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Center for Compact and Efficient Fluid Power

LIQUID PISTON GAS COMPRESSOR FOR COMPRESSED AIR ENERGY STORAGE (CAES) & CARBON DIOXIDE SEQUESTRATION

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http://www.me.umn.edu/~lixxx099/

http://www.me.umn.edu/~lixxx099/EFRI_CAES

Goals

- NSF PFI-TT Program:
  - Partnerships for Innovation: Technology Transfer
  - Program Goal: Advance previously NSF supported research towards commercialization
- Project Goal: Develop a prototype of a reciprocating high pressure (~200bar), high efficiency, liquid piston gas compressor
  - Start date: 9/1/2018

Outline

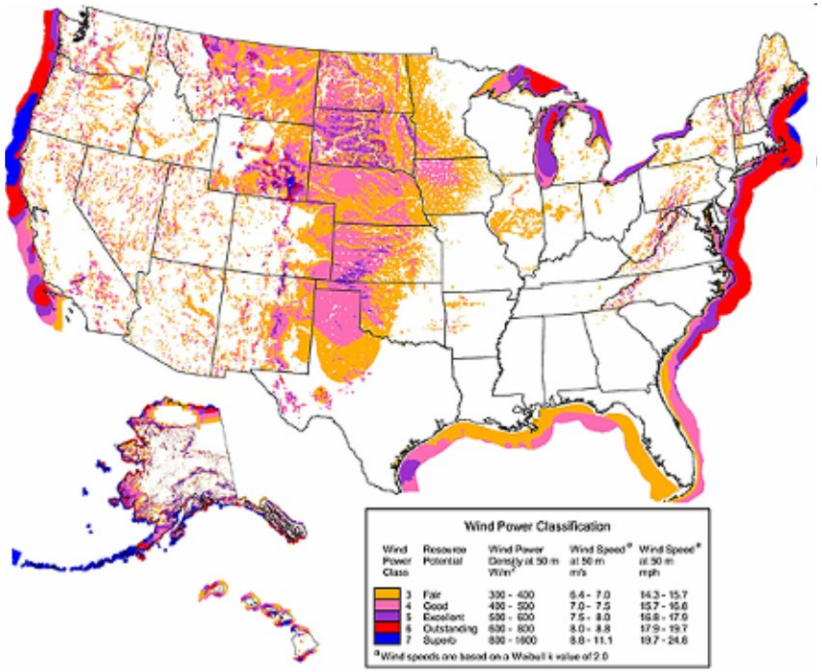
- Motivation / applications
- Challenge of isothermal gas compression/expansion
- Our approach and previous work
- Current research

Motivation:

- Grid scale energy storage as compressed air (CAES)
- Carbon dioxide sequestration / reuse
- Industrial gas

Grid scale energy storage

- Renewable energies – abundant but also intermittent
- Requires fossil fuel powered “peaker” plants to supplement when renewables not available
- Storage can replace peaker plants
  - Increase revenue via price arbitrage
  - Stabilize electrical grid frequency
  - and …..

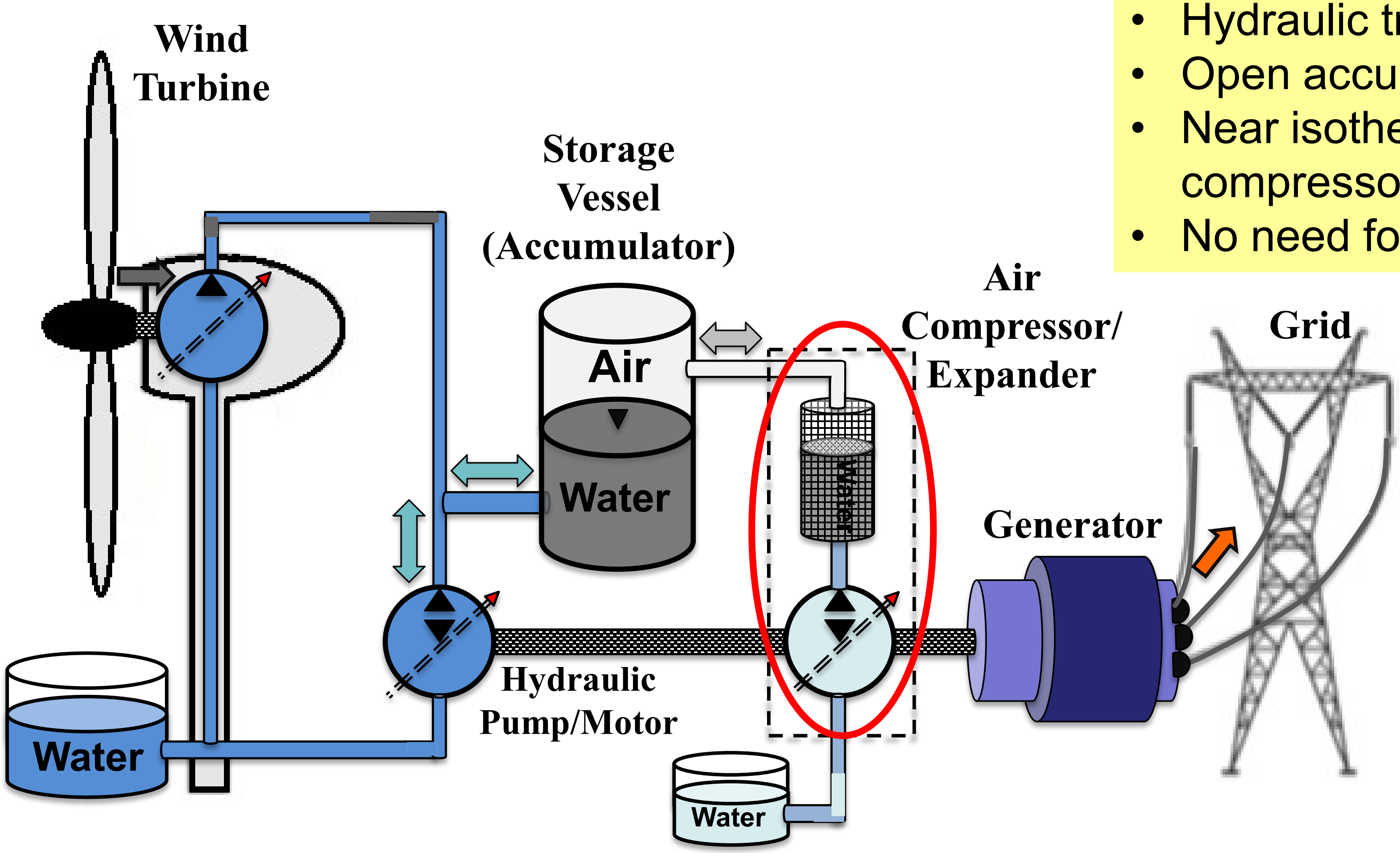


Compressed air energy storage

- Potentially cost effective for long duration (10-100hours):
  - **Competition** - Lithium battery:
    - Cost $270/kWh (2016), short life, rare materials.
  - Isothermal compressed air energy storage (200-350bar)
    - Engineered pressure vessels: $40-80/kWh
    - Underground caverns: $5/kWh
  - Energy density of “open accumulator” CAES:
    - 25kWh/m^3 (210bar) and 47kWh/m^3 (350bar)
      - 20 times higher than closed hydraulic accumulator at similar pressures
      - 5.5 times of conventional CAES

