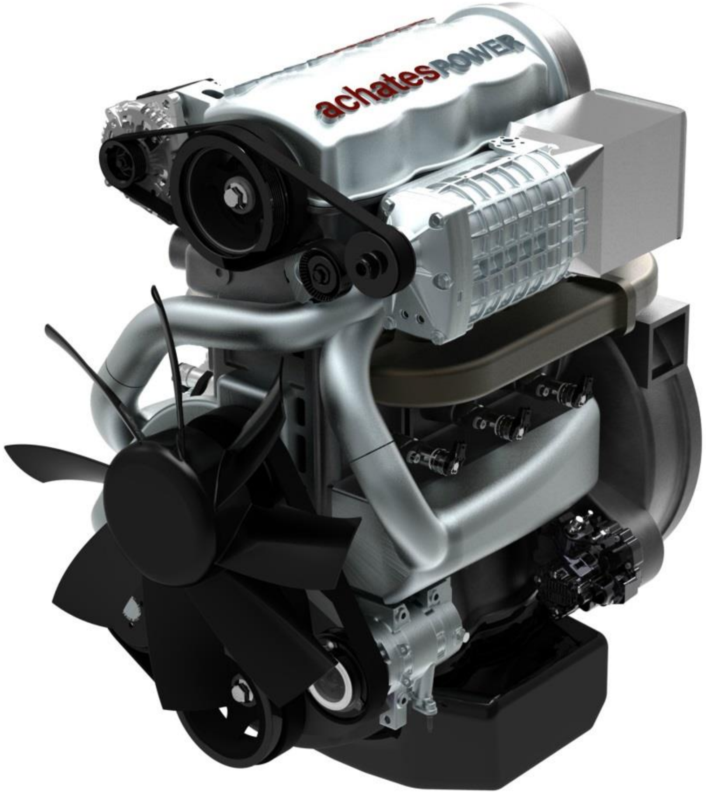

Advanced CFD for the Modeling and Optimization of Opposed Piston Combustion Systems

Rishi Venugopal
Achates Power Inc.

November 12th 2014

Acknowledgements: Achates CFD Team, Achates Leadership Team

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Outline

- **Company and Technology Overview**
- **Achates CAE Tools and Computing Environment**
- **Achates Combustion System Design Process**
- **Combustion System Development with Advanced CFD**
  - Multi-cylinder scavenging simulations
  - Single-cylinder combustion simulations
  - Combustion Optimization (DOEs and Genetic Algorithms)
  - Piston Thermal Modeling
- **Potential Applications of HPC for OP Combustion Modeling**
- **Summary**

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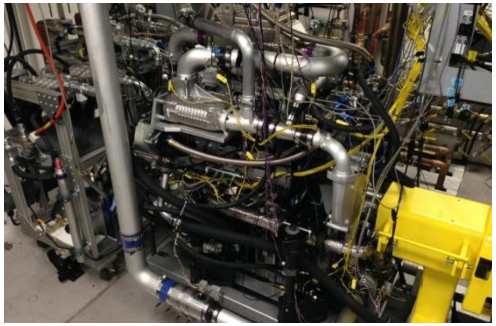
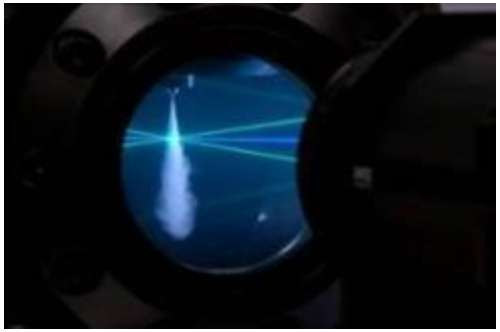
Company Overview

Clean, more efficient, lower cost engines

- Founded in 2004 by Dr. James Lemke and the late John Walton
- More than $100 million of capital invested
- State-of-the-art facilities and analytical tools
- Demonstrated and customer validated results based more than 6,000 dynamometer test hours
  - Clean: meets the most stringent standards
  - Dramatically more efficient:
    - 20+% versus the most efficient engines (CI)
    - 50+% versus the most common engines (SI)
  - Lower cost, mass and complexity
  - Multi-fuel capable
- Comprehensive, global IP portfolio with more than 2,000 claims in 57 issued and 105 pending patents
- World class team (~70 and growing)





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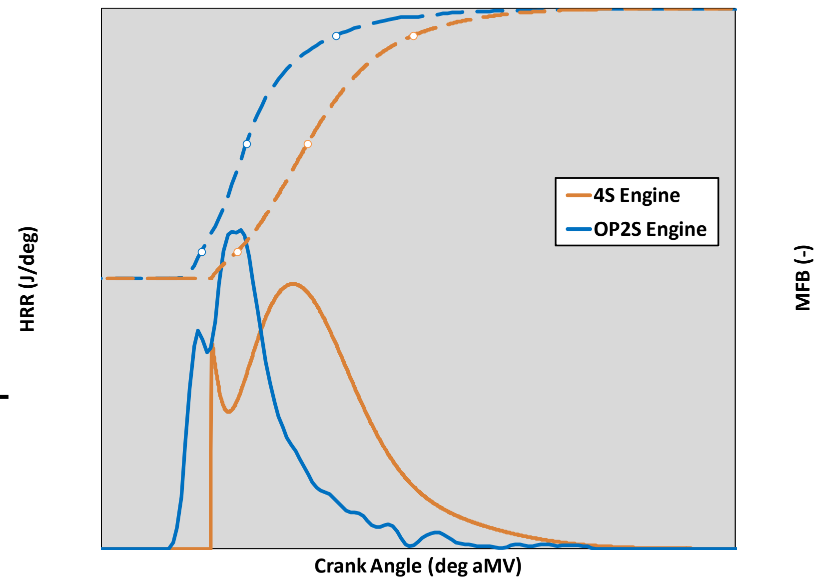
OPE Technology: Fundamental Efficiency Enablers

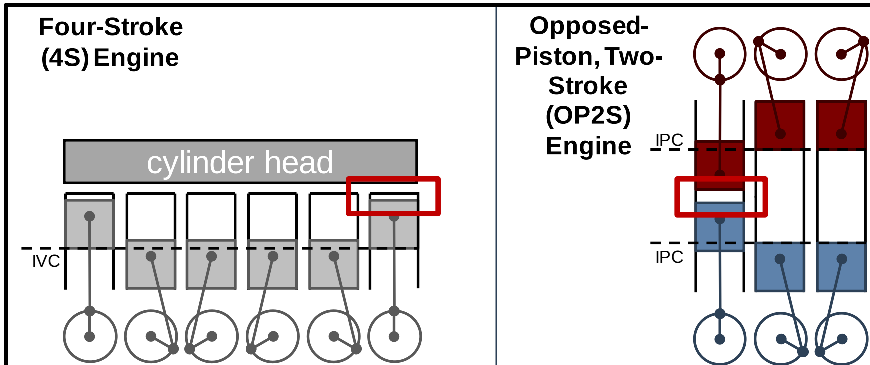
Versus four-stroke engines

- Lower heat transfer
- Leaner combustion
- Optimally phased and faster combustion at equivalent pressure rise rate
- Lower pumping work



Four-Stroke (4S) Engine

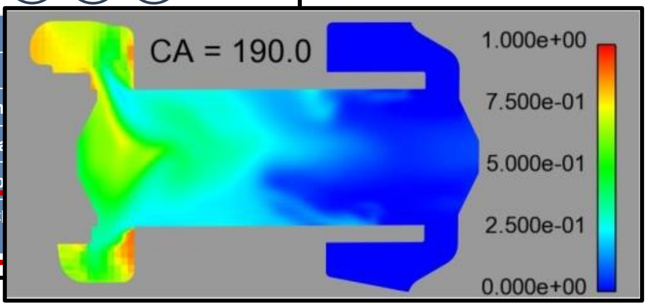
Opposed-Piston, Two-Stroke (OP2S) Engine

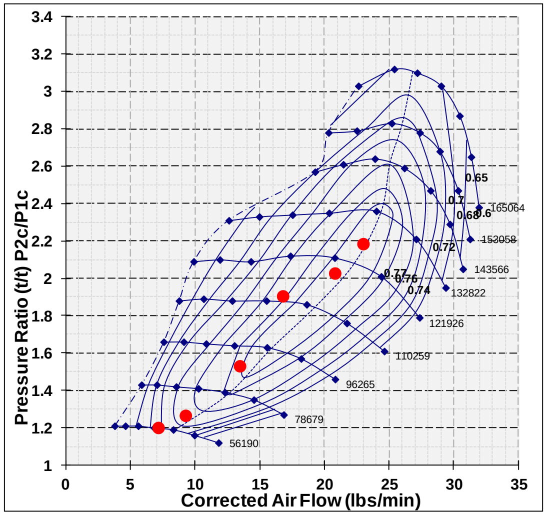


Engine	4S
Cylinders	6
Trapped Volume/Cylinder	1.0 L
Stroke/Bore Ratio	1.1
Trapped Comp. Ratio	15:1
Combustion Chamber Surface Area / Volume(mm⁻¹)	0.28

36% Reduction

Engine
Cylinders
Trapped Volun
Stroke/Bore Ra
Trapped Comp
Combustion C Surface Area /





