Capstone Project #136: Gas Turbine from Automotive Turbocharger

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(with contributions from Hector Castro Noguez)

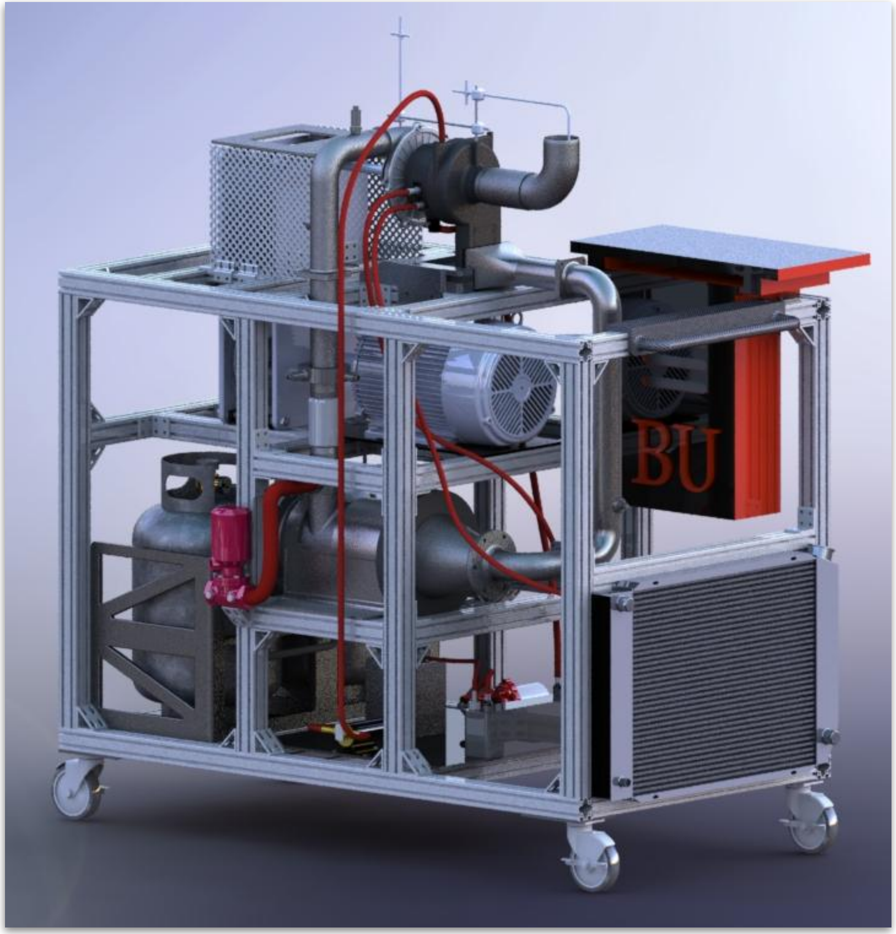
Problem Statement

“The Boston University Mechanical Engineering department doesn’t have the equipment to physically demonstrate compressible flow and propulsion principles to students interested in aerospace and fluids. Therefore, students don’t have the chance to interact with real thermodynamic systems and learn how they react under varying conditions. Creating a demonstration of the Brayton Cycle would give students valuable experience with a system that they may work with in the future.”

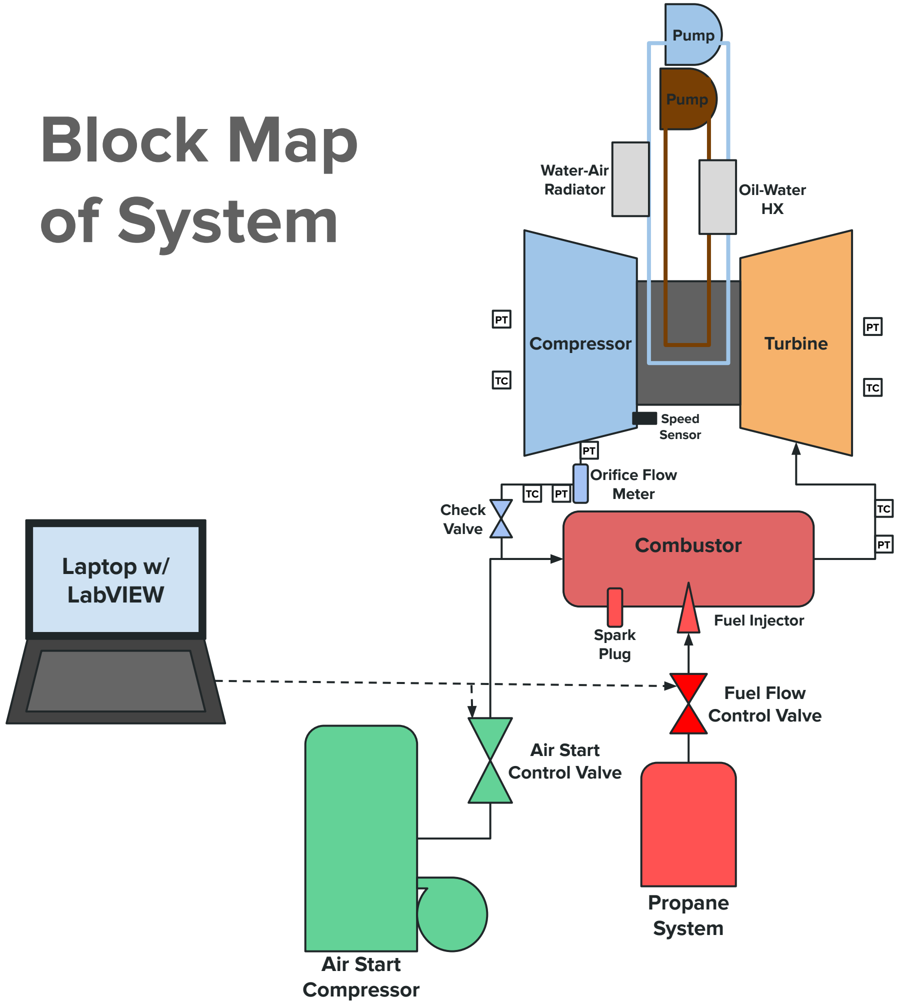
Customer Specifications

1) Provided turbocharger runs off of a combustion system with a propane fuel source
2) Instrumentation recording system (pressures, RPM, and temperatures)
3) Closed loop control for fuel system
4) Able to be transported around campus (fits into ENG elevator)
5) Power generation system implementation

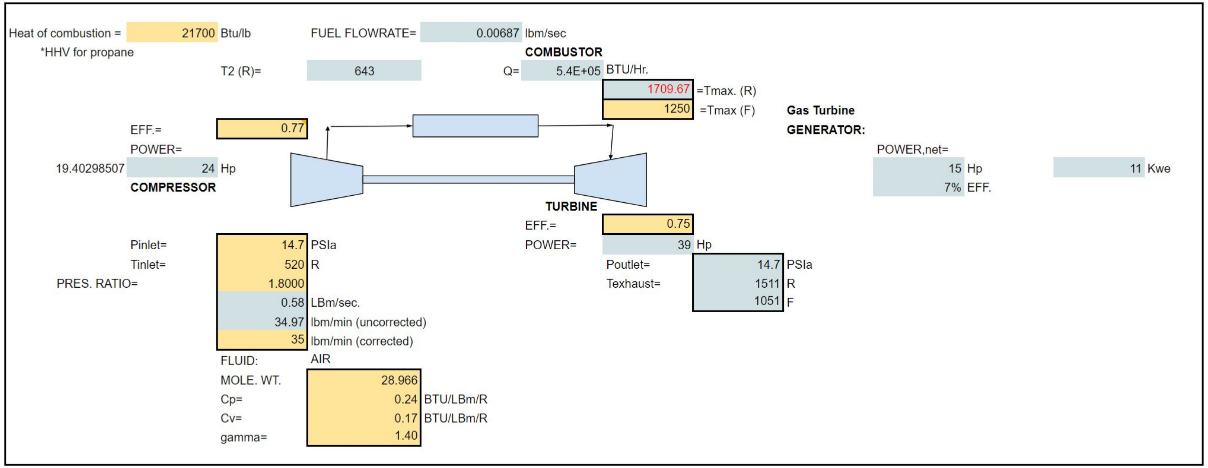
Final Render of Gas Turbine System

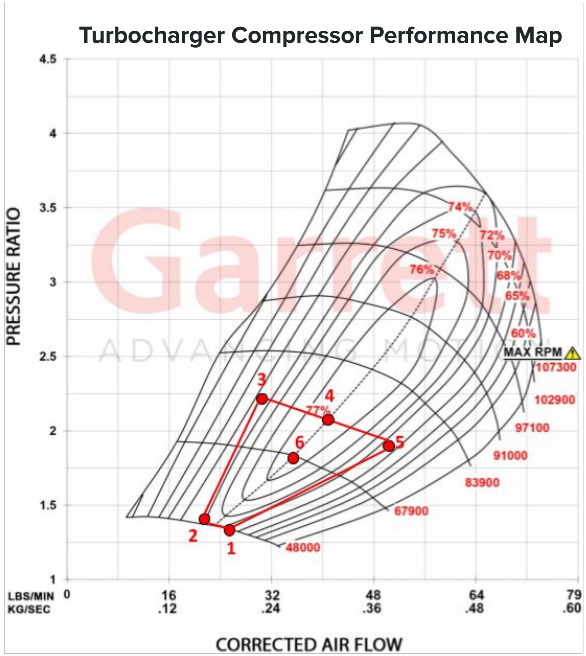


Block Map of System



Cycle Modeling



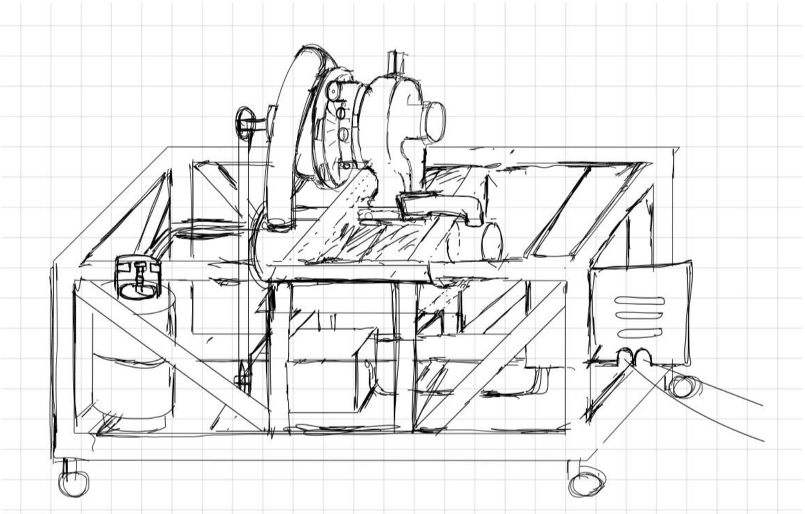


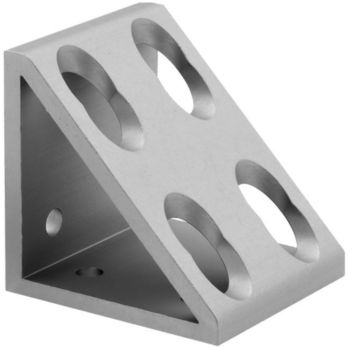
	INPUT					OUTPUT							
Point	RPM	Pres. Ratio	Mass Flow (lbm/sec)	Eff,c	Eff,t	T2 (R)	Power,c (HP)	Power,t (HP)	Power,net (HP)	Eff,total	Comb. Heat (Btu/hr)	Fuel Flowrate (lbm/s)	Texhaust (R)
1	48000	1.35	0.433	0.72	0.75	584.7	9.51	15.78	6.27	3.79%	4.21E+05	0.00539	1604.31
2	48000	1.45	0.350	0.72	0.75	600.9	9.61	15.62	6.01	4.56%	3.35E+05	0.00429	1580.52
3	75900	2.25	0.500	0.72	0.75	708.3	31.96	45.83	13.87	8.16%	4.33E+05	0.00554	1444.49
4	75900	2.1	0.667	0.77	0.75	679.5	36.11	56.47	20.36	8.73%	5.94E+05	0.00760	1464.73
5	75900	1.9	0.833	0.72	0.75	665.4	41.13	61.89	20.76	7.03%	7.52E+05	0.00962	1494.82
6	67900	1.8	0.583	0.77	0.75	643.5	24.44	39.95	15.51	7.35%	5.37E+05	0.00687	1511.44

