MEAM 6900 Final Project

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Introduction

Project Motivation: rocket engines involve supersonic compressible flow of multiple fluids that react with one other, which can be difficult to model analytically. By using CFD, we can accurately model complex combustion and flow and predict rocket behavior

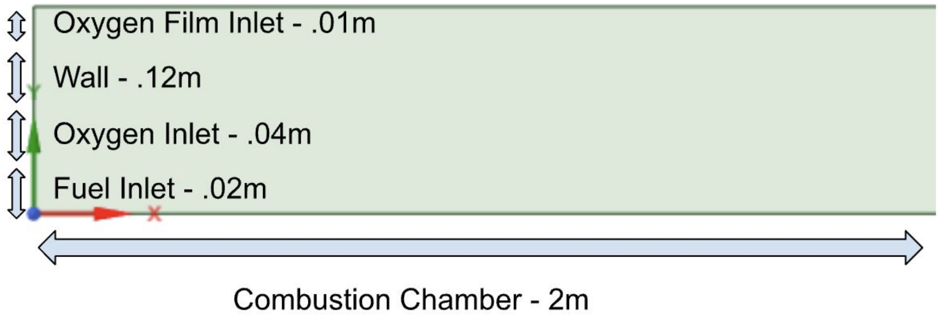
Project Goal: obtain and demonstrate skills used to model and simulate complex flow and combustion in rocket engines using Ansys Fluent software. Modeling a methane-oxygen rocket engine and studying the effects of backpressure, swirl percentage, and mixture ratio.

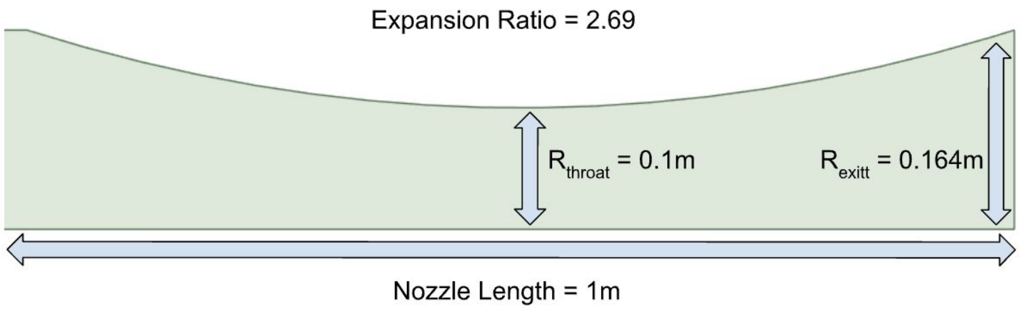
Geometry

Injector and CC geometry is the same as Lab 3

Nozzle is modeled as parabola with inlet and exit OD matching CC OD

2D Axisymmetric with Swirl





Turbulence and Combustion Model

We used a k–ε model, which models turbulent viscosity using:

- k = turbulent kinetic energy
- ε = dissipation rate of turbulence

K–ε is best suited for high Reynolds number flows (~50,000), and is more stable and computationally efficient than other models such as k-ω or LES.

For modeling combustion we used species transport with volumetric reactions and eddy dissipation, which is ideal for high-speed, turbulent combustion like that of a rocket engine

Boundary Conditions

Walls - adiabatic, non-reactive, no-slip

Mass flow inlet - used to adjust mixture ratio (Nominal O_2: 0.22 kg/s, Nominal CH_4: 0.055 kg/s)

Pressure outlet - used to vary backpressure (Nominal: 0 kPa absolute)

Velocity inlet - used for oxygen film inlet

Center axis

Fuel Type

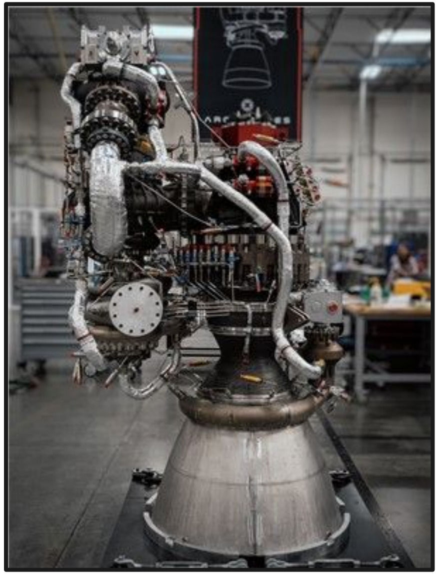
Oxidizer: Gaseous O_2

Fuel: Gaseous CH_4

Reason

- Increasingly common in industry
- Between H_2 and RP-1 in density, O/F ratio, I_{sp}

