High Temperature High Velocity Direct Power Extraction Using an Open-Cycle Oxy-Combustion System

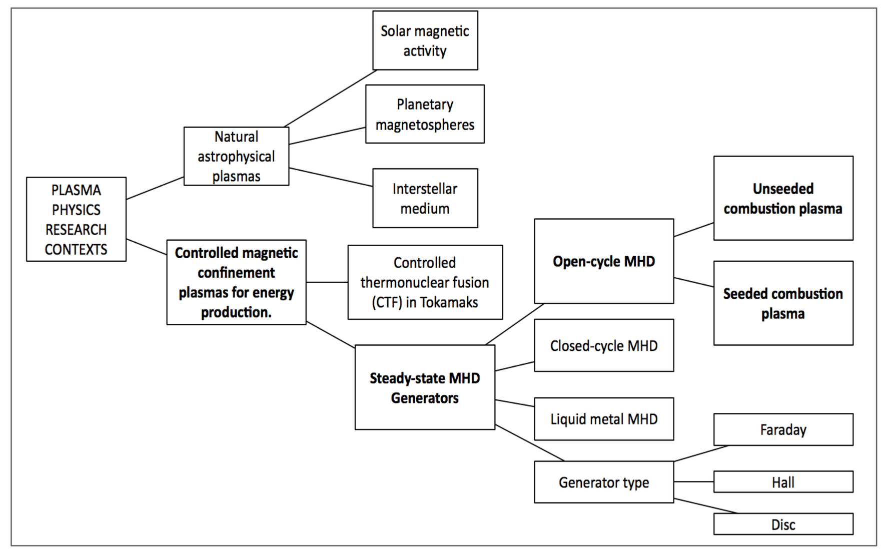
M. Hernandez, L. Cabrera, M. Chaidez, O. Vidana, A. Choudhuri, and N. Love
Department of Mechanical Engineering, The University of Texas at El Paso

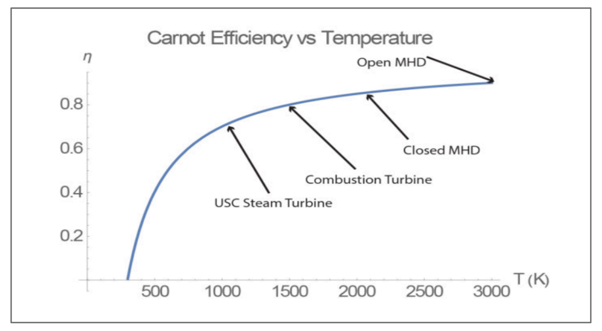
1. Introduction

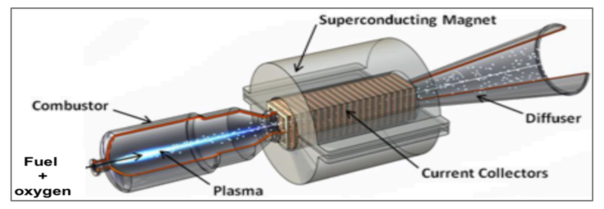
- Open cycle DPE is sensitive to the electrical conductivity of the exhaust gases, which is a strong function of temperature and has a functional range of 2300 to 3500 K.
- This temperature range is difficult to manage due to material constraints, thus flow is usually seeded to enhance the conductivity of the gases allowing for operation near the lower temperature limit.
- The current study investigates the use of a DPE oxy-combustion system, which can reach the required high temperatures needed to ionize the exhaust without or with reduced seeding of the flow.

1.1 What is Direct Power Extraction (DPE)?

- DPE is a macroscopic theoretical model or description of plasma physics, where the behavior is described by ionized gas theory, which averages microscopic phenomena. The following diagram describes the research contexts.