Design

Cart Design

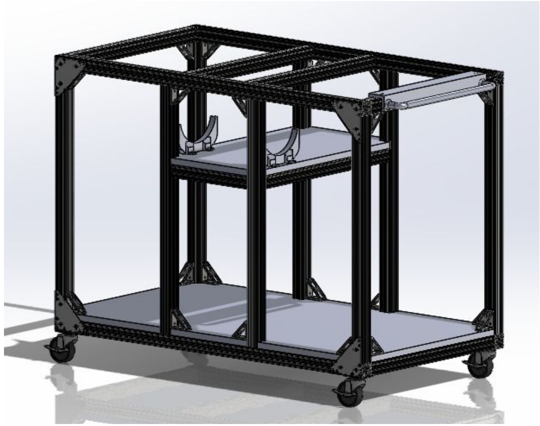
- The design of the cart revolved around the idea of being both self containing and transportable
    - Also needs to fit through a standard size door and elevator
- The finalized dimension of the cart: 60” x 33” x 42” (L x W x H)
- Made using 2” quad rail aluminum extrusions (6105 T5)
    - Held together with gussets, corner brackets, T-Slots and M6 Screws





Cart Design Process

At the end of the previous semester:
Decided on the general structure of the cart design



Beginning of this semester:

Overhauled the structure, removing the larger and panels and and adding some more extrusions to account for the newer components

Finalized Structure:

Iterating further, more extrusions were added as needed to provide support to even more components for the system

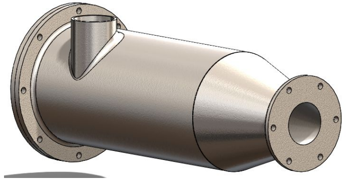
Gas Turbine System Design

Main components of the system:

1. Turbocharger
2. Combustion Chamber
3. Propane Tanks
4. Pulley Assembly
5. Induction Motor

1

2



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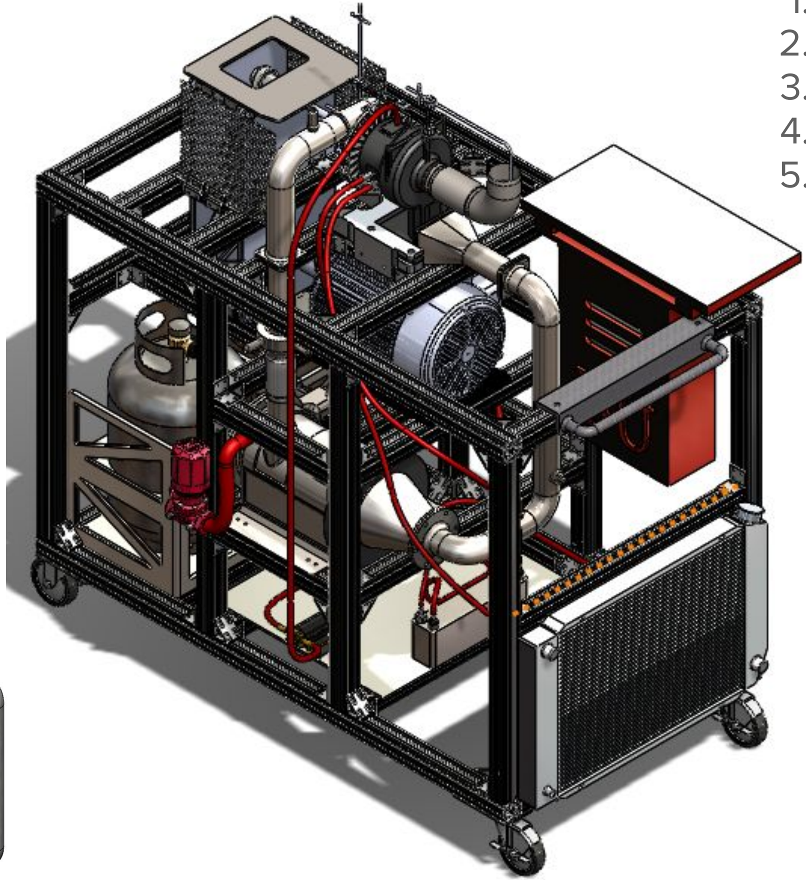

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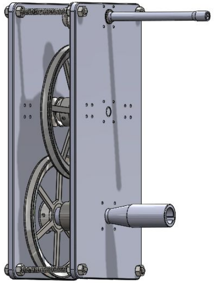

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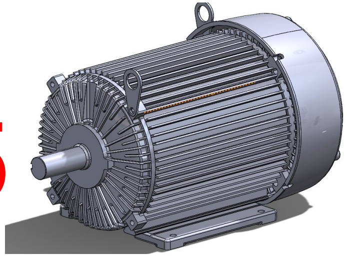
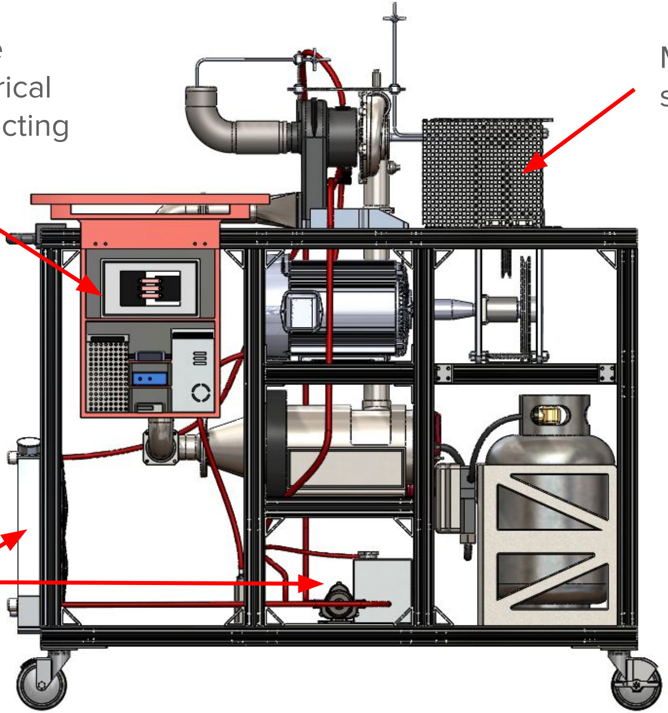


Gas Turbine System Design: Continued

Control box containing the systems electrical and data collecting devices

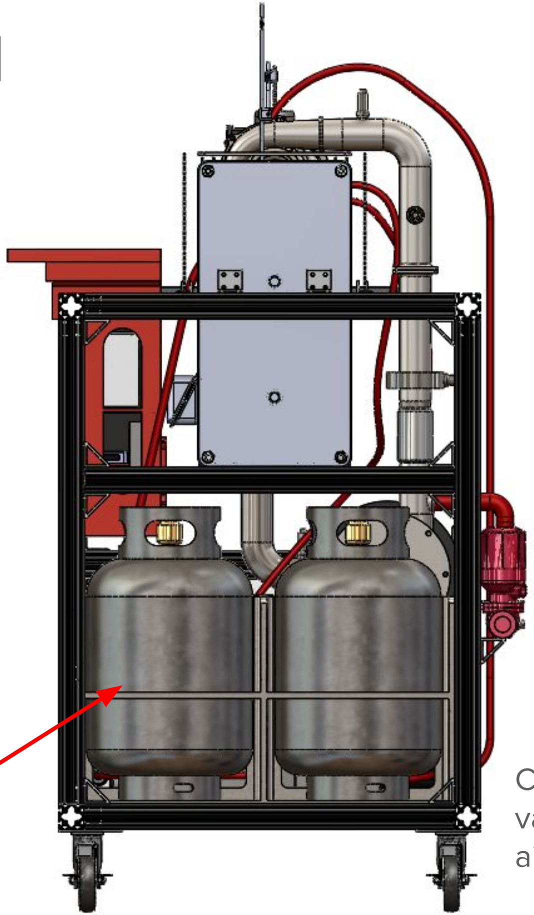
Radiator, Oil Pump, Water Pump, etc, used for the cooling system



Mesh panel added for safety precautions

42 in

60 in



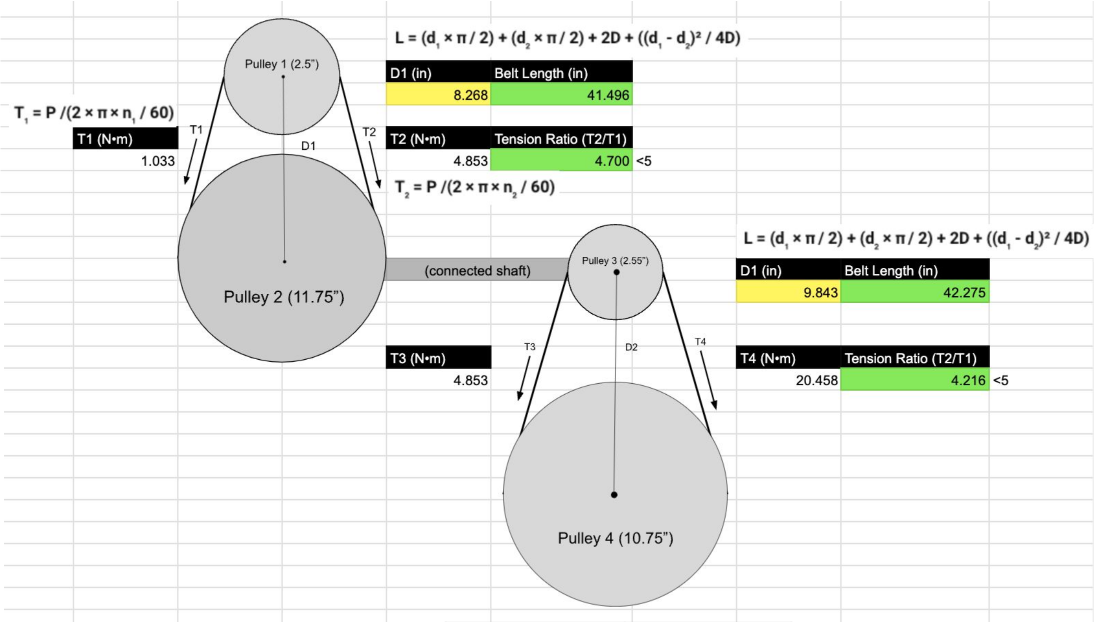
Can hold up to two propane tanks at a time, situated to be easily accessible

