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Raj Pandya

Performance Evaluation of Rotating Detonation Engines using
Shock-Tube Extrapolation

Raj Pandya

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Committee:

Carl Knowlen

Robert Breidenthal

Program Authorized to Offer Degree:

William E. Boeing Department of Aeronautics and Astronautics

University of Washington

ABSTRACT

Performance Evaluation of Rotating Detonation Engines using Shock-Tube Extrapolation

Raj Pandya

Chair of Supervisory Committee

Prof. Carl Knowlen

Department of Aeronautics and Astronautics

Rotating Detonation Engines (RDEs) represent a promising pressure-gain combustion technology capable of higher efficiency and compactness compared to conventional propulsion systems. However, the inherently unsteady nature of detonation presents challenges for both experimental characterization and computational modeling.

This thesis evaluates RDE performance through a shock-tube-based methodology that captures the essential detonation-driven flow fields within annular combustion chambers. Verification is carried out using Sod shock tube problems, followed by simulations of methane–oxygen mixtures under Chapman–Jouguet (CJ) detonation conditions. The analysis tracks detonation fronts, contact surfaces, and expansion waves using time-resolved pressure, velocity, and temperature fields.

Azimuthal duplication of one-dimensional shock-tube results enables the construction of a two-dimensional unwrapped domain, revealing detonation propagation, reaction structures, and triangular wave features consistent with experimental observations. Comparisons with NASA CEA equilibrium calculations validate predicted detonation velocities and post-detonation states.

Performance metrics including thrust, impulse, and specific impulse are quantified under vacuum and expanded boundary conditions. Results demonstrate the ability of the framework to reproduce pressure-gain combustion trends and characteristic detonation structures, while also identifying areas for future development such as injector coupling, higher-order solvers, and full annular simulations. This work establishes a computationally efficient framework for analyzing RDE flow physics and performance, contributing to the advancement of detonation-based propulsion research.

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Chapter 1

Introduction

Modern aerospace propulsion systems are predominantly based on deflagration combustion operating under the Brayton cycle. In such engines, exemplified by gas turbines and conventional chemical rockets, combustion occurs at approximately constant pressure [3]. While mature and reliable, these systems suffer from a fundamental thermodynamic limitation: a large fraction of the chemical energy is lost as thermal irreversibility rather than being converted into useful propulsive work. This inefficiency has motivated researchers to explore alternative combustion strategies that can achieve higher efficiency and compactness. Among these, *pressure-gain combustion* (PGC) has emerged as one of the most promising pathways [4, 5].

1.1 Background

Pressure-gain combustion enables a rise in pressure across the combustion process, in contrast to the constant-pressure heat addition of the Brayton cycle. Cycles incorporating pressure-gain, such as the Humphrey cycle (constant-volume heat addition), offer higher theoretical thermal efficiency than their Brayton counterparts [6]. Detonation-based combustion is particularly attractive for implementing PGC, as detonations inherently generate a sharp pressure rise across a supersonic reaction front [7, 3]. This has positioned detonation engines at the forefront of next-generation propulsion concepts, with potential applications ranging from advanced aircraft engines to space launch systems [4].

1.2 Concepts and Challenges in Rotating Detonation Engines

Among detonation-based technologies, Rotating Detonation Engines (RDEs) are of particular interest. Unlike Pulse Detonation Engines (PDEs), which rely on intermittent ignition and purge cycles, RDEs sustain a continuous detonation wave that rotates azimuthally within an annular combustor. This self-sustaining wave consumes reactants continuously and produces a high-pressure region that directly contributes to thrust generation. As a result, RDEs promise higher thrust-to-weight ratios, reduced system complexity, and significant thermal efficiency gains compared to deflagration-based propulsion [8, 9, 10].

Despite their promise, RDEs are extremely challenging to model and simulate. The flow field is dominated by strong shock waves, steep gradients in pressure and temperature, and finite-rate chemistry. Accurate modeling requires sub-millimeter grid resolutions and very small time steps to satisfy Courant–Friedrichs–Lewy (CFL) stability limits. Furthermore, the inclusion of detailed chemical kinetics compounds convergence difficulties. Boundary conditions at injectors and exhaust further add to the complexity: capturing effects such as choked flow, detonation wave reflection, and unsteady exhaust dynamics is critical for physical realism. Any misrepresentation can produce spurious instabilities or suppress wave propagation. Even two-dimensional simplified models often demand millions of grid cells and long runtimes on high-performance computing platforms [11, 12].

1.3 Simplified Modeling Approach

Given these challenges, this thesis adopts a simplified modeling framework to investigate RDE-relevant flow physics. Instead of directly simulating full annular RDEs, we employ pulsejet configurations as analog systems. Pulsejets exhibit unsteady pressure oscillations due to resonant combustion. While classical pulsejets operate in a deflagration mode, in this work they are modeled under conditions

favorable to detonation in order to approximate pressure-gain effects. Their comparatively simple geometry and reduced numerical stiffness make them well-suited for exploration using commercial CFD tools such as ANSYS Fluent [13].

The simulation results from pulsejet configurations are then extrapolated, using established theoretical correlations and scaling arguments, to infer the behavior of RDEs. In particular, we make use of shock tube theory and detonation scaling laws as a bridge between simplified simulations and realistic annular engine conditions. This stepwise methodology — *shock tube* $\rightarrow$ *pulsejet* $\rightarrow$ *RDE* — provides a cost- and time-effective framework for studying detonation-based propulsion and helps to establish a theoretical foundation for further, high-fidelity RDE simulations.

In summary, this work contributes toward understanding pressure-gain combustion by combining simplified CFD studies with detonation theory and scaling methods. The broader goal is to evaluate the potential of RDEs as future aerospace propulsion systems, and to provide a computationally tractable pathway toward their performance prediction.

1.4 Context and Motivation

1.4.1 Historical Perspective on Detonation Engines

Research into detonation-based propulsion dates back to the mid-20th century, when Nicholls and colleagues first proposed the concept of intermittent detonations as a propulsion mechanism [14]. These early efforts anticipated the thermodynamic benefits of detonation but were constrained by the experimental tools of the time. Interest in detonation engines resurfaced in the 1990s and 2000s with investigations into Pulse Detonation Engines (PDEs), supported by advances in ignition systems, diagnostics, and computational modeling [5, 3]. PDEs demonstrated measurable pressure-gain benefits, but their intermittent nature imposed penalties related to filling, purging, and mechanical valving.

The Rotating Detonation Engine (RDE) emerged as an attractive successor.

Bykovskii and coworkers demonstrated continuous spin detonations in annular combustors, providing the first experimental evidence of stable rotating detonation fronts [8]. Parallel work by the U.S. Air Force Research Laboratory (Schauer et al.) validated RDE operation under practical injection conditions [9]. Since then, RDE research has expanded rapidly, with major reviews highlighting their potential efficiency advantages and unresolved modeling challenges [4, 6, 12].

1.4.2 Theoretical Underpinnings

The feasibility of detonation-based engines is grounded in the Chapman–Jouguet (CJ) theory and the Zeldovich–von Neumann–Döring (ZND) model [7, 15, 16]. The CJ model defines the limiting detonation velocity and associated post-shock states, while the ZND framework accounts for finite-rate chemistry and provides more accurate estimates of induction length and detonation cell size. These concepts not only describe the fundamental combustion physics but also set the performance bounds relevant to propulsion.

Shock tube research has historically provided the bridge between theory and application, producing canonical data on ignition delays, detonation velocities, and reaction rates under controlled conditions [17, 18]. The Rankine–Hugoniot relations and CJ/ZND frameworks derived from shock tube studies directly inform RDE models, where accurate estimation of pressure gain, reaction length scales, and detonation velocities is critical [3, 19].

1.4.3 Applications and Relevance

The interest in RDEs extends well beyond academic curiosity. For aerospace propulsion, RDEs offer compact, high-thrust-to-weight systems suitable for hypersonic aircraft and space launch applications [20, 4]. In defense, they provide the potential for high-energy, storable propulsion systems that are simpler and more robust than turbine-based counterparts [10]. Beyond propulsion, detonation-based combustors are being studied for terrestrial energy applications

such as power generation, where their inherent pressure-gain capability could improve the efficiency of gas turbine systems [6].

Taken together, these historical, theoretical, and applied perspectives reinforce the motivation for simplified modeling approaches pursued in this thesis. By combining shock tube theory, surrogate pulsejet simulations, and scaling to RDE conditions, the present work seeks to contribute to a deeper understanding of pressure-gain combustion and its role in future aerospace propulsion.

1.5 Research Objectives and Scope

The overarching aim of this thesis is to investigate pressure-gain combustion through simplified numerical models and to establish theoretical links to Rotating Detonation Engines. Specifically, the objectives are:

1. To review and summarize the theoretical foundations of shock tube dynamics, detonation theory (CJ and ZND), and RDE operation.
2. To develop and validate simplified pulsejet models in ANSYS Fluent under detonation-favorable conditions.
3. To use shock tube results as a surrogate framework for extrapolating detonation behavior in pulsejets toward RDE-relevant regimes.
4. To evaluate thermodynamic performance metrics such as pressure gain, specific impulse, and thrust estimates using both theoretical and numerical approaches.

The scope of the thesis is limited to methane–oxygen mixtures at stoichiometric conditions, with emphasis on two-dimensional pulsejet geometries as surrogates for RDE chambers. While full three-dimensional RDE simulations are beyond the present computational resources, the simplified framework is designed to capture the essential detonation physics and provide a pathway for scaling toward realistic RDE configurations.

1.6 Thesis Outline

The remainder of this thesis is organized as follows. Chapter 2 reviews the theoretical background, covering shock tube fundamentals, detonation theory, and Rotating Detonation Engines. Chapter 3 presents the methodology, including simulation setup, numerical strategies, and performance post-processing. Chapter 4 reports the results of pulsejet simulations and their extrapolation to RDE conditions. Chapter 5 discusses the implications of the findings, followed by concluding remarks and recommendations for future research.

Chapter 2

Theoretical Background

2.1 Shock Tubes and Detonation Fundamentals

Shock tubes are canonical experimental devices used to generate controlled shock waves and study high-speed compressible flows. A conventional shock tube consists of two primary sections: a high-pressure driver and a low-pressure driven section, separated by a diaphragm. Upon rupture, a shock wave propagates into the driven section while an expansion fan travels back into the driver. These interacting waves create a well-defined, high-enthalpy flow environment that mimics propulsion-relevant conditions [7, 17].

In detonation and combustion research, shock tubes are indispensable for quantifying ignition delay times, species formation, and reaction rates under propulsion conditions. Depending on initial temperature, pressure, and equivalence ratio, reactive mixtures such as CH_4/O_2 or CH_4/air may produce either detonation or deflagration waves. These datasets provide critical benchmarks for validating computational detonation models [18, 21].

In this research, shock tube theory serves as a foundational reference. The post-shock thermodynamic states—pressure, temperature, and density—are determined using the Rankine–Hugoniot relations. These serve as initial parameters for both CFD setup in ANSYS Fluent and for extrapolating transient detonation wave behavior into surrogate geometries [3].

2.1.1 Rankine–Hugoniot and Normal Shock Relations

The one-dimensional normal shock relations for an ideal gas are given by:

$$\frac{P_2}{P_1} = 1 + \frac{2\gamma}{\gamma + 1}(M_1^2 - 1) \quad (2.1)$$

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma + 1)M_1^2}{2 + (\gamma - 1)M_1^2} \quad (2.2)$$

$$\frac{T_2}{T_1} = \frac{(P_2/P_1)}{(\rho_2/\rho_1)} \quad (2.3)$$

where M_1 is the upstream Mach number and γ is the ratio of specific heats. These relations describe the thermodynamic jump across the shock and form the basis for estimating downstream equilibrium conditions. [22, 23, 7]

2.2 Chapman–Jouguet vs. ZND Detonation Theory

The theoretical description of detonation is typically framed in two models of increasing fidelity: the Chapman–Jouguet (CJ) theory and the Zeldovich–von Neumann–Döring (ZND) model.

2.2.1 Chapman–Jouguet Theory

CJ theory models detonation as a discontinuous front followed by instantaneous energy release. It predicts a unique detonation velocity (the CJ velocity) and post-combustion state for a given mixture. The CJ point corresponds to the condition where the flow behind the detonation front becomes sonic relative to the wave [7]. While simplistic, CJ theory is widely used because of its analytical tractability.

2.2.2 ZND Model

The ZND model extends CJ by taking into account the finite-rate chemical reaction zone behind a normal shock wave propagating at the CJ Mach Number. Its wave structure consists of:

- A leading shock that compresses and heats the mixture
- An induction zone where radicals form with negligible heat release
- A main reaction zone of rapid exothermic release
- A final equilibrium zone where products relax thermodynamically

This produces the well-known von Neumann spike in pressure, followed by subsonic combustion that proceeds toward equilibrium that results in sonic flow relative to the normal shock wave at the CJ point. The ZND structure is more physically realistic than the CJ approximation, especially for modeling ignition delays and detonation stability. [15, 16]

2.2.3 Importance in RDE Modeling

CJ theory provides the baseline detonation velocity and pressure rise that supports the engine cycle analyses, while ZND theory informs chemical kinetics, induction length, and detonation cell size - parameters essential for numerical models of RDEs. Both perspectives are needed to bridge experimental shock tube data with CFD-based RDE simulations.

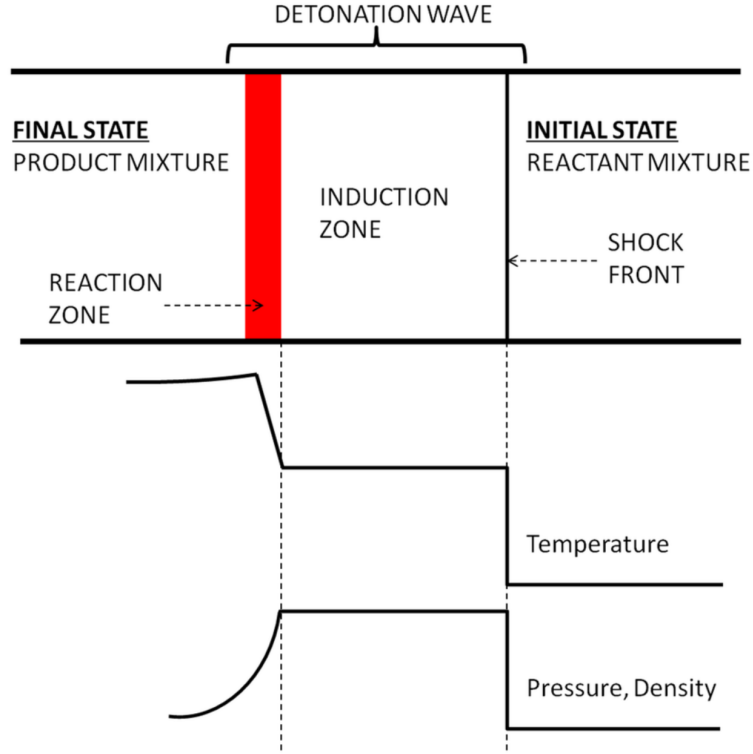
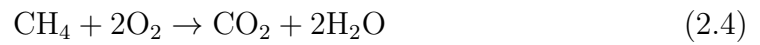


Figure 2.1: A schematic showing a Z-N-D detonation model propagating towards the right and temperature, pressure and density profile across the detonation wave.[1]

2.3 Stoichiometry and CH_4/O_2 Mixture Fundamentals

2.3.1 Stoichiometric and Equivalence Ratio

The stoichiometric fuel–oxidizer ratio is the exact proportion needed for complete combustion:



giving a stoichiometric mass ratio:

$$\frac{m_{\text{CH}_4}}{m_{\text{O}_2}} = 0.2506 \quad (2.5)$$

The equivalence ratio ϕ is defined as:

$$\phi = \frac{(F/O)_{\text{actual}}}{(F/O)_{\text{stoich}}} \quad (2.6)$$

where $\phi = 1$ is stoichiometric, $\phi < 1$ lean, and $\phi > 1$ rich.

