Novel Compressor Technologies

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- Z-compressor
- Rotating spool compressor
- Miniature linear compressor
- Miniature diaphragm compressor
- Conclusions

Introduction
Overview of Refrigeration Compressors

Compressor Types

- Positive Displacement Compressors
  - Reciprocating Compressors
  - Rotary (Rotational Piston) Compressors
    - Rolling Piston Compressor
    - Rotary (Sliding) Vane Compressor
    - Screw Compressor
      - Single Shaft: Single-Screw Compressor
      - Double Shaft: Twin-Screw Compressor
    - ...
  - Orbital Compressors
    - Scroll Compressor
    - Trochoidal Compressor
    - ...
  - ...
- Dynamic Compressors
  - Axial Flow Machines
  - Radial Flow Machines
  - ...

green ellipse
main stream

Wankel

Introduction
Range of Applications of Compressors

Cooling Capacity

Domestic Refrigerators & Freezers — Automotive Air Cond'g — Room Air Conditioners — Unitary Air Conditioners & Heat Pumps — Commercial Air Cond'g & Refrigeration — Large Air Conditioning

Fractional ↔ *200 kW (50 tons)*: Reciprocating

Fractional ↔ *10 kW (3 tons)*: Rotary

5 kW (1.5 tons) ↔ *70 kW (20 tons)*: Scroll

150 kW (40 tons) ↔ *1500 kW (400 tons)*: Screw

350 kW (100 tons) and up: Centrifugal

Introduction
Motivation for Novel 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
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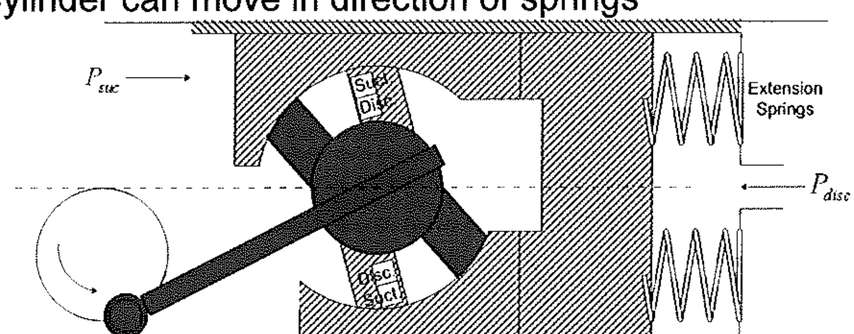
  - Orbital Compressors
    - Scroll Compressor
      - ... flooded scroll
    - Trochoidal Compressor
    - ...
  - ... Diaphragm
- Dynamic Compressors
  - Axial Flow Machines
  - Radial Flow Machines

Contents

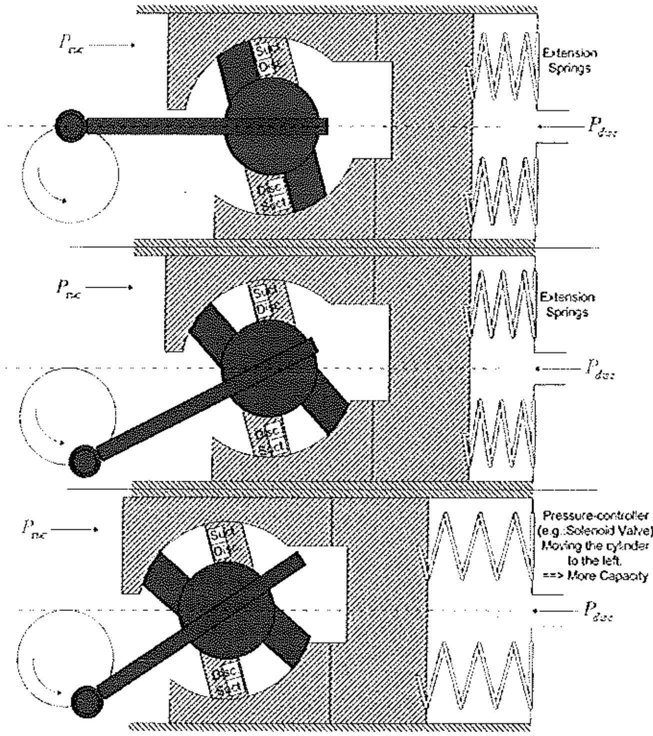
Bowtie Compressor Motivation

1982 Gordon

- *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

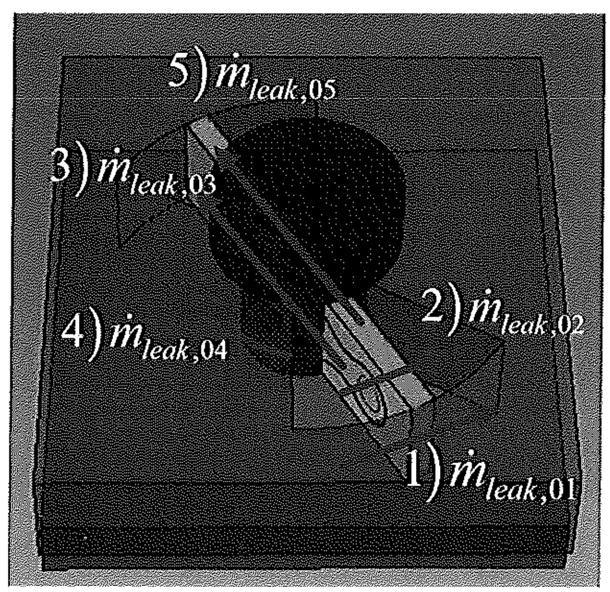


Bowtie Compressor Basic Geometry

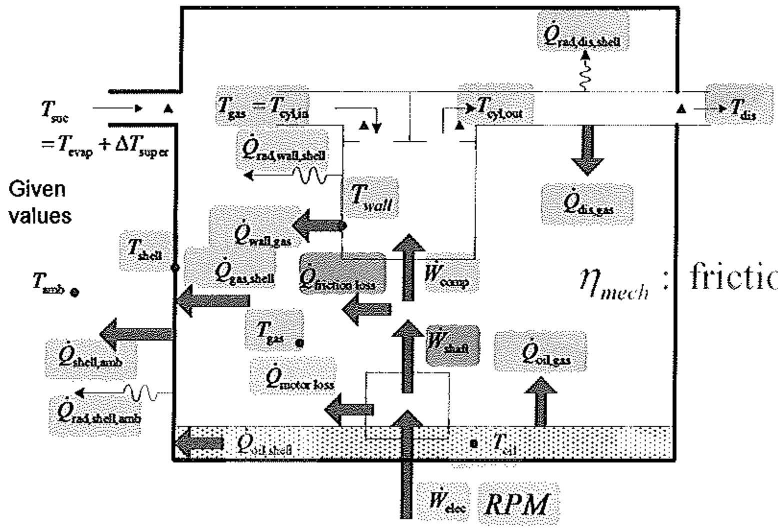


Bowtie Compressor Prototype Design

- 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
Overall Compressor Model

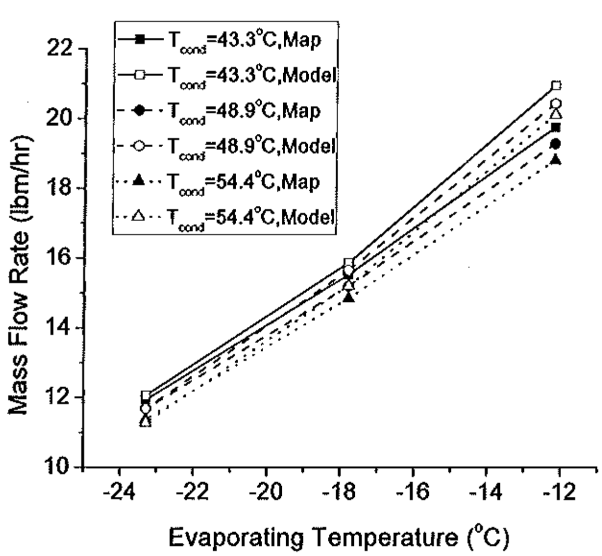


η_{mech} : friction model

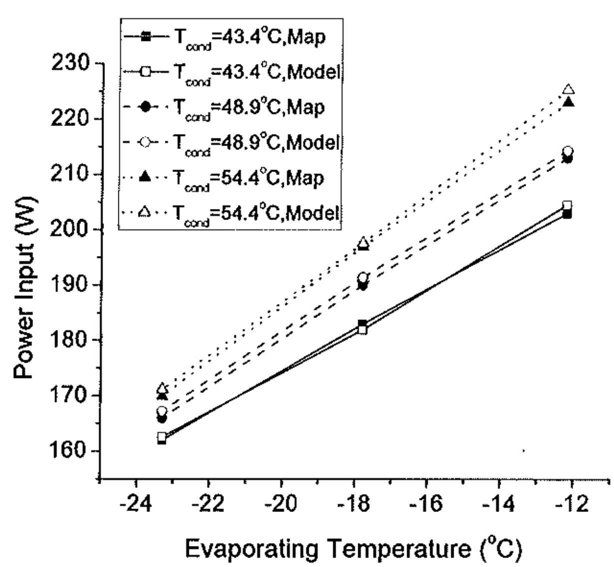
η_{motor} : motor map

Bowtie Compressor
Model Validation

Mass Flow Rate



Power Consumption



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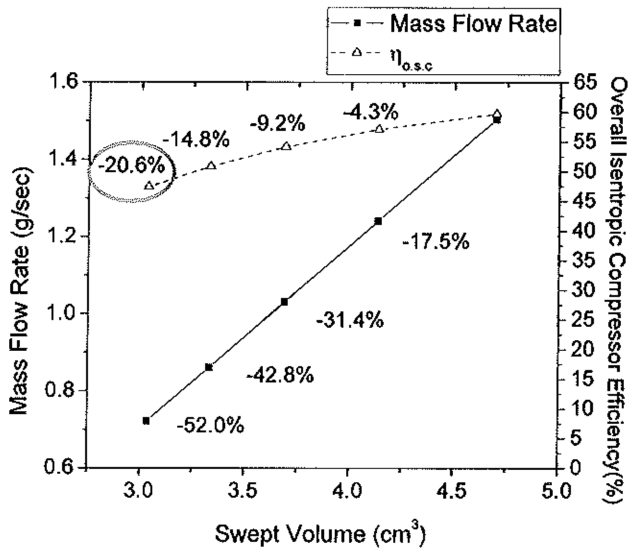
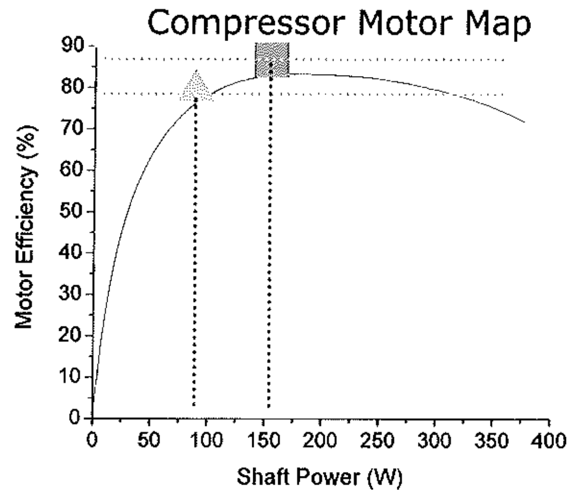
Bowtie Compressor Performance Results

