CCEFP Project 16HS3: Controlled Stirling Power Unit

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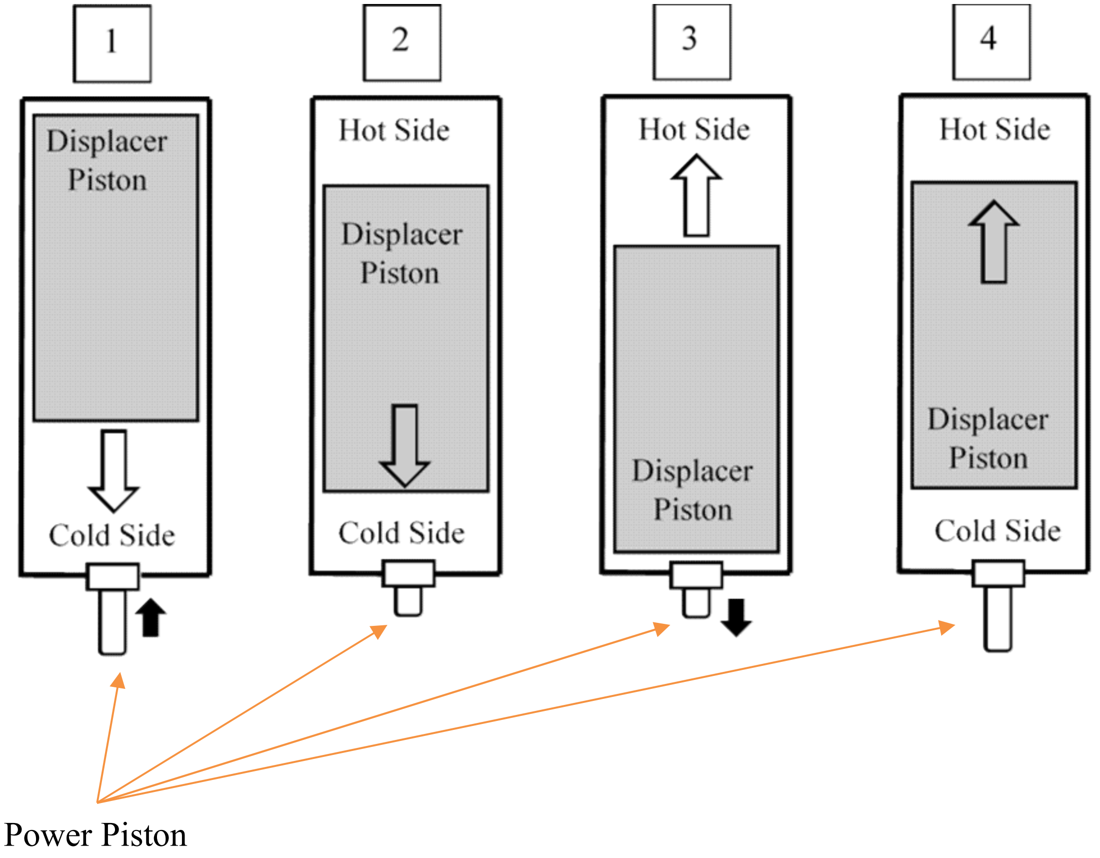
Outline

- Project Overview
- Methods of Control
  - Controlled Displacer Motion
  - Controlled Inter-Unit Mass Flow
- Potential Applications
- Next Steps
- Conclusion

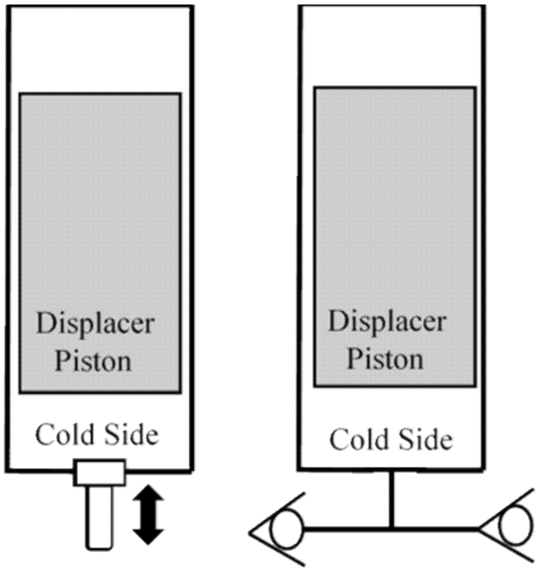
Controlled Stirling Power Unit

- Capable of using heat from many different sources, including waste heat.
- Output power can be hydraulic, pneumatic, mechanical, or electric
- Virtually noiseless operation
- Low maintenance
- Efficient (Stirling cycle approaches Carnot efficiency at high temperatures and pressures)
- Thermodynamics can be controlled

Stirling Engine Cycle



Thermocompressor Arrangement



The Beale Number

$$P \propto V_0 \times f \times p$$

Controlled Displacer Piston

- Decoupled from power piston
- Multiple motion profiles

P = Output power (watts)
p = Median operating pressure (Pa)
f = Power piston frequency (Hz)
V_0 = Volume displaced by power piston (m^3)

Model and Verification

$$\dot U = \dot H + \dot Q - \dot W$$

$$\dot U = \dot m (c_v) T + m (c_v) \dot T = \frac{1}{\gamma - 1}\left(\dot P V + P \dot V\right)$$

