Liquid Piston Gas Compressor/Expander

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Cost Optimization of a Liquid Piston Compressor/Expander

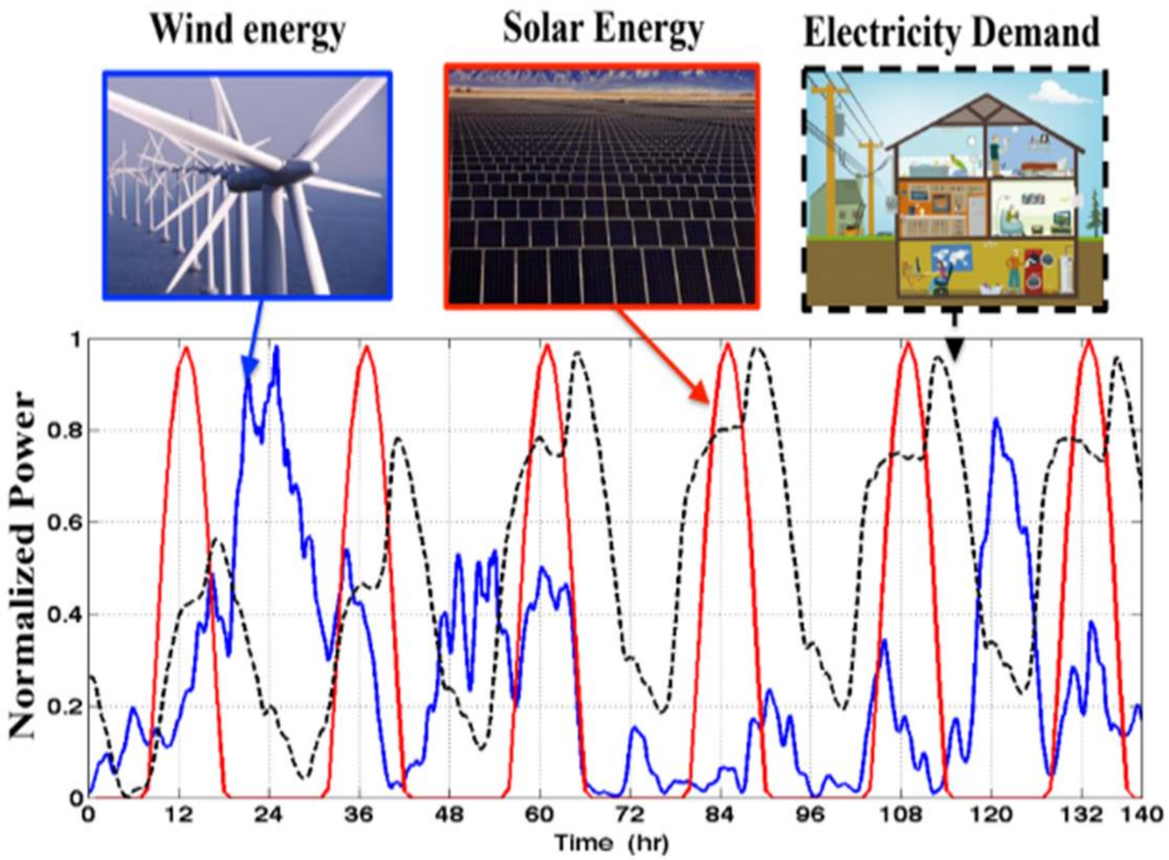
- Objective: Reduce cost associated with building a liquid piston compressor/expander for application of a compressed air energy storage system. Optimization will result in a system that efficiently and quickly compresses gas for low system price.

Agenda

- Research Motivation/Background
- Gas Compression Thermodynamics
- Liquid-Piston Compressor Concept
- Optimization of System Parameters
- Flow Intensifier Concept

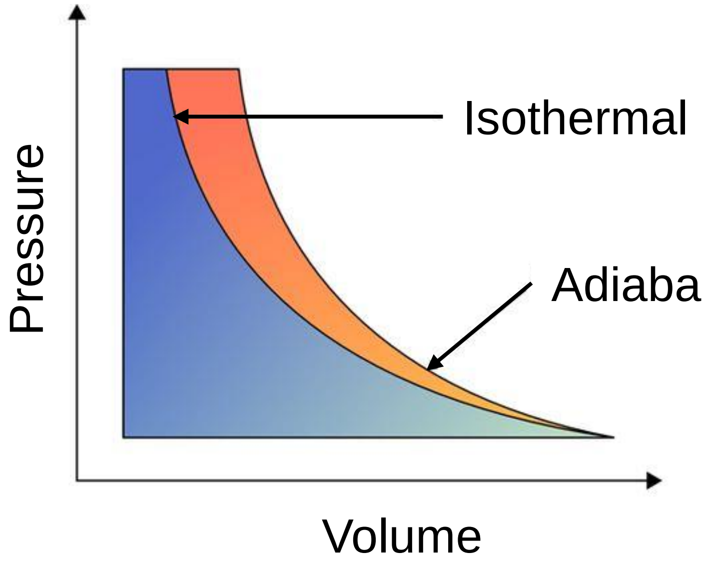
Research Motivation

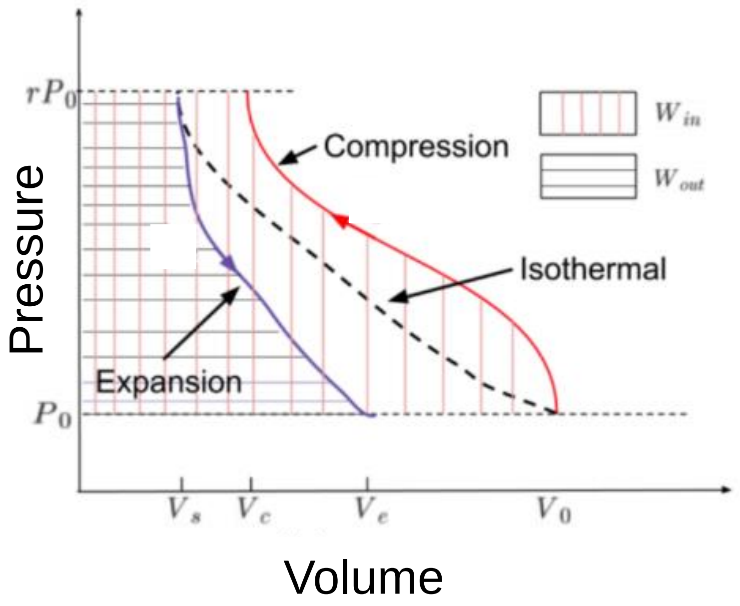
- Objective: develop method to quickly and efficiently compress gas to high pressure for storage
- Want to store energy as compressed gas and store CO_2 in compact space