Control valve for air starter

33 in

Motor Pulley Safety

- Pulley tension ratio < 5 ensures no slippage of the belt



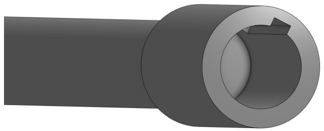
T2/T1	4.700
T4/T3	4.216

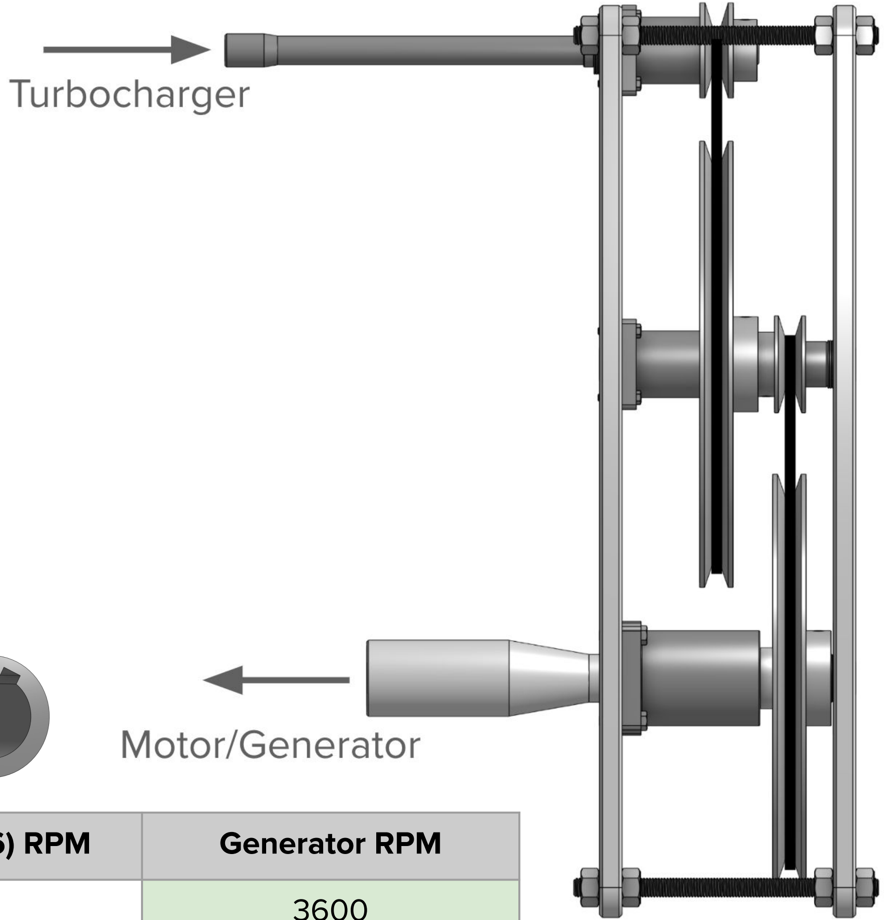
- 3600 RPM (10HP) generator to be used

Generator Pulley Assembly

- Dual pulley belt design (1:19.78 total ratio)
- Plates are meant to secure and protect the components
- Motor shaft runs below maximum RPM (for safety)
- Mesh shroud to cover pulleys

- Motor shaft is keyed to fit

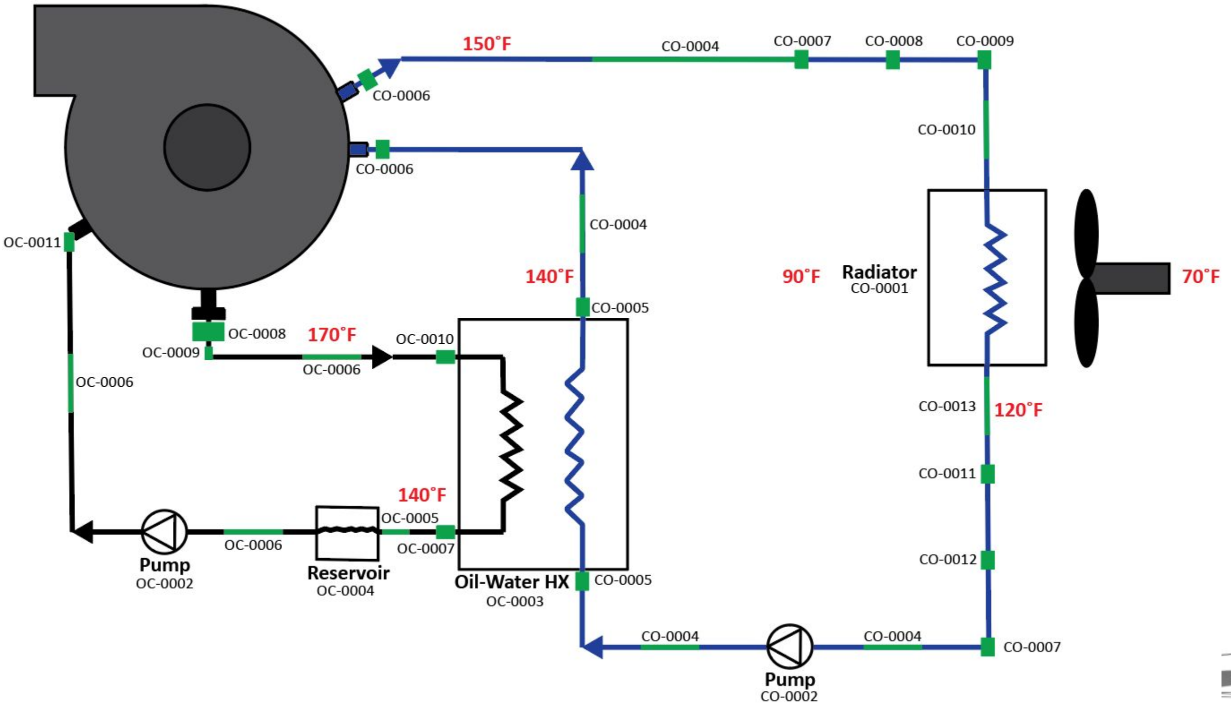


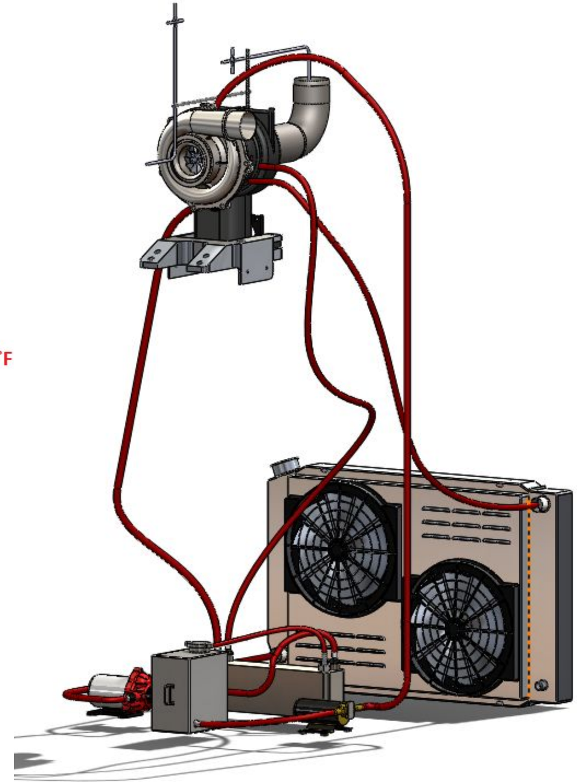


Turbo RPM	Pulley#1 (1:4.3) RPM	Pulley#2 (1:4.6) RPM	Generator RPM
69000	16,046	3,488	3600

Cooling System

Cooling Line Diagram





- **2** heat exchangers (**1** plate heat exchanger and **1** radiator)
- Turbocharger has built-in oil and coolant lines

Heat Exchanger Analysis

Oil-Water

- Oil flow rate: 3 gpm
- Water flow rate: 2 gpm
- Area: 8.8 ft^2

Radiator

- Air flow rate: 1515 cfm
- Water flow rate: 2 gpm
- Area: 12.3 ft^2

- NTU-Effectiveness method
- Flow rate analysis determined pump and radiator fan size

OIL-WATER

HX Type Plate

Th,i 170 → Th,o 140

Tc,o 140 ← Tc,i 120

OIL	values	units	**WATER**	values	units	**HT Parameters**	values	units	
v =	5	ft/s	v =	3.57	ft/s	U =	100	Btu/(hr*ft^2*R)	
ID =	0.5	in	ID =	0.5	in	Cmin =	0.202	Btu/R*s	
A,pipe =	0.0014	ft^2	A,pipe =	0.0014	ft^2	Cr =	0.667	-	
Vol flow =	0.00682	ft^3/s	Vol flow =	0.00487	ft^3/s	A,required =	8.8	ft^2	0.82
rho =	53.91	lb/ft^3	rho =	62.3	lb/ft^3	effectiveness =	0.6		m^2
m,dot =	0.37	lb/s	m,dot =	0.30	lb/s				
cp =	0.549	Btu/lb*R	cp =	0.998	Btu/lb*R	NTU =	1.216		
C =	0.202	Btu/R*s	C =	0.303	Btu/R*s	***counterflow**			
Q_dot =	6.05	Btu/s	Q_dot =	6.05		cmax mixed, cmi	1.45		
	21794	Btu/hr		21794	Btu/hr	cmin mixed, cma	1.42		
	8.56	hp							
Vol flow =	**11.58**	**lpm**	Vol flow =	**8.27**	**lpm**				
	3	**gpm**		**2**	**gpm**				
Cp source (SAE30)			rho source						
https://scholarly.(			https://www.engi		0.299				
2.3 kj/kgK									
rho source									
https://www.engi									

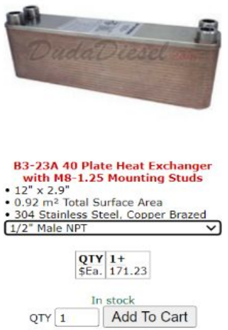
WATER-AIR

HX Type Cross Flow

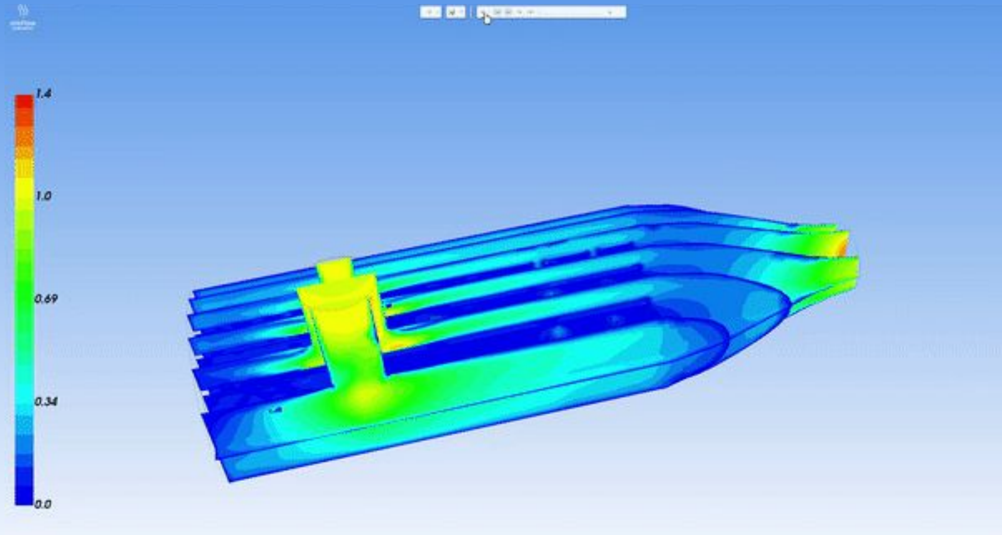
Th,i 150 → Th,o 120

Tc,o 90 ← Tc,i 70

WATER	values	units	**AIR**	values	units	**HT Parameters**	values	units	
v =	0.40	ft/s	v =		ft/s	U =	50	Btu/(hr*ft^2*R)	
ID =	1.5	in	ID =		in	Cmin =	0.303	Btu/R*s	
A,pipe =	0.0123	ft^2	A,pipe =		ft^2	Cr =	0.667	-	
Vol flow =	0.00487	ft^3/s	Vol flow =	25.25792	ft^3/s	A,required =	12.3	ft^2	1.1
rho =	62.3	lb/ft^3	rho =	0.0749	lb/ft^3	effectiveness =	0.38		m^2
m,dot =	0.30	lb/s	m,dot =	1.89	lb/s				
cp =	0.998	Btu/lb*R	cp =	0.24	Btu/lb*R	NTU =	0.547		
C =	0.303	Btu/R*s	C =	0.454	Btu/R*s	cross flow			
Q_dot =	9.08	Btu/s	Q_dot =	9.08	Btu/s	cmax mixed, cmi	0.56		
Cp source (SAE30)				13	hp	cmin mixed, cma	0.56		
https://scholarly.(			Vol flow =	**42913**	**lpm**				
2.3 kj/kgK			Vol flow =	**11337**	**gpm**				
				1515	**cfm**				
rho source									
https://www.engi			https://www.engineeringtoolbox.com/air-density-specific-weight-d_600.html						