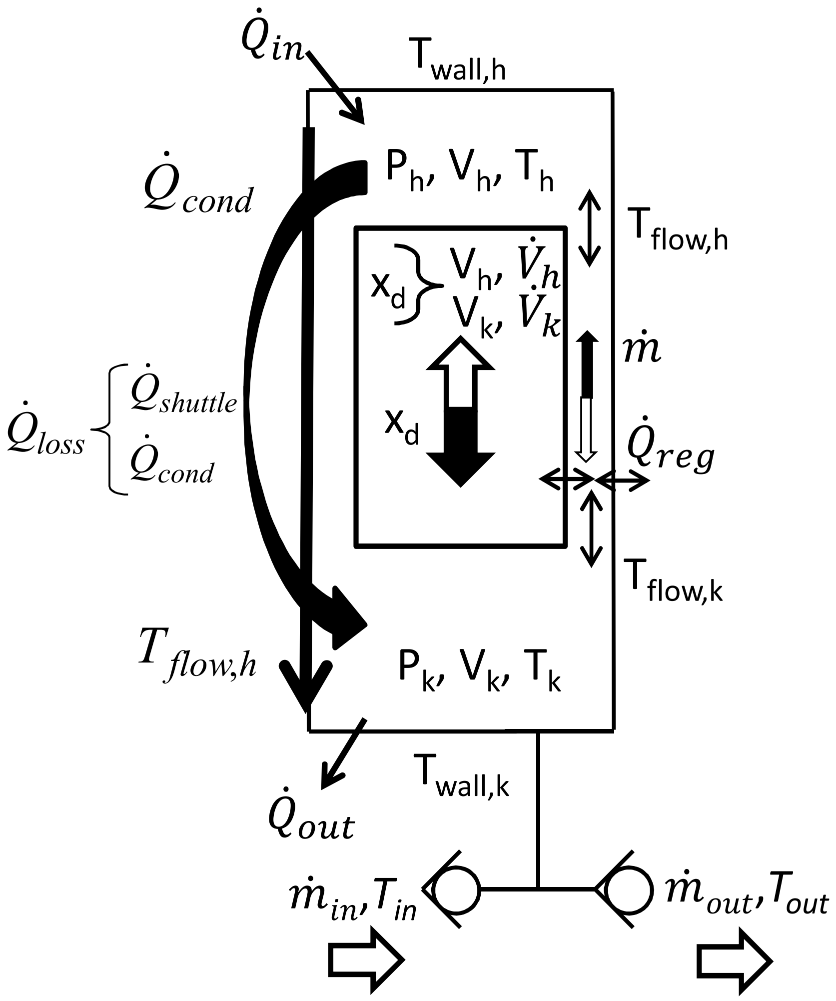
$$\dot H = \sum_k \dot m_k \left(c_p\right)_k (T)_k$$