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





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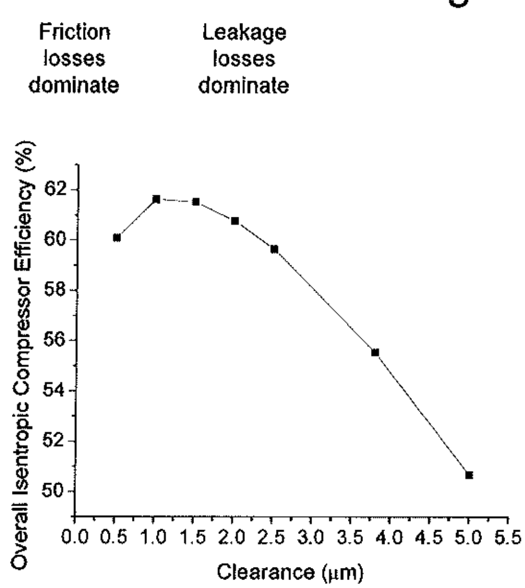
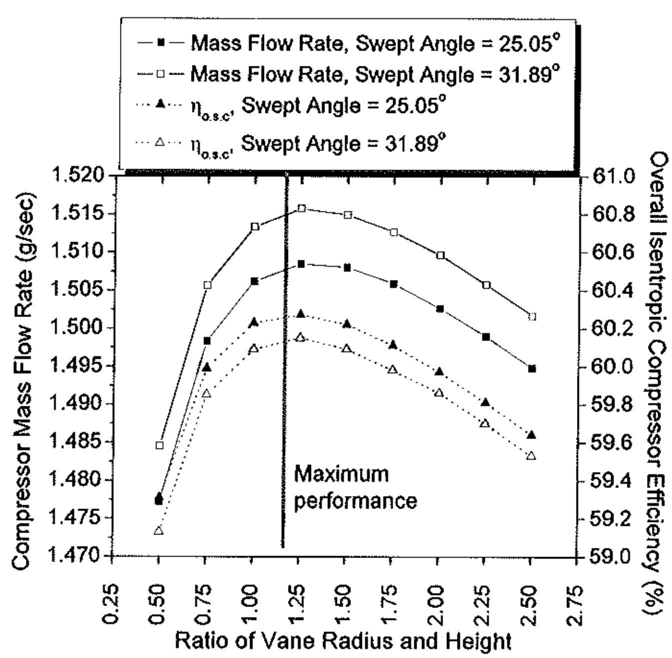
Bowtie Compressor Design Optimization

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





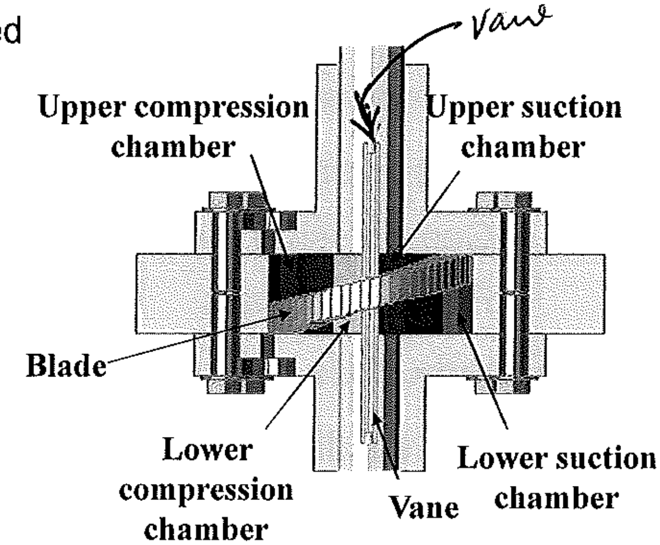
Bowtie Compressor Summary

- 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, "low-cost" alternative to electronic variable speed compressor for domestic refrigerator/freezer

Contents

Z-Compressor Motivation

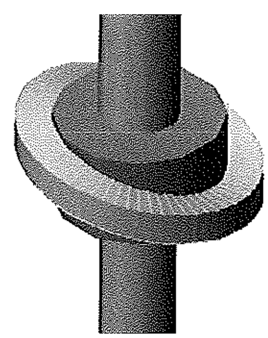
- Motivation: Reduce noise and vibration by developing a rotary compressor without an eccentric
  - » Simultaneously compresses two pockets of gas separated by a Z-blade
  - » Z-blade provides continuous variation in chamber volume without eccentric
  - » Cylindrical vane separates suction and compression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

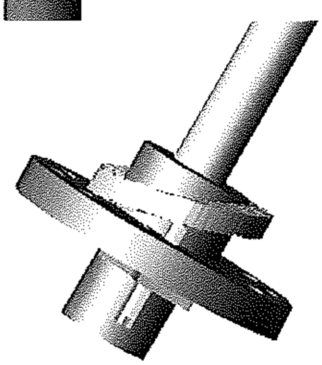


Sponsor mini-splits (Asia)

Z-Compressor Basic Geometry

- *Modeled assuming:*
  - » Upper and lower chambers identical, but separated by 180° rotation
  - » Constant pressure suction
  - » Negligible heat transfer
  - » Frictional and electric losses rejected to high pressure gas in shell
  - » Shell exchanges heat with ambient

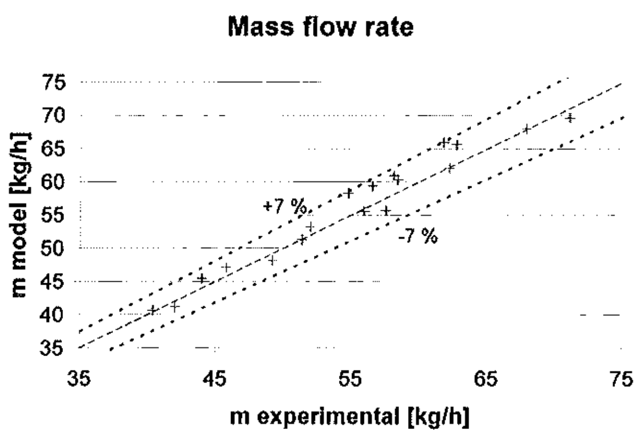


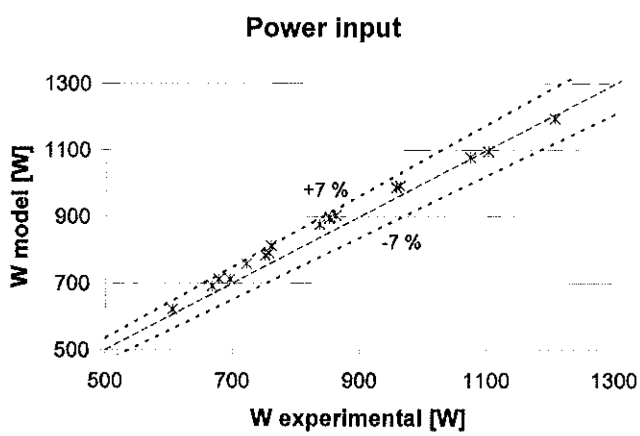


Z-Compressor
Model Development

- Transient analysis of the processes within the chambers of the compressor
  - » Conservation of mass
  - » Conservation of energy
- Shaft power model
  - » Compression power
  - » Frictional losses
- Steady state energy balance
- Model validated using experimental results