Modeled in Fluent using mole fractions



Experimental Design

Varying back pressure

- Values: 0 kPa, 7 kPa, 10 kPa (all absolute)
- Allows exploration of different flow regimes

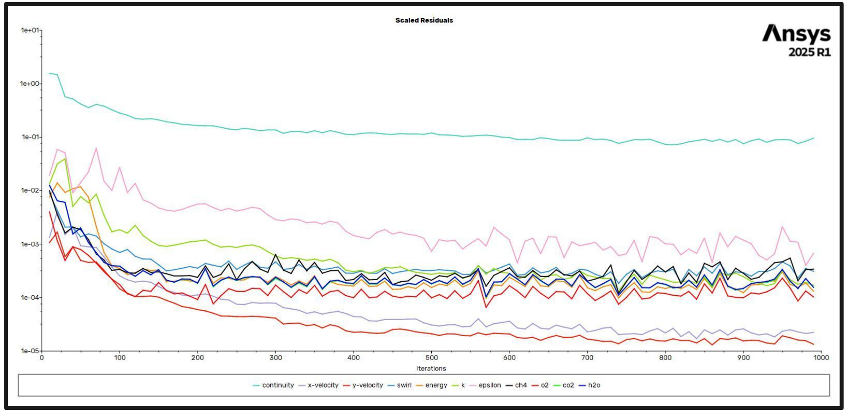
Varying mixture ratio

- Values: 3.5, 3.8, 4, 4.5, 4.3
- Expect lower combustion temperatures

Varying swirl percentage

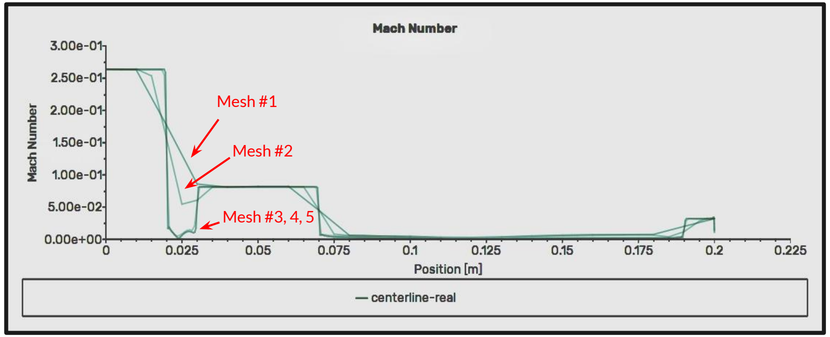
- Values: 10%, 40%, 70%
- Expect higher combustion temperatures and more combustion product as % increases

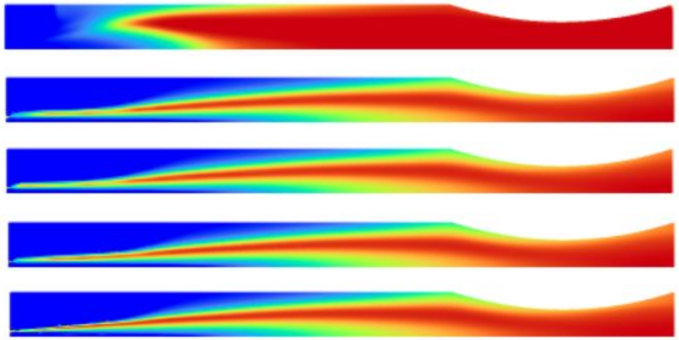
Calculation Activities



- For each simulation, we ran 2500 iterations and compared mass flow in vs out t o check convergence
- Solving time: ~4 minutes
- Saved contour plots of temperature, mass fraction, pressure, mach number, plus centerline plots for temperature, pressure, and mach number
- Requires no remeshing or geometry changes (can use same workbench file for many sims)