$$\dot W = P \dot V$$

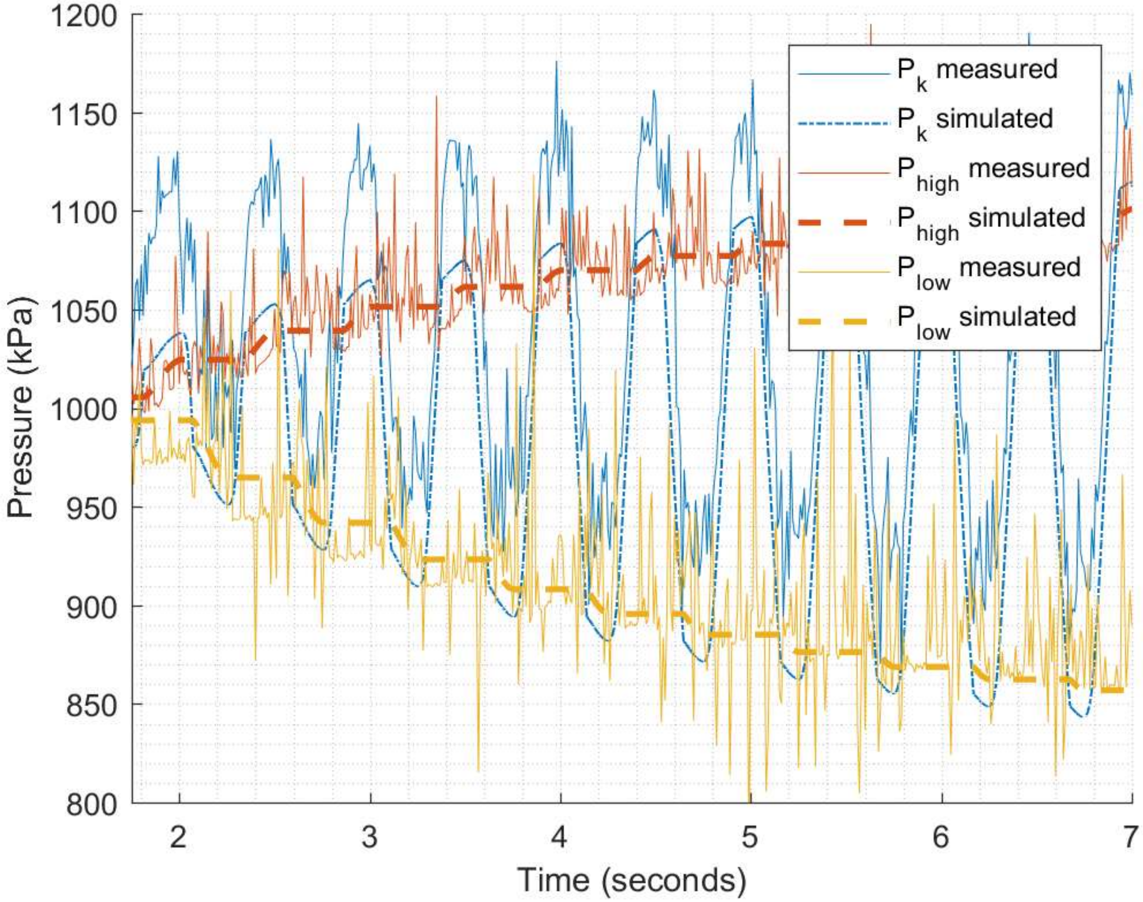
$$R = c_p - c_v$$

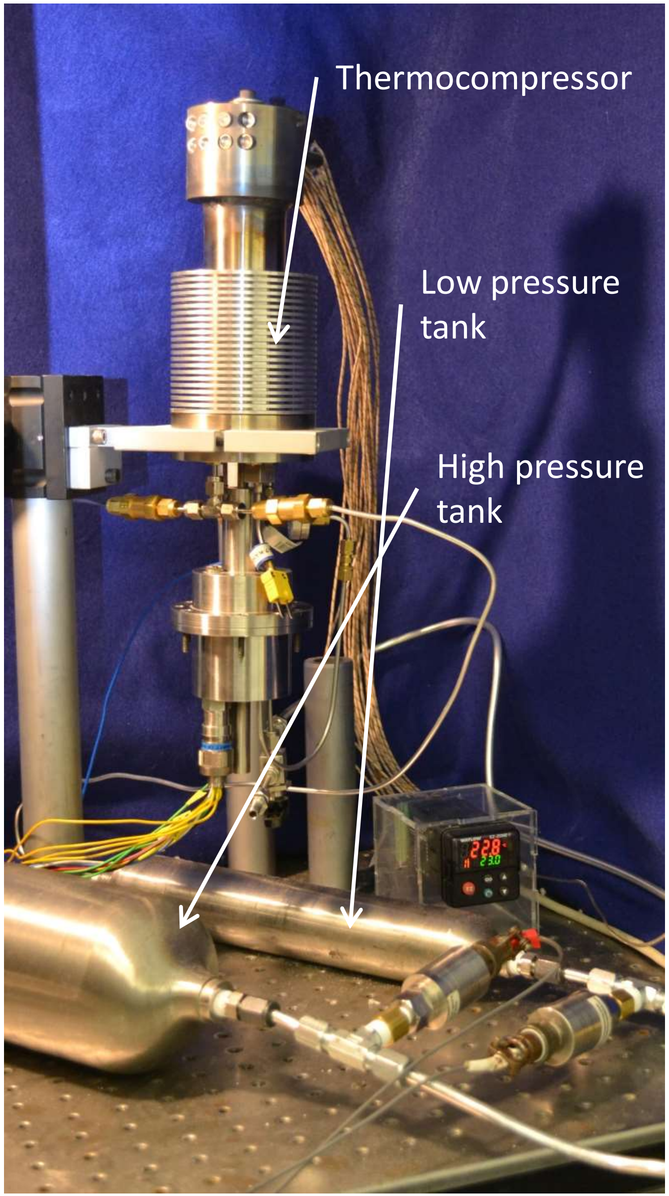
$$\gamma = \frac{c_p}{c_v}$$

$$\boxed{\dot P = \frac{\sum_k \dot m_k T_k (R\gamma) + \dot Q(\gamma - 1) - P \dot V \gamma}{V}}$$



Controlled Displacer





The Beale Number

$$P \propto V_0 \times f \times p$$

