# 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.
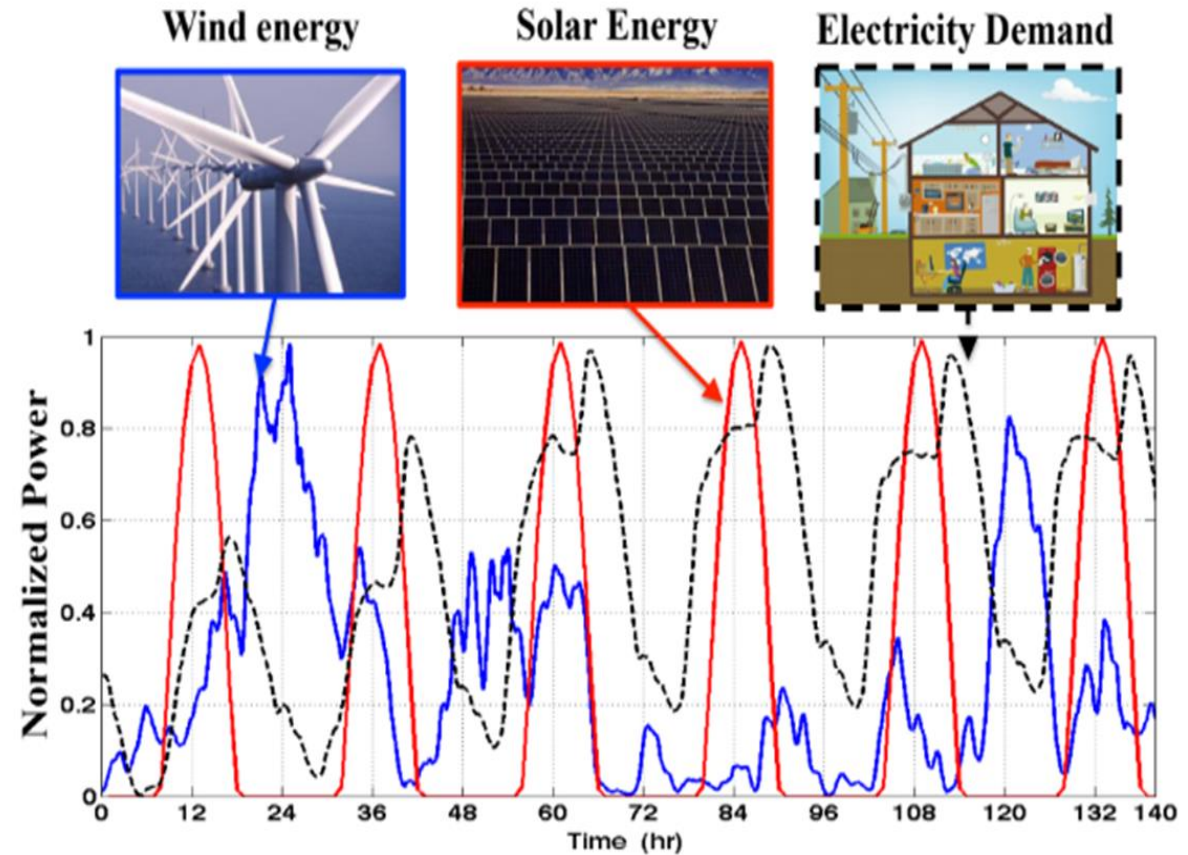
# Agenda

- 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
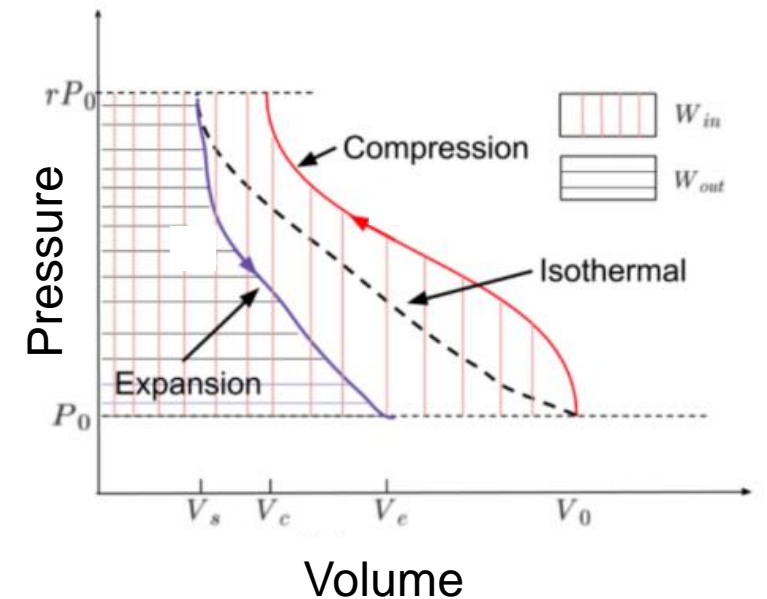