Performance of Novel Compression Concepts for Heat Pumping, Air Conditioning and Refrigeration Applications

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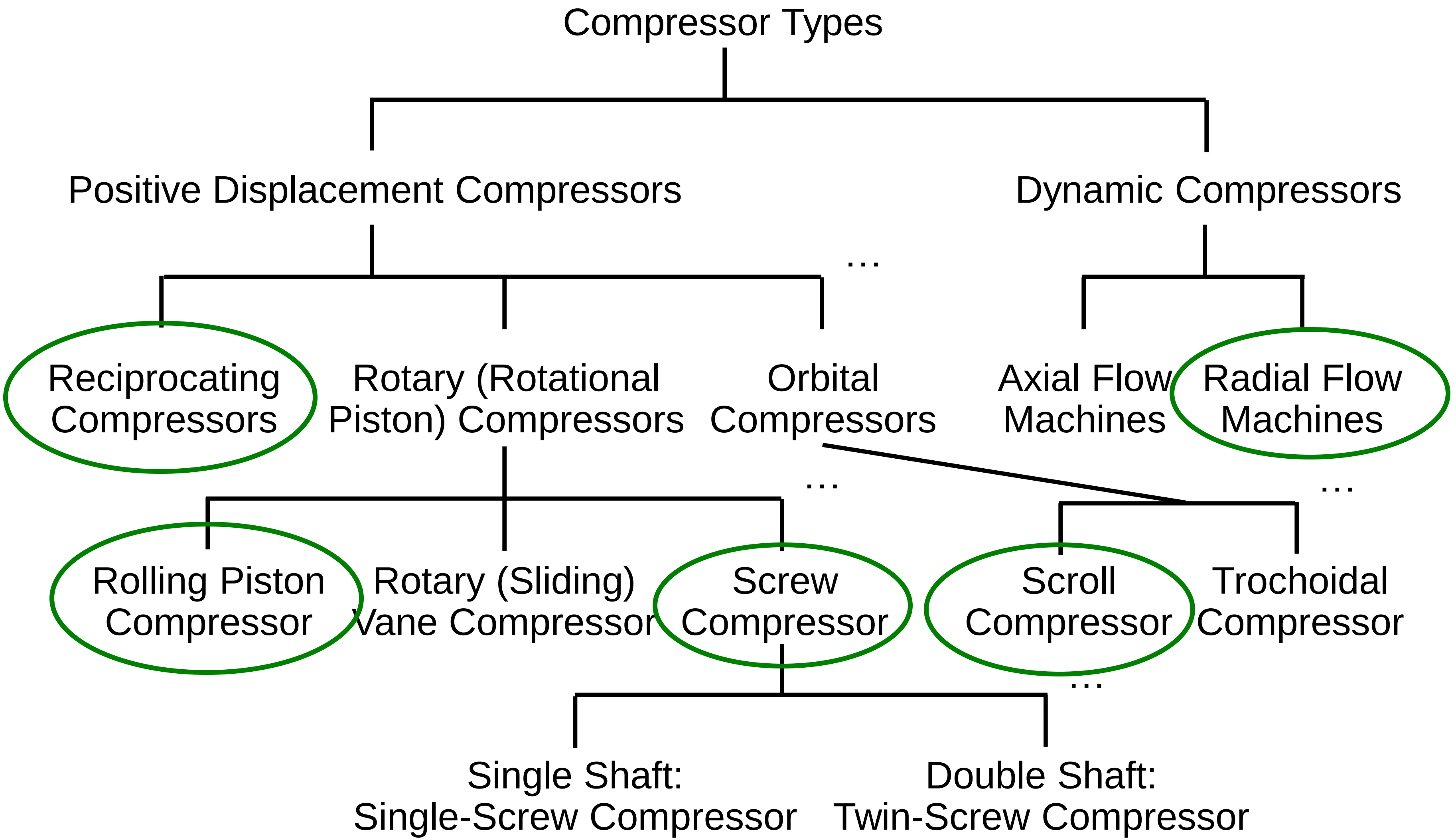
Contents

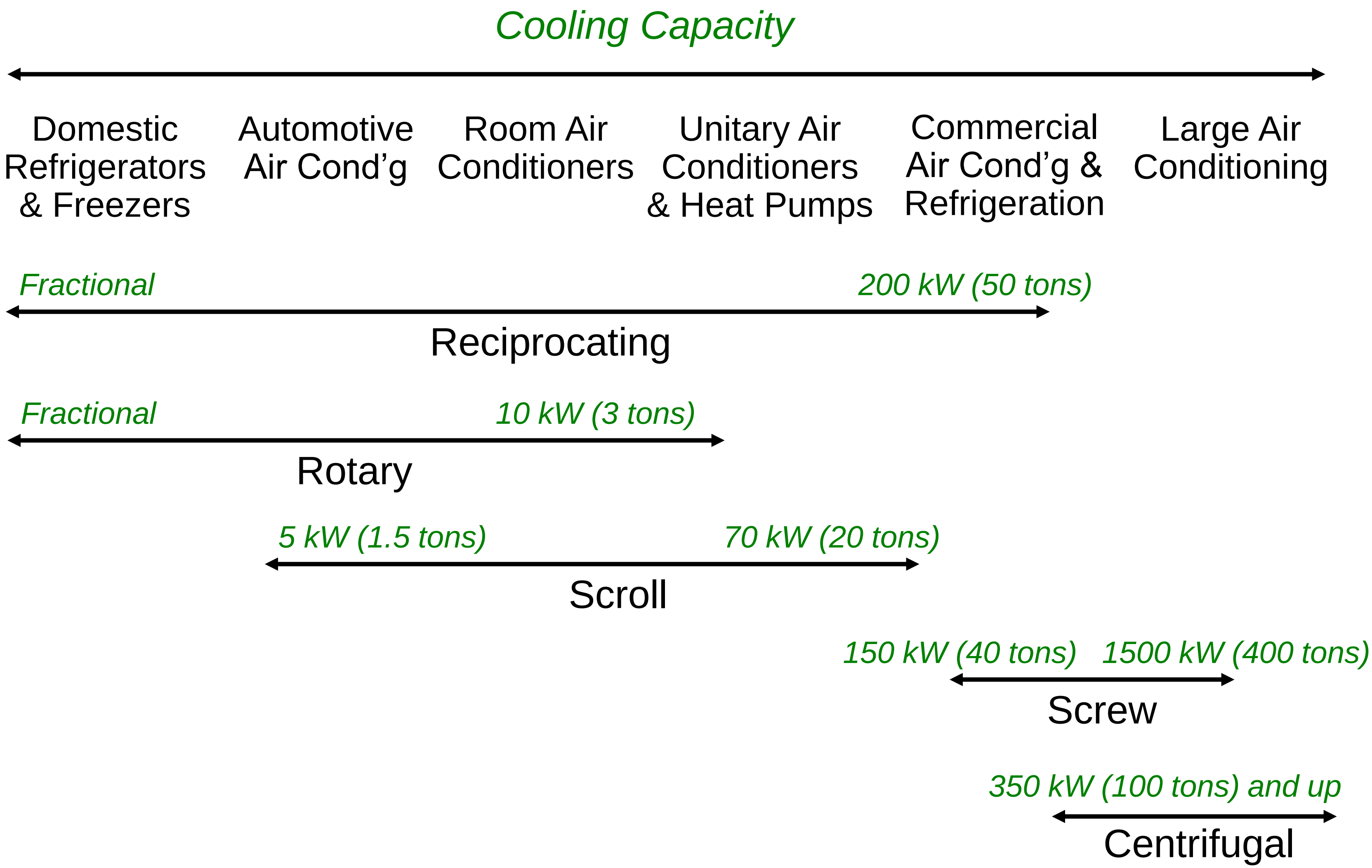
- Introduction
- Modeling of Compressors
- Rotating Spool Compressor
- Bowtie Compressor
- Z-Compressor
- Linear Compressor
- S-RAM Compressor

Introduction
Overview of Refrigeration Compressors



Introduction

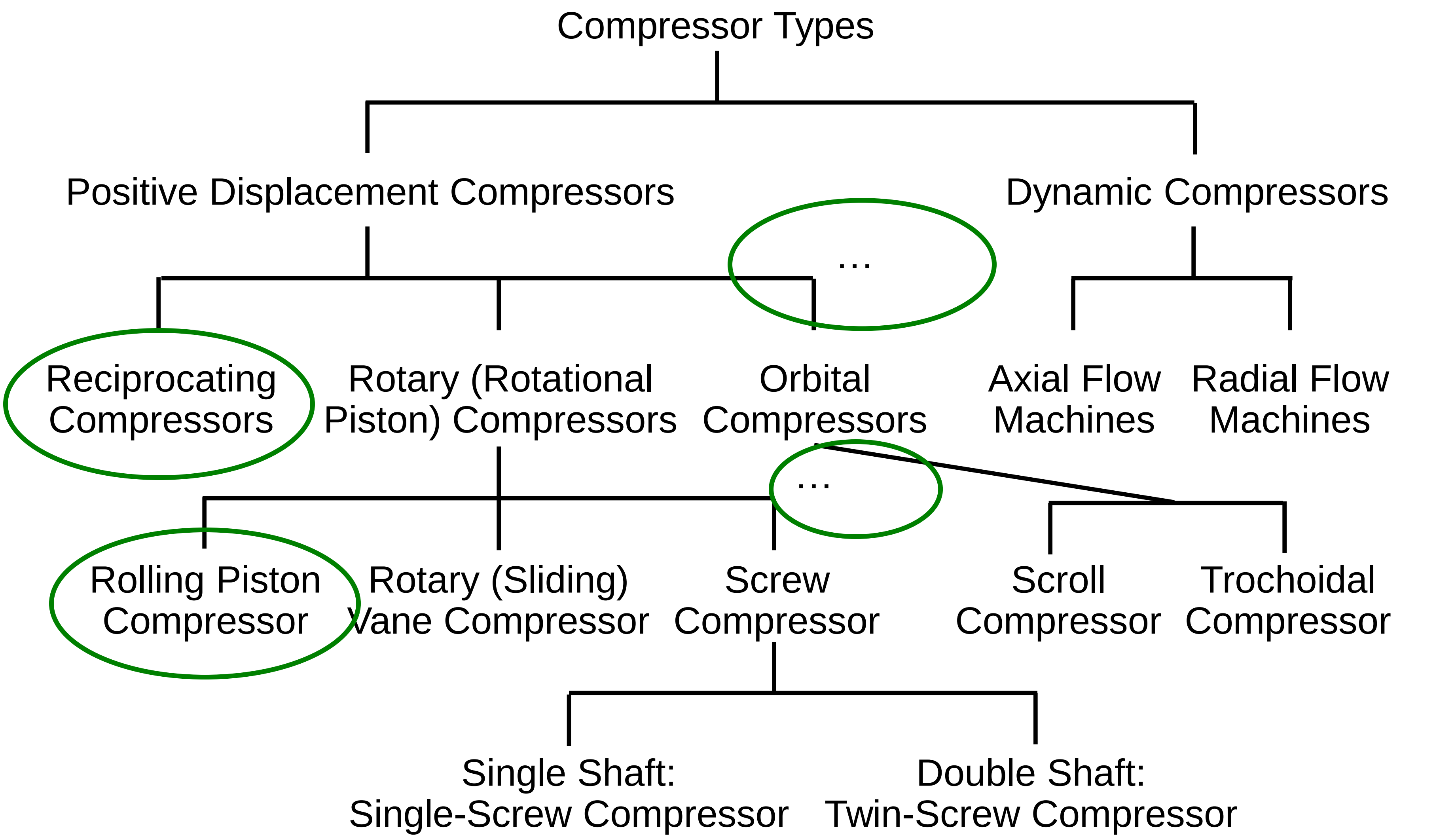
Range of Applications of Compressors



Motivation for New Compression Concepts

- Political and economic concerns
  - » Global warming
  - » Ozone depletion
  - » Increased competition
- Technological advances
  - » New working fluids
  - » New design and manufacturing capabilities
  - » New applications

Introduction
Overview of Refrigeration Compressors



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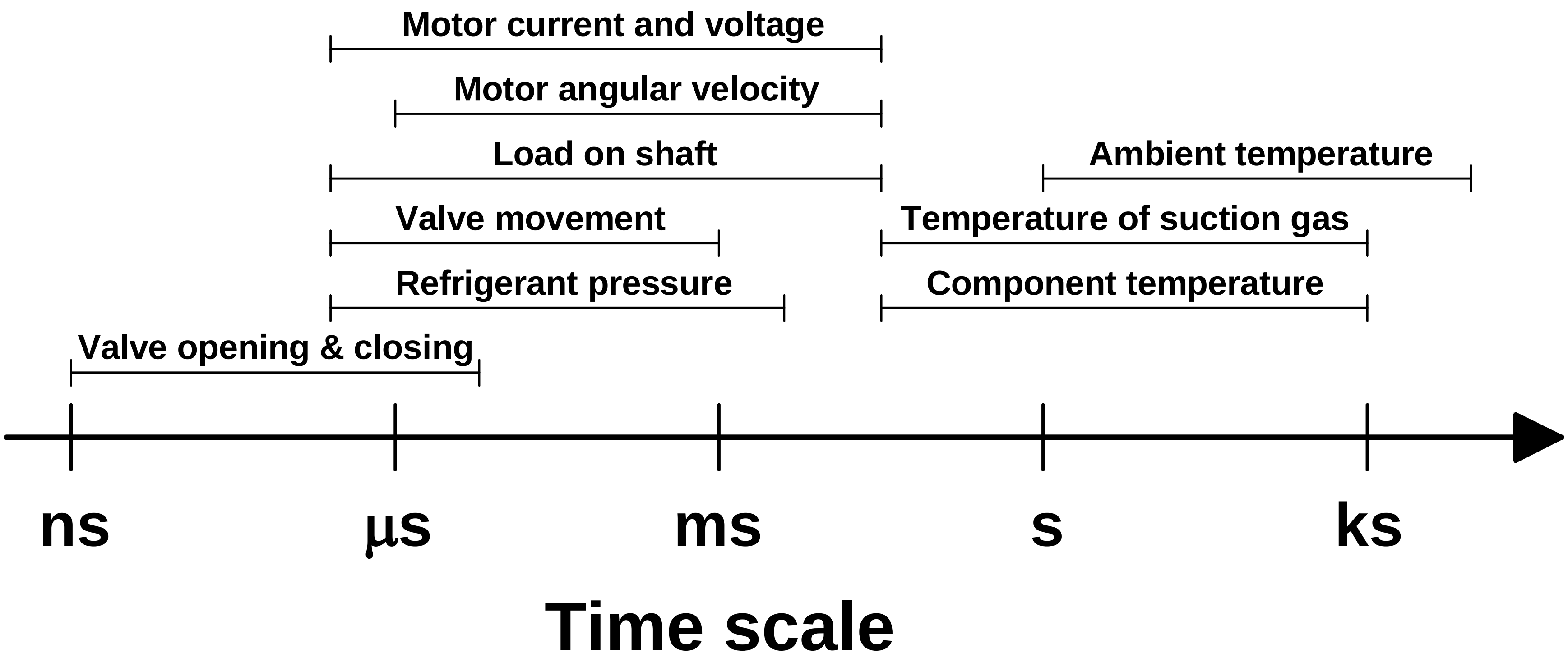
Modeling of Compressors: Underlying Principles