<u>Controlled Displacer Piston</u>

- Decoupled from power piston
- Multiple motion profiles

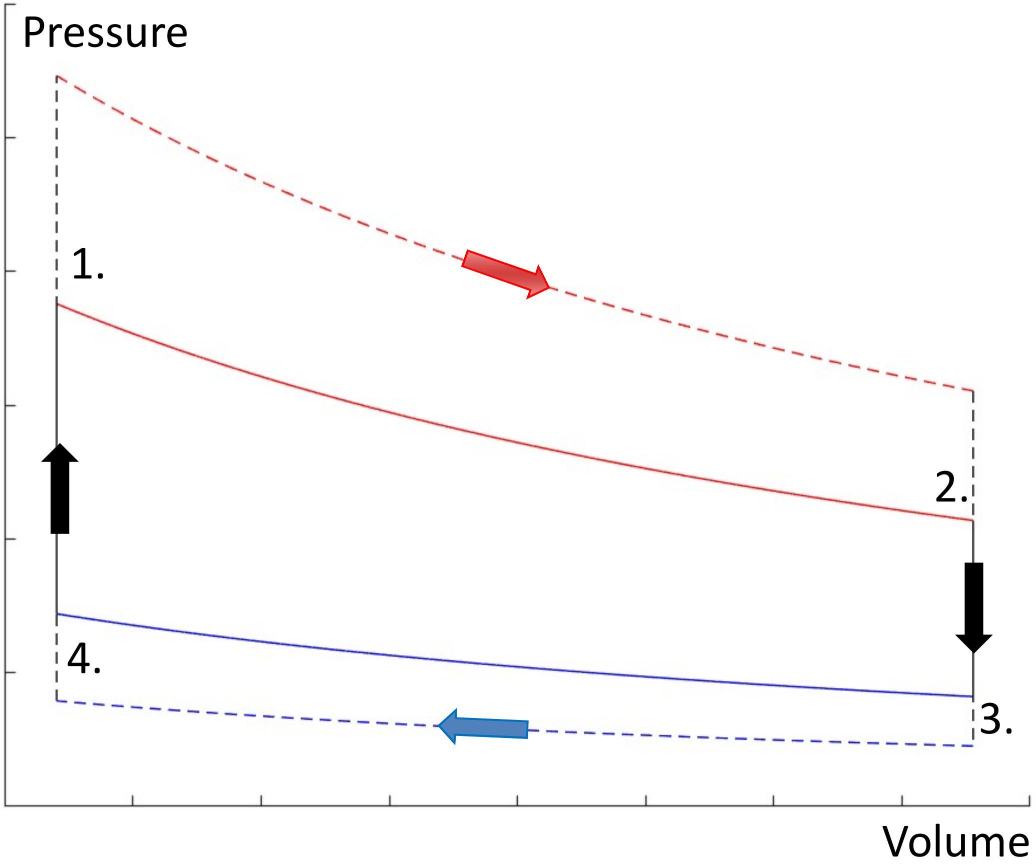
<u>Controlled Mass Flow</u>

- Pressure controlled from mass injected at strategic stages

P = Output power (watts)
p = Median operating pressure (Pa)
f = Power piston frequency (Hz)
V_0 = Volume displaced by power piston (m^3)