2.3.2 CH₄/O₂ vs. CH₄/Air Thermodynamic Implications

While air is a practical oxidizer, pure oxygen is commonly used in detonation studies due to its enhanced reactivity and higher adiabatic flame temperature. CH₄/O₂ mixtures generally result in:

- Faster ignition and shorter induction times
- Higher detonation velocities and CJ pressures
- Cleaner combustion products (minimal dilution from N₂)

CH₄/air mixtures are diluted with nitrogen, which lowers the overall flame temperature and detonation velocity. However, these mixtures better represent air-breathing engine environments. [16, 24]

2.3.3 Effect of Equivalence Ratio on Stability

The equivalence ratio (ϕ) significantly affects detonation characteristics. As ϕ increases from lean to stoichiometric:

- The heat release increases, raising flame and detonation temperatures.
- The Chapman–Jouguet (CJ) detonation velocity correspondingly increases [25].

For fuel-rich conditions ($\phi > 1$), additional trends are observed:

- Wave propagation becomes more stable, with maximum CJ speed observed near $\phi \approx 1.5$ in CH₄-O₂ mixtures [26, 2].
- Excess fuel at equilibrium reduces complete oxidation, shifting CO₂ production toward CO and enhancing soot formation [27].

Experimental detonation sensitivity data indicate that a smaller range of ϕ values supports sustained detonations than the range of flammability limits [7].

2.3.4 CEA to Estimate Detonation Properties

The NASA Chemical Equilibrium with Applications (CEA) program is used to calculate equilibrium thermodynamic properties of combustion mixtures. By specifying pressure, temperature, and mixture composition, CEA returns:

- Adiabatic Flame Temperature
- Specific heat (C_P) and ratios of specific heats (γ)
- Molecular weight of the product gases
- Species mole fractions and enthalpy

CEA can also be used to compute the Chapman-Jouguet velocity. These values are critical inputs for estimating post-detonation properties, evaluating CJ conditions, and defining boundary conditions in CFD models. In this thesis, CEA is used to compute properties of CH₄/O₂ mixtures at conditions representative of the detonation environment.

2.4 Rotating Detonation Engine Theory

2.4.1 Structure and Principle

Rotating Detonation Engines (RDEs) represent a class of pressure-gain propulsion systems that utilize detonation waves to continuously combust a fuel-oxidizer mixture. Unlike Pulse Detonation Engines (PDEs), which rely on intermittent ignition and combustion, RDEs sustain a continuous detonation front that travels azimuthally in a closed-loop, annular combustion chamber. This annular configuration typically comprises of an inner and outer cylindrical wall, between which the reactive mixture is injected axially or radially depending on the specific design.

The combustion process is initiated by a local ignition source that forms a detonation wave. This wave stabilizes and rotates along the annular path, continually consuming incoming fresh mixture and producing a high-pressure, high-

temperature exhaust. The detonation front acts as a moving boundary that separates unburned reactants from detonation products, thereby maintaining high reaction rates and sustaining combustion without external ignition after startup. The principal advantage of this configuration is its ability to convert more of the chemical energy into useful thrust by generating a pressure rise across the combustion front, a phenomenon not seen in conventional Brayton cycle engines. The sustained detonation wave also enables more compact designs, potentially leading to lighter and more efficient propulsion systems[8, 9, 10].

RDE operation involves highly unsteady and multidimensional flow fields, featuring interactions between the detonation wave, expansion fans, shock reflections, and injector flow. The interaction of the wave with the fresh fuel-oxidizer jets plays a critical role in stabilizing or destabilizing the detonation front. For effective operation, the detonation wave must outrun the mixing and replenishment timescales of the injectors to avoid wave extinction.

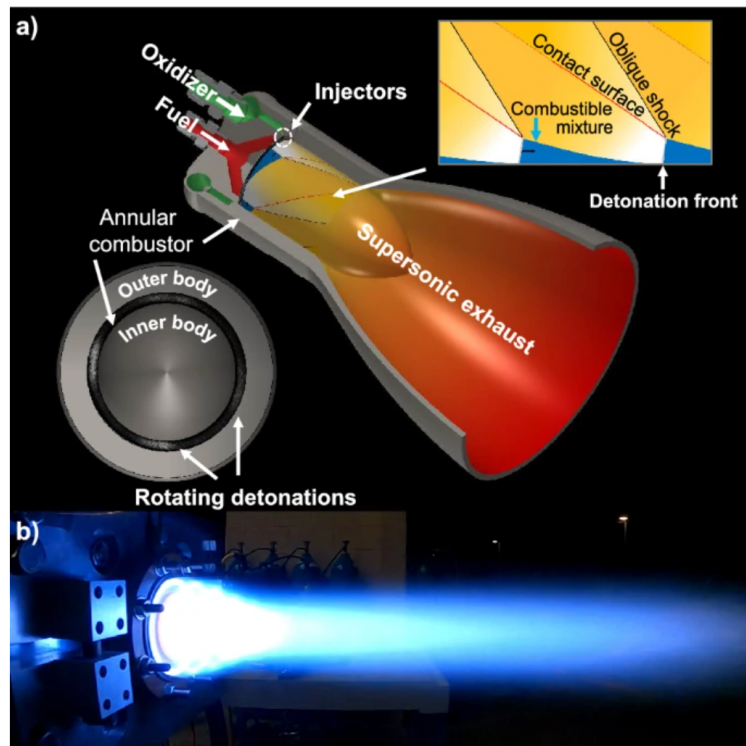


Figure 2.2: Rotating detonation rocket engine showing (a) the hardware schematic and (b) a firing test of the canonical configuration [2].

2.4.2 Detonation Wave Behavior in Annular Geometries

The unique annular geometry of RDEs introduces several complexities to wave propagation. The curvature of the combustion chamber affects wave stability, as the detonation front must maintain its velocity and strength while continuously navigating the curved annular path. In contrast to planar detonation propagation, the confined annular layout introduces variable boundary interactions which influence the local pressure field and energy release.

Additionally, the rotating detonation wave interacts with the unsteady injection boundary and expansion waves trailing the products. These interactions lead to characteristic flow structures such as slip lines, oblique shock intersections, and vortex shedding. Incomplete mixing or non-uniform injection can result in detonation weakening or transition to deflagration, undermining engine efficiency and performance stability [19, 5].

Numerical and experimental studies have shown that the number of detonation waves that can coexist in the chamber, their azimuthal velocity, and their spatial spacing all significantly influence overall performance. Understanding these geometric and physical effects is essential to optimizing injector placement, chamber design, and operational limits [8, 9, 10].

2.4.3 Thermodynamic Performance Metrics

RDEs offers the potential for higher thermodynamic efficiency by exploiting pressure-gain combustion. In contrast to Brayton cycle engines, where combustion occurs at nearly constant pressure, RDEs feature combustion accompanied by a sharp pressure rise. This fundamental distinction enables better conversion of chemical energy to kinetic energy.

The specific impulse (I_{sp}), defined as the thrust produced per unit mass flow rate of propellant, is a key performance metric and can be estimated from the momentum flux exiting the nozzle that expands the flow from the annular combustor:

$$I_{sp} = \frac{F}{\dot{m}g_0}, \quad (2.7)$$

where F is the thrust, $\dot{m}$ is the total mass flow rate, and g_0 is the standard gravitational acceleration.

Another important figure of merit is the total pressure ratio across the engine, which quantifies the pressure gain due to detonation:

$$\text{Pressure Gain Ratio} = \frac{P_{exit}}{P_{inlet}} \quad (2.8)$$

RDEs also tend to exhibit high thrust-to-weight ratios due to the compact nature of the annular geometry and the elimination of rotating components like turbines or compressors. Collectively, these metrics underscore the propulsion advantage RDEs may provide over traditional systems [20, 4].

2.5 Bridging Concept: From Shock Tube to Pulsejet to RDE

A key element of this thesis is the theoretical and methodological bridge that connects canonical shock tube experiments with the complex dynamics of Rotating Detonation Engines. This bridge proceeds in three stages:

2.5.1 Shock Tube Surrogates

Shock tubes replicate the fundamental physics of strong shock and detonation propagation. The Rankine–Hugoniot conditions define post-shock states, which approximate the environment that fresh reactant mixtures encounter inside an RDE annulus. Normal shock reflections and expansion fans in shock tubes are directly analogous to the reaction triangle observed in RDE flow fields [3, 7].

2.5.2 Pulsejets as an Intermediate Model

Pulsejets or simplified one-dimensional detonation tubes serve as computationally efficient surrogates for detonation research. Each pulse resembles a slice of an RDE’s azimuthal detonation cycle. By analyzing these transient pulses, one can capture ignition delays, pressure rise, and blowdown dynamics that approximate localized RDE physics.

2.5.3 RDE as Continuum of Shock Tubes

Conceptually, an RDE annulus is regarded here as an unwrapped shock tube in the azimuthal direction. In this work, simulations of shock tubes are extrapolated by duplicating axial profiles into circumferential segments, thereby reconstructing a two-dimensional detonation expansion process. This approach links canonical detonation theory to rotating wave propagation in RDEs.

The stability and performance of RDEs ultimately depend on parameters measurable in shock tube/ZND studies: detonation velocity, cell size, and induction length. Thus, the shock tube $\rightarrow$ pulsejet $\rightarrow$ RDE framework provides stepwise bridge between fundamental detonation physics and applied propulsion modeling [8, 9, 19, 20].

Chapter 3

Methodology

3.1 Overview of Methodology

This chapter outlines the computational methodology adopted to simulate pulsejet engine behavior and extrapolate the resulting performance data to approximate that of a Rotating Detonation Engine. Given the high computational cost and complexity of direct RDE simulation [10, 19, 20], a simplified approach is employed by modeling the blowdown process of pulsejet configuration as that of a shock tube in ANSYS Fluent [28]. The simulation results are subsequently post-processed to estimate performance metrics such as thrust, impulse, and specific impulse [22, 24].

The methodology involves the following key stages:

1. Development of a 2D axisymmetric computational domain replicating a simplified pulsejet engine [10].
2. Mesh generation with appropriate refinement in regions of expected gradients [29, 30].
3. Finalizing the driver-driven geometries based on the wave arrival at the end of the shock tube.
4. Specification of initial and boundary conditions that mimic the thermodynamic environment of an RDE using the values extracted from CEA. [31, 15].
5. Transient simulations in ANSYS Fluent, capturing unsteady detonation wave propagation and reflection [10, 19].

6. Extraction of time-dependent data and integration to compute performance quantities [23, 20].

By leveraging the detonation-like conditions within a pulsejet surrogate, this strategy offers a tractable alternative for evaluating RDE-relevant behavior [3]. Each subsequent section of this chapter elaborates on the above steps in detail, starting from the geometric and meshing setup to solver configuration, physical modeling, and post-processing procedures.

3.2 Geometry and Computational Domain

The computational domain is based on a two-dimensional rectilinear representation of a pulsejet engine with initial conditions tailored to induce detonation-like conditions [3, 8]. The choice of geometry is influenced by classical shock tube configurations with added nozzle or expansion regions to replicate key features observed in rotating detonation environments [19].

The domain consists of a high-pressure driver region, a central combustion or driven chamber, and an outlet section to allow for wave propagation and exhaust. The total shock tube length is 80 mm, comprising a 16 mm long driver section and a 64 mm driven section. The geometry is discretized such that shock propagation, wave reflection, and mixing effects can be resolved.

This design enables simplified modeling of detonation products expansion under simplified conditions, while retaining the essential physical interactions of interest—namely shock interaction, pressure rise, and transient mixing. Two-dimensional modeling is employed to reduce computational cost while capturing radial flow development and detonation characteristics in the longitudinal direction [10].

The geometry was created using ANSYS Design Modeler and imported into ANSYS Meshing for further refinement. To evaluate the effect of domain proportions on wave behavior, three different driver-to-driven length ratios were tested: 16 mm / 64 mm, 28 mm / 52 mm, and 40 mm / 40 mm. Each configuration was

simulated under identical initial conditions of driven temperature of 2000 K and driver temperature of 3847.76 K.

The graphs 3.1, 3.2 and 3.3 show the arrival of the shock for the 3 different driver-driven ratios of 16 mm / 64 mm, 28 mm / 52 mm, and 40 mm / 40 mm under conditions stated above.

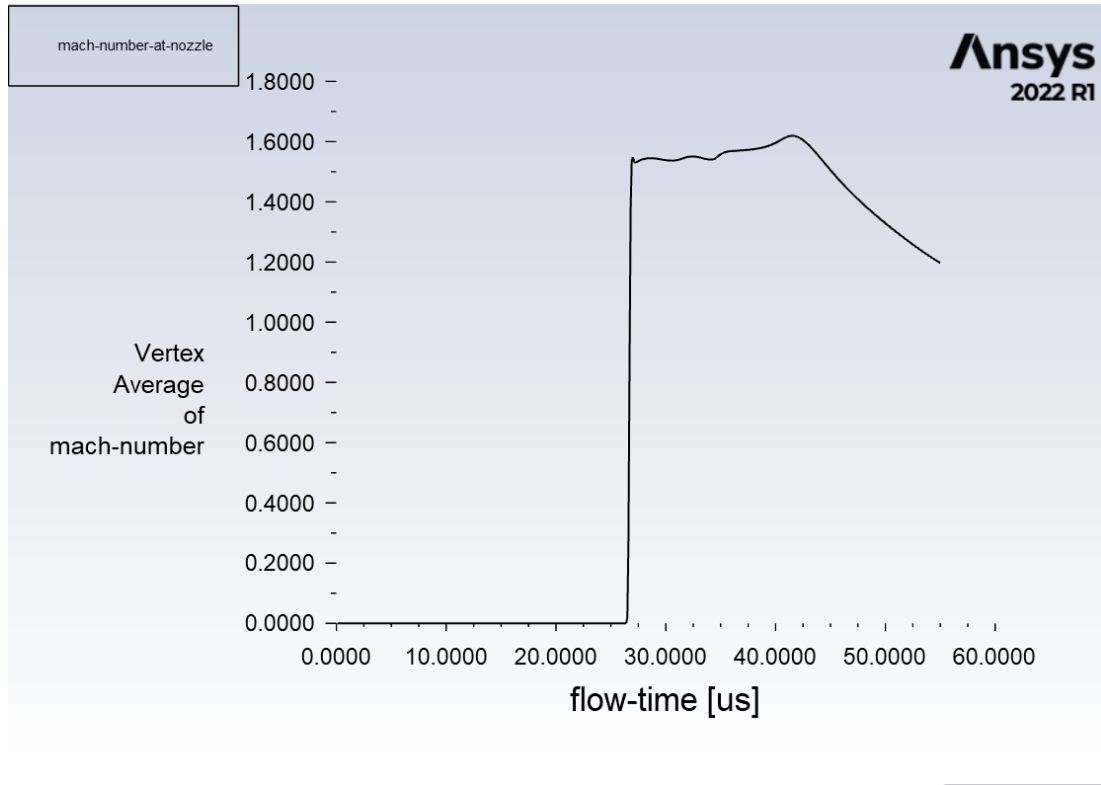


Figure 3.1: Shock arrival for geometry of 16 mm driver and 64 mm driven

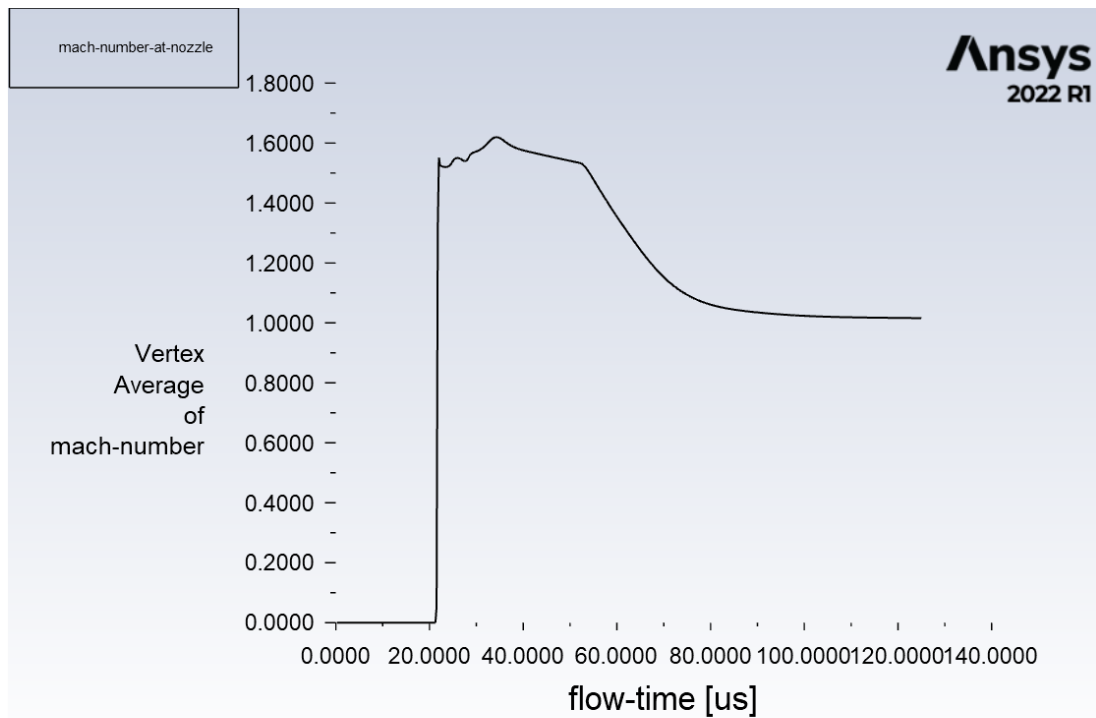


Figure 3.2: Shock arrival for geometry of 28 mm driver and 52 mm driven.