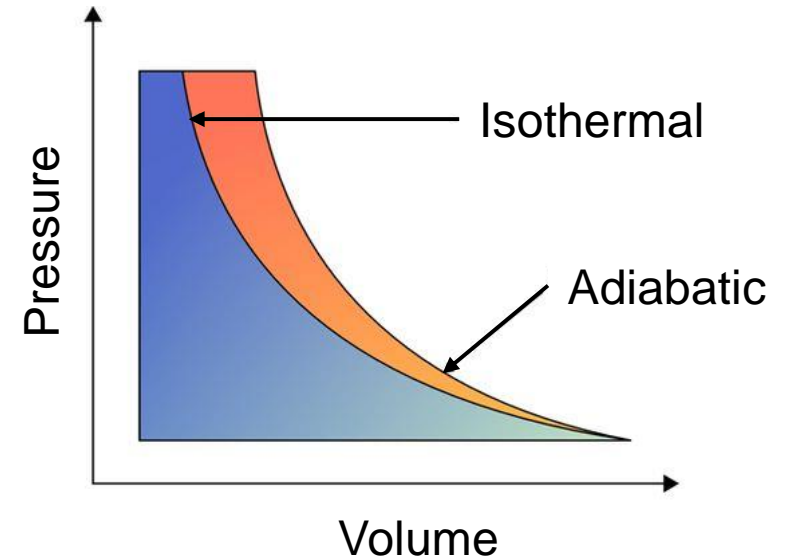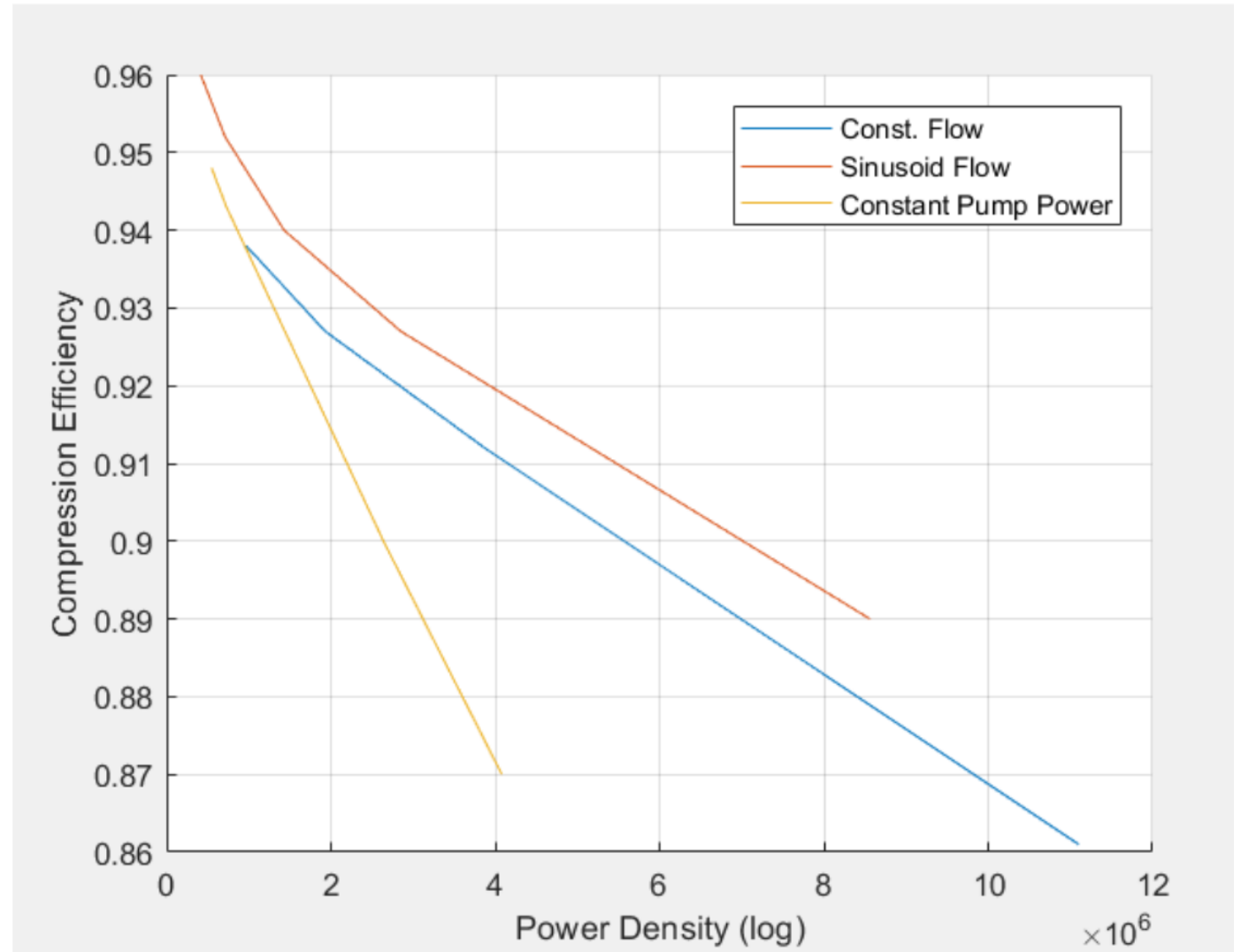
# Power Density and Efficiency
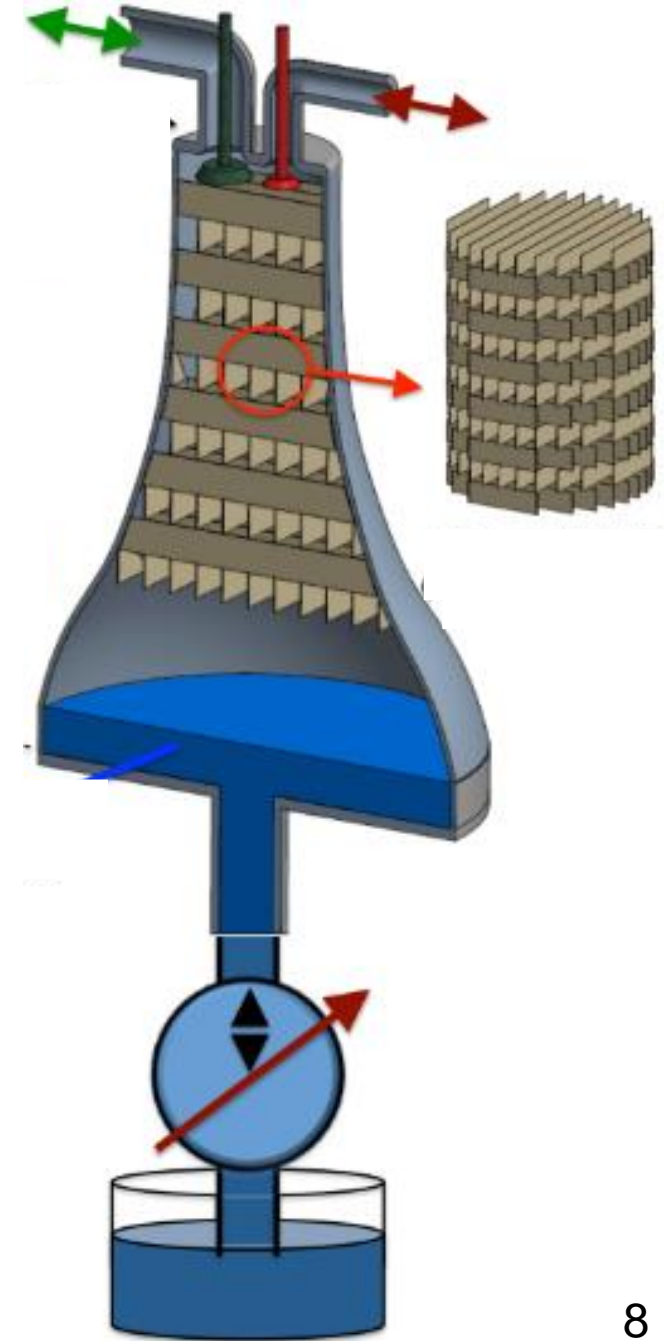
- Trade-off between efficiency and power density