Open Accumulator Isothermal CAES

- Hydraulic transmission
- Open accumulator
- Near isothermal air compressor/ expander
- No need for fossil fuel

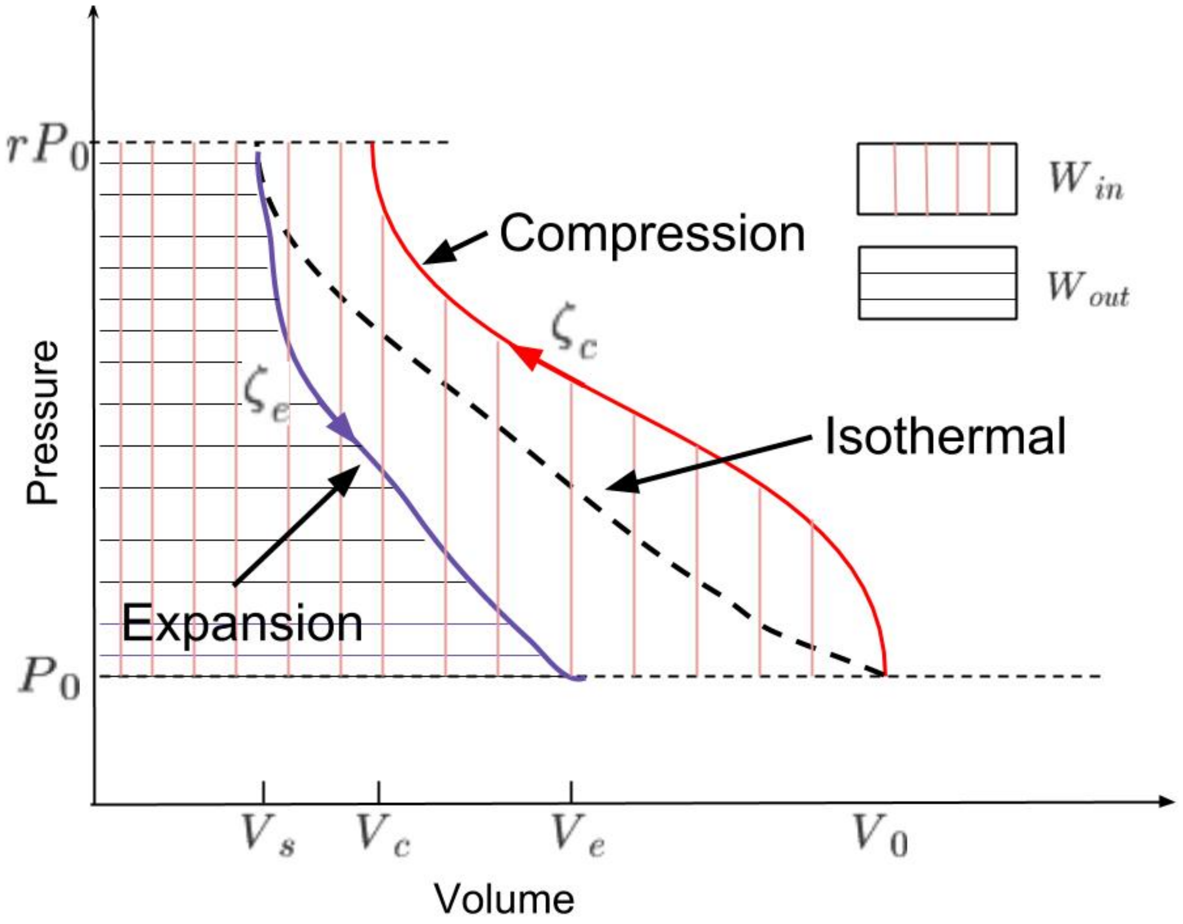


NSF – Emerging Frontier Research and Innovation: (2010-2016) #1038294

- High pressure, efficient and high power (fast) gas compressor/expander:
  - Key for isothermal compressed air energy storage
  - Other applications:
    - CO_2 compression prior to transport for sequestration or reuse
    - Industrial gas compression:
      - Linde, Praxair & Air Products together consume 1% of U.S. electricity

Challenge in Air Compression / Expansion Process

1. Compression : $(P_0, T_0) \rightarrow (rP_0, T_c)$
2. Constant-pressure cooling : $(rP_0, T_c) \rightarrow (rP_0, T_0)$
3. Expansion: $(rP_0, T_0) \rightarrow (P_0, T_e)$



Assume heat source & sink at ambient temp T_0

Power = Work / Time

First law : $$mC_v\dot{T} = -P\dot{V} - \underbrace{h \cdot A \cdot [T - T_0]}_{Q:\ \text{heat transfer}}$$

Time taken: $$t_{c/e} = \int dt = \int \frac{mC_v dT + PdV}{Q}$$

- P-V-T curve – determines work and efficiency
- Heat transfer – determines time
- Decreasing time increases power ➔ lower capital cost

Adiabatic (r=350, T_0=298K): t = 0
- Comp./expan temp: 1583K/56K
- Efficiency < 35-38%

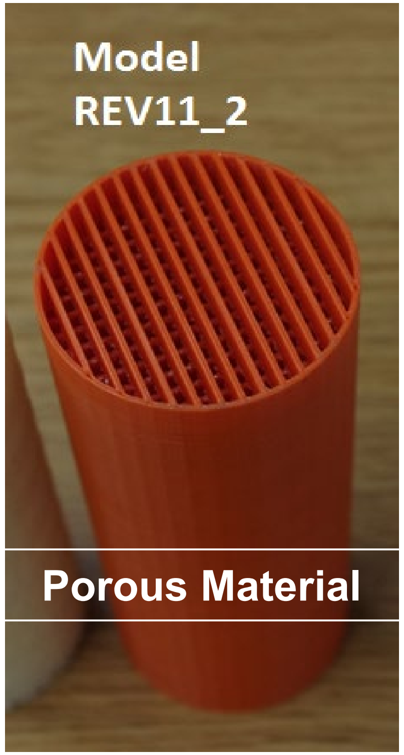
Isothermal (T_0=298K):
- Efficiency = 100%
- t = infinite

