# EXPERIENCE IN TURBOMACHINERY DESIGN

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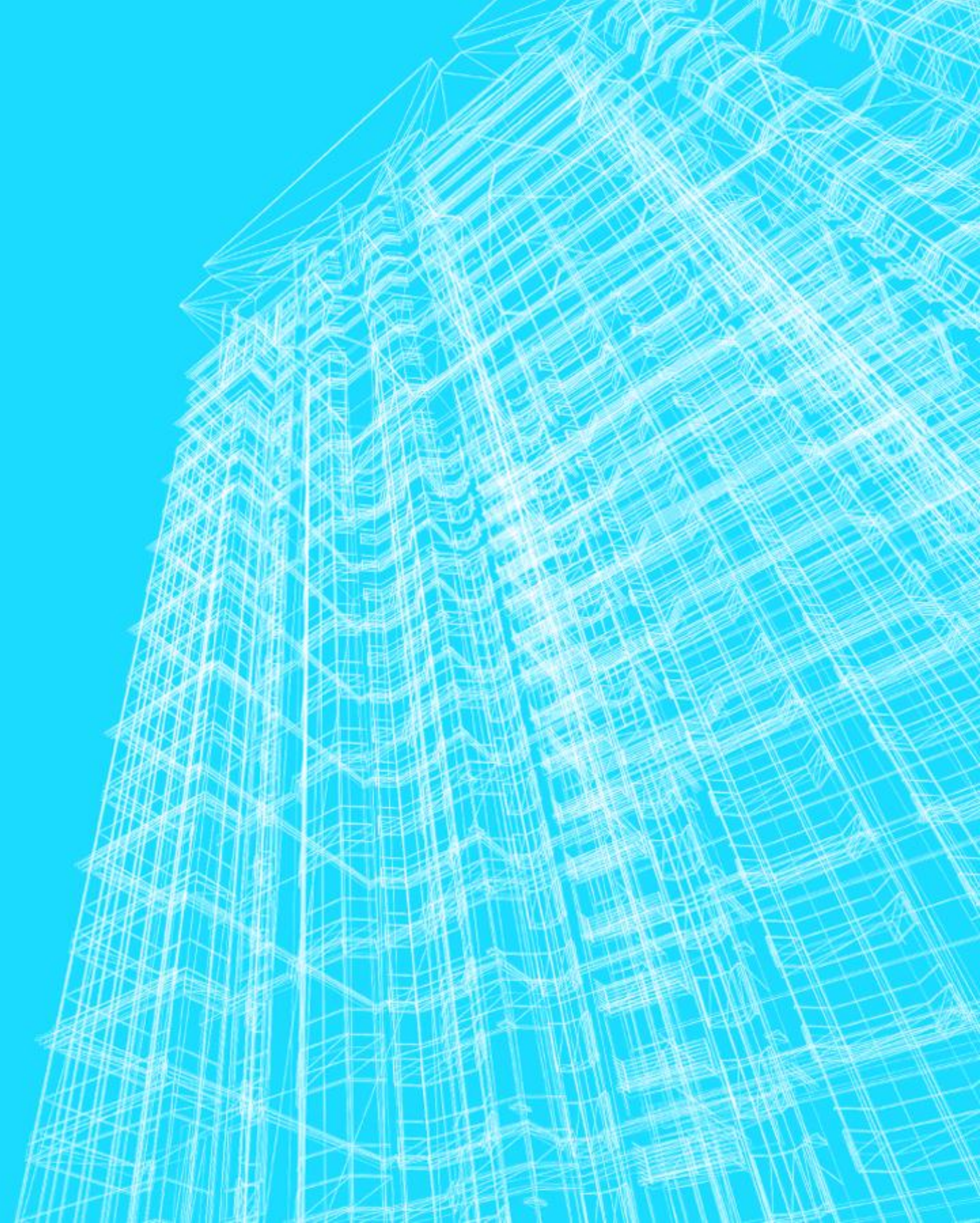


# ROCKET ENGINE DESIGN PROJECT

Methane/Oxygen open gas generator cycle liquid rocket engine

I found a YouTube tutorial on the use of **TURBOdesign1** last semester and I thought it would be fun to do a project with it. By the time I had access to the software I had been assigned a project for my rocket propulsion class. The **goal of the project** was to design the engine of a **single-stage-to-orbit (SSTO) rocket**. I used TURBOdesign1 to design the **powerpack** of the engine. If you are interested, please check out my full project report on my website.

[Rocket Propulsion / coding Projects | cosimoLikesRockets]