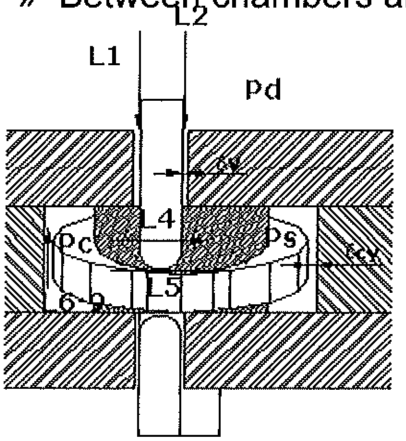
Z-Compressor
Model Validation

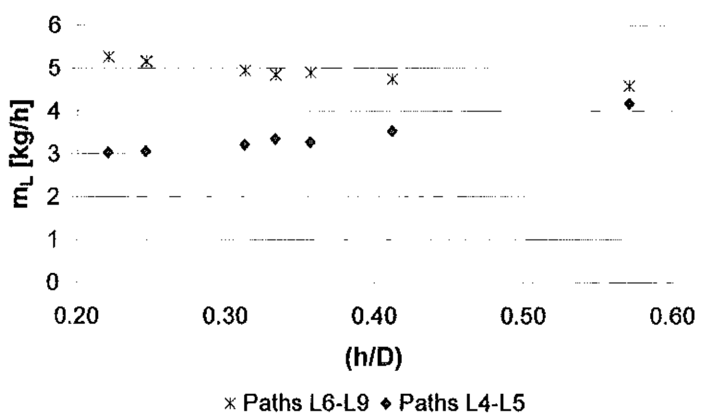




Z-Compressor Performance Results

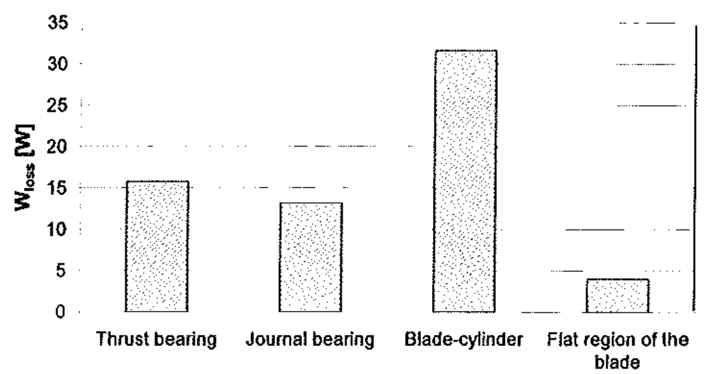
- Lower volumetric efficiency than currently available rolling piston compressors due to increased leakage paths
  - » Between suction and compression chambers on same level
  - » Between levels
  - » Between chambers and shell





Z-Compressor Design Optimization

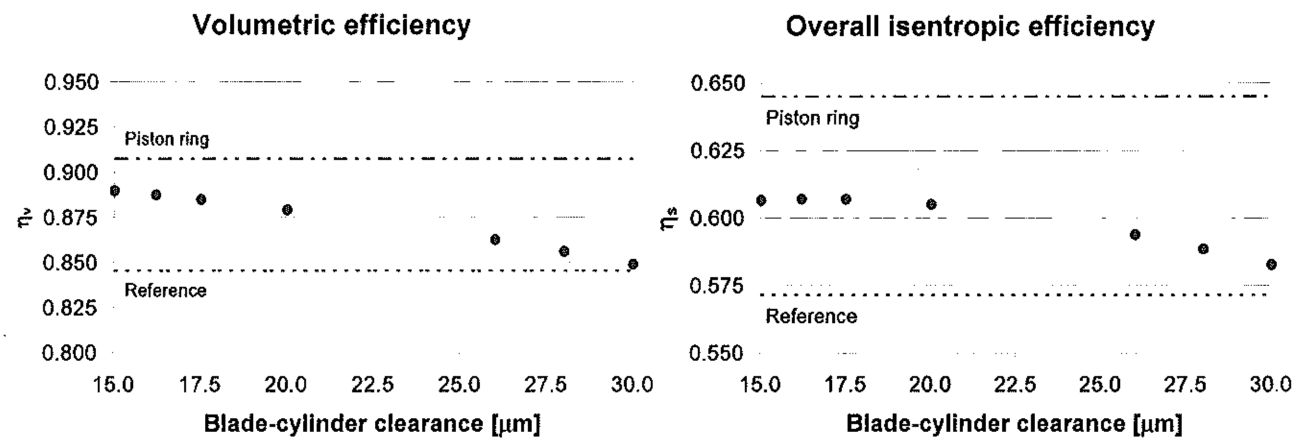
- Improve volumetric efficiency by reducing mass flow through the most significant leakage path, which is between the Z-blade and cylinder wall
  - » Reduce clearance between z-blade and cylinder
    - – Frictional losses increase
  - » Reduce diameter of Z-blade
    - – If cylinder height is increased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

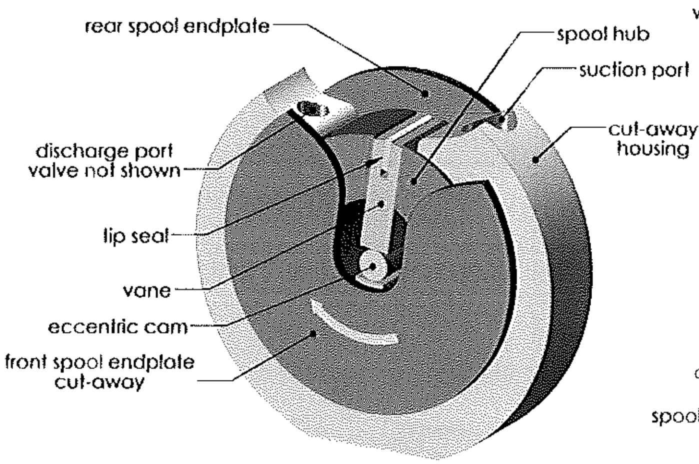
- Compared to current rotary compressors:
  - » Lower noise and vibration
  - » But also, lower volumetric efficiency

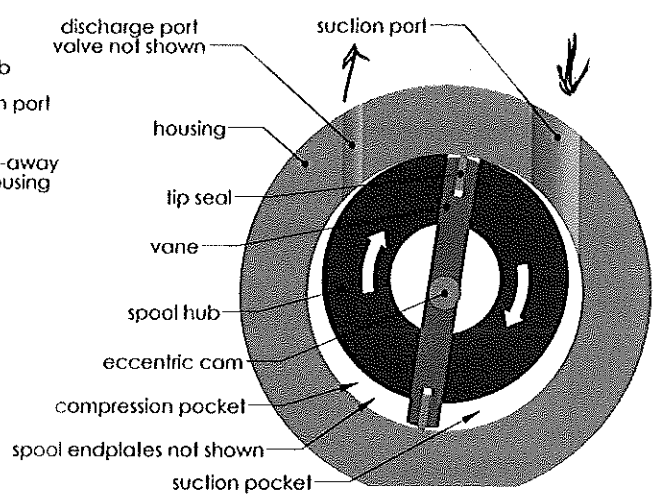
good for low lift?

- 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

Rotating Spool Compressor Geometry

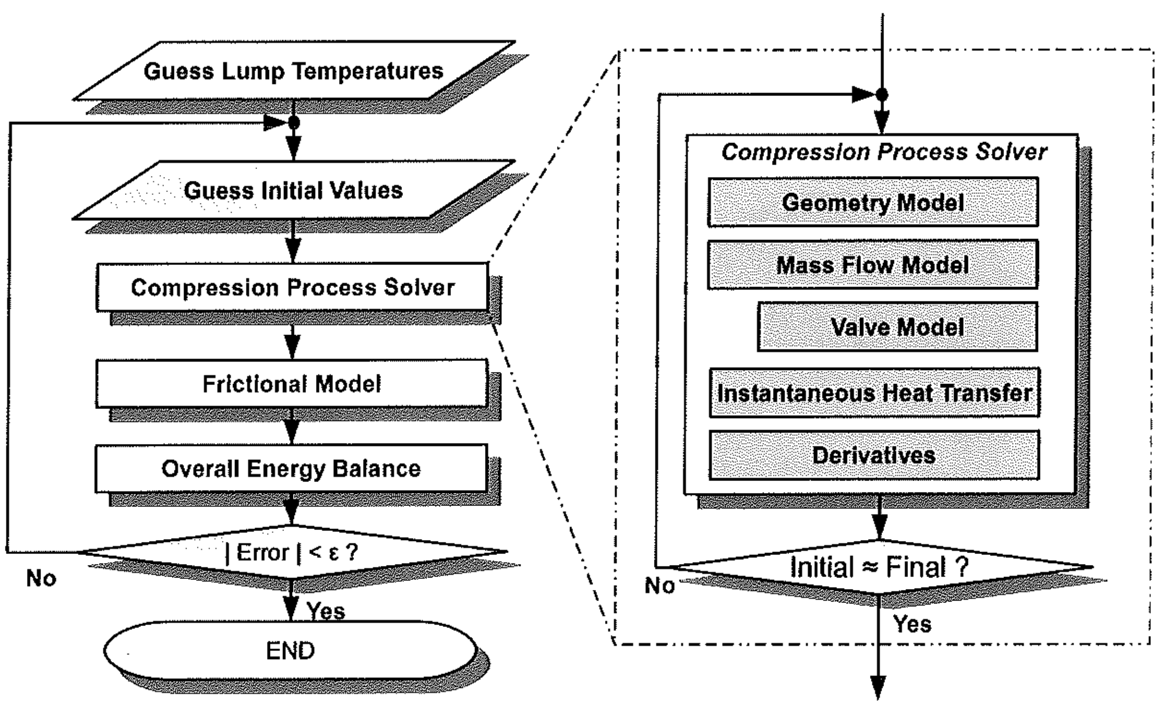




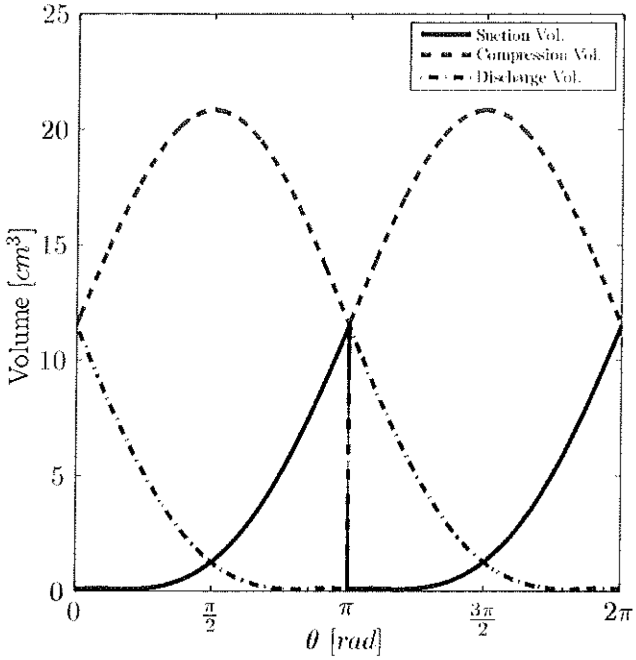
Rotating Spool Compressor Features

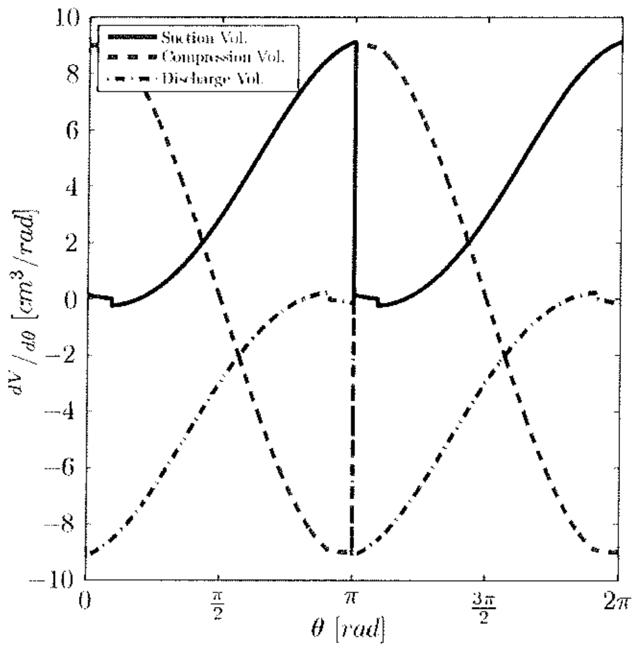
- Four major components with simple geometry for reduced manufacturing cost
- Spool face motion nearly eliminates frictional and leakage losses between the vane and face
- Active sealing elements allow for creative solutions to minimize leakage and friction