- Efficiency = $\dfrac{E_{store}}{W_{in}}$

- Power Density $= \dfrac{E_{store}/t_c}{V_{cham}}$
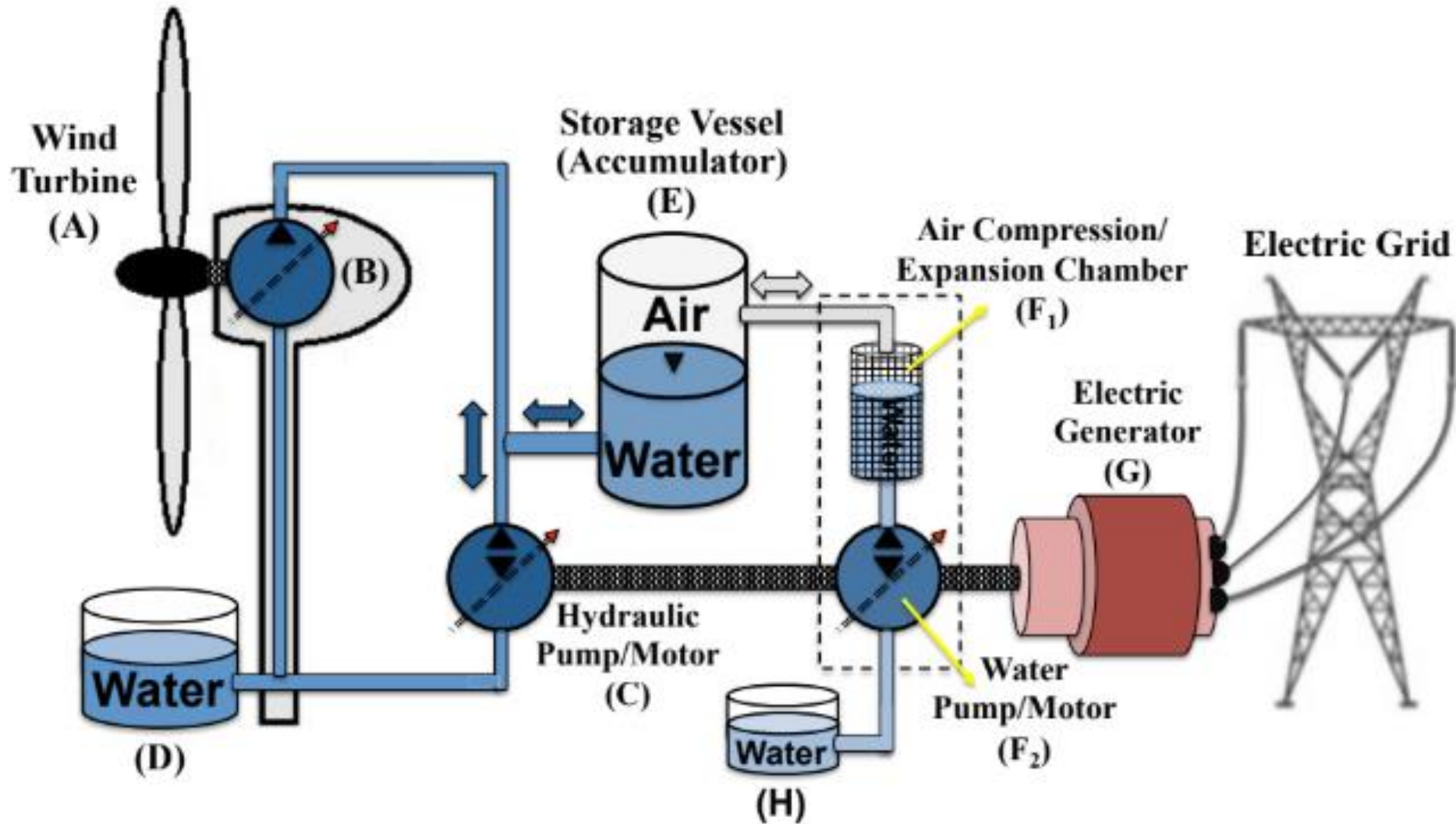