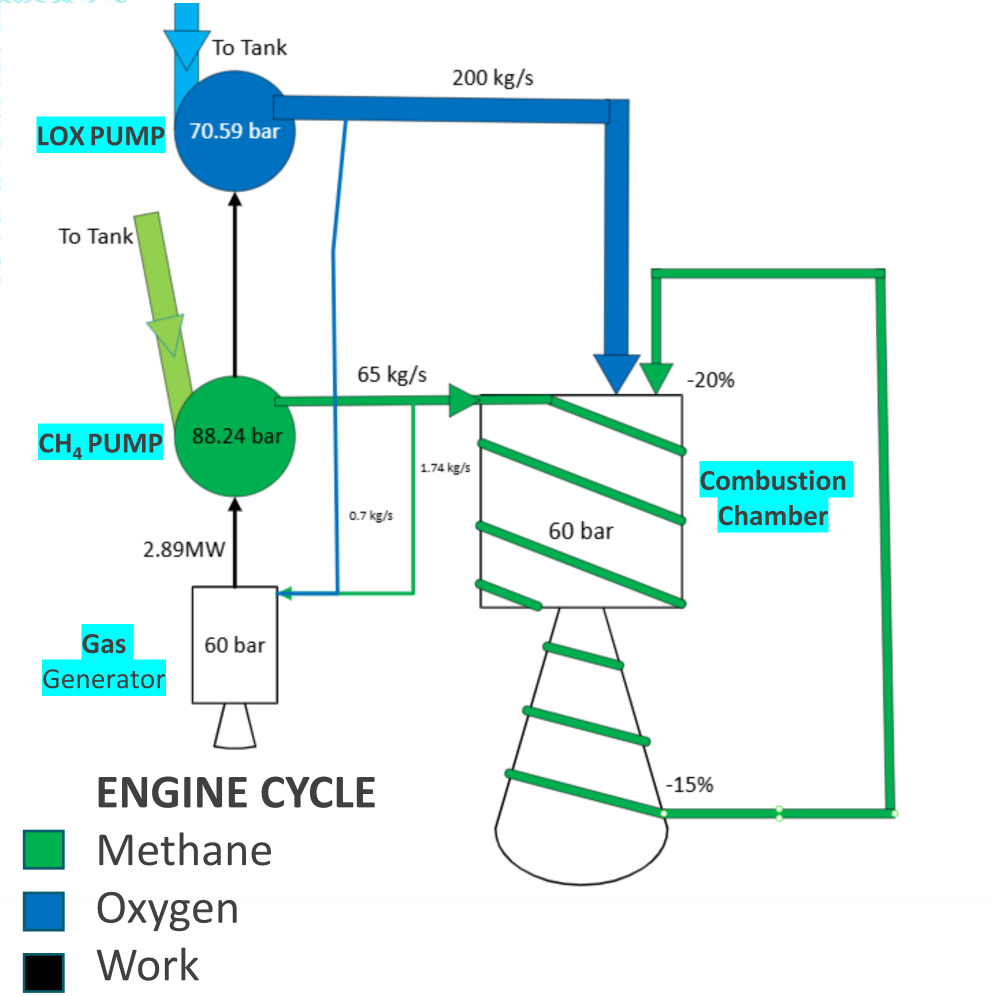
## ROCKET ENGINE PARAMETER SUMMARY

| Inputs | Value |
|---|---|
| Design Thrust | 1MN |
| Pcc | 60 bar |
| m_dot (oxygen) | 200 kg/s |
| m_dot (Methane) | 65 kg/s |
| Design altitude | 0 m (sl) |
| Number of Engines | 1 Engine |
| Turn Start | 130 km |
| Turn end | 162.9 km |

| Outputs | Value |
|---|---|
| Final Altitude | 162.9 km |
| Initial Mass | 2909.03 kg |
| Nozzle Expansion ratio | 30.5 |
| Throat Radius | 16 cm |
| Tcc | 3522.98 K |
| Isp | 384.67 s |

# ENGINE CYCLE AND POWERPACK

I calculated the **pump parameters** using equations seen in class.
I used those calculations to plug the numbers into the TURBOdesign1 software to obtain performance plots and **blade profiles** of the oxygen and methane pumps.




| | Oxygen Pump | Methane Pump |
|---|---|---|
| Head $H$ [m] | 599.11 | 2049.2 |
| Flow Rate $Q$ [m$^3$/s] | 0.17 | 0.15 |
| Rotational Speed $N$ [rpm] | 6148.16 | 16470.16 |
| Impeller Diameter $D$ [m] | 0.31 | 0.21 |
| Specific Speed $S_s$ | 4.48 | 6.39 |
| Power Input [MW] | 1.37 | 1.52 |

**TURBOdesign1**

Liquid Methane Pump

Liquid Oxygen Pump

# PUMP CALCULATIONS

I used these equations to estimate the pump parameters

1. $$H = \frac{\Delta P}{\rho\, g}$$ Pump Head

2. $$Q = \frac{\dot{m}}{\rho}$$ Volumetric flow rate

3. $$U_{\text{energy}} = \sqrt{\frac{g\, H}{\psi}}$$ Tip velocity based on **the Euler head relation** for centrifugal pumps

4. $$N = N_s \frac{(H\, g)^{0.75}}{Q^{0.5}}$$ Rotational speed from specific speed

5. $$D = d_s \frac{Q^{0.5}}{(H\, g)^{0.25}}$$ Impeller diameter from specific diameter

6. $$U_{\text{geom}} = \frac{D}{2} N$$ Recalculate tip speed, based on the impeller diameter

7. $$\Psi_{\text{new}} = \frac{H\, g}{U_{\text{geom}}^2}$$ Recalculate loading coefficient based on geometric tip speed → Accept if within **5%** of original value

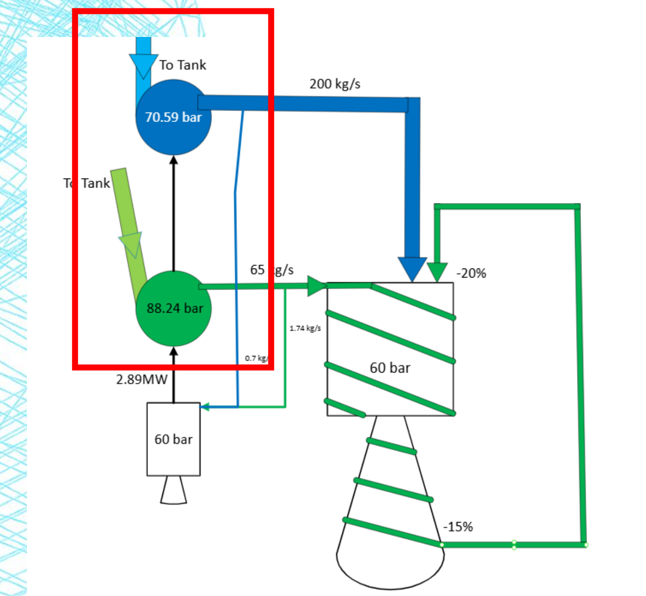
8. $$P_{\text{hyd}} = \frac{\dot{m}\, \Delta P}{\eta\, \rho}$$ Get pump hydraulic power