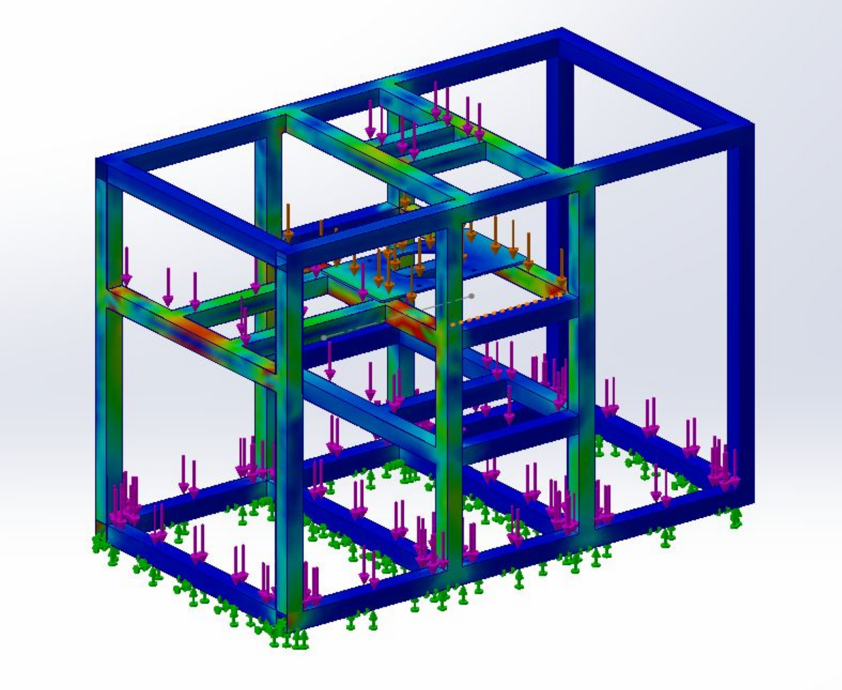


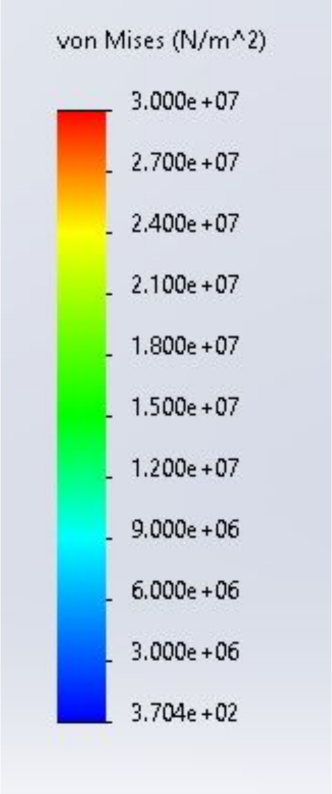
Simulation Analysis

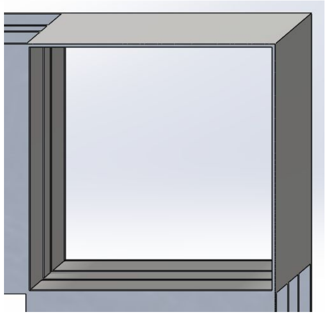


Structural Analysis

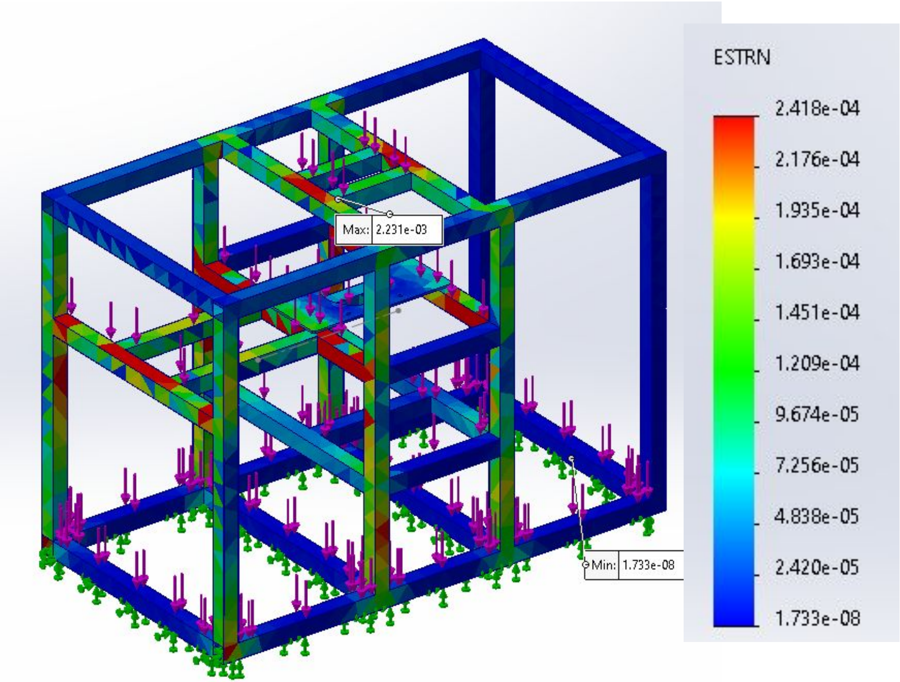
- FEA analysis conducted on a skeleton model of the cart
- Forces applied are based on an estimate of the components weight
- Modeled with hollow beams since aluminum extrusions are also hollow
- Stresses on the structure range from 3700 Pa to 30 MPa
- Extrusions are made of 6105 T5
- Aluminum which have a yield strength of 120-260 MPa (17-38 KSI)
- M6 Screws used have yield strength of 170 KSI