Thermodynamics

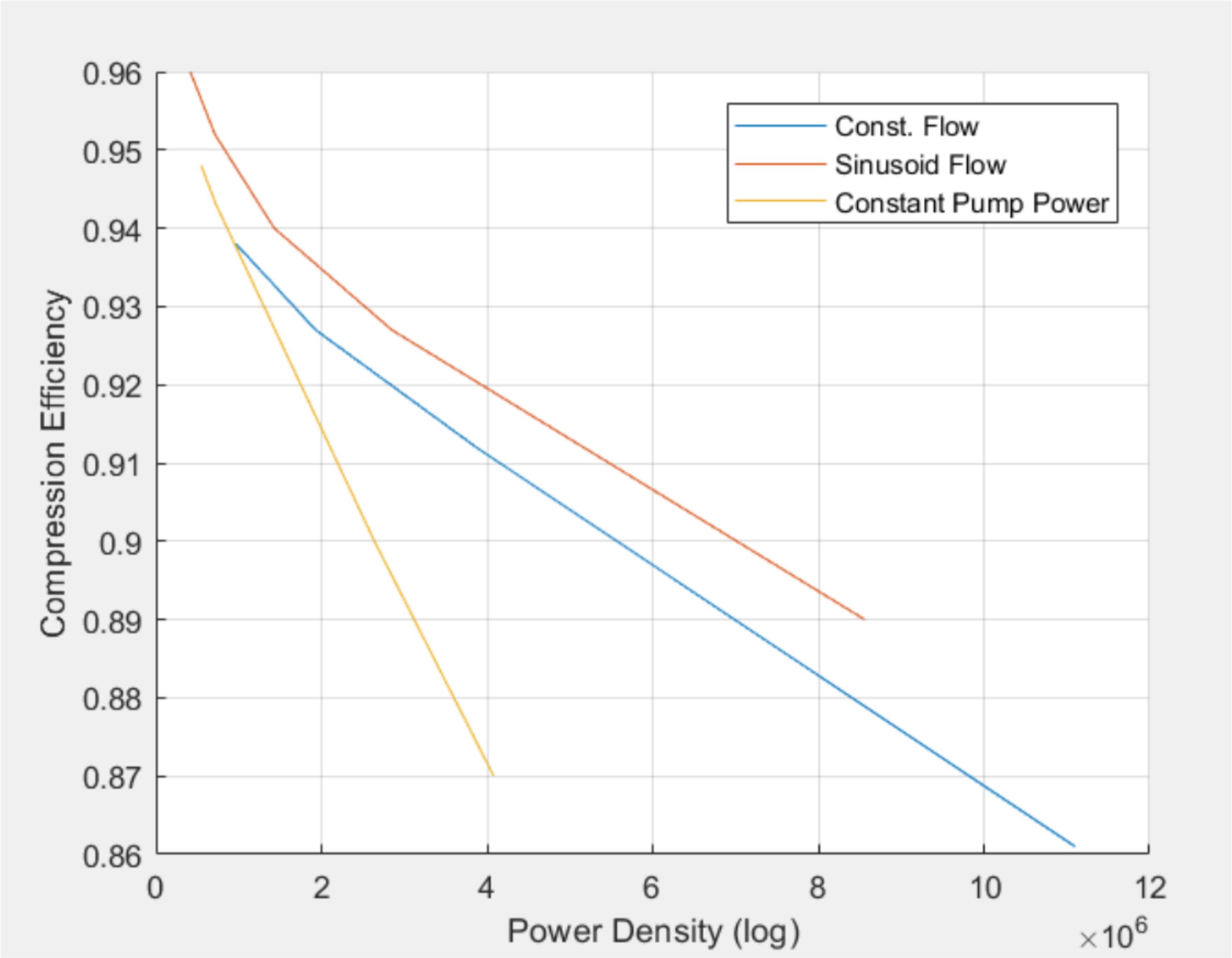
- Adiabatic process is quick but inefficient (temperature increases)
- Isothermal process is efficient but slow
- Want a quick, near-isothermal process for maximum power density and efficiency