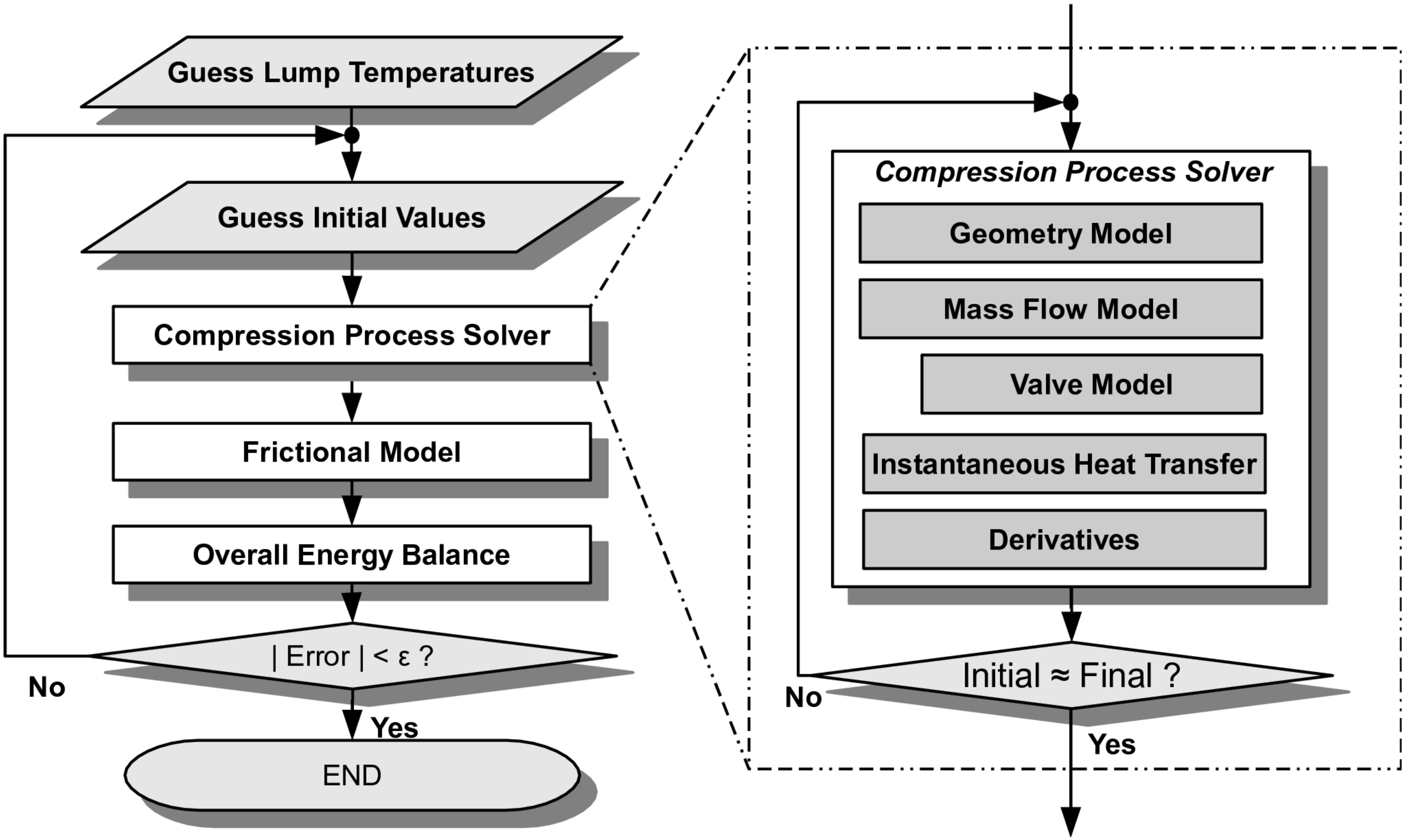
- Compressor modeling relies on many engineering disciplines:
  - » Thermodynamics
    - – e.g.: Changes in refrigerant properties
  - » Fluid mechanics
    - – e.g.: Flow of refrigerant in chambers and flow passages
  - » Solid mechanics
    - – e.g.: Forces acting on valves and the resulting deformations
  - » Electrical engineering
    - – e.g.: Conversion of electrical energy to mechanical energy in a motor
  - » Chemical engineering
    - – e.g.: Unwanted decomposition of refrigerant and oil

Modeling of Compressors: Process Dynamics

- Compressor modeling relies on understanding of various time scales inside the compressor



Modeling of Compressors: Model Flow Chart



Modeling of Compressors: Compression Process Equations

- Conservation of Mass and Energy
  - » Combined mass and energy balance can be solved in series for dρ/dθ and dT/dθ:

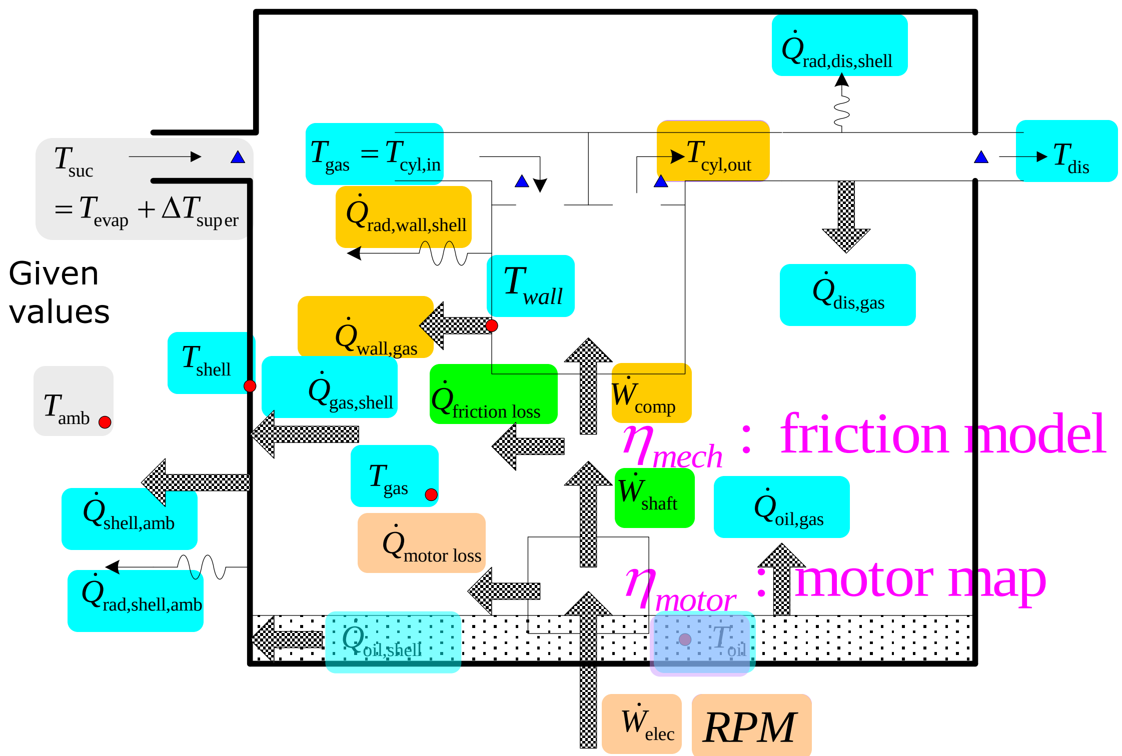
(properties) (leakage) (geometry) (heat transfer)

$$\frac{d\rho}{d\theta} = \frac{1}{V}\left[-\rho\frac{dV}{d\theta} + \frac{1}{\omega}\left(\sum \dot{m}_{in} - \sum \dot{m}_{out}\right)\right]$$

$$\frac{dT}{d\theta} = \frac{-\rho h\frac{dV}{d\theta} - \left(uV + \rho V\frac{\partial u}{\partial \rho}\right)\frac{\partial \rho}{\partial \theta} + \frac{1}{\omega}\left(\dot{Q} + \sum \dot{m}_{in}h_{in} - \sum \dot{m}_{out}h_{out}\right)}{\rho V\frac{\partial u}{\partial T}}$$

Modeling of Compressors: Modeling Approach

Schematic of energy flows inside a hermetic compressor



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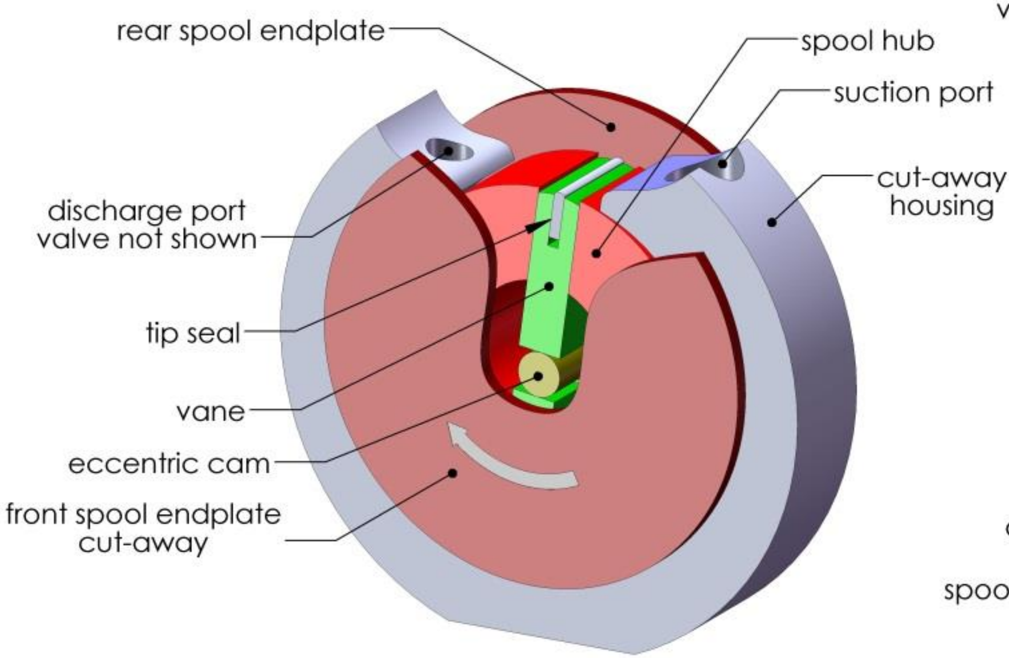
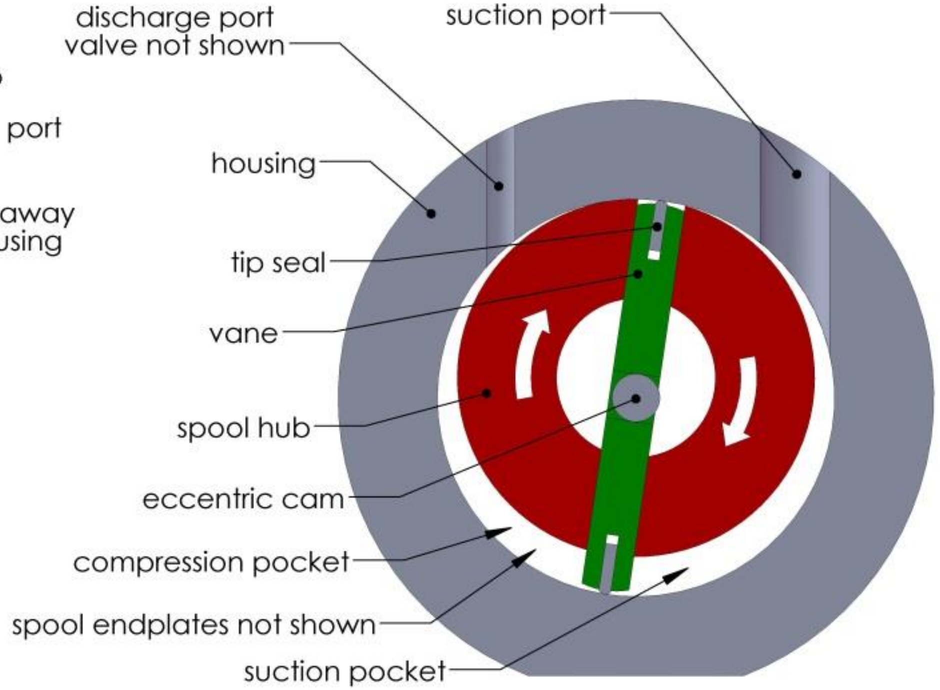
Rotating Spool Compressor: Design

Motivation: Achieve competitive compressor performance at significantly reduced manufacturing costs