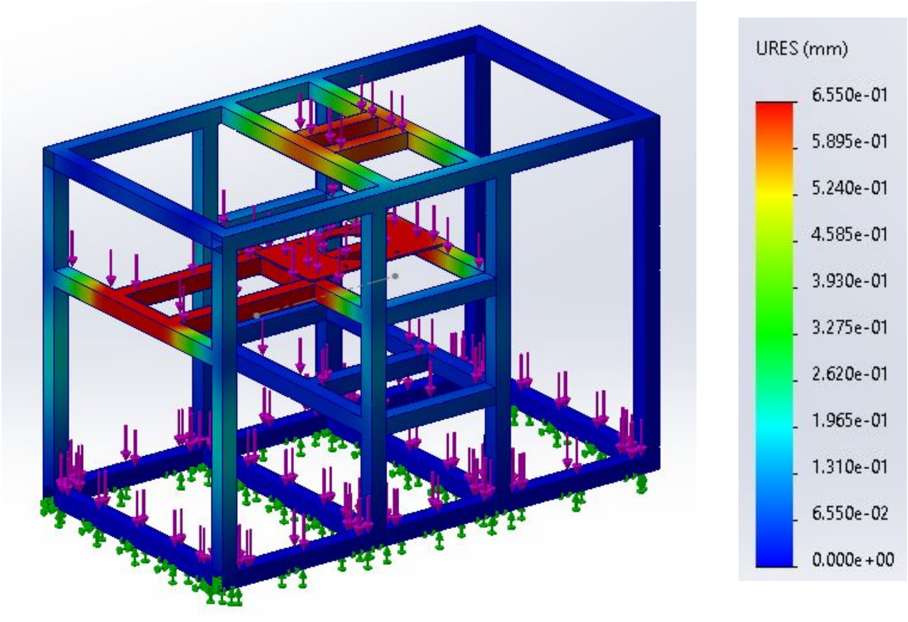






Structural Analysis Continued

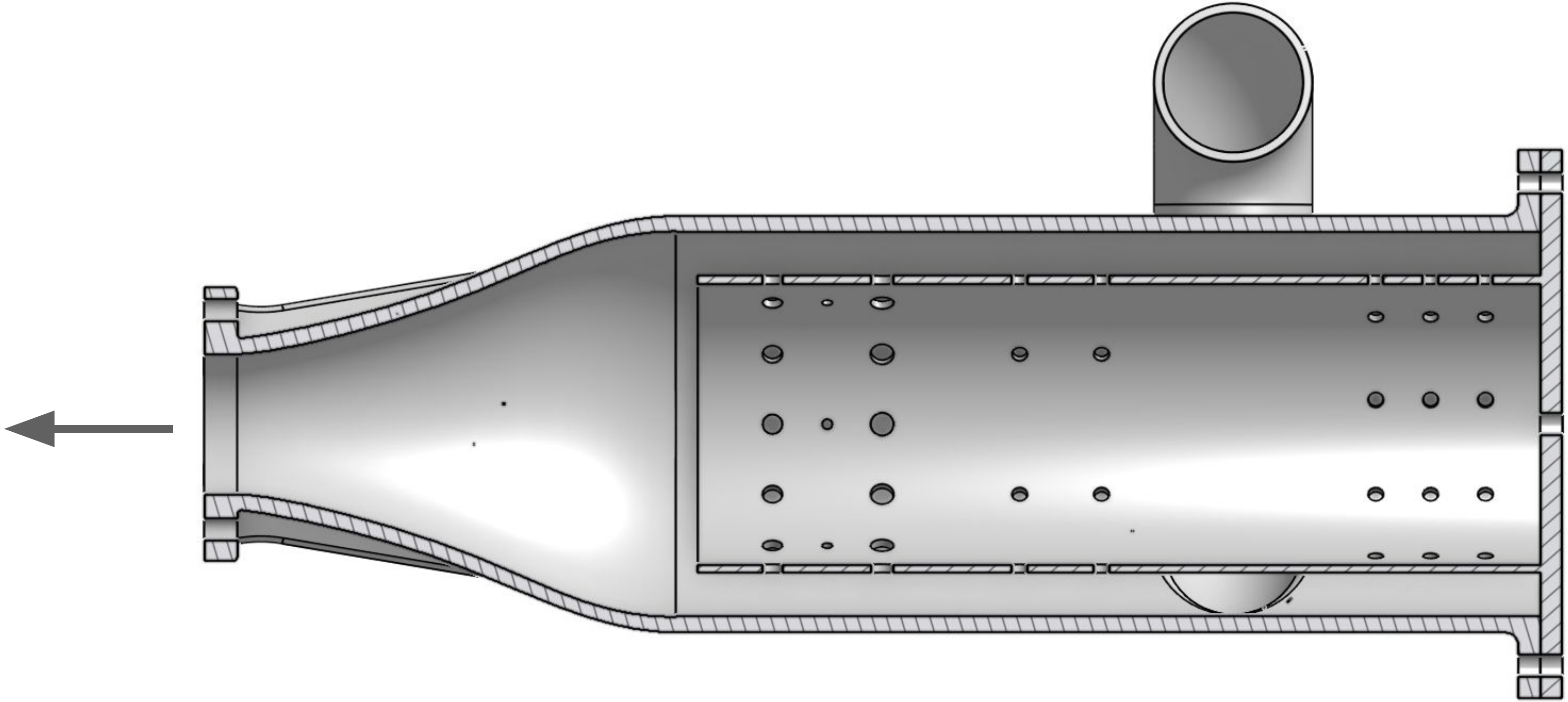




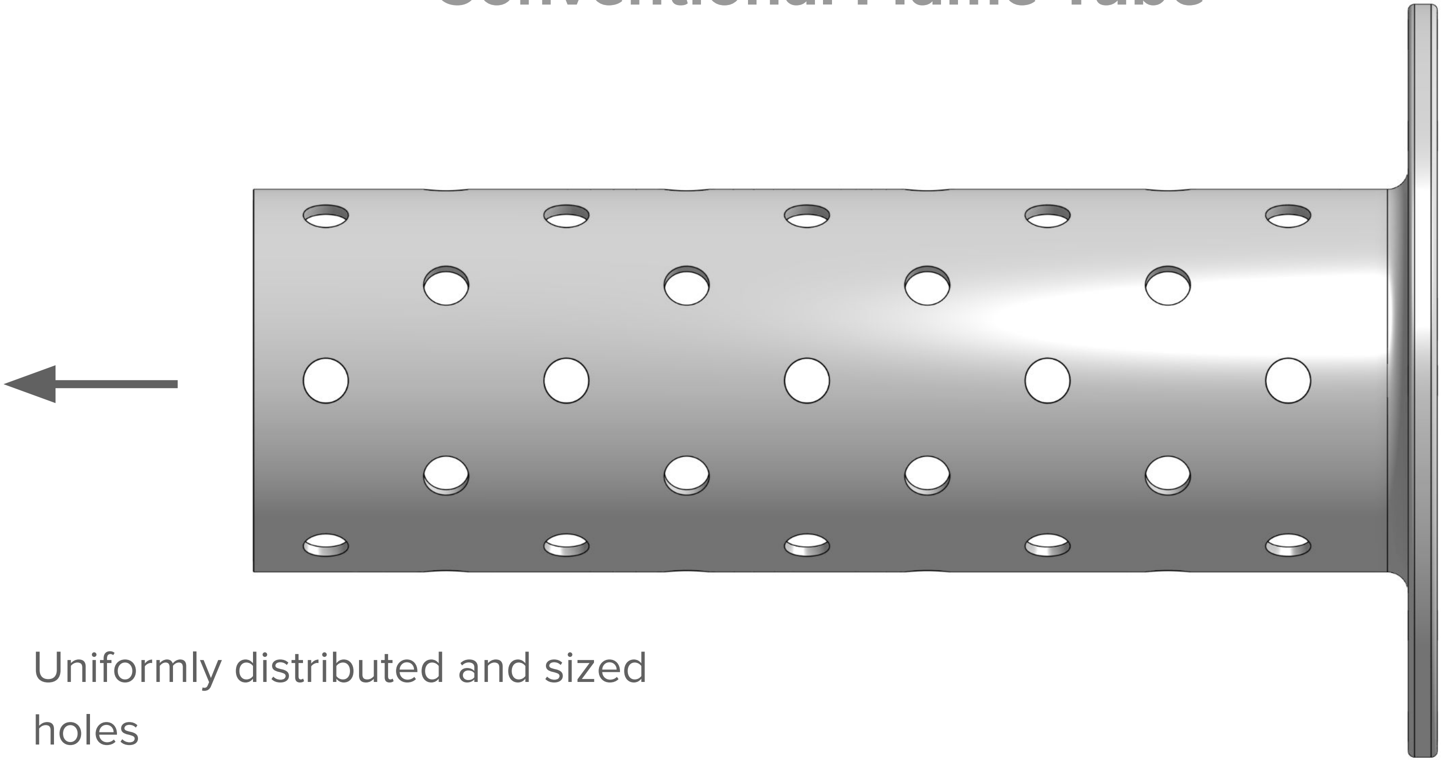
Strain range from 1.733e-8 to 2.418e-4

Displacement: Range from none to 0.65 mm at the highest

The Combustion Chamber

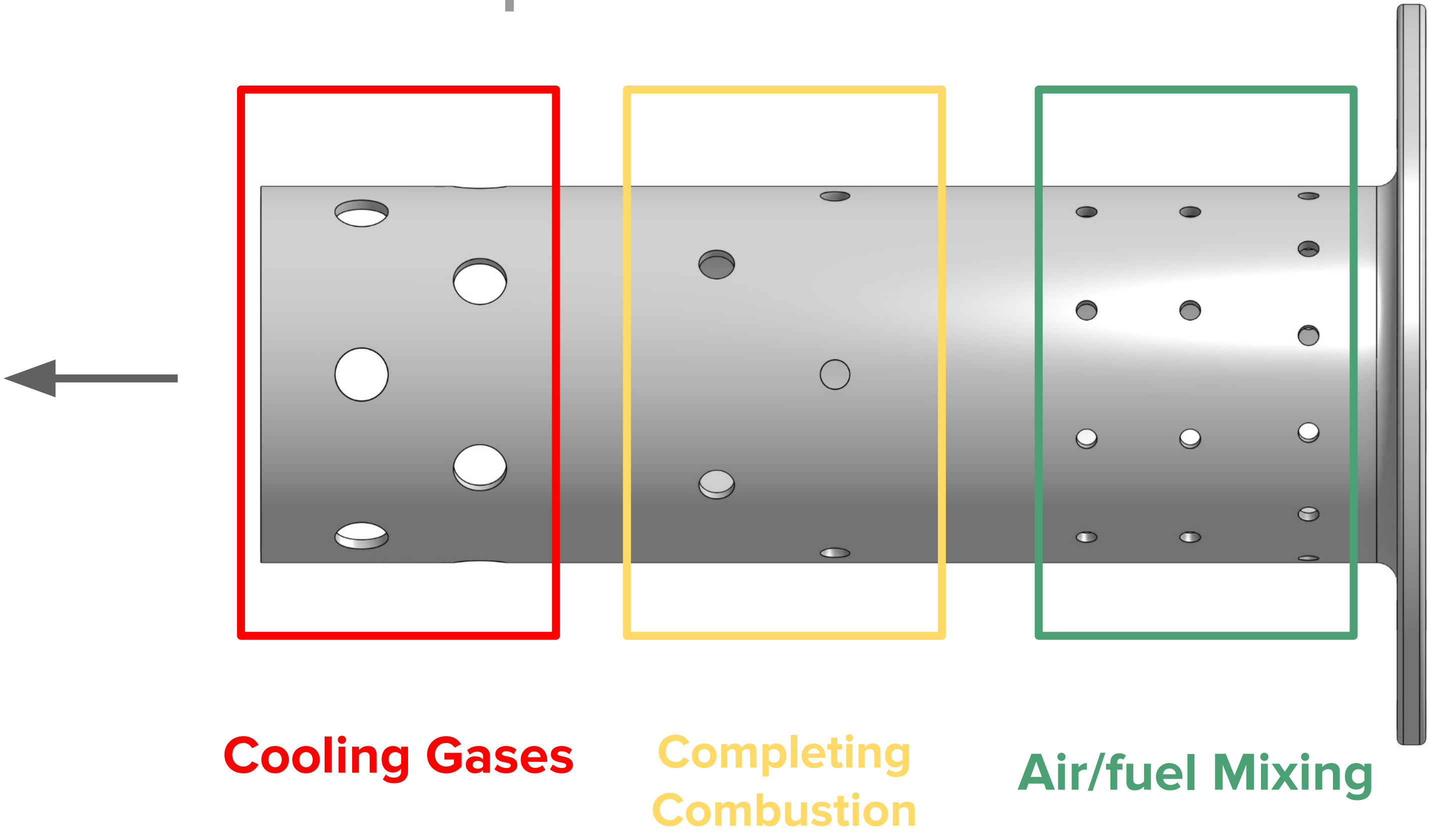


Conventional Flame Tube

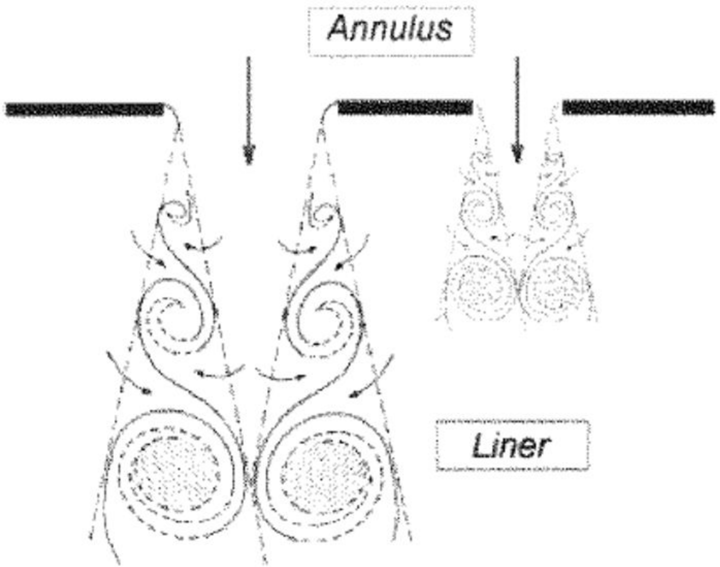


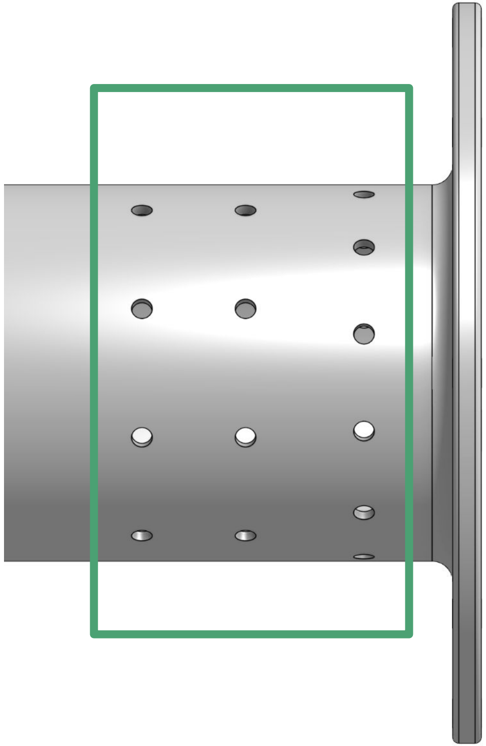
- Uniformly distributed and sized holes
- Not fully optimized for combustion