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# Liquid Piston Concept

- 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
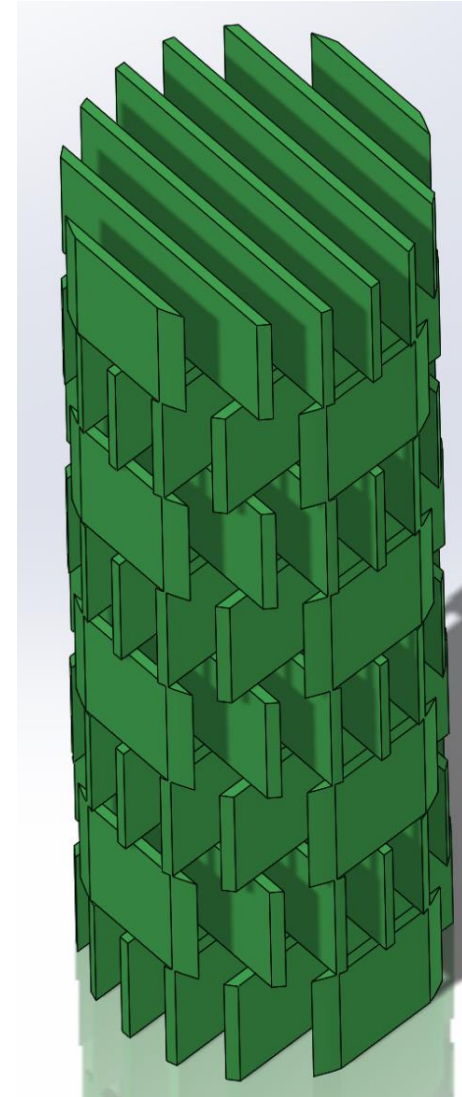
# System Overview