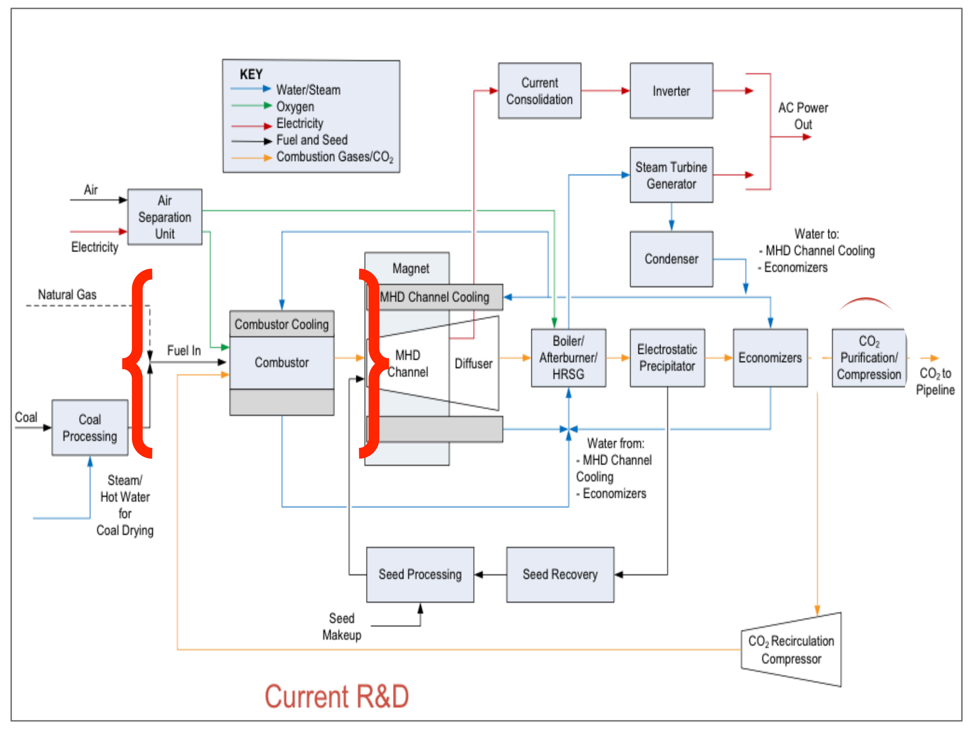


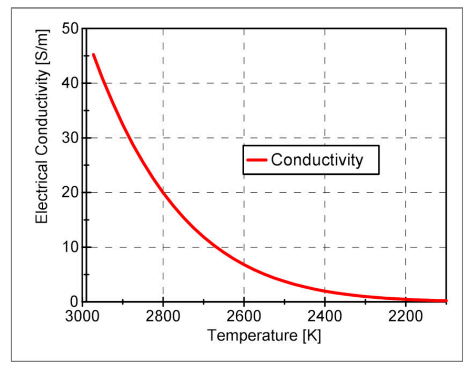


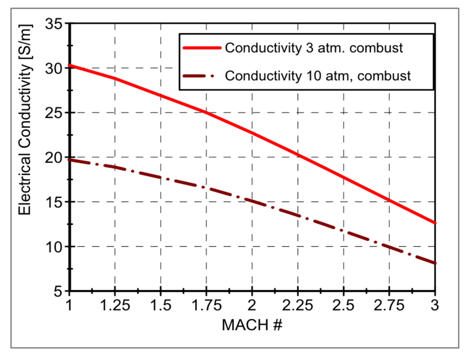


Woodside, R. (2014). Retrospective and Prospective Aspects of MHD generation. DOE NETL MHD Workshop.

1.2 Open cycle CH_4/O_2 and H_2-CO/O_2 Fed DPE Combustion Plasma







Strock, J. (2014). Oxyfuel Combustion Components Relative to a Future MHD Concept. DOE NETL MHD Workshop.