Rotating Spool Compressor Comprehensive Model

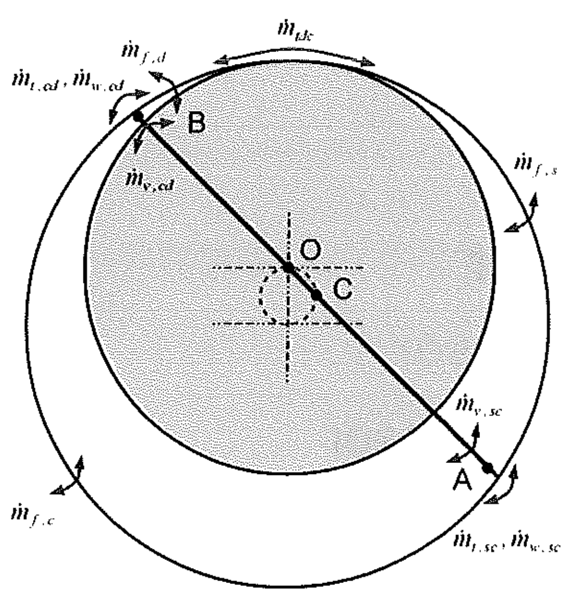


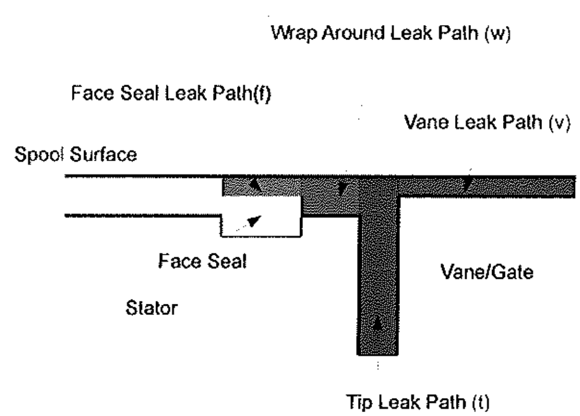
Rotating Spool Compressor
Spool Geometry





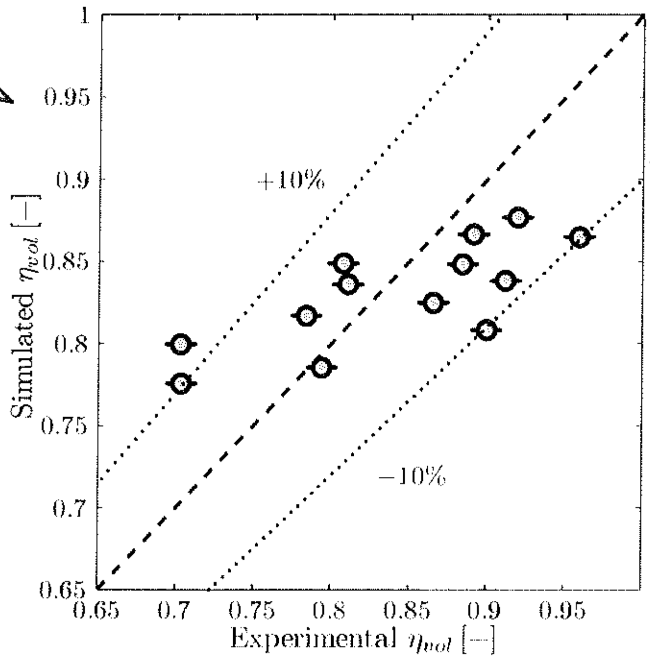
Rotating Spool Compressor
Leakage Modeling

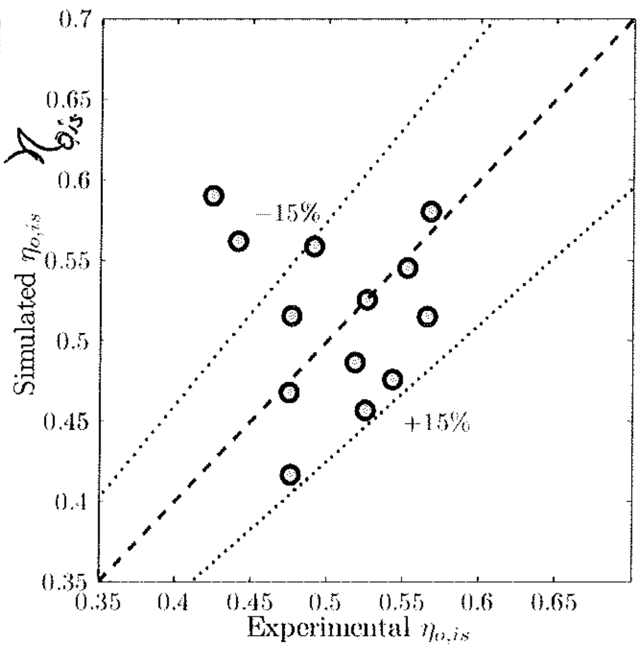




Rotating Spool Compressor Model Validation

η_v





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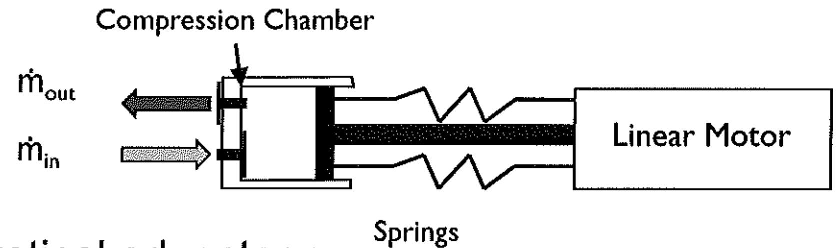
- Miniature diaphragm compressor
- Conclusions

Miniature Linear Compressor
Introduction

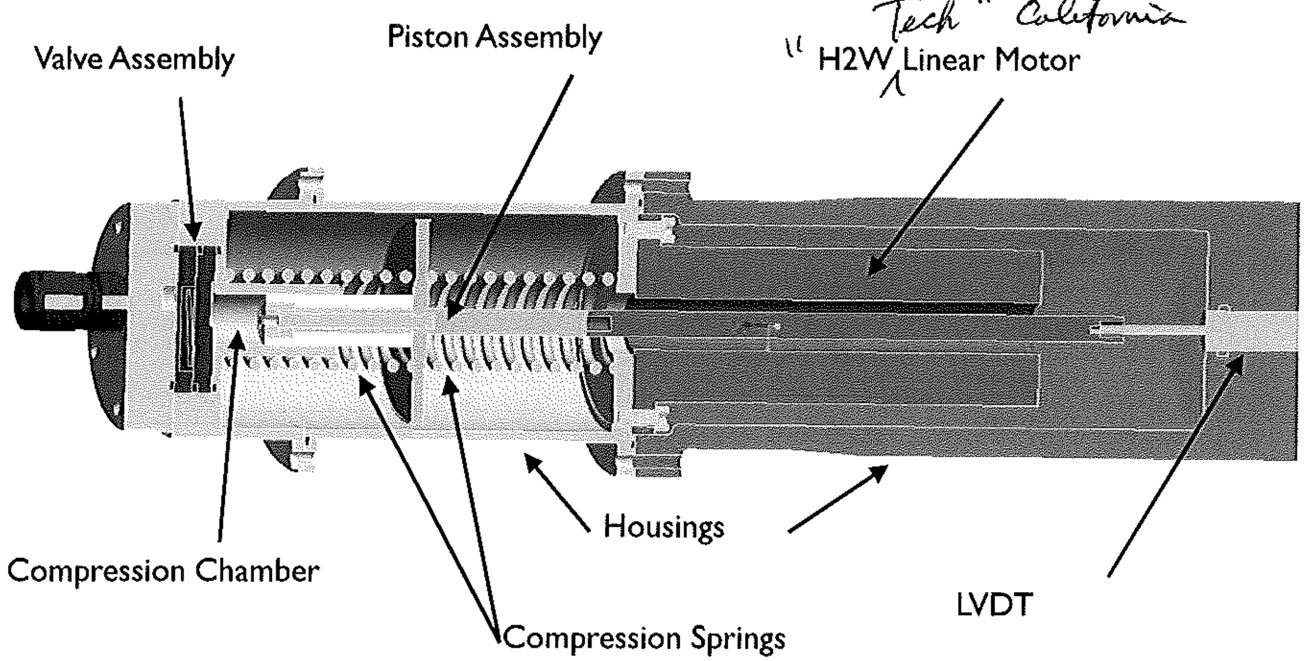
- Resonantly operated positive-displacement compressor with a single moving part (free-piston)