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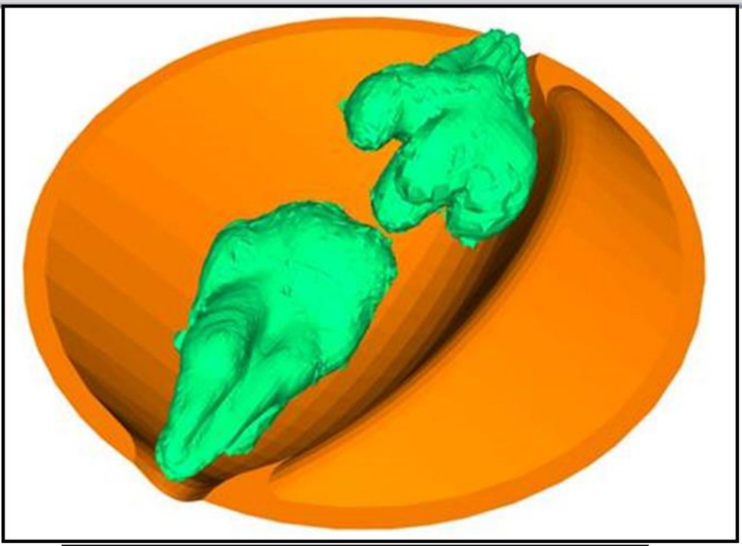
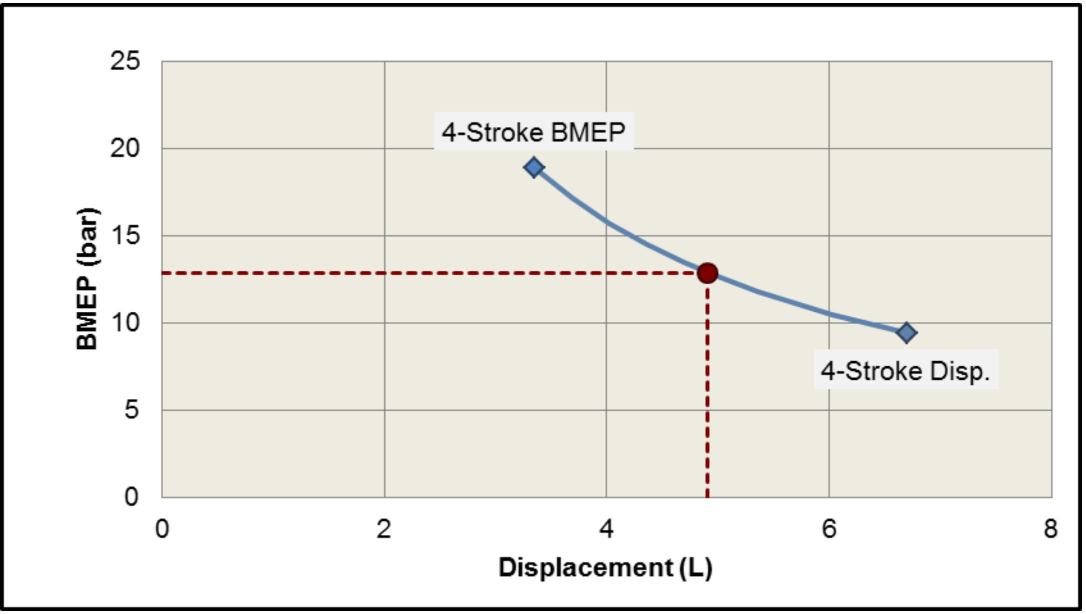
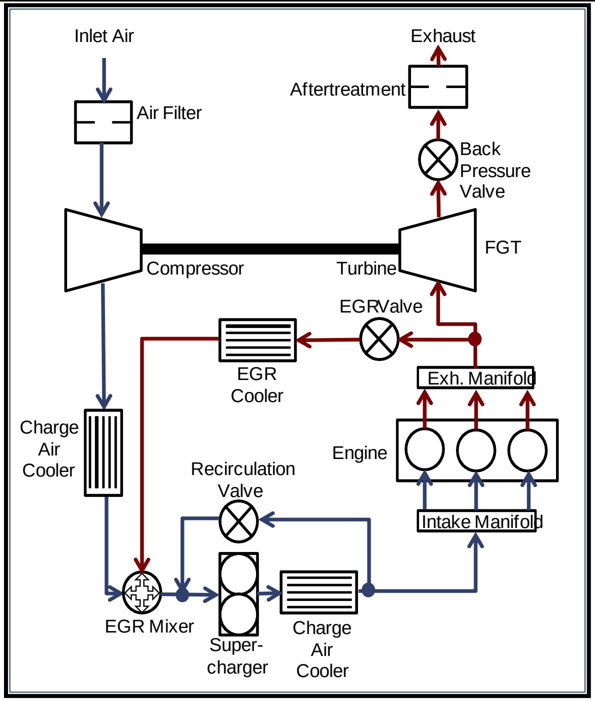
OPE Technology: Fundamental Emissions Enablers

Versus four-stroke engines

- Lower BMEP
- Proprietary combustion system
- Dual injector
- Inherent internal EGR capability and flexible charge control







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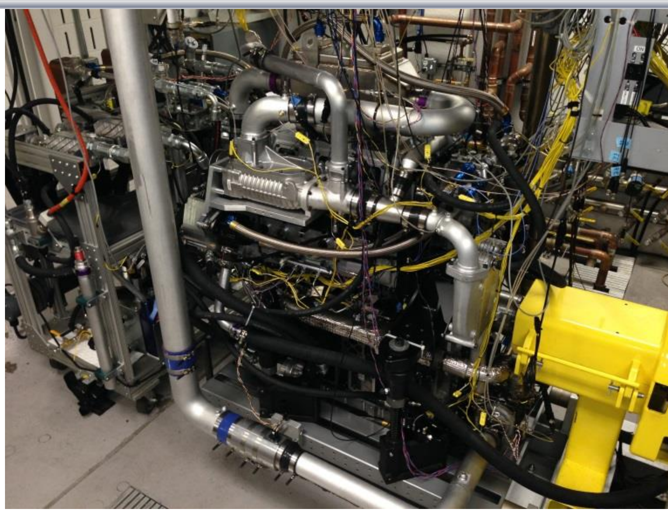
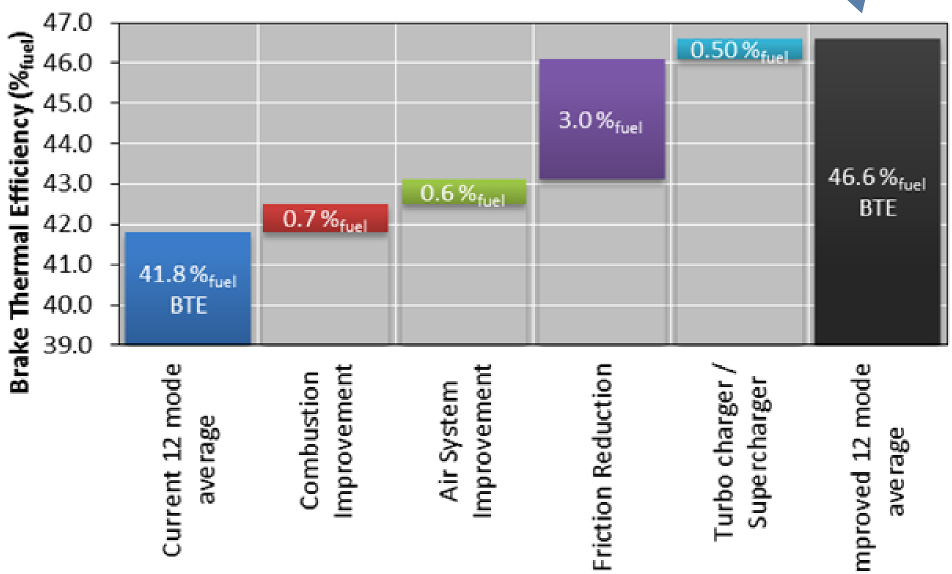
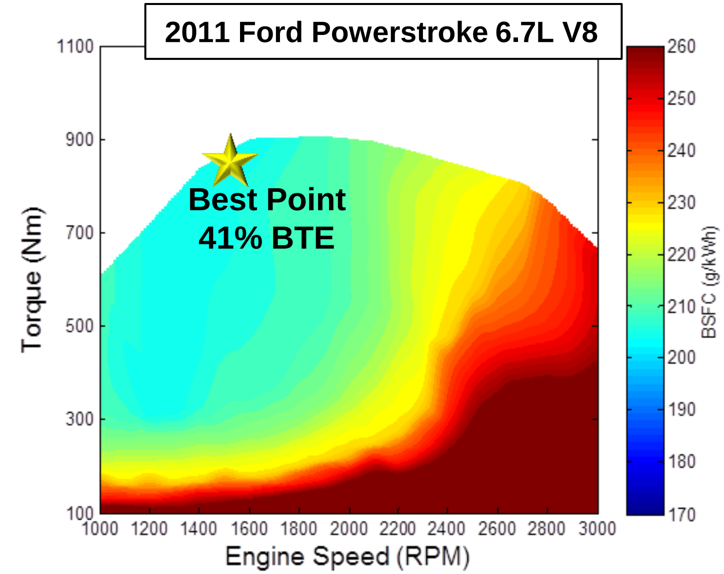
OPE Technology: Demonstrated MCE Results & Roadmap

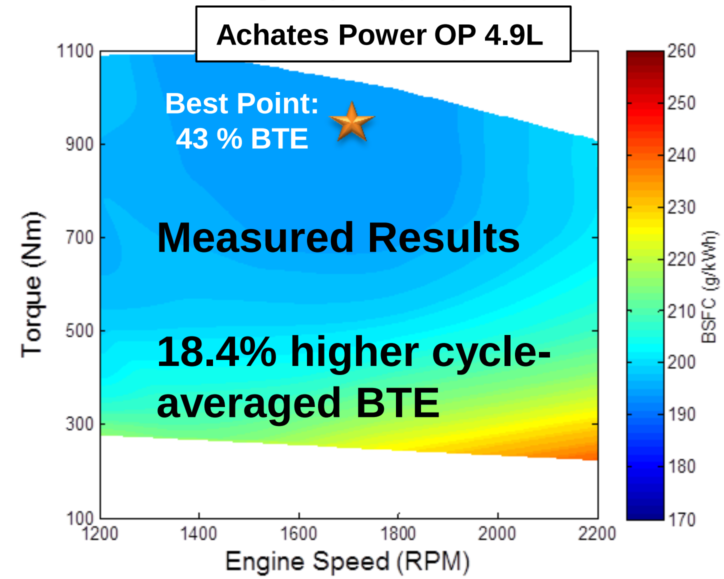


API 4.9L 3-cylinder research engine

CAE predicted roadmap to 46.6% cycle averaged BTE







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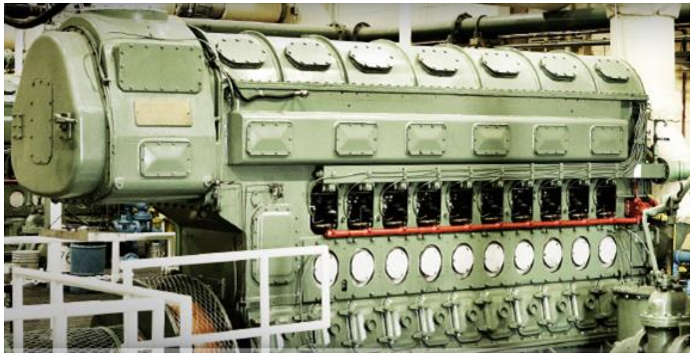
Announced Commercial Contracts

Fairbanks Morse Engine

Large Engines for Marine and Power Generation

- Has manufactured OP engines since 1937
- Selected as technology development partner
- Licensee of Achates Power patents
- Improved efficiency while meeting Tier4 Final



TARDEC Next Generation Combat Engine

- $4.9M contract awarded December 2012
- 2+ year program; partnered with AVL
- High power density (70 HP/L) with low heat rejection
- Follow-on programs planned

Several development programs with customers in NA, Japan, India and China spanning LD, MD and HD market segments

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Achates CAE Tools and Computing Environment

Analysis-led Approach

CFD

CONVERGE

- Custom user routines and features for the simulation of OP engines
- Multi-cylinder scavenging simulations
- Single-cylinder combustion simulations
- Genetic Algorithm and DOE optimization