# 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
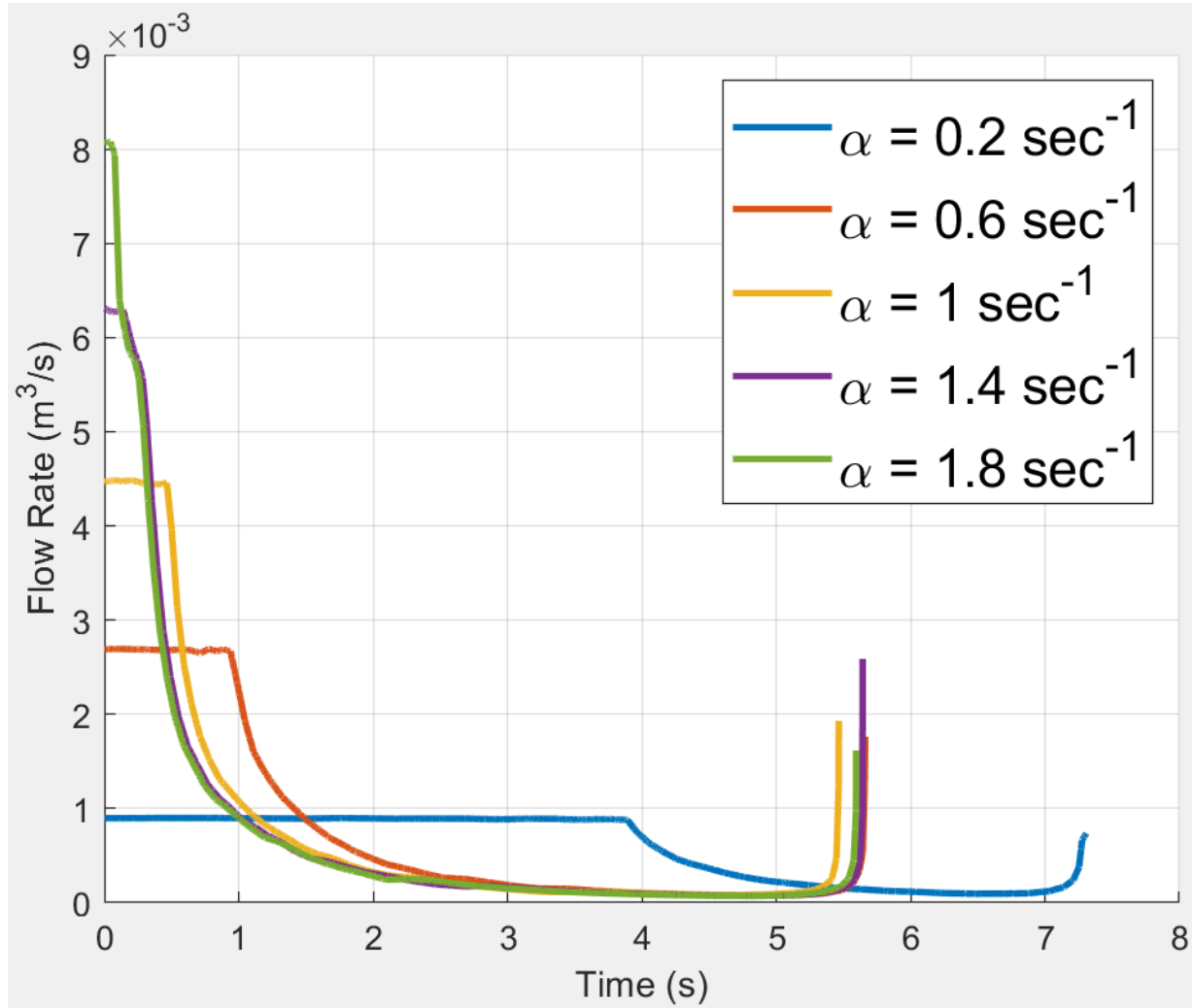


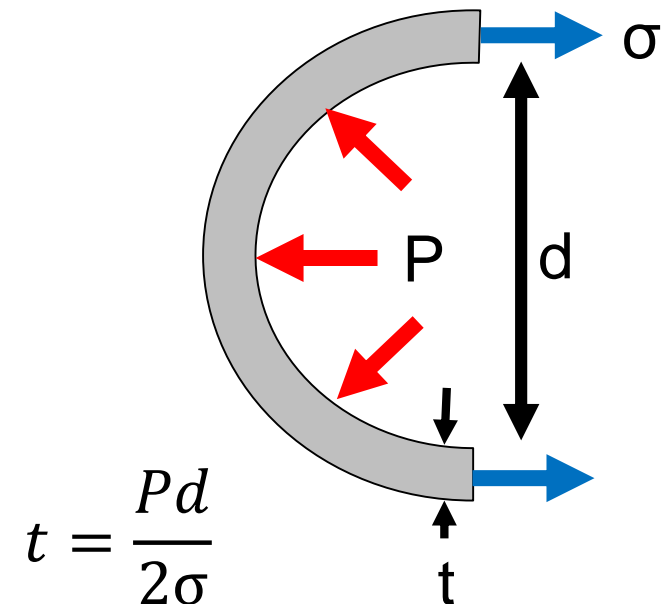$$\alpha = \frac{Q_{max}}{V_{cham}} = \frac{1}{sec}$$

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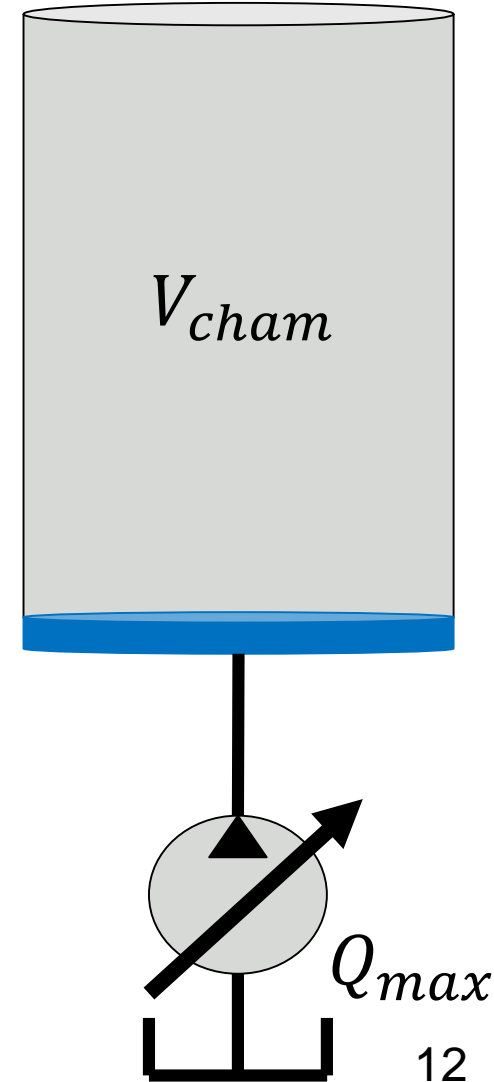