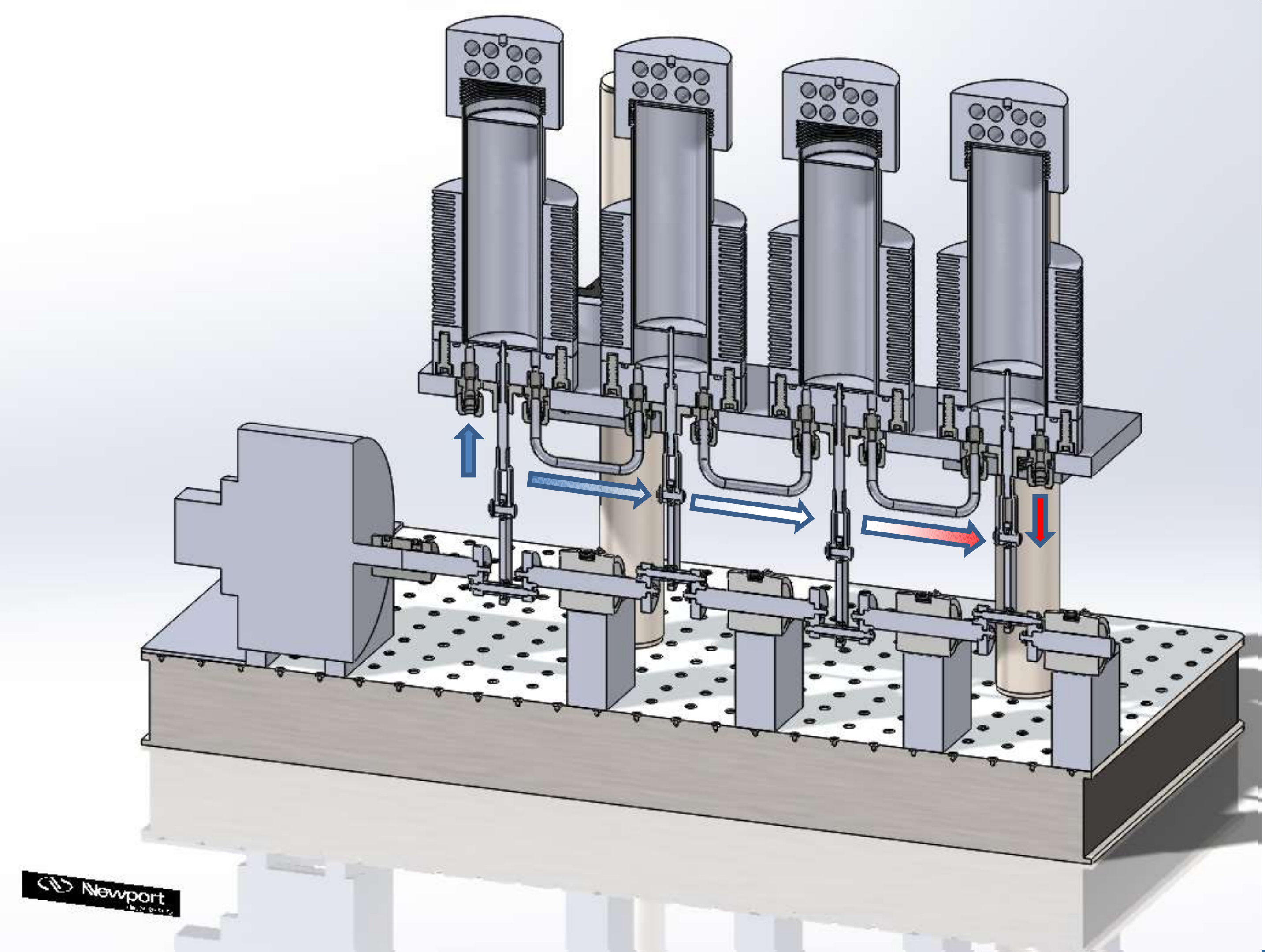
Controlled Inter-Unit Mass Flow

Ideal Stirling Cycle

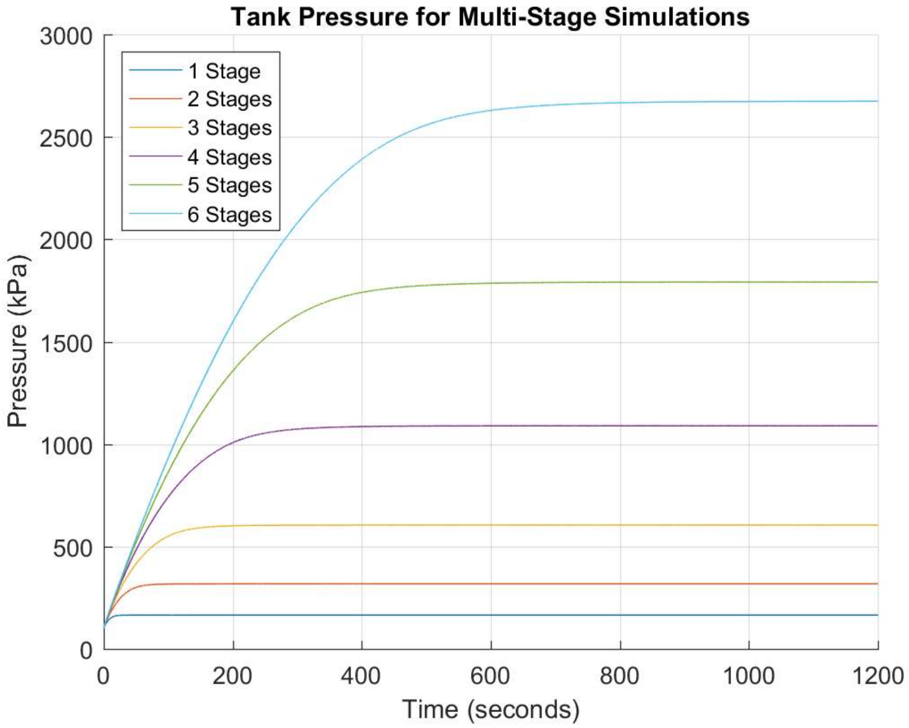


1. Isothermal Process (Work Out)
2. Isochoric Process
3. Isothermal Process (Work In)
4. Isochoric Process

Inter-Unit Mass Flow Simulation

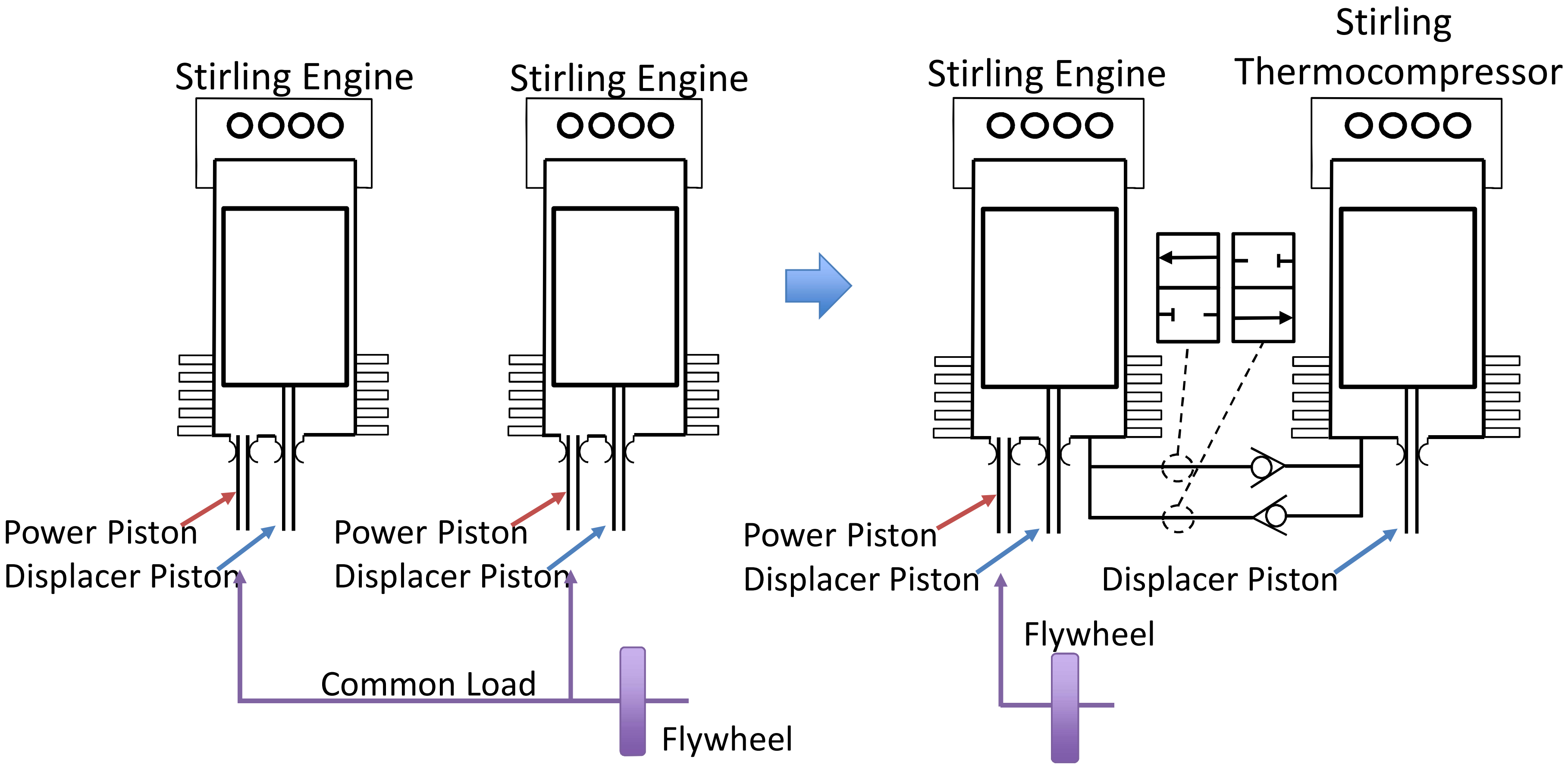


Inter-Unit Mass Flow Simulation