CAE

ANSYS Mechanical

FLUENT/CFX

FEMFAT

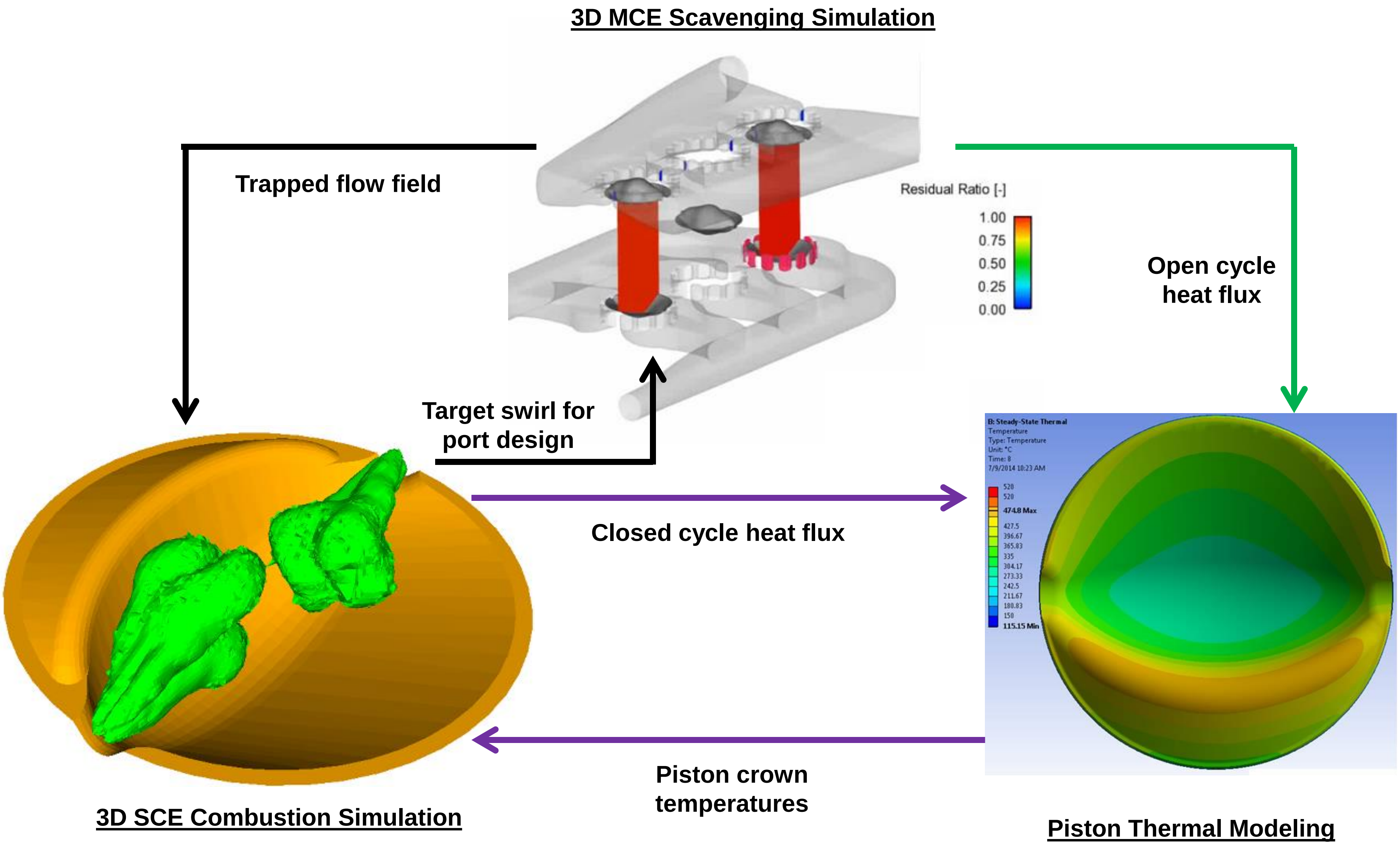
PISDYN

Proprietary tools

Computing Environment

- 192 total cores
- 6 boxes 2x Intel E5-2670 @2.6GHz, 2 boxes 2x Intel E5-2690v2 @3.0 GHz
- QDR Infiniband (40 Gbps)

Achates Combustion System Design Process



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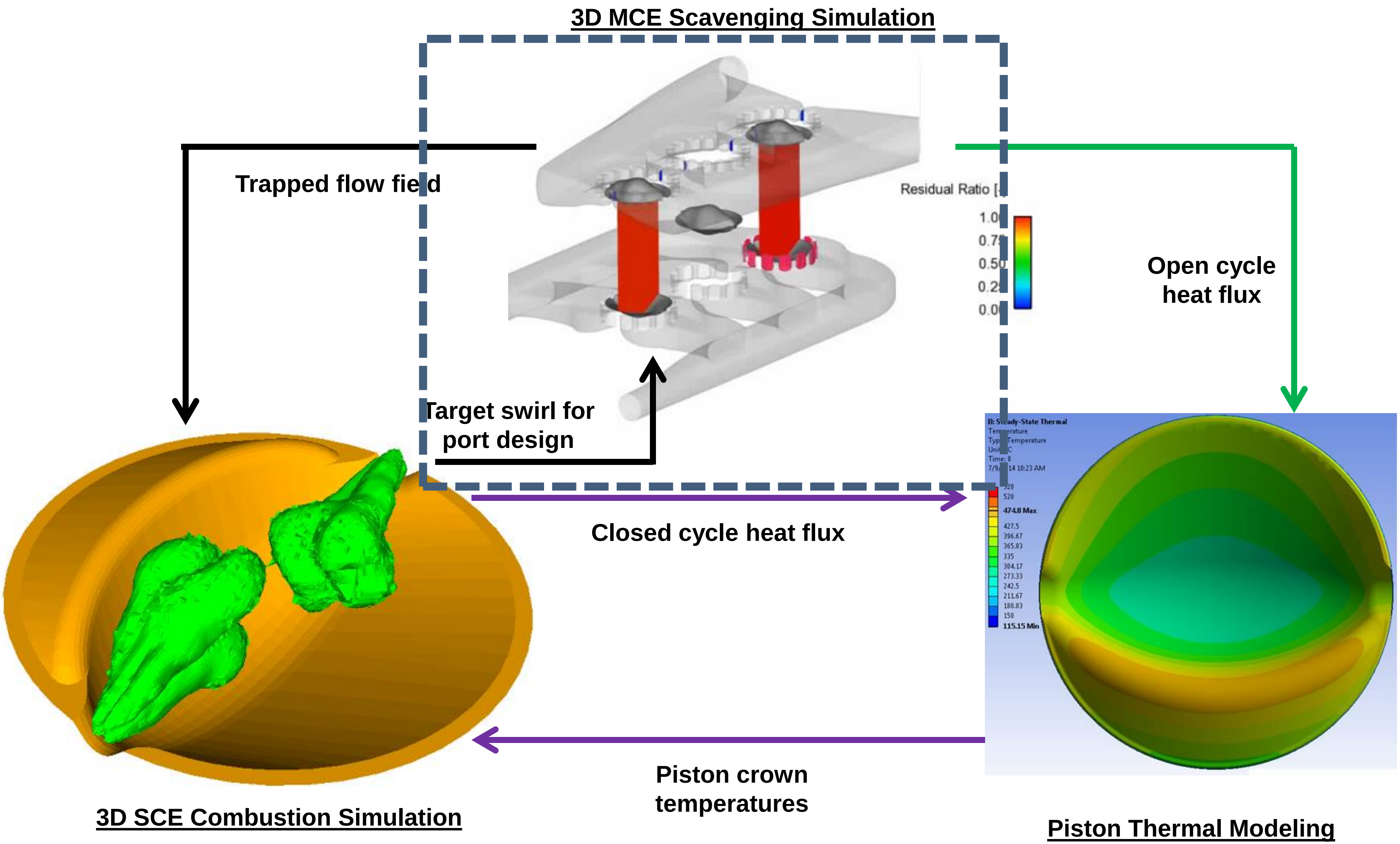
Achates Combustion System Design Process



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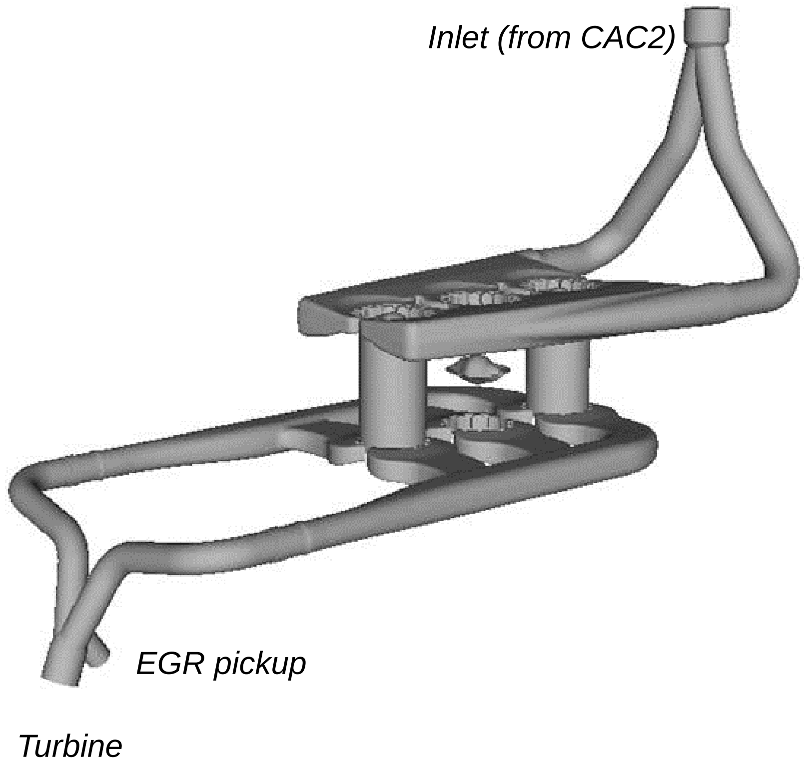
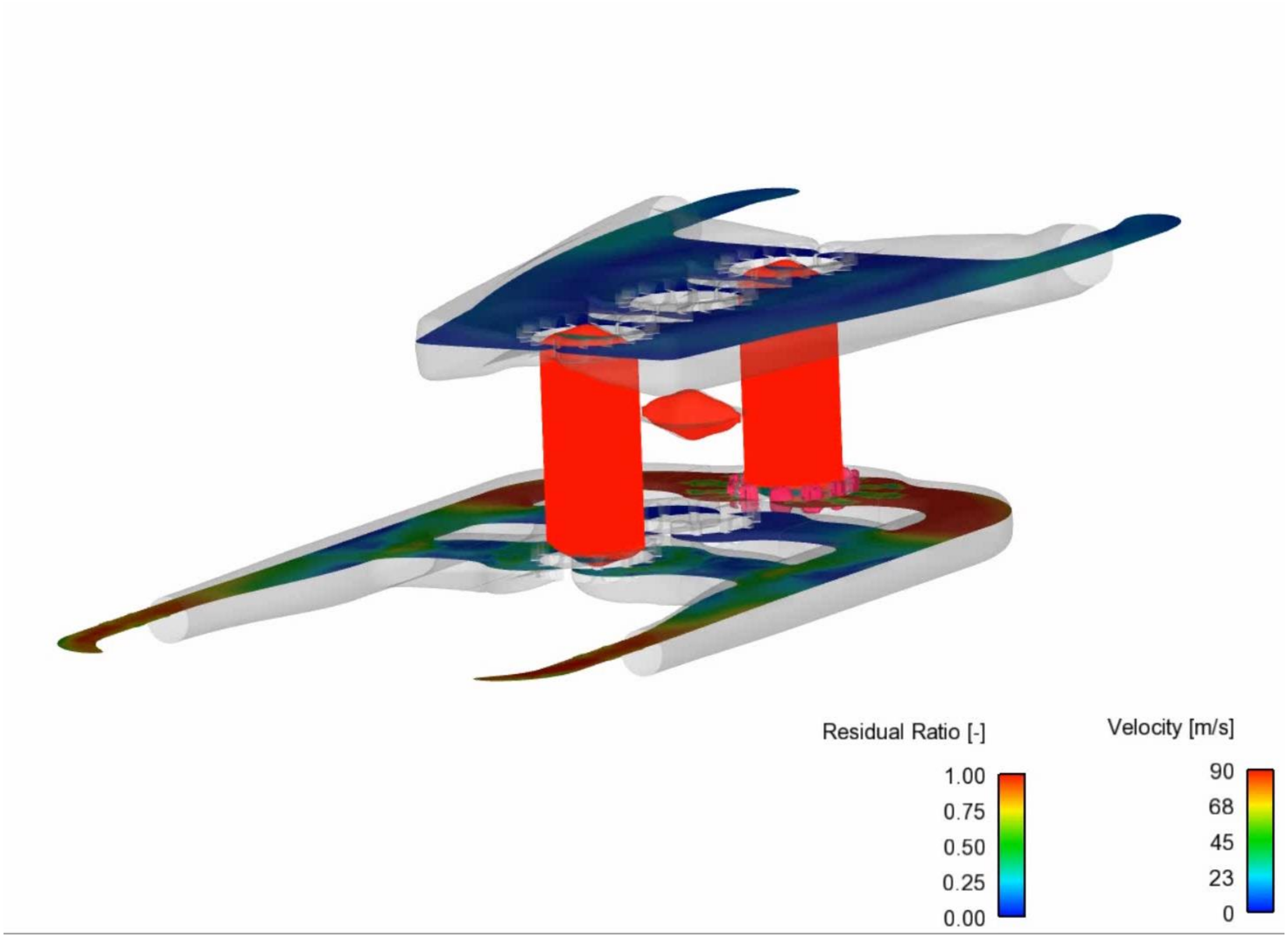
Multi-cylinder Scavenging Simulations