# Cost Derivation

- 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:

- $J(\alpha) = \left(\dfrac{[\$]}{[V]} + \dfrac{Q_{max}}{V_{cham}}\dfrac{[\$]}{[Q]}\right)\dfrac{1}{\left(\dfrac{P}{V}\right)} = \dfrac{[\$]}{[P]}$
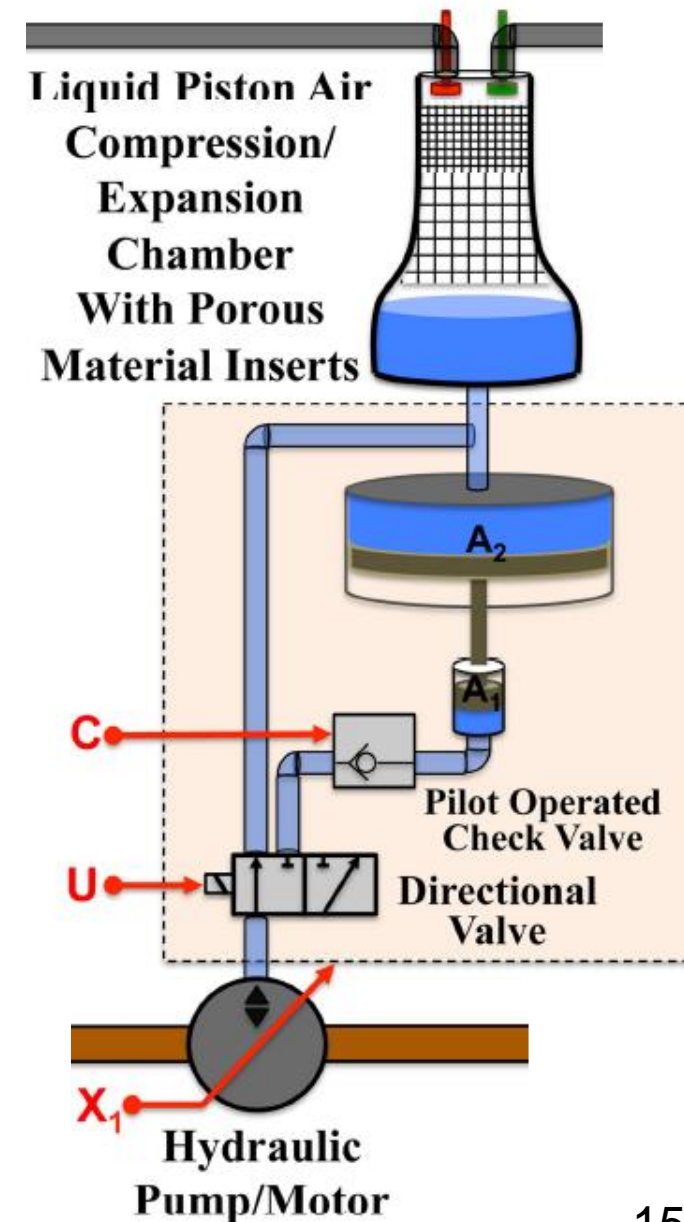