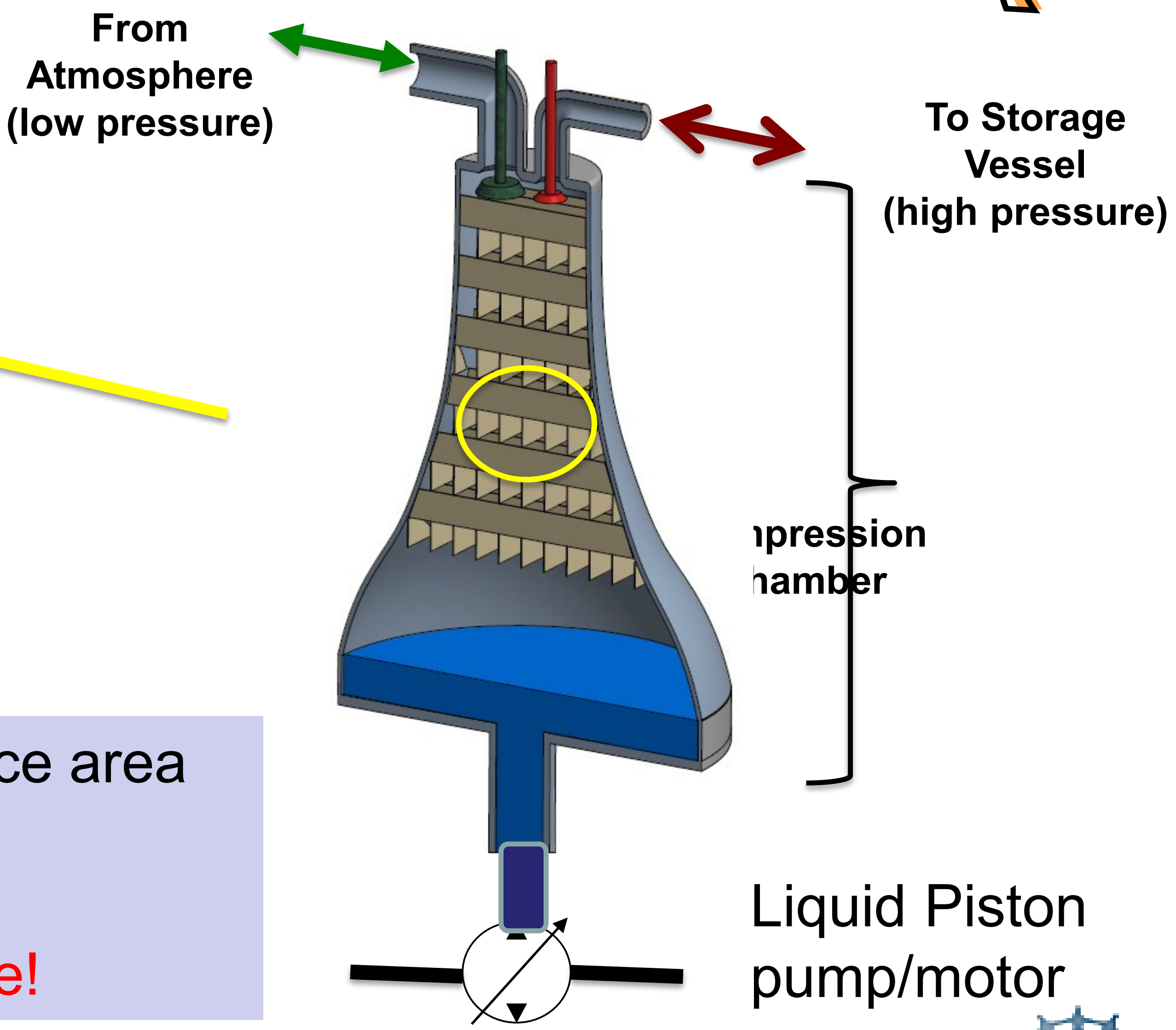
Target:
Eff: 90-95%
t =1 to 2 s

Our approach:

Improve heat transfer during compression/expansion process

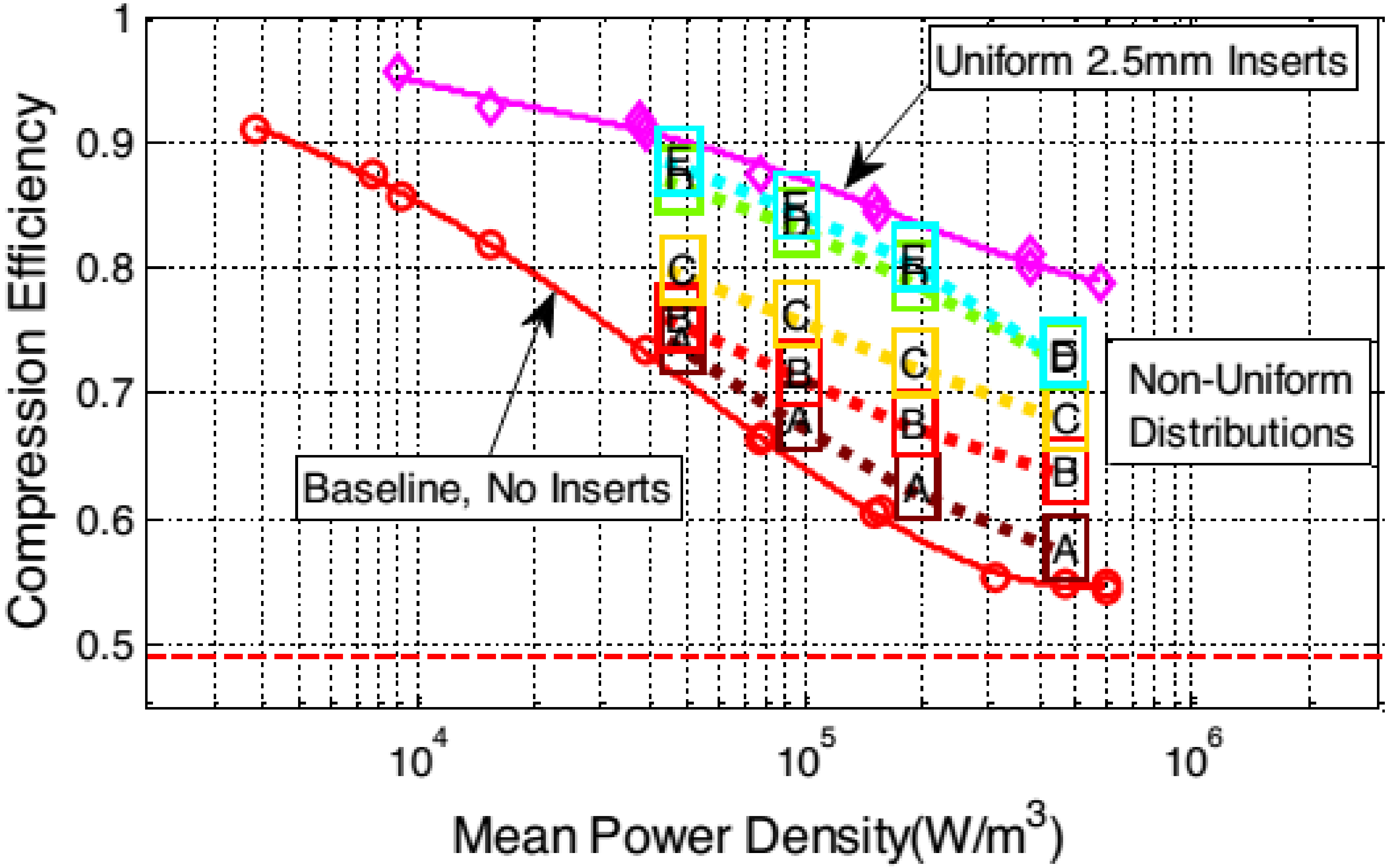
Liquid Piston C/E with Porous Media





- Porous material → increase surface area
- Reduce dead-volume
- Good, low friction seal
- Liquid piston trajectory controllable!