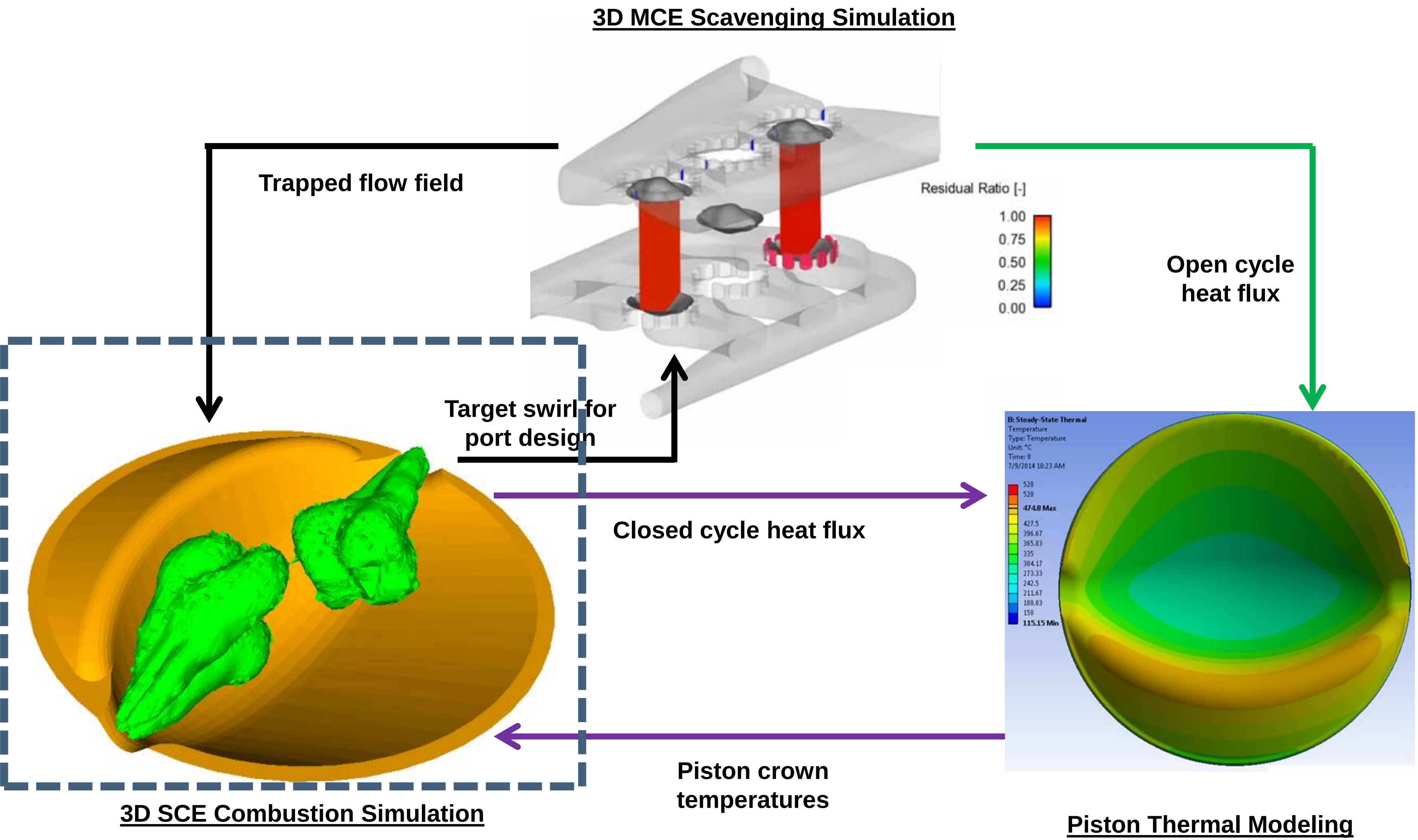
- 3-cylinder simulations with imposed source heat to match cylinder pressure trace.
- Entire length of intake and exhaust runners modeled to accurately capture wave dynamics.
- Model size ~800,000, typically 16 cores, 5-6 days wall time for 3 consecutive cycles.
- Multiple operating points simulated.
- Provide trapped flowfields for in-cylinder combustion simulations.
- *HPC can enable 3-cylinder simulations with detailed chemistry.*