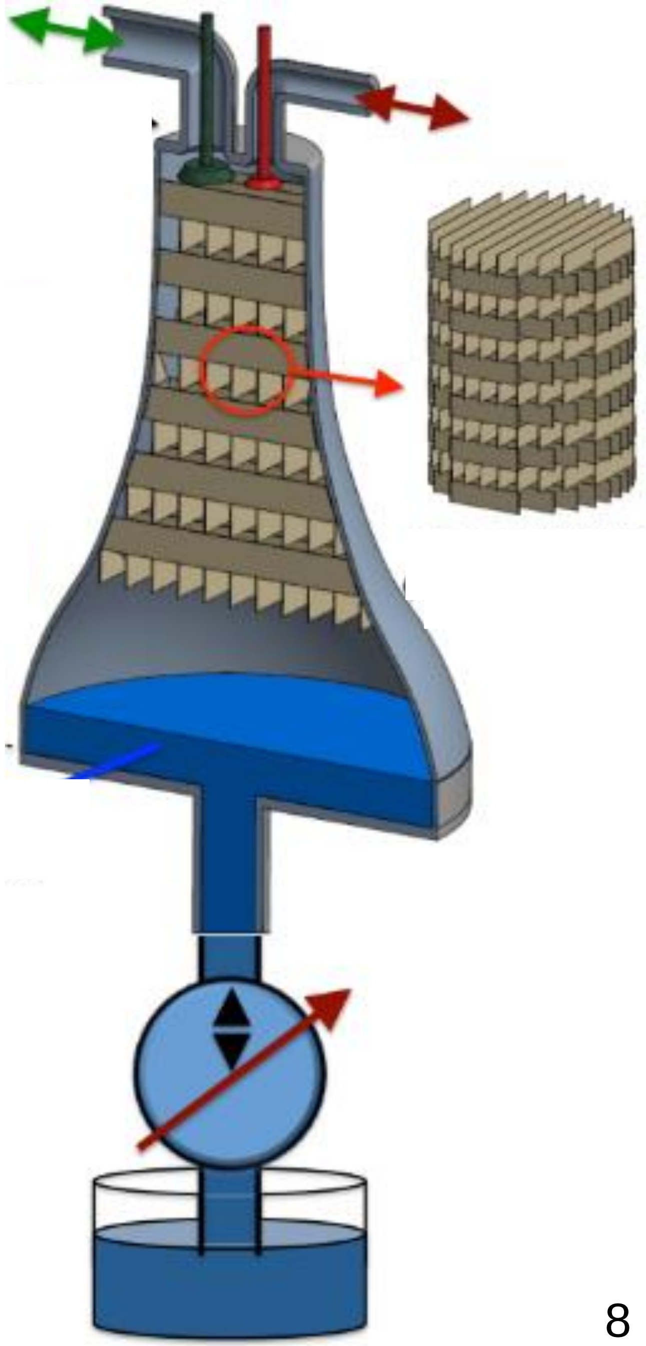
Power Density and Efficiency

- Trade-off between efficiency and power density
- Efficiency$= \frac{E_{store}}{W_{in}}$
- Power Density $= \frac{E_{store}/t_c}{V_{cham}}$

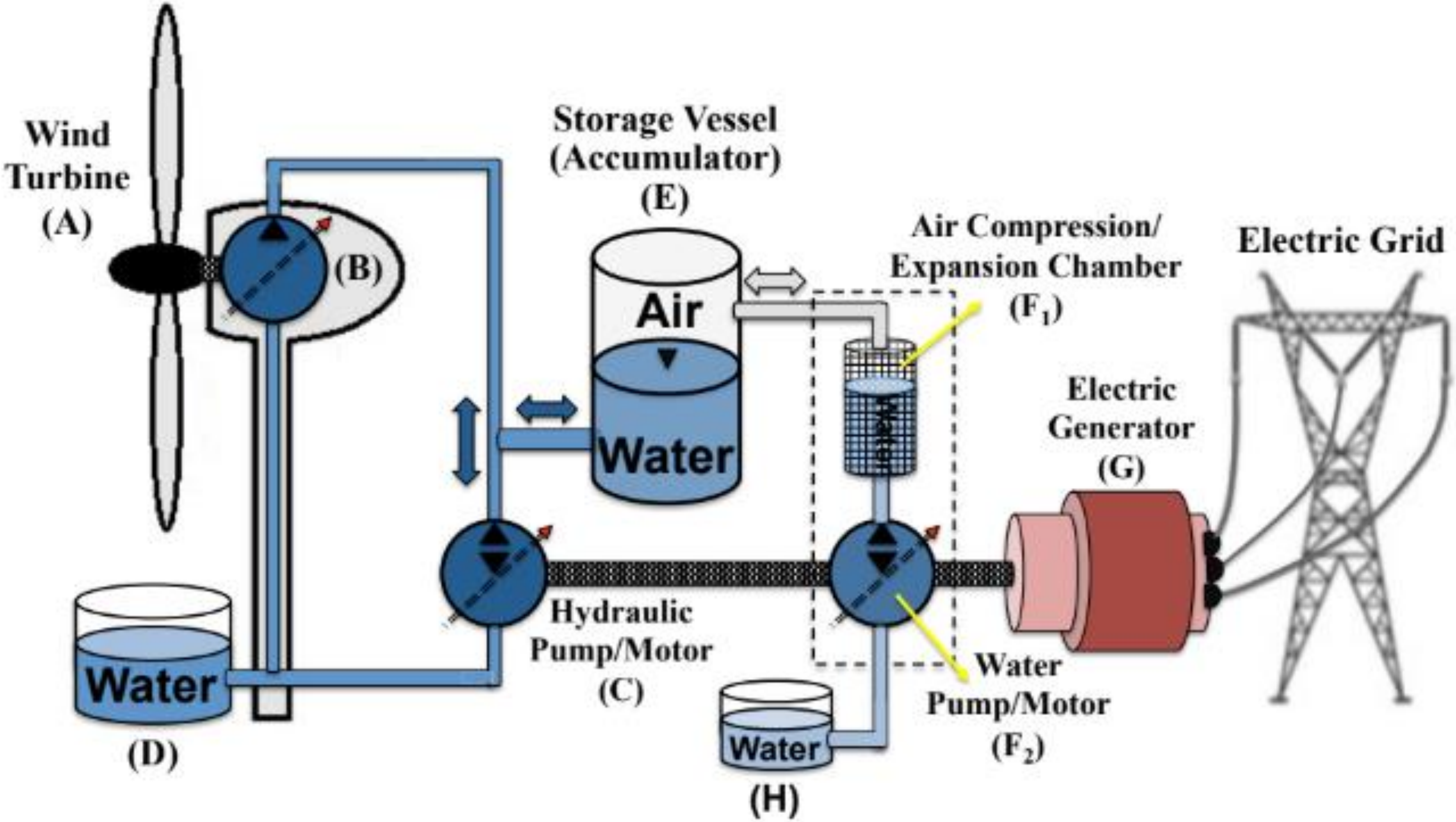


Liquid Piston Concept

- Water pump (bottom) fills compression chamber to compress air
- Valves to high pressure storage (red), low pressure inlet (green)
- Optimize chamber shape, flow rate vs. time, heat transfer inserts, cost