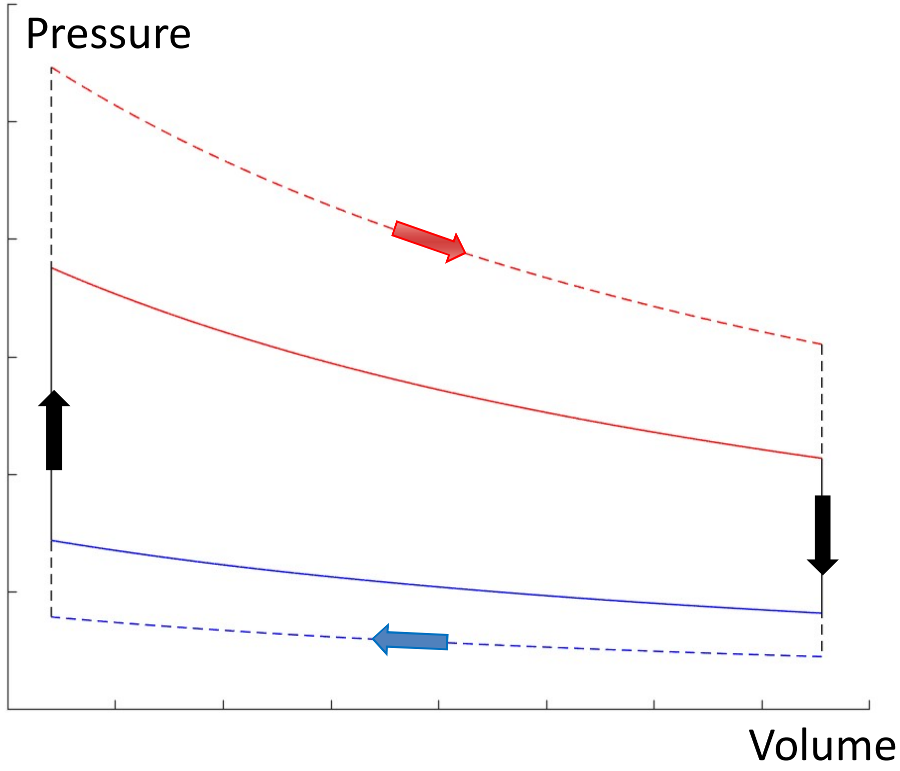


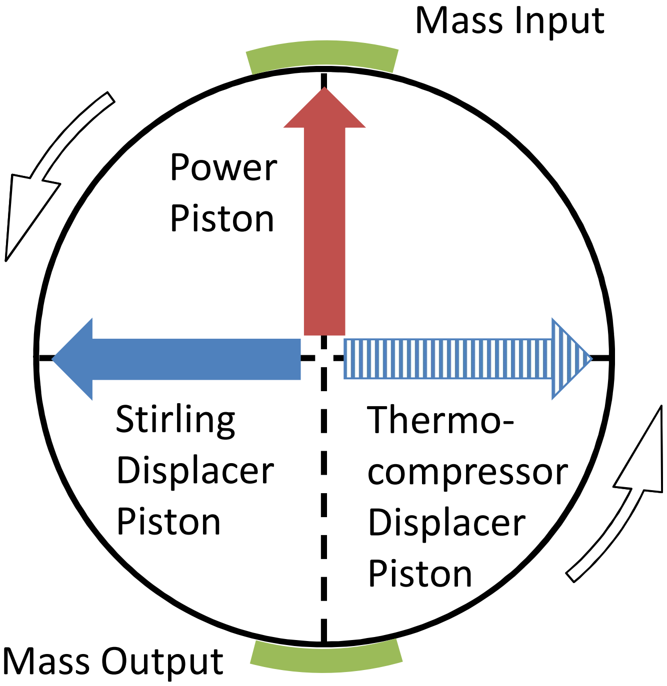
Number of Stages	Steady State Pressure		Adjusted Steady-State Pressure	
	kPa	psia	kPa	psia
1	165.2	24.0	145.6	21.1
2	317.8	46.1	253.2	36.7
3	604.8	87.7	453.9	65.8
4	1,089.6	158.0	789.8	114.5
5	1,791.5	259.8	1,266.9	183.7
6	2,674.0	387.9	1,855.3	269.1

