On the Need for Multidimensional Stirling Analysis
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Dual Opposed Convertors

- High Efficiency, Low Mass Space Power
One-Dimensional Analysis

- Sage, LASER, DeltaE, ARCOPTR, REGEN 3.1, others…
- Successful 1D Navier-Stokes solvers
- Set up quickly
- Computations are fast
- Design optimizations are easily done
Need for Multidimensional Modeli

- Simulate all geometrical details and check the one-dimensional results
- Properly simulate flow turbulence and transition
- Provide empirical heat transfer and friction factors
- Integrate all parts to test structures and clearance
- Assist experimentalists with hard to reach data
- Provide fluid-structure interaction capability
- Generate linear reduced order models for controller
- Model large, high-power and low delta T devices
- Generating Linear Models for Controls (Chicatelli)
- Identify areas of excessive flow losses
Axisymmetric Simulation

Contours of Static Temperature (h) (Time=1.1060e-01)

FLUENT 6.2 (axi, dp, segregated, dynamesh, lam, unsteady) Nov 28, 2004
Flow Characteristics

- Oscillating flow & pressure – affects effective flow and heat transfer properties
- Low mach number (no shocks)
- Compressible due to varying volumes and heat transfer
- Laminar, Transitional, and Turbulent
- Conjugate heat transfer
Third Order Analysis

- Finkelstein, Urieli, and Berchowitz
- GLIMPS, Sage – implicit space-time (Gedeon)
- HFAST – linearized harmonic analysis
- Martini Engineering, Renfroe – explicit RK
- LASER, DeltaE, ARCOPTTR, REGEN3.1
- SDM – electric circuit analogy (Regan, et. al.)
Fourth Order (Multi-Dimensional) Tools

- Modified CAST – Schuerer, later CSU
- CFD-ACE – Used by CSU, later NASA
- Fluent – Used by Infinia, UK, NASA, later CSU
- Star-CD – Used in Korea (Noh, KSME)
- CFX- Preliminary test cases (Demko)
- All utilize low order techniques
Recent Whole Engine Modeling

- Mahkamov claims success with 3D gamma (embargoed)
  - Compared to experiment
- Zhang claims success with simplified 3D Free Piston (no conjugate heat transfer)
- Dyson, Tew, Wilson, Demko, 1 hour per axisymmetric (2-D) cycle (Most complete to date but no flexures, shields…)
- Run-time becoming less of an issue
Regenerator Geometry Not 1-D
Regenerator Impacts System

- 3 to 40 times more effective heat transfer

\[ \eta = \frac{\eta_1}{1 + \left( \frac{Q_{in}}{Q_{hi}} \right) (1 - \varepsilon)} \]

D90 Ross Yoke Drive
Ideal Adiabatic Model
Pmean = 2 bars
Tk = 27°C, Th = 650°C
Areas Ripe for Multidimensional Analysis

- Seal & Appendix Gap Phenomena (shuttle losses, other heat transfer phenomena)
- Effect of geometrical details such as heat exchanger end effects and regenerator jetting on heat transfer
- Effect of vortices in expansion and compression spaces (causing non-uniform flow in heat exchangers?)
- Flexure Temperatures, important for reliability
- Effect of slight asymmetries on performance
- Displacer gas spring dynamics and losses
Turbulence Modeling

- Turbulence is random, not quasi-steady periodic.
- Turbulence is a fully 3D phenomena.
- Transition is a key feature of oscillating flow.
- 1D modeling requires empirical data from experiment.
- Large Eddy Simulation could be employed.
Check One-Dimensional Results

- Inexpensive one-dimensional results depend upon often unknown empirical coefficients
- Check one-dimensional from first principles without resorting to experiment
Flat Head Heater Not 1-D

- Significant error until empirical coefficients adjusted experimentally.
Empirical Coefficients Needed

- Empirical coefficients are used to adjust magnitude of frictional pressure drops and to enhance or degrade heat transfer.
- Models can be calibrated after the fact, once test data is available but may be too late to change hardware designs.
- Utilize CFD to get proper pressure drop and heat transfer coefficients (1-D uses correlations based on regenerator friction factor tests)
- Sage expected accuracy is 10-20% and improves to 5% once calibrated with test data

S. Qiu, Stirling Convertor Performance Mapping Test Results for Future Radioisotope Power Systems, STAIF, 2004
S. Qiu, Preliminary Computational Fluid Dynamics Modeling of STC Stirling Engine IECEC 2004
Part Integration

Examine how actual parts fit and interact
Flow Distribution

- Sensor Placement, Calibration, Validation

Contours of Velocity Magnitude (m/s) (Time=4.8824e-01)
FLUENT 6.2 (axi, swirl, dp, segregated, dymesh, lam, unsteady)

Contours of Static Temperature (k) (Time=4.8824e-01)
FLUENT 6.2 (axi, swirl, dp, segregated, dymesh, lam, unsteady)
Fluid-Structure Interaction

- Radiation Shield, Flexure Bending/Heating
### Dimensionality of Losses

Thermal Conduction + Diffusion + Viscosity = Entropy

<table>
<thead>
<tr>
<th>TYPE OF LOSS</th>
<th>D</th>
<th>Model</th>
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<tbody>
<tr>
<td>(Enhanced) Thermal conduction in gases and solids</td>
<td>3D</td>
<td>Fourier, Kurzweg, Gedeon Correl.</td>
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<tr>
<td>Gas Thermal and Magnetic Hysteresis</td>
<td>3D</td>
<td>Lumped</td>
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<tr>
<td>Gas Shuttle Losses</td>
<td>2D</td>
<td>?</td>
</tr>
<tr>
<td>Gas Bearing, Seal, and Center port Leakage</td>
<td>1-3D</td>
<td></td>
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<tr>
<td>Electrical resistance losses in windings</td>
<td>1D</td>
<td>$I^2R$</td>
</tr>
<tr>
<td>Pressure drop in heat exchangers (friction and area)</td>
<td>3D</td>
<td>Steady Flow Correlations</td>
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<tr>
<td>Enthalpy transport through regenerators</td>
<td>2D</td>
<td></td>
</tr>
<tr>
<td>Temperature gradients across heat exchangers wall</td>
<td>1D</td>
<td>Use Q =&gt; Delta</td>
</tr>
<tr>
<td>Friction in seals and crank mechanisms</td>
<td>1D</td>
<td>Use forces</td>
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Design and Integration Analysis Options

- Multi-D Sage
- Engineering Services Engine/Component Modeling
- New High-Order Transient Code Development

- Develop Commercial Transient Code Add-ons For Fluent, CFD-ACE, CFX
- SDM (System Dynamic Model) SDM-CFD Integration

Correlations

Component Modeling

Fast

Turbo

Today

Piston Dynamics Coefficients + Therm.
Comprehensive Analysis Tree

1D Initial (Sage) & Optimize

Desired performance

Initial CAD Design

SDM

2D or 3D – Validate, Get empirical coefficients

Agreement?

Yes

No

Build Prototype
Conclusions

- Need 1D, 2D, and 3D Stirling design tools.
- The combination of all three paradigms provides for initial design, empirical coefficient adjustment, optimization, and final prototype demonstration before the first part is cut.