Effect of porous media (7- 210 bar) : Experiments

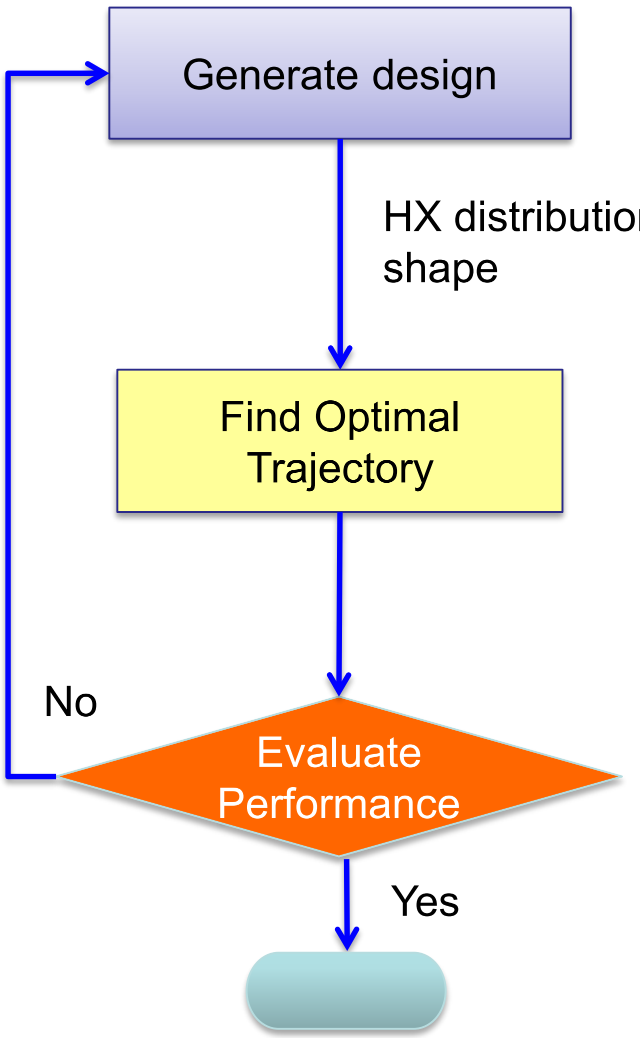


10x increase in power density

10-15% increase in efficiency

Design of LP Compressor/Expander

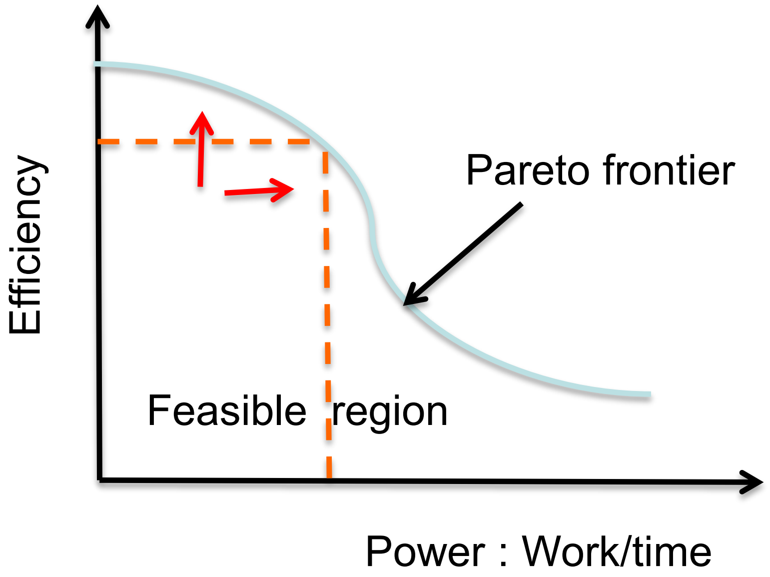
- Choice and distribution of HX porous media
  - Heat transfer vs. space/cost, drag
- Choice of shape
  - Heat transfer coefficient vs liquid drag
- Choice of flow (control) trajectories
  - Efficiency vs power

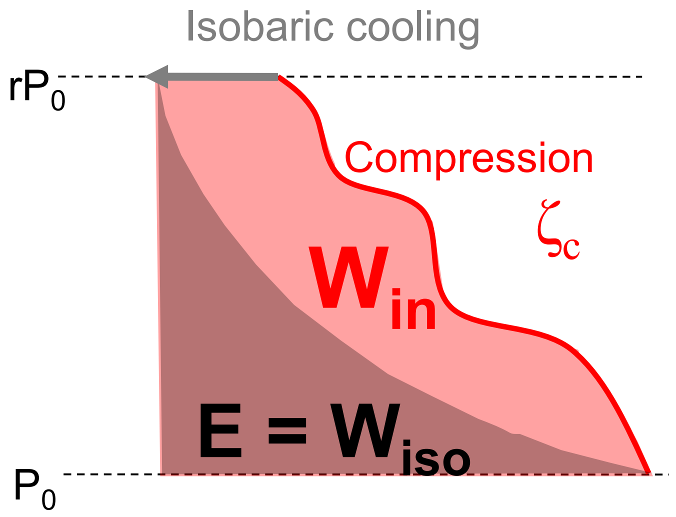


Pareto Optimal Compression/ Expansion Control Problem

Given shape and porous media design, find P-V path s.t. either

1. For a given efficiency (fixed work), power is maximized (minimize time); or
2. For a given power (time), efficiency is optimized (minimize compression work or maximize expansion work)