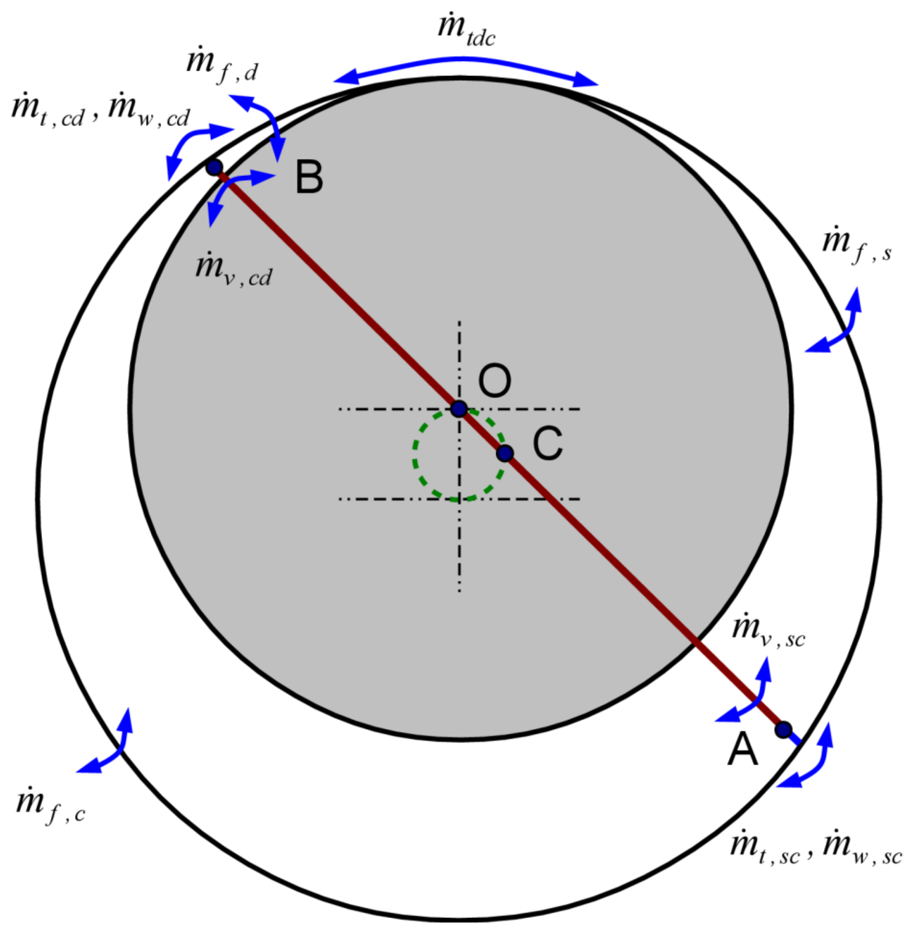
- Introduced by Kemp et al. (2008, 2010)
- Performance data presented by Orosz et al. (2012)
- Model(s) presented by Bradshaw et al. (2013) and Bradshaw, C.R. (2013)

Rotating Spool Compressor: Design

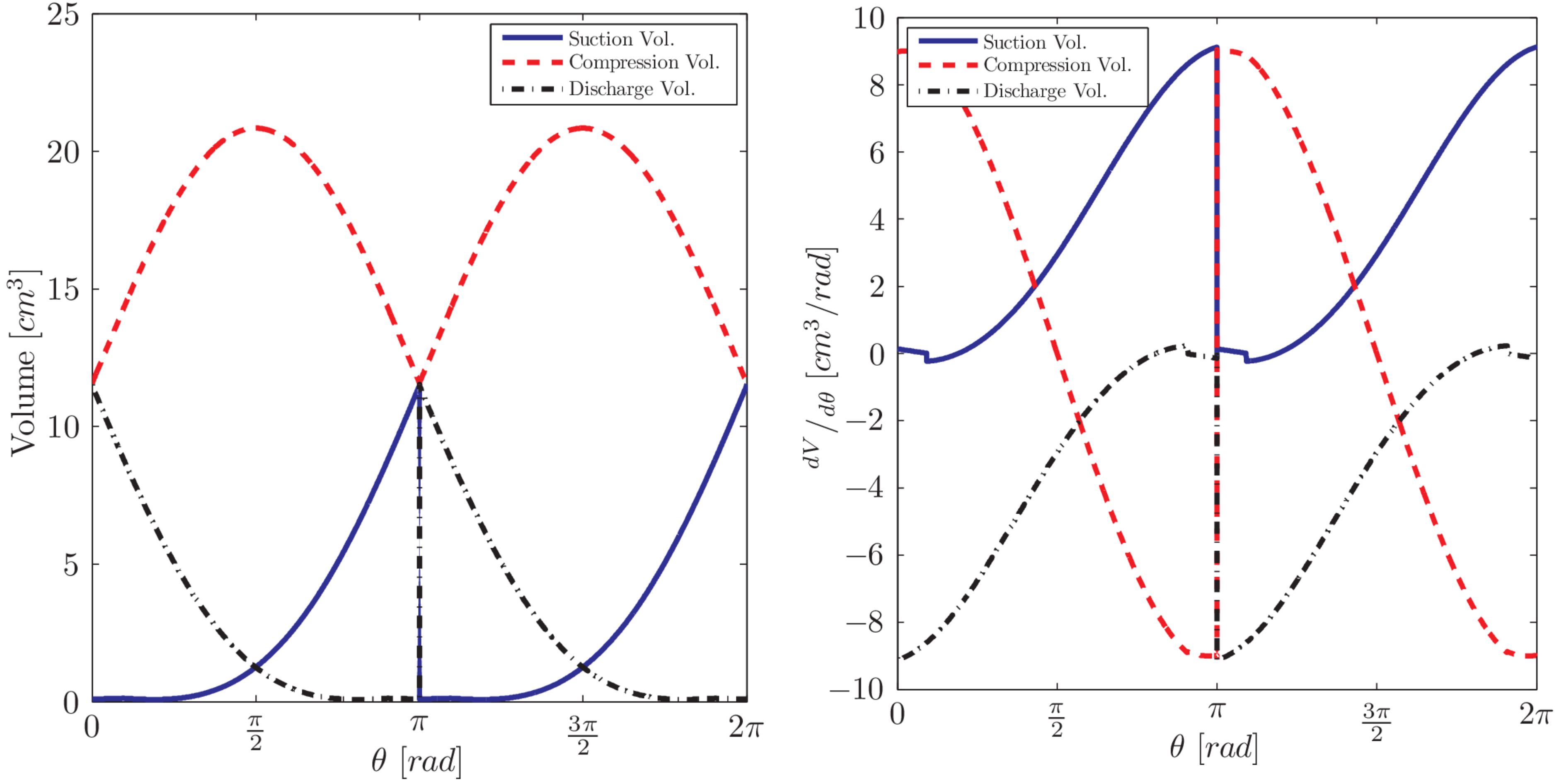
Rotating Spool Compressor: Features

- Four major components with simple geometry for reduced manufacturing cost
- Spool face motion nearly eliminates frictional and leakage losses between the vane and face
- Active sealing elements allow for creative solutions to minimize leakage and friction