Specialized Flame Tube



Specialized Flame Tube



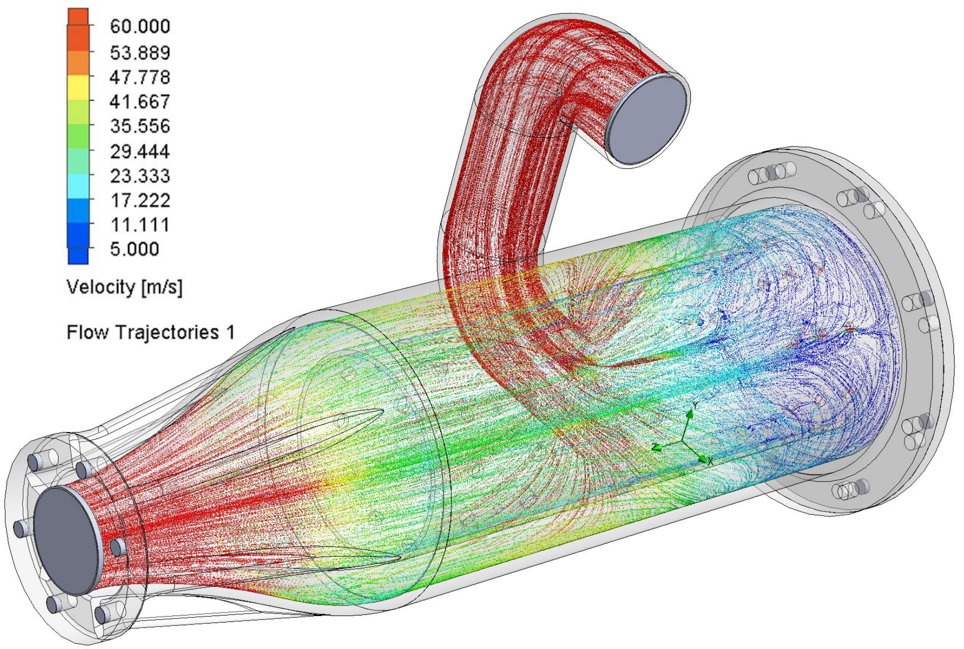


- "Micro-mixing" occurs with high velocity air flows through small radius holes

Airflow Distribution

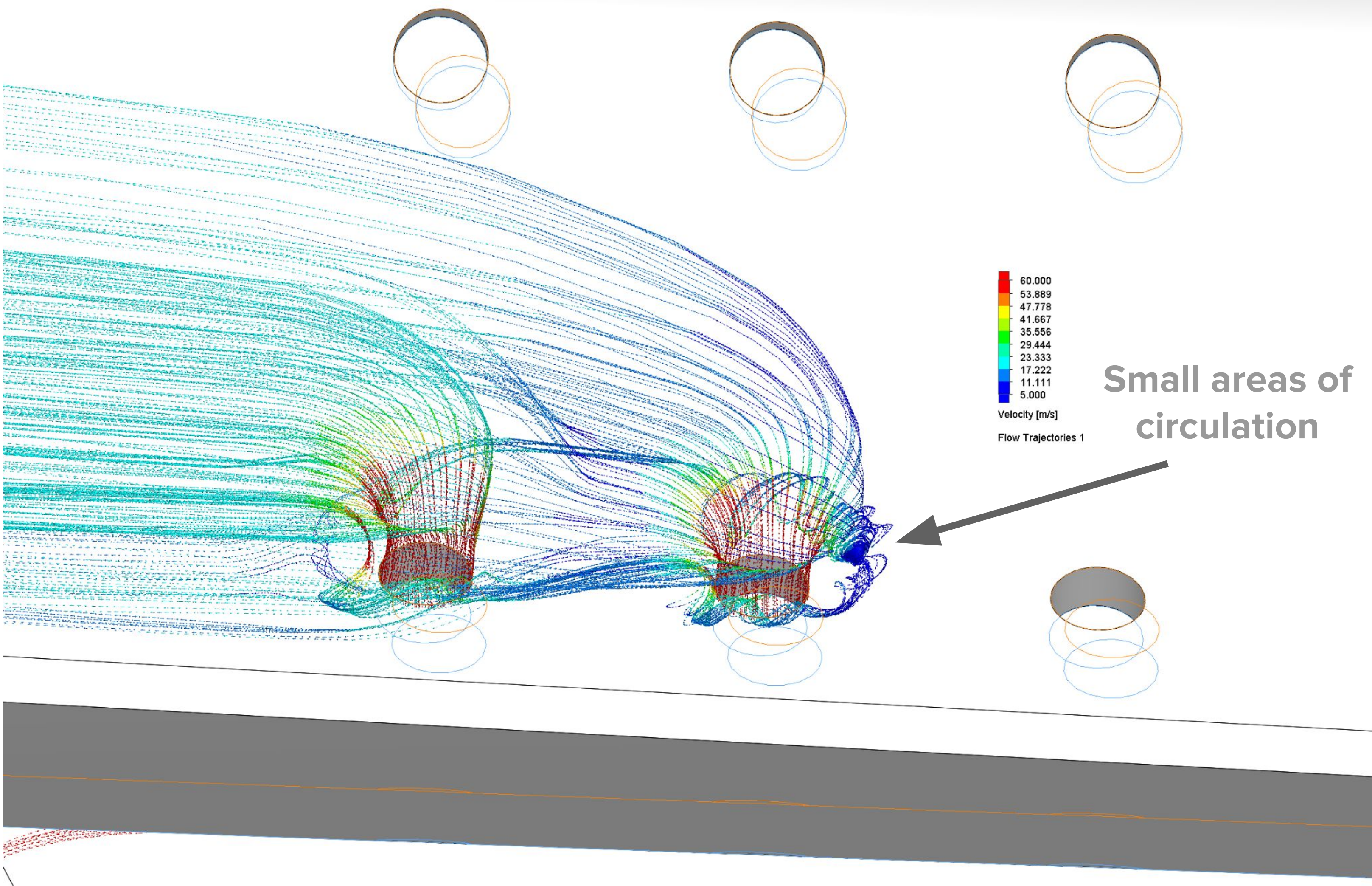
- Total hole area is 1.89x the compressor inducer area for complete combustion

- Focused on improvements in the primary zone airflow for better fuel/air “micro-mixing”



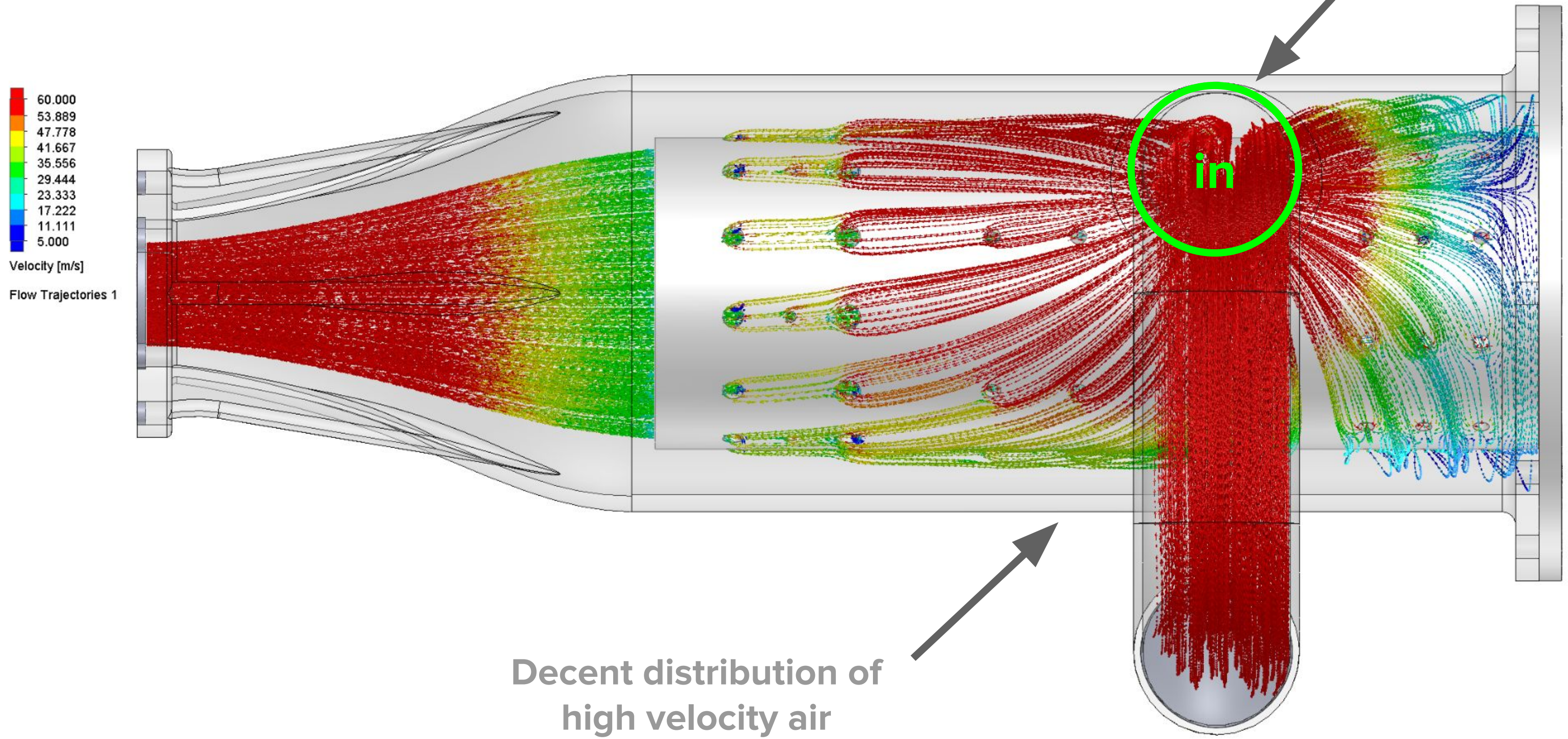
Iteration	Hole Arrangement (per hole)	% of Zone Hole Area	% Total Holes	Total Hole Area (mm^2)
Rev. 5	Zone 1: (27x) 7.0325 mm Zone 2: (12x) 7.071 mm Zone 3: (12x) 10.62 mm (6x) 4.792 mm (12x) 9.079 mm	Zone 1: 69% Zone 2: 31% Zone 3: 89%	189%	6,080.13

Primary Zone Micro Mixing

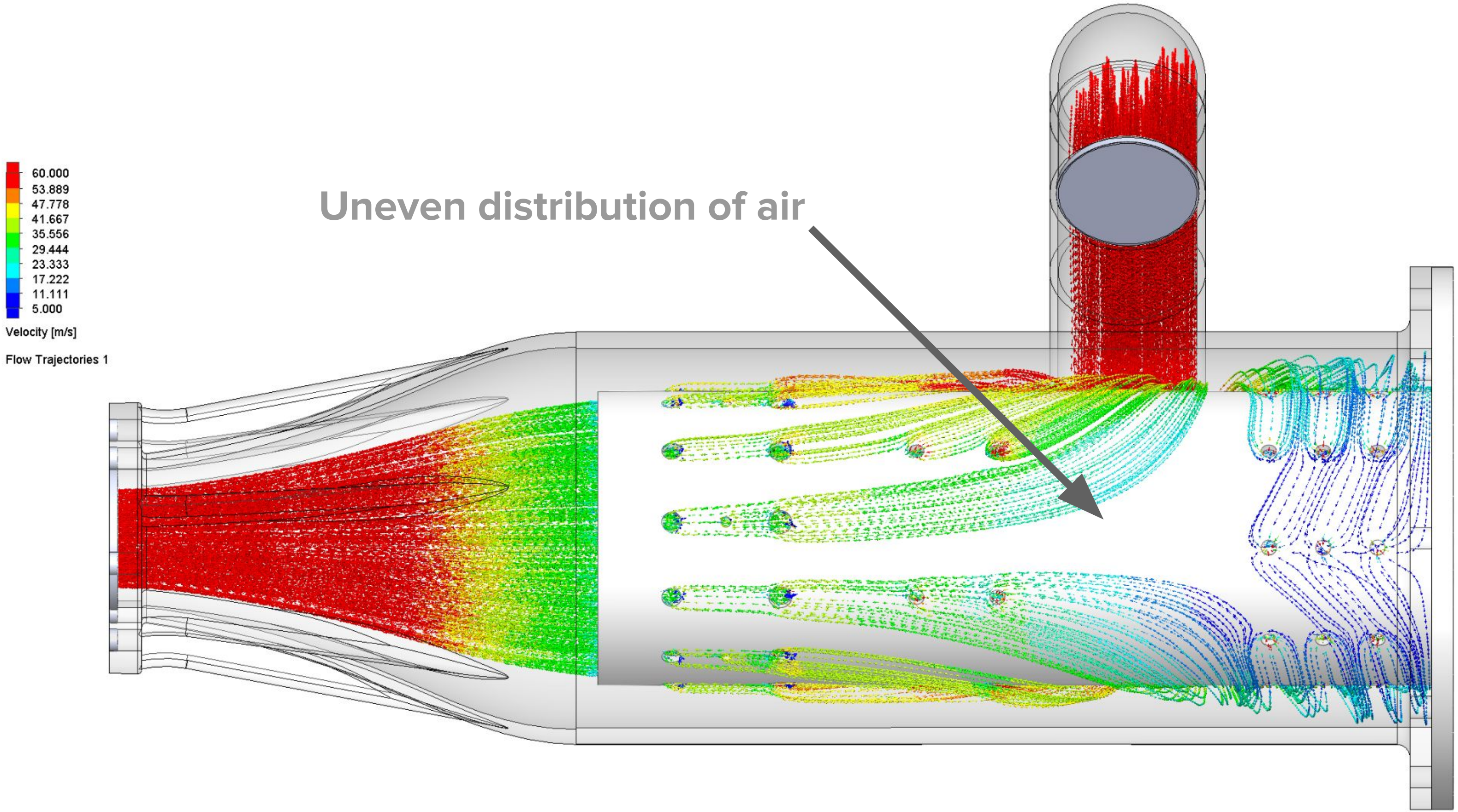


(Compressor Inlet side)

Offset inlet placement



Decent distribution of high velocity air


60.000
53.889
47.778
41.667
35.556
29.444
23.333
17.222
11.111
5.000
Velocity [m/s]
Flow Trajectories 1
Uneven distribution of air