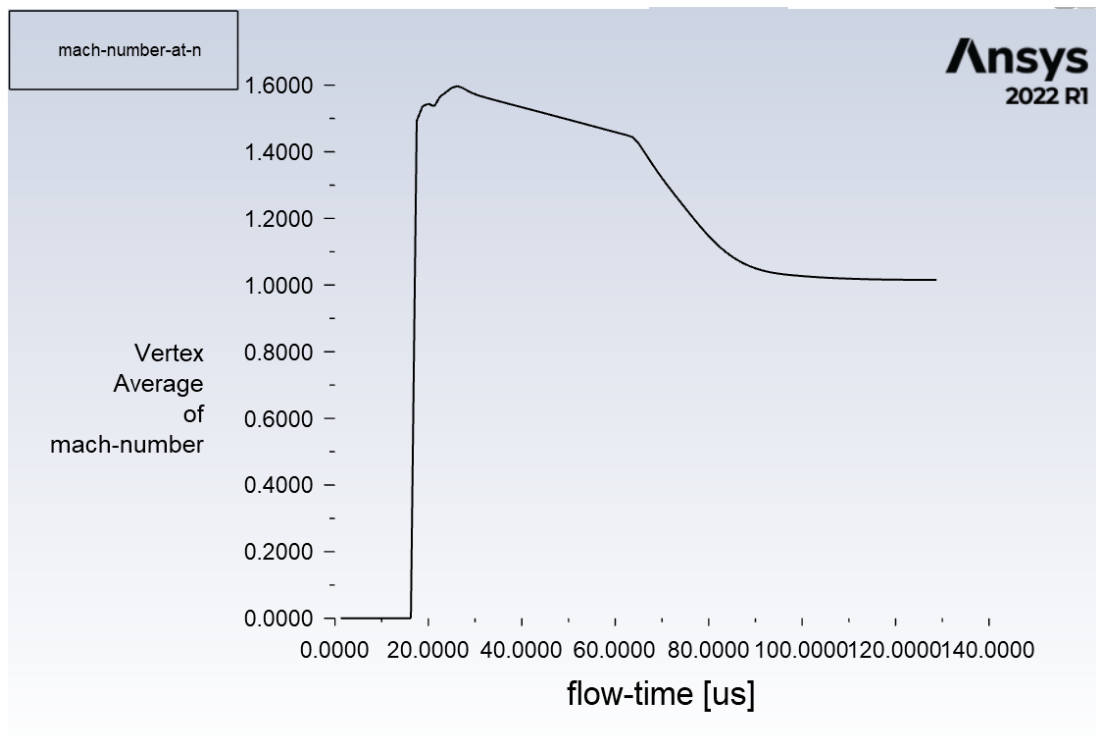


Figure 3.3: Shock arrival for geometry of 40 mm driver and 40 mm driven

The 16 mm / 64 mm configuration was selected based on its ability to allow a single detonation wave to fully traverse and exit the chamber within the

observation window while keeping the diameter of the RDE large enough to not worry about the effects caused by the curvature of the engine [19]. This choice was also consistent with the effective azimuthal length of the modeled annular RDE domain, thereby enabling a valid extrapolation of results. Boundary condition zones, such as the inlet (driver), combustion region, and outlet, were clearly defined to enable tailored specification of pressure and temperature conditions.

3.3 Mesh Generation

Mesh generation was carried out in ANSYS Meshing using a structured grid layout wherever possible to minimize numerical diffusion and improve solution accuracy [29]. The mesh was refined along expected gradients, such as the diaphragm location, shock front path, and outlet regions, to capture transient flow features with high fidelity [10].

A grid independence study was conducted to ensure that key flow variables such as peak pressure, shock velocity, and temperature profiles did not vary significantly with further mesh refinement [30]. The final mesh consisted of 28800 cells and 29521 nodes, providing a balance between solution accuracy and computational efficiency.

The mesh quality metrics, including skewness and orthogonality, were maintained within the recommended thresholds to ensure numerical stability. A visual representation of the mesh layout is shown in figures below.

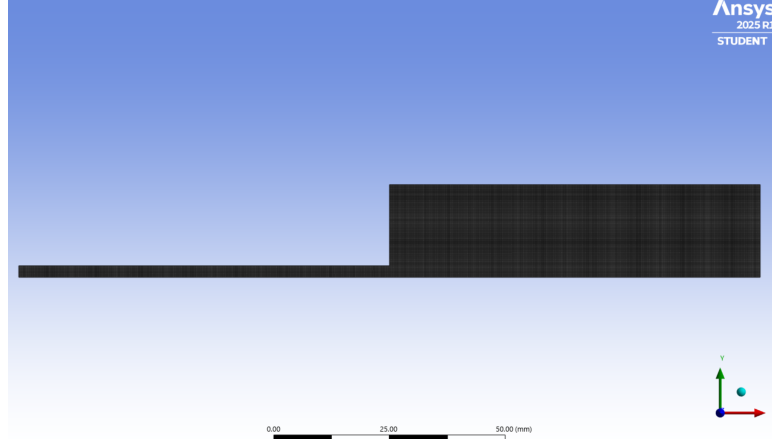


Figure 3.4: Finalized Mesh of Shocktube and Domain

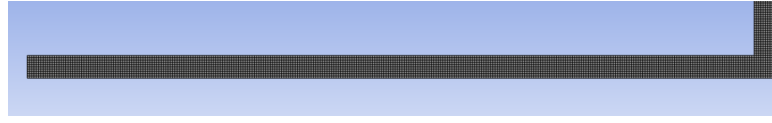


Figure 3.5: Detailed mesh of Shock Tube

3.4 Governing Equations and Physical Models

The flow inside the pulsejet engine domain can be modeled with the unsteady, compressible Navier–Stokes equations [22, 24, 8]. For the purpose of simplifying RDE performance modeling, the combustor of a pulsejet is modeled as the driver of the shock tube filled with post-detonation combustion products. The primary equations solved in ANSYS Fluent are:

- Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \quad (3.1)$$

- Momentum equation:

$$\frac{\partial (\rho \vec{u})}{\partial t} + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho \vec{g} \quad (3.2)$$

- Energy equation:

$$\frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\vec{u} (\rho E + p)) = \nabla \cdot (k_{eff} \nabla T) + S_E \quad (3.3)$$

The viscosity, thermal conductivity, and diffusion coefficients are evaluated based on local species composition and temperature. The solver accounts for compressibility effects and incorporates real gas behavior through temperature-dependent property inputs [24, 15].

For turbulence modeling, the SST $k-\omega$ model is employed due to its robustness in capturing shock-boundary layer interactions while maintaining numerical stability near walls [32]. This model blends the $k-\epsilon$ formulation in the free stream with the $k-\omega$ model near the wall, allowing it to accurately predict flow separation, adverse pressure gradients, and shock-induced boundary layer effects. These capabilities are essential for capturing the dynamics of transient high-speed reacting flows in confined geometries such as detonation tubes [3].

The physical models collectively enable simulation of detonation, propagation, and decay across the domain, while capturing key thermodynamic transitions relevant to RDE operation.

3.5 Boundary and Initial Conditions

Boundary and initial conditions were prescribed to reflect the intended high-enthalpy, shock-driven environment. The driver section was initialized with the combustion products and properties at CJ conditions for stoichiometric $\text{CH}_4\text{-O}_2$ mixture. NASA CEA simulations [31] predicted a driver pressure of 35.7 bar and temperature of 3847.76 K, for an initial pre-detonation condition of 4 bars of pressure and 1000 K, temperature consistent with ideal detonation product conditions for CH_4/O_2 combustion [15], while the driven section contained high-temperature product gases.

For the driven section, the initial conditions were 4 atm and approximately 3100 K, reflecting the post-detonation environment resulting from expanding detonation products from a previous cycle [15, 24]. These conditions were selected based on the desired pressure ratio and CJ temperature estimates for CH_4/O_2 combustion [15]. The outlet of the domain was modeled as a pressure outlet set

to 1 atm to allow free expansion.

Interior zones separating the six sections of the domain were coupled using non-reflecting or continuity conditions to ensure smooth propagation of shock and expansion waves across interfaces [10]. No-slip, adiabatic conditions were applied at the solid walls to capture wall-bounded shock effects without heat transfer losses.

The initial pressure discontinuity between the driver and driven sections triggered the formation of a shock wave that propagated downstream and generated the desired detonation-like conditions. These boundary and initial settings were critical in ensuring that the simulated dynamics faithfully replicated experimental observations and provided physically meaningful results for performance extrapolation [3, 4].

3.6 Post-Processing in ANSYS Fluent

To enable quantitative analysis of the simulated detonation phenomena and subsequent extrapolation to Rotating Detonation Engine (RDE) performance, a structured post-processing procedure was implemented within ANSYS Fluent [10]. The primary objective was to capture high-resolution temporal and spatial data of the detonation wave evolution and associated flow parameters.

3.6.1 Probe Placement and Spatial Resolution

Static probes were positioned at 1 mm intervals along the full axial length of the computational domain, covering the driver section, driven section, and outlet. This configuration provided a detailed spatial mapping of wave propagation, enabling precise analysis of pressure, temperature, and velocity histories at multiple locations [22].

3.6.2 Temporal Resolution and Time-Stepping

Given the high propagation speeds and microsecond-scale transients inherent to detonation waves, the transient solver was configured with a fixed time step of 5×10^{-10} s. This temporal resolution ensured satisfaction of the Courant–Friedrichs–Lewy (CFL) condition across the domain, while capturing the shock and expansion features without numerical smearing [22, 29].

- The solver employed an **explicit time-stepping scheme** to maintain numerical stability in the presence of strong discontinuities [29].
- Data was recorded at every 1000 time-step intervals, corresponding to an effective sampling interval of 5×10^{-7} s.

3.6.3 Monitored Quantities

At each probe location, the following flow variables were monitored:

1. **Static Pressure** (Pa) — to track wave arrival times, peak pressures, and decay rates.
2. **Density** (kg/m^3) — to observe post-shock compression and expansion zones.
3. **Static Temperature** (K) — to monitor thermal energy distribution and reaction zone heating.
4. **Velocity Magnitude** (m/s) — to characterize acceleration and deceleration across wave fronts.
5. **Mach Number** — to identify shock strengths, expansion fan regions, and subsonic/supersonic transitions.

3.6.4 Data Export and File Management

The data was collected using ANSYS Fluent’s *Report Definitions* feature, enabling automated recording of all monitored quantities during transient simu-

lation. The resulting text-based output files were subsequently converted into comma-separated value (CSV) format for compatibility with the post-processing environment described in Section 3.7.

3.6.5 Rationale for Chosen Settings

The combination of fine probe spacing and ultra-small time step was selected to ensure that the detonation front and associated features were fully resolved without temporal or spatial aliasing. This approach allowed for:

- Accurate determination of wave propagation velocities at multiple axial locations.
- Direct comparison of simulated wave characteristics with theoretical predictions [3, 15].
- Provision of high-fidelity input data for subsequent performance metric calculations [23, 20].

3.7 Performance Metric Extraction

Following the high-resolution data acquisition process outlined in Section 3.6, the recorded simulation outputs were post-processed to derive key propulsion performance metrics. The objective was to transform raw time-dependent flow field data into quantities directly relevant for evaluating Rotating Detonation Engine performance [23, 20].

3.7.1 Data Preparation

The output files generated by ANSYS Fluent’s *Report Definitions* were converted into comma-separated value (CSV) format for ease of handling in external analysis tools. Each CSV file contained time histories of pressure, density, temperature, velocity magnitude, and Mach number for all probe locations.

To ensure numerical consistency, time stamps were cross-checked against the simulation time step and sampling interval (5×10^{-7} s effective output spacing). Any incomplete or corrupted entries were discarded. The data were then structured into arrays indexed by probe location and time for streamlined processing.

3.7.2 Thrust Calculation

The instantaneous thrust of the combustor was determined from the momentum flux and pressure differential at the nozzle:

$$F(t) = \dot{m}(t) U(t) + [P(t) - P_{\text{amb}}] A_{\text{exit}}, \quad (3.4)$$

where:

- $\dot{m}(t) = \rho(t)U(t)A_{\text{exit}}$ is the instantaneous mass flow rate,
- $U(t)$ is the axial velocity at the nozzle,
- $P(t)$ is the nozzle static pressure,
- P_{amb} is the ambient pressure, depending on the application
- A_{exit} is the cross-sectional area of the nozzle, i.e. area of the circle with outer combustor annulus diameter

This approach captures both the momentum and pressure contributions to thrust, which is essential for unsteady detonation-driven flows [23].

3.7.3 Impulse and Specific Impulse

The total impulse over a chosen time window Δt was obtained via time integration of the thrust:

$$I = \int_{t_0}^{t_f} F(t) dt, \quad (3.5)$$

The specific impulse, a measure of propulsion efficiency, was then calculated as:

$$I_{\text{sp}} = \frac{\overline{F}}{\overline{\dot{m}} g_0}, \quad (3.6)$$

where:

- $\overline{F}$ is the time-averaged thrust,
- $\overline{\dot{m}}$ is the time-averaged mass flow rate,
- $g_0 = 9.80665 \text{ m/s}^2$ is standard gravitational acceleration.

Cycle-averaging was applied in periodic operating regimes to determine an average calculated I_{sp} [23, 20].

3.7.4 Additional Performance Quantities

For completeness, the following supplementary metrics were also derived:

- **Pressure Gain Ratio:**

$$\Pi_{\text{gain}} = \frac{P_{\text{exit}}}{P_{\text{inlet}}}, \quad (3.7)$$

where P_{exit} and P_{inlet} are cycle-averaged total pressures at the outlet and inlet, respectively [20, 3].

- **Estimated Power Output:**

$$\dot{W} = \overline{F} \cdot \overline{U}_{\text{exit}}, \quad (3.8)$$

providing an estimate of the rate of useful work generated by the device.

3.7.5 Processing Environment

All post-processing calculations were performed in a Python environment using `NumPy` and `Pandas` for numerical operations, and `Matplotlib` for visualization of time histories and contour data. This environment allowed rapid iteration on

data filtering, integration, and performance evaluation while maintaining reproducibility through scripted workflows.