Leakage Paths

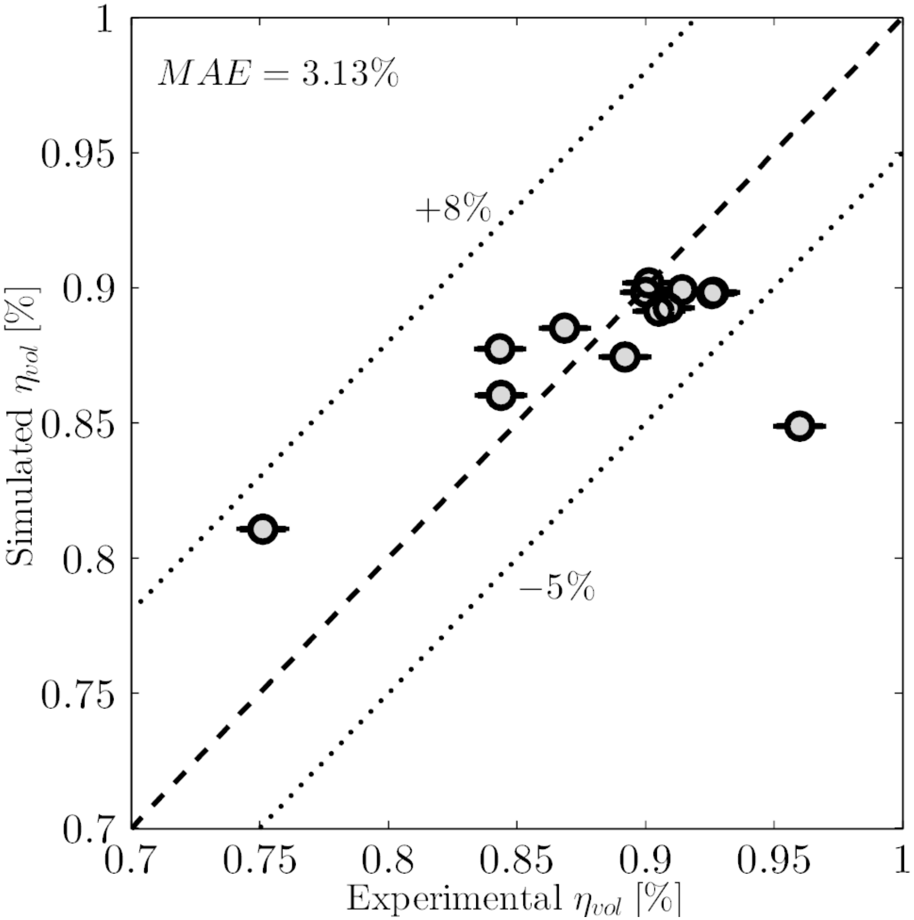


Rotating Spool Compressor: Geometry

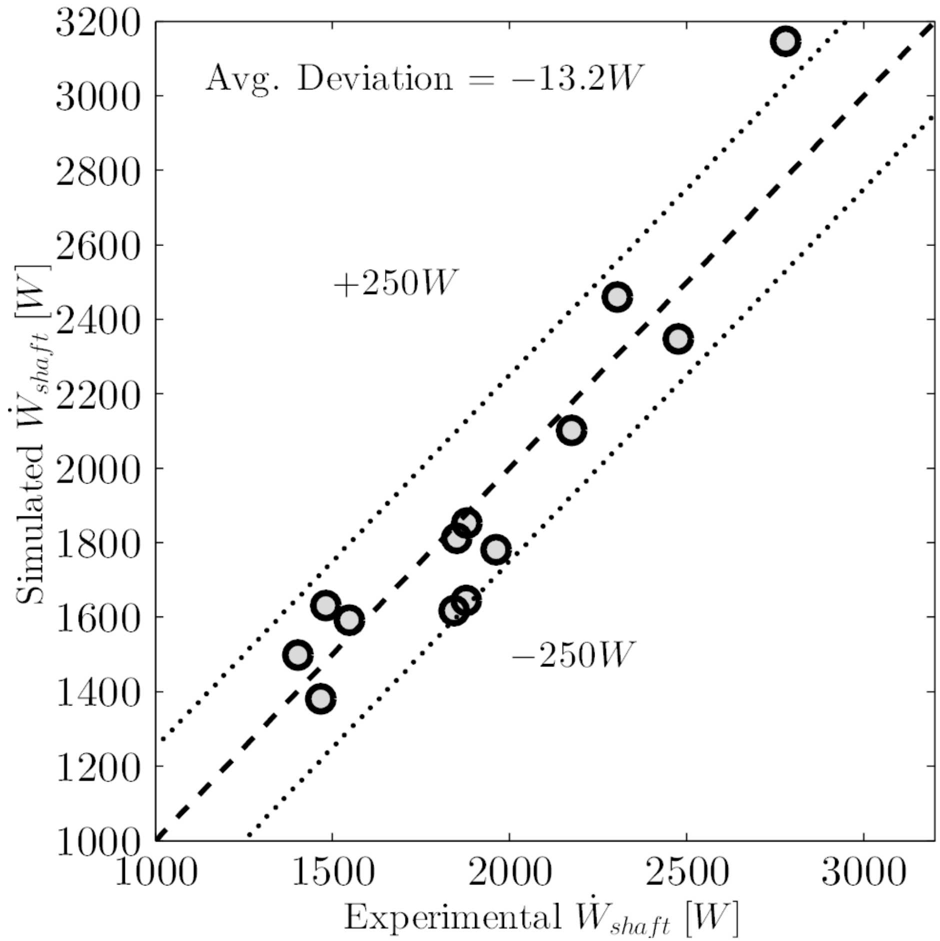


Rotating Spool Compressor: Model Validation

Volumetric Efficiency

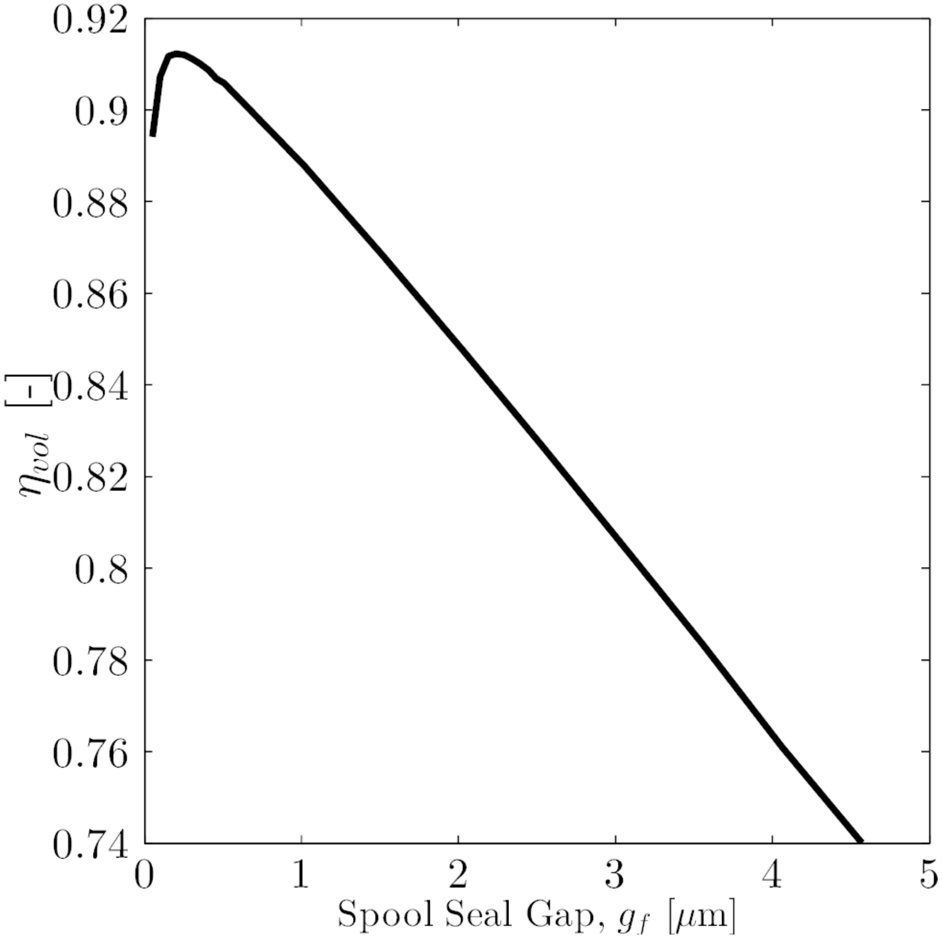


Power Consumption

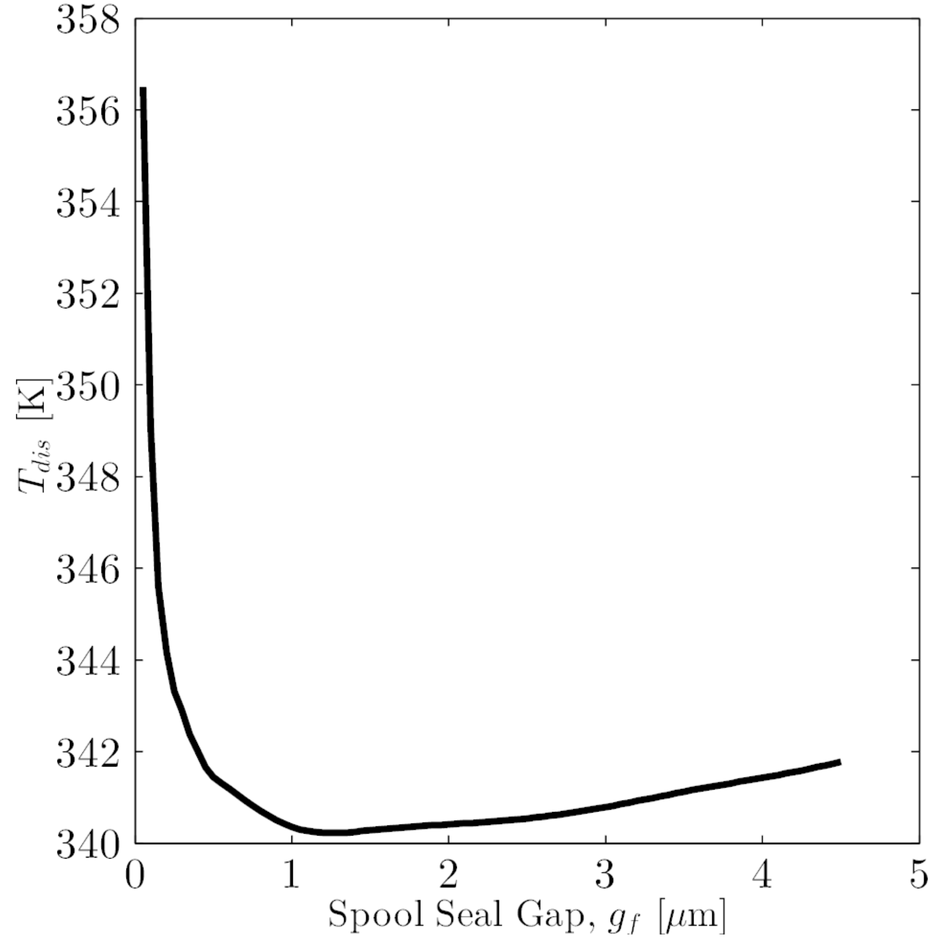


Rotating Spool Compressor: Design Optimization

Volumetric Efficiency

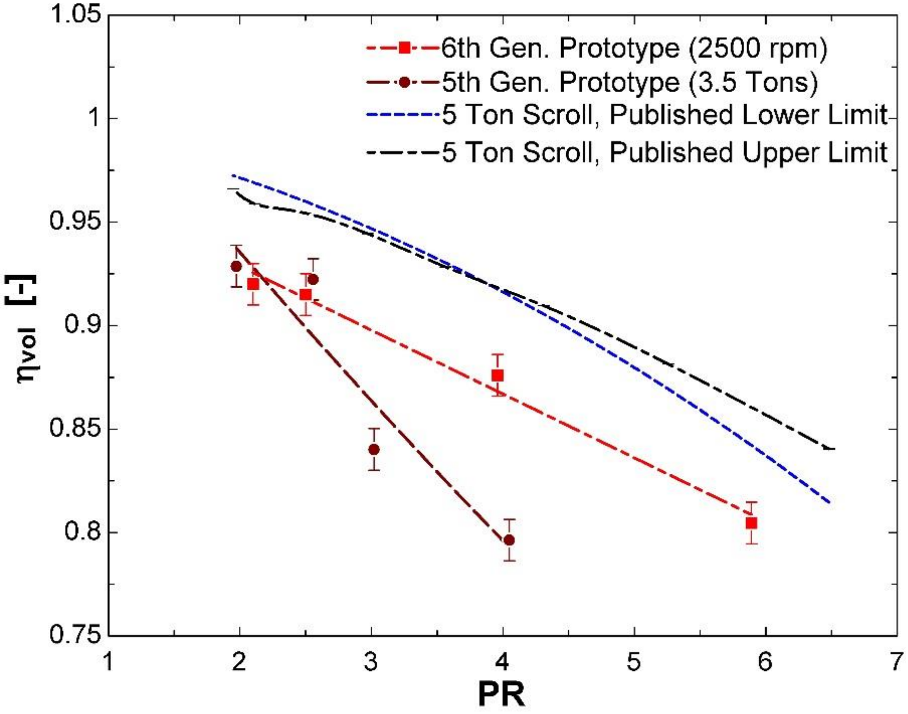


Discharge Temperature

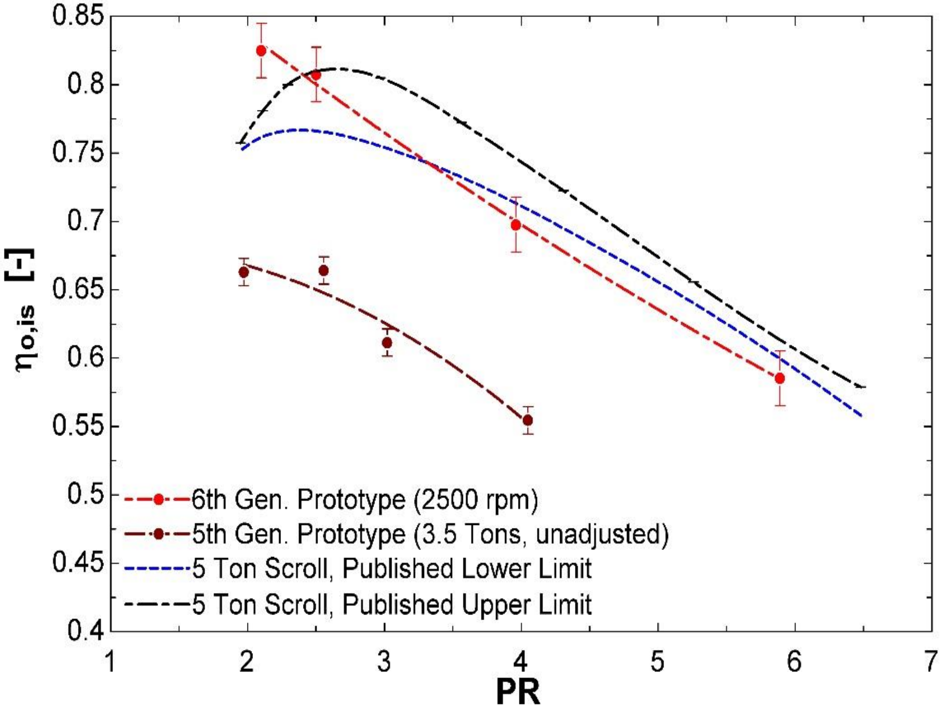


Rotating Spool Compressor: Performance as of Summer 2014

Volumetric Efficiency



Overall Isentropic Efficiency



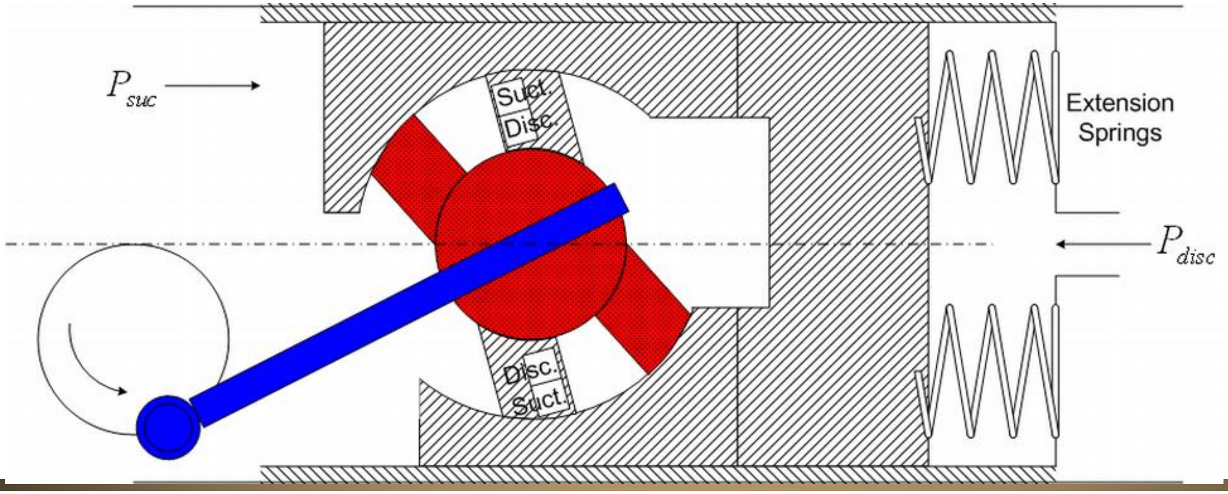
Rotating Spool Compressor: Summary

- 6^{th} generation prototype achieves competitive volumetric and energy efficiencies
- Manufacturing cost much lower than scroll compressors
- Size range comparable to reciprocating compressors
- Commercialization interaction with multiple compressor manufacturers
- Concept shows good performance as an expander in ORC applications

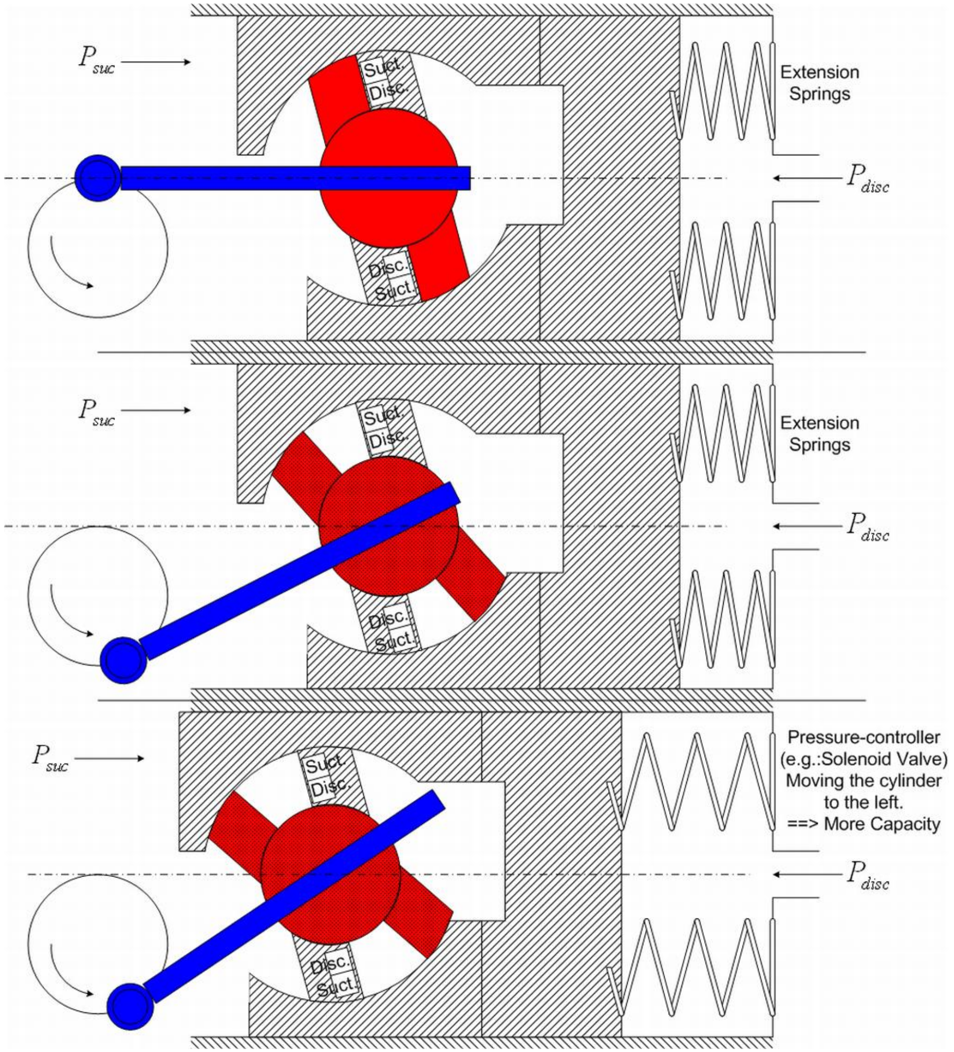
Contents

Bowtie Compressor: Overview

- *Motivation:* Provide mechanical capacity control without changing clearance volume
  - » Avoid re-expansion losses associated with the increased clearance volumes in many capacity control solutions
  - » Based on Beard-Pennock variable-stroke compressor
  - » Blade reciprocates axially instead of linearly
  - » Cylinder can move in direction of springs

