuities and truncation error and a maximum allowable stress less than or equal to that found in the current ACE flexure at maximum deflection.

### *Settling Chamber Requirements*

The current ACE settling chamber design provides multiple opportunities to improve flow conditioning and ease of maintenance. The new settling chamber design will increase the length and height and allow for variable aerogrid/screen configurations. The requirements that remain the same are low freestream turbulence, thin stable wall boundary layers, maximum uniformity, and preventing leaks at a pressure of 200 psia. The implementation of these requirements will be improved in the new design to achieve improved incoming flow into the nozzle.

Following Reshotko [40], the length of the settling chamber shall accommodate a separation of 250 characteristic mesh sizes between screens allowing for adequate turbulence decay. The aerogrids will have a hexagonal perforation pattern to increase porosity and decrease pressure loss. The number of aerogrids and screens shall be variable to allow for future flow conditioning experiments. The inlet shall include a baffle system that will provide an acceptable initial distribution and mixing of the air received from the high-pressure inlet piping. The overall design will accommodate future boundary layer suction or bleed slots.

A settling chamber height of 6 inches was chosen to keep the velocity as slow as possible without going below 10 ft/s, according to Pope [41], for the majority of the Mach number range.

The reason for this minimum is to prevent thermal convection vortices from dominating the flow at the walls, but the interior of ACE2.0 will be heated prior to the start of the run to avoid this gradient. With this in mind, the height of 6 inches was chosen as a good compromise as seen in Table 2.1.

Height	Mach Number			
	5	6	7	8
4"	73.57	34.55	17.64	9.66
5"	58.83	27.64	14.11	7.73
6"	49.01	23.03	11.76	6.44
7"	42.00	19.74	10.08	5.52
8"	36.75	17.27	8.82	4.83
9"	32.66	15.35	7.84	4.29

Table 2.1: Settling chamber velocities (ft/s) for combinations of settling chamber heights and Mach numbers.

## 2.2.2 Nozzle Contour Codes

The method-of-characteristics Fortran script written by Bowersox that produced the ACE nozzle contour was used for the new nozzle contour. In order to achieve continuous first and second derivative continuity, a section of the code was modified to produce a fourth-order expansion section instead of the original second-order curve. This allowed the expansion section to match the curvature of both the subsonic section and the straight section.

### Before:

```
do 10 i=1, nch
  theta(i) = dthetai + float(i-1)*dth
  x(i) = tan(theta(i))/2./k
  xw(i) = x(i)
  y(i) = 1.0 + k*x(i)**2
  yw(i) = y(i)
10 continue
```

### After:

```
do 10 i=1, nch
```

```

theta(i) = dthetai + float(i-1)*dth
xthetai = sqrt(tan(thetai)/k)
k4 = -k/2./xthetai
pc = -9.*(k**2)/3./((4.*k4)**2)
qc = (2.*(3.*k)**3 - 27.*((4.*k4)**2)*tan(theta(i)))
& /27./((4.*k4)**3)
npi = 2.*pi/3.
tc = 2.*sqrt(-pc/3.)
& *cosacos((3.*qc/2./pc)*sqrt(-3./pc))/3. - npi)
if((3.*qc/2./pc)*sqrt(-3./pc).lt.-1.) then
    tc = 2.*sqrt(-pc/3.)*cosacos(-1.)/3. - npi)
end if
x(i) = tc - k/4./k4
xw(i) = x(i)
y(i) = 1.0 + k*x(i)**3 + k4*x(i)**4
yw(i) = y(i)
10 continue

```

After the points were produced by the Fortran script, they were imported into a MATLAB script to fit with analytic functions. The subsonic curve is given by a fifth-order polynomial with six boundary conditions of  $y(-L) = H$ ,  $y'(-L) = 0$ ,  $y''(-L) = 0$ ,  $y(0) = h$ ,  $y'(0) = 0$ , and  $y''(0) = 0$ . The straightening section is given by a function found using the *lsqcurvefit* function in MATLAB. The equations for each section are as follows:

**Subsonic:**  $-0.0002679752287799994x^5 - 0.0066993807195x^4 - 0.04466253813x^3 + 0.033746187$

for  $-10 < x < 0$

**Throat:**  $-2689.610971179115x^4 + 181.528229581324x^3 + 0.033746187$  for  $0 < x < 0.033746187$

**Straight:**  $0.206725280364801x + 0.030258092015591$  for  $0.033746187 < x < 6.1460114$

**Straightening:**  $2.180909737850381x^{0.960492634168194} + 5.934566177927477 \times 10^{284}x^{-367.9331632104439} -$

$0.585293189697896 - 1.684363604007221x^{1.011336503949665} - 0.023814395465567 \ln(0.418646933043039x)$

for  $6.1460114 < x < 40.07774$

### 2.2.3 CFD

In order to verify the above nozzle contour performance compared to the original ACE contour, both contours were simulated in 2D with CFD. First, a mesh was created in Pointwise for each contour with 400 equally spaced columns of cells in the x-direction. Each column had the spacing