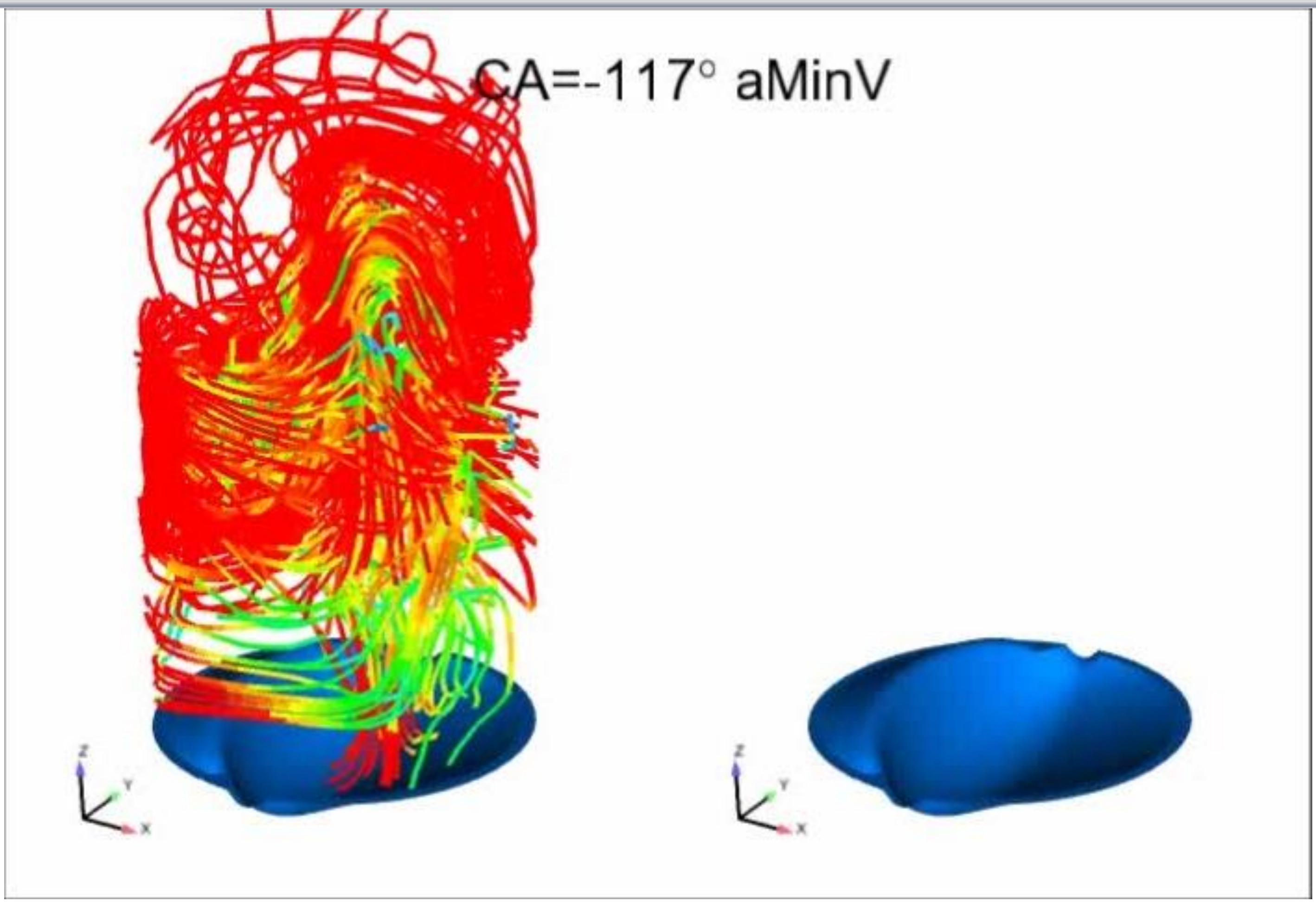
Multi-cylinder Scavenging: Rated Power



Achates Combustion System Design Process

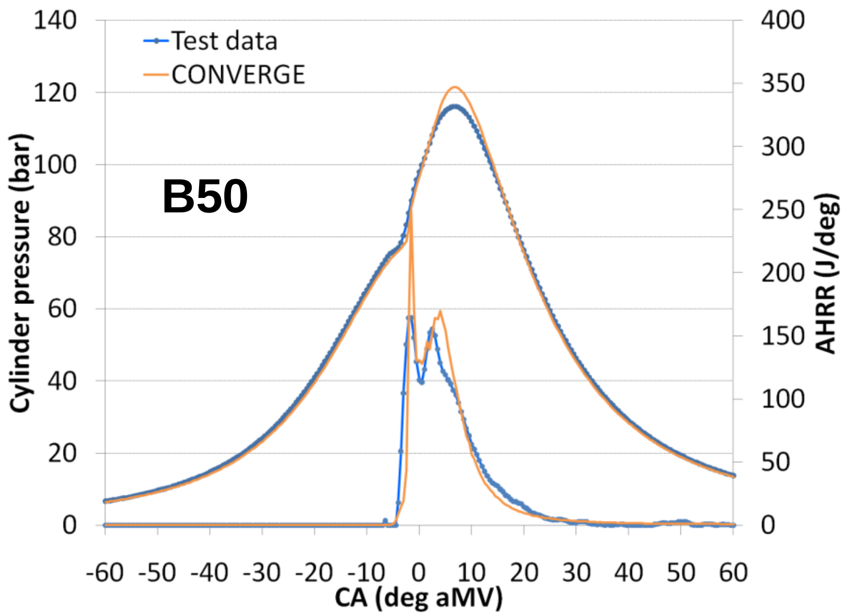


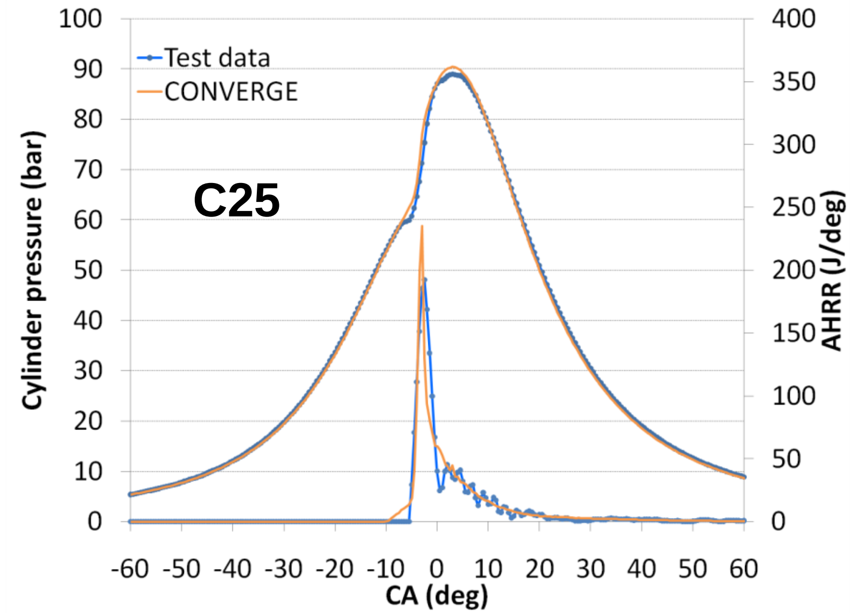
Single-cylinder combustion simulations

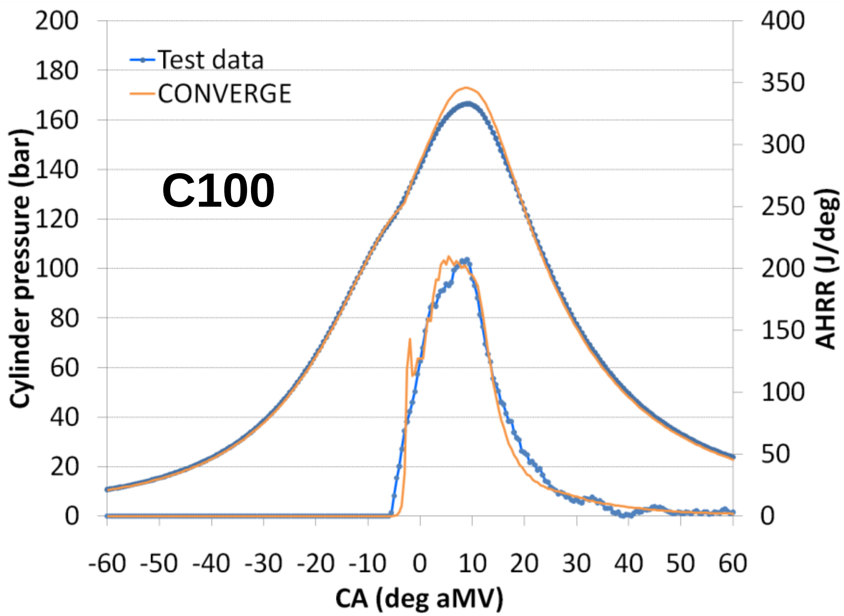


- CONVERGE detailed chemistry model, state-of-the-art spray breakup and atomization models.
- Typical model size (100,000-250,000), typically run with 8 cores.

Single-cylinder combustion: multi-mode correlation







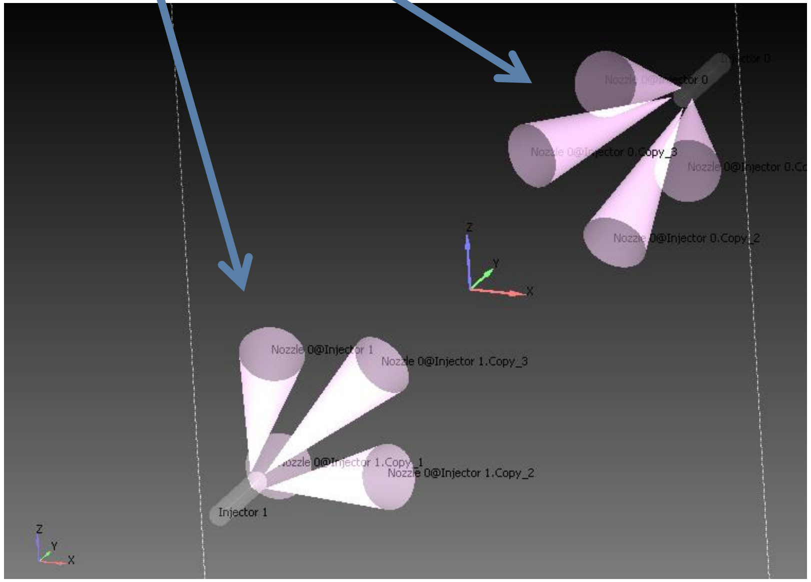
- Strong emphasis on multi-mode correlated models (up to 9 modes).
- Allows exploration of multiple modes for combustion hardware optimization.
- *HPC can enable multimode combustion optimization.*

Combustion Optimization: Genetic Algorithms

Independent variable
Hole size for top injector
Hole size for bottom injector
Spray angle for top injector
Spray angle for bottom injector
Number of holes for top injector
Number of holes for bottom injector
Swirl ratio

- 32 cores, 2 weeks model setup and calibration time, 2 weeks run time.
- 300+ designs simulated

Each injector of the twin injector configuration is uniquely optimized (for a piston bowl shape and operating condition)



$$Merit = C_1\,(CCW) - C_2\,\big(fn(Piston\_hot\_spot\_area)\big)$$

Performance term

Piston thermal management term

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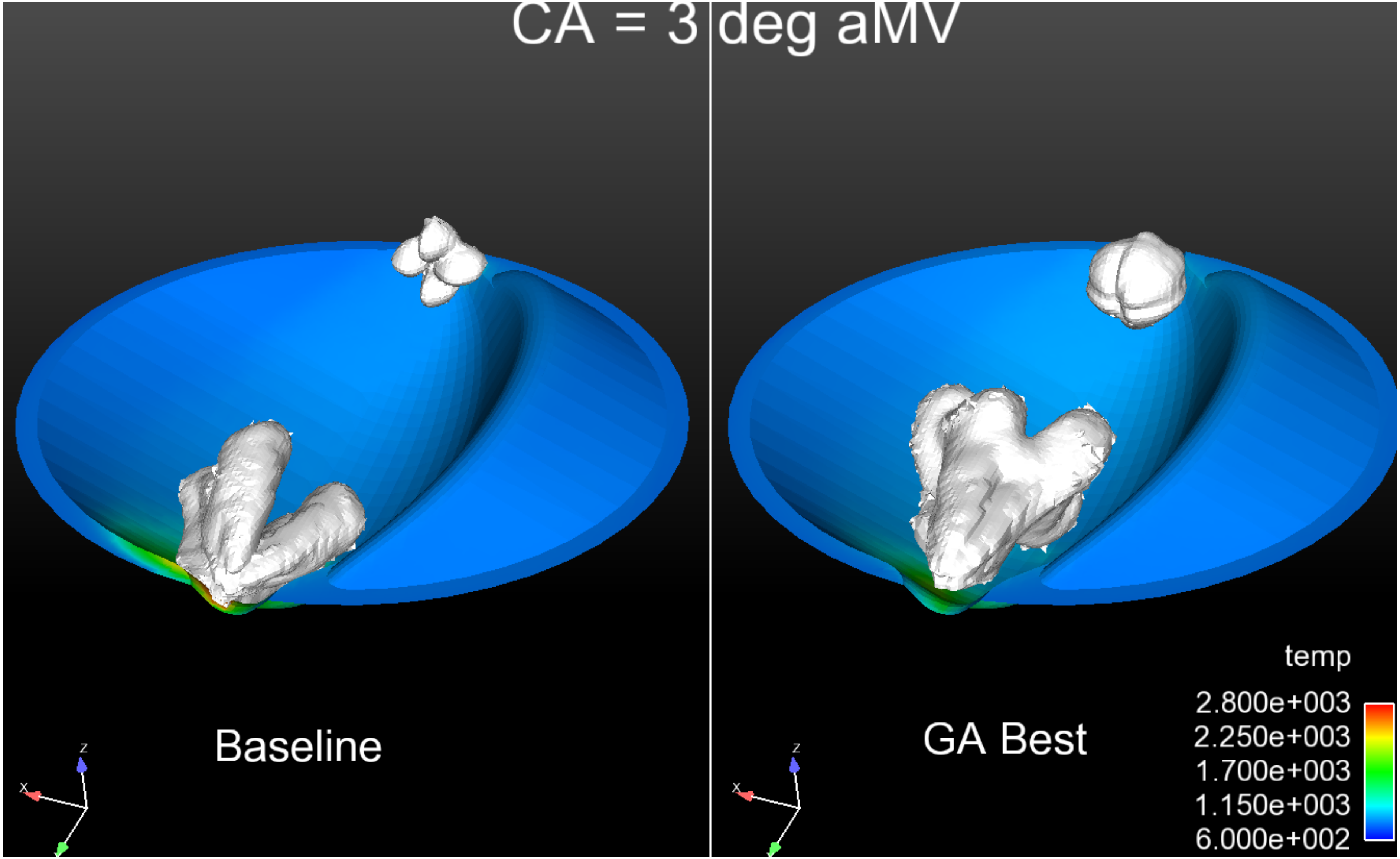
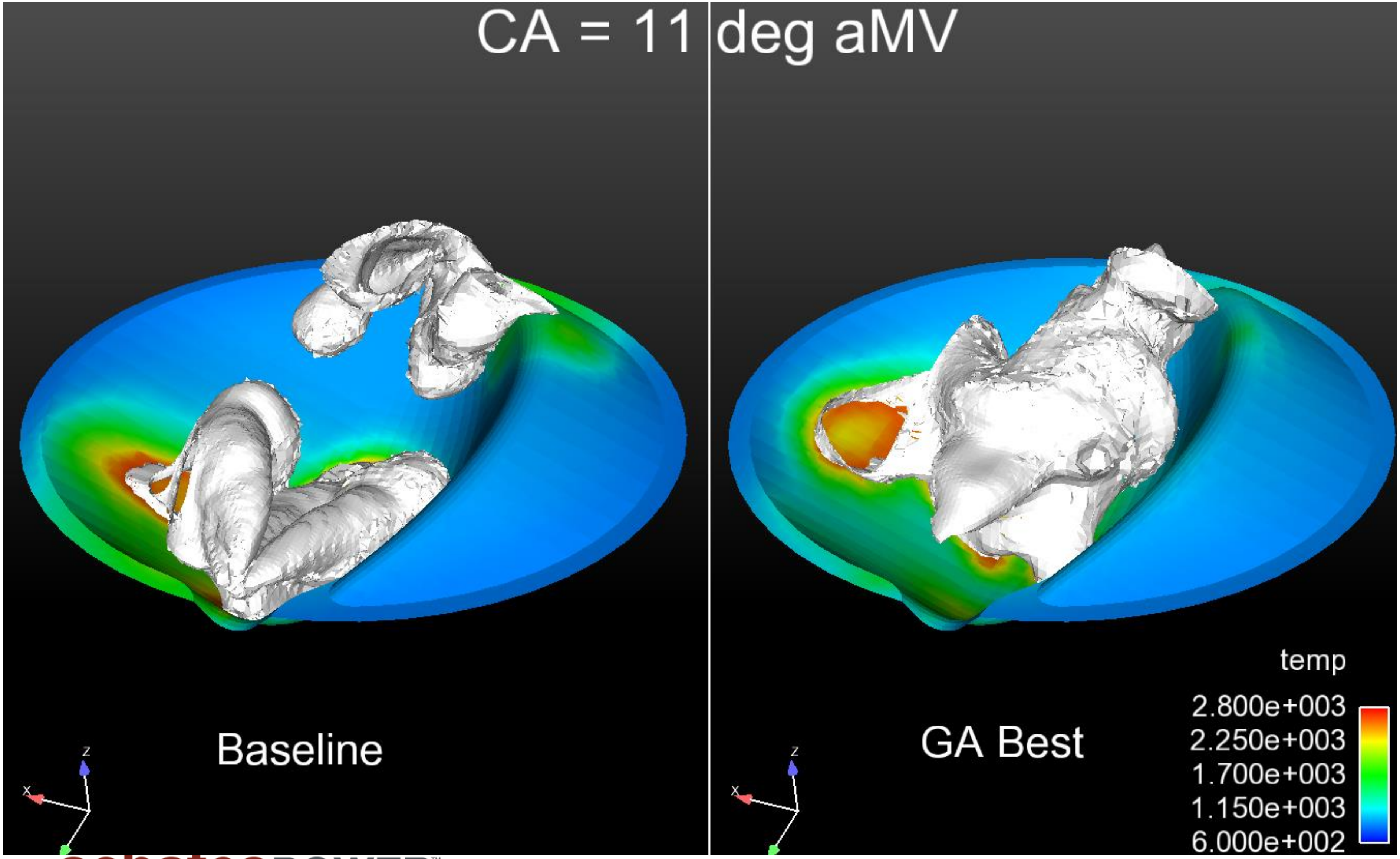
Combustion Optimization: Genetic Algorithms