Combustion Analysis

Combustion Analysis

- SimFlow CFD was used for a spray injection type combustion simulation

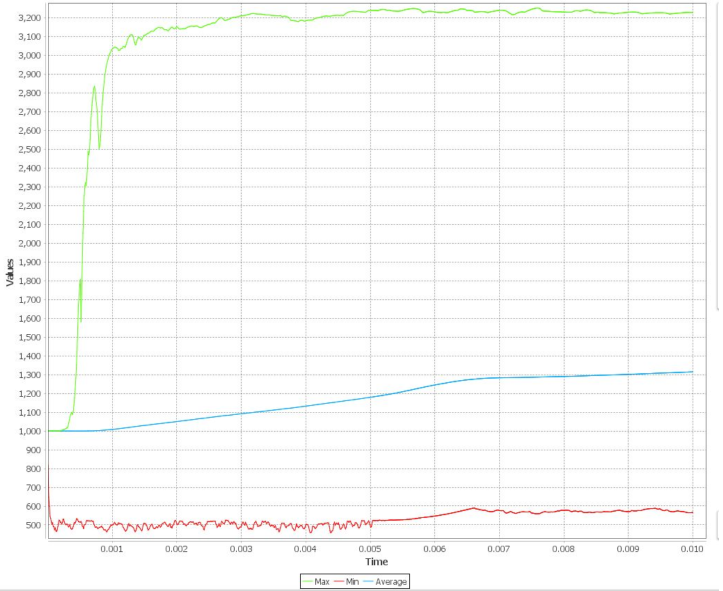
<u>Goal:</u>

  - Visualize and understand the interaction between compressed air and expanding gasses

- Results are <u>inconclusive</u> due to a lack of detail in the mesh and no compressor air is represented

  (more on that later)

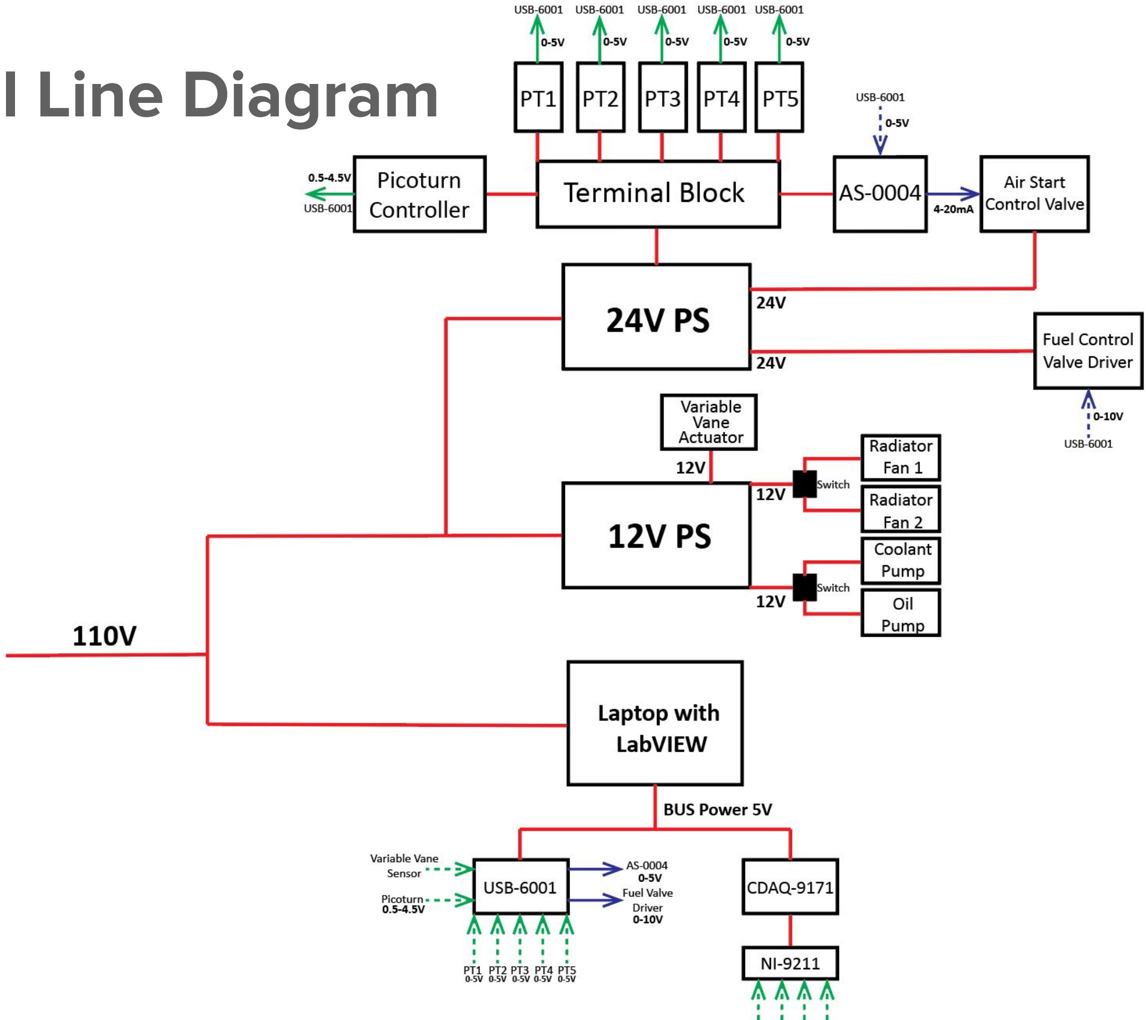
Temperature (°F) vs. Time (s)



Scale showing temperature (°F)

Instrumentation and Controls

Electrical Line Diagram



Instrumentation

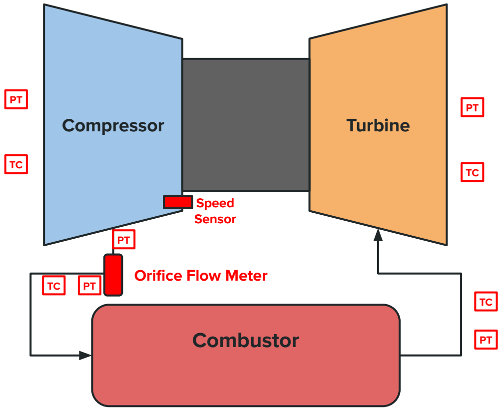
Station 1:
- Pitot-static tube with SS pressure transducer
- Exposed K-type thermocouple

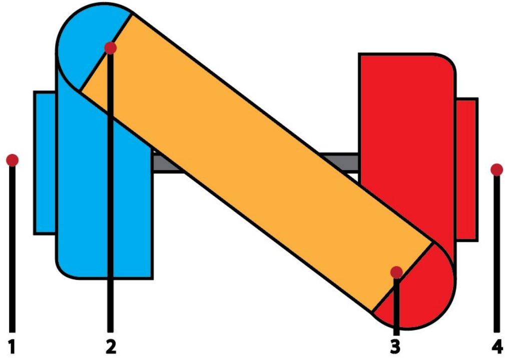
Station 2:
- SS pressure transducer
- K-type thermocouple probe

Station 3:
- SS pressure transducer
- K-type thermocouple probe

Station 4:
- Pitot-static tube with SS pressure transducer
- Exposed K-type thermocouple

- Orifice flow meter uses 2 pressure transducers to measure air flow rate
- Picoturn speed sensor directly measures compressor RPM (need to drill into housing)





T= 60.3°F P= 14.7psia

T= 183.3°F P= 26.5psia

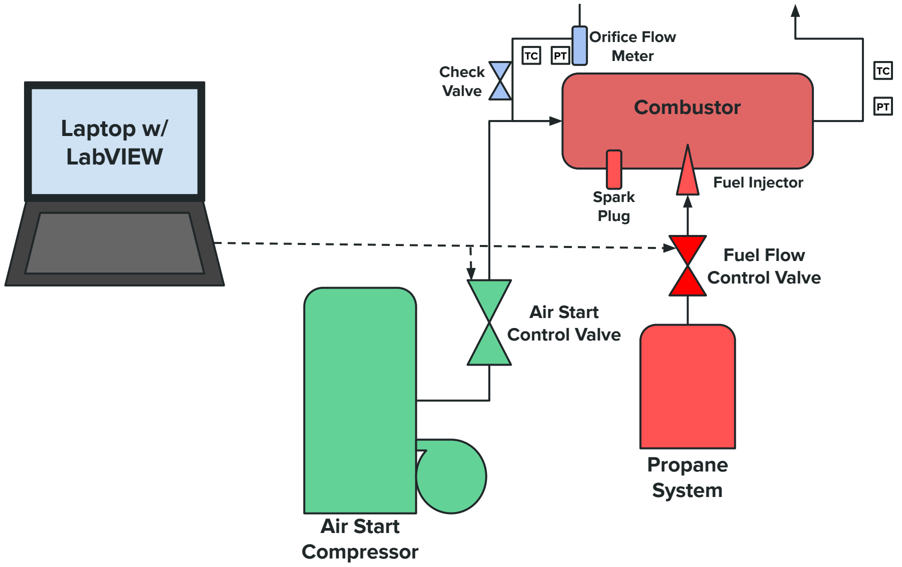
T= 1250°F P= 26.5psia

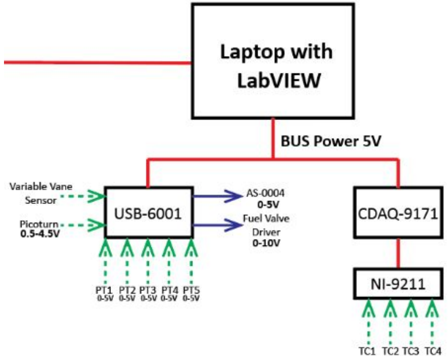
T= 1051°F P= 14.7psia

*values based on design point

Controls

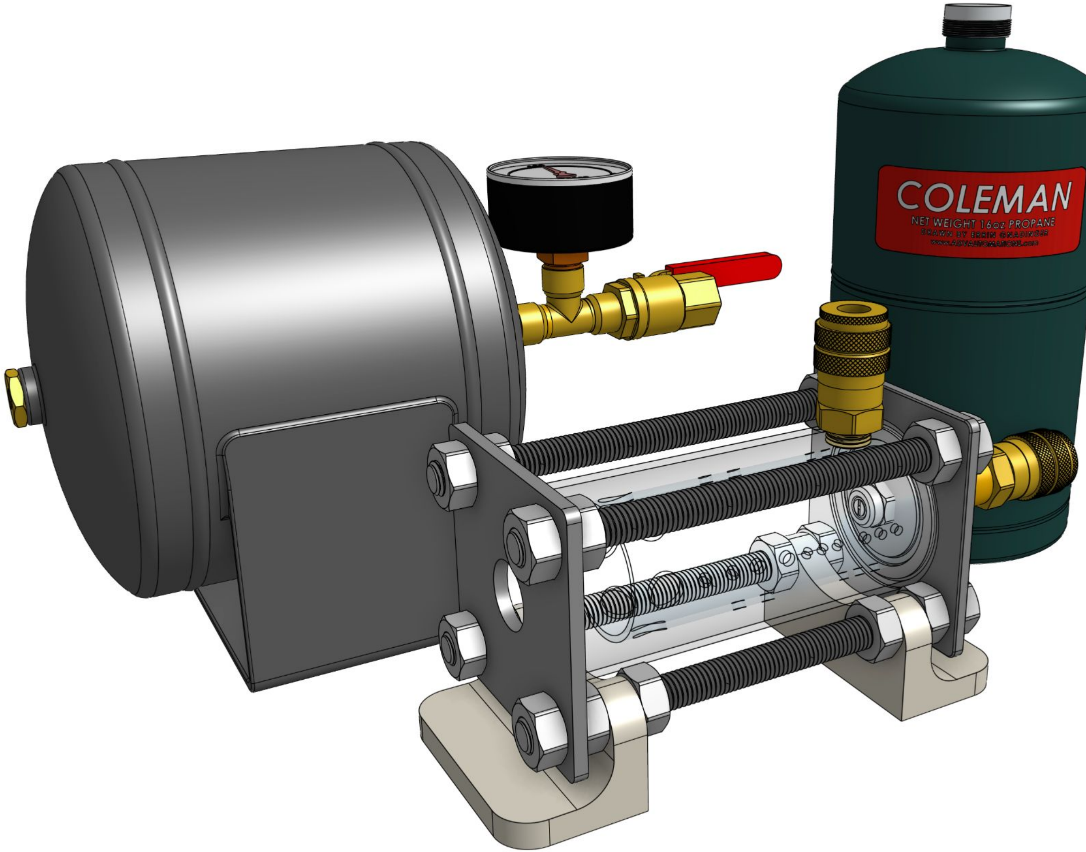
- DAQ system includes 2 USB DAQ devices
- Get signals from sensors and send signals to control valves
- Air start control valve restricts compressed air flow to retain pressure
- Fuel flow valve opens variably based on the combustor exhaust temperature