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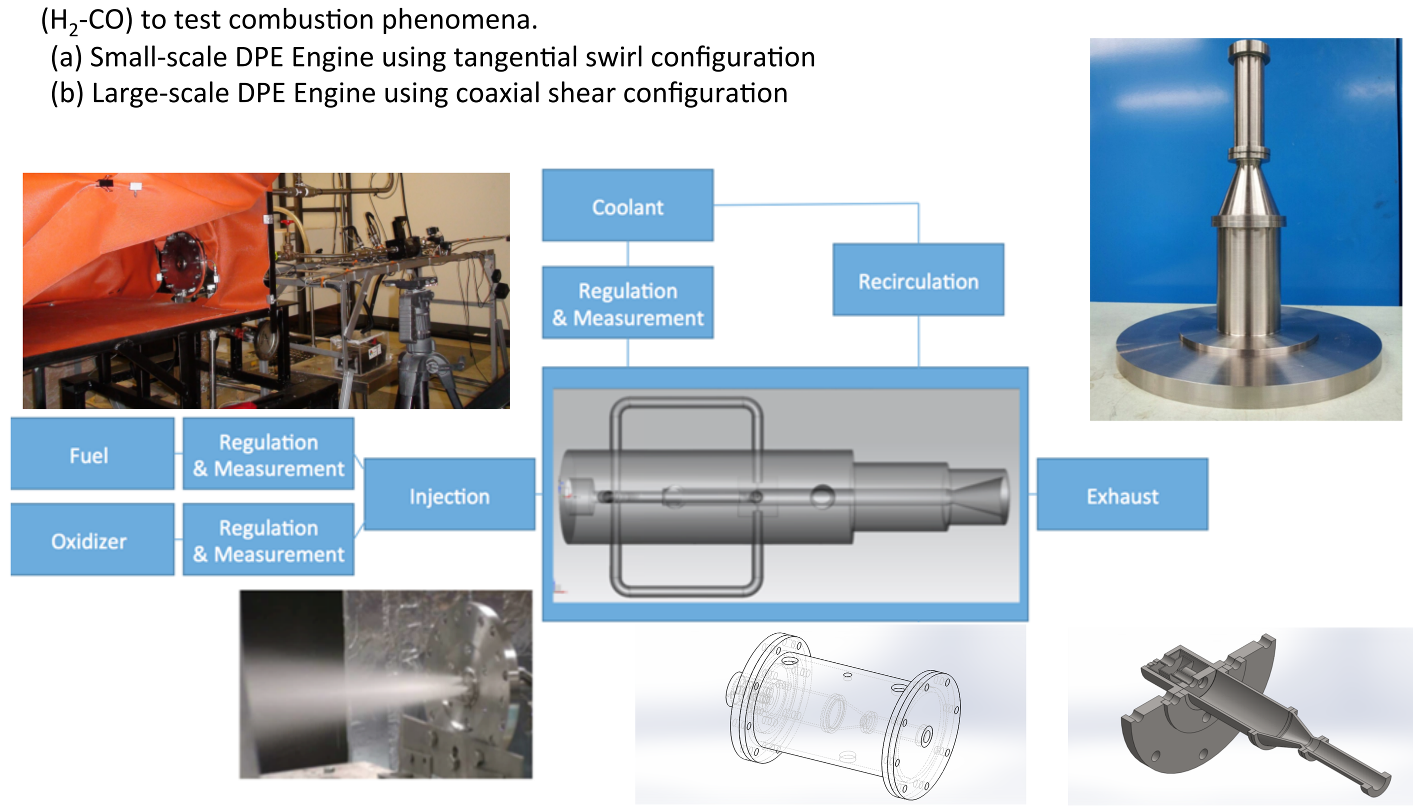
1.3 Research Objectives

- Investigate the flame structure and flame stability of a steady-state DPE Open-Cycle Engine at 2800 to 3000 K
- Develop two experimental DPE setups to operate at this temperature using Natural Gas (Methane) and Syngas (H_2-CO) to test combustion phenomena.
  - (a) Small-scale DPE Engine using tangential swirl configuration
  - (b) Large-scale DPE Engine using coaxial shear configuration