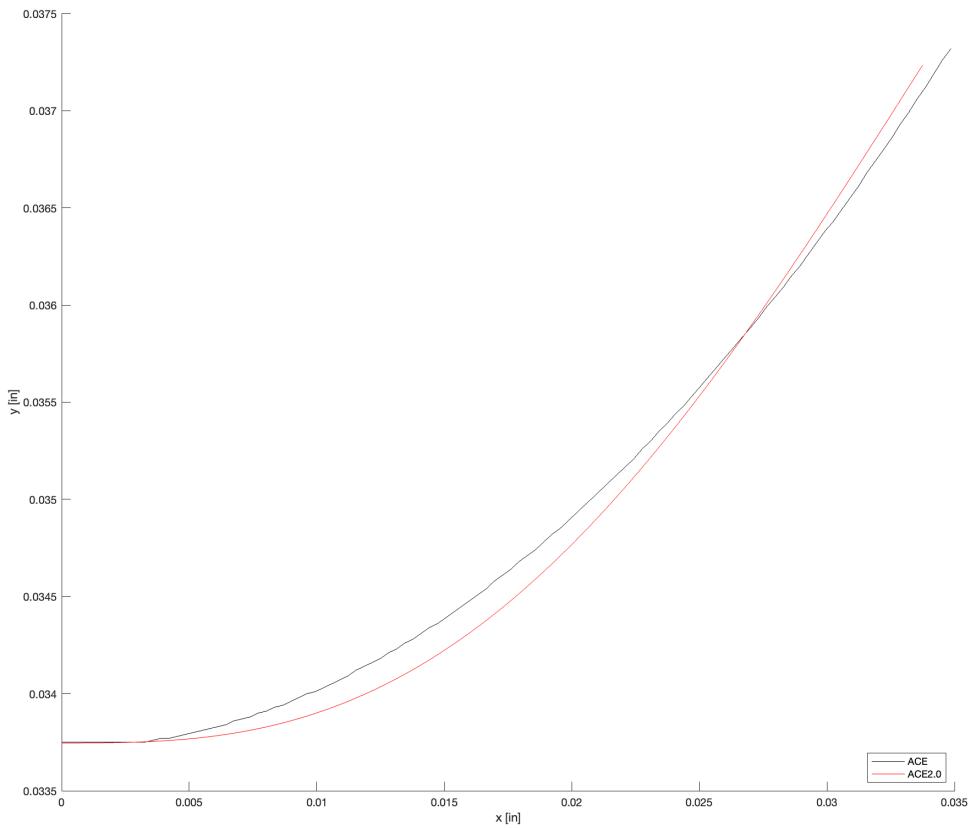


Figure 2.7: Comparison of ACE (quadratic) and ACE2.0 (quartic) expansion at throat

scaled to accurately capture the boundary layer with the smallest cell height around  $1\text{e-}5$  meters at the curved wall and the largest around 0.1 meters at the centerline as seen in Figure 2.8. The CFD analysis was performed at a time when the settling chamber design was still at a height of 9 inches, so the analysis will be performed once more with the correct 6 inch height during future work.

After creating a mesh for each, they were simulated using US3D on the Texas A&M supercomputer, GRACE. *Stuff about inputs and convergence conditions*

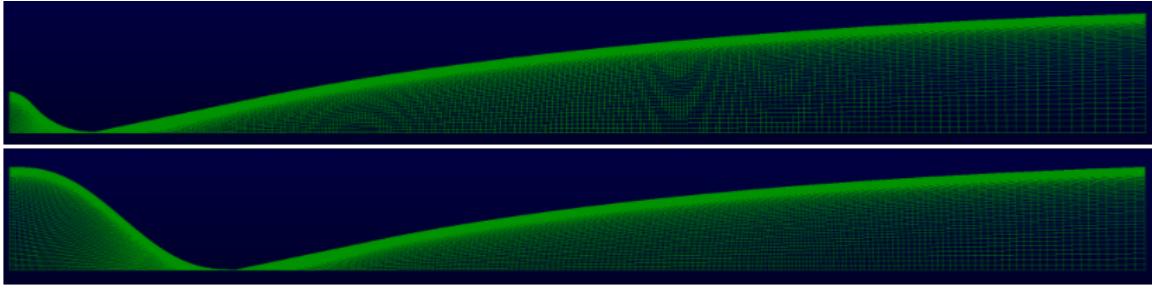


Figure 2.8: Mesh in Pointwise for ACE (top) and ACE2.0 (bottom) nozzle contours

## 2.2.4 20-Ton Linear Actuators Design

The updated ACE design follows the requirements above and is shown in the following figures.