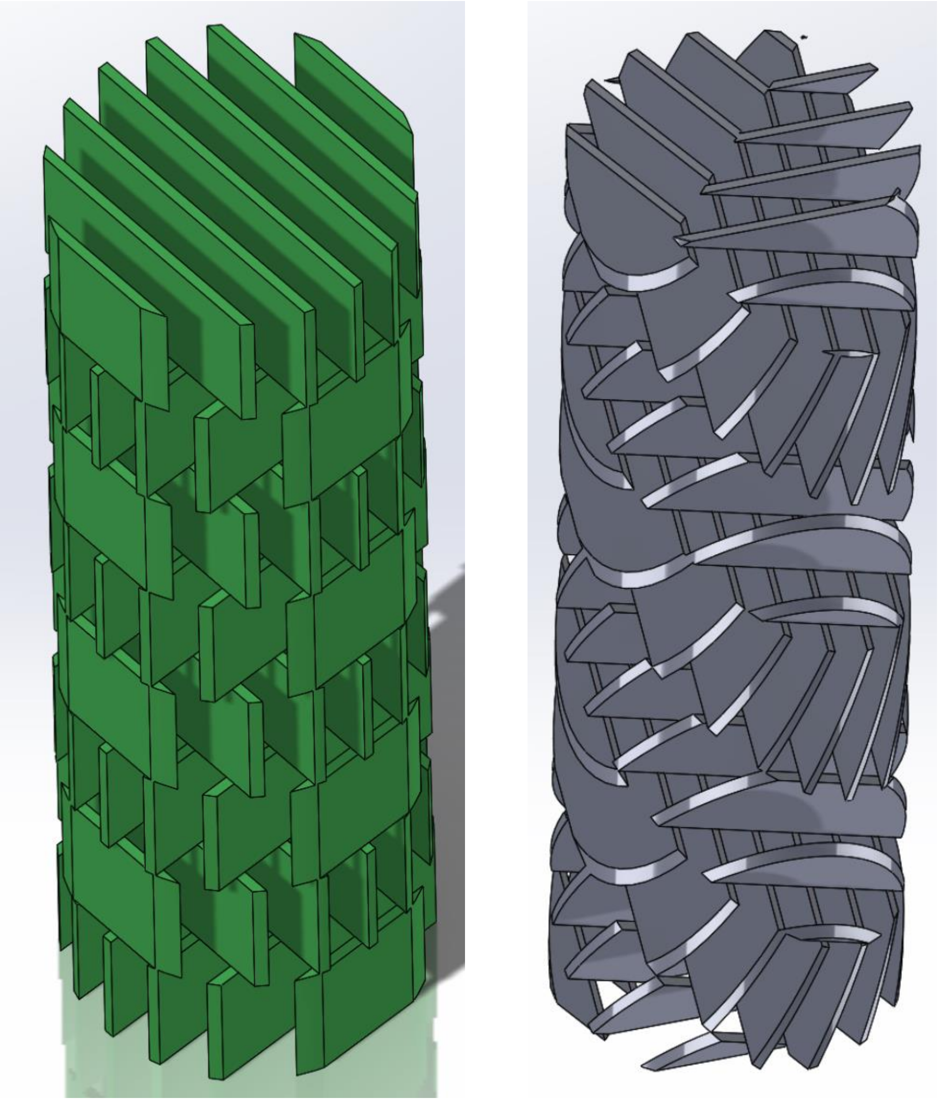


System Overview



Heat Transfer Media

- Porous media adds extra surface area
- Liquid piston can flow through media
- Inclusion of media reduces air temperature, improves efficiency
- 3D printing various designs

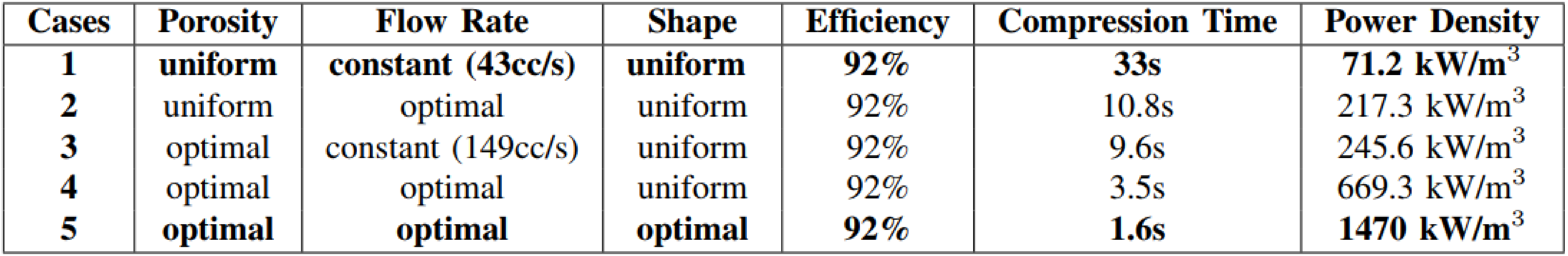


System Optimization

- Dynamic Programming used to find optimal chamber shape, flow rate vs. time, and heat transfer media configuration
- Additional study performed to determine cost-optimal design for future commercialization
- Results give cheapest design that rapidly compresses gas for a specified efficiency