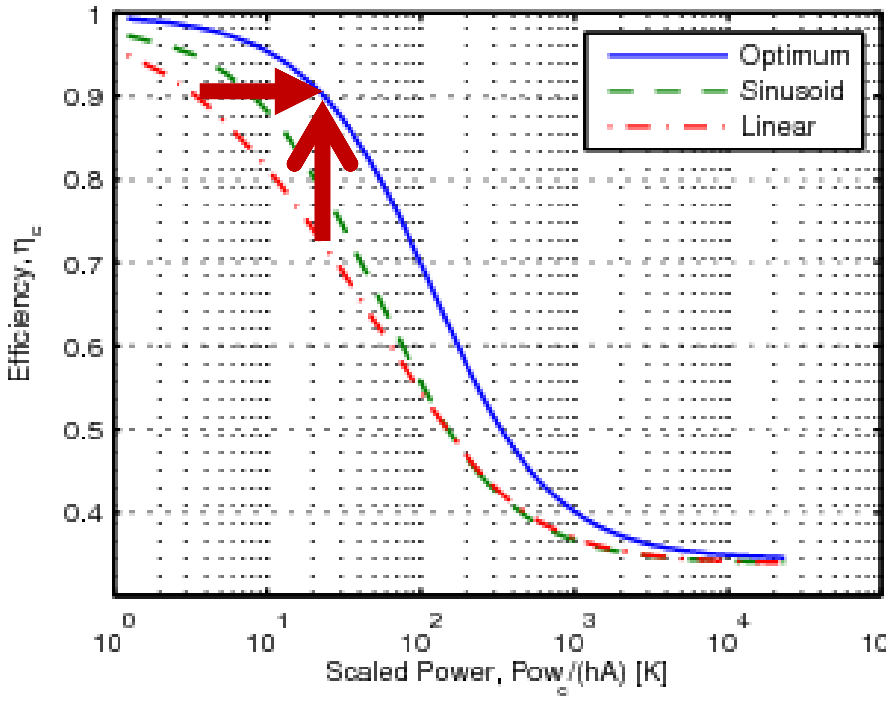




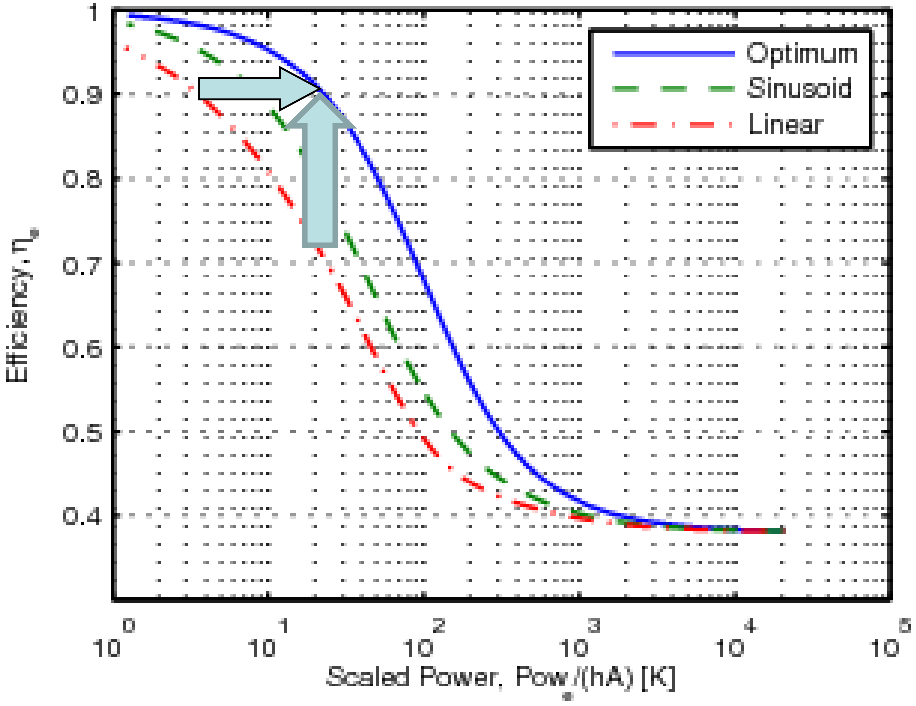
Efficiency-Power trade-off (theoretical)