9. $$\text{NPSH} = \frac{P_{\text{in}} - P_{\text{vap}}}{\rho\, g}$$

10. $$S_s = \frac{N\, Q^{0.5}}{(\text{NPSH}\, g)^{0.75}}$$

Cavitation check (9–10)

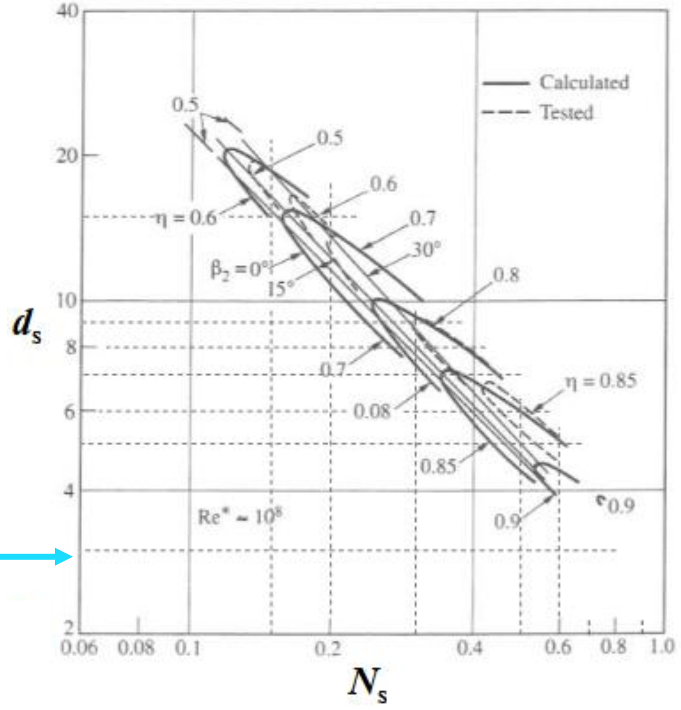
→ Accept if **3.7 < Ss < 9.1**




# PUMP HYDRAULIC POWER

The **hydraulic power** of each of the two pumps is calculated as:

$$P_{hyd} = f(\dots)$$




**Ψ = 0.59**
(between
0.4 and 0.7 for LREs)

From **Balje/Stepanoff** similarity charts

Density from **thermodynamic state**

$$f(\rho, \dot{m}, \Delta P, \psi, N_s, d_s, \eta, g, P_{in}, P_{vap})$$

**Mass flow** chosen for engine performance parameters

Vapor pressure

3 bar (assumed tank pressure)

η = 0.86 arbitrarily chosen

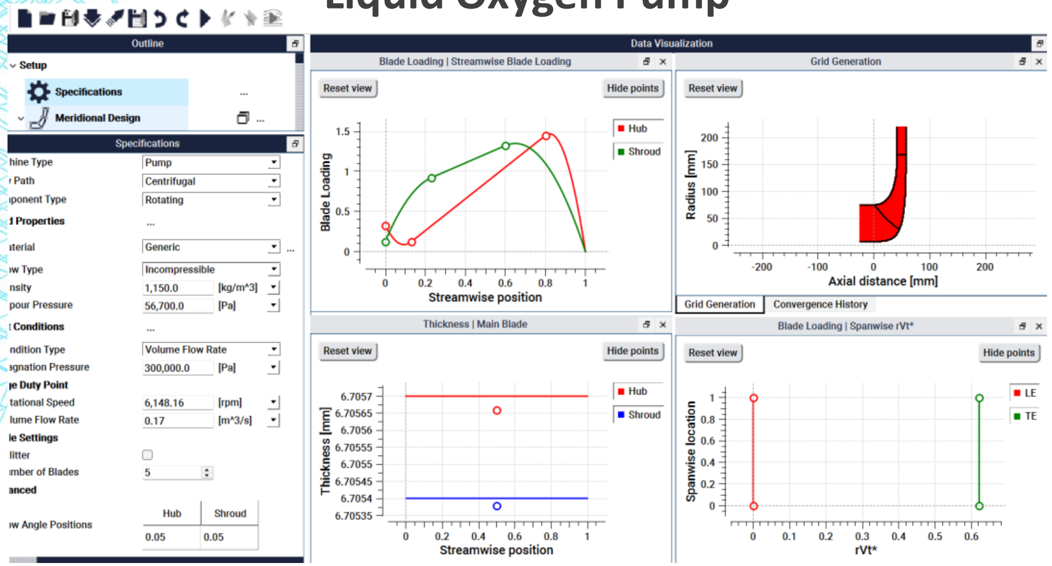
$\Delta P(CH_4)$ = **Pcc /(0.85 * 0.8)** assuming 20% loss on the injector and 15% loss in the cooling channels