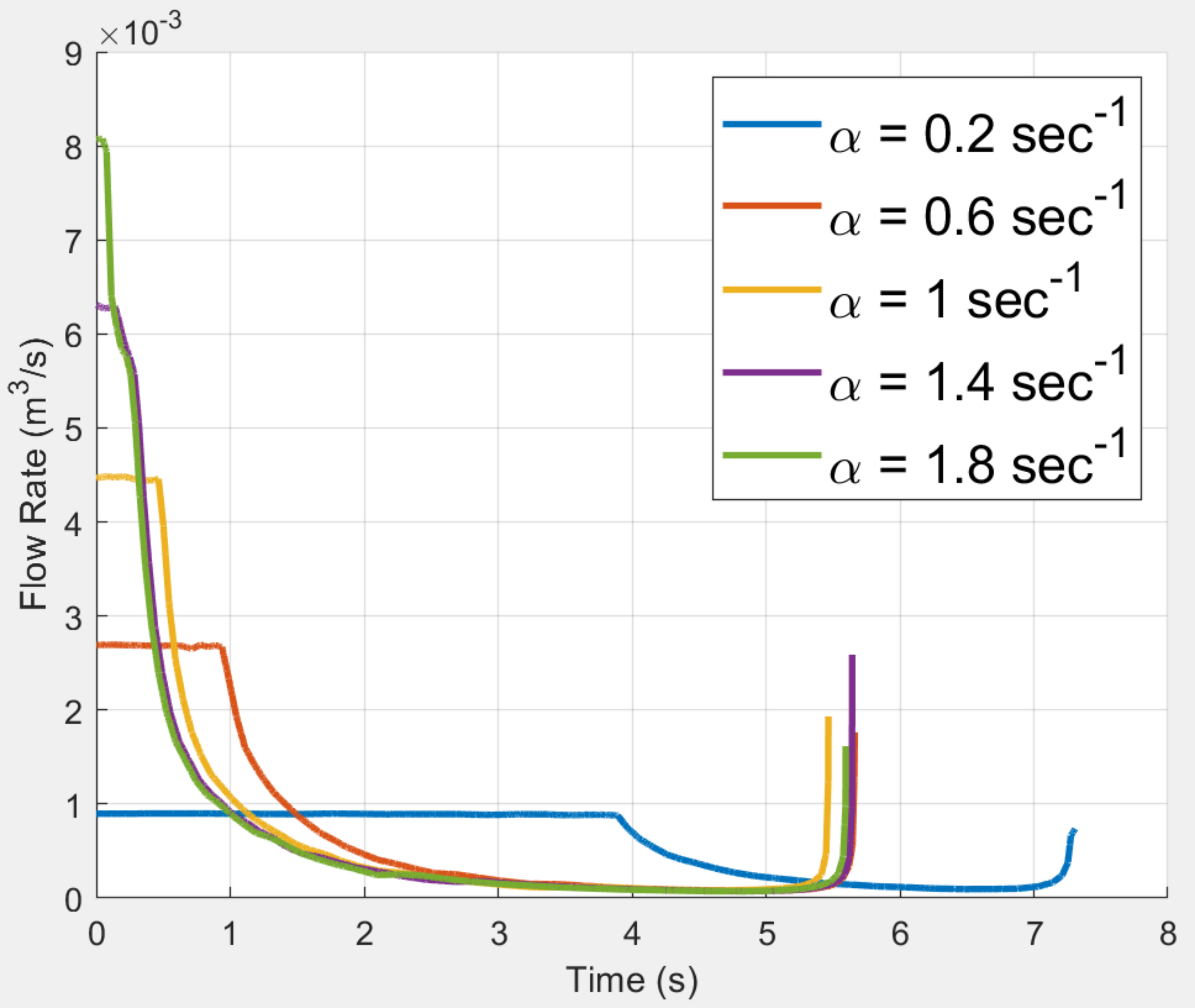
Chamber Property Optimization

- Variable displacement pump used with varying chamber shape, porosity of heat transfer inserts
- Bounds placed on maximum, minimum values of optimization parameters



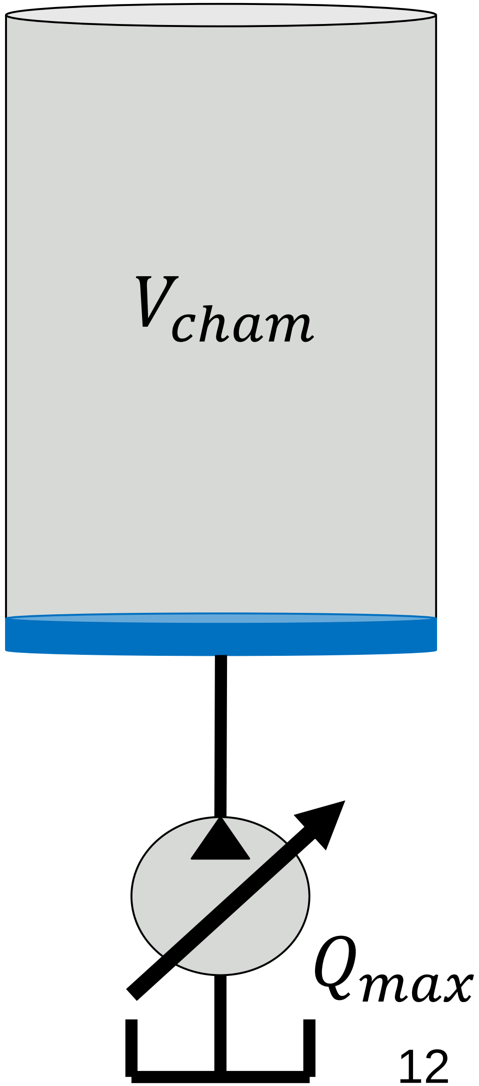
Cases	Porosity	Flow Rate	Shape	Efficiency	Compression Time	Power Density
1	**uniform**	**constant (43cc/s)**	**uniform**	**92%**	**33s**	**71.2 kW/m^3**
2	uniform	optimal	uniform	92%	10.8s	217.3 kW/m^3
3	optimal	constant (149cc/s)	uniform	92%	9.6s	245.6 kW/m^3
4	optimal	optimal	uniform	92%	3.5s	669.3 kW/m^3
5	**optimal**	**optimal**	**optimal**	**92%**	**1.6s**	**1470 kW/m^3**

Chamber Property Optimization



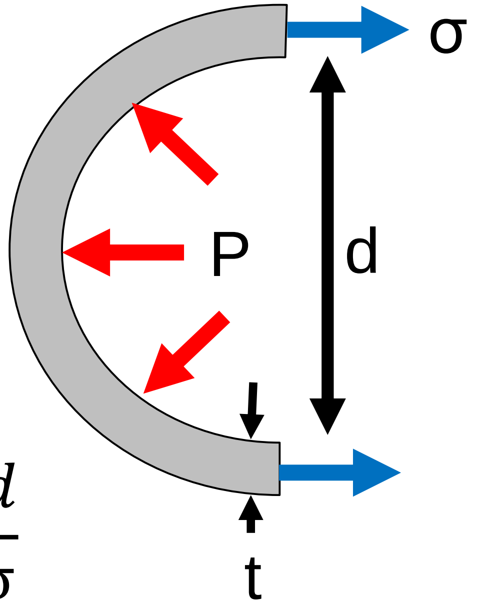
$$\alpha = \frac{Q_{max}}{V_{cham}} = \frac{1}{sec}$$

