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

Eckhard A. Groll
Reilly Professor of Mechanical Engineering
Director of the Office of Professional Practice

Purdue University
Ray W. Herrick Laboratories
West Lafayette, Indiana 47907, USA
Phone: 765-496-2201; Fax: 765-494-0787
E-mail: groll@purdue.edu
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- Modeling of Compressors
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- Bowtie Compressor
- Z-Compressor
- Linear Compressor
- S-RAM Compressor
Introduction
Overview of Refrigeration Compressors

Compressor Types

Positive Displacement Compressors
- Reciprocating Compressors
  - Rolling Piston Compressor
- Rotary (Rotational Piston) Compressors
- Orbital Compressors
- Rotary (Sliding) Vane Compressor

Dynamic Compressors
- Axial Flow Machines
  - Screw Compressor
    - Single Shaft: Single-Screw Compressor
  - Scroll Compressor
    - Double Shaft: Twin-Screw Compressor
- Radial Flow Machines
  - Trochoidal Compressor
Introduction
Range of Applications of Compressors

Cooling Capacity

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

Fractional

Reciprocating

200 kW (50 tons)

Rotary

10 kW (3 tons)

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 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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    - Double Shaft: Twin-Screw Compressor

Dynamic Compressors
  - Orbital Compressors
    - ... (not fully visible)
  - Axial Flow Machines
  - Radial Flow Machines
    - Scroll Compressor
    - Trochoidal Compressor
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- Introduction
- **Modeling of Compressors**
- Rotating Spool Compressor
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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
Compressor modeling relies on understanding of various time scales inside the compressor.
Modeling of Compressors: Model Flow Chart

1. Guess Lump Temperatures
2. Guess Initial Values
3. Compression Process Solver
4. Frictional Model
5. Overall Energy Balance
6. | Error | < ε ?
   - No
   - Yes: END
7. Compression Process Solver
   - Geometry Model
   - Mass Flow Model
   - Valve Model
   - Instantaneous Heat Transfer
   - Derivatives
8. Initial ≈ Final ?
   - No
   - Yes
• Conservation of Mass and Energy
  » Combined mass and energy balance can be solved in series for $\frac{d\rho}{d\theta}$ and $\frac{dT}{d\theta}$:

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

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

  \[
  \rho \frac{\partial u}{\partial T}
  \]
Modeling of Compressors: Modeling Approach

Schematic of energy flows inside a hermetic compressor

\[ T_{\text{suc}} = T_{\text{evap}} + \Delta T_{\text{super}} \]

\[ T_{\text{gas}} = T_{\text{cyl,in}} \]

\[ \dot{Q}_{\text{wall, gas}} \]

\[ W_{\text{comp}} \]

\[ \dot{Q}_{\text{motor loss}} \]

\[ \eta_{\text{mech}} : \text{friction model} \]

\[ \eta_{\text{motor}} : \text{motor map} \]

\[ \dot{W}_{\text{electric}} \]

\[ RPM \]

\[ T_{\text{wall}} \]

\[ W_{\text{shaft}} \]

\[ \dot{Q}_{\text{oil, gas}} \]

\[ \dot{Q}_{\text{rad, gas}} \]

\[ \dot{Q}_{\text{rad, dis, shell}} \]

\[ \dot{Q}_{\text{rad, shell, amb}} \]

\[ \dot{Q}_{\text{shell, amb}} \]

\[ \dot{Q}_{\text{rad, shell, amb}} \]

\[ Q_{\text{shell, amb}} \]

\[ Q_{\text{dis, rad, shell}} \]

\[ Q_{\text{dis, gas}} \]

\[ Q_{\text{gas, shell}} \]

\[ Q_{\text{gas, cyl, in}} \]

\[ Q_{\text{wall, gas}} \]

\[ Q_{\text{friction loss}} \]

\[ Q_{\text{elec}} \]

\[ Q_{\text{rad, shell, amb}} \]

\[ Q_{\text{rad, dis, shell}} \]

\[ Q_{\text{rad, shell, amb}} \]

\[ Q_{\text{shell, amb}} \]

\[ Q_{\text{dis, shell}} \]

\[ Q_{\text{dis, rad, shell}} \]

\[ Q_{\text{dis, gas}} \]

\[ Q_{\text{gas, shell}} \]

\[ Q_{\text{gas, cyl, in}} \]

\[ Q_{\text{rad, shell, amb}} \]

\[ Q_{\text{shell, amb}} \]

\[ Q_{\text{dis, shell}} \]

\[ Q_{\text{dis, rad, shell}} \]

\[ Q_{\text{dis, gas}} \]

\[ Q_{\text{gas, shell}} \]

\[ Q_{\text{gas, cyl, in}} \]

\[ Q_{\text{rad, shell, amb}} \]

\[ Q_{\text{shell, amb}} \]

\[ Q_{\text{dis, shell}} \]

\[ Q_{\text{dis, rad, shell}} \]

\[ Q_{\text{dis, gas}} \]

\[ Q_{\text{gas, shell}} \]

\[ Q_{\text{gas, cyl, in}} \]

\[ Q_{\text{rad, shell, amb}} \]

\[ Q_{\text{shell, amb}} \]

\[ Q_{\text{dis, shell}} \]

\[ Q_{\text{dis, rad, shell}} \]

\[ Q_{\text{dis, gas}} \]

\[ Q_{\text{gas, shell}} \]
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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
Rotating Spool Compressor: Geometry
Rotating Spool Compressor: Model Validation