Constant hA, 350:1 comp ratio

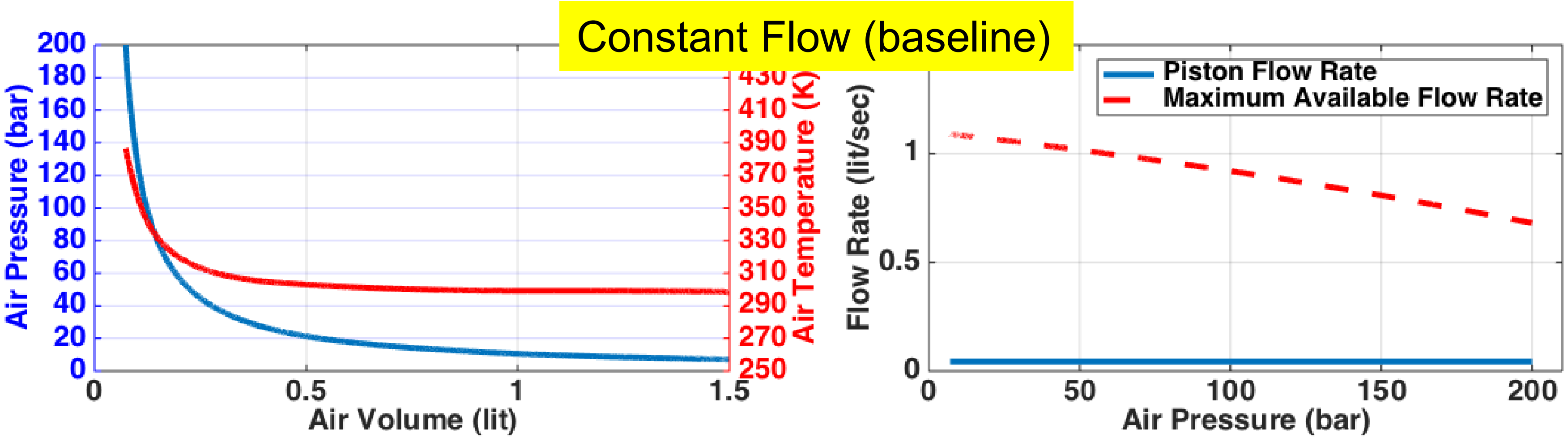
Compressor



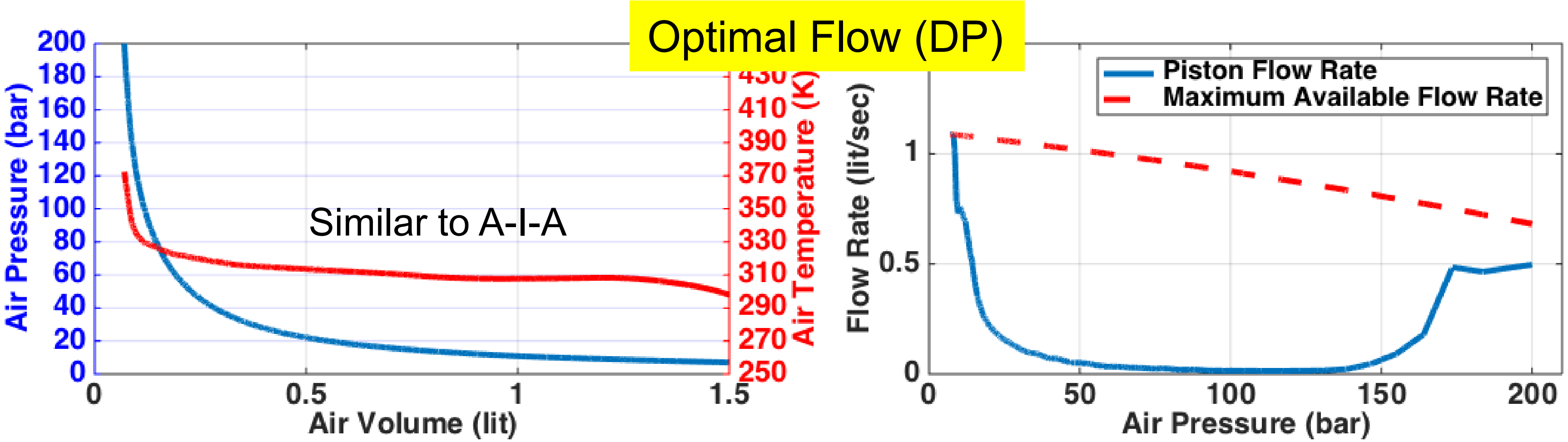
Motor



Optimal profile increases power for the same efficiency by 3 to 5 times over linear and sinusoidal profiles
Increases efficiency by 15%-20%



Realistic heat transfer model



Simulations

	Flow Rate	Efficiency	Compression Time	Power Density (based on air volume)
Baseline	Constant (43.2 cc/s)	92%	33 sec	71.2 kW/m^3
DP Optimal Flow	Variable	92%	10.8 sec	217.3 kW/m^3

300% faster (smaller) !!!

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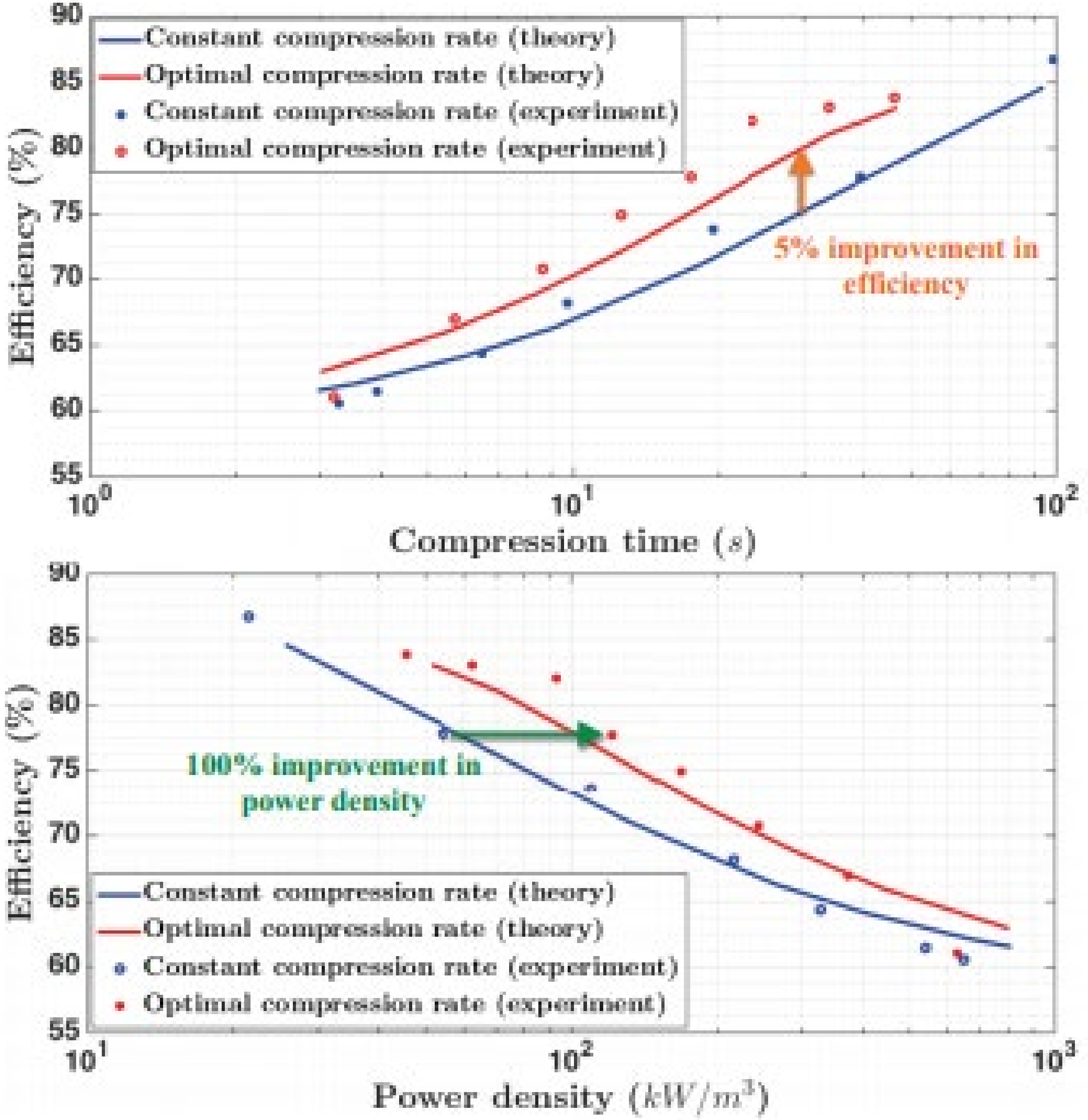


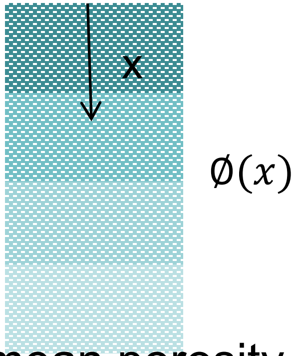
Efficiency-Power trade-off (experimental)

> 2x power density or 5-10% increase in efficiency

Optimal Design of Compressor/Expander

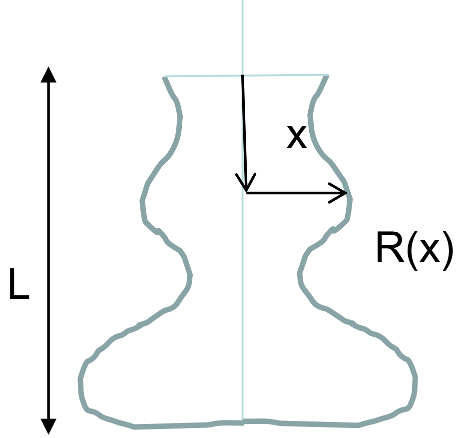
- HX porous media distribution
  - Heat transfer vs. space/cost, drag, gas/liquid trapping
- Shape
  - Heat transfer coefficient. vs liquid drag and length constraint