The new design exhibits an improved nozzle contour, settling chamber, and actuation design:

- The overall length was increased by 16 inches to accommodate the much larger settling chamber.
- The actuation design consists of multiple worm gears to achieve a high gear ratio with minimal backlash. The Mach number can be changed quickly and accurately with a 0.005 inch throat height adjustment per control shaft rotation.
- The settling chamber exhibits inlet flow spreaders and an adaptable flow conditioner design.
- The nozzle is a single piece to eliminate any potential manufacturing steps and discontinuities.
- The stand will integrate with existing ACE infrastructure.

### 2.2.4.1 Nozzle and Settling Chamber Design

The nozzle and settling chamber are combined to accommodate active control.

The flow conditioners will be enclosed in a standalone box that can be modified or replaced easily.

The nozzle blocks will be made from 304 stainless steel, and the flexures will be made from 17-4 PH stainless steel.

#### *2.2.4.2 Frame Design*

Stuff and figures

Originally planned to water jet bars from brace stock to save material cost and reduce excess.

Later discovered that the cost of time and tooling on water jet to cut all pieces from 3 inch 4140 allot steel exceeds the cost of ordering bar stock.

#### *2.2.4.3 Actuation System Design*

Detailed specifics of actuation components

The actuation system will comprises 20-ton linear actuators, 20:1 gearboxes, servo motors, and a PLC to receive feedback inputs and control the system.

#### *2.2.4.4 Final Overall Design*

Pictured below is the final overall ACE2.0 assembly.

#### *2.2.4.5 FEA*

Stress and FOS stuff with figures

### **2.3 Fabrication Plans**

ACE2.0 is currently being fabricated. Most machining is completed. Pictures of machining and fabrication.

#### **2.3.1 Pressure Test**

Check structural integrity at 200 psia and evaluate sealing.

#### **2.3.2 Polishing**

Astro Pal polishing nozzles and sidewalls to 1 Ra.

### **2.4 Final Assembly, Installation, and Calibration**

The final assembly will occur at the NAHL. Once nozzles and actuators are assembled in the frame, ACE2.0 will be rolled into the lab to replace ACE. All hoses, wires, and instrumentation

attached to the nozzle and settling chamber will be removed and ACE will be rolled out of the lab. ACE2.0 will roll in and reconnect all hoses, wires, and instrumentation.

#### **2.4.1 Actuation Homing and Calibration**

Before the sidewalls are installed, the nozzles will be aligned by homing the servo motors with the limit switches. At this point shims will be used to make fine adjustments to limit switch positions to ensure a minimum Mach number of 4.9??? and a maximum Mach number of 8.5???.

#### **2.4.2 Shakedown and First Runs**

Decide what the first runs' purposes should be to properly calibrate.