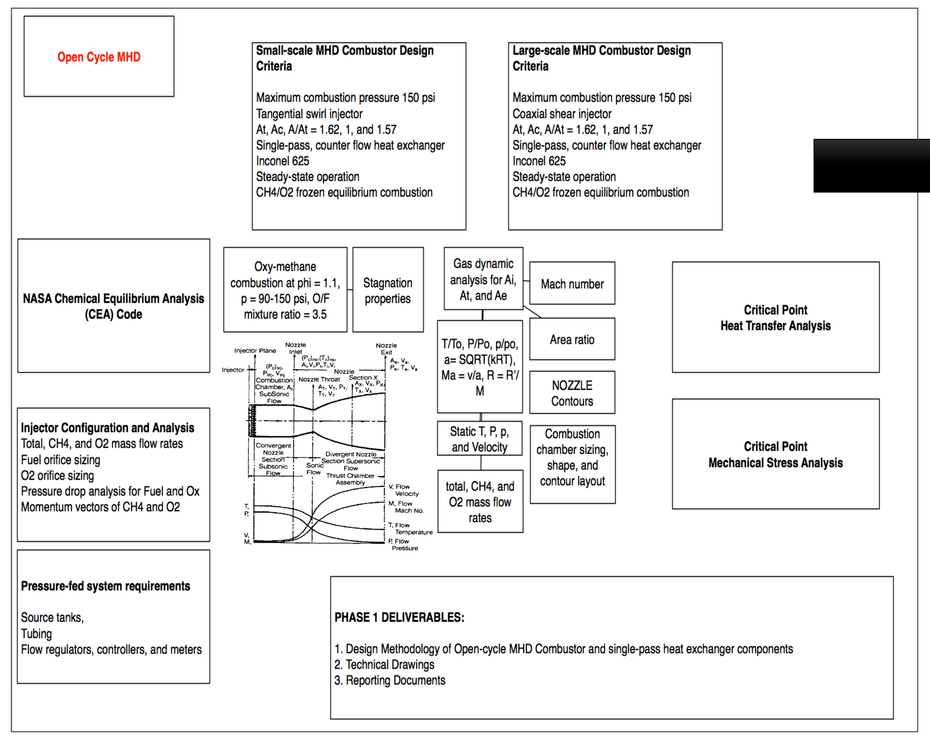


2. Methodology

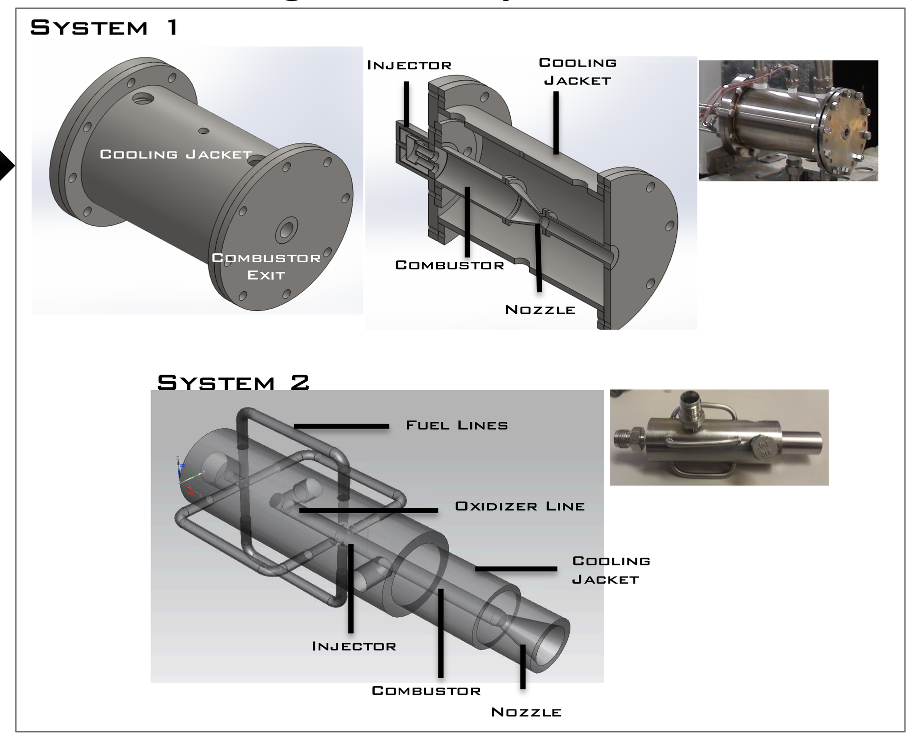
- The experiment requires two test apparatuses to study the scaling effects, injector configuration, and DPE combustion processes. The experimental design of the DPE engines encompass designs from rocket thrust chambers and thermal spray configurations.

2.1 Experimental Requirements and Design Approach

The design framework of the small-scale DPE engine with tangential swirl injector elements and configuration is shown below.