Combustion Optimization: Genetic Algorithms



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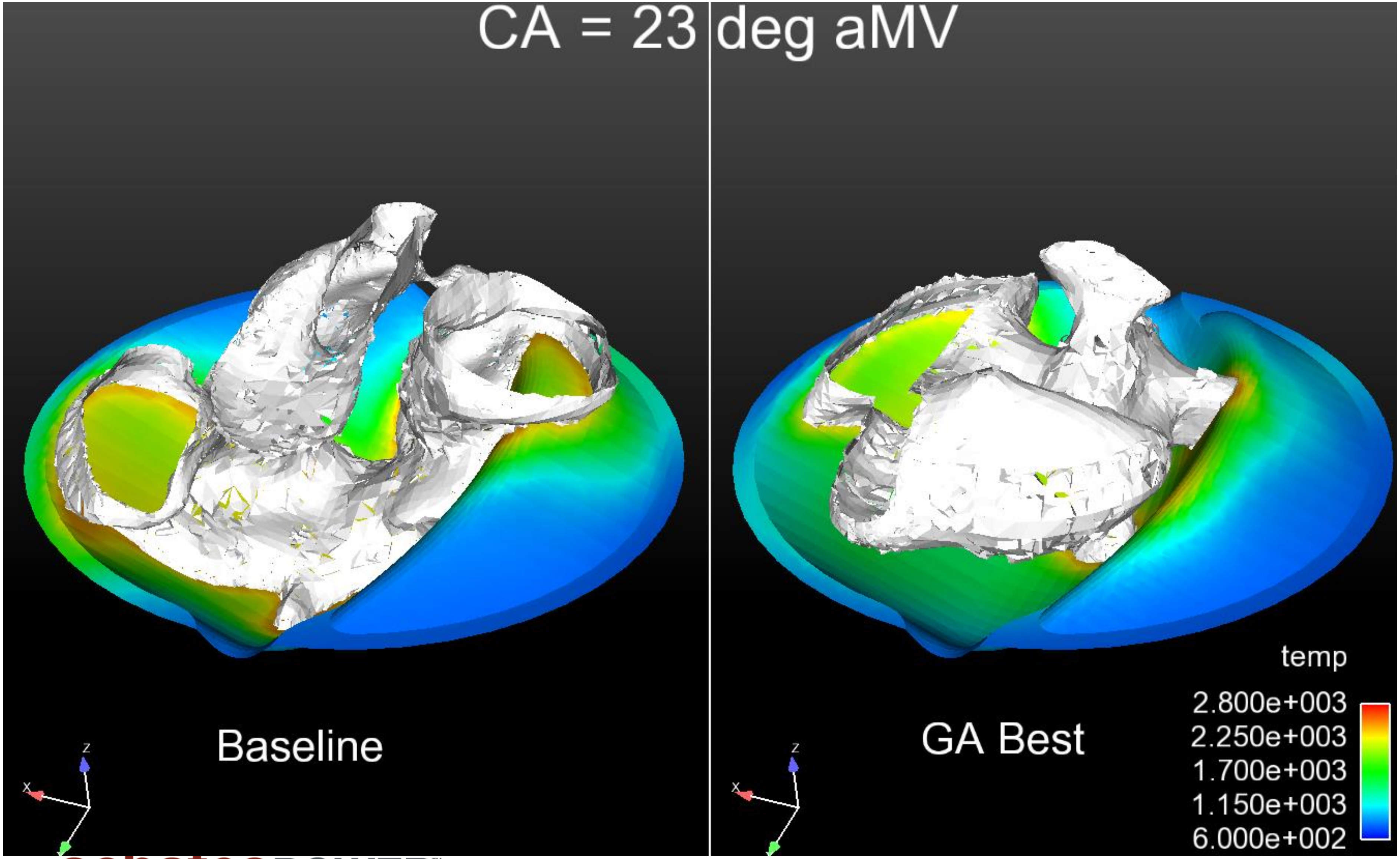
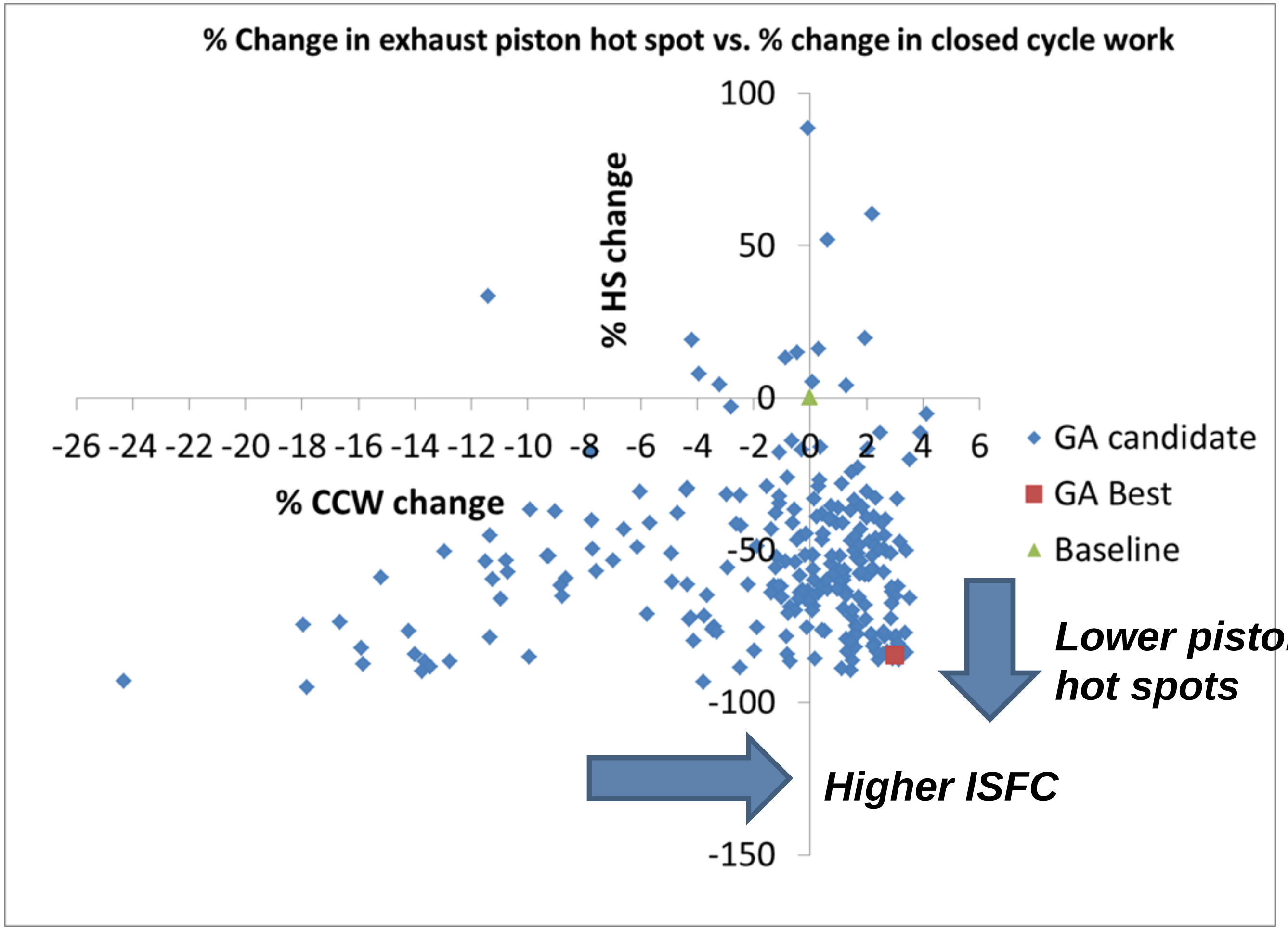
Combustion Optimization: Genetic Algorithms



Combustion Optimization: Genetic Algorithms



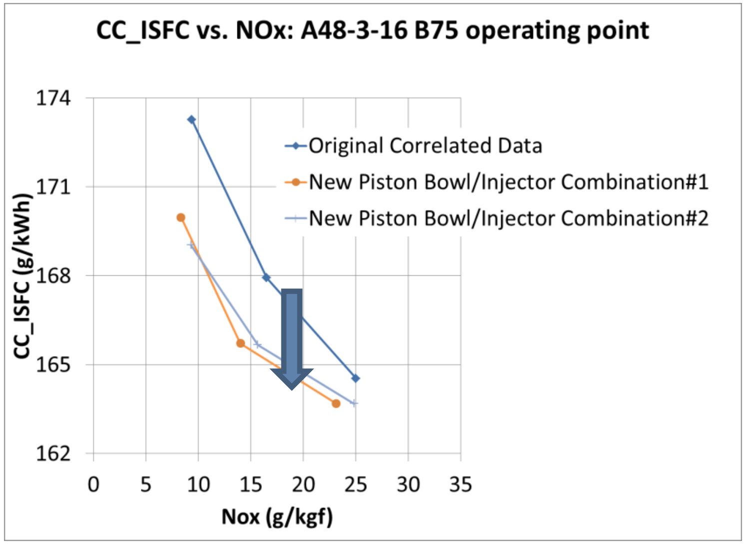
- *GA best achieves a significant reduction in the exhaust piston hot spot area (weighted average of lip and overall piston) along with an increase in closed cycle work.*