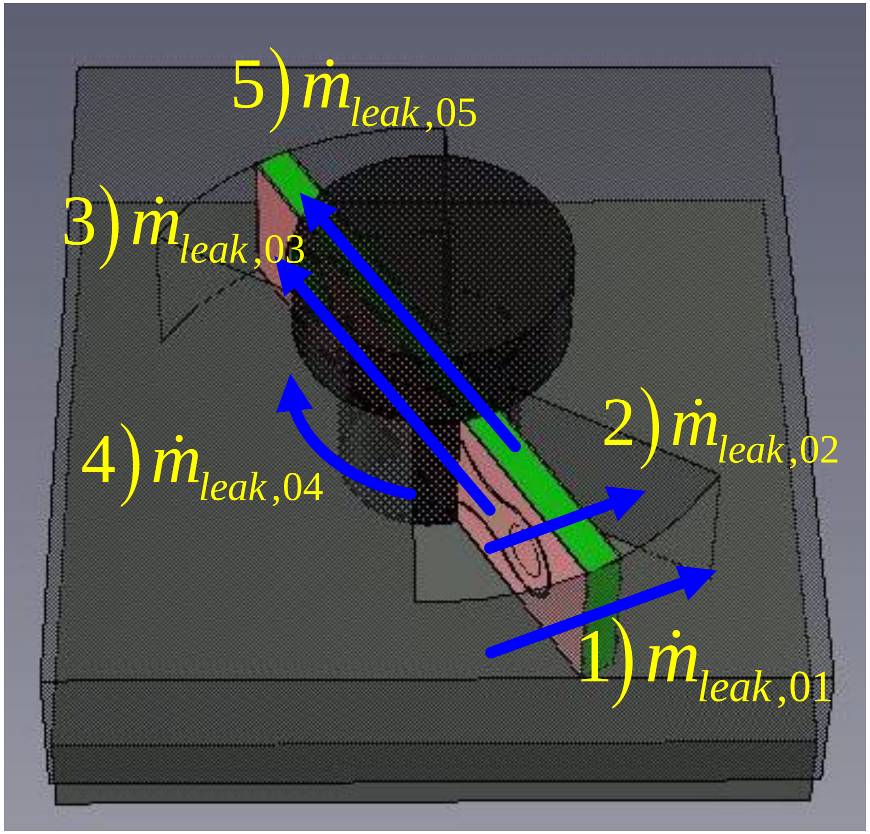


Bowtie Compressor: Basic Geometry



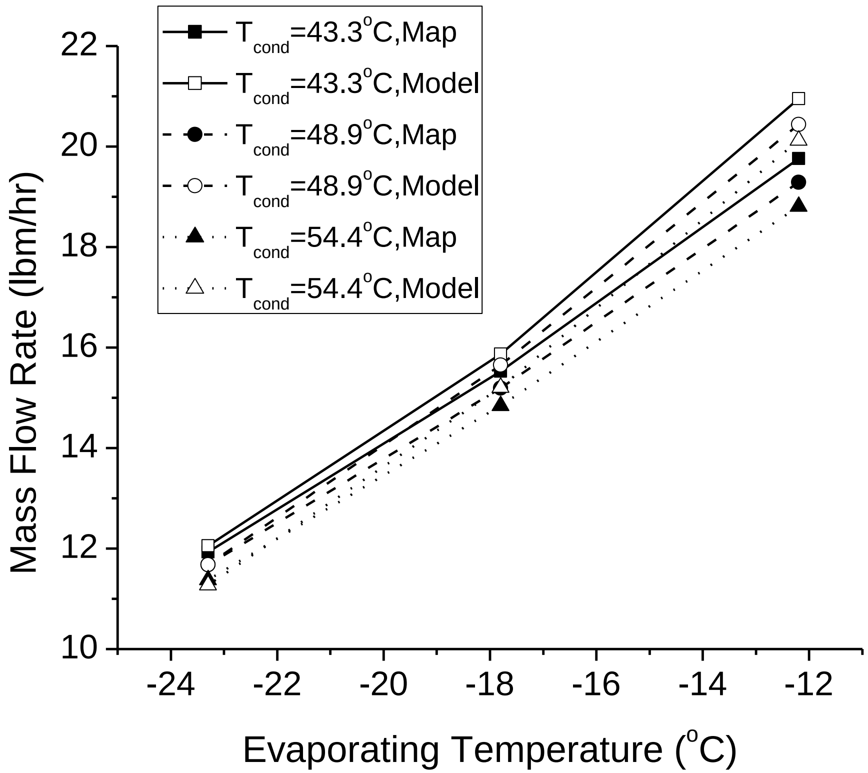
Bowtie Compressor: Prototype Design

- Leakage passages:
  - » Through the radial clearance
  - » Over the vane
  - » Between the side vane and the journal shaft
  - » Between the journal bearing and the journal shaft
  - » Between the top vane and the journal shaft

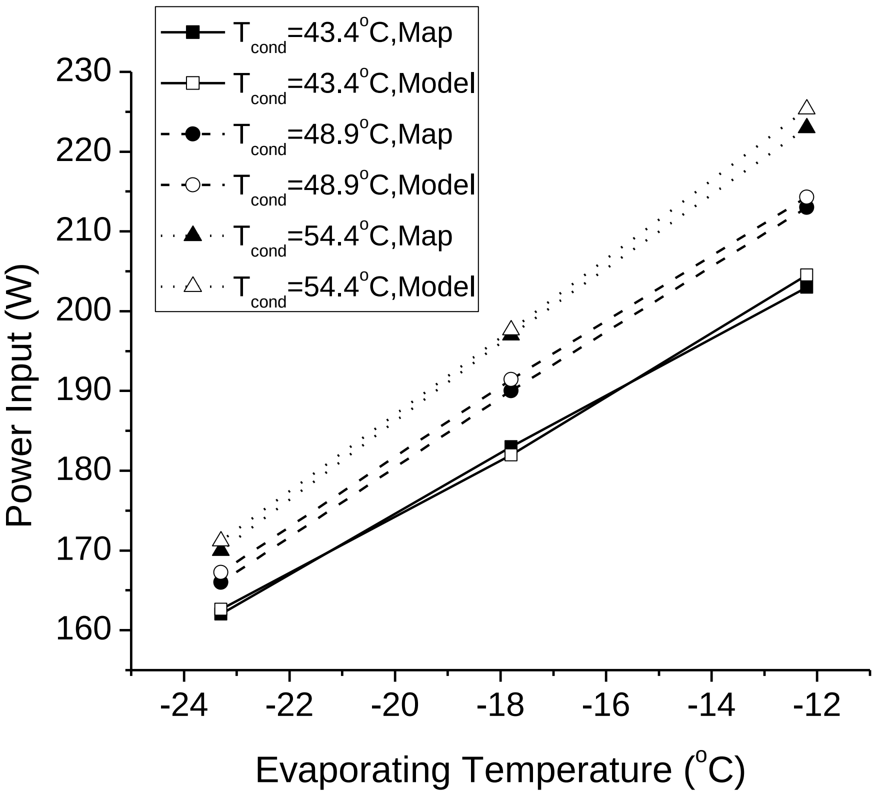


Bowtie Compressor: Model Validation

Mass Flow Rate

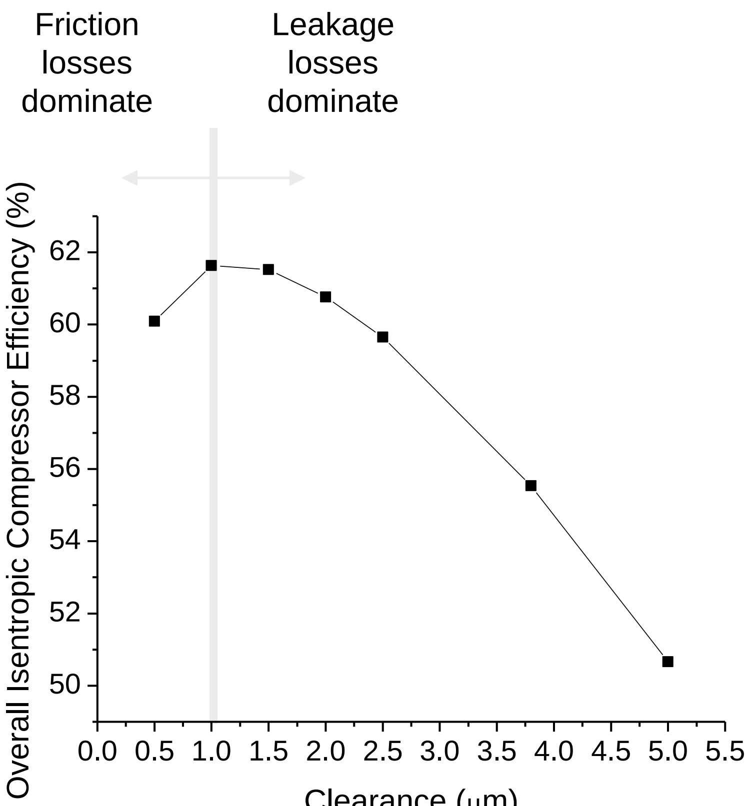


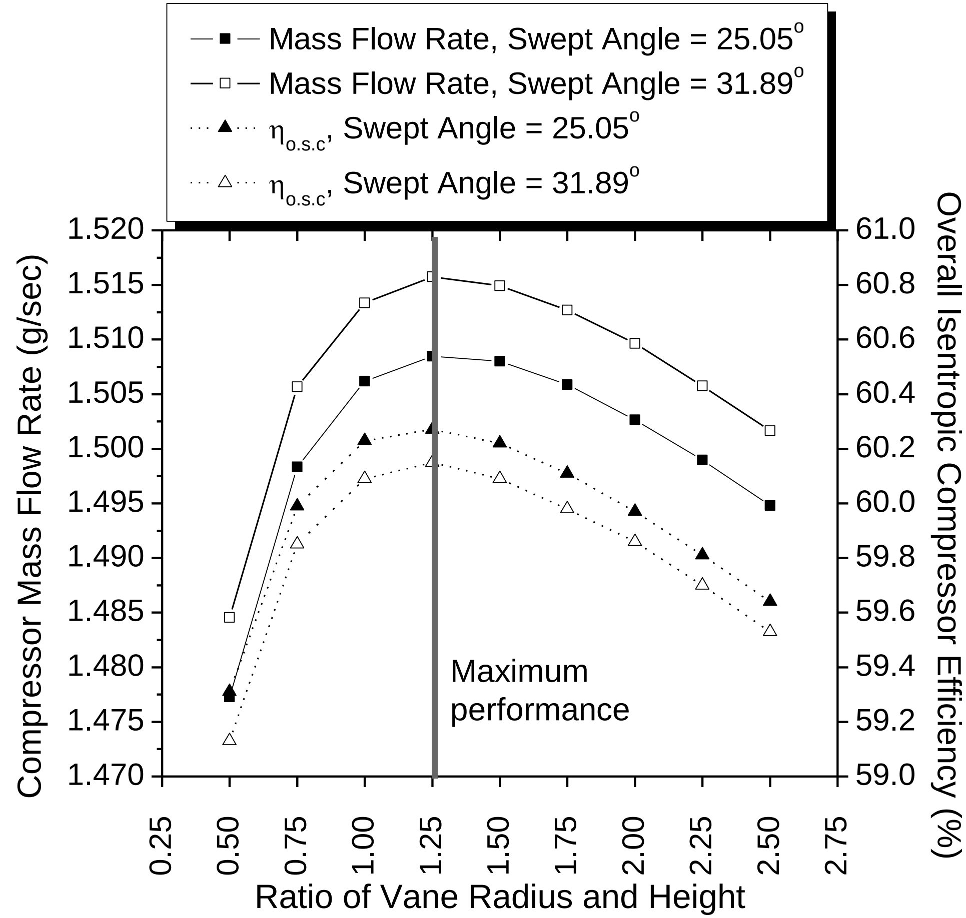
Power Consumption



Bowtie Compressor: Design Optimization

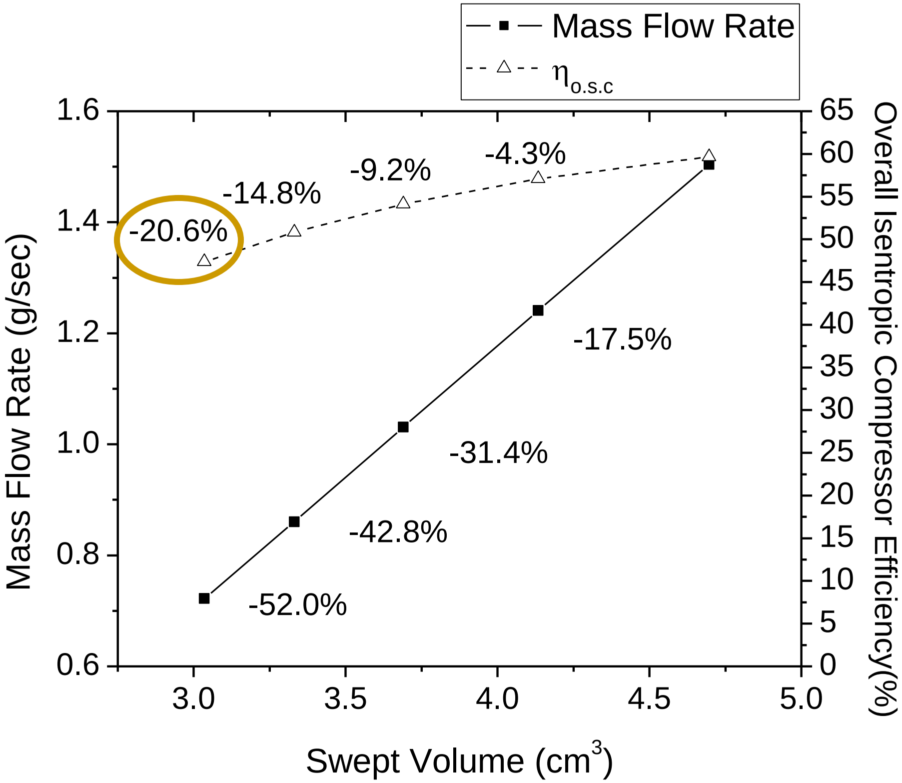
- Use model to optimize clearance dimensions and ratio of vane radius to height

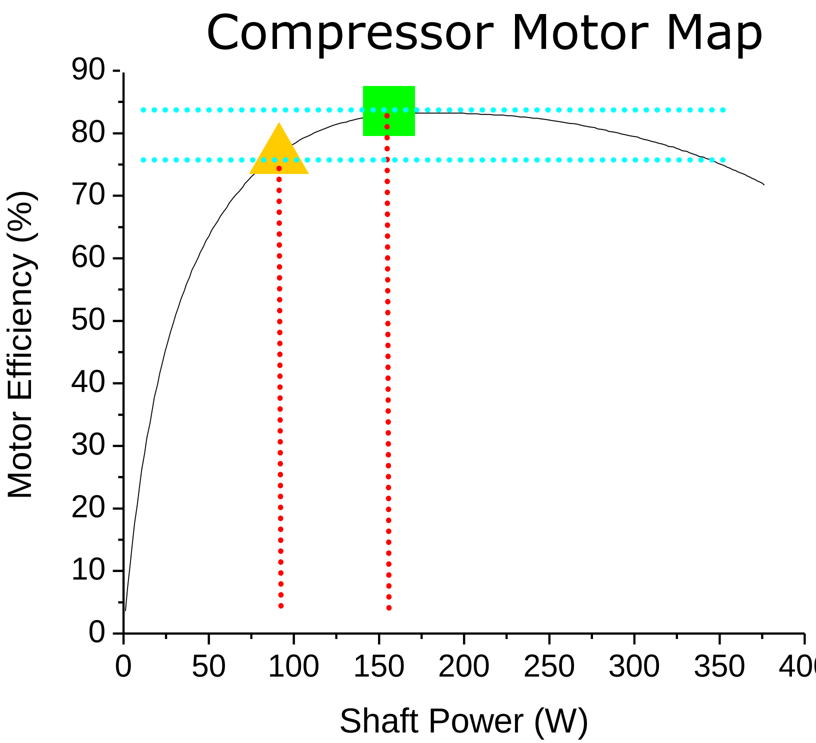




Bowtie Compressor: Performance Results

- Modeled results for compressor at 54.4ºC condensing, -23.3ºC evaporating and 32.2ºC suction temperature:





Bowtie Compressor: Summary

- Overall isentropic efficiency only drops from 60 to 50% when suction volume is reduced from 4.70 cm^3 to 3.04 cm^3 (almost 50% decrease)
- Change in overall isentropic efficiency could be significantly less if appropriate electric motor is used
- Feasible, “lower-cost” alternative to electronic variable speed compressor for domestic refrigerator/freezer

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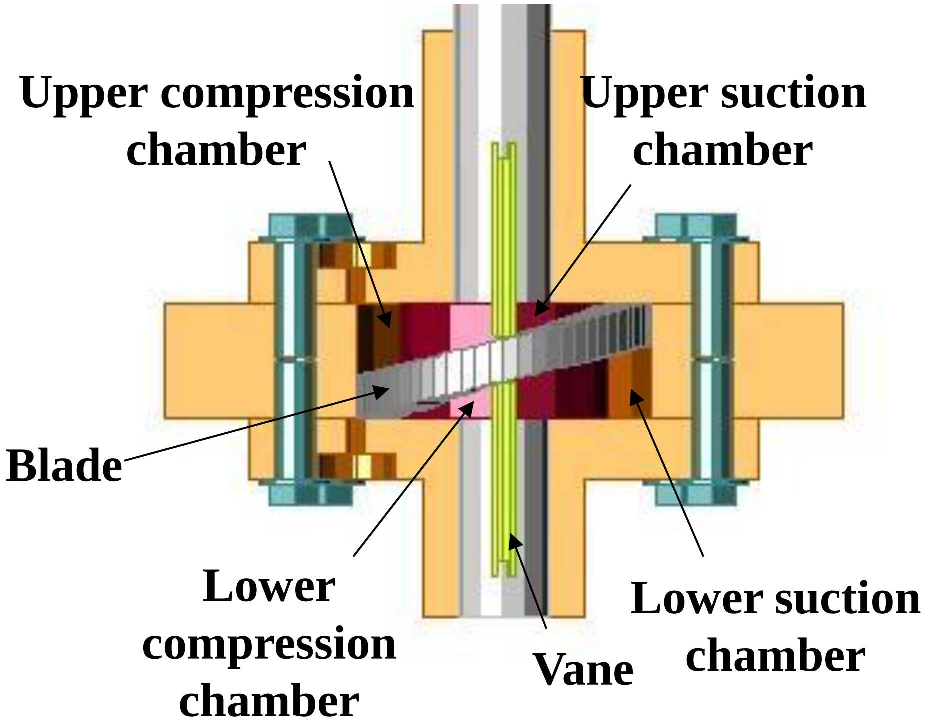
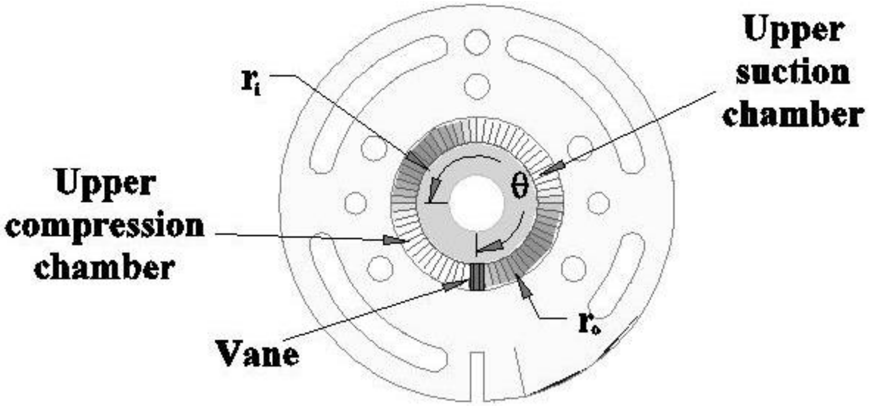
Z-Compressor: Motivation

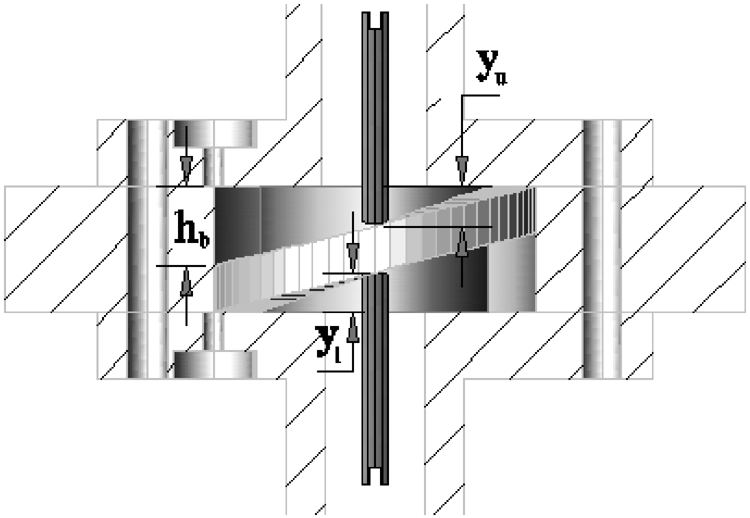
- Motivation: Reduce noise and vibration by developing a rotary compressor without an eccentric
  - » Simultaneously compresses two pockets of gas separated by a Z-blade
  - » Z-blade provides continuous variation in chamber volume without eccentric
  - » Cylindrical vane separates suction and compression chambers on each level



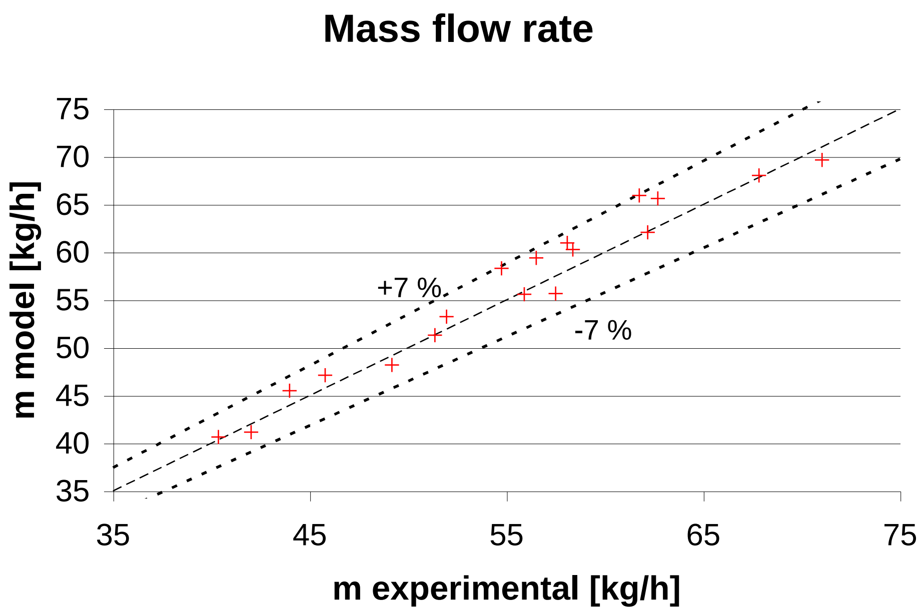
Z-Compressor: Basic Geometry

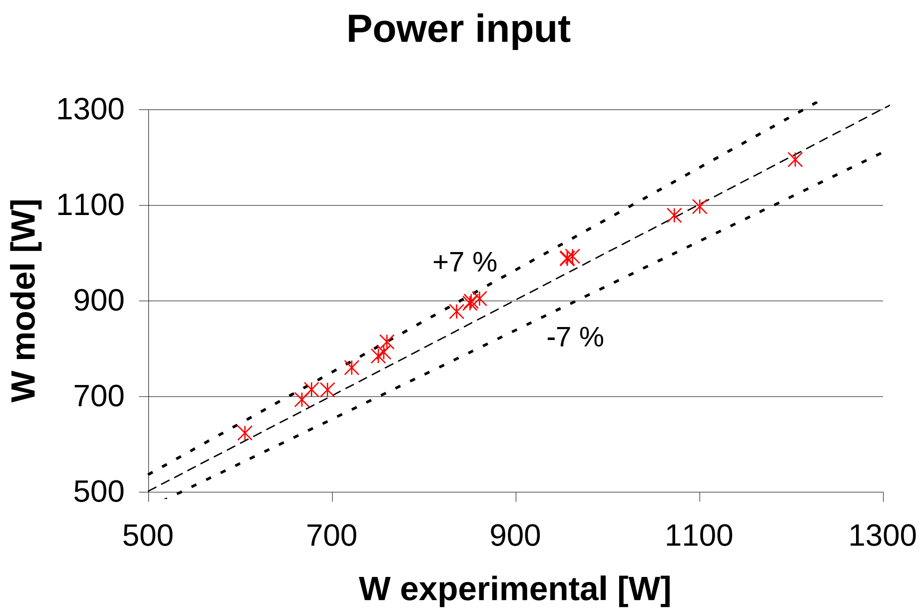
- Modeling Assumption:
  - » Upper and lower chambers identical, but separated by 180º rotation
  - » Frictional and electric losses rejected to high pressure gas in shell
  - » Shell exchanges heat with ambient
  - » Constant pressure suction





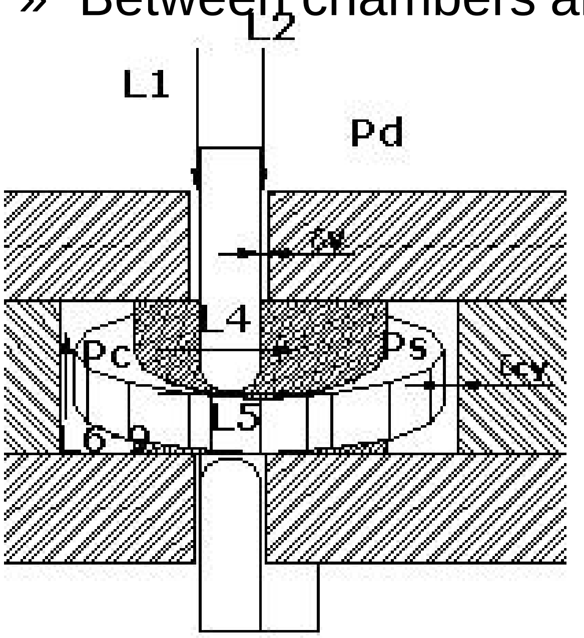
Z-Compressor: Model Validation

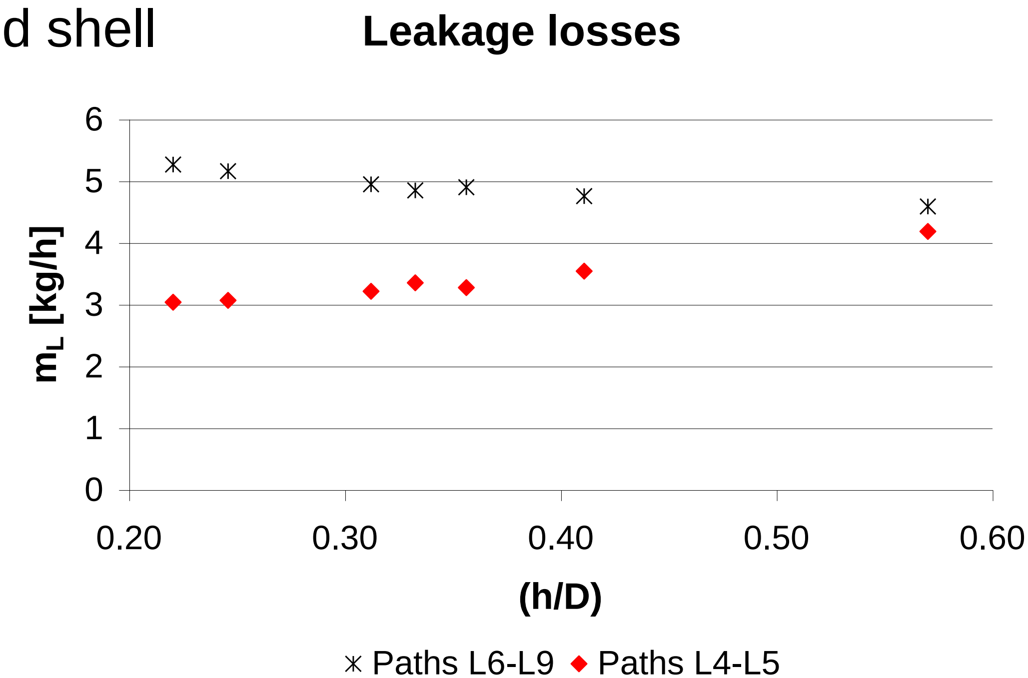




Z-Compressor: Performance Results

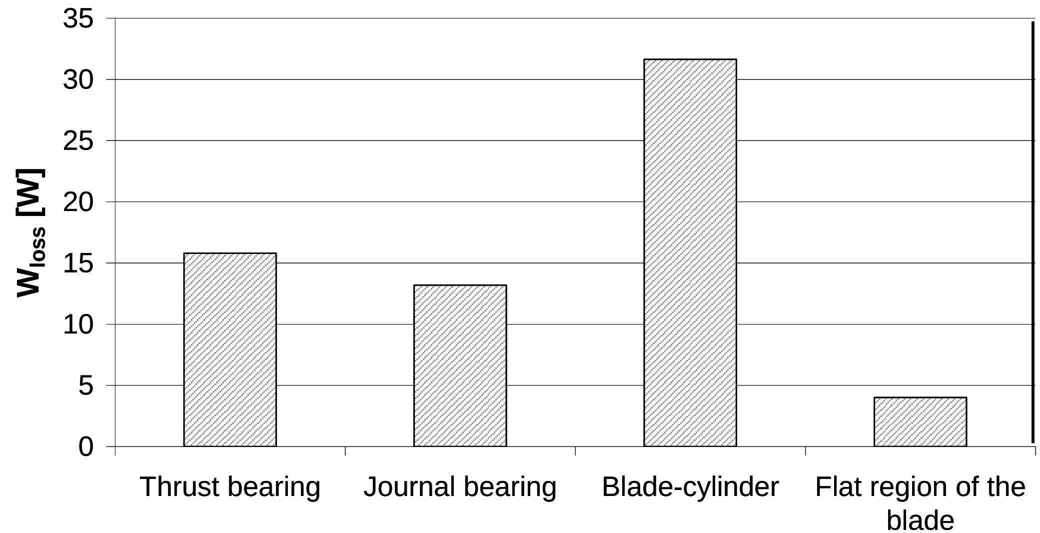
- Lower volumetric efficiency than currently available rolling piston compressors due to increased leakage paths
  - » Between suction and compression chambers on same level
  - » Between levels
  - » Between chambers and shell





