Enabling the Next Generation of High Efficiency Engines

Opportunities and challenges of new technologies and an ever expanding parameter space

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Meeting new U.S. fuel economy standards and CO₂ regulations will require significant *production viable* advances in technology.

An International Challenge: Current and future CO₂ regulations in many countries similar to or more stringent than those in the U.S.

* Spread is due to range in standards for small/large passenger and light-duty truck.
Must also simultaneously meet evolving emissions standards

• CO₂ and criteria emissions standards vary around the world but all becoming increasingly aggressive

• New technology approaches to meet CO₂/efficiency regulations may have unintended emissions consequences
  – Higher efficiency engines have lower exhaust temperatures which will be a major challenge for aftertreatment systems
  – Gasoline-based particulate matter now a concern with gasoline direct-injection systems
  – Must be aware of potential “new” exhaust species (from combustion or emissions controls) in sufficient concentrations to be a new health issue

• Requires systems approach to maximize efficiency with lowest possible emissions and minimum cost
Major challenge is the implementation of fundamental innovations with minimal loss in translation

**Fundamental combustion**
*Metric: Indicated efficiency*
- Pressure work only
- Simulated boundaries

**Engine-system**
*Metric: Brake (shaft) efficiency*
- Hardware limitations
- Parasitic losses
- Friction
- Engine-system controls
- Cylinder imbalances
- Aftertreatment integration

**Full vehicle**
*Metric: Drive cycle efficiency*
- Drive system
- Fuel mix
- Drive cycle mismatch
- Vehicle system management
Many high efficiency engine concepts historically limited by the state of technology

- **Direct Injection Spark Ignition**

- **Low Temperature Combustion**

- **Dual-fuel Combustion**
Technology advances leading to a paradigm shift in engine management

- **Component development**
  - Robust and fast response turbomachinery
  - Flexible intake and/or exhaust valve systems
  - Variable compression ratio
  - Flexible fast-acting fuel injection systems
  - High pressure direct-injection fuel systems
  - Advanced ignition technologies

- **Sensor development**
  - High-speed pressure and temperature
  - Onboard emissions diagnostics

- **ECU development**
  - New, faster architectures
  - Combustion feedback
  - Ability to solve complex problems on-the-fly

**TAKEAWAY:** Unprecedented opportunities in combustion strategy and controls
Options no longer limited to conventional SI and CI combustion

- More optimal combustion for highest efficiency
  - More rapid energy release
  - Reduction in heat transfer losses
  - Reduction in NOx and soot emissions – less aftertreatment to meet emissions regulations

- New opportunities for control
  - Pushing edge of stability
  - Prediction and avoidance
  - Self-learning

- Technology development on track for more widespread production use of advanced combustion
Regardless of approach – end game objective is to maximize efficiency with lowest possible emissions

Need to manage the combustion process to avoid soot and NOx formation ...

...while at the same time avoid CO and UHC emissions

Charge must end up in this region after combustion is complete

Slide adapted from DOE presentation, Gurpreet Singh et al.
**Example:** Reactivity Controlled Compression Ignition (RCCI) combustion