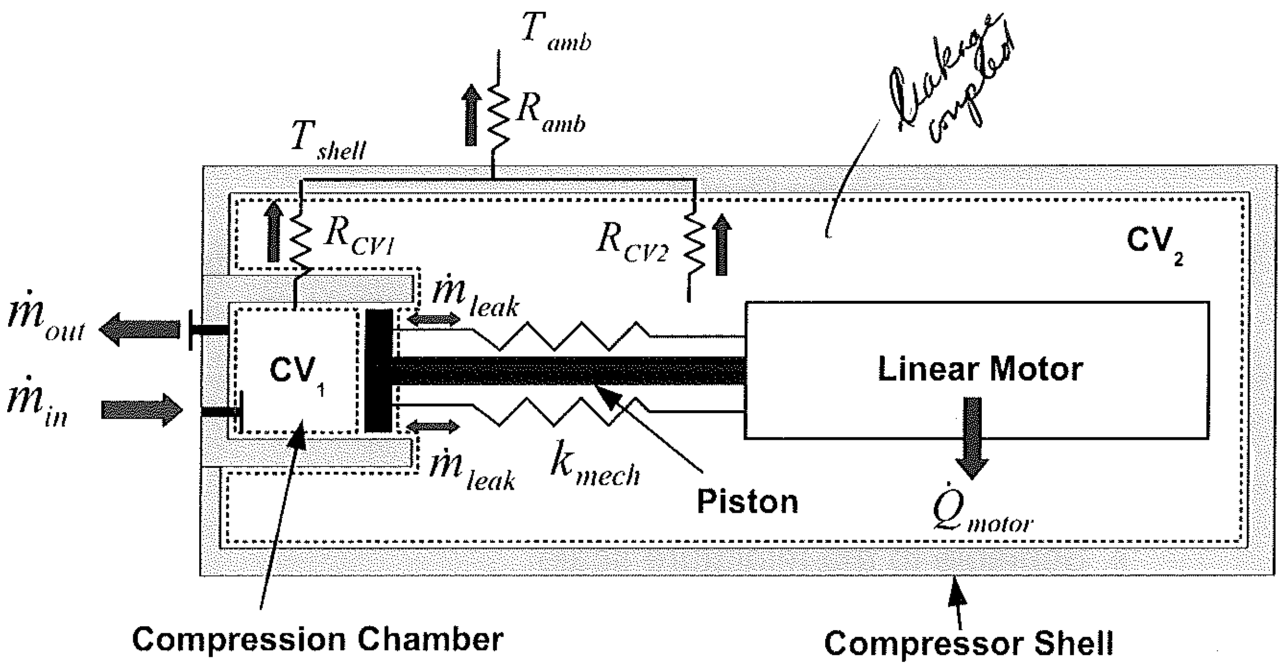
- Theoretical advantages
  - » Lower friction losses (higher efficiency)
  - » Scalable to the miniature scale
  - » Capable of capacity control (variable stroke)

LG Domestic Refr./freezer

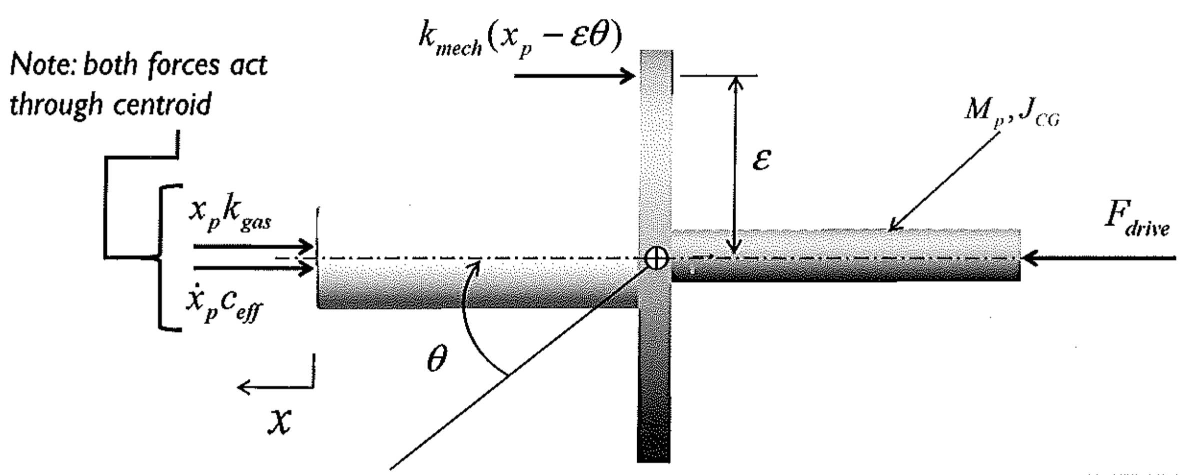
Miniature Linear Compressor
Prototype Compressor



Miniature Linear Compressor Control Volumes



Miniature 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)

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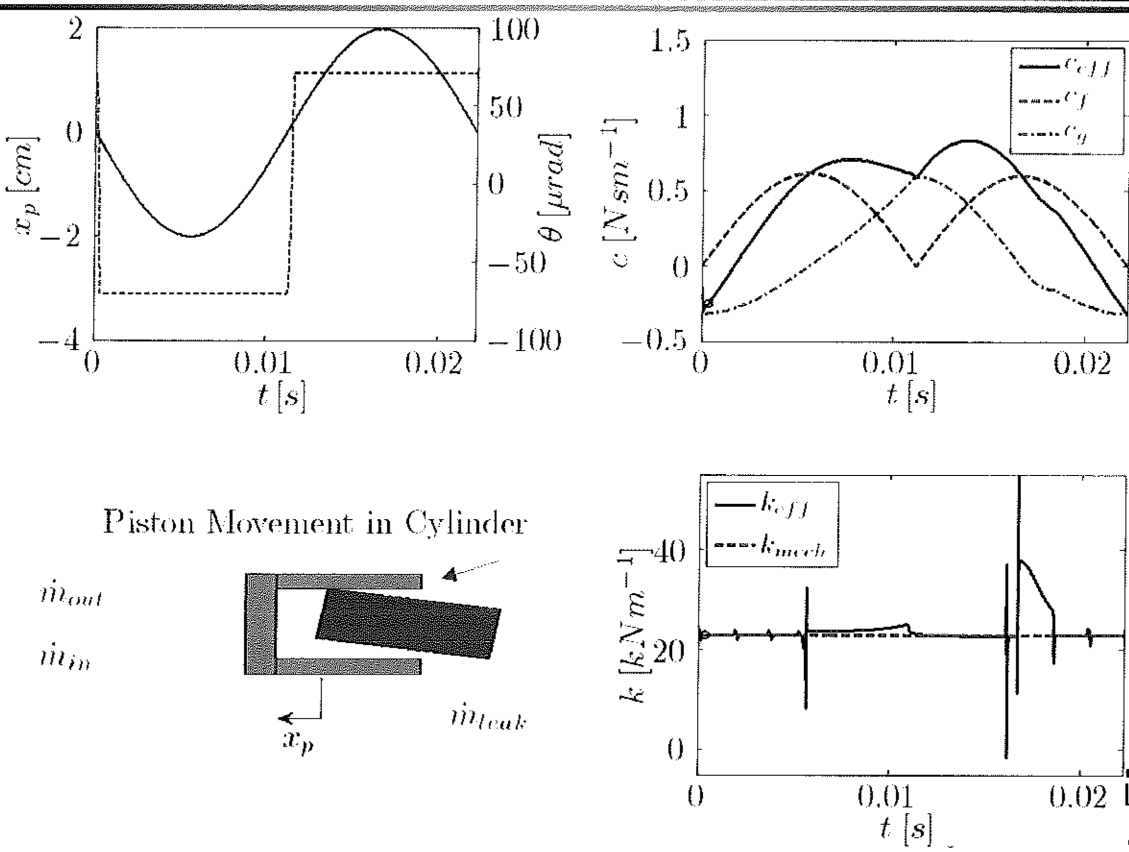
Miniature Linear Compressor Vibration Model Visualization



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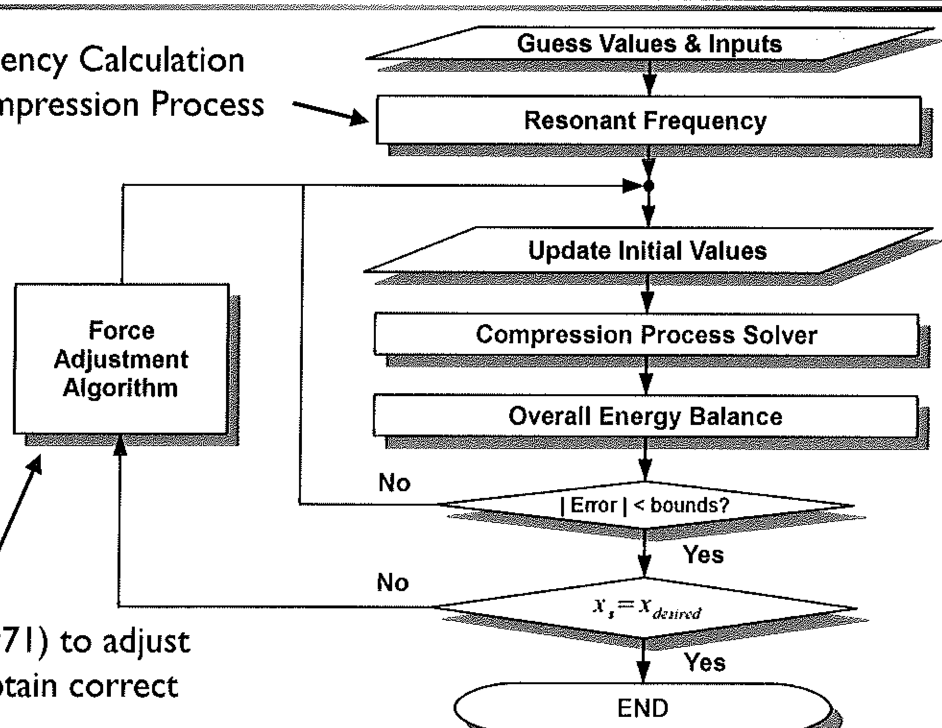
Miniature Linear Compressor Model Algorithm