Z-Compressor: Design Optimization

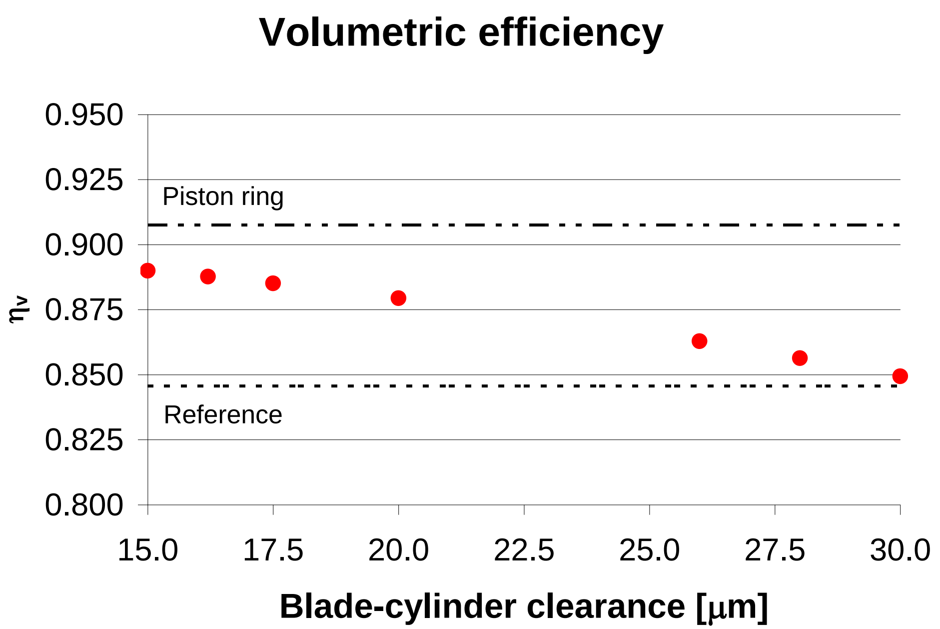
- Improve volumetric efficiency by reducing mass flow through the most significant leakage path, which is between the Z-blade and cylinder wall
  - » Reduce clearance between z-blade and cylinder
    - – Frictional losses increase
  - » Reduce diameter of Z-blade
    - – If cylinder height is increased to maintain same chamber volume, leakage around vane increases

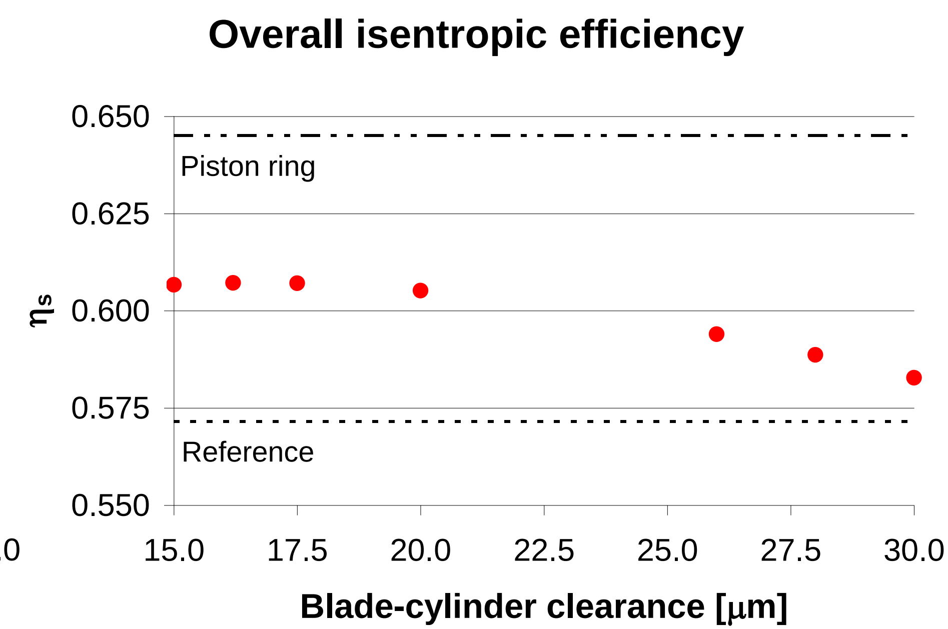


Comparison of friction losses at various contacts

Z-Compressor: Design Optimization, cont'd

Impact of blade-cylinder clearance change on compressor efficiencies



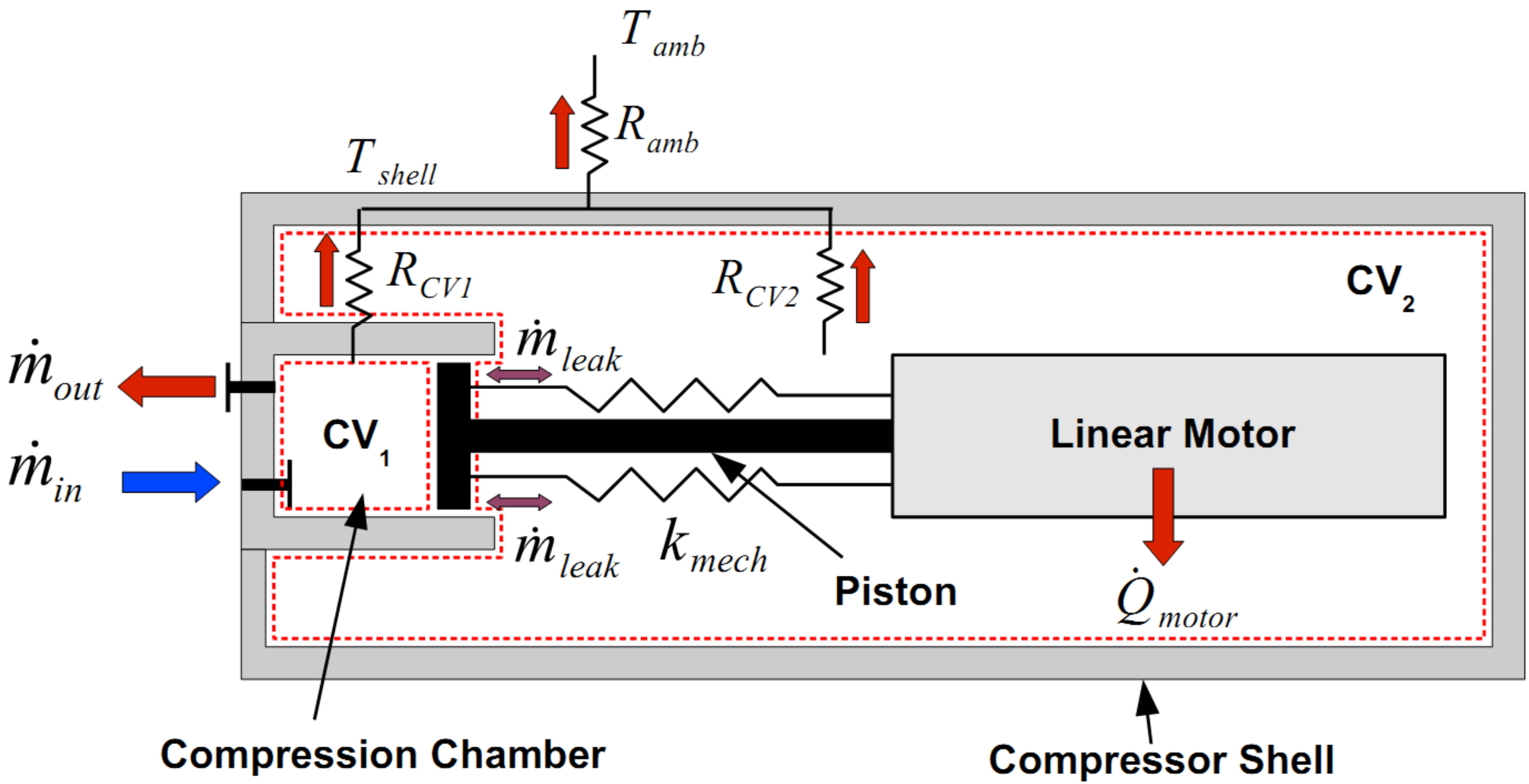


Z-Compressor: Summary

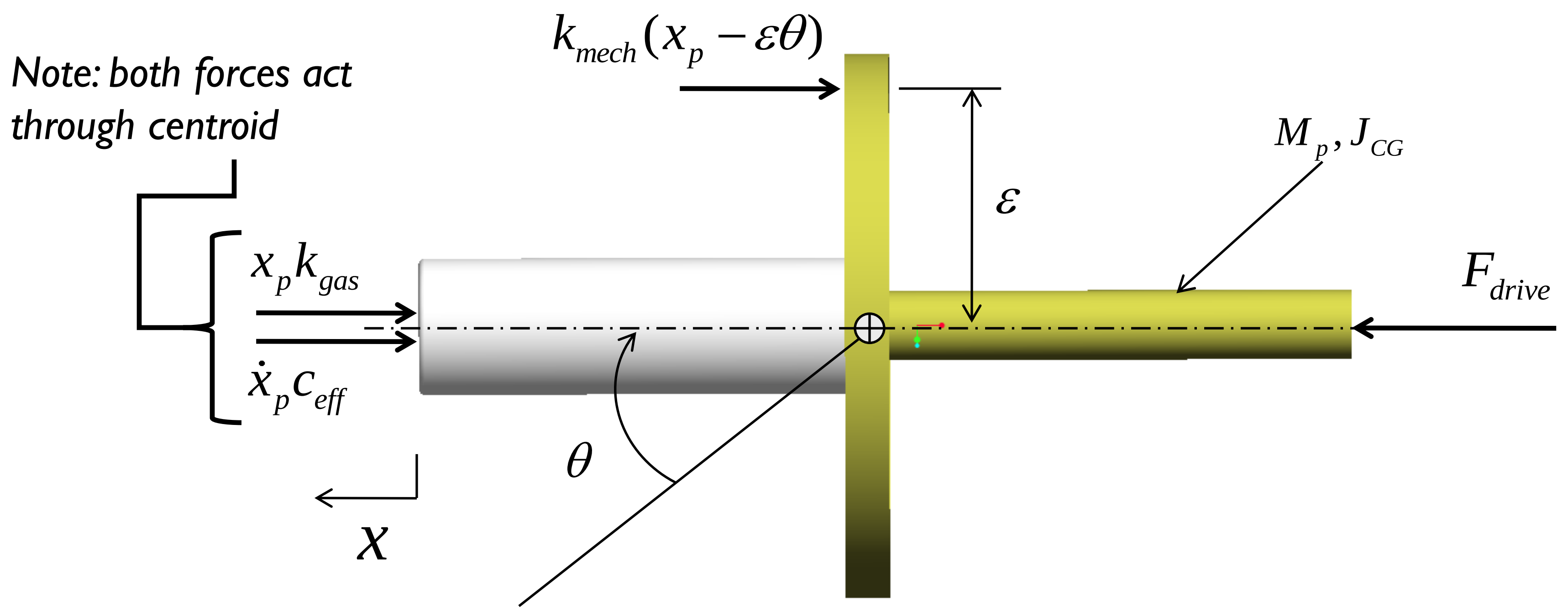
- Compared to current rotary compressors:
  - » Lower noise and vibration
  - » But also, lower volumetric efficiency
- Dimensions can be optimized to balance leakage and friction losses for maximum isentropic efficiency
- Feasible alternative to rolling piston compressor for room and small unitary air conditioners, but “higher” manufacturing costs

Contents

Linear Compressor: Control Volumes



Linear Compressor: FBD of Piston with EOM



$$M_p \ddot{x}_p + c_{eff}\dot{x}_p + (k_{gas} + k_{mech})x_p = k_{mech}\varepsilon\theta + F_{drive}$$

$$J_{CG}\ddot{\theta} + k_{mech}\varepsilon^2\theta = k_{mech}x_p\varepsilon$$

(Inertial)

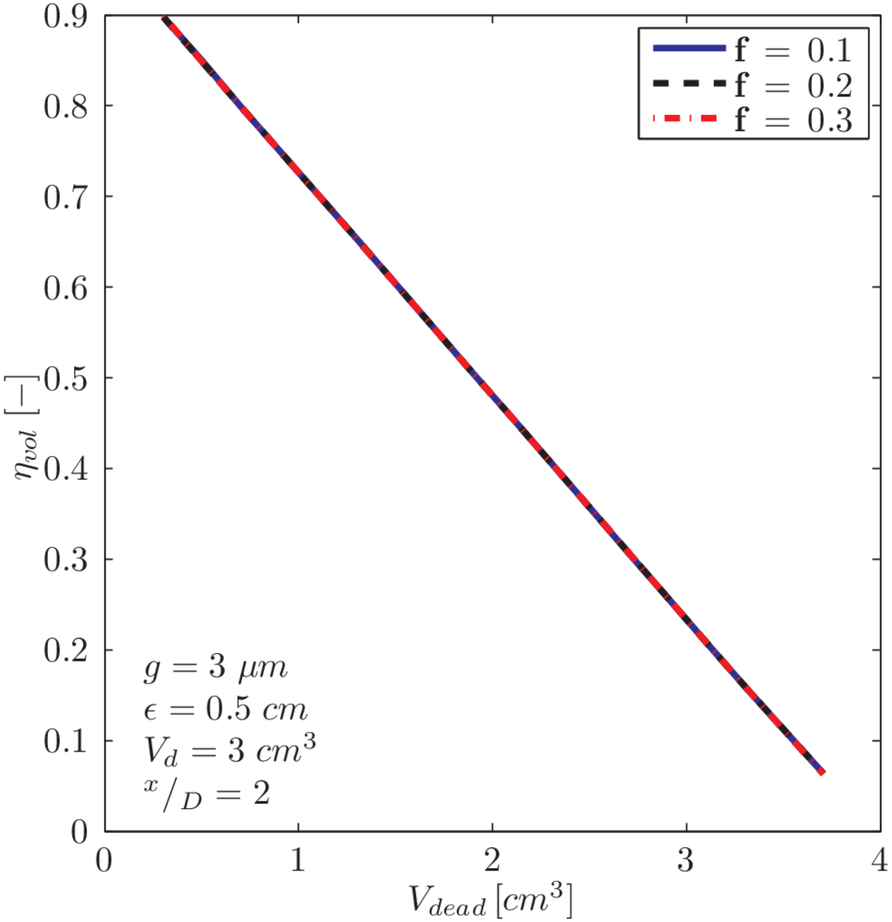
(Damping)