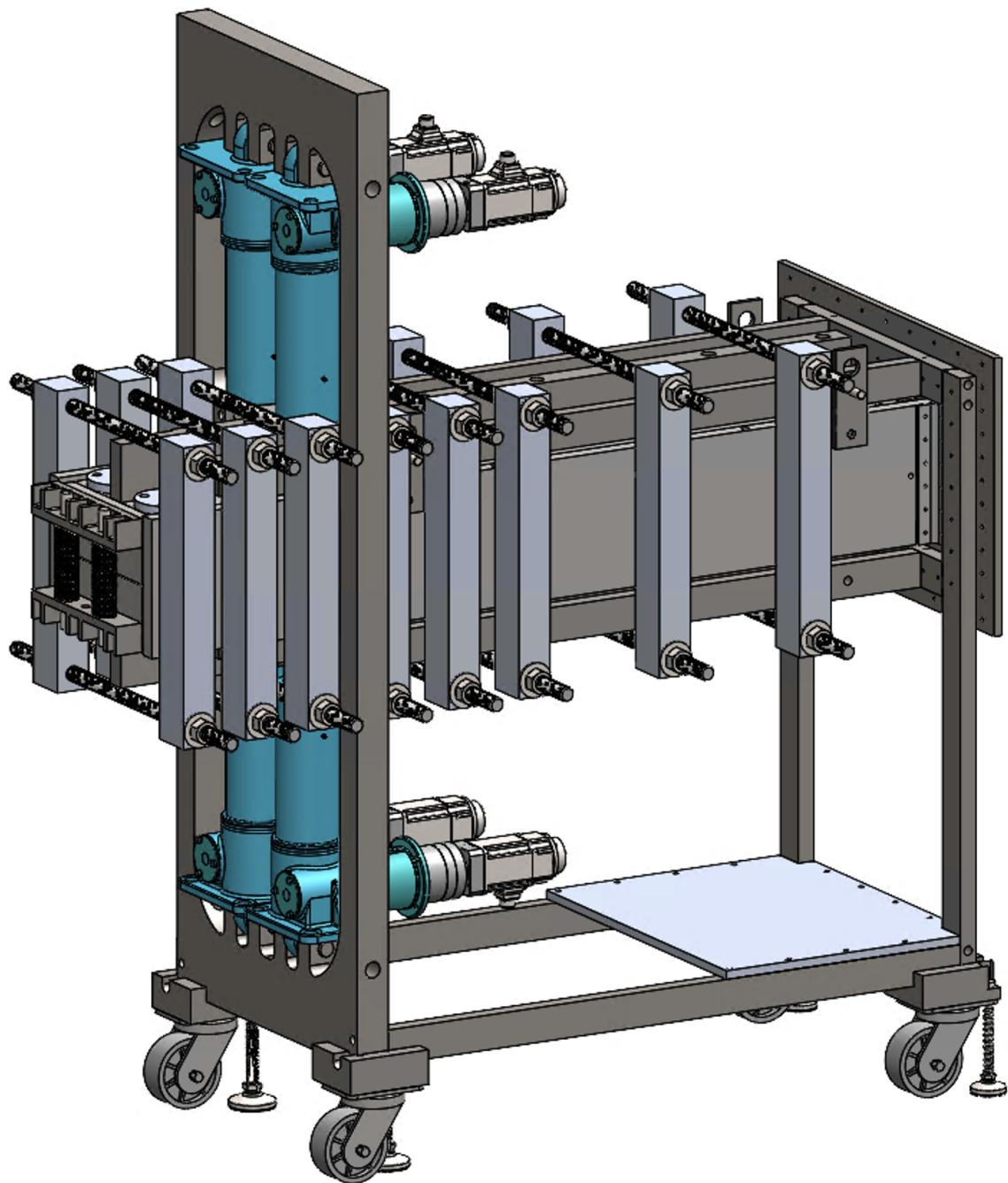


Figure 2.9: Temporary full CAD design

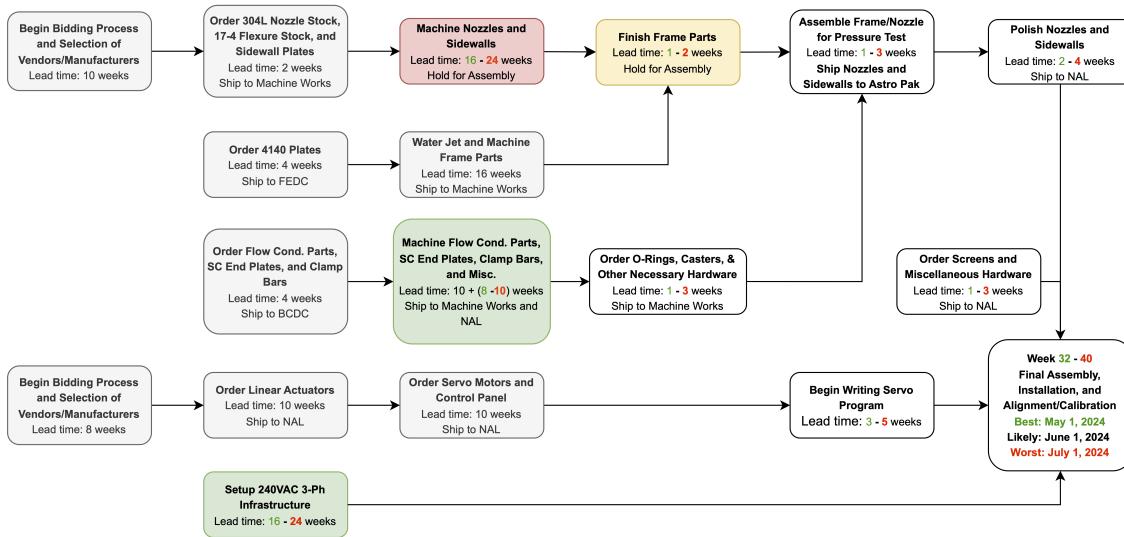


Figure 2.10: Manufacturing schedule beginning from September 25, 2023.

### 3. EXPERIMENTAL APPROACH & OBJECTIVES

Following the completed installation discussed above, each of the three primary objectives will be accomplished or demonstrated sequentially. First, the improved experimental control and efficiency as the result of the above ACE2.0 design will be demonstrated by calibrating and verifying the feedback-controlled active Mach selection capability and the Reynolds number control scheme. Second, the flow produced by the calibrated nozzle will be characterized in terms of noise and uniformity with an exploration of both uncerntainty quantification and hysteresis. Third, the overall capabilites of ACE2.0 will be demostrated in a preliminary experimental investigation of hysteretic behaviour of the flow characterisitcs of a fin-cone during Mach trajectories and oscillations. As a result of this work, the foundation will be set for future researchers to explore dynamic hypersonic vehicle flight in a more sophisticated and efficient manner with the control capabilities of ACE2.0.

#### 3.1 Experimental Control and Efficiency Improvements

The overall objective here is establish and substantiate the mechanisms of ACE2.0 that allow greater control of the tunnel input paramters for both more efficent and dyanmic experiments. The primary objective design objective of ACE2.0 was to enable active Mach number control during a run, which alone provides many key experimental advantages. However, there is still much to be desired with the parameter control capabilities to achieve full aerodynamic similarity for any flight trajectory. Thus, more precise control methods for Mach number and Reynolds number will be explored.