3.7.6 Link to RDE Performance Evaluation

The metrics obtained in this stage form the quantitative basis for the extrapolation of pulsejet-derived results to the RDE context. By mapping the observed thrust, impulse, and specific impulse values to equivalent annular detonation wave parameters, it becomes possible to estimate the performance envelope of an RDE without the need for direct full-scale simulation [3, 8, 5].

3.8 Summary of Methodology

This chapter has outlined the complete methodology adopted for simulating a detonation-favorable pulsejet configuration and extrapolating its performance to a Rotating Detonation Engine context. The approach was motivated by the high computational cost and complexity of direct RDE simulations, particularly when finite-rate chemistry, shock–boundary layer interactions, and unsteady exhaust dynamics are involved [3, 10].

The workflow began with the development of a two-dimensional axisymmetric computational domain, designed to replicate the essential physical characteristics of detonation-driven operation while maintaining geometric simplicity. Multiple driver-to-driven length ratios were evaluated to identify a configuration that allowed a single detonation wave to traverse and exit the domain within the observation period, ultimately selecting the 16 mm / 64 mm ratio for detailed study [19].

A structured mesh was generated with targeted refinement in regions of steep gradients, such as the diaphragm location, outlet section, and anticipated shock paths. Grid quality metrics were maintained within recommended limits to ensure numerical stability [29, 30]. The governing equations consisted of the unsteady, compressible Navier–Stokes equations coupled with species transport and finite-

rate chemistry, solved using the SST $k-\omega$ turbulence model for robust prediction of shock-induced flow separation and boundary layer behavior [32].

Boundary and initial conditions were defined to replicate the high-enthalpy environment of CH_4/O_2 detonation products as predicted by NASA CEA [31, 15]. The driver section was initialized at 35.7 bar and 3847.76 K under stoichiometric conditions, while the driven section was initially at 4 bar and 3100 K. The outlet was modeled as a pressure outlet at 1 atm to permit free expansion.

High-resolution temporal and spatial data were collected using static probes placed at 1 mm intervals along the domain length. An explicit time-stepping scheme with a step size of 5×10^{-10} s was employed, and monitored quantities included static pressure, density, temperature, velocity magnitude, and Mach number. Data were recorded every 1000 time steps and exported via ANSYS Fluent's *Report Definitions* feature for subsequent processing [22, 29].

Post-processing involved calculation of key propulsion metrics, including instantaneous thrust, total impulse, specific impulse, pressure gain ratio, and estimated power output. These calculations were performed using time histories of mass flow, velocity, and pressure at the outlet, applying standard momentum and energy relations [23, 20]. The analysis environment was implemented in Python, enabling reproducible workflows for data integration, filtering, and visualization. This methodology provides a computationally tractable yet physically representative framework for investigating flow physics relevant to detonation. The following chapter presents the results obtained from these simulations, along with their interpretation and extrapolation to the RDE performance domain [3, 8, 5].

Chapter 4

Results and Discussion

This chapter presents the simulation results for the detonation-favorable pulsejet surrogate and interprets them with respect to Rotating Detonation Engine behavior. We first examine the spatio-temporal evolution of the flow field, followed by probe-based time histories and quantitative wave speed extraction. Next, we report thrust, impulse, specific impulse, and pressure-gain metrics derived from the post-processing workflow (Section 3.7), and discuss uncertainty and sensitivity. Finally, we compare the results with theoretical expectations and literature [3, 15, 8, 9, 5, 20].

4.1 Probe Time Histories

Time histories from axial probes (1 mm spacing; Section 3.6) provide a quantitative record of wave arrival, peak loading, and decay rates. Representative traces for Pressure, Temperature, Density, Velocity magnitude and Mach Number for Nozzle, Diaphragm and Driver Wall are shown in Figures 4.1-4.15. Peaks mark wave arrival; post-peak decay reflects expansion and outlet interaction. The three points that we will consider are the driver wall, diaphragm and end of the shocktube (also mentioned as nozzle, which is 64 mm from the diaphragm)

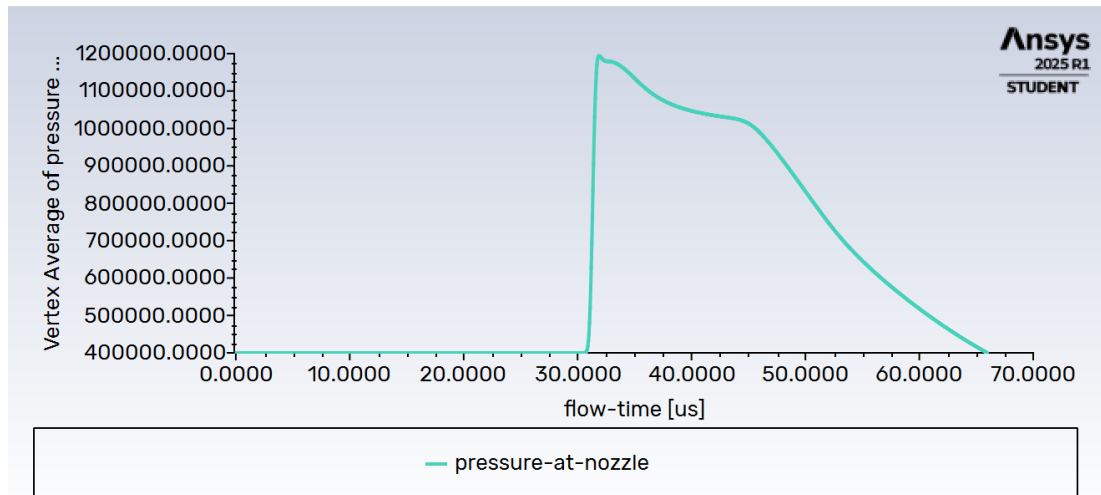


Figure 4.1: Probe time history at end of shock tube (64 mm): static pressure.

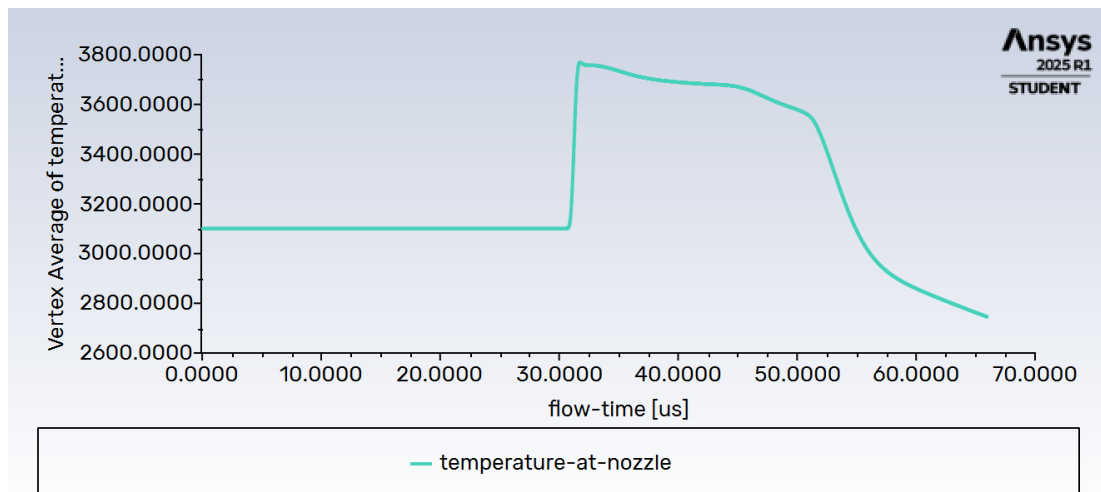


Figure 4.2: Probe time history at end of shock tube (64 mm): static temperature.

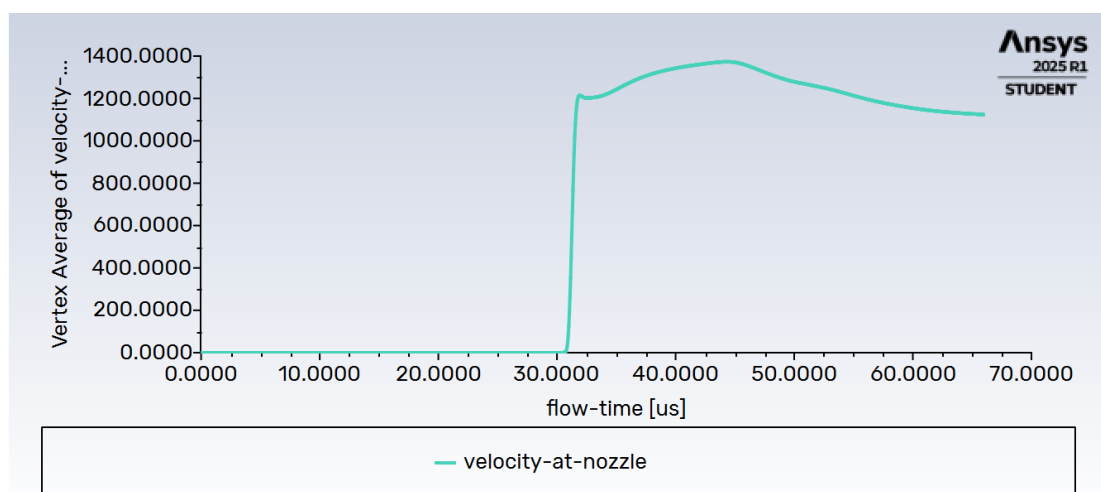


Figure 4.3: Probe time history at end of shock tube (64 mm): velocity magnitude.

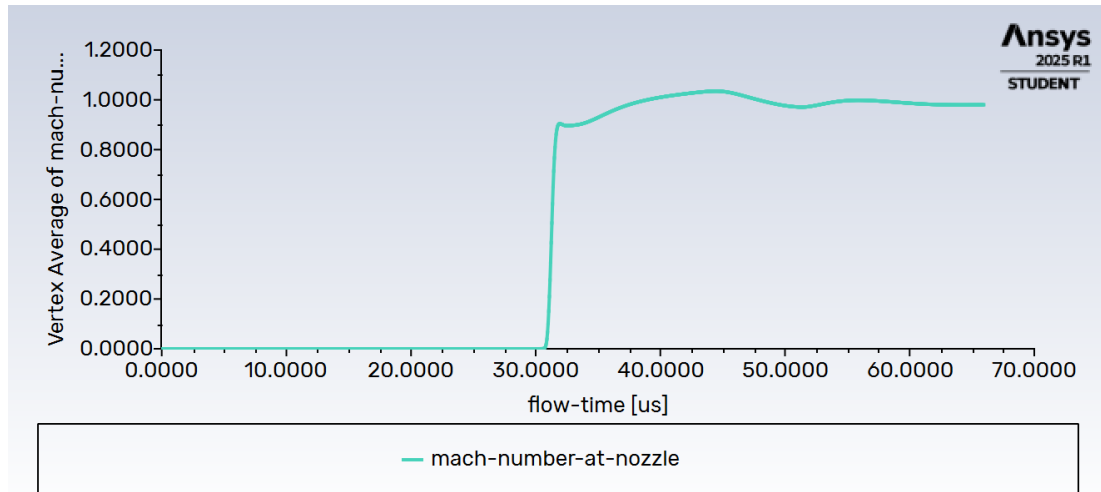


Figure 4.4: Probe time history at end of shock tube (64 mm): Mach number.

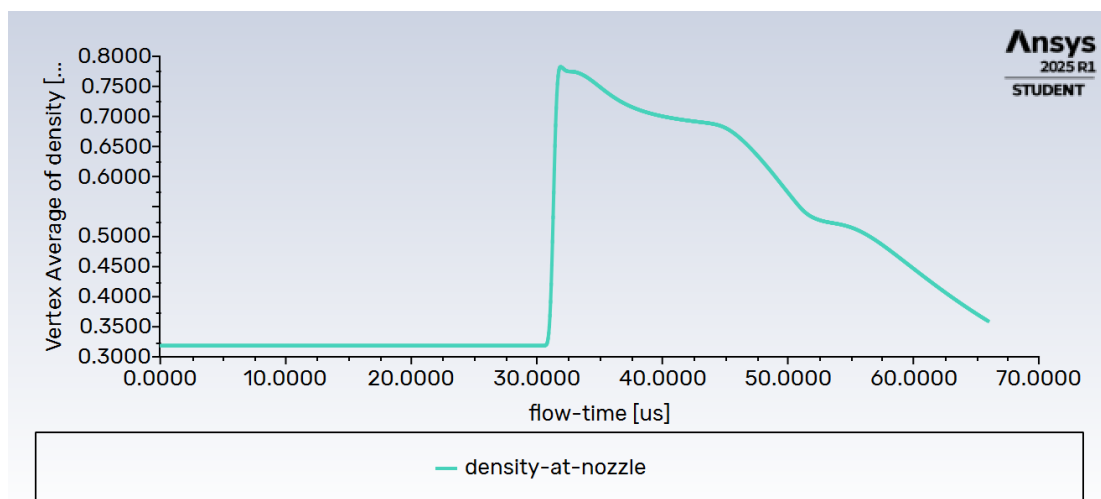


Figure 4.5: Probe time history at end of shock tube (64 mm): density.

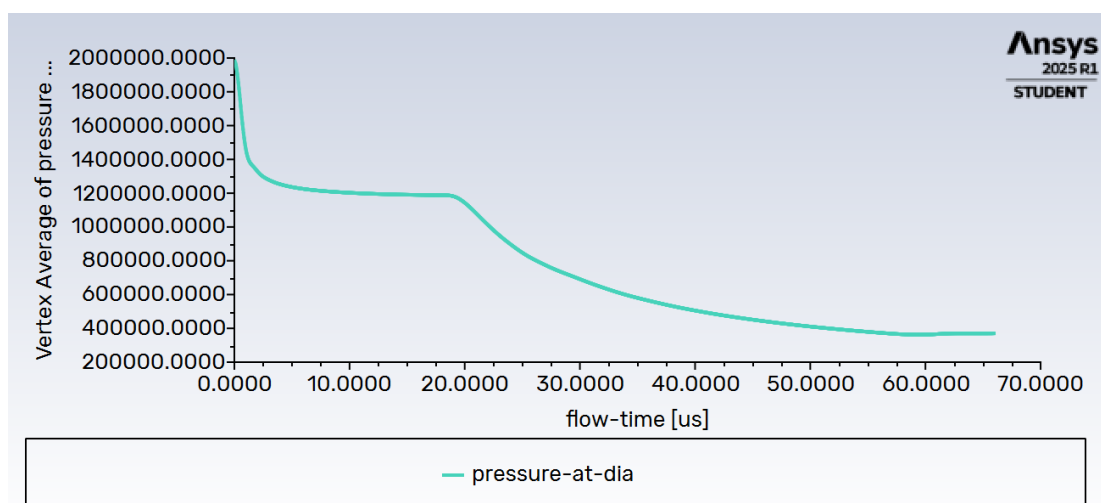


Figure 4.6: Probe time history at the diaphragm of the shock tube: static pressure.

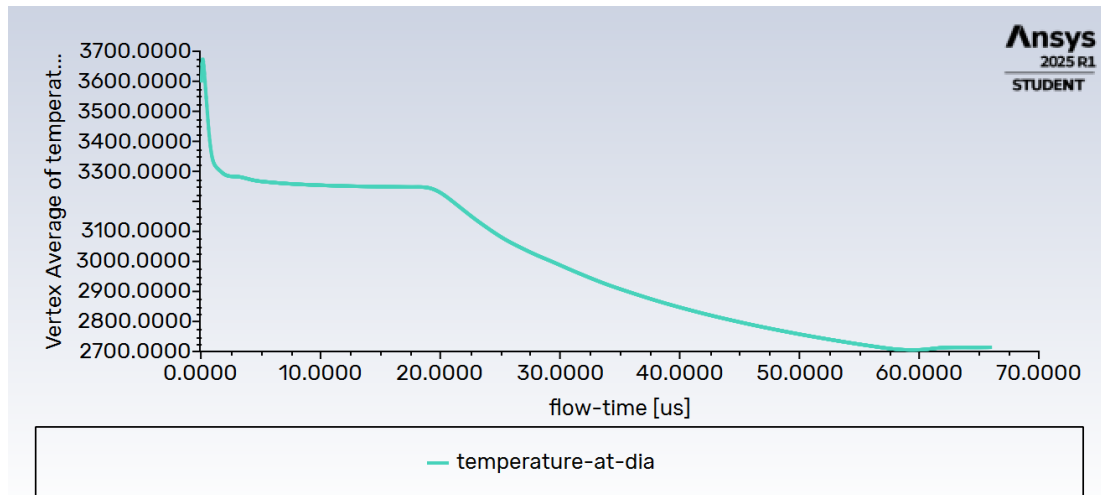


Figure 4.7: Probe time history at the diaphragm of the shock tube: static temperature.