Resonant Frequency Calculation External to Compression Process Loop



ms for control, feedback req'd for same reason

Brent's method (1971) to adjust piston force and obtain correct stroke

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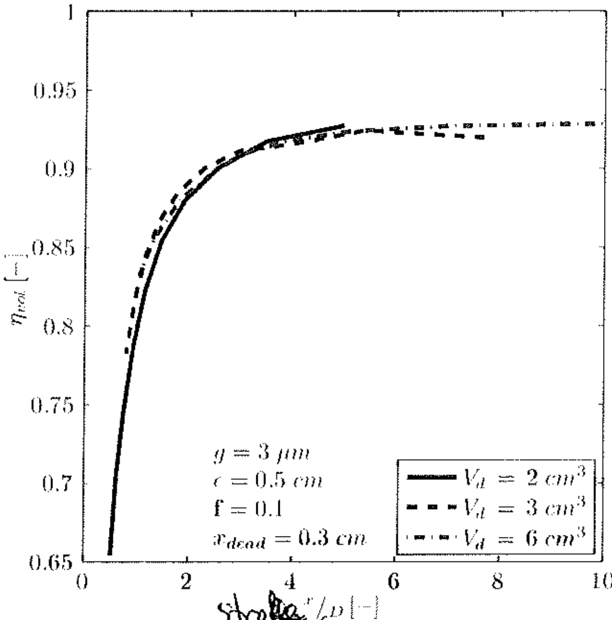
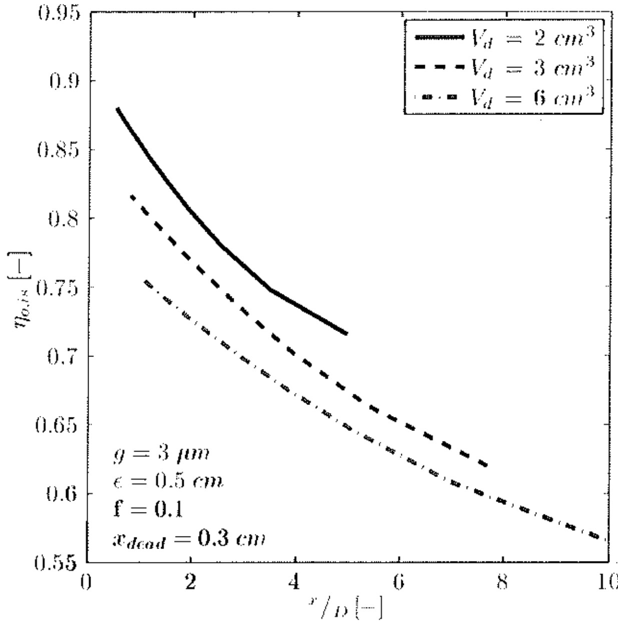
Miniature Linear Compressor Piston/Scaling

vary stroke/dead volume w/o loss of isentropic efficiency

Impact of stroke-to-bore ratio and displaced volume on efficiencies



Volumetric Efficiency



Overall Isentropic Efficiency

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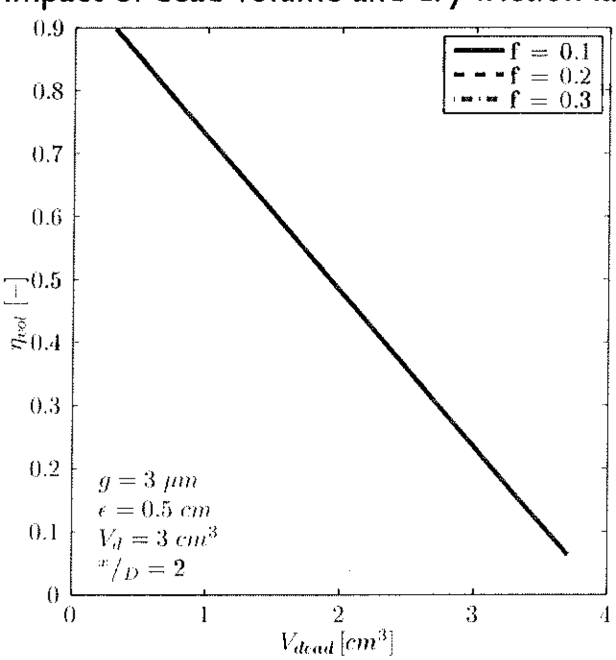
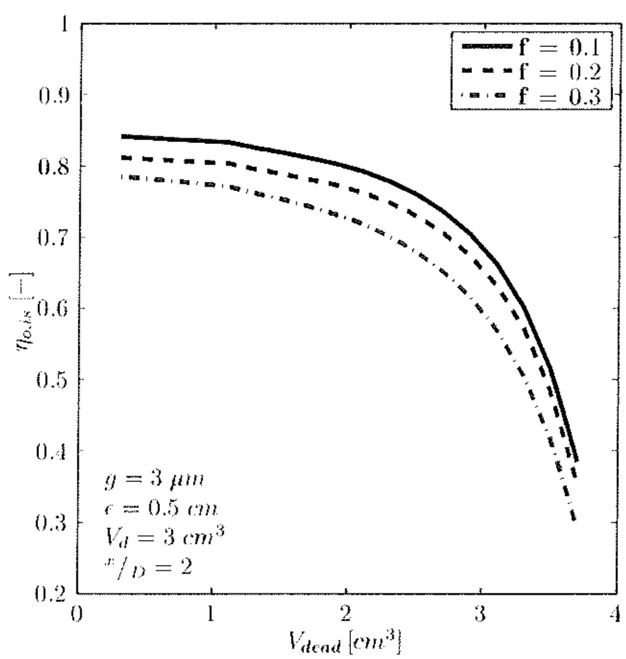
Miniature Linear Compressor Stroke Control/Friction Factor

Impact of dead volume and dry friction factor on efficiencies



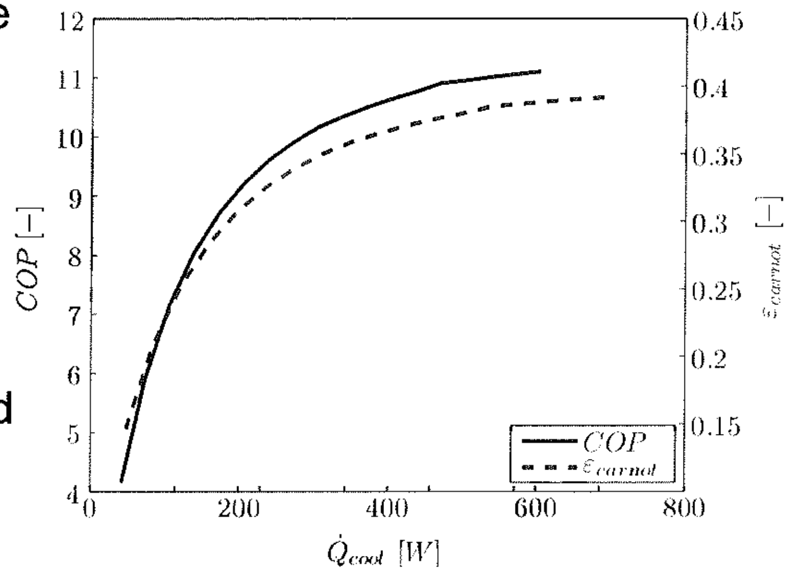
Volumetric Efficiency



Overall Isentropic Efficiency

Miniature Linear Compressor Capacity Control

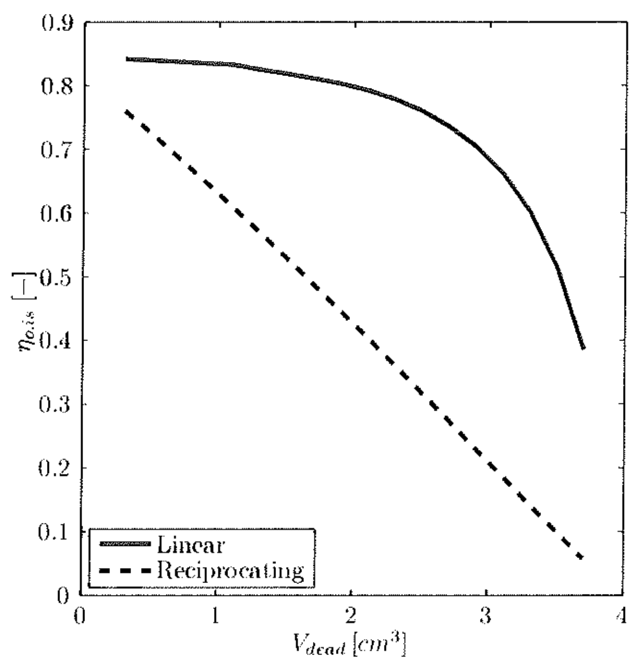
- Variable stroke can be utilized to generate variable capacity
- By assuming 10 °C subcooling at the condenser outlet, a cycle can be simulated
- A linear compressor provides high performance over wide capacity ranges



System COP and 2nd Law Effectiveness

Miniature Linear Compressor Comparison to Recip. Compr.