(Stiffness)

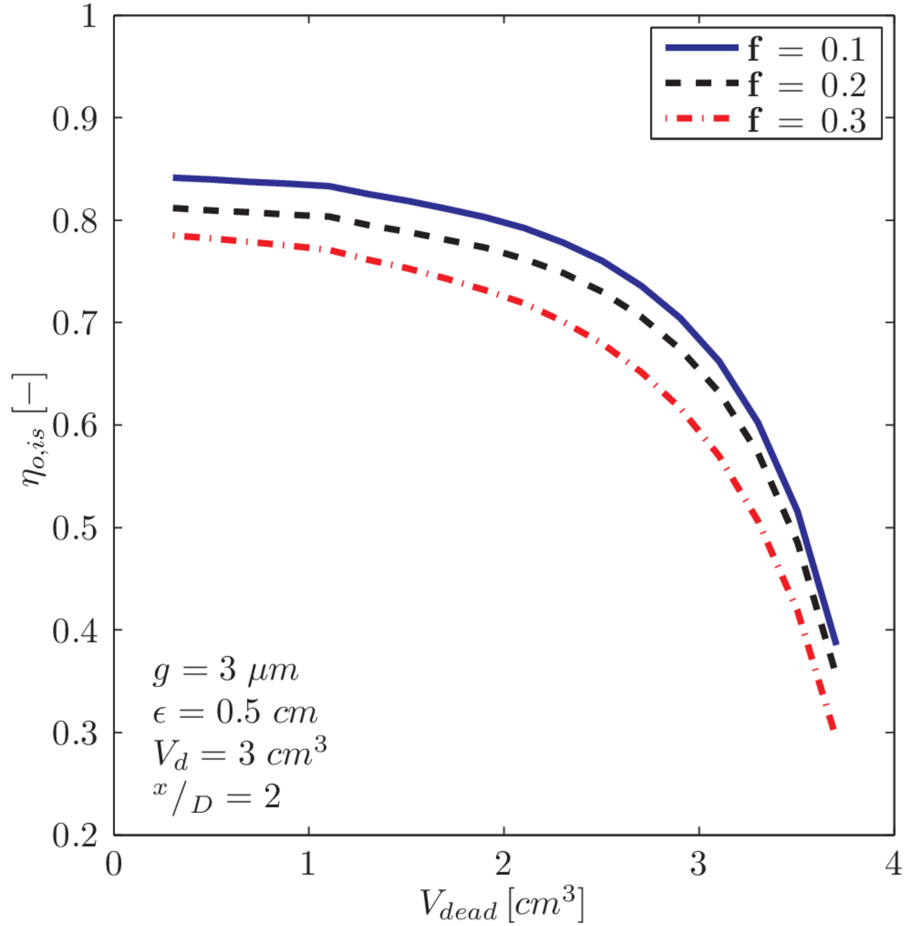
(Coupling)

Linear Compressor: Stroke Control/Friction Factor

Impact of dead volume and dry friction factor on efficiencies



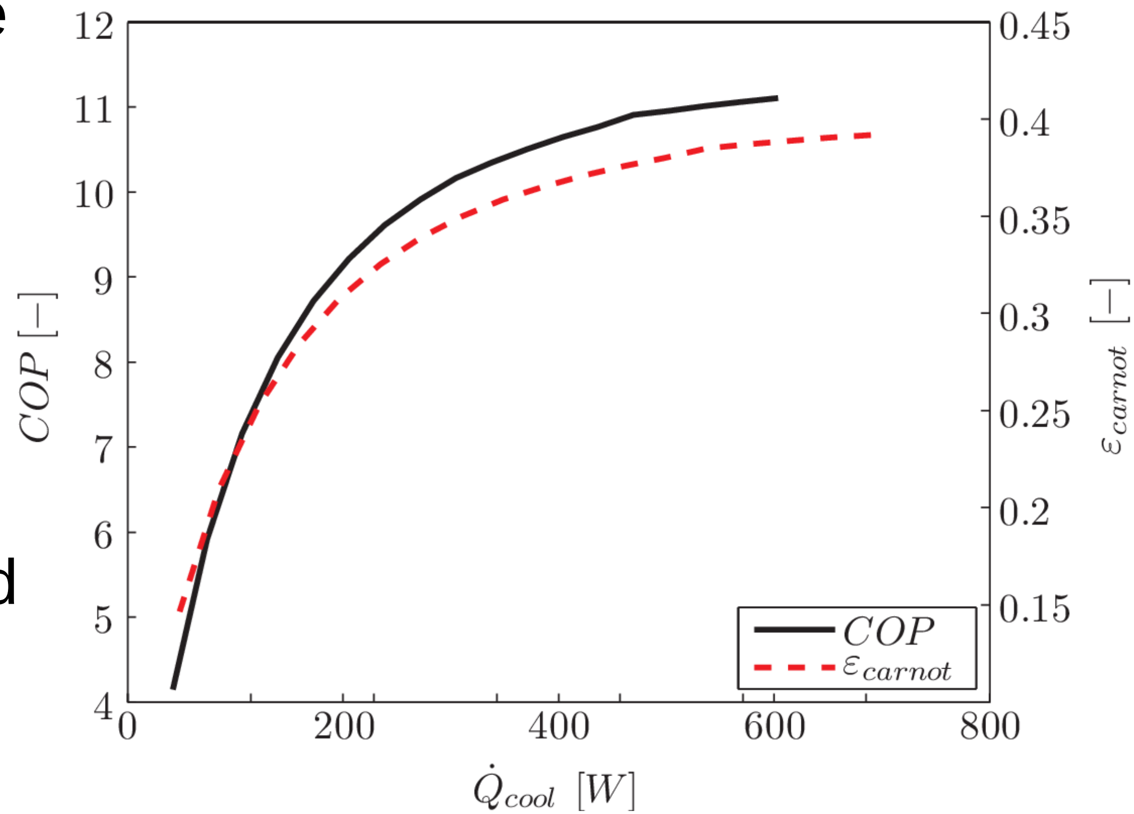
Volumetric Efficiency



Overall Isentropic Efficiency

Linear Compressor: Capacity Control

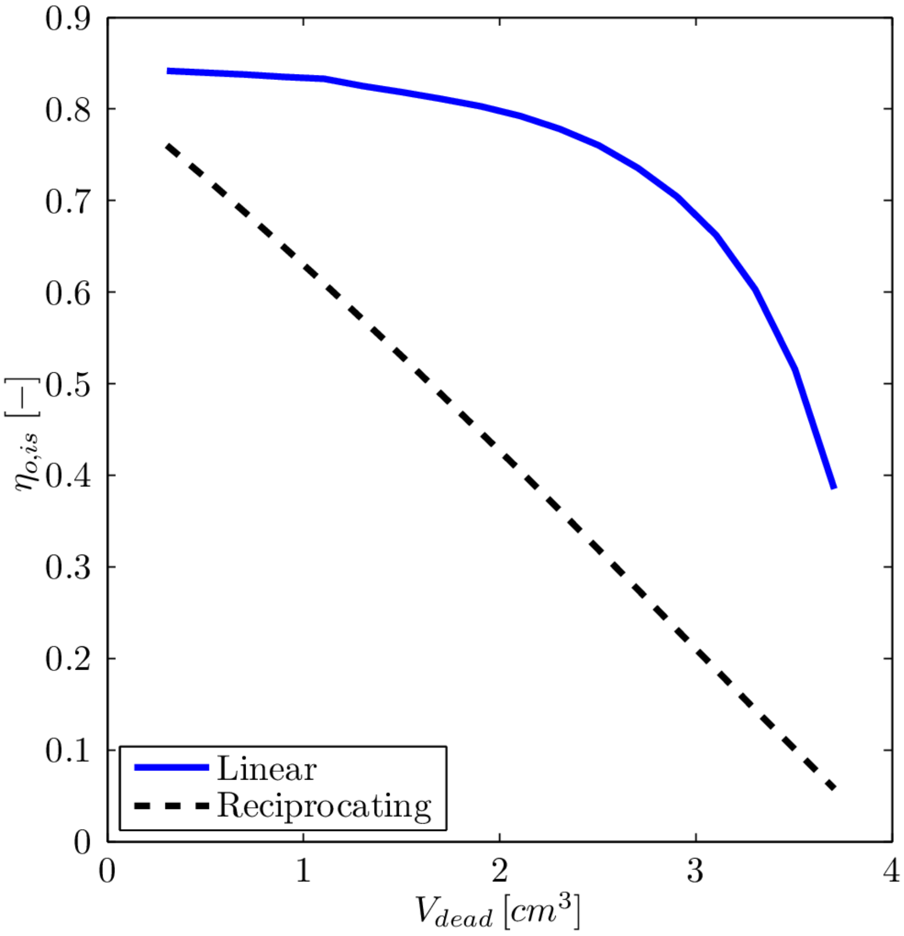
- Variable stroke can be utilized to generate variable capacity
- By assuming 10 °C subcooling at the condenser outlet, a cycle can be simulated
- A linear compressor provides high performance over wide capacity ranges



System COP and 2nd Law Effectiveness

Linear Compressor: Comparison to Reciprocating Compr.

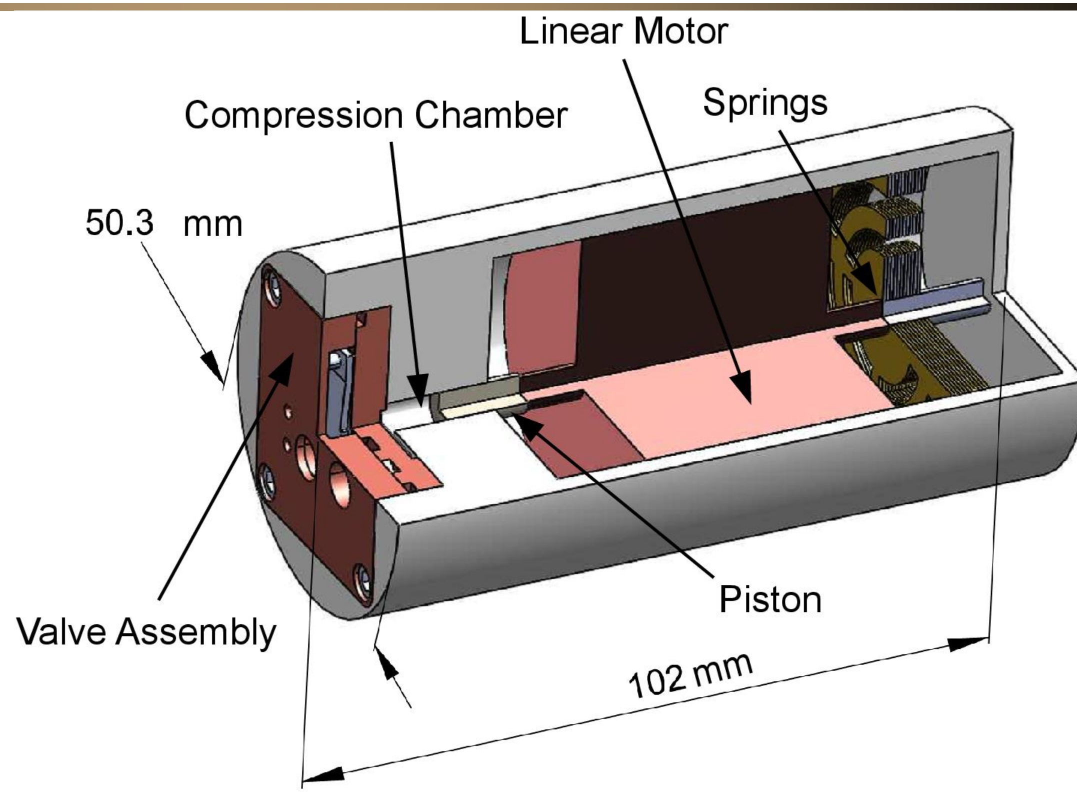
- All else constant, vary net dead volume by increasing x_{dead}
- Simulates a variable stroke compressor
- As dead volume increases the recoverable energy increases
- The mechanical springs act as capacitance, allowing energy to be recaptured that would otherwise be lost



Overall Isentropic Efficiency

Linear Compressor: Final Design

- 200W cooling capacity
- Replaced compression springs with planar springs
- Moved location of mechanical springs
- New linear bearing selection



Key Compressor Dimensions and Predicted Performance

k_{mech}	f	g	ε	V_d	f_{res}	x/D	η_{vol}	$\eta_{o,is}$
N/m	-	μm	cm	cm^3	Hz	-	-	-
30600	0.2	4	0.5	2	60	0.4	0.96	0.86

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S-RAM Compressor: Overview

- Variable displacement, low friction, axial drive
  - » 47 international patents
- Can mechanically change displacement independent of speed……No VFDs
- Oil free compression

S-RAM Compressor: CO_2 Compressor Specifications

- 345 cc (30 m^3/hr or 17.7 cfm)
- Variable displacement (25% to 100%)
- Oil free refrigerant
- 90 Bar -1.5 to 5.0 pressure ratio

S-RAM Compressor: Summary

- 1st generation prototype tested
- Currently manufacturing 2nd generation prototype
- Comprehensive modeling effort under way

Thank you!