Volumetric Efficiency

Power Consumption

$MAE = 3.13\%$

$+8\%$

$-5\%$

Avg. Deviation $= -13.2W$

$+250W$

$-250W$
Rotating Spool Compressor: Design Optimization

Volumetric Efficiency

Discharge Temperature

Spool Seal Gap, $g_f$ [μm]

$\eta_{vol}$

T$_{dis}$ [K]

$0$ $1$ $2$ $3$ $4$ $5$

$0.74$ $0.76$ $0.78$ $0.8$ $0.82$ $0.84$ $0.86$ $0.88$ $0.9$ $0.92$

$0$ $1$ $2$ $3$ $4$ $5$

$340$ $342$ $344$ $346$ $348$ $350$ $352$ $354$ $356$ $358$

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Rotating Spool Compressor: Performance as of Summer 2014

Volumetric Efficiency

Overall Isentropic Efficiency

[Graphs showing performance data for different prototypes andscroll compressors, with curves indicating efficiency vs. PR (Pressure Ratio).]
Rotating Spool Compressor: Summary

- 6th 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
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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

- Mass Flow Rate (lbm/hr) vs. Evaporating Temperature (°C)
- Power Consumption (W) vs. Evaporating Temperature (°C)

- Graphs show the relationship between mass flow rate and power consumption with varying evaporating temperatures (T_{cond})
- Multiple lines represent different conditions: T_{cond}=43.3°C, 48.9°C, and 54.4°C for both Map and Model predictions
Use model to optimize clearance dimensions and ratio of vane radius to height.

- Friction losses dominate
- Leakage losses dominate

![Graph showing the relationship between clearance and overall isentropic compressor efficiency.](image)

- Overall Isentropic Compressor Efficiency (%)
- Clearance (μm)

![Graph showing the relationship between ratio of vane radius and height and compressor mass flow rate and overall isentropic compressor efficiency.](image)

- Mass Flow Rate, Swept Angle = 25.05°
- Mass Flow Rate, Swept Angle = 31.89°
- \( \eta_{o.s.c} \) Swept Angle = 25.05°
- \( \eta_{o.s.c} \) Swept Angle = 31.89°

January 27, 2015
Bowtie Compressor: Performance Results

- Modeled results for compressor at 54.4°C condensing, -23.3°C evaporating and 32.2°C 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 180° rotation
  - Frictional and electric losses rejected to high pressure gas in shell
  - Shell exchanges heat with ambient
  - Constant pressure suction
Z-Compressor: Model Validation

**Mass flow rate**

![Graph showing mass flow rate](image)

**Power input**

![Graph showing power input](image)
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

Leakage losses

- Paths L6-L9
- Paths L4-L5
- 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

**Volumetric efficiency**

<table>
<thead>
<tr>
<th>Blade-cylinder clearance [μm]</th>
<th>0.800</th>
<th>0.825</th>
<th>0.850</th>
<th>0.875</th>
<th>0.900</th>
<th>0.925</th>
<th>0.950</th>
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<td>ηv</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Piston ring</td>
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</tbody>
</table>

**Overall isentropic efficiency**

<table>
<thead>
<tr>
<th>Blade-cylinder clearance [μm]</th>
<th>0.550</th>
<th>0.575</th>
<th>0.600</th>
<th>0.625</th>
<th>0.650</th>
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</thead>
<tbody>
<tr>
<td>ηs</td>
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<tr>
<td>Piston ring</td>
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<td>Reference</td>
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</tbody>
</table>

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
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Linear Compressor:
Control Volumes

Diagram showing the linear compressor with control volumes, mass flow rates, and thermal resistances. The diagram includes symbols for the mass flow rates ($m_{out}$, $m_{in}$), the thermal resistances ($R_{CV1}$, $R_{CV2}$), and the ambient temperature ($T_{amb}$). The diagram also highlights the compression chamber and the compressor shell.
Linear Compressor: FBD of Piston with EOM

Note: both forces act through centroid

\[ \begin{align*}
M_p \ddot{x}_p + c_{eff} \dot{x}_p + (k_{gas} + k_{mech}) x_p &= k_{mech} \varepsilon \theta + F_{drive} \\
J_{CG} \ddot{\theta} + k_{mech} \varepsilon^2 \theta &= k_{mech} x_p \varepsilon
\end{align*} \]
Linear Compressor:
Stroke Control/Friction Factor

Impact of dead volume and dry friction factor on efficiencies

Volumetric Efficiency

Overall Isentropic Efficiency

\[ g = 3 \, \mu m \]
\[ \epsilon = 0.5 \, cm \]
\[ V_d = 3 \, cm^3 \]
\[ x/D = 2 \]
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
• All else constant, vary net dead volume by increasing $x_{\text{dead}}$

• 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
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

<table>
<thead>
<tr>
<th>$k_{\text{mech}}$</th>
<th>f</th>
<th>g</th>
<th>$\varepsilon$</th>
<th>$V_d$</th>
<th>$f_{\text{res}}$</th>
<th>$x/D$</th>
<th>$\eta_{\text{vol}}$</th>
<th>$\eta_{o,\text{is}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/m</td>
<td>-</td>
<td>µm</td>
<td>cm</td>
<td>cm³</td>
<td>Hz</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>30600</td>
<td>0.2</td>
<td>4</td>
<td>0.5</td>
<td>2</td>
<td>60</td>
<td>0.4</td>
<td>0.96</td>
<td>0.86</td>
</tr>
</tbody>
</table>
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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!