$\Delta P(LOX)$ = **Pcc / 0.85** assuming 20% loss on the injector

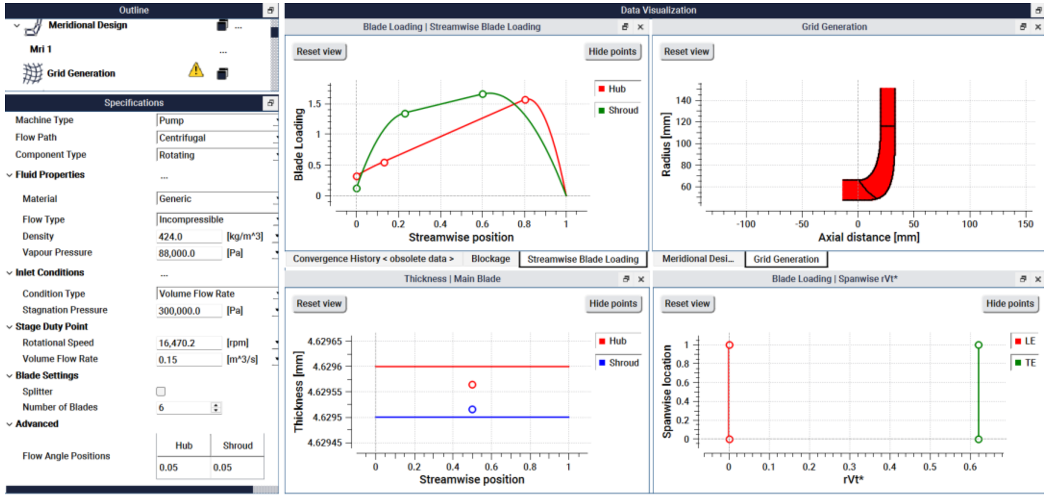
$$W_{total} = P_{hyd}(LOX) + P_{hyd}(CH_4)$$

# PUMP PLOTS

## Liquid Oxygen Pump




## Liquid Methane Pump




Used **TURBOdesign1** to create the following plots:

1. Top Left: Streamwise Position vs **Blade Loading.** In both cases the hub is aft-loaded. There is a **risk of separation**. The loading on the shroud looks acceptable.

2. Top right: **Meridional design.**

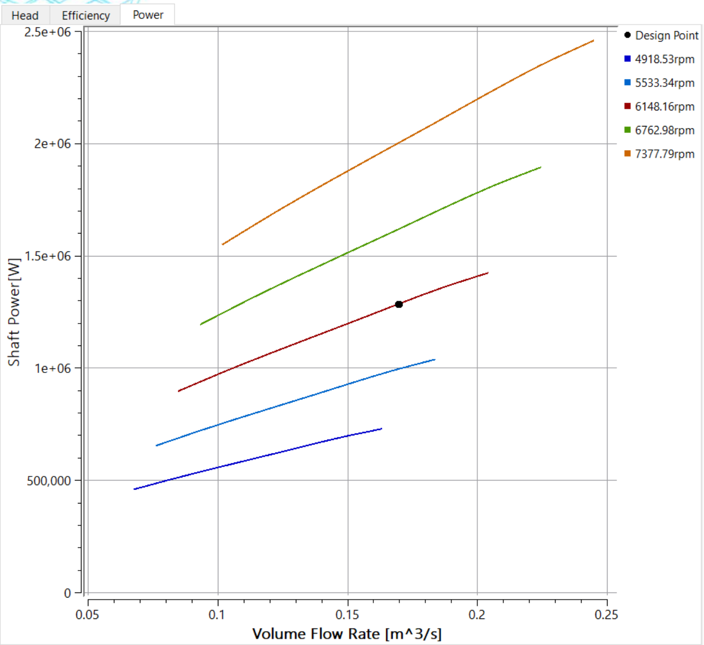
3. Bottom left: Streamwise position vs **thickness.** I chose a constant thickness blade design.

4. Bottom right: **Swirl ($rV_\theta$)** vs spanwise location. These plots look good, with 0 swirl at the inlet and a **constant swirl** at the trailing edge.

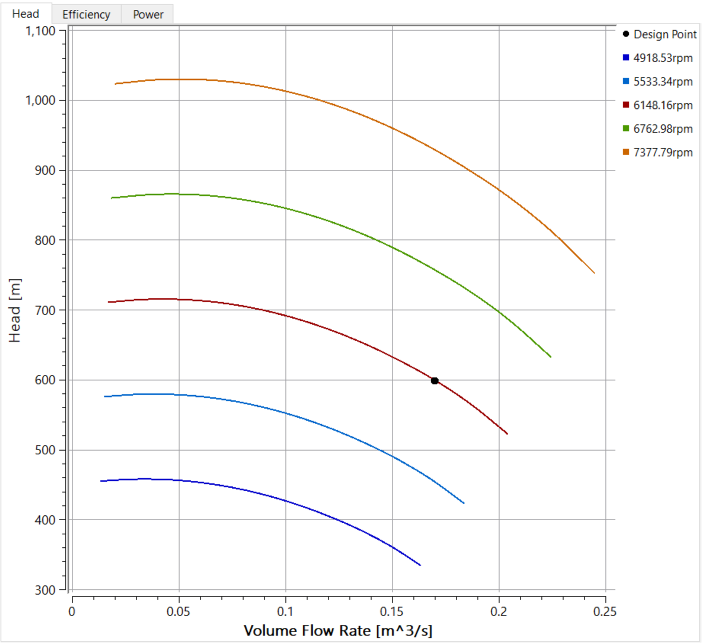
# RESULTING PUMP PARAMETERS

TURBOdesign1 also generated these performance maps, which highlight the operating point of my oxygen pump.