Mesh Design / Convergence

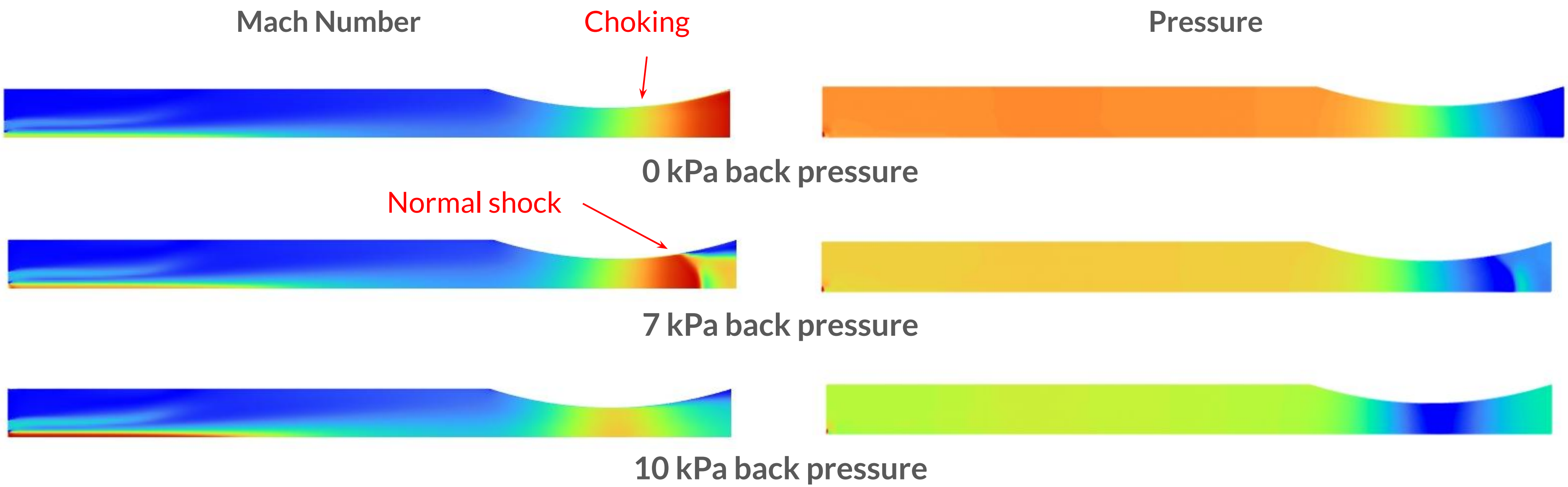




1. 5k elements, no inflation or local sizing
2. 6.3k elements, 2 inflation layers and sizing on inlet/outlet
3. 9.3k elements, 5 inflation layers and finer edge sizing
4. 15.2k elements, 10 inflation layers and finer edge sizing
5. 48.2k elements, 10 inflation layers and finer edge sizing

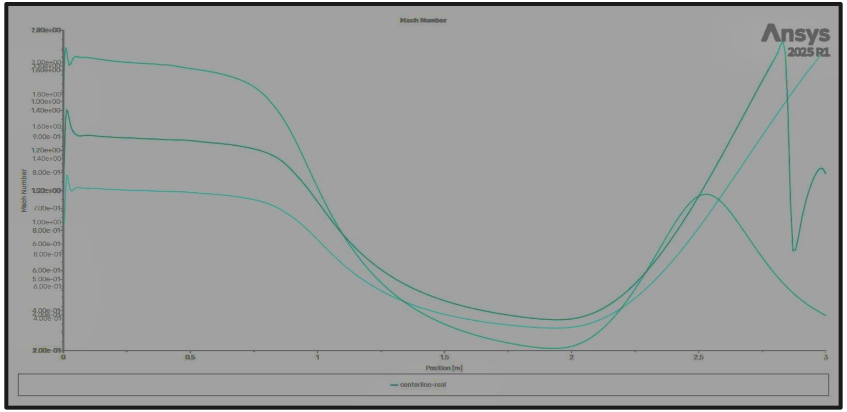
Selected mesh #3: matched results of 4 & 5 without wasting computational power