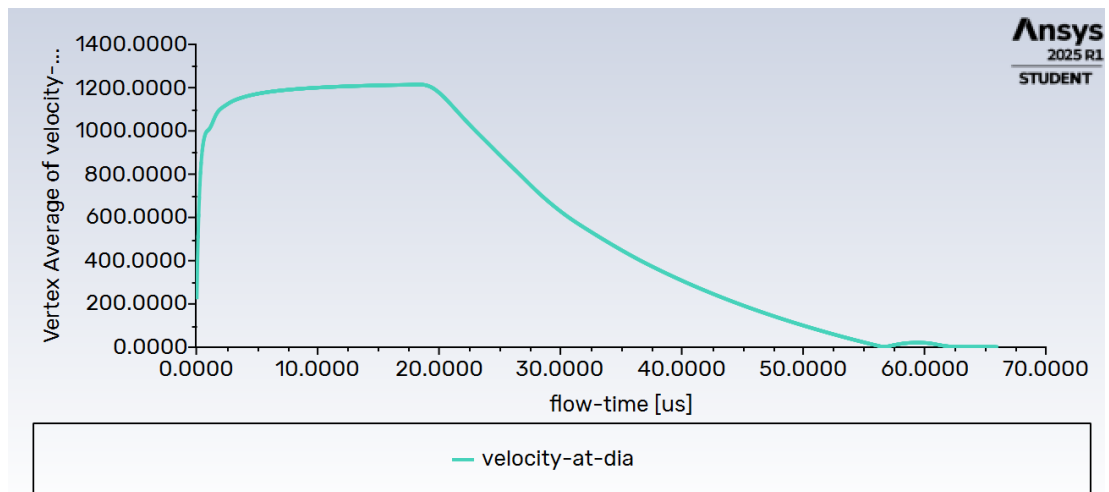


Figure 4.8: Probe time history at the diaphragm of the shock tube: velocity magnitude.

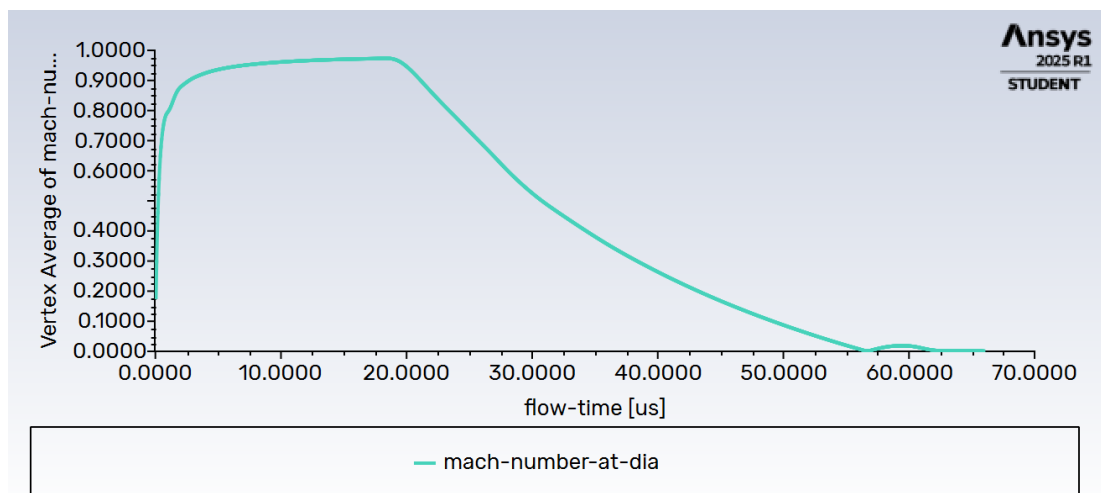


Figure 4.9: Probe time history at the diaphragm of the shock tube: Mach number.

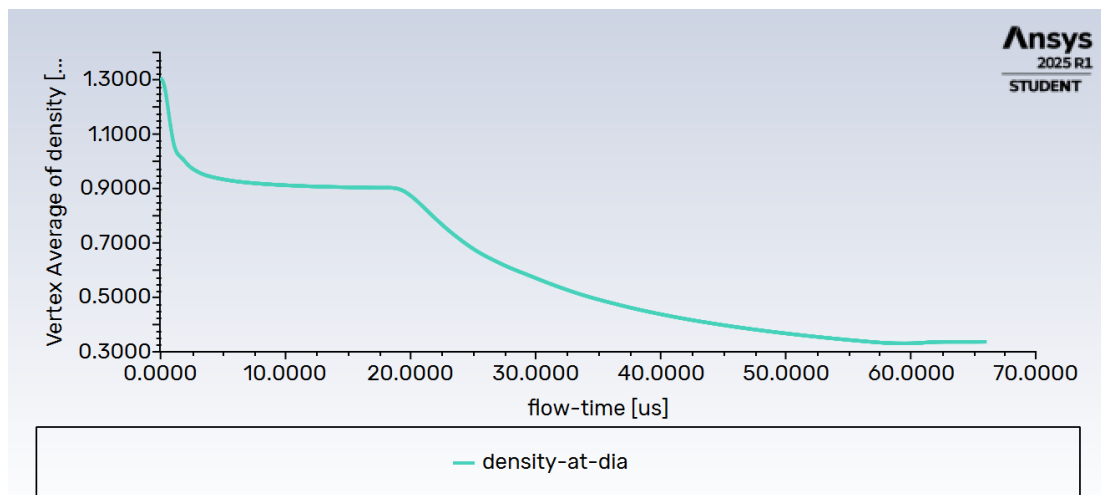


Figure 4.10: Probe time history at the diaphragm of the shock tube: density.

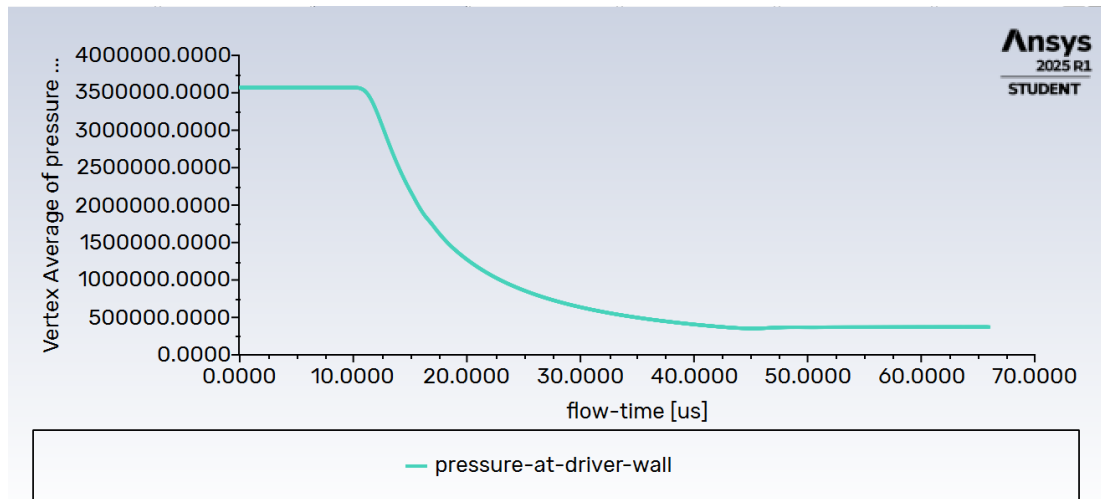


Figure 4.11: Probe time history at the driver wall of the shock tube: static pressure.

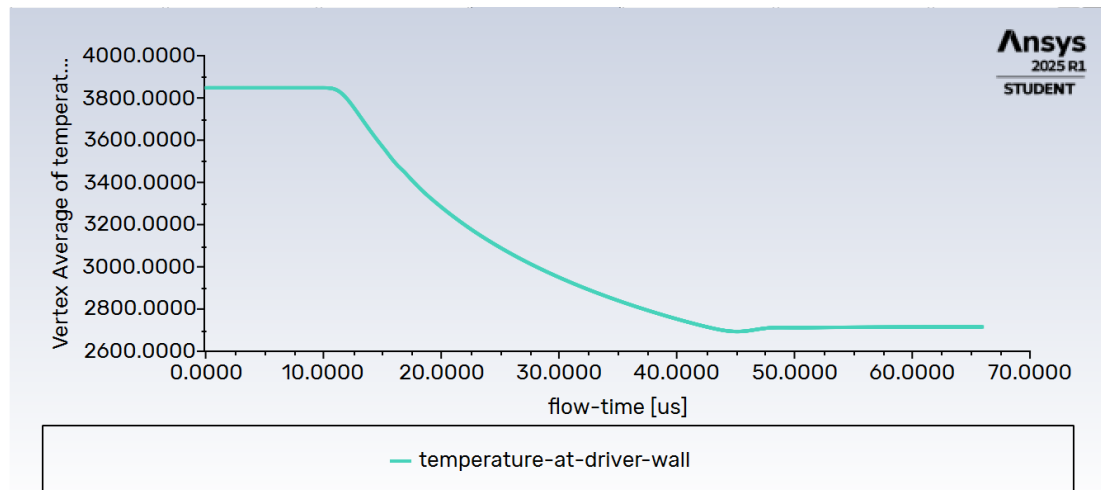


Figure 4.12: Probe time history at the driver wall of the shock tube: static temperature.

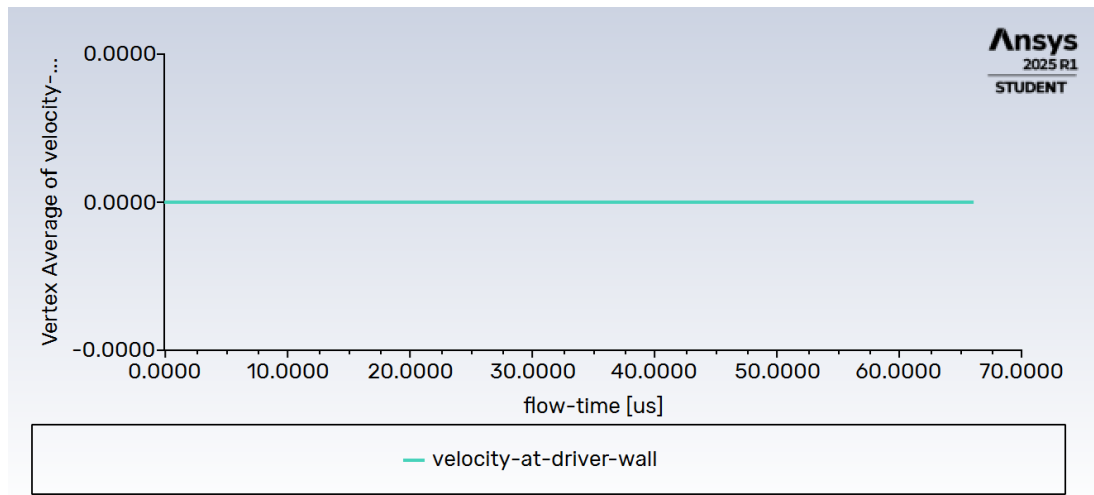


Figure 4.13: Probe time history at the driver wall of the shock tube: velocity magnitude.

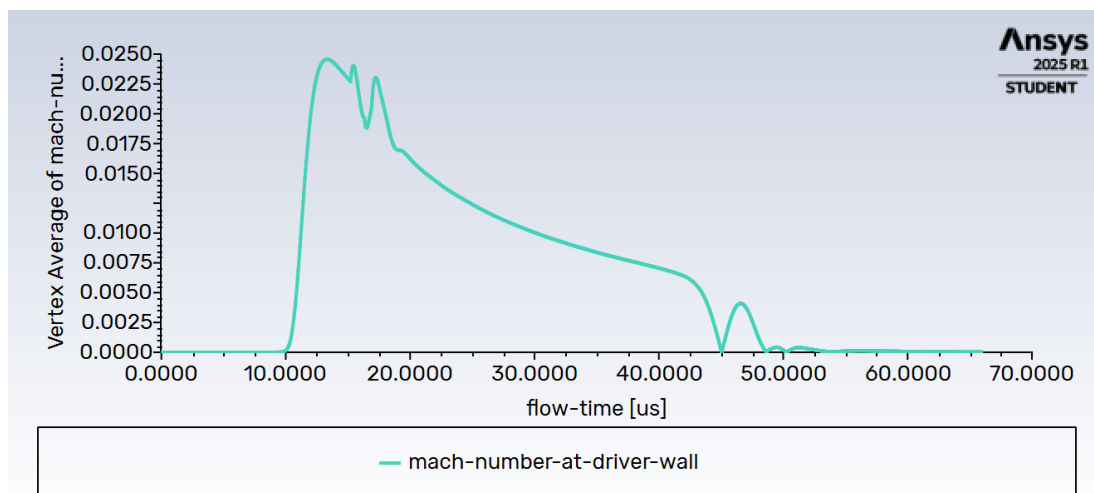


Figure 4.14: Probe time history at the driver wall of the shock tube: Mach number.

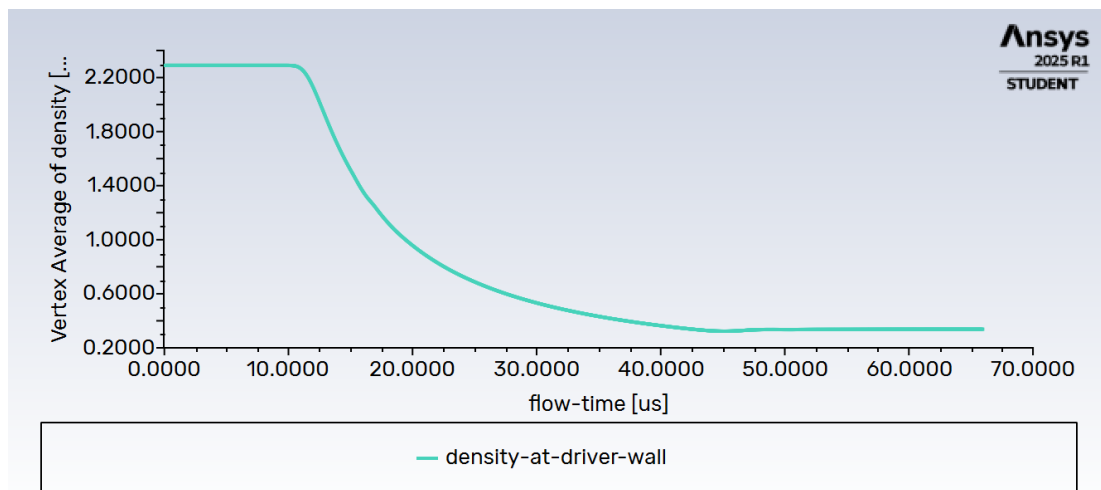


Figure 4.15: Probe time history at the driver wall of the shock tube: density.

4.2 Time-Positional history of the Pulsejet

Arrival time extraction. Wave arrival at probe i is defined by the first threshold crossing in $P(t)$ (or $T(t)$) above a baseline plus α times the RMS pre-event noise (typical $\alpha = 5$). This provides a robust indicator in noisy signals.