$t = \dfrac{Pd}{2\sigma}$

# 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



Cost vs Alpha

Vair = 0.004

(0.25 184.1819)

$$\alpha = \frac{Q_{max}}{V_{cham}}$$
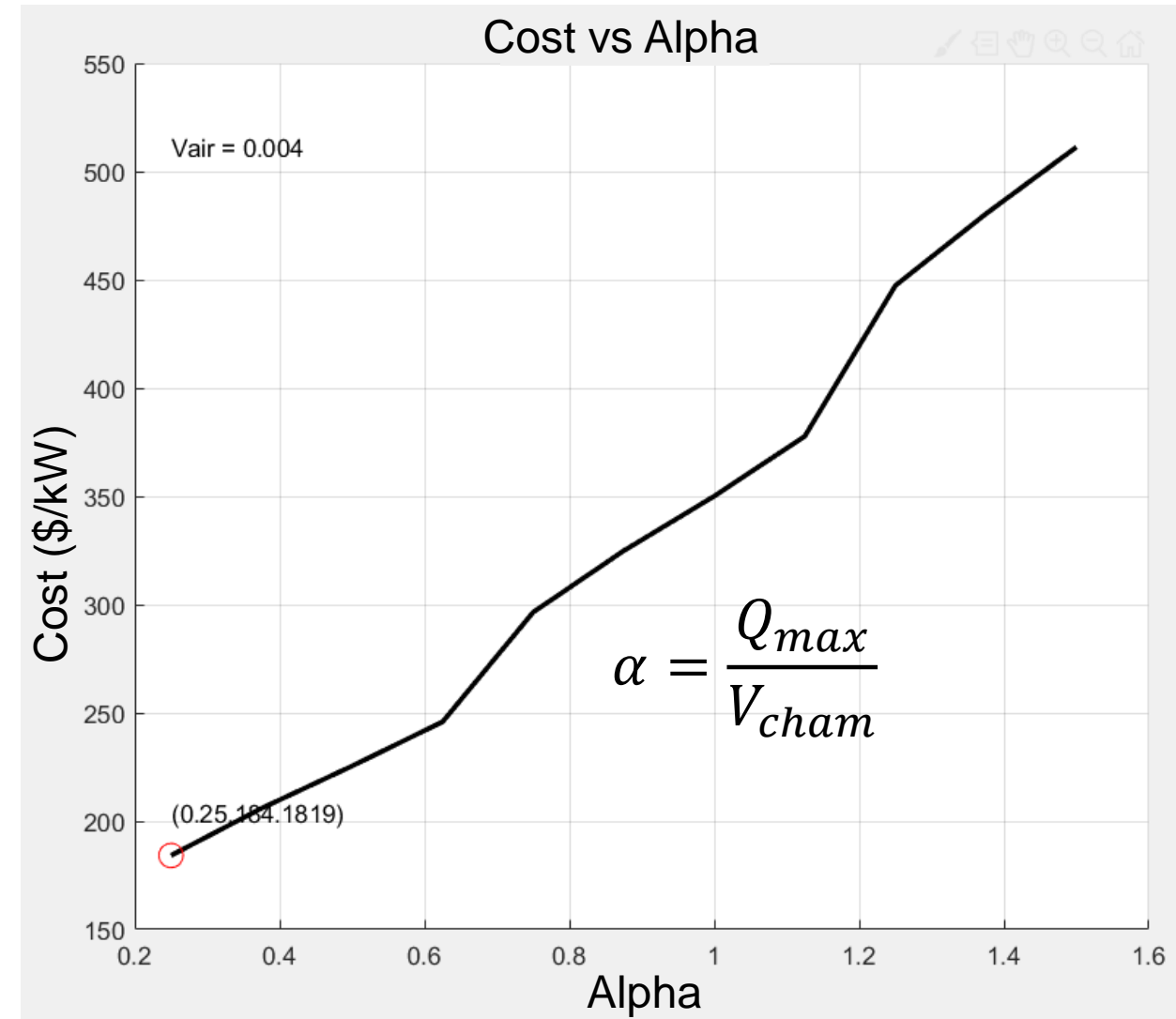
# Flow Intensifier Concept
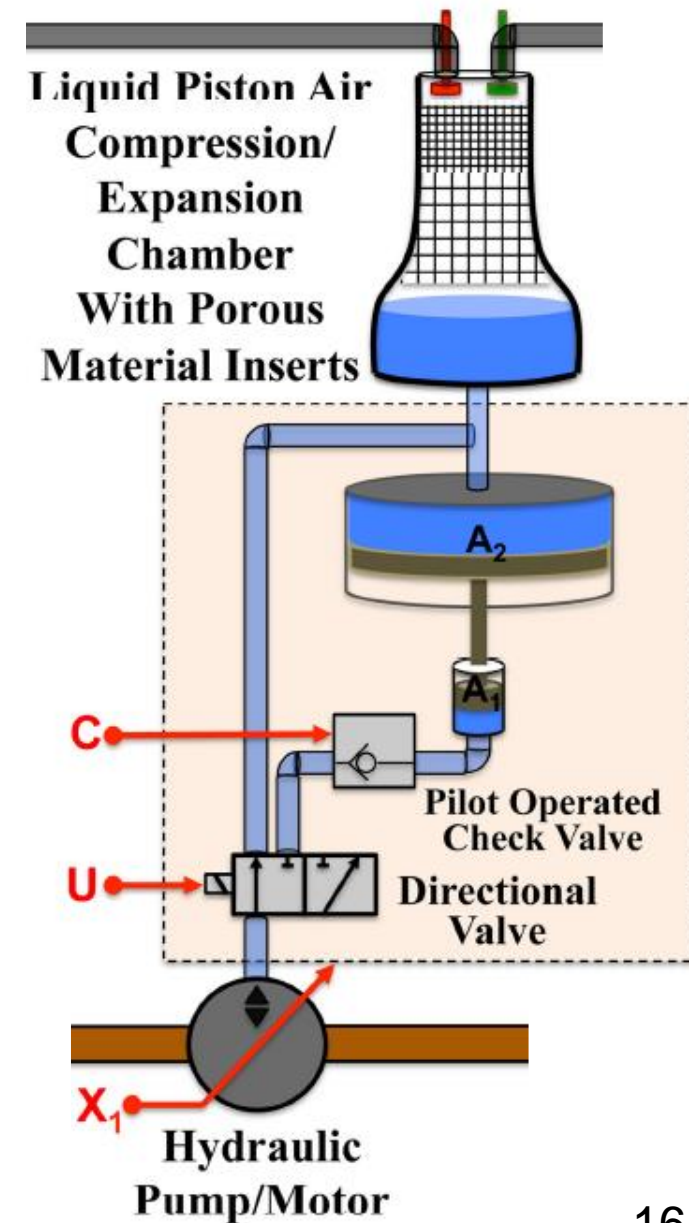
- Previous work studied "flow intensifier"
- Amplify flow rate early when chamber pressure is low
- Use valves to direct flow to intensifier or chamber
- Intensifier reduces size of pump and associated cost