DPE Engine Concepts 1 and 2



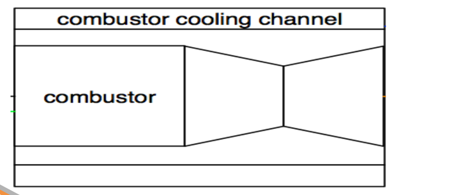
2.2 Thrust Chamber Configuration and Design

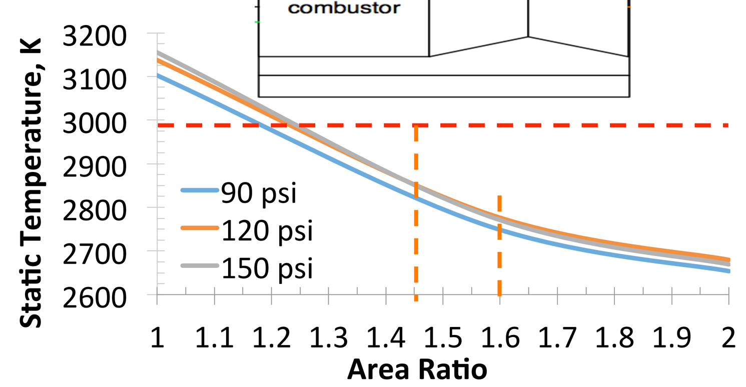
Design Criteria

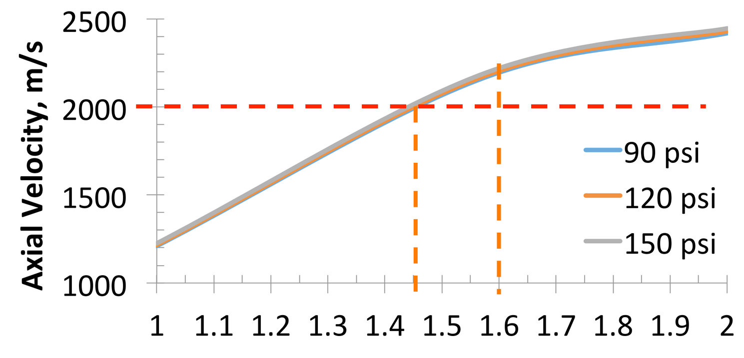
- Maximum constant pressure 150 psi combustion of CH_4/O_2, inlet T = 298 K, phi=1.1, and O/F ratio = 3.5.
  - T_{ad} = 3358 K
  - M = 21.059 1/n
  - $k = C_p/C_v = 1.12$
- Fixed throat diameter = 0.145 in.
- Fixed chamber diameter = 0.185 in.
- Tangential swirl injector injection-plane
- Assumed complete combustion with a characteristic length = 2 in.
- Well-rounded curvature at throat = $1.5R_t$
- Divergence angle of 2-15 degrees
- Wall material options: nickel-based alloys or cobalt-based alloys

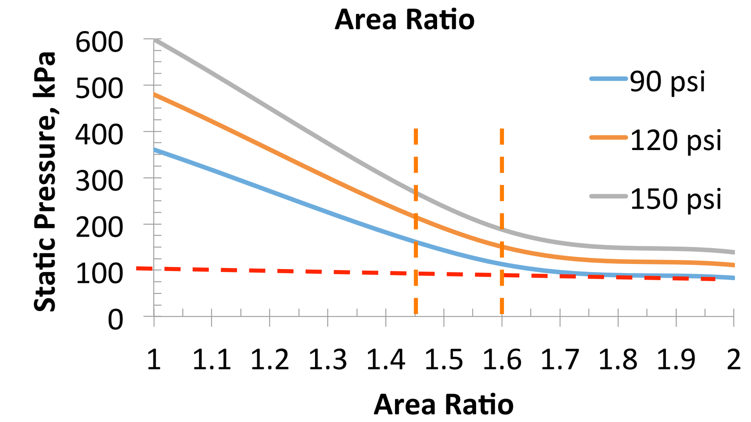
Conventional Gas Dynamic Solution-Space

The gas dynamic solution-space is presented for three constant-pressure CH_4/O_2 stagnation-static property combustion data sets.