Porosity distribution



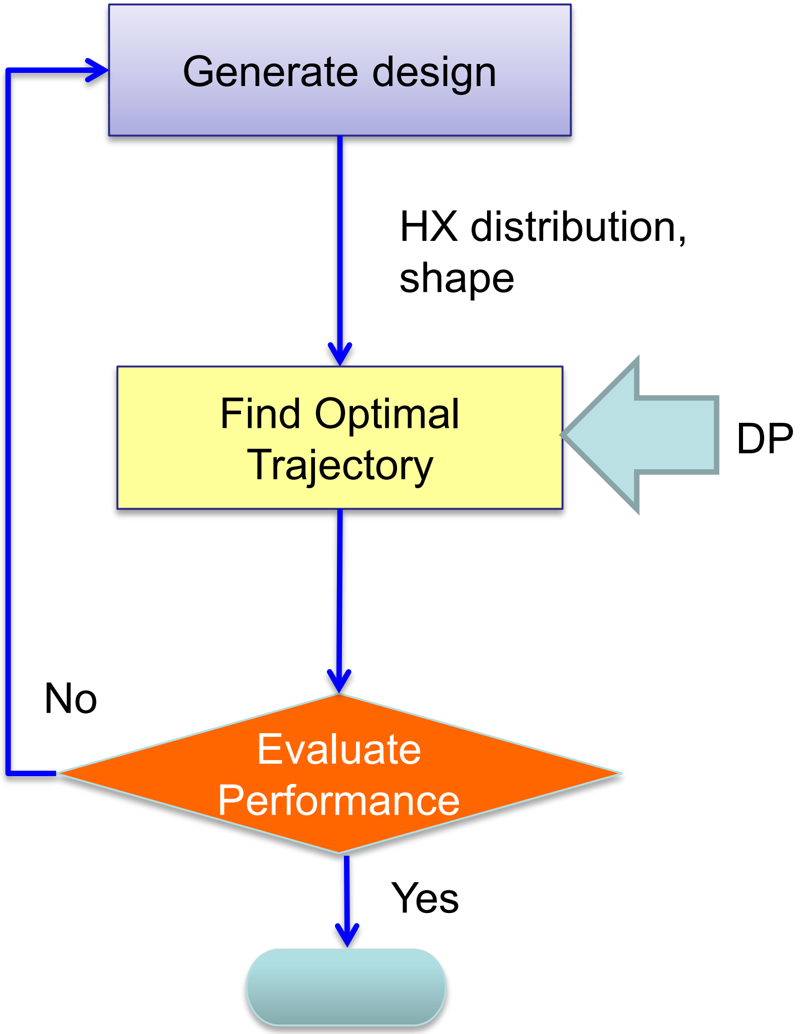
Fix mean porosity (total porous media)

$$\underline{\phi} \le \phi(x)$$

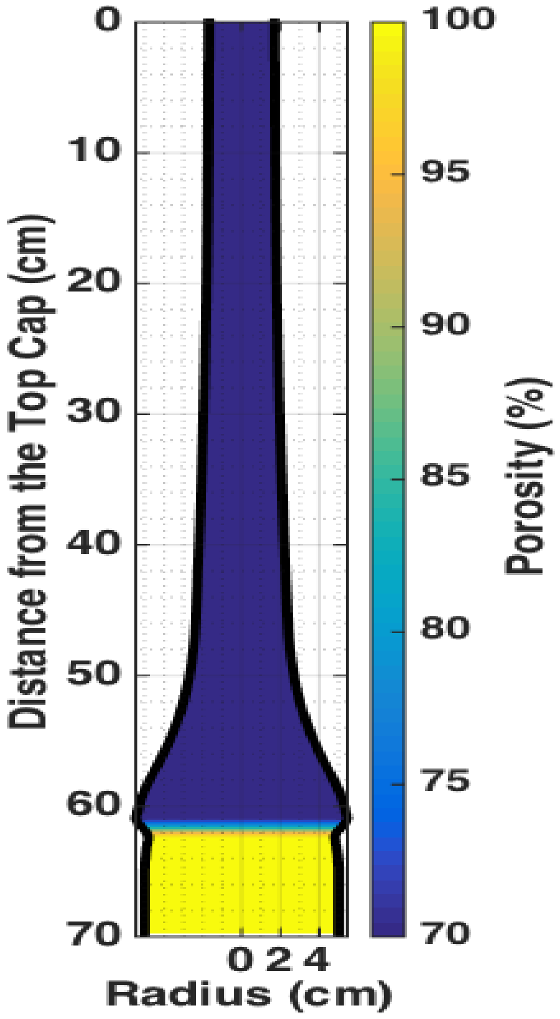


Fixed volume

$$\underline{R} \le R(x) \qquad L \le \bar{L}$$



Optimal Design Results (92%eff)



	Porosity	Flow Rate	Shape	0-D Model	
				time	Power Density
Case # 1	80% Uniform	Constant	Uniform ($21.5\ cm^2$)	33 sec	$71.2\ kW/m^3$
Case # 2	80% Uniform	Optimal	Uniform ($21.5\ cm^2$)	11 sec	$217.3\ kW/m^3$
Case # 3	80% Optimal	Constant	Uniform ($21.5\ cm^2$)	9.6 sec	$245.6\ kW/m^3$
Case # 4	80% Optimal	Optimal	Uniform ($21.5\ cm^2$)	3.5 sec	$669.3\ kW/m^3$
Case # 5	80% Optimal	Optimal	Optimal (L=69 cm)	1.6 sec	$1.47\ MW/m^3$

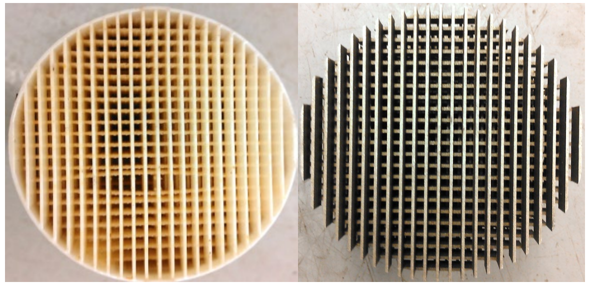
Opt. Porosity: 3x improvement, as much porous media at the top
Opt. Shape: 2x improvement, narrow at top