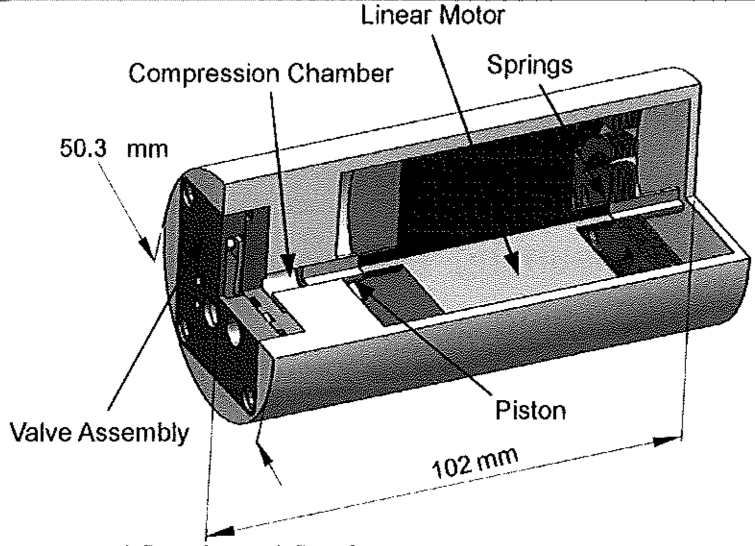
- All else constant, vary net dead volume by increasing x_{dead}
- Simulates a variable stroke compressor
- As dead volume increases the recoverable energy increases
- The mechanical springs act as capacitance, allowing energy to be recaptured that would otherwise be lost



Overall Isentropic Efficiency

Miniature Linear Compressor
Improved Compressor 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

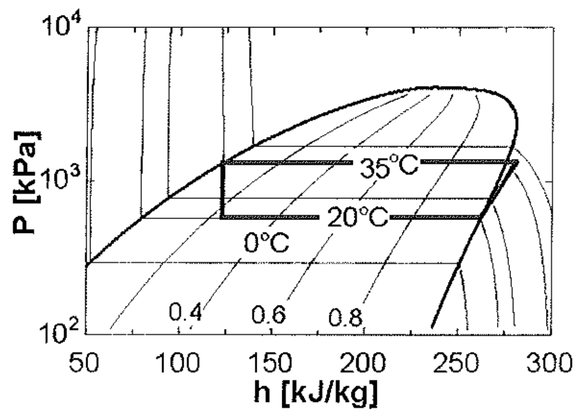
Miniature Linear Compressor
Conclusions

- Linear compressor scales well for small-scale applications
- The unique behavior of the linear compressor piston allows for efficient capacity control
- The single moving part could allow for reduced manufacturing costs

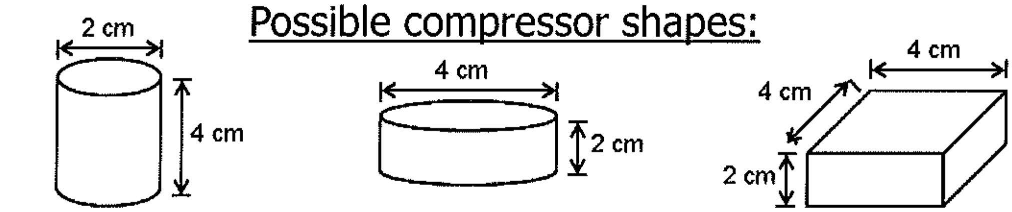
Contents

Miniature Diaphragm Compressor
Application of Laptop Computer Cooling

- Miniature-scale refrigeration system for cooling a laptop (notebook) computer:
  - » Evaporator temperature: 20 ° C
  - » Condenser temperature: 35 ° C
  - » Cooling capacity: **80 W**
- For refrigerant **R-134a:**
  - » Pressure rise ΔP: 320 kPa
  - » Flow rate: 1000 ml/min



Possible compressor shapes:

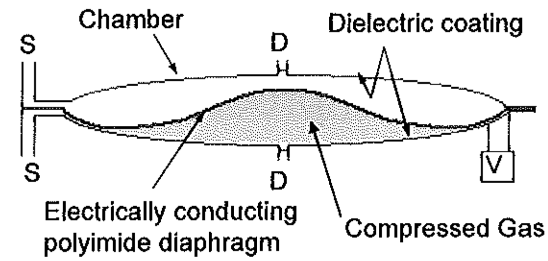


Volume = 12.6 cm³ Volume = 25.1 cm³ Volume = 32 cm³

Miniature Diaphragm Compressor Motivation

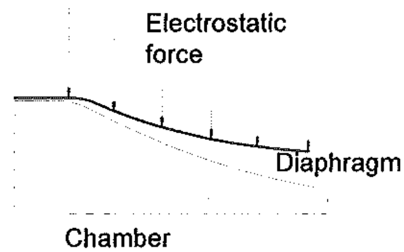
- *Motivation:* Develop miniature-scale refrigeration compressor that can be used for electronics cooling

Compressor schematic



- Diaphragm compressor uses electrostatic force to "zip" a thin circular diaphragm in a domed compression chamber

Progressive zipping

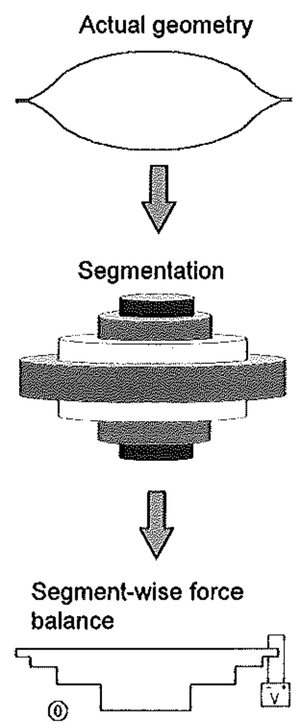


- Diaphragm compressor consists of
  - » A chamber coated with dielectric material
  - » A metallized diaphragm
  - » Suction ports (S) and discharge valves (D)
  - » DC power supply (V) and control electronics

Diaphragm covers suction port from one side or other

Miniature Diaphragm Compressor Model Development

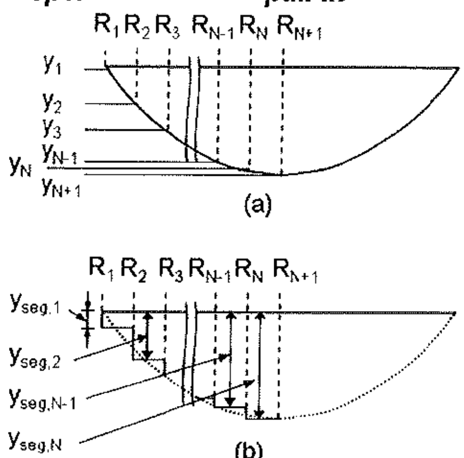
- Previous models are not sufficient
  - » Either too simple by neglecting curvature of electrodes to model moveable parallel plates
  - » Or too complex, requiring significant calculations to solve computational fluid dynamics model
- Developed new model to balance accuracy and computation time
  - » Model as a series of moveable plate capacitors
  - » Assume diaphragm is quasi-static
  - » Balance elastic force in diaphragm, fluid pressure acting on the diaphragm, and electrostatic force for each segment
  - » Calculate voltage required to move each segment

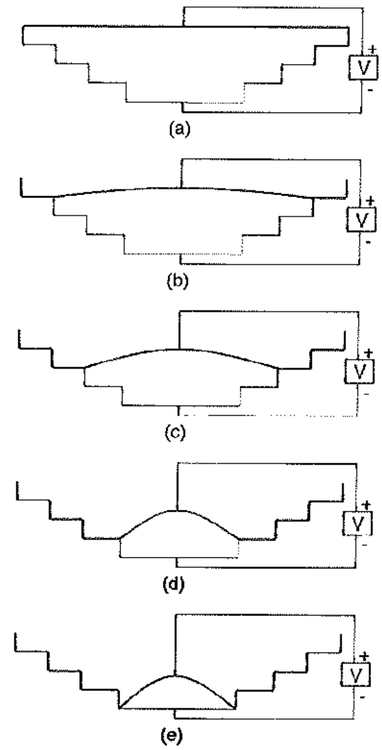


Miniature Diaphragm Compressor Segmentation Modeling Approach

- Pull-in voltage calculated for each segment from force balance
- Required operating voltage is the maximum voltage for segments

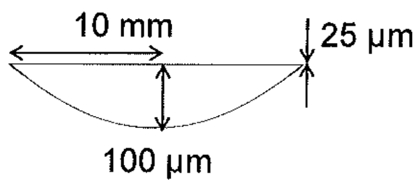
V_{oper} = max ($V_{pull\text{-}in}$)