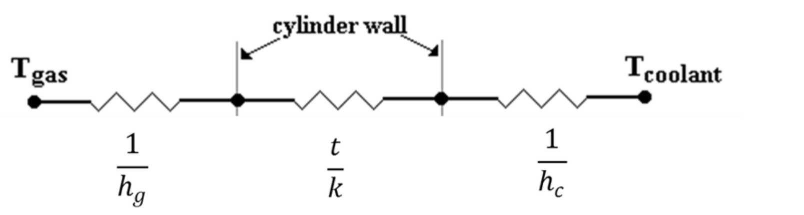




2.3 Single-pass Heat Exchanger Design

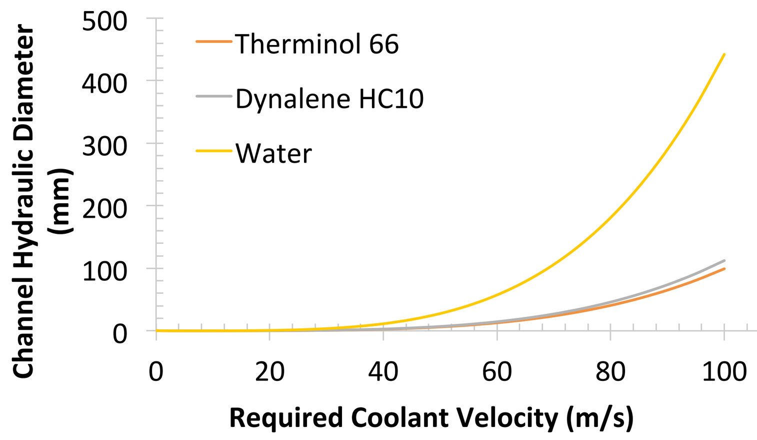
Design Criteria

- Thermal resistance model employed
- Reduced Bartz's equation taken for initial estimation
- Heat flux fixed by wall temperature, T_{wall} = 1273 K
- Optimal wall thickness range = 3 to 5 mm
- Heat flux @ 114 psi= 5.8 MW/m²
- Total Heat @ 114 psi= 8.7 W

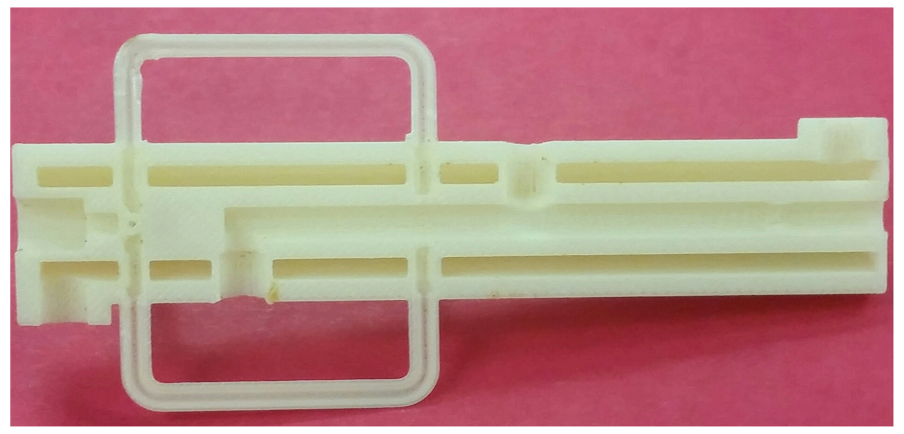


- Sieder-Tate correlation employed to relate coolant velocities to hydraulic diameters
- Nucleate boiling regime not accounted for
- Coolants with maximum temperature range considered desirable