##### 3.1.1 Feedback-Controlled Active Mach Number Selection

As stated, the primary design objective of ACE2.0 was to enable active control of the Mach number, but this capability will be taken one step further to accurately maintain the desired Mach number once set. During a typical tunnel run, the nozzle is under both pressure and thermal loads that cause the set throat height to vary and the gas dynamics in the nozzle are non-ideal, which both result in the set Mach number to vary by up to 5%. The attempt of the implementation of

feedback control is to minimize this error to less than 1%.

The general approach for this feedback control is straightforward by designing a PID controller with an input of the measured Mach number and output of actuator position or velocity. The measured Mach number is calculated from the measured stagnation pressure and static pressure by solving the isentropic relation:

$$M = \sqrt{\frac{2}{\gamma - 1} \left[ \left( \frac{P_0}{P} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]} \quad (3.1)$$

The relationship between the throat height and the Mach number is given by:

$$\frac{A_*}{A} = \frac{h}{9} = M \left[ \left( \frac{2}{\gamma + 1} \right) \left( 1 + \frac{\gamma - 1}{2} M^2 \right) \right]^{-\frac{\gamma+1}{2(\gamma-1)}} \quad (3.2)$$

This is then subtracted from the set throat height to get the error signal for the PI transfer function:

$$E(s) = h_{set} - H(s) \quad (3.3)$$

$$G(s) = \frac{H(s)}{E(s)} = K_p \left( 1 + \frac{1}{K_i s} \right) \quad (3.4)$$

$$H(s) = K_p \left( 1 + \frac{1}{K_i s} \right) (h_{set} - E(s)) \quad (3.5)$$

This model is simulated in MATLAB and results are shown in Figure .

In practice, the Sysmac software used to write the logic for the PLC has a built-in PID function with gain autotuning capability. This will be explored in detail first in simulations in Sysmac followed by active tests in ACE2.0.

### 3.1.2 Reynolds Number Control Scheme

In subscale model experiments, the Reynolds number plays an important role in maintaining similarity with real-world situations. Controlling the Reynolds number more effectively will enable more accurate and intentional experiments. The primary goal of this objective is to provide a model that allows the Reynolds to be both held constant and varied proportionally to some dynamic trajectory. For the purposes of this discussion, any mention of the Reynolds number will actually mean the unit Reynolds number,  $Re/m$ .

This main control parameter for Reynolds number will be the settling chamber stagnation pressure. Shown below, the Reynolds number is coupled with respect to pressure, temperature, and Mach number. The goal will be to control the stagnation pressure to counteract changes in both temperature and Mach number. For reference, the settling chamber stagnation temperature typically increases during a run from an initial set point around 400 K to around 440 K, and of course the Mach number can vary anywhere between 5 and 8. The effect of temperature will be examined during both simulations and experiments to determine if a more adequate control system is required to maintain constant temperature or if this effect on the Reynolds number can be compensated by changing the pressure.

A mathematical model will be developed to be implemented for future physical PID control of the pressure regulator and the Reynolds number as a result. The physical implementation of this controller in this work will be dependent on some constraints. The primary constraint here will be the ability to quickly replace the existing regulator manual valve control with a controlled valve. The M6QT utilizes the same air supply infrastructure, so any complications throughout the valve replacement process would result in both facilities being inoperable and a delay in all planned research for this work and others.

One other factor to be considered in the stagnation pressure control is the time response delay due to the distance between the regulator and the tunnel. This distance is only around 7 meters, resulting in a maximum response time of 0.02 milliseconds with a sound speed of  $a = \sqrt{\gamma RT_0} = \sqrt{(1.4)(287)(400)} = 400 \frac{m}{s}$ .

The following derivation provides a starting point for the mathematical model.

$$Re/m = \frac{\rho U}{\mu} \quad (3.6)$$

$$\frac{T_0}{T} = (1 + \frac{\gamma - 1}{2} M^2) = F \quad (3.7)$$

$$\frac{P_0}{P} = (1 + \frac{\gamma - 1}{2} M^2)^{\frac{\gamma}{\gamma+1}} = F^{\frac{\gamma}{\gamma+1}} \quad (3.8)$$

$$\rho = \frac{P}{RT} = \frac{P_0 F^{\frac{-\gamma}{\gamma-1}}}{R T_0 F^{-1}} = \frac{P_0}{R T_0 F^{\frac{1}{\gamma-1}}} \quad (3.9)$$

$$U = M \sqrt{\gamma R T} = M F^{-\frac{1}{2}} \sqrt{\gamma R T_0} \quad (3.10)$$

$$\begin{aligned} Re/m &= \frac{\rho U}{\mu} = \frac{1}{\mu} \frac{P_0}{R T_0 F^{\frac{1}{\gamma-1}}} M F^{-\frac{1}{2}} \sqrt{\gamma R T_0} \\ Re/m &= \sqrt{\frac{\gamma}{R T_0}} \frac{M P_0}{\mu} F^{-\frac{\gamma+1}{2(\gamma-1)}} \end{aligned} \quad (3.11)$$