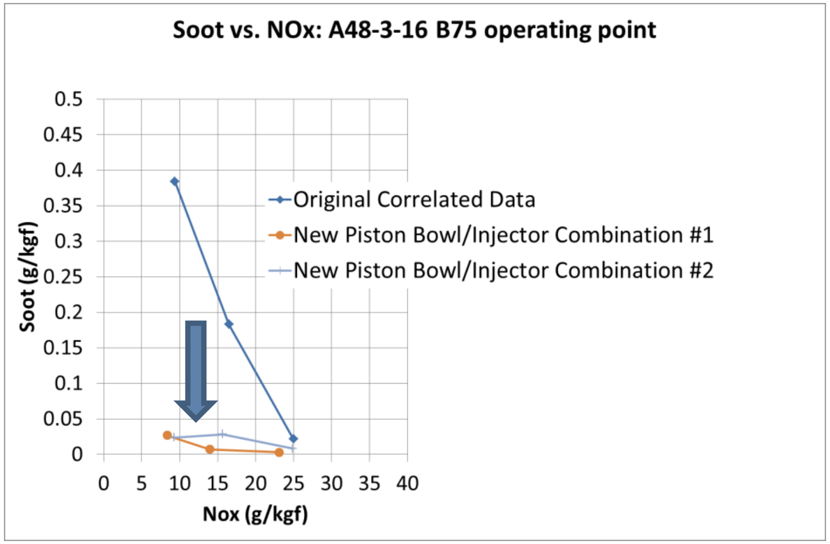
Combustion Optimization: Design of Experiments

DOE Structure

Lever	# levels
Bowl shape	18
SOI	3 (-10, -7, -4 degrees aMV)
Spray angle	2 (17.5 degree, 20.5 degree)
# Holes	2 (3-hole and 4-hole)
Total # cases, run time	**216 cases**, **16 cores**, **8 days**

- About 8 days of wall time per operating point.
- Spot checks of optimized hardware at multiple operating points.





Significant improvements in performance and emissions tradeoffs achieved at multiple operating points

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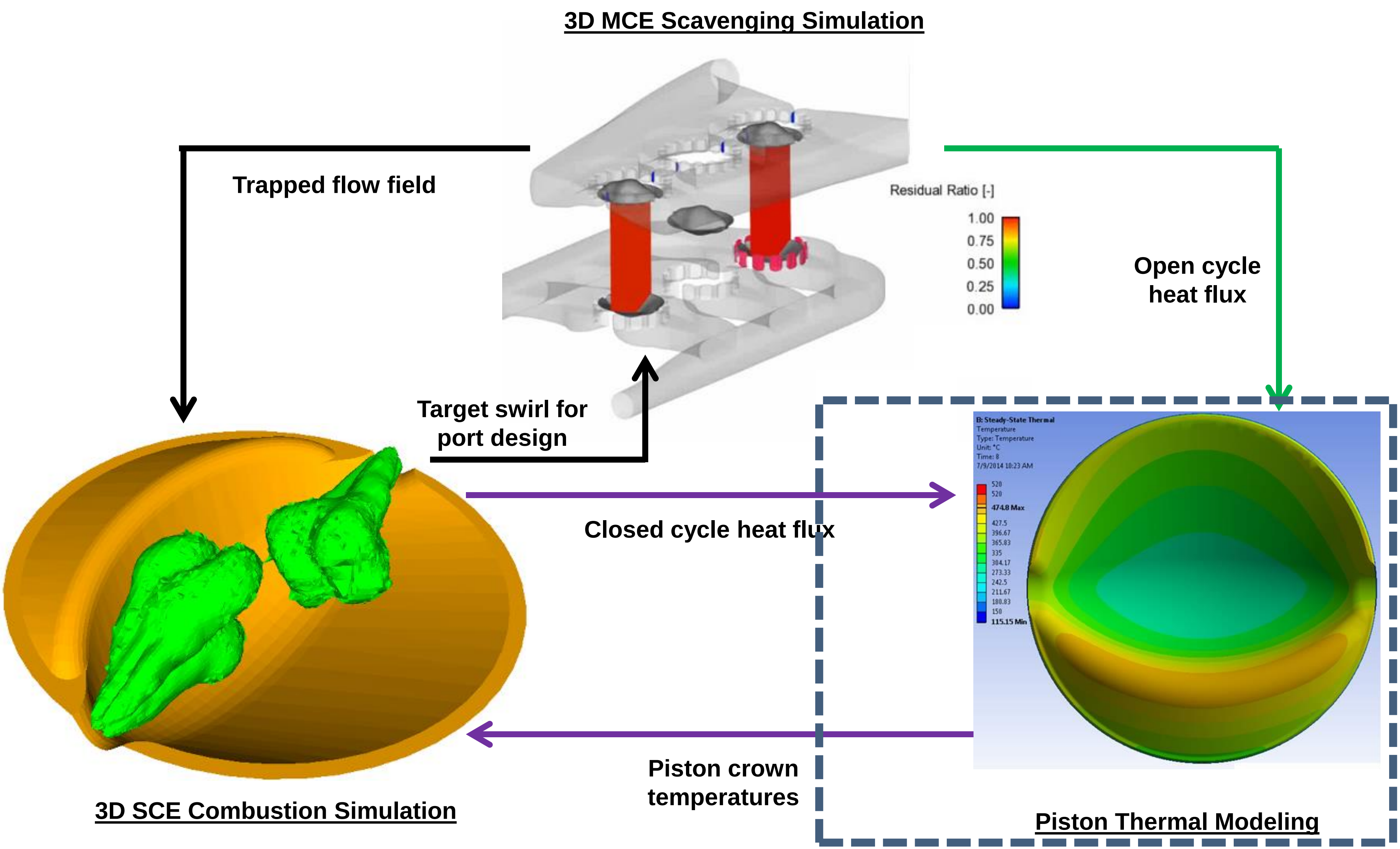
Achates Combustion System Design Process



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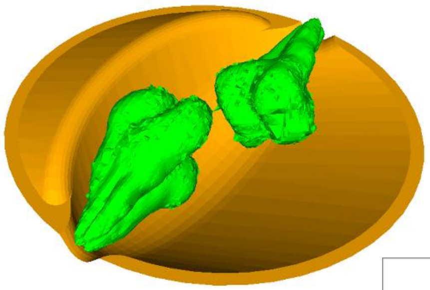
Piston Thermal Modeling Methodology

Spatially-resolved heat flux

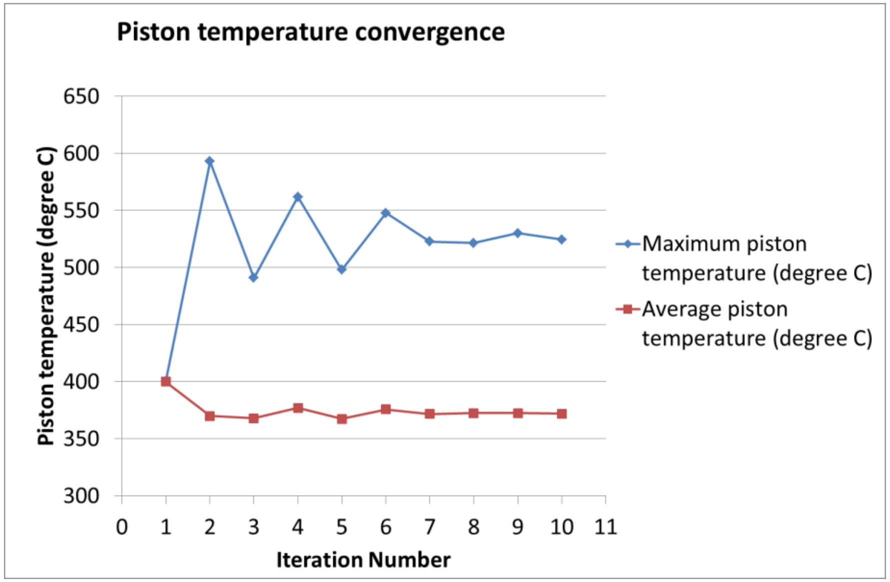
Iterative process

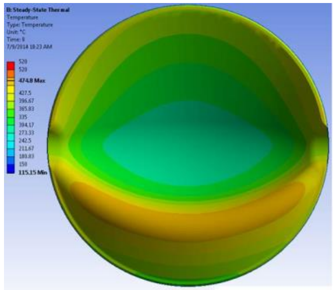
Spatially-resolved temperatures



3D CFD Simulations

- Transient simulations of the open and closed cycles in CONVERGE.
- Accounts for the influence of trapped conditions, spray patterns and bowl shapes.
- Provides spatially-resolved and time-averaged heat flux on the piston crown.