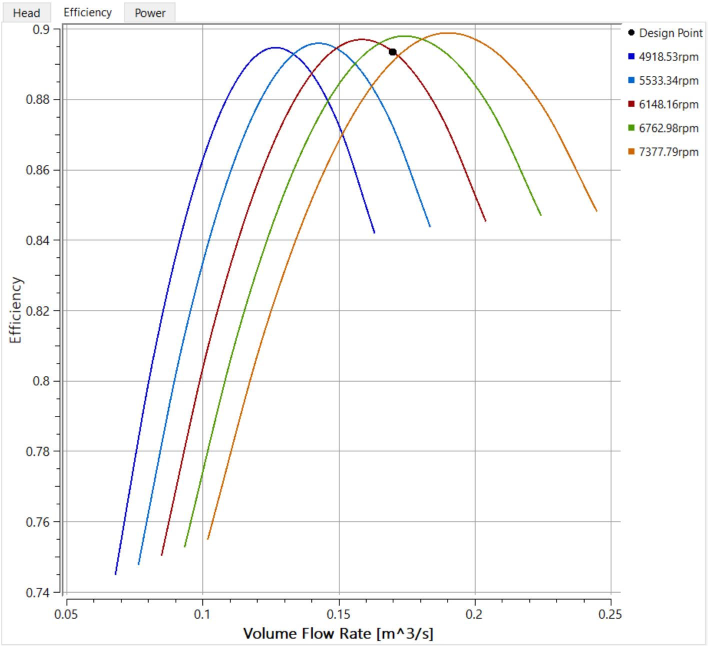
**Power** map ($P_{shaft}$ vs Q)




**Head** map (H vs Q)




**Efficiency** map (η vs Q)




We can see that the oxygen pump is operating near the ***Best Efficiency Point.*** Slightly decreasing the volumetric flow rate would increase the efficiency and pump head while also decreasing the necessary shaft power. However, we are already operating at a **higher efficiency** than the conservatively estimated efficiency **(η = 0.86)** for the preliminary calculations.

# PUMP CAD

TURBOdesign1 has the option of outputting a **CAD file** of the pump **blade** as well as the **volute**. I imported these into Fusion360 and added the shroud and hub.

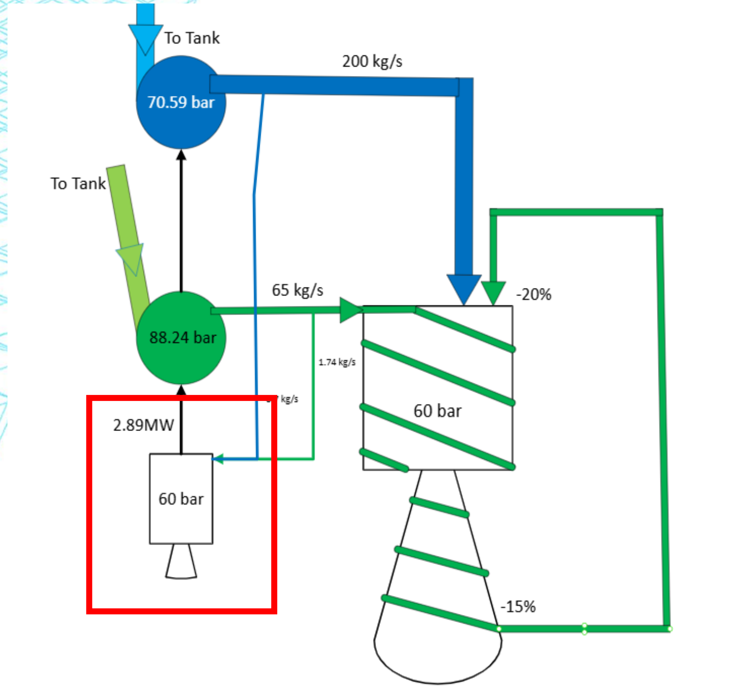
Note: This is only for the purpose of 3D printing the engine, the design of the **hub and shroud** is **not detailed**. Also, in the current version, both pumps are placed on the same shaft. Since they rotate at different speeds this is not an ideal design. Separating the shafts and using a gear system would improve the design.

LOX Pump

$CH_4$ Pump

# TURBINE CALCULATIONS

A very **rich mixture**, with an **equivalence ratio of 10**, goes into the preburner. This is done to keep **the temperature of the combustion gases** acceptable for the turbine blades. The **Python Cantera** library is used to calculate the **combustion gas** properties.




$$\frac{T_{\text{out}}}{T_{\text{in}}} = \left(\frac{P_{exit}}{P_{cc}}\right)^{\frac{\gamma-1}{\gamma}}$$

60 bar (combustion pressure)

Combustion Gases

Ambient

Mass specific turbine work

$$w_t = \eta_t\, c_p \left(T_{\text{in}} - T_{\text{out}}\right) = \eta_t\, c_p\, T_{\text{in}} \left[1 - \left(\frac{P_{exit}}{P_{cc}}\right)^{\frac{\gamma-1}{\gamma}}\right]$$

Combustion Gases

efficiency = 0.7

Mass flow through the turbine

$$\dot{m}_t = \frac{W_{\text{total}}}{w_t} = \frac{W_{\text{total}}}{\eta_t\, c_p\, T_{\text{in}} \left[1 - \left(\frac{P_{exit}}{P_{cc}}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