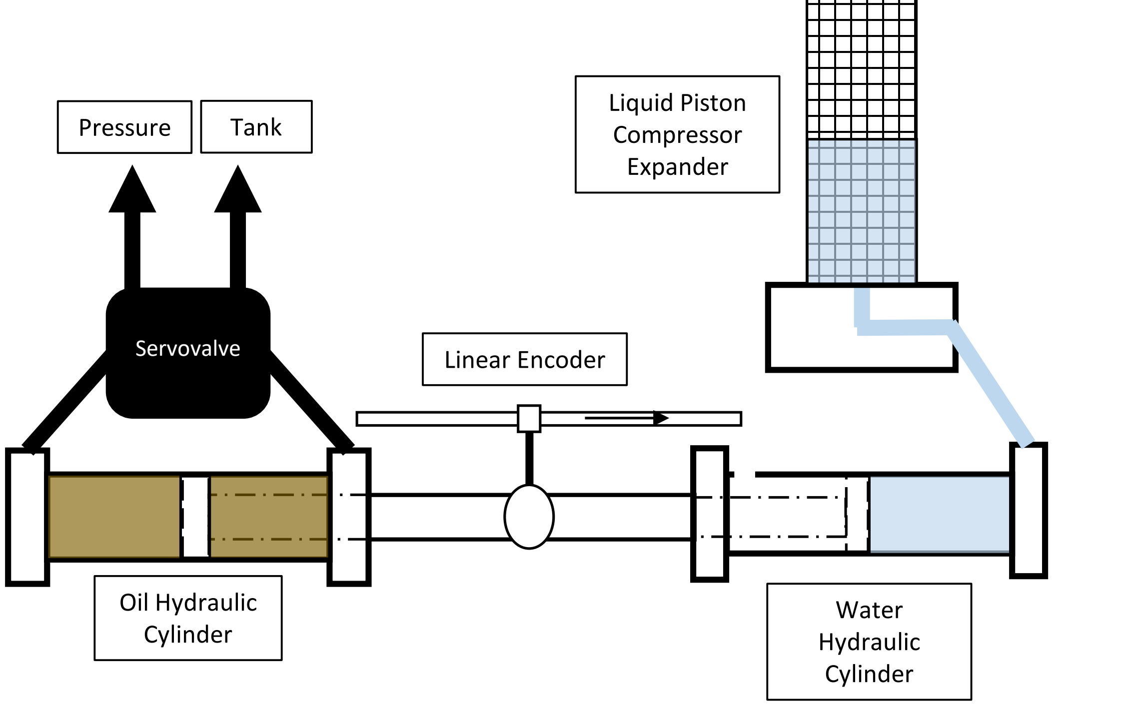
33 sec → 1.6 sec (20 x improvement over uniform porous media)

Previous experimental compressor/expander

Pressure: 7bar to 210bar,
Time: >2sec

2.5mm Interrupted Plate HX





J. Wieberdink and B. Yan

Previous experimental system

- Emphasizes validating thermodynamic states
- Controllable flow
- Accurate measurements (pressure, volume etc.)

- Only capable of 1 compression and 1 expansion stroke
- Inefficiency liquid piston generation
- Cannot store compressed air

Current 5kW prototype design

Repeated operation:

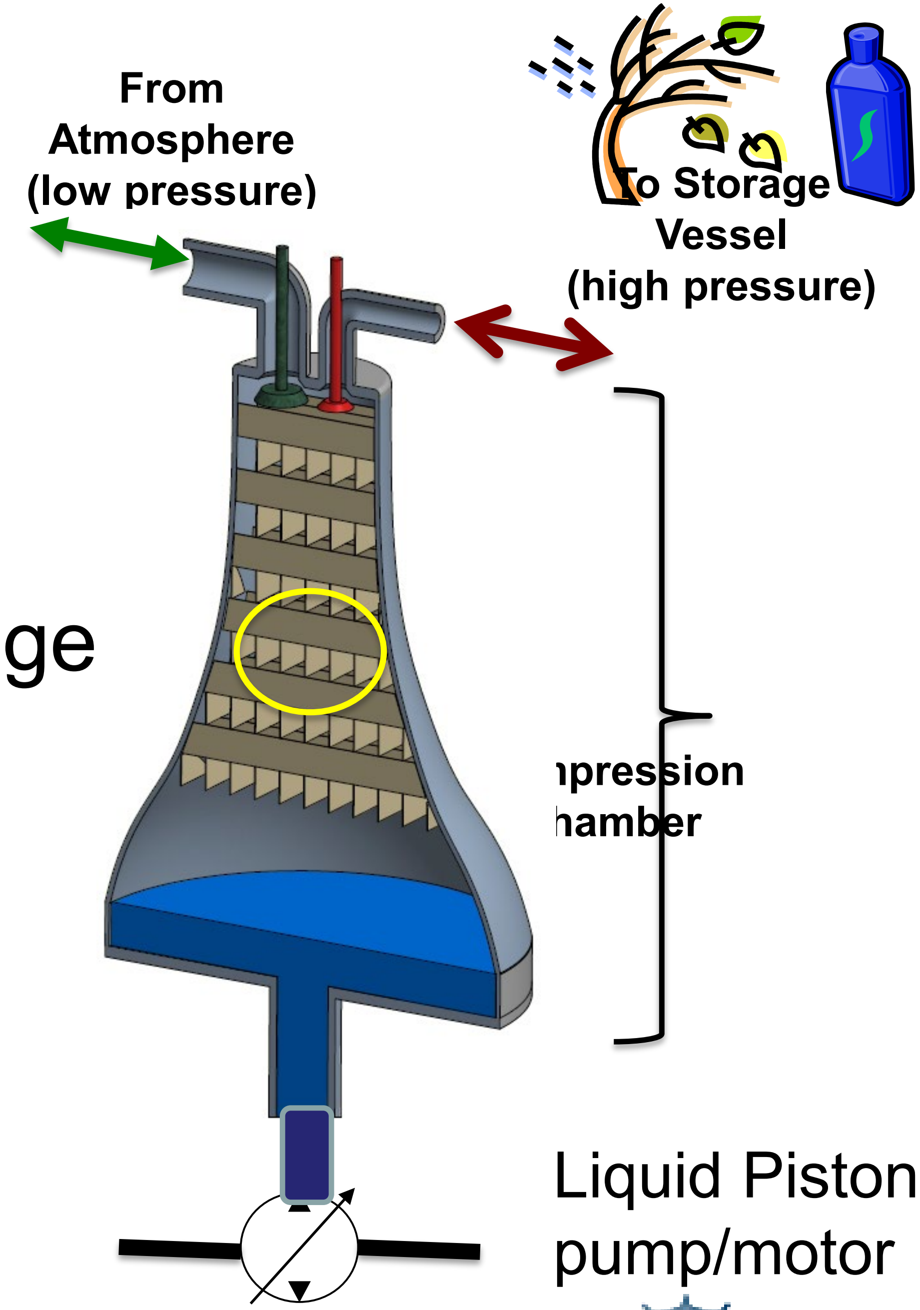
- Reciprocating, multi-cycle

Input-output:

- Shaft power ←→ compressed air storage

Optimize cost instead of size

Challenges: Valve design; liquid piston sensing and control; dead-volume management; efficient PTO



Summary

- Isothermal gas compressor/expander have wide market potential for green economy
- Key challenge: high efficiency <u>AND</u> high power
- Previous research has shown:
  - optimized liquid piston w/ porous media C/E approach achieves 200x increased power density at 92% efficiency
- Current research aims to create and validate a reciprocating prototype based on concept