Simulation Results: Varying Back Pressure

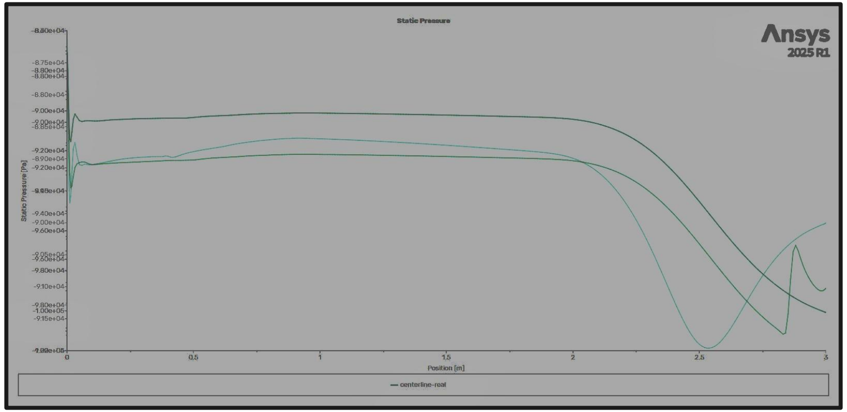


Higher back pressure → suppresses choking and introduces shocks

Back Pressure Flow Regimes



Mach Number



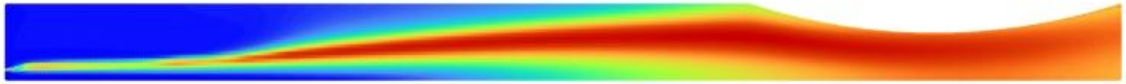
Static Pressure

Higher backpressure suppresses supersonic flow and moves shock structures upstream into the nozzle

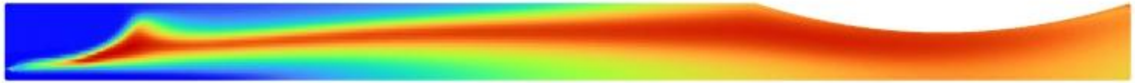
Simulation Results: Varying Swirl Percentage (Plots of Temperature)

Adding swirl increases shear and mixing quality and thus raises peak combustion temperature

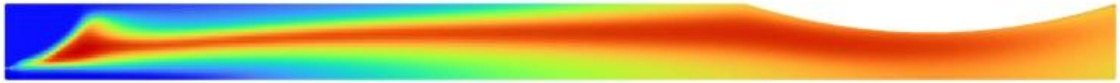
- 10% → 4360 K
- 40% → 4830 K
- 70% → 4960 K



10% Swirl



40% Swirl



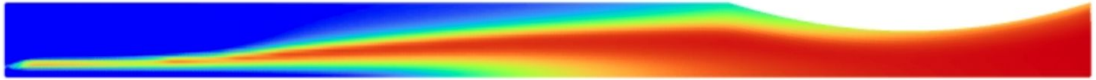
70% Swirl

Simulation Results: Varying Swirl Percentage (Plots of CO_2)

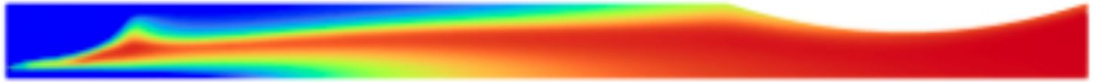
Increased swirl increases mixing quality and produces more combustion

- 10% → 0.480
- 40% → 0.501
- 70% → 0.493

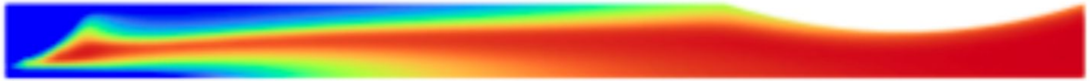
It also spreads the combustion products, leading to a local lower concentration at a given location