Coolant Configuration Comparison



- 3D printing aids in visualization of cooling concepts

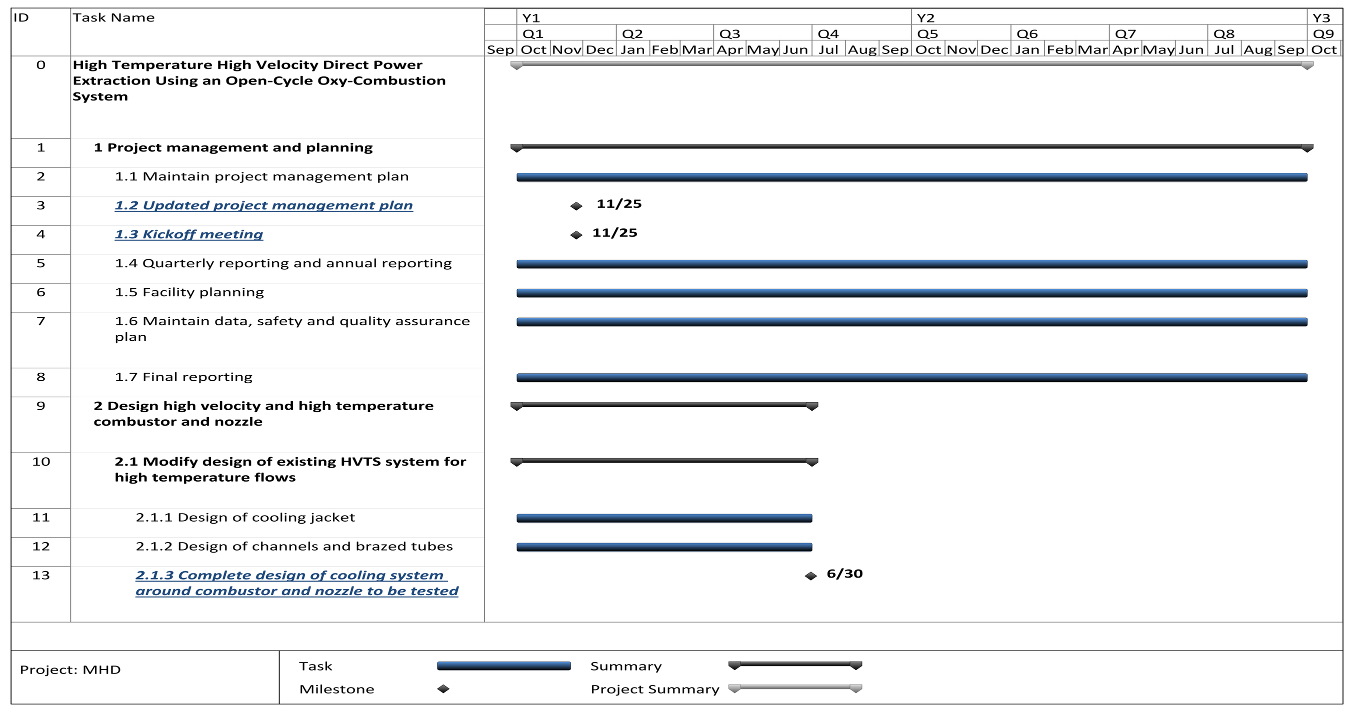


3. Findings

- A comparison of chamber stagnation pressures allows for the simple visualization of the critical parameters, such as required mass flow, attainable exit conditions, and the magnitude of heat rejection to the walls.

General Properties	Units	Condition 1	Condition 2	Nozzle exit properties	Units	Condition 1	Condition 2
Fuel		CH_4	CH_4	Expansion ratio		1.57	1.57
Oxidizer		O_2	O_2	Diameter	mm	4.6	4.6
Equivalence ratio		1.14	1.14	Temperature	K	2838	2785
Reactant state		gas/gas	gas/gas	Pressure	kPa	267	154
Stagnation properties				Velocity	m/s	2004	1985
Stagnation pressure	psi (kPa)	200 (1379)	114 (786)	**Heat transfer**			
Stagnation temperature	K	3398	3320	Adiabatic wall temperature	K	3426	3358
Specific heat ratio		1.12	1.12	Gas-side wall temperature	K	1273	1273
Nozzle throat properties				Throat radius of curvature	in	0.11	0.11
Diameter	m	0.004	0.004	Gas convective coefficient	Btu/in²-s-F	0.002	0.001
Temperature	K	3200	3131		W-m²-K	4463	2830
Pressure	kPa	799	456	Heat flux at throat	Btu/in²-s	5.9	3.5
Choked mass flow rate	g/s	8.29	4.75		MW/m²	9.6	5.8

4. Future Work



Project Milestones List – the next steps

Q4 9/30/2015 Optimize system components
Q5 3/31/2016 Fabrication of finalized cooling unit
Q6 3/31/2016 Fabrication of finalized injector and nozzle systems
Q7 6/30/2016 Testing using cooling facility and novel fuel injectors
Q8 9/30/2016 Systematically characterize flame stability characteristics

DPE Combustion Research Group

Principle Investigators
Norman Love, Ph.D.
Ahsan Choudhuri, Ph.D.

Ph.D. Research Assistants
Luisa A. Cabrera
Manuel J. Hernandez

M.S. Research Assistants
Omar Vidana
Mariana Chaidez
Jad Aboud

Undergraduate Research Assistants
Brian Lovich
Cynthia Gamboa
Gabriela Enriquez

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