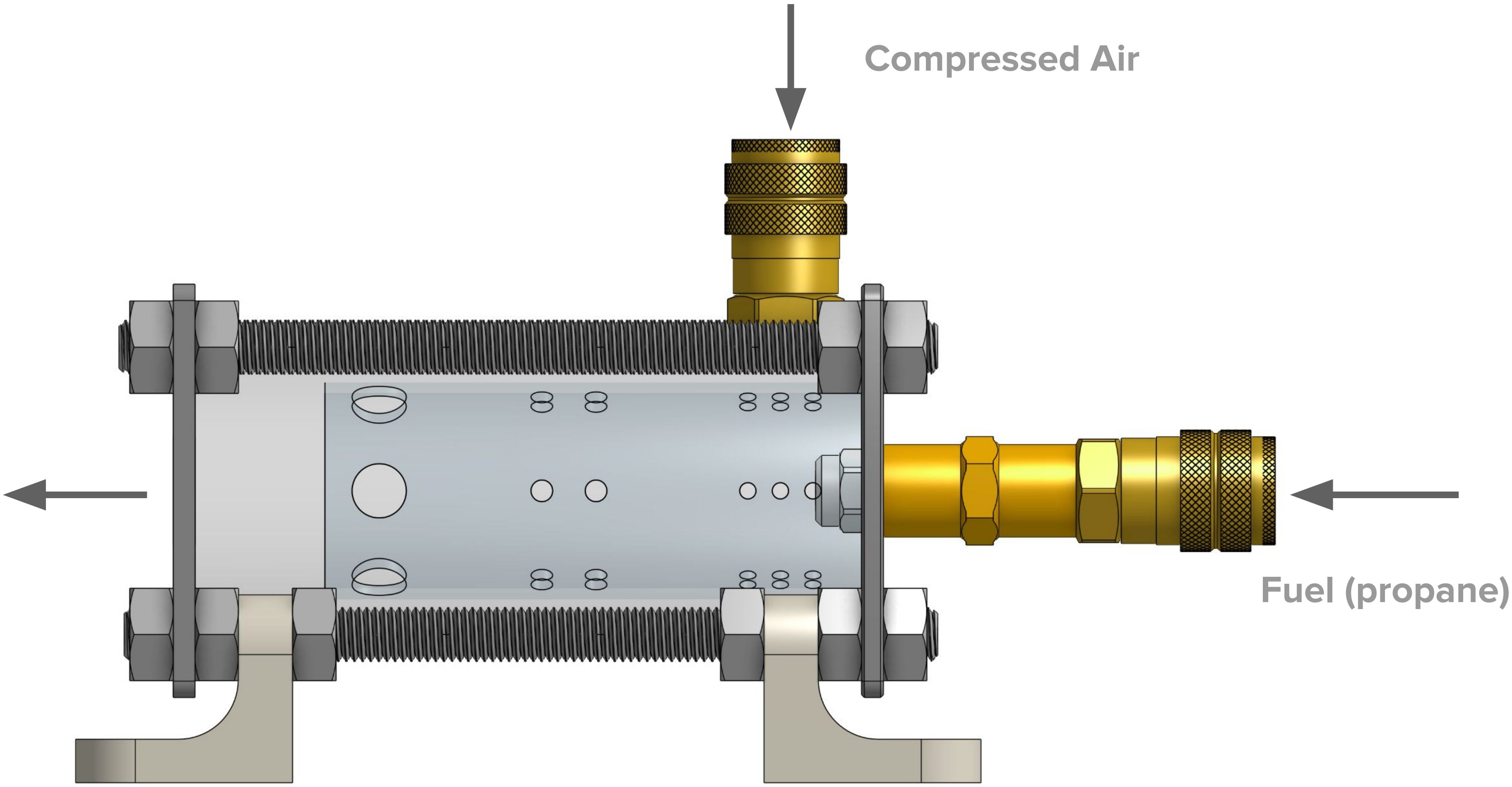




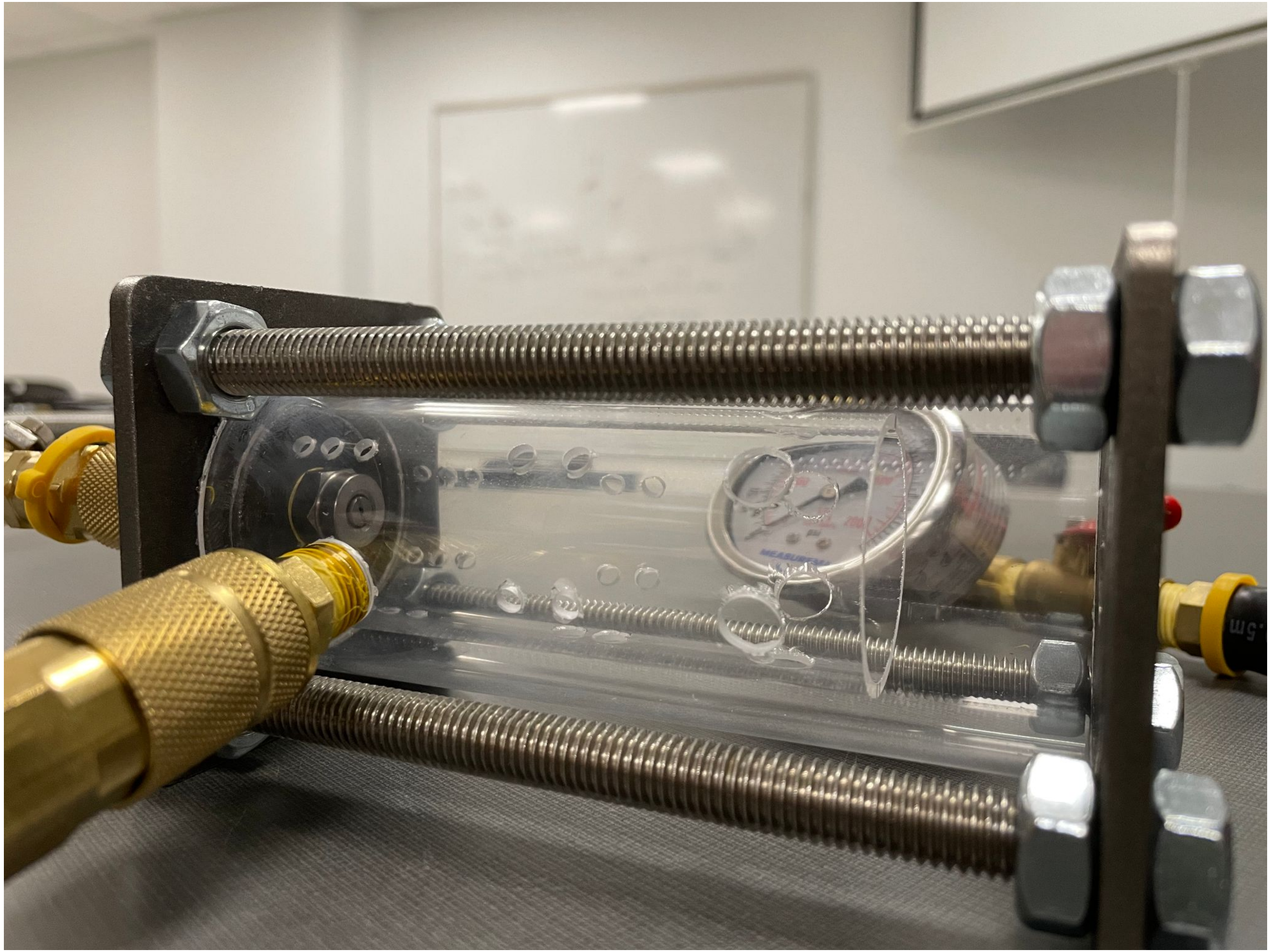
Scale Model Combustion Chamber

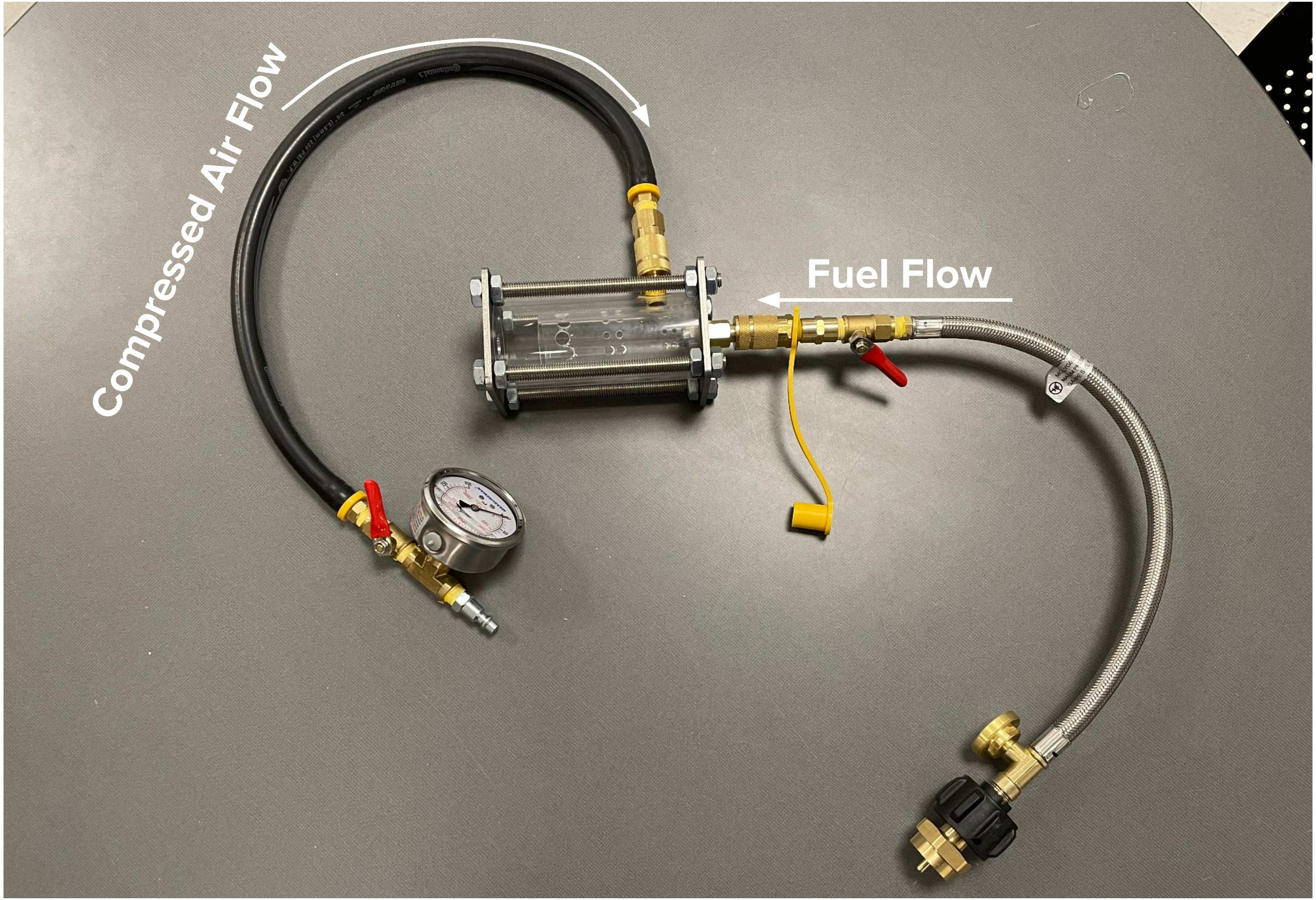
Scale Model Combustion Chamber




Compressed Air
Fuel (propane)

Quartz Glass Flame Tube




Compressed Air Flow
Fuel Flow

Conclusions

Deliverables

- CAD model of the test stand system design
- BOM for ordering parts to construct the system
- Line diagrams of fluid and electrical components to assist construction

Future Work...

- MGU-H (motor/generator) in series
- Scaled combustion chamber prototype testing
- Circuit diagrams and LabVIEW interface coding