Total power necessary to run the pumps

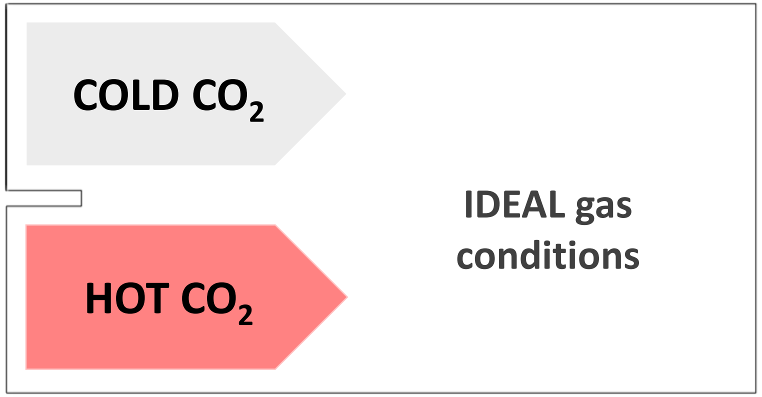
# ABOUT MYSELF

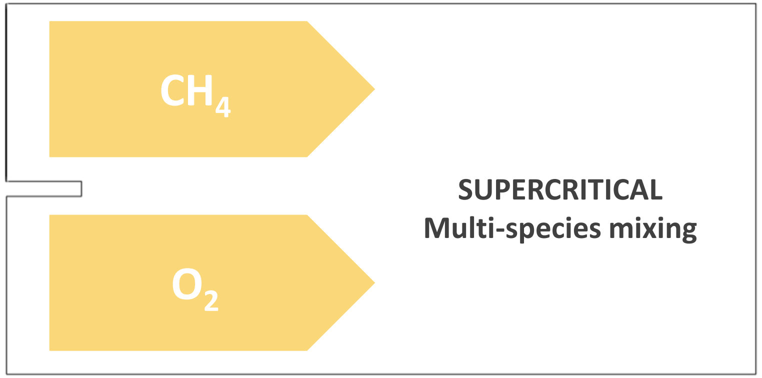
- Graduating **in December** with a master's in Aerospace Engineering from **Georgia Tech**
- **CFD researcher** at Georgia Tech in Dr. Oefelein's High Performance Computing Lab
- Experience in **CFD** (Georgia Tech & NASA)
- Experience in **production engineering** (Rocket Factory Augsburg)
- Experience in **test engineering** (Technology for Propulsion and Innovation)

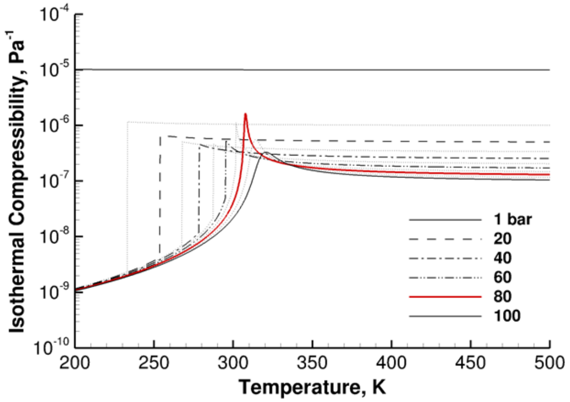
# RESEARCH AT GEORGIA TECH

- My research centers around the **compressibility effects** in **supercritical mixing layers**
- In the vicinity of critical pressure and temperature, supercritical fluids exhibit **strong non-linearities** in their properties (ex: Isothermal compressibility plot in the bottom right of the slide.)
- The goal of my work is to identify and quantify the key **differences** between **ideal and supercritical** mixing, as well as in **single-species** and **multi-species** supercritical mixing

**Setup of CFD simulations for 2 different datasets**



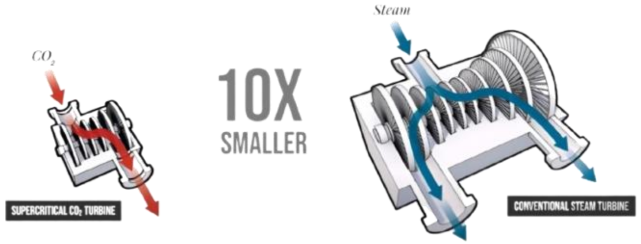




Isothermal compressibility

$$\alpha = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial p}\right)_T$$

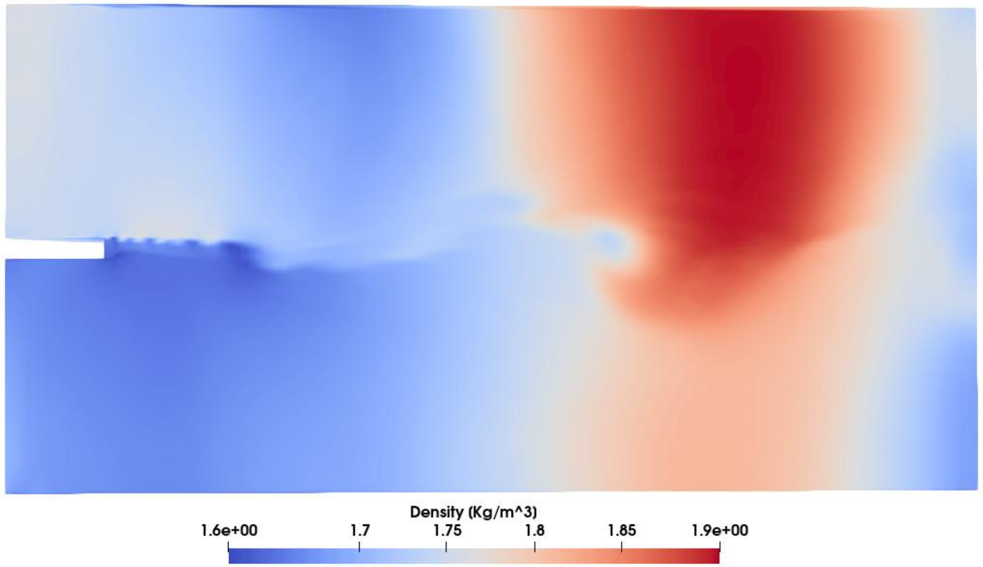
Supercritical fluids in turbomachinery:

- More efficient thermodynamic cycles
  - High heat capacity
  - No phase change, enabling higher temperatures
- Higher density
  - Smaller systems can produce the same amount of work

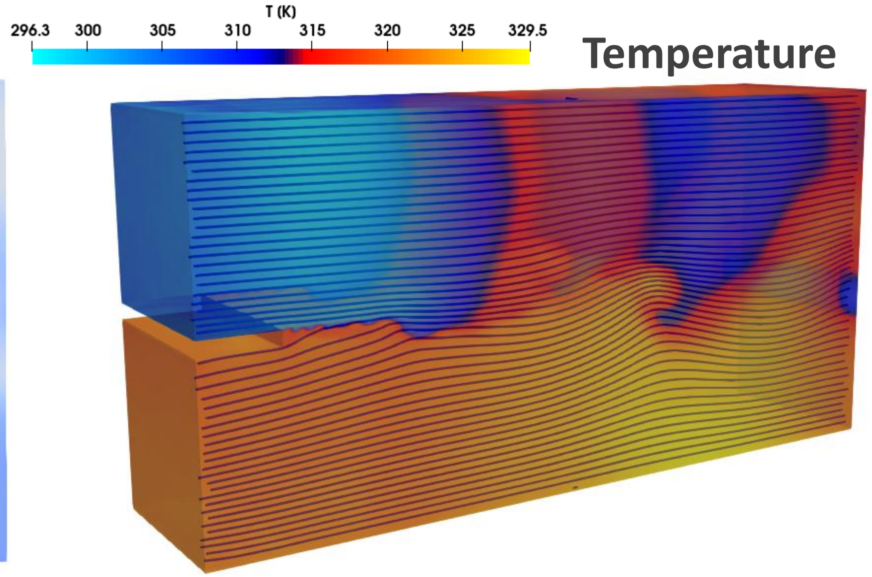


# SOME CONTOUR PLOTS

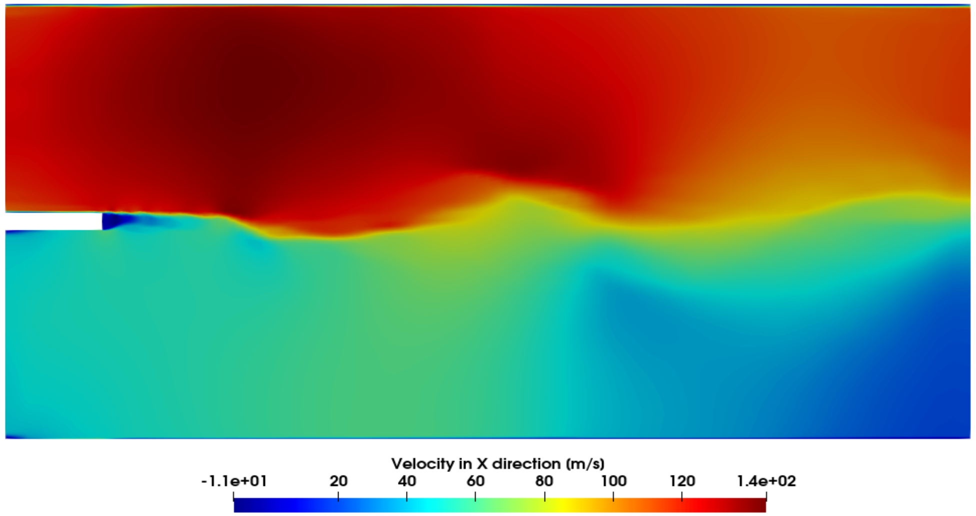
## Density



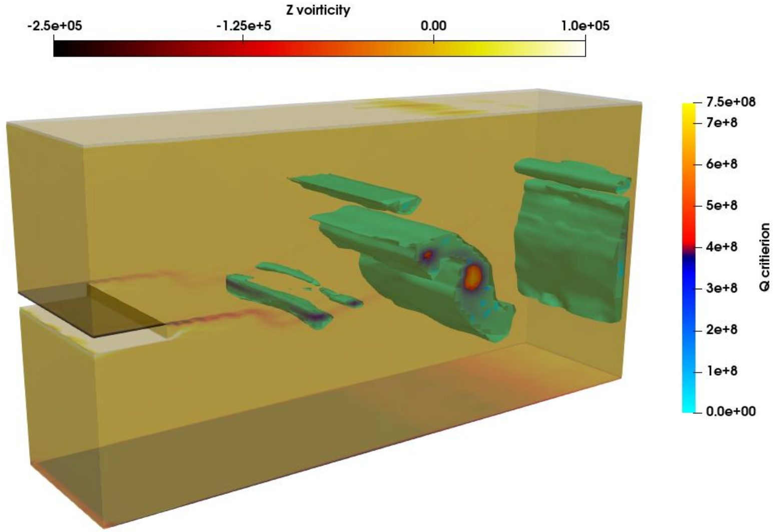

## Temperature




## Velocity



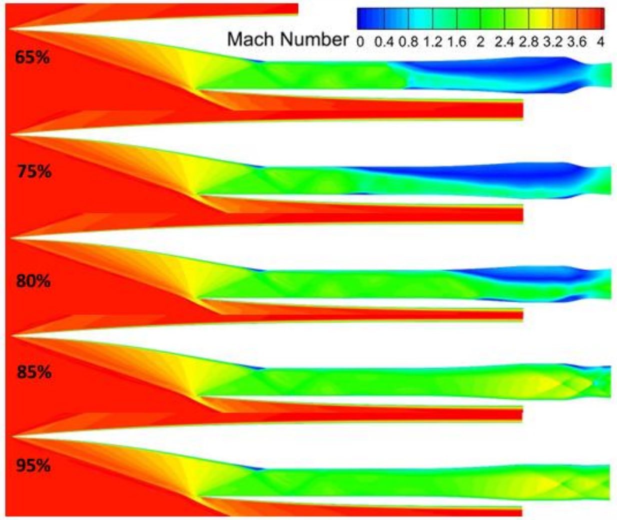

## Q criterion

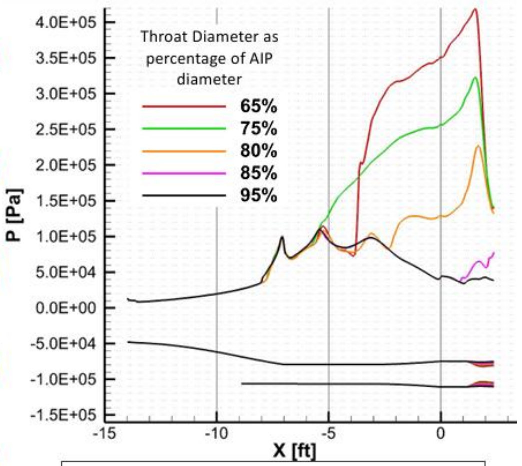



Two streams (upper/lower) mix downstream of the mixing plate. **Observations** on the **mixing behavior** of the 2 flows can be made.

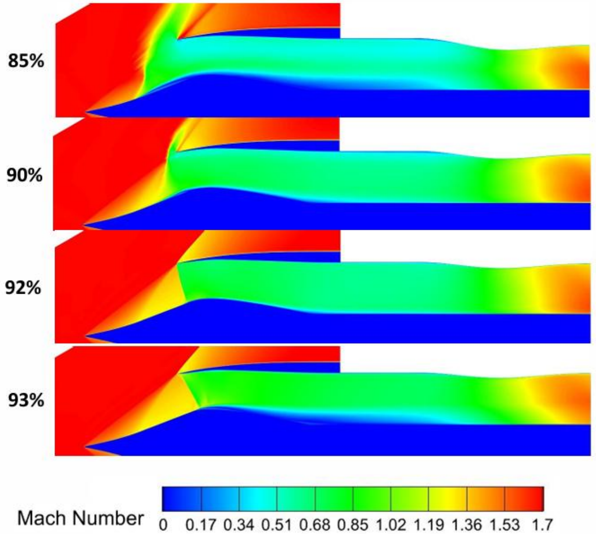
# CFD INTERNSHIP AT NASA

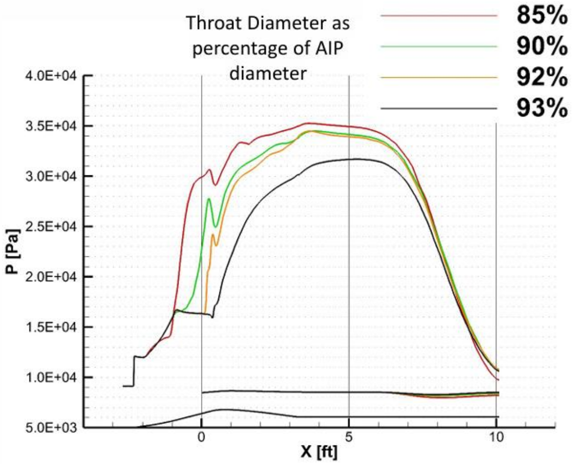