All systems are 92% efficient, large pumps do not increase power density



Cost Derivation

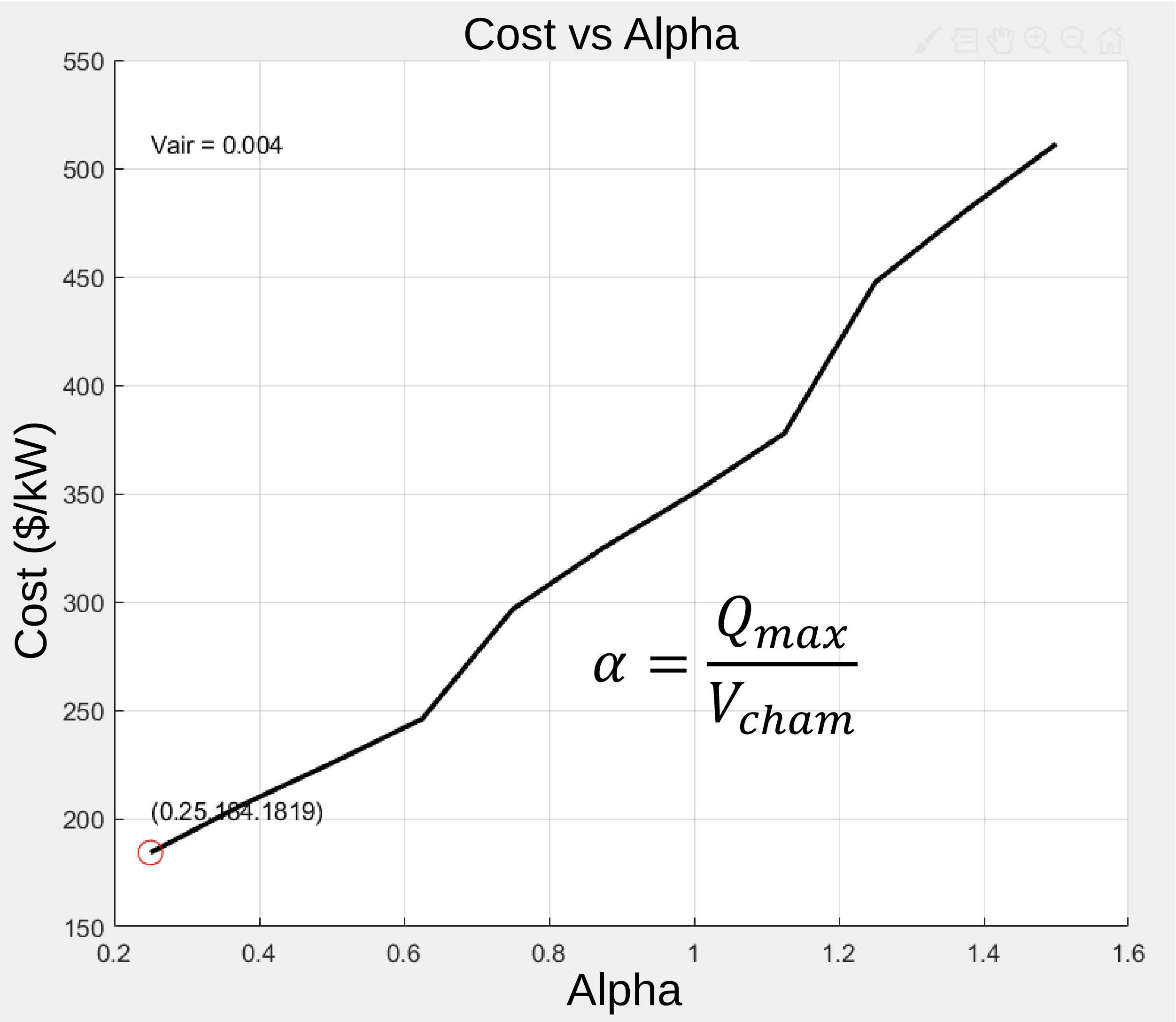
- Costs assigned to both compression chamber body and pump based on each component's size
- Chamber thickness calculated using hoop stress
- Cost expressed as function of α:
- $J(\alpha) = \left(\frac{[\$]}{[V]} + \frac{Q_{max}}{V_{cham}} \frac{[\$]}{[Q]}\right) \frac{1}{\left(\frac{P}{V}\right)} = \frac{[\$]}{[P]}$



$$t = \frac{Pd}{2\sigma}$$

Cost Optimization

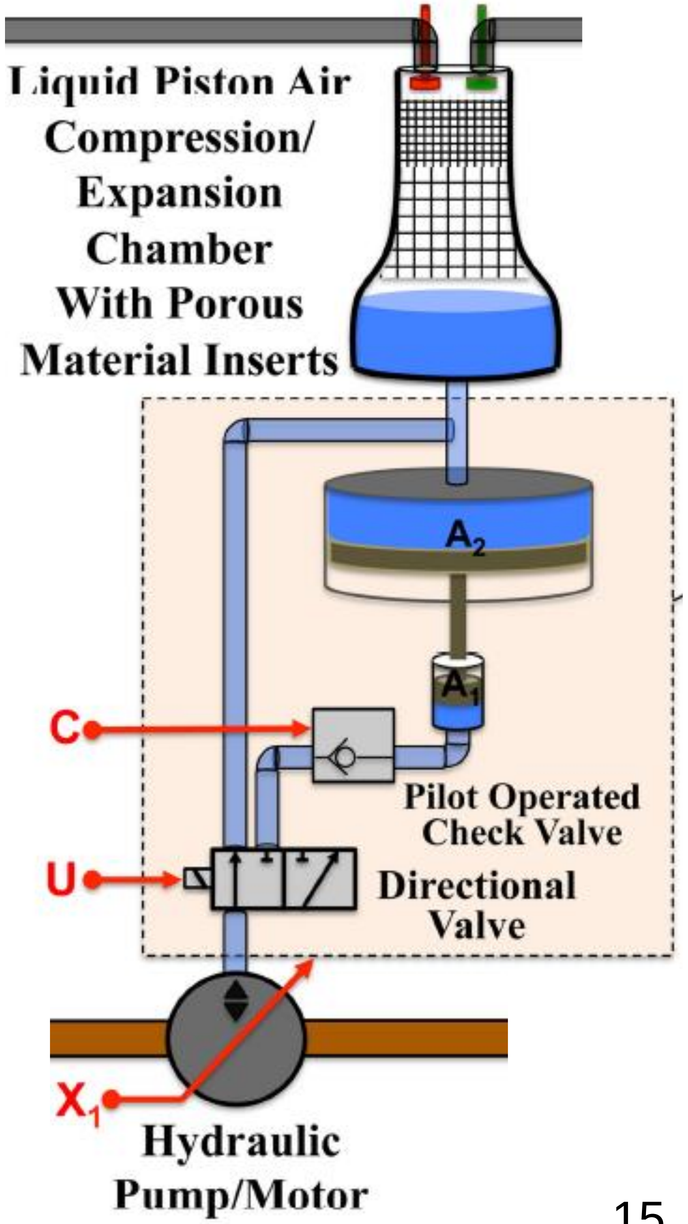
- Large pumps are expensive, dominate system cost
- Chamber shape prefers long, thin, straight tube
- Small pump is cheap, but takes more time to complete process