Liquid Piston Air Compression/ Expansion Chamber With Porous Material Inserts

$A_2$

$A_1$

C

Pilot Operated Check Valve

U

Directional Valve

$X_1$
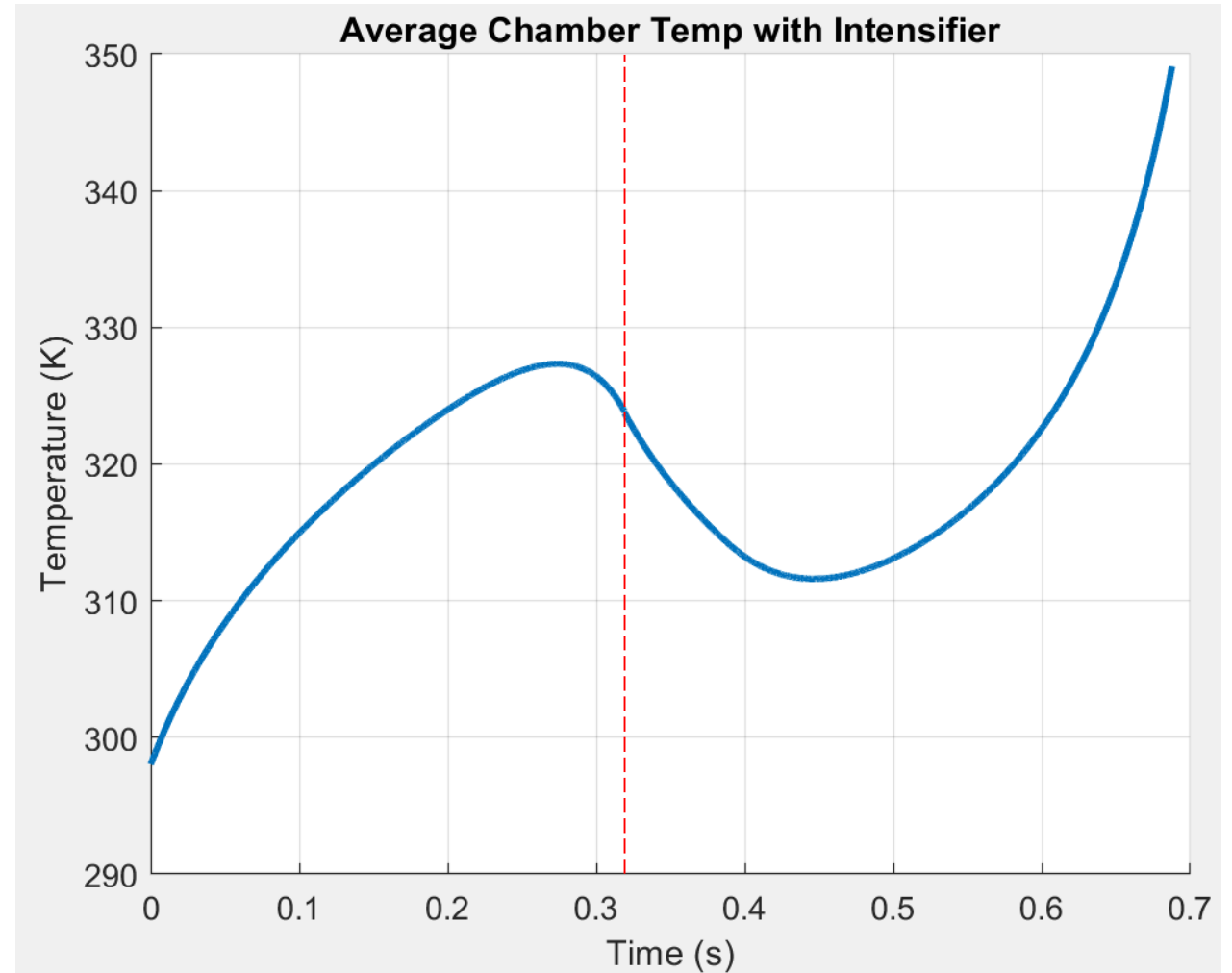
Hydraulic Pump/Motor

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# Flow Intensifier Pump Study
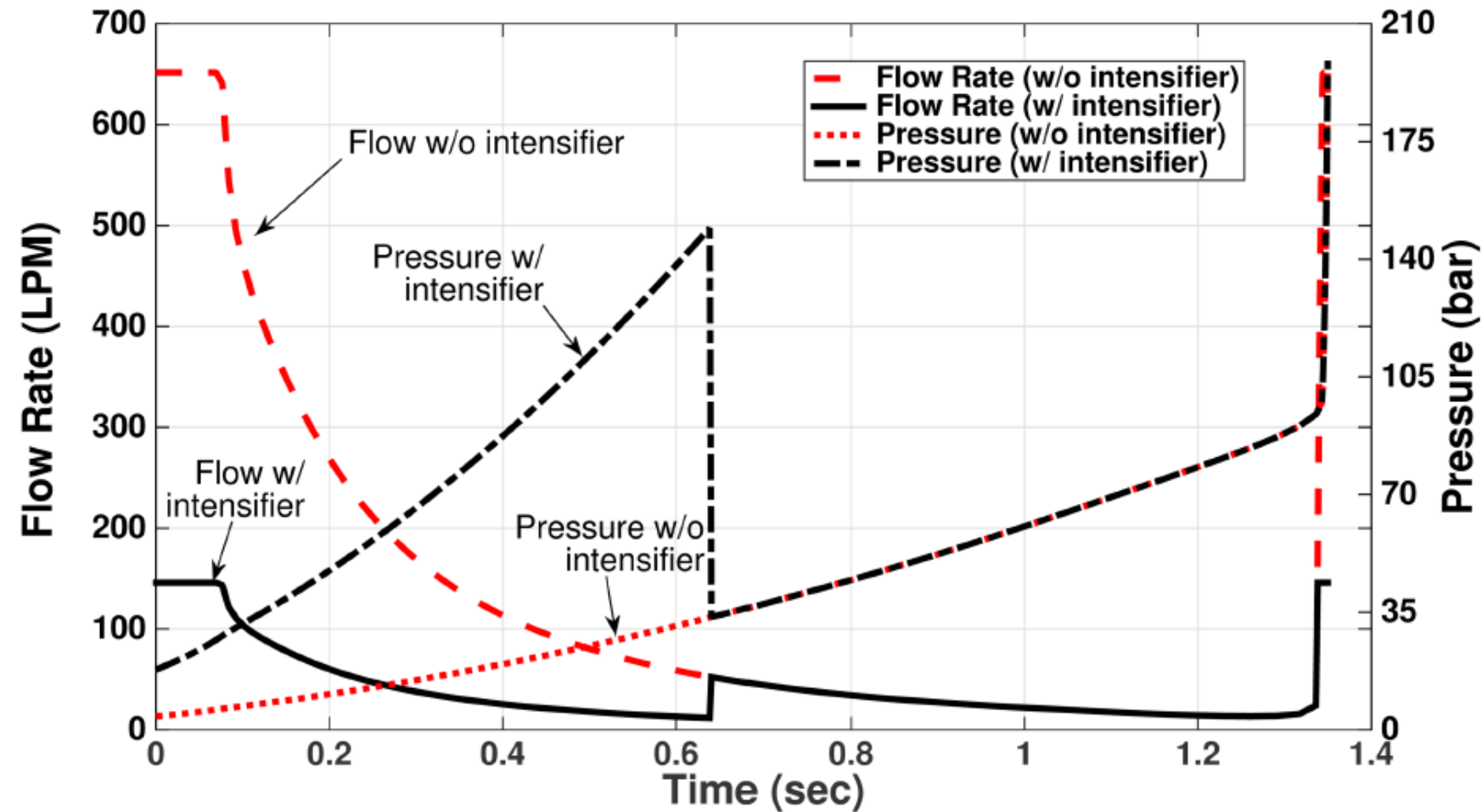
# Combined Intensifier/Cost Optimization

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



Average Chamber Temp with Intensifier

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# 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