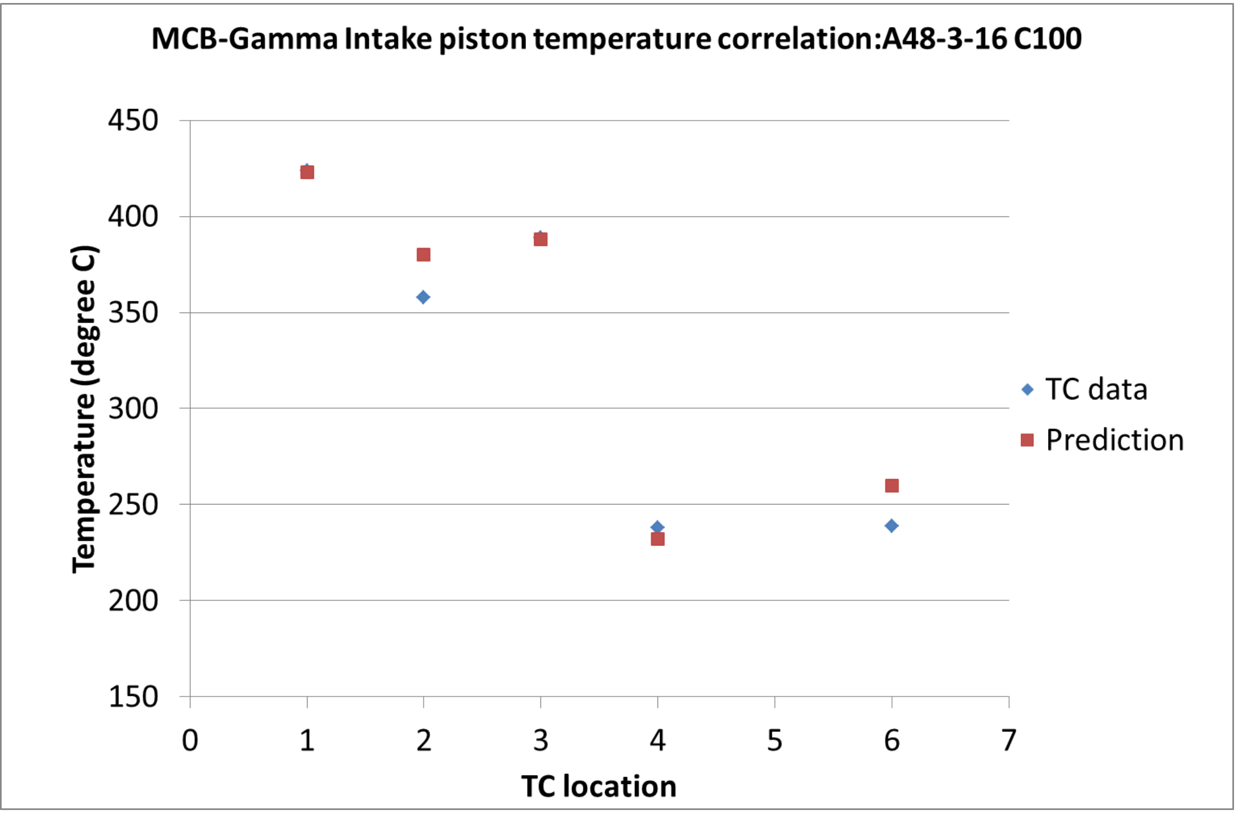


Steady State Thermal Modeling

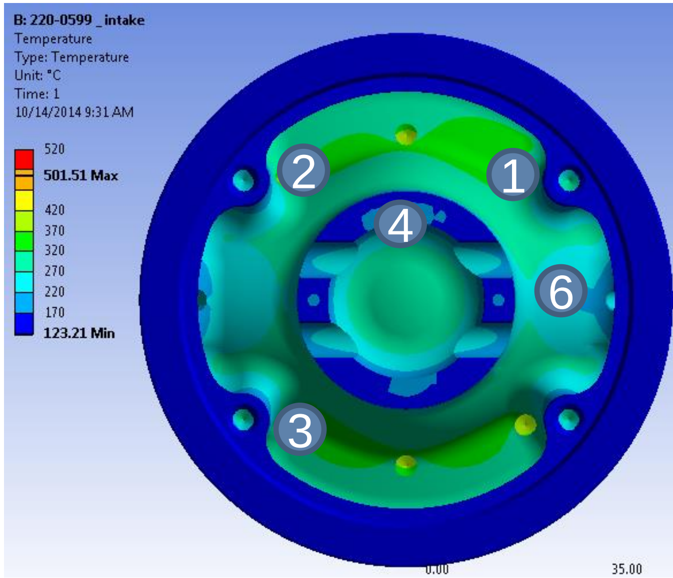
- Steady-state piston thermal modeling in ANSYS.
- Detailed cooling gallery modeled.
- Spatially-resolved hot side heat flux.
- Cold-side heat transfer coefficients imposed on all the surfaces; no CFD of oil flow to save computational time.

- Not doing CFD on the cold-side results in significant computational time savings.
- Simplified approach above yields reasonable accuracy and predictive capability.
- CONVERGE's super-cycling feature (v2.2) currently under exploration.
- *HPC can enable full-blown CHT for piston thermal modeling.*

Piston Thermal Model Correlation



Thermocouple locations on the Intake piston



- Model predicts temperatures at the thermocouple locations reasonably well.
- The piston thermal model is applied predictively to investigate effects of calibration levers, injection patterns and bowl shapes on piston thermal management.

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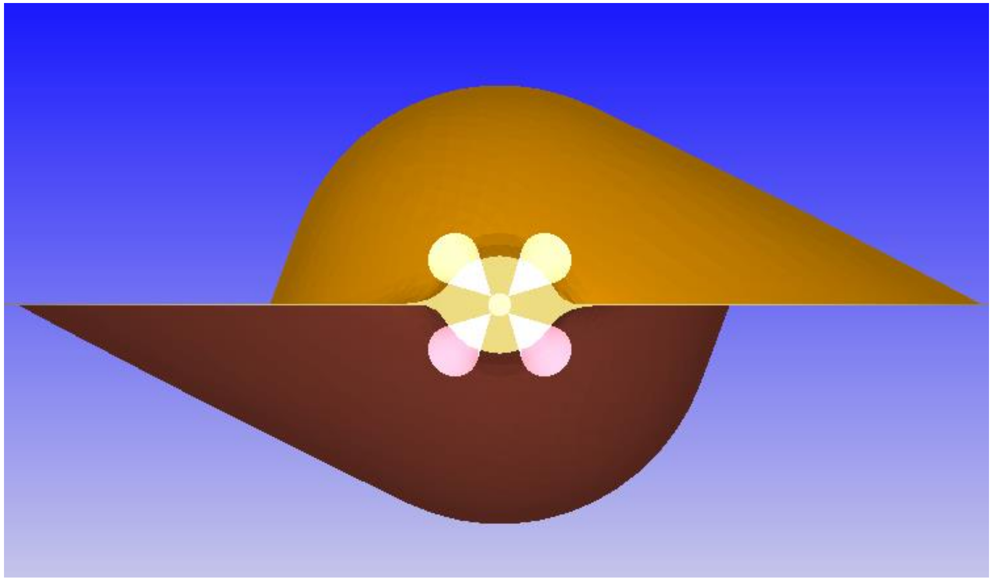
HPC for OP Combustion Optimization



For an OPE, open and closed cycles are <u>very strongly coupled</u> and result in a very large optimization space
Need for <u>fully coupled optimization</u> to optimize ports and combustion system for optimum performance, emissions and thermal management

Optimization design levers

- **Ports** – port shape and vane angles ~ *10 independent parameters*
- **Bowl shape** parameters (features, aspect ratio) *~ at least 3 independent parameters*
- **Spray parameters** – spray angle, hole size, hole number, clocking angle *for each injector ~ at least 8 independent parameters*
- **Total of at least 21 independent Hardware parameters.**

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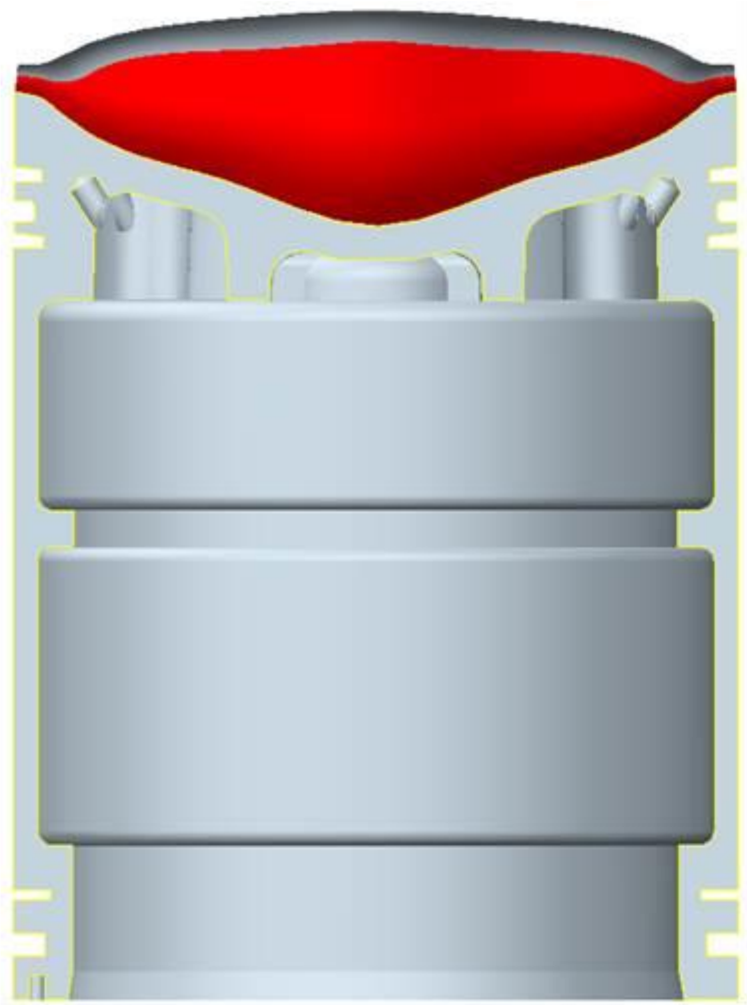
HPC for OP Conjugate Heat Transfer



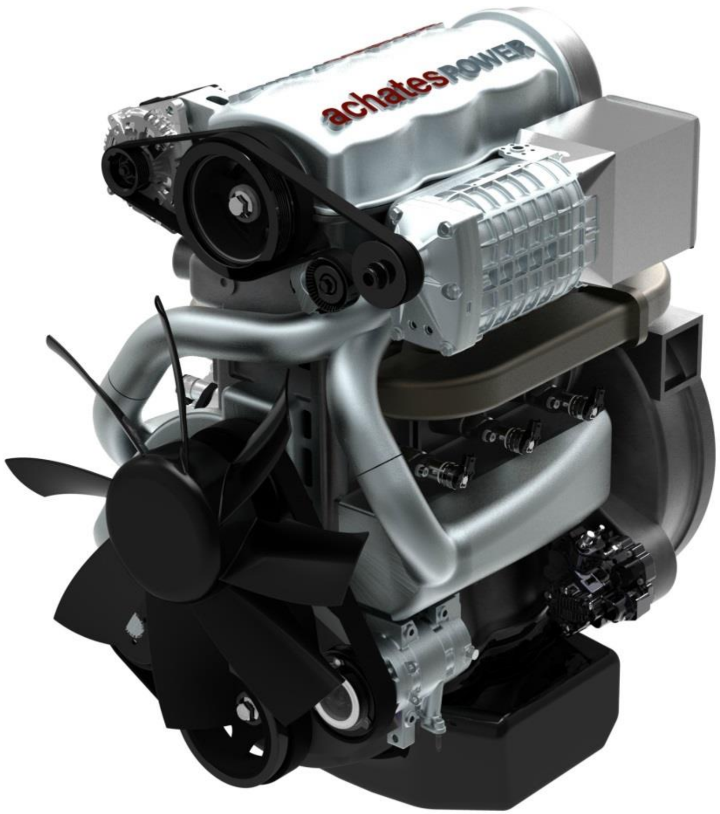
Piston Thermal Management Levers

- **Hot-side:**
  - Piston bowl geometry
  - Injection and spray parameters
  - Charge motion – swirl/tumble ratio
  - Calibration – SOI, Rail Pressure, A/F, EGR
- **Cold-side:**
  - Gallery size and shape parameters
  - Gallery fill ratio
  - Impingement jet cooling parameters
  - Inlet and outlet hole sizes

HPC can enable a DOE of CHT simulations to build a piston thermal modeling database for simpler uncoupled approaches

Summary

- Achates Power is employing state-of-the-art CFD / CAE tools to predictively design and develop *highly efficient*, *clean* and *durable* opposed-piston engines.
- The *high degree of design flexibility* of OP combustion systems presents unique opportunities for HPC applications.



Thank You

Acknowledgements

CFD Team

Leadership Team

Securing America's Future Energy

Energy Security Prize - First Runner-Up 2013

Bloomberg Businessweek

25 Companies to Watch in Energy Tech

FROST & SULLIVAN 2013 BEST PRACTICES AWARD

NORTH AMERICAN MEDIUM AND HEAVY-DUTY COMMERCIAL VEHICLES NEW PRODUCT INNOVATION AWARD

Global Cleantech '09 100

AlwaysOn GOINGGREEN GGSV 200 WINNER

CONNECT MOST 2013 INNOVATIVE NEW 26th annual PRODUCT AWARDS WINNER

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