Conceptual Architecture



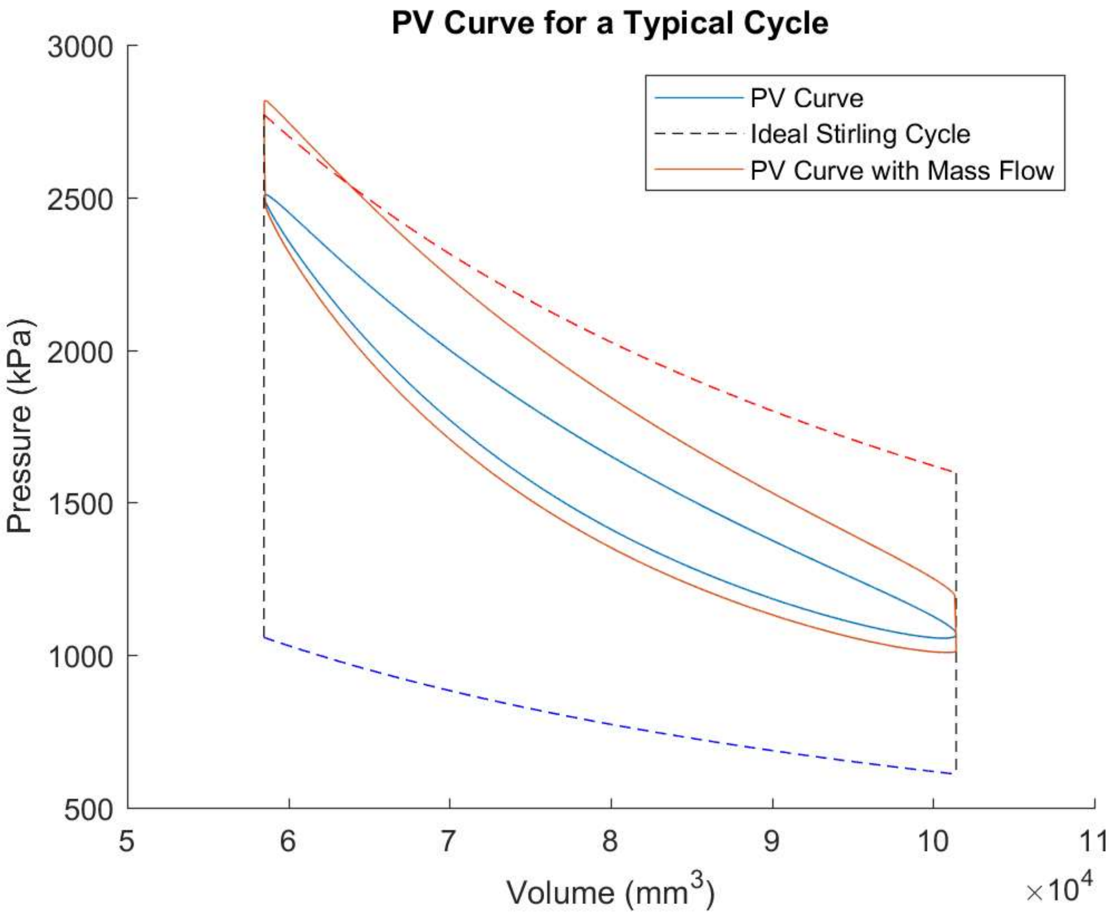
Conceptual Architecture





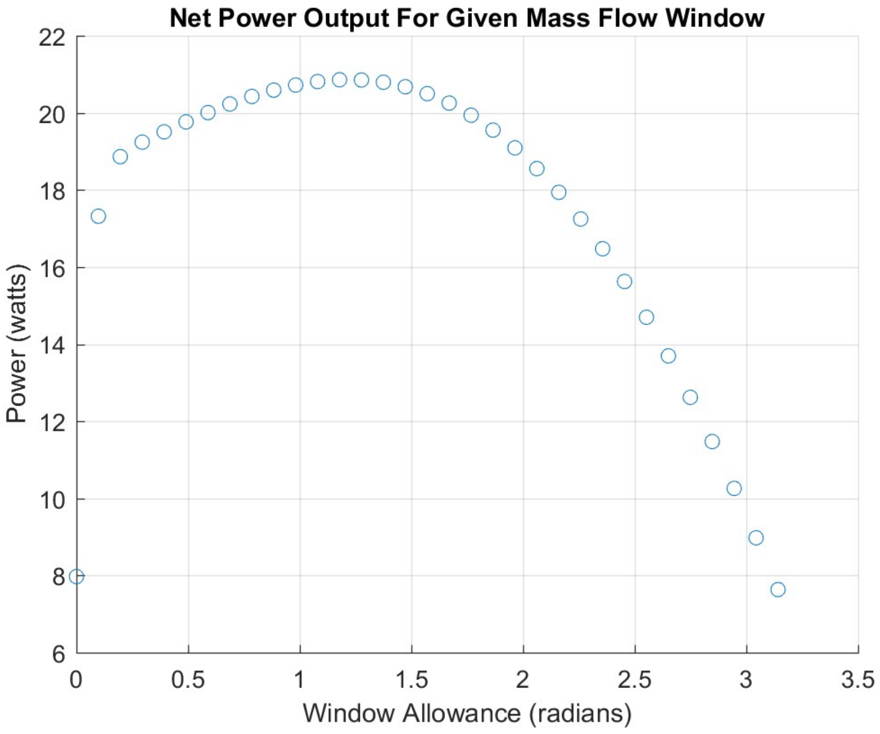
Relative Phases

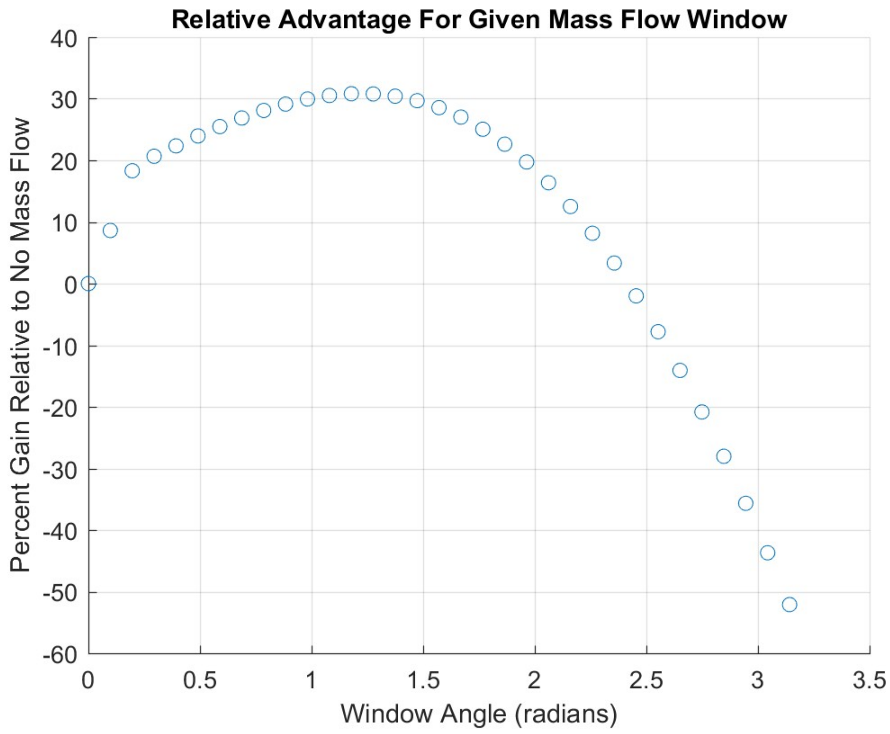
Simulation Results



Mass Flow Window	$^{\pi}/_{16}$ radians
Modelled Power Piston Displacement	42.94 cm^3
Frequency	1 Hz
Median Operating Pressure	16.57 bar
Net Power Output (no mass flow)	7.97 watts
Net Power Output (mass flow)	18.86 watts
Relative Power Gain	2.92 watts (18.34%)