**Wall pressure rise** from increase in backpressure



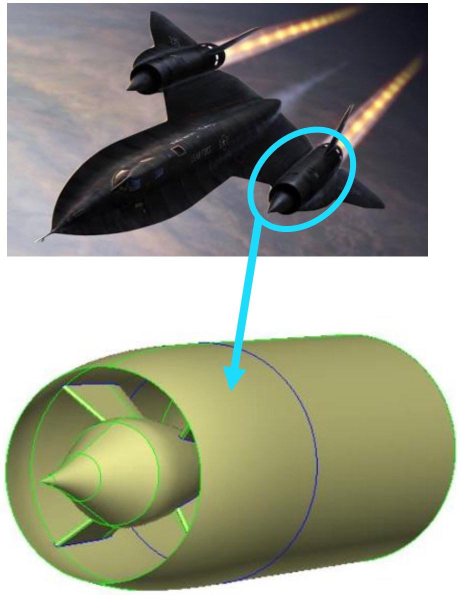



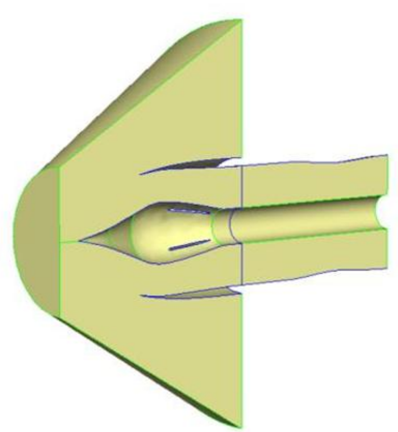

As expected, backpressuring the inlet causes the pressure rise to increase and move upstream




Below **92%** $D_{th}/D_{AIP}$ **ratio** inlet is in subcritical state





**Inlet negative-volume simulation domain**

- Worked in the *Inlets and Nozzles* branch in the ***Propulsion Division*** at the ***NASA Glenn Research Center.***
- Focused on creating and validating a **workflow** to speed up the **design and analysis** of supersonic **jet engine inlets.**
- Validated workflow for mixed-compression, Pitot, and streamline-traced inlets
- Demonstrated the **effects** of **backpressuring** the inlet by restricting the nozzle throat diameter.