Miniature Diaphragm Compressor Model Results

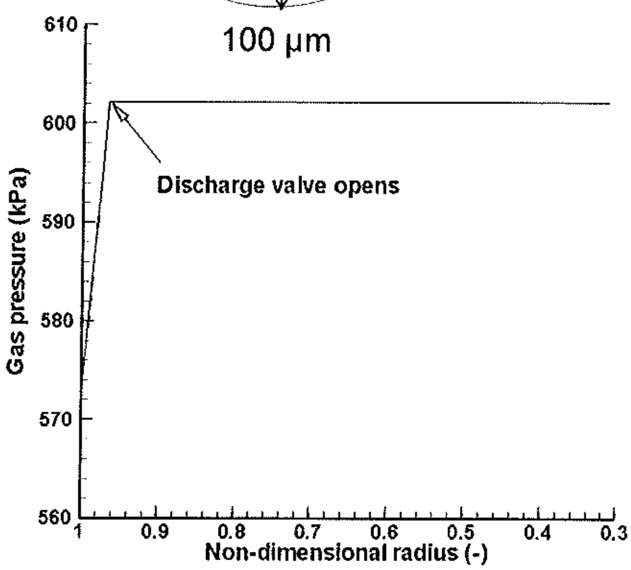
Dome-shaped Chamber

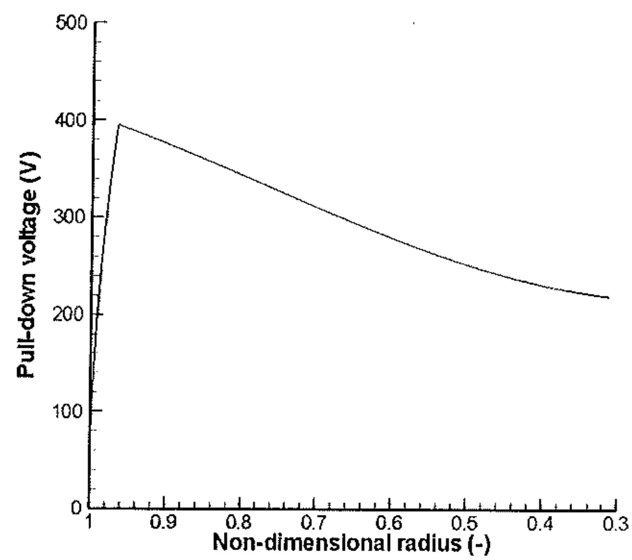


Pressure rise = 30 kPa

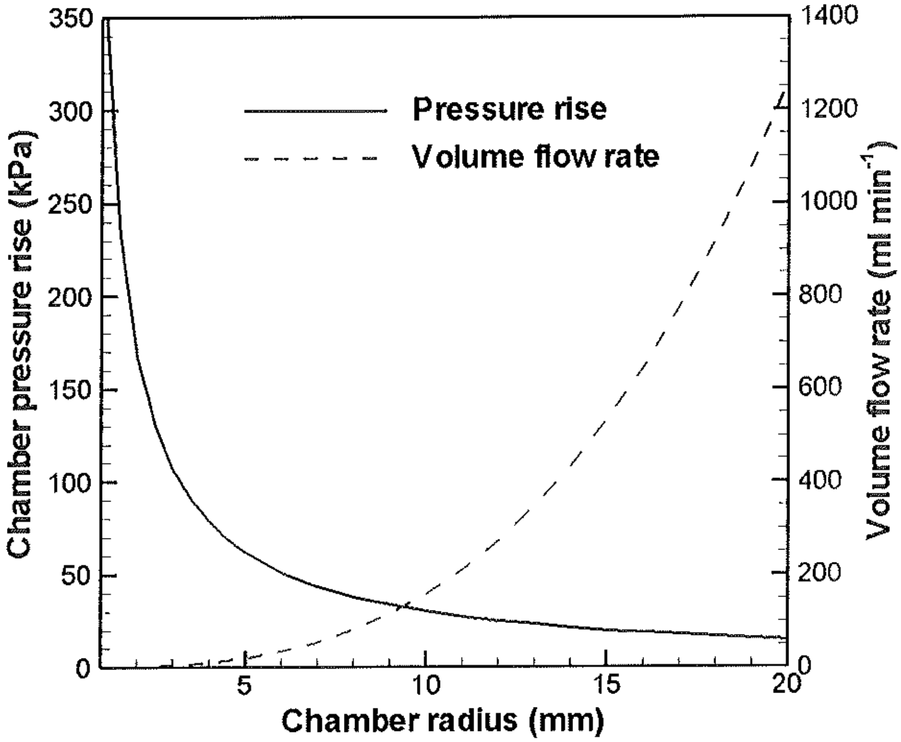
Volume flow rate = 83 ml/min

Pull-in Voltage = 400 V





Miniature Diaphragm Compressor Design Optimization



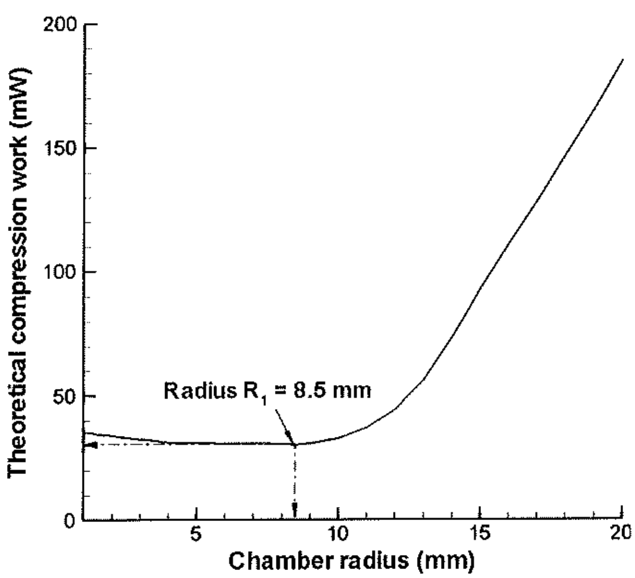
$$\Delta P \propto \frac{1}{R^2}$$

$$\dot{V} \propto R^3$$

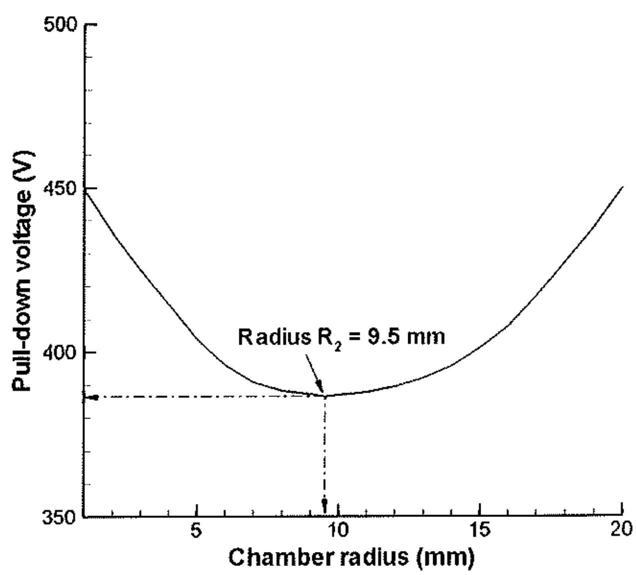
Note:
As diaphragm thickness ↑ :
→ ΔP ↑,
but also Volt ↑

Miniature Diaphragm Compressor Optimization Parameters

Minimizing theoretical compression power



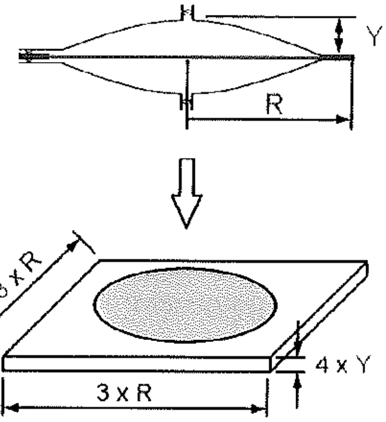
Minimizing operating voltage of the compressor



Miniature Diaphragm Compressor
Application of Laptop Computer Cooling

Optimized Design:

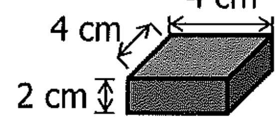
Chamber radius	8.5 mm
Chamber depth	85 μm
Pressure rise	35.6 kPa
Volume flow rate	97 ml min^{-1}
Pull-down voltage	387 V



Requirements:

Laptop cooling application: 80 W				
Refrigerant		R134a	R236fa	R245fa
	Suction pressure [kPa]	572	230	124
	Dis. pressure [kPa]	888	376	213
	Pressure rise [kPa]	316	146	89
	Vol. flow rate [ml min^{-1}]	1141	2496	4119

Possible Shape:



Volume = 32 cm^3

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Miniature Diaphragm Compressor
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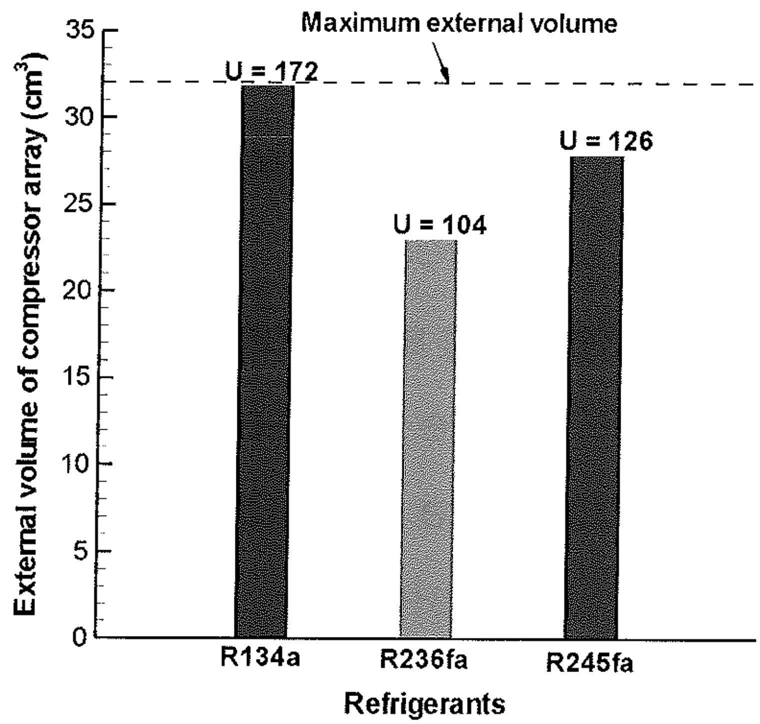
Unit in series: $m = \frac{\Delta P_{req}}{\Delta P_{unit}}$

Unit in parallel: $n = \frac{\dot{V}_{req}}{\dot{V}_{unit}}$

Total units: $U = m \times n$



Miniature Diaphragm Compressor Summary

- An electrostatically actuated diaphragm compressor is a possible miniature-scale compression technology
- A diaphragm compressor was analytically modeled using a novel segmentation technique that simulates the zipping actuation of the diaphragm from circumference towards the center
- The model results were compared to the literature and show good agreement
- A single diaphragm compressor that produces a pressure rise of 36 kPa and flow rate of 97 ml/min is proposed
- The required operating voltage for the compressor is ~400 V
- For satisfying higher pressure rise and flow rate demands, 3-D array of diaphragm compressors has to be constructed
- Outlook
  - » Though the diaphragm compression technology is possible, manufacturing and reliability issues need to be resolved before commercial usage

Contents

Conclusions

- Reviewed recent research of novel compression concepts for refrigeration applications
  - » Bowtie compressor is good option for mechanical capacity control but high manufacturing cost
  - » Z-compressor has low noise and vibration, but may not have sufficient efficiencies
  - » Spool compressor provides efficient operation with simplified geometry and potential for low manufacturing cost
  - » Linear compressor provides capacity control and scaleability
  - » Miniature diaphragm compressor is feasible technology for electronics cooling, but complex array of mini compressors needed