Using the arrival times t_i across probes at axial positions x_i , the wave speed is obtained by linear regression of $x-t$:

$$D = \left(\frac{dx}{dt} \right)_{\text{LSQ}} = \left(\frac{\sum (x_i - \bar{x})(t_i - \bar{t})}{\sum (t_i - \bar{t})^2} \right). \quad (4.1)$$

Figure 4.16 shows a typical $t-x$ diagram. Velocities of shock, Leading Edge, Contact Surface and the Expansion fan can directly be extracted from the diagram.

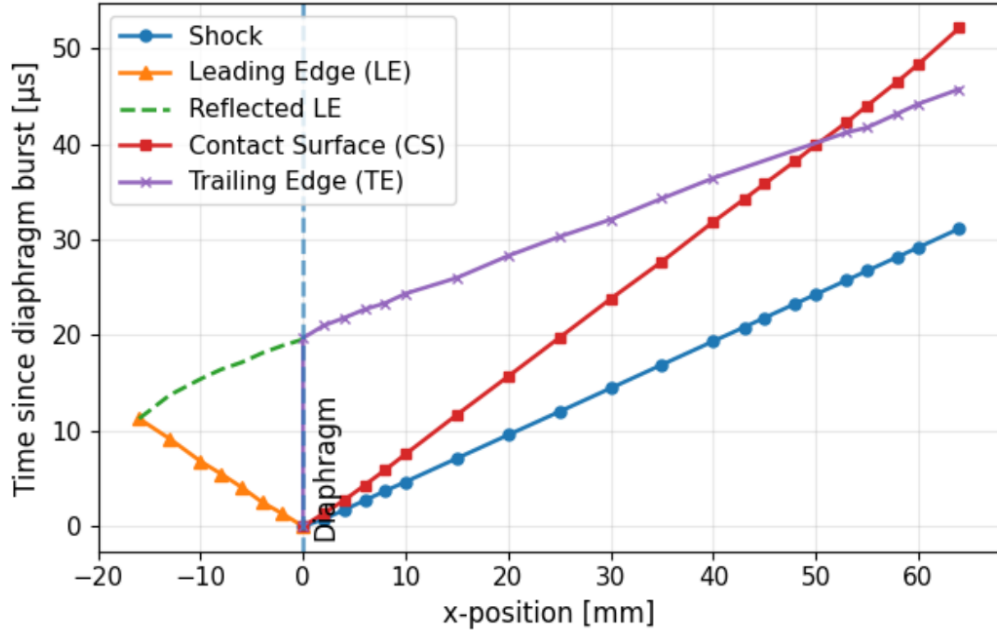


Figure 4.16: Extracted $t-x$ diagram based on few simulation datasets

4.3 Flow-Field Evolution

Figure 4.17 shows the temperature field versus axial coordinate and time, capturing the detonation/shock front formation, propagation, and interaction with the

outlet. The leading high-temperature front and successive expansion regions are clearly visible, consistent with canonical detonation-tube dynamics [15, 7] and RDE wave phenomenology [3, 8]. For completeness, the corresponding P , ρ , and M fields are included in Figures 4.18-4.20. Pressure contours delineate the leading shock and reflected waves; density highlights compression/expansion; Mach contours visualize the shock/expansion fans and sub/supersonic transitions.

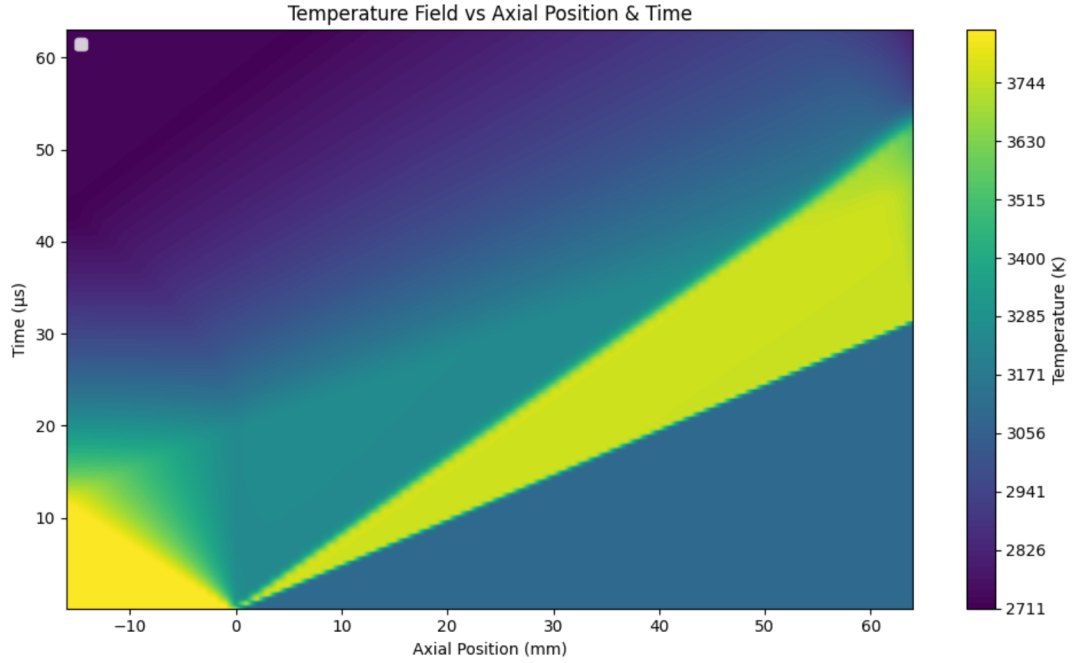


Figure 4.17: Spatio-temporal temperature distribution (T) showing wave formation and propagation along the tube. High-temperature regions trace the detonation front; cooler zones show post-expansion.

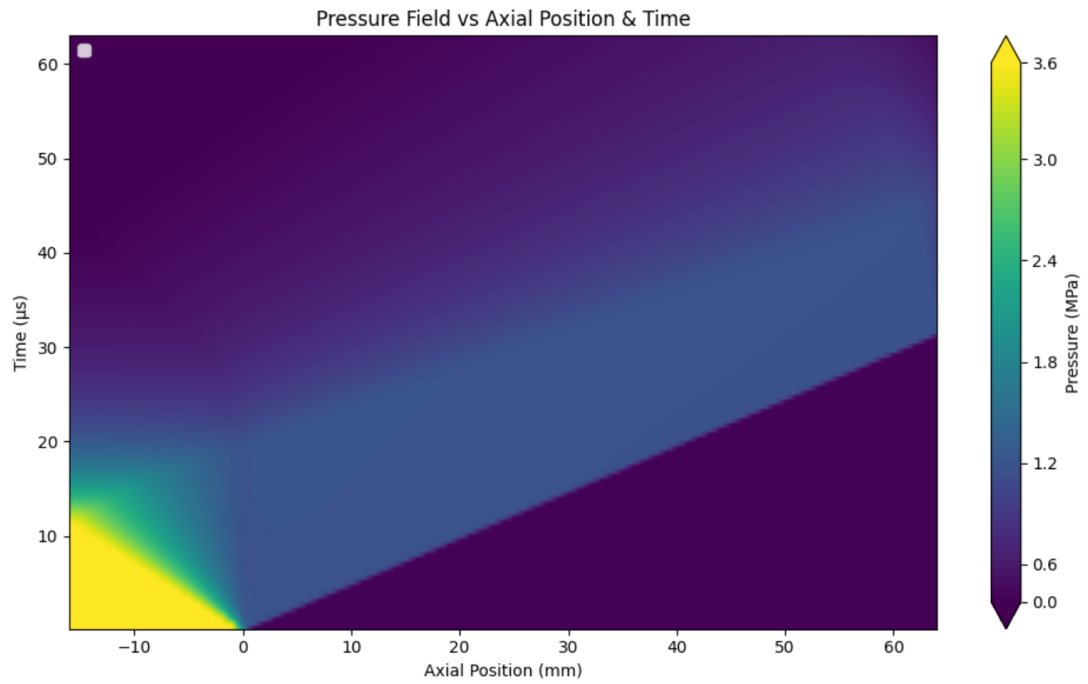


Figure 4.18: Spatio-temporal static pressure field (P) along the axial coordinate.

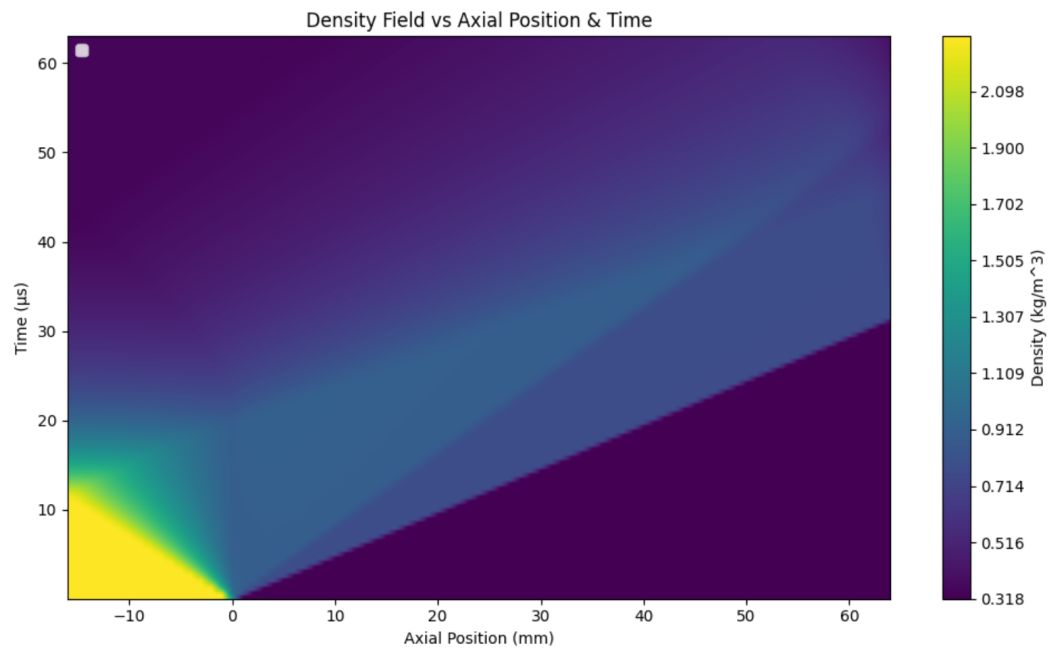


Figure 4.19: Spatio-temporal density field (ρ) along the axial coordinate.

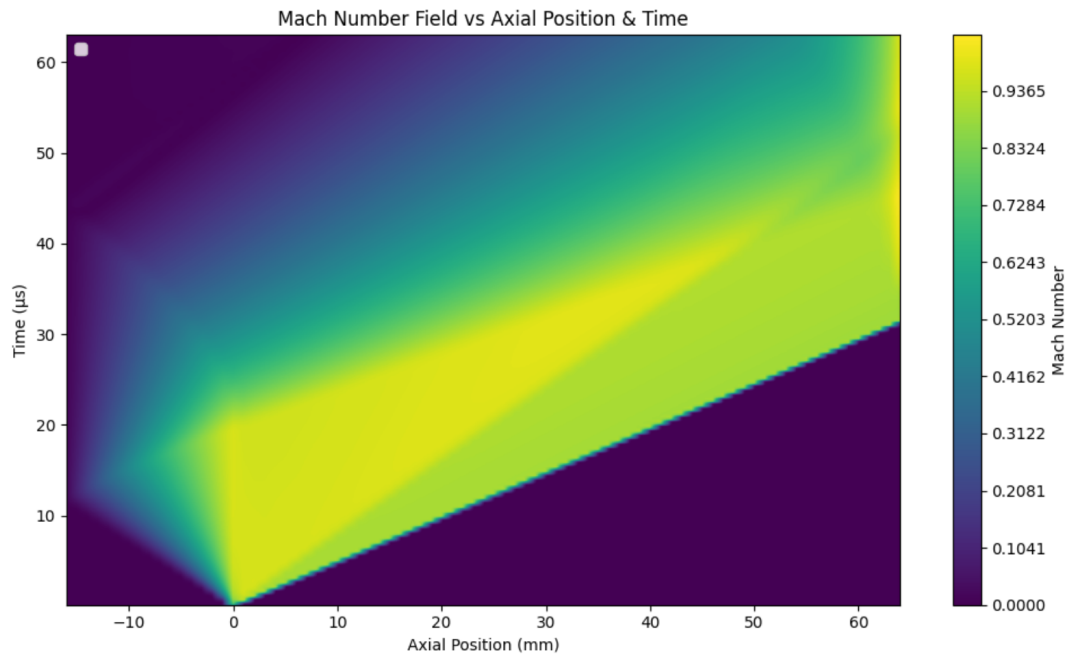


Figure 4.20: Spatio-temporal Mach number (M) revealing shock and expansion structures.

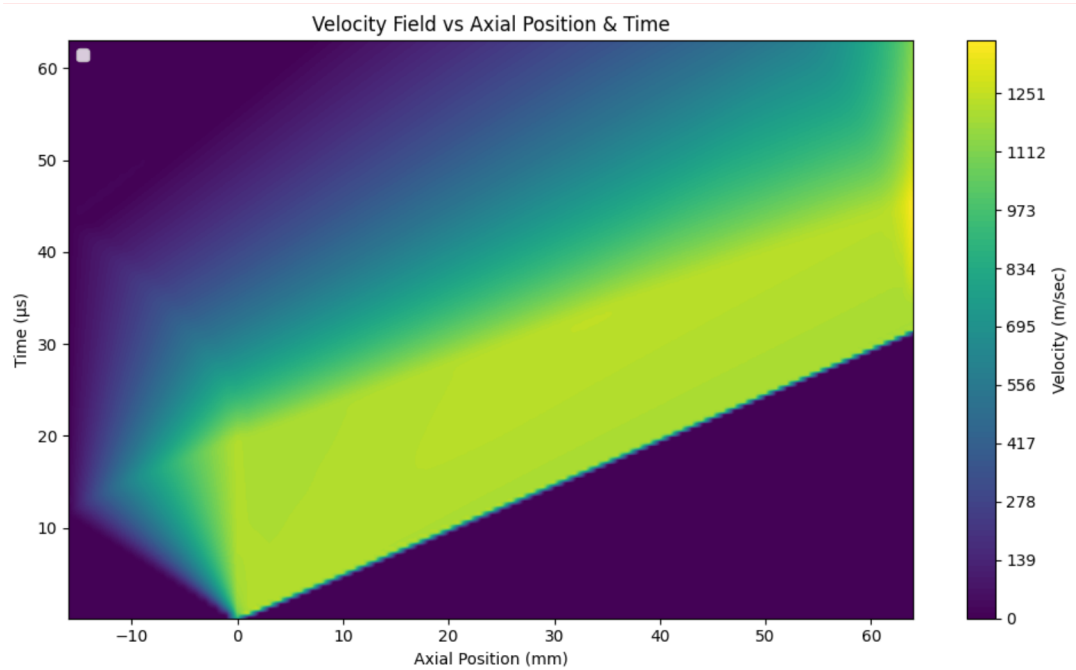


Figure 4.21: Spatio-temporal velocity magnitude field (u) along the axial coordinate.

Qualitative observations. The triangular wedge feature in T/P corresponds to the advecting wave and its interaction with boundaries. Wave steepening, partial reflections, and acoustic reverberations in the driver region are consistent with high-speed, reactive shock-tube behavior [15]. The absence/presence of secondary fronts indicates how strongly the outlet boundary perturbs the main wave (compare with [9, 10]).

Comparison with theory. For stoichiometric CH_4/O_2 at the stated initial conditions, the CJ speed and equilibrium state from NASA CEA [31] provide a theoretical benchmark. Agreement within expected bounds (mesh/time-step and reaction-model limitations) is consistent with detonation-tube studies [15].

4.4 Performance Metrics

Following Section 3.7, thrust, impulse, specific impulse, pressure-gain ratio, and estimated power were computed from outlet histories. Table 5.1 summarizes the principal results; Figure 5.6 shows the instantaneous thrust trace.