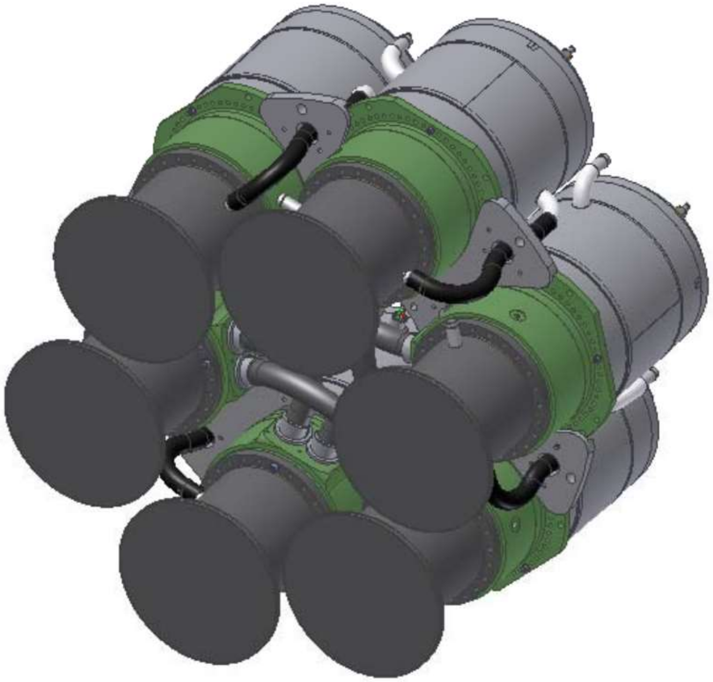
Controlled Mass Flow Window Range


Net Power Output For Given Mass Flow Window


Relative Advantage For Given Mass Flow Window

Potential Applications

Increased Power Density in Multi-Engine Systems



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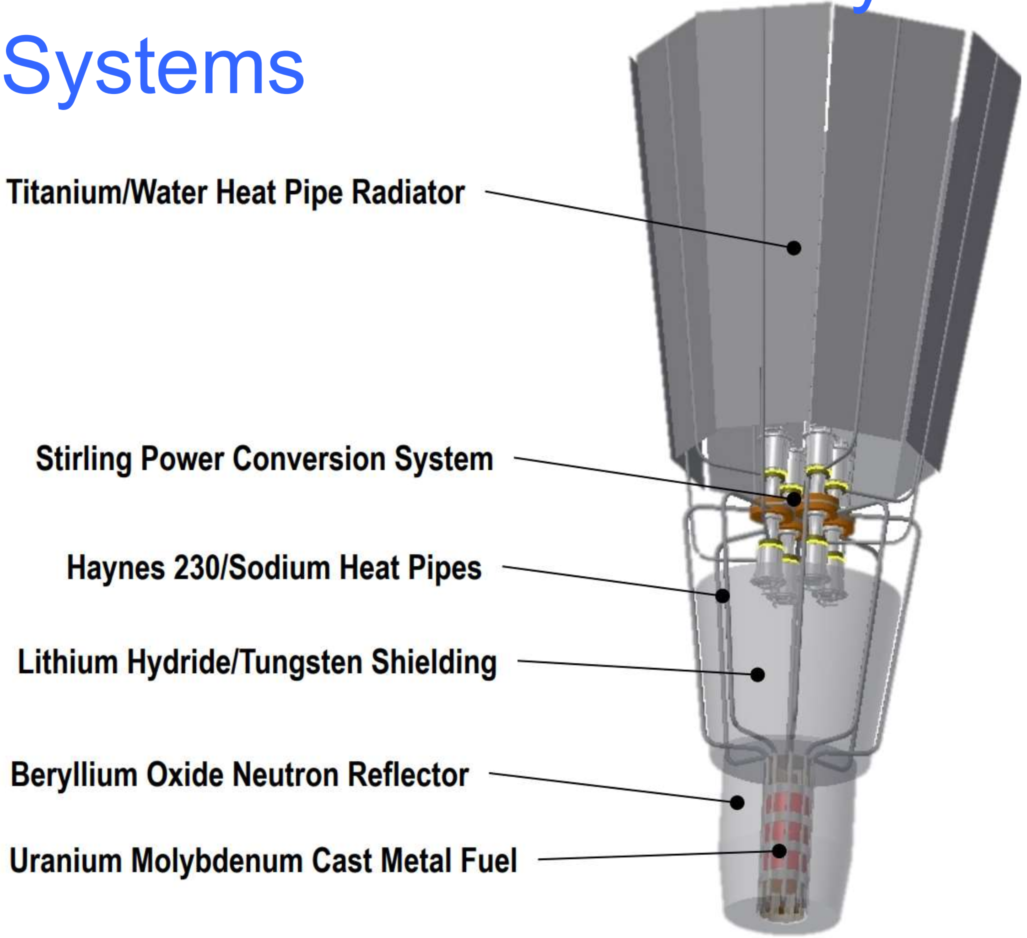
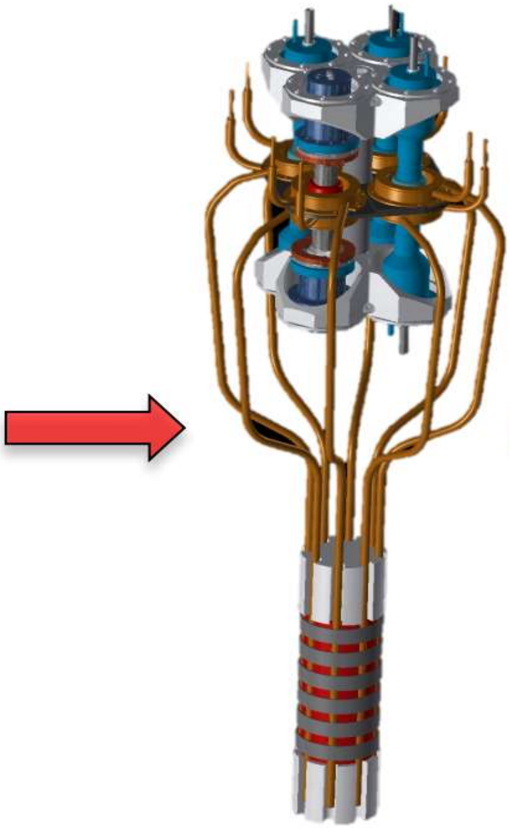
Potential Applications

Increased Power Density in Multi-Engine Systems





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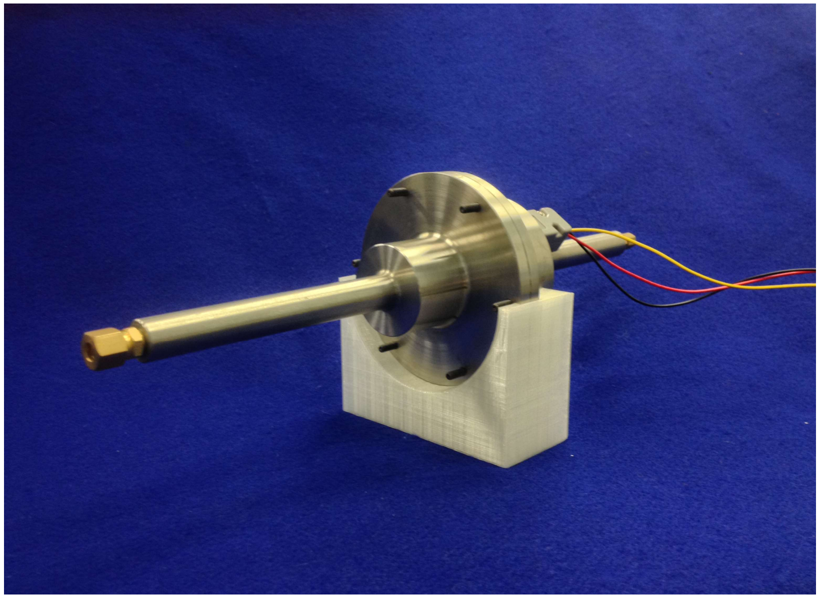
Next Steps

- Validate Controlled Mass Flow Simulation Results with Experimental Data
  - Install Linear Alternator on Current Stirling Thermocompressor to make a Traditional Stirling Engine
  - Emulate Thermocompressor Pressure Oscillations Using Reservoirs Held at High/Low Temperatures, Pressures
  - Regulate Mass Flow using Control Valves
- Experimentally Validate Full Control of Stirling Engine



Linear Alternator

Conclusions

- A control strategy for increasing power output from Stirling devices using controlled mass flow from accompanying Stirling thermocompressors was introduced and simulated.
- Simulation results corroborate that power output can be greater using an engine-thermocompressor arrangement than with an equivalent pair of Stirling engines. Experimental validation is forthcoming.
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Additional Image Credits

30 kW Maintenance Free Stirling Engine for High Performance Dish Concentrating Solar Power. (2010). (Presentation Slides) Available: https://www1.eere.energy.gov/solar/pdfs/csp_prm2010_infinia_30kw.pdf

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