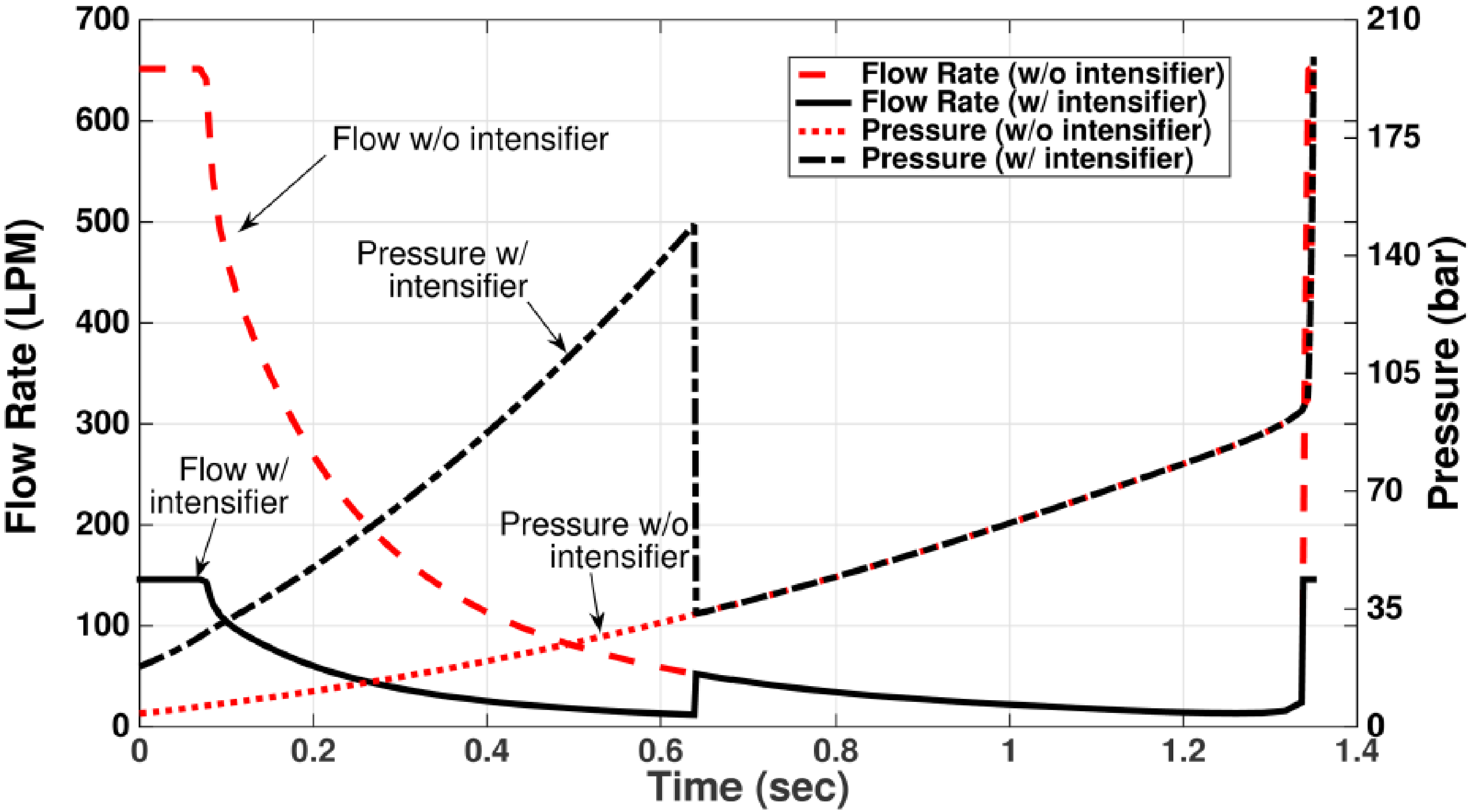
$$\alpha = \frac{Q_{max}}{V_{cham}}$$

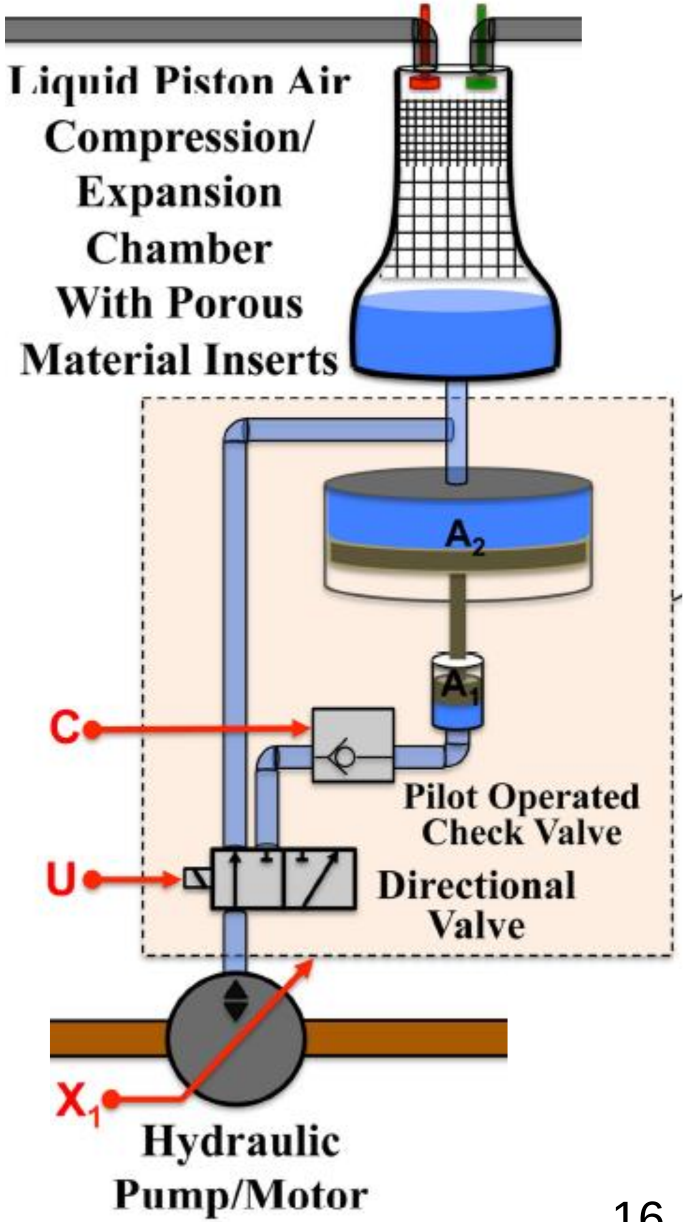
Flow Intensifier Concept

- Previous work studied “flow intensifier”
- Amplify flow rate early when chamber pressure is low
- Use valves to direct flow to intensifier or chamber
- Intensifier reduces size of pump and associated cost



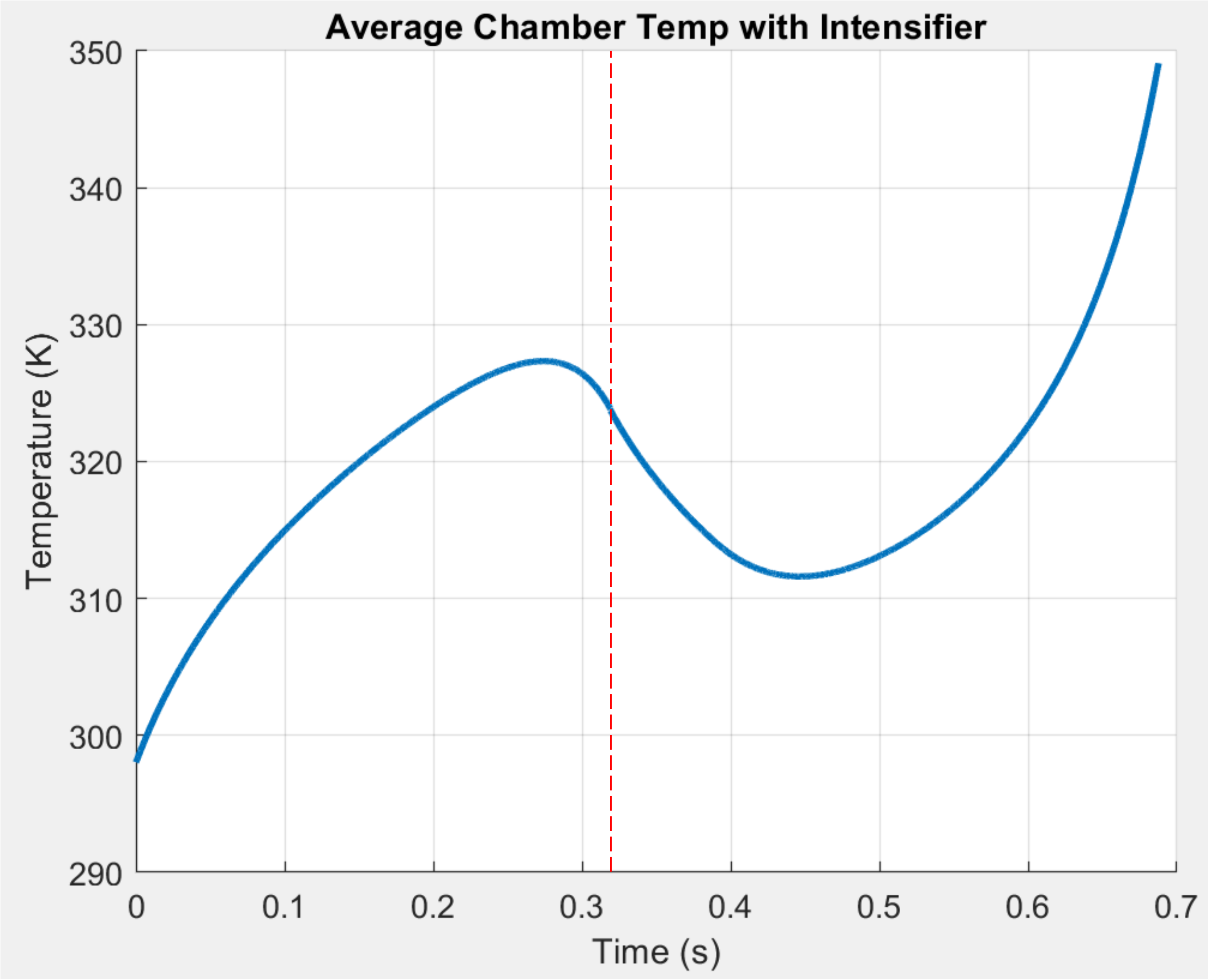
Flow Intensifier Pump Study





Combined Intensifier/Cost Optimization

- Use small, fixed displacement pump to reduce cost, simplify control
- Easy to track position of flow intensifier piston
- System is efficient, fast, and cheap



Design Iterations at 92% Efficiency

Design	Porosity	Flow	Shape	Cost	Flow Intensifier?	Power Density	Cost/kW
1	Uniform	Constant	Uniform	N/A	No	71.2 kW/m3	$244.42/kW
2	Uniform	Optimal	Uniform	N/A	No	217.3 kW/m3	$80.09/kW
3	Optimal	Constant	Uniform	N/A	No	245.6 kW/m3	$131.71/kW
4	Optimal	Optimal	Uniform	N/A	No	669.3 kW/m3	$245.33/kW
5	Optimal	Optimal	Optimal	N/A	No	1470 kW/m3	$248.89/kW
6	Optimal	Optimal	Optimal	Optimal	No	559 kW/m3	$183.98/kW
7	**Optimal**	**Optimal**	**Optimal**	**Optimal**	**Yes**	**2941 kW/m3**	**$59.30/kW**

Optimization of parameters and inclusion of flow intensifier results in significant improvements in power and cost savings

Future Work

- Develop control strategy for repetitive operation
- Design sensors to determine water height in compression chamber
- Study impacts of compressing other gasses
- Determine importance of media insert geometry
- Build and test 5 kW prototype