10% Swirl



40% Swirl



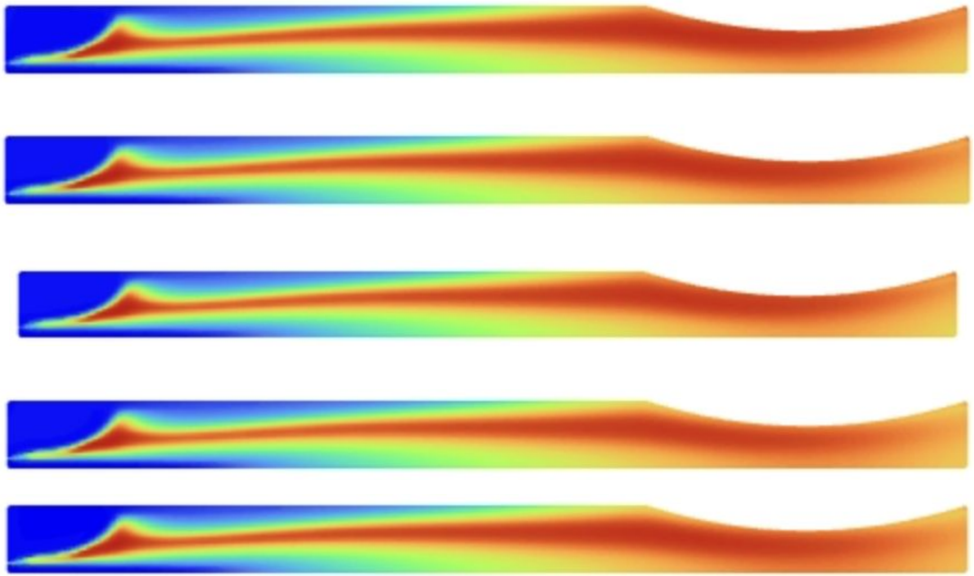
70% Swirl

Simulation Results: Varying Mixture Ratio (Plots of Temperature)

Tested 5 different mixtures ratios from fuel rich to ox rich

- MR = 3.5 → 4810 K
- MR = 3.82 → 4830 K
- MR = 4 → 4940 K
- MR = 4.29 → 4920 K
- MR = 4.5 → 4770 K

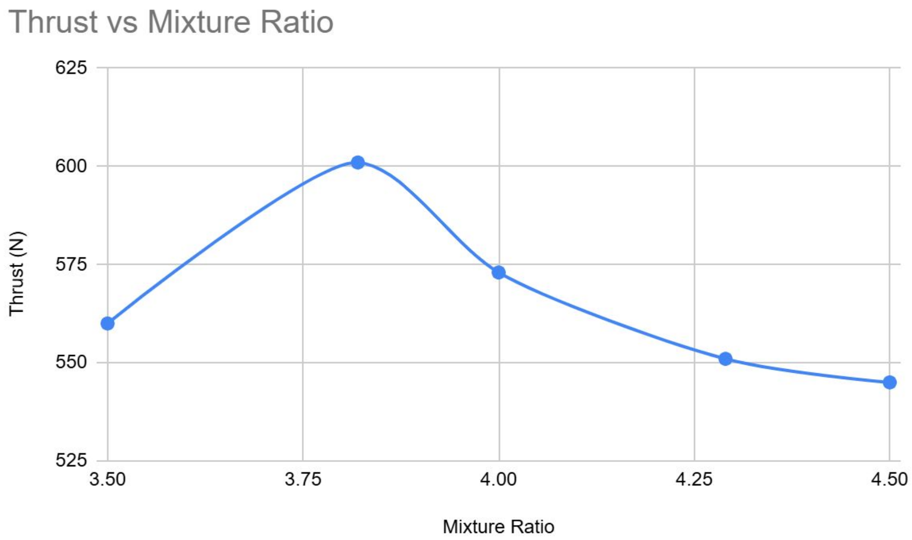
Plots of pressure, temperature, and velocity are nearly identical for each MR → Changing MR affects energy release not flow structure



Mixture Ratio impacts on thrust

- MR = 3.5 ⟶ 560 N
- MR = 3.82 ⟶ 601 N
- MR = 4 ⟶ 573 N
- MR = 4.29 ⟶ 551 N
- MR = 4.5 ⟶ 545 N

Peak thrust occurs at a slightly fuel-rich mixture ratio (lower molecular weight produces higher exhaust velocity)



Key Takeaways

Back Pressure

- Controls flow regime (choked, shock, subsonic)
- High pressure ratio → supersonic flow

Swirl

- Increases mixing → higher combustion temperature
- Diminishing returns at high swirl

Mixture Ratio

- Affects energy release, not flow structure
- Temperature peaks near stoichiometric

Performance

- Depends on both temperature and molecular weight
- Peak thrust occurs at fuel-rich conditions

Conclusion

Demonstrated Skills

- Modeling and simulation of rocket engines
- Proficiency in Ansys Fluent and Workbench

Limitations

- 2D axisymmetric model
- Simplified turbulence model (k–ε, isotropic)
- Mixing-limited combustion (no finite-rate chemistry)

Further Areas of Interest

- Injector inlet patterns
- Full combustion chamber length