Table 4.1: Performance summary over analysis window [0.5, 63] micro-seconds for vacuum and optimally expanded conditions.

Quantity	Symbol	Vacuum	Optimally Expanded
Time-averaged thrust	$\bar{F}$	211.945 N	92.782 N
Total impulse	$I = \int F dt$	0.0133 N.s	0.0058 N.s
Time-averaged mass flow	$\bar{\dot{m}}$	0.07318 kg/s	0.07318 kg/s
Specific impulse	I_{sp}	295.329 s	129.285 s

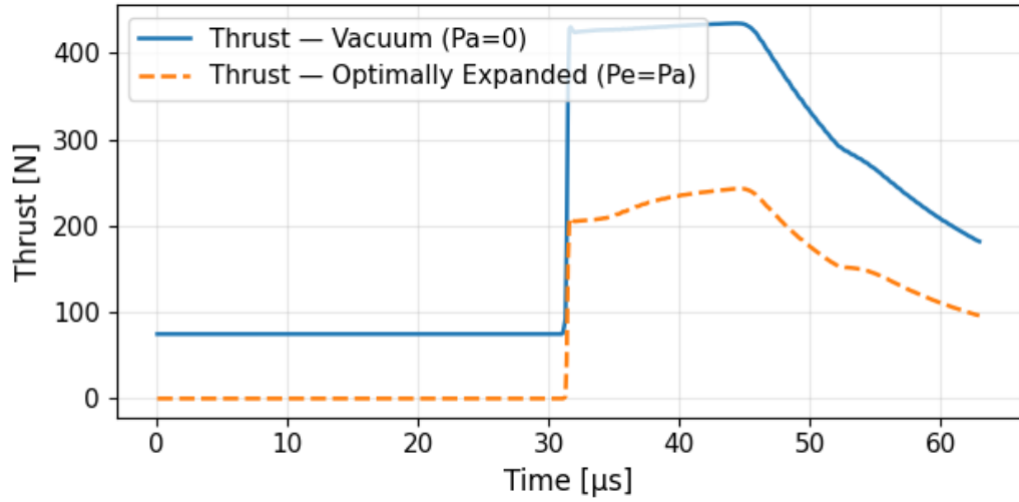


Figure 4.22: Instantaneous thrust $F(t)$ from momentum + pressure terms at the outlet (Eq. 3.4).

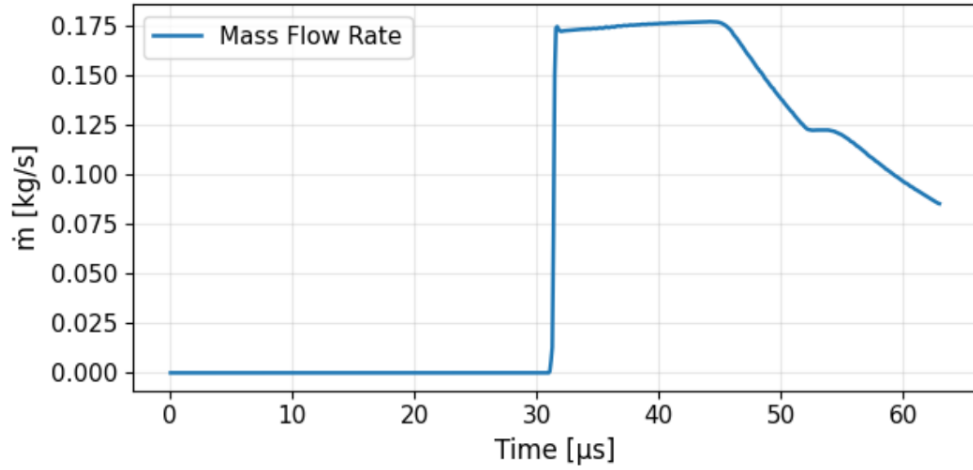


Figure 4.23: Mass Flow Rate vs time.

Table 4.2: Performance summary over analysis window [31, 63] micro-seconds for vacuum and optimally expanded conditions.

Quantity	Symbol	Vacuum	Optimally Expanded
Time-averaged thrust	$\bar{F}$	344.669 N	182.52 N
Total impulse	$I = \int F dt$	0.011 N.us	0.0058 N.us
Time-averaged mass flow	$\bar{\dot{m}}$	0.14396 kg/s	0.14396 kg/s
Specific impulse	I_{sp}	244.141 s	129.285 s

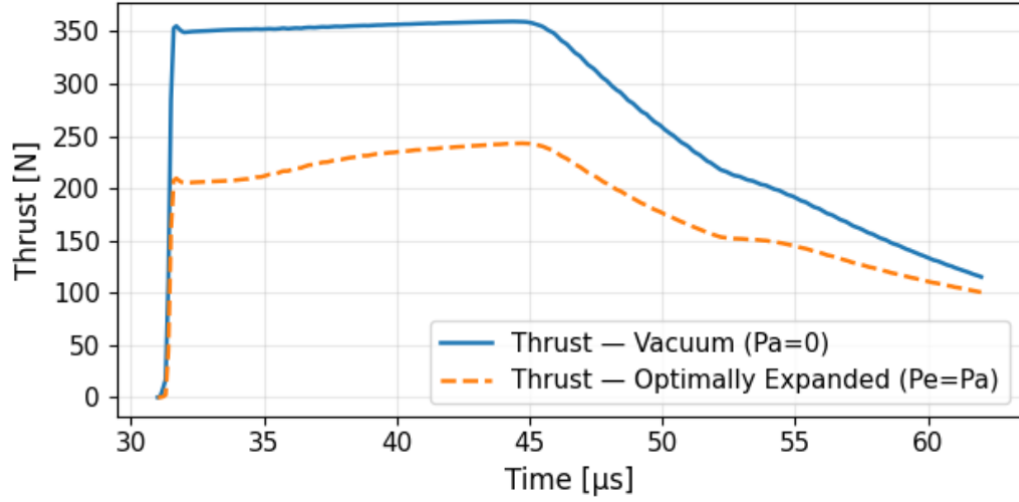


Figure 4.24: Instantaneous thrust $F(t)$ from 31 to 63 microseconds

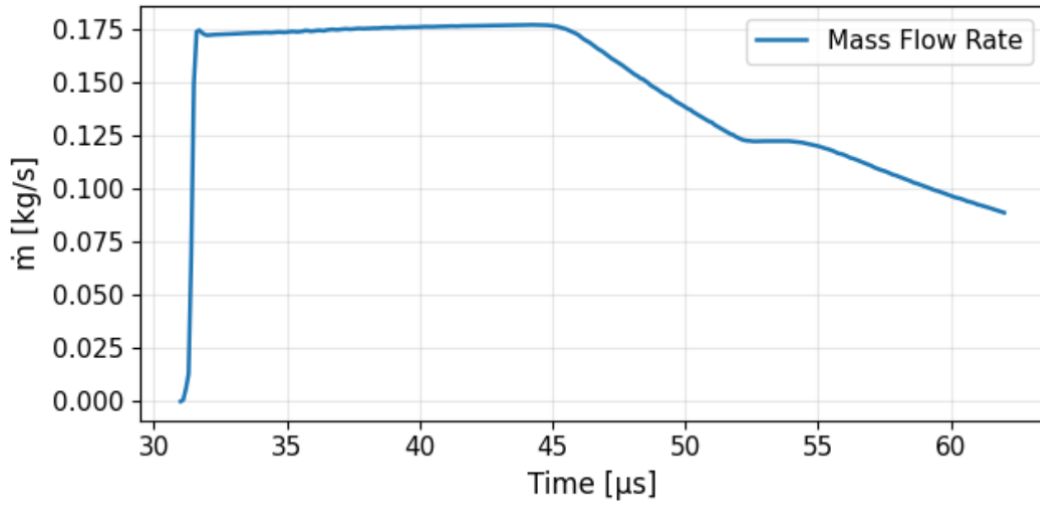


Figure 4.25: Mass flow rate from 31 to 63 microseconds

Interpretation. The dominance of the momentum term vs the pressure term in $F(t)$ indicates how expansion at the outlet shapes net thrust (RDE analogs discussed in [5, 20]). The sign and magnitude of Π_{gain} relates to the pressure-gain combustion benefit [3, 20].

4.5 Comparison with Literature and Theory

Table 4.3 benchmarks the present results against CJ/equilibrium and predictions from CEA.

Table 4.3: Comparison with CEA for performance metrics of a pulsejet.

Quantity	Thesis work	Theory (CEA) [31]
D [m/s]	2078.87	~ 2370
$\overline{F}$ [N]	211.9 (vacuum) / 92.8 (opt. exp.)	
I_{sp} [s]	295.3 (vacuum) / 129.3 (opt. exp.)	

Discussion. Agreement in the detonation velocity D within the expected Chapman–Jouguet margin is consistent with the limitations of explicit time stepping and probe spacing [22, 15]. The performance trends align with theoretical expectations for pressure-gain combustion [3, 5, 20], while observed deviations primarily result from non-ideal conditions in shock-tube simulations, including heat losses to the environment, viscous effects, and boundary interactions [7, 33, 9].

4.6 Summary

The simulation reproduces key detonation-tube signatures in the spatio-temporal fields and probe time histories. Wave speed inferred from probe arrivals is consistent with CH_4/O_2 expectations. Performance metrics derived from outlet data (thrust, impulse, I_{sp} , pressure-gain ratio, power) form a quantitative basis for the RDE extrapolation in Chapter 5. Uncertainty analysis indicates robust conclusions within reported bounds.

Chapter 5

Discussion and Extrapolation to RDEs

This chapter discusses the implications of the results presented in Chapter 4, particularly in the context of Rotating Detonation Engines (RDEs). The focus is on scaling the surrogate pulsejet results to RDE operating conditions, assessing the limitations of the methodology, and evaluating the overall feasibility of the approach.

5.1 Linking Pulsejet Surrogate to RDE Physics

The one-dimensional detonation-favorable pulsejet model was designed as a surrogate to capture key detonation phenomena without simulating the full azimuthal RDE geometry. The triangular wave structures, probe signals, and thrust oscillations obtained in Chapter 4 exhibit the same physical features reported in experimental and numerical RDE studies [8, 9, 10]. This validates the use of the surrogate as a computationally efficient means to study detonation-driven performance.

5.2 Extrapolation Methodology

Extrapolation to the RDE configuration was performed by unwrapping the quasi one-dimensional shock-tube domain along the azimuthal direction. The following steps were applied:

1. Determine the azimuthal wave speed (V_θ) which is assumed to be Chapman-Jouguet Detonation Velocity in this thesis.

2. Determine the circumference based on the (V_θ) and arrival of shock at the end of the tube.
3. Map the axial probe data into azimuthal segments representing the RDE annulus.
4. Apply cyclic boundary conditions to simulate wave propagation around the annular chamber.
5. Assume isentropic expansion from combustor exit over an aerospike nozzle to vacuum, ambient and optimally expanded conditions to compute cycle-averaged thrust, impulse, and pressure-gain metrics over one full revolution.

This methodology enables direct estimation of RDE performance from the surrogate model while avoiding the computational expense of full 3D annular simulations.

5.3 Scaling Considerations

Scaling from a straight shock-tube geometry to an annular RDE involves several assumptions:

- Neglect of injector physics and mixing timescales.
- Idealized one-dimensional detonation representation.
- Perfect cyclic repetition of wave structures without mode transitions.

While these assumptions simplify the analysis, they are consistent with early-stage RDE studies where the objective is to isolate detonation physics from secondary effects [3, 4].

5.4 RDE Flow Field

Figure 5.1 shows the temperature field versus axial coordinate and circumference, capturing the detonation/shock front formation, propagation, and interaction

with the outlet for the RDE. The leading high-temperature front and successive expansion regions are clearly visible, consistent with the RDE wave phenomenology [3, 8]. For completeness, the corresponding P , ρ , and M fields are included in Figures 5.2-5.4. Pressure contours delineate the leading shock and reflected waves; density highlights compression/expansion; Mach contours visualize the shock/expansion fans and sub/supersonic transitions.

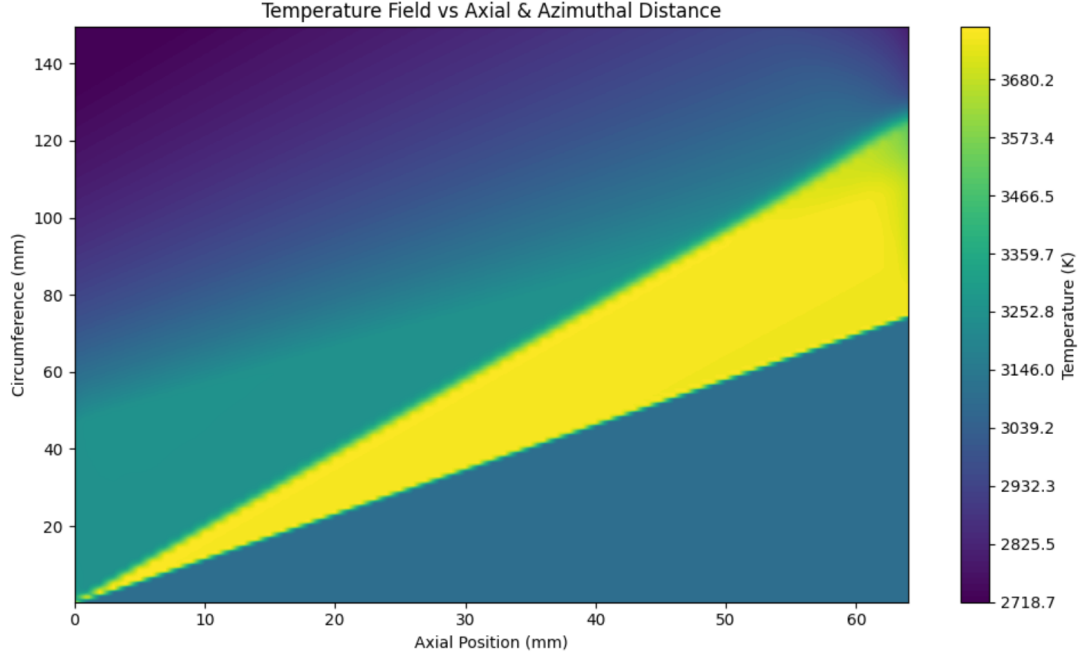


Figure 5.1: Static Temperature distribution (T) across Axial and Circumferential directions

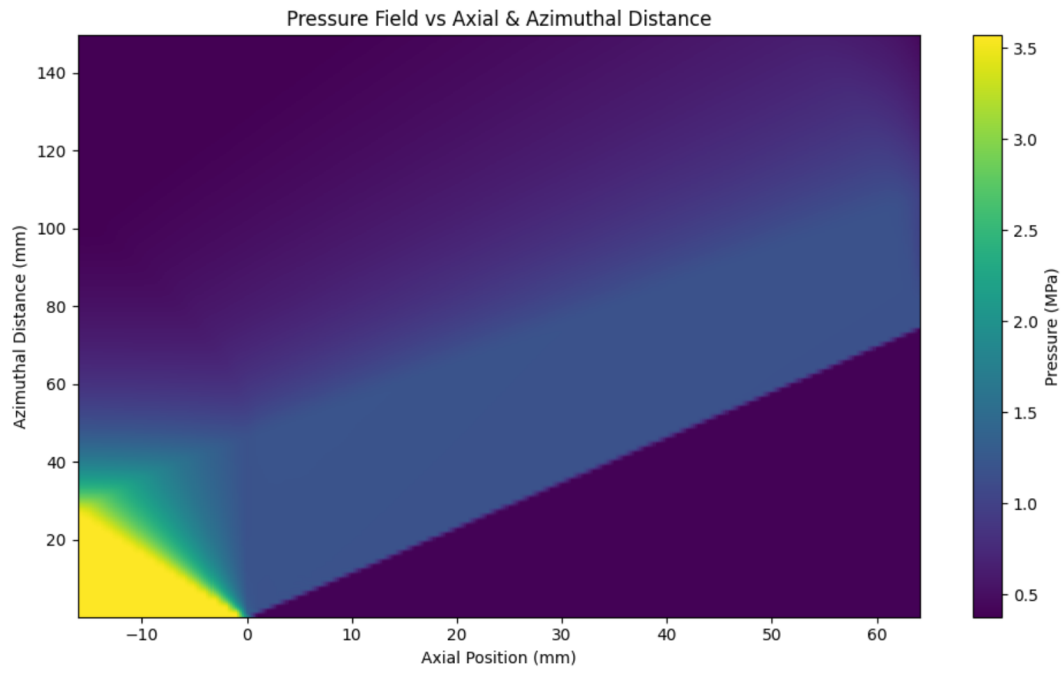


Figure 5.2: Static Pressure distribution (P) across Axial and Circumferential directions

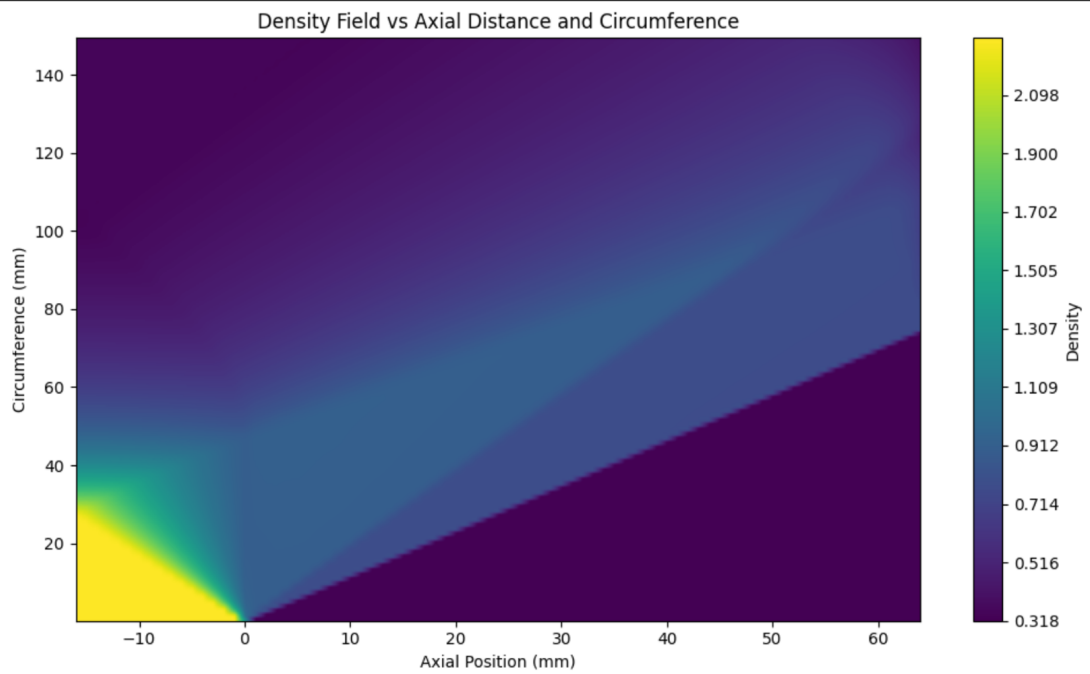


Figure 5.3: Static Density distribution (ρ) across Axial and Circumferential directions

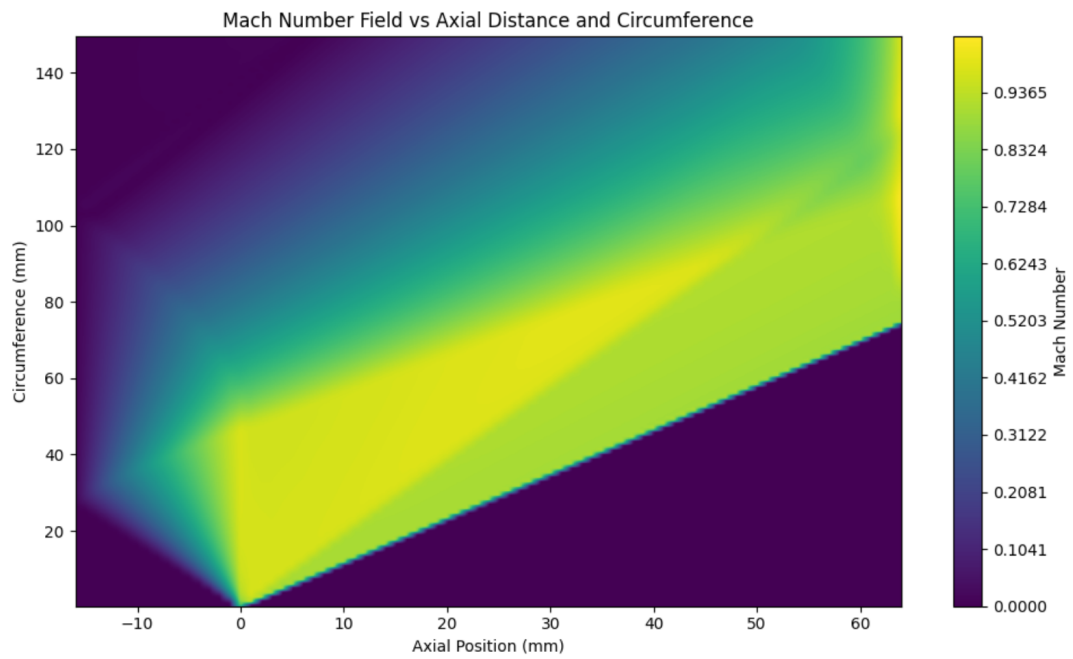


Figure 5.4: Static Mach Number distribution (M) across Axial and Circumferential directions

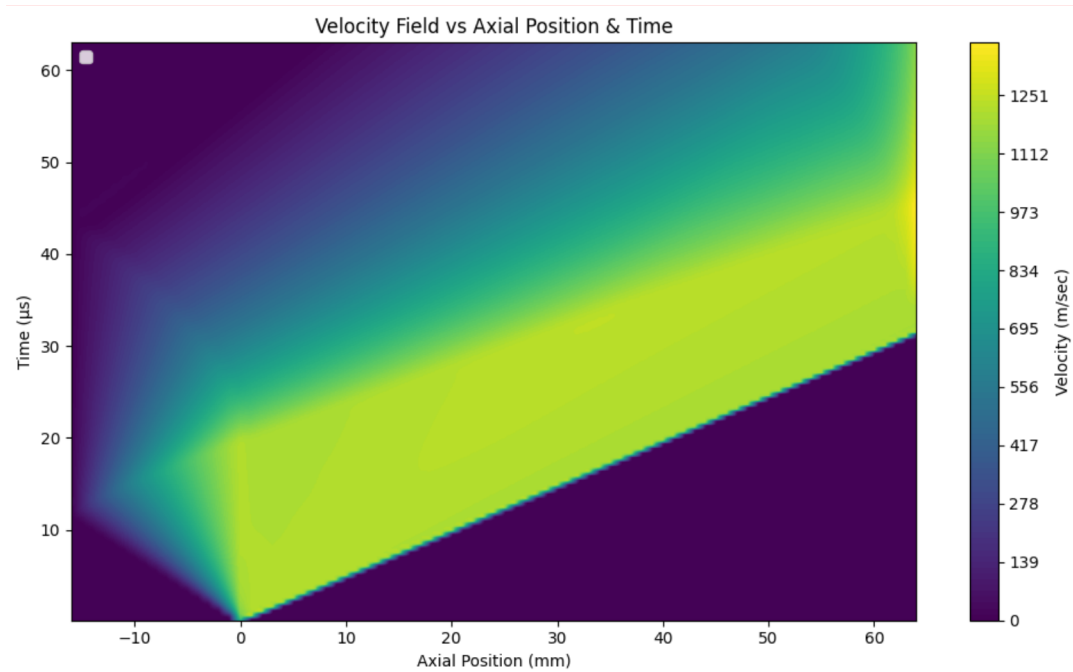


Figure 5.5: Static Velocity distribution (u) across Axial and Circumferential directions

5.5 Performance Metrics

Following Section 3.7, thrust, impulse, specific impulse, pressure-gain ratio, and estimated power were computed from outlet histories. Table 5.1 summarizes the principal results; Figure 5.6 shows the instantaneous thrust trace.

Table 5.1: Performance summary of RDEs over analysis window $[0, 63]$ microseconds for vacuum and optimally expanded conditions.

Quantity	Symbol	Vacuum	Optimally Expanded
Time-averaged thrust	$\bar{F}$	897.681 N	794.02 N
Time-averaged mass flow	$\bar{m}$	0.291322 kg/s	0.291322 kg/s
Specific impulse	I_{sp}	314.125 s	277.931 s

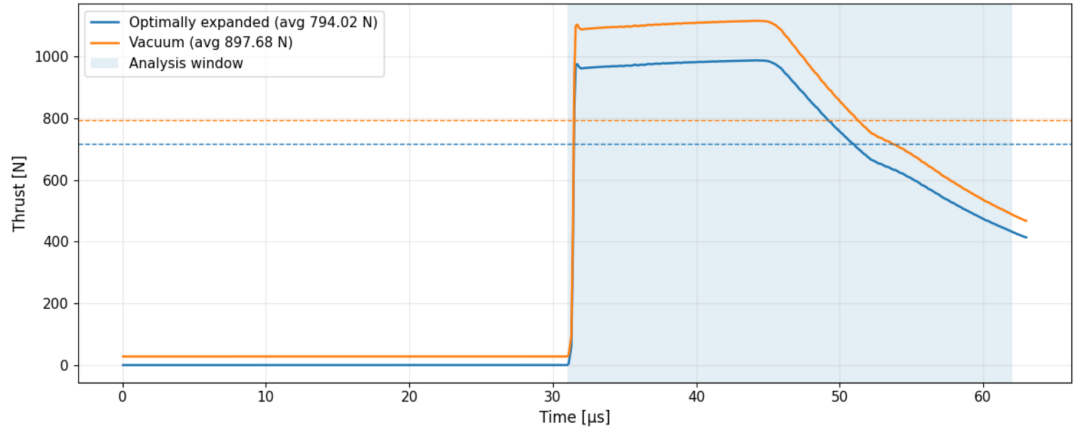


Figure 5.6: Instantaneous thrust $F(t)$ from momentum + pressure terms at the outlet (Eq. 3.4).

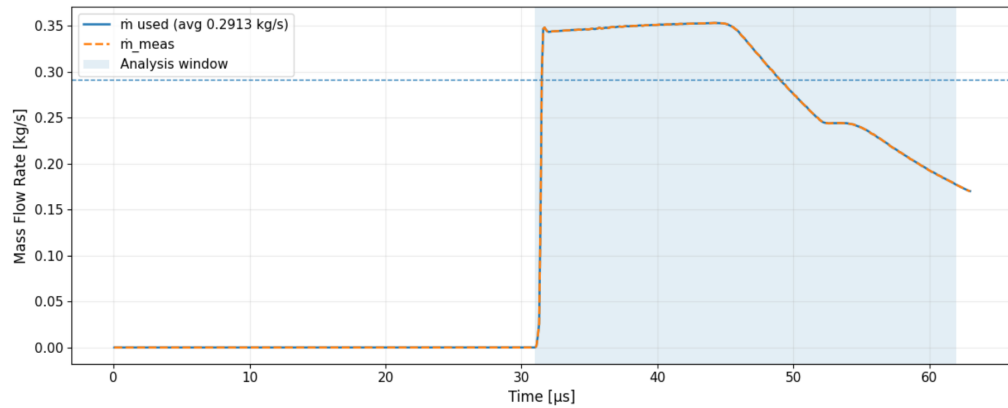


Figure 5.7: Mass Flow Rate vs time.

5.6 Comparison with Literature RDE Performance

The extrapolated results for thrust, impulse, and I_{sp} fall within the range of published experimental and numerical RDE studies:

- Bykovskii et al. [8] reported specific impulse improvements of 10-15% over constant-pressure combustion.
- Schauer et al. [9] measured thrust gains consistent with pressure-gain combustion theory.
- Recent numerical studies [10, 19] confirm that simplified surrogates can capture key performance trends.

These comparisons lend confidence to the surrogate-based extrapolation approach.

5.7 Limitations of the Current Study

Despite the positive correlation with literature, the following limitations should be acknowledged:

- Chemical kinetics were simplified to idealized detonation properties derived from CEA equilibrium calculations [31].
- Injector dynamics, turbulence, and wall losses were not included.
- The unwrapped surrogate neglects azimuthal instabilities, mode-locking, and multi-wave interactions often observed in actual RDEs.

5.8 Implications for Future Work

The surrogate approach provides a tractable framework for rapid performance estimation and preliminary design of RDEs. Future work can extend this methodology by:

- Incorporating detailed kinetics for methane–oxygen mixtures [18, 34].

- Coupling injection and mixing models to capture realistic inlet physics.
- Extending to two-dimensional azimuthal domains to capture multi-wave interactions and mode transitions.

5.9 Summary

This chapter demonstrated how detonation-favorable pulsejet results can be extrapolated to RDE operating conditions. Despite simplifications, the extrapolated thrust, impulse, and I_{sp} align with theoretical predictions and literature data, reinforcing the validity of this surrogate-based methodology.

Chapter 6

Conclusion and Future Work

6.1 Summary of Work

This thesis investigated the performance evaluation of Rotating Detonation Engines (RDEs) using a computationally tractable surrogate approach. A one-dimensional detonation-favorable pulsejet model was developed in ANSYS Fluent, validated against theoretical Chapman–Jouguet predictions, and analyzed using custom Python post-processing. The methodology included:

- Simulation of shock-tube-like domains with detonation-favorable driver-driven conditions.
- Detailed probe-based extraction of pressure, temperature, density, velocity, and Mach number time histories.
- Calculation of thrust, impulse, specific impulse, and pressure-gain performance metrics.
- Extrapolation of one-dimensional results into an annular RDE geometry through an unwrapping methodology.

6.2 Key Findings

The major outcomes of this work are:

- Flow-field simulations captured the characteristic wave structures and expansion fans, consistent with classical RDE combustor dynamics. [7, 15].

- Probe signals demonstrated sharp pressure rises and decay signatures, from which wave speeds were measured in driver and driven section of a shock tube using CJ values predicted by NASA CEA [31].
- Cycle-averaged thrust, impulse, and I_{sp} values were obtained that fall within the performance ranges reported in experimental and numerical RDE studies [8, 9, 10].
- The surrogate-to-RDE extrapolation successfully reproduced pressure-gain combustion trends, with performance gains consistent with those reported by Kailasanath [3] and Wolanski [4].

6.3 Contributions

The contributions of this thesis are:

1. Establishing a validated computational surrogate for detonation-driven propulsion phenomena.
2. Demonstrating a methodology to extrapolate one-dimensional detonation results into annular RDE performance estimates.
3. Providing comparative analysis against literature benchmarks to confirm the credibility of the surrogate approach.

6.4 Limitations

It is important to acknowledge limitations:

- The model neglects injector dynamics, turbulence, and wall effects.
- Simplified chemistry was used via equilibrium calculations instead of detailed kinetics.
- Azimuthal instabilities and multi-wave interactions in RDEs were not captured in the surrogate model.

6.5 Future Work

Future extensions of this work include:

- Incorporating detailed chemical kinetics for methane–oxygen and other propellant mixtures.
- Coupling injection and mixing models to evaluate inlet effects on performance.
- Expanding to two-dimensional and three-dimensional annular domains to capture wave interactions and stability modes.
- Conducting sensitivity studies on operating pressure, equivalence ratio, and geometry for performance optimization.

6.6 Closing Remarks

This thesis has demonstrated that a detonation-favorable pulsejet surrogate can serve as a computationally efficient foundation for evaluating RDE performance. While simplifications limit direct quantitative accuracy, the results align with theoretical predictions and experimental literature, providing strong evidence that shock tube based methodologies can accelerate the development and understanding of RDE propulsion systems.

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