For constant Re/m assuming  $\gamma, R, T_0 = const.$  and with  $\frac{dF}{dt} = (\gamma - 1)M \frac{dM}{dt}$ :

$$\frac{d(Re/m)}{dt} = 0 = P_0 \frac{dM}{dt} + M \frac{dP_0}{dt} - \frac{M P_0}{\mu} \frac{d\mu}{dt} - \frac{\gamma + 1}{2} M^2 P_0 F^{-1} \frac{dM}{dt} \quad (3.12)$$

Sutherland's Law with  $T_\mu = 273, S_\mu = 111$ , and  $\mu_0 = 1.716 \times 10^{-5}$ :

$$\mu = \mu_0 \frac{T_\mu + S_\mu}{T + S_\mu} \left( \frac{T}{T_\mu} \right) \quad (3.13)$$

$$\mu = \frac{\mu_0 (t_\mu + S_\mu)}{T_\mu^{\frac{3}{2}}} \frac{T_0^{\frac{3}{2}} F^{-\frac{3}{2}}}{T_0 F^{-1} + S_\mu} \quad (3.14)$$

$$\frac{\frac{d\mu}{dt}}{\mu} = (\gamma - 1) M F^{-1} \frac{dM}{dt} \left( \frac{T_0 F^{-1}}{T_0 F^{-1} + S_\mu} - \frac{3}{2} \right) \quad (3.15)$$

Substiuting and solving for  $\frac{dP_0}{dt}$ :

$$\frac{dP_0}{dt} = P_0 M F^{-1} \frac{dM}{dt} \left[ (\gamma - 1) \left( \frac{T_0 F^{-1}}{T_0 F^{-1} + S_\mu} - \frac{3}{2} \right) + \frac{\gamma + 1}{2} - \frac{1}{M^2 F^{-1}} \right] \quad (3.16)$$

$$E(s) = Re_{set} - Re(s) \quad (3.17)$$

$$G(s) = \frac{P_0(s)}{E(s)} = K_p \left( 1 + \frac{1}{K_i s} \right) \quad (3.18)$$

$$P_0(s) = K_p \left( 1 + \frac{1}{K_i s} \right) (Re_{set} - Re(s)) \quad (3.19)$$

Simulation results of the above model result in acceptable performance of the PID controller as shown in Figure .

### 3.2 Nozzle Noise and Uniformity Characterization

In order to establish a baseline of performance characteristics for future work within the ACE2.0 facility and validate the design and manufacturing, a pitot survey will be performed to measure and characterize the freestream pressure fluctuations (noise) and uniformity throughout the nozzle. The survey will utilize both a single pitot probe and a pitot rake with kulites mounted on traverse to characterize entire nozzle exit plane and centerline into nozzle up to 24 inches upstream of nozzle exit.

A final noise survey was performed in ACE to establish a control for comparison with ACE2.0 as well as provide a preliminary exploration of noise hysteresis. The three runs for this survey are shown in Table 3.1. The survey utilized a single pitot probe to measure the noise along the centerline at different axial locations. For each run, the Reynolds number was increased above the transition value ( $3 \times 10^6 m^{-1}$ ) discussed in the previous chapter and then decreased back down to the initial value below the transition value. This process provided a preliminary look at the hysteresis of the pressure fluctuation levels.

The results are shown in Figure . As seen, ...

The characterization test matrix for ACE2.0 is shown in Table 3.2. These runs are divided into a few distinct objectives: (1) uniformity, (2) uncertainty, (3) pressure fluctuation transition, and

(4) hysteresis. The last seven runs will be replicates of the first seven to quantify the uncertainty in pressure fluctuations, Mach number, and uniformity.

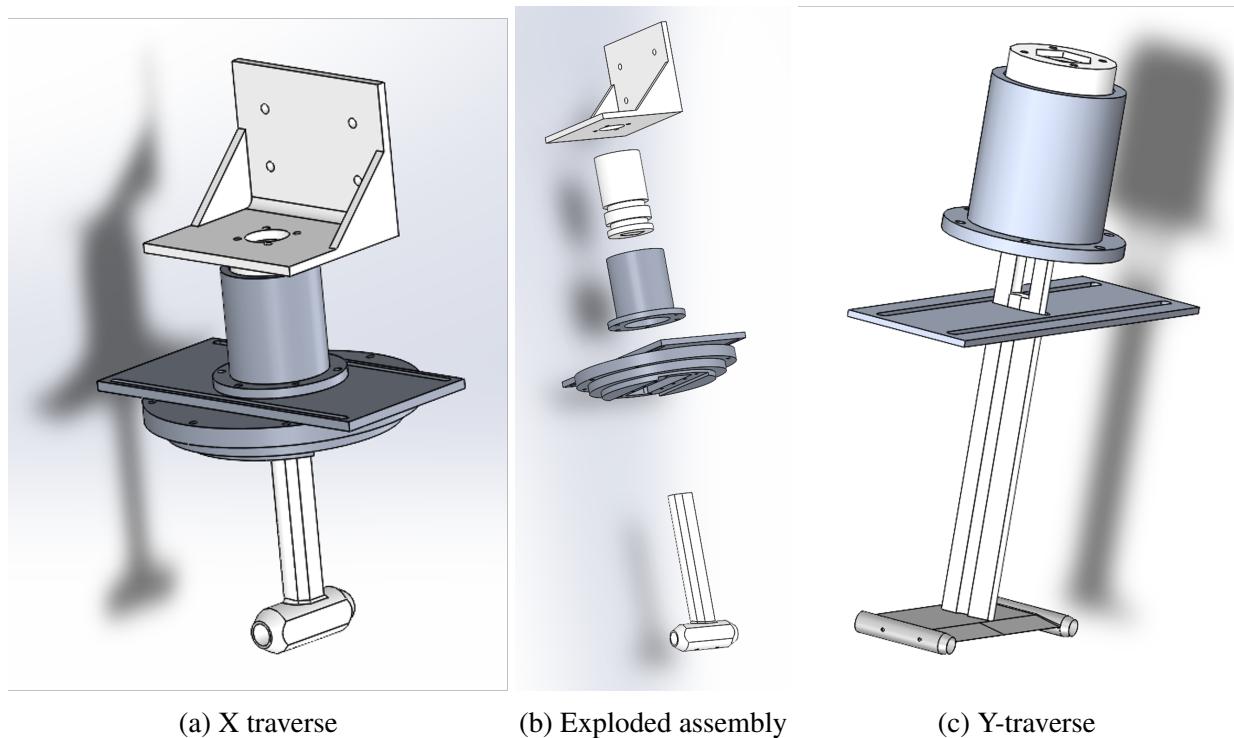


Figure 3.1: Traverse configurations

<b>Run</b>	<b>X (in.)</b>	<b>Y (in.)</b>	<b>Z (in.)</b>	<b>Re/m (<math>\times 10^6</math>)</b>
1	0	0	0	2→7→2
2	-17	0	0	2→7→2
3	-24	0	0	2→7→2

Table 3.1: Test matrix for preliminary noise hysteresis in ACE.

### 3.2.1 Uncertainty Quantification

Reference [21] and [22] for how to proceed. Both repeat and replicate data...



Figure 3.2: Pitot probe measuring 17 in. upstream of nozzle exit.

The process to quantify the uncertainty of the various parameters for this work will vary from Curriton's approach by simply focusing on establishing a baseline for the uncertainty and making recommendations for improvement. The three steps to establish this baseline uncertainty for ACE2.0 will be (1) gather/measure systematic elemental uncertainties, (2) measure replicate data points through a few repeat experiments, and (3) input measurements and data reduction equations into a monte carlo code to calculate random uncertainties.

First, the systematic elemental uncertainties can be gathered and measured from the various sensors, which includes the static pressure transducer, stagnation pressure transducer, stagnation temperature thermocouple, servo motor internal encoders, and any sensors utilized in each experiment.

Next, the replicate data points will be measured by repeatedly settling on and off the set condi-

<b>Run</b>	<b>X (in.)</b>	<b>Y (in.)</b>	<b>Z (in.)</b>	<b>Mach</b>	<b>Re/m (<math>10^6</math>)</b>
1	0	0	0	6*	3*
2	0	0	0	6	$2 \rightarrow 7 \rightarrow 2$
3	0	0	0	$5 \rightarrow 8 \rightarrow 5$	3
4	0	0	-3:1:3	6	3
5	0	-3	-3:1:3	6	3
6	0	-1.5	-3:1:3	6	3
7	0	1.5	-3:1:3	6	3
8	0	3	-3:1:3	6	3
9	-6	0	0	6	$2 \rightarrow 7 \rightarrow 2$
10	-6	0	0	$5 \rightarrow 8 \rightarrow 5$	3
11	-6	0	-3:1:3	6	3
12	-6	-3	-3:1:3	6	3
13	-6	-1.5	-3:1:3	6	3
14	-6	1.5	-3:1:3	6	3
15	-6	3	-3:1:3	6	3
16	-17	0	0	6	$2 \rightarrow 7 \rightarrow 2$
17	-17	0	0	$5 \rightarrow 8 \rightarrow 5$	3
18	-24	0	0	6	$2 \rightarrow 7 \rightarrow 2$
19	-24	0	0	$5 \rightarrow 8 \rightarrow 5$	3
20(1)	0	0	0	6*	3*
21(4)	0	0	-3:1:3	6	3
22(5)	0	-3	-3:1:3	6	3
23(6)	0	-1.5	-3:1:3	6	3
24(7)	0	1.5	-3:1:3	6	3
25(8)	0	3	-3:1:3	6	3

Table 3.2: Test matrix for ACE2.0 characterization and hysteresis study.

tion for the parameter of interest. While data will be gathered throughout the entire characterization test matrix, runs 1 and 20 will be solely for replicate data measurements.

Finally, the data measured from these two runs will be run through a monte carlo code along with the specific data reduction equations for the facility. This output will provide the random uncerntainty component for each parameter of interest, which will be added to the systematic uncerntainty to give the total uncerntainty.

In addition to this, a sensitivity analysis of the uncerntainty to the various input paramerters will be provided with recommendations if the final calculated uncerntainty is not sufficient.

### **3.2.2 Hysteresis**

Dynamic sweeps of both Mach number and Reynolds number will be performed to explore any potential hysteresis effects in either the noise or the control parameters. Specifically, this will be accomplished in the dynamic runs in the characterization test matrix.

### **3.3 Model Flow Characteristics Hysteresis During Mach Trajectory**

This objective will primarily serve as a demonstration of the capabilities for ACE2.0, but it will also provide preliminary insight into the hysteretic behaviour of dynamic Mach number experiments. The flow characteristics that will be specifically explored in this research will be surface heat flux and shock interactions using IR thermography and schlieren.

The first experiment will follow closely with the work of Wirth [32] to compare measurements from the dynamic runs to his results with the fin-cone model. This model, shown in Figure 3.3, consists of a 7° half-angle cone body with a single fin at an angle of 8° from the body surface. The specific model used by Wirth will be used for these experiments as well. This physical, shown in Figure , was 3D printed with a ceramic-like material using SLA... The entire model is 15 inches long with the fin beginning 4 inches from the nose tip. The nose tip for this model has a radius of 0.0025 inches as this was the limit for the 3D printer.

The second experiment will be based on

Use fin-cone model for public and HARV for army and verbal?

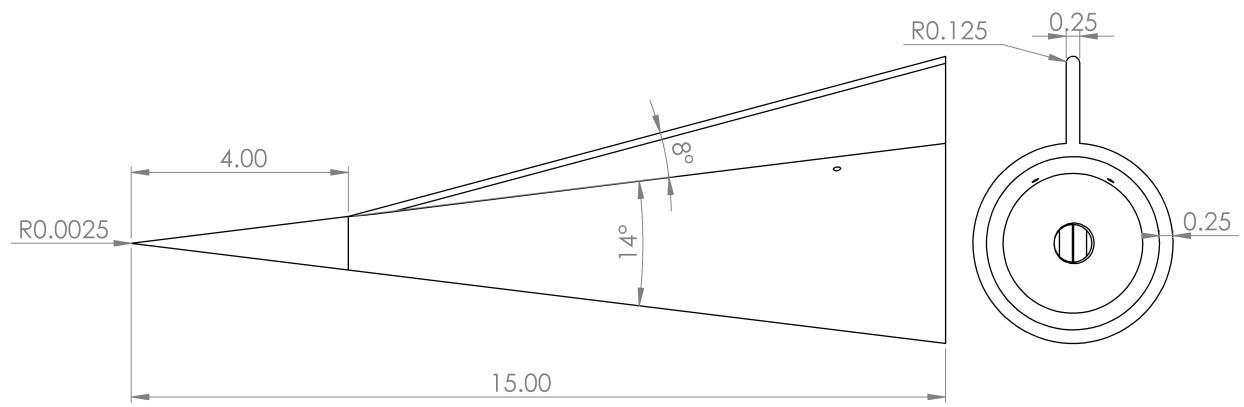


Figure 3.3: Drawing of 7° half-angle fin-cone model used for heat flux hysteresis study.

## 4. FUTURE WORK

The path forward at this point in time will first follow the manufacturing schedule shown in Figure 2.10. The pressure test will be performed as soon as the nozzles are finished machining, which should be by May 1. Depending on the results of the pressure test, the process could be anywhere from a single day to two weeks. Once complete though, the nozzles and sidewalls will be shipped out for polishing, which should have a quick turn around of two weeks. Upon arrival to the NAHL, the full ACE2.0 nozzle will be finally assembled and installed. With proper planning prior to the final installation, the process should not take more than a week to begin shakedown and characterization.

In the meantime, the servo control program will be written between now and the final nozzle machining. The Mach number feedback will be implemented, and the Reynolds number control capability will be explored and potentially implemented before the final install. Again, this will primarily depend on the test schedule for the M6QT and the amount of time needed to replace the manual valve with a controlled valve.

The characterization and hysteresis experiments will be performed immediately following installation and initial calibration. The primary goal is to ensure complete function of ACE2.0 along with a demonstration of the capabilities and potential for future research. Additionally, the documentation for the nozzle operation will be written based on the best practices deduced throughout the experiments.

### 4.1 Maybe

Might have another section

### 4.2 Possibly

Could possibly have another section

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## APPENDIX A

### FIRST APPENDIX

Text for the Appendix follows.



Figure A.1: A caption here

## APPENDIX B

## APPENDIX 2

Text for the Appendix follows.



Figure B.1: A caption here

### B.1 Appendix Section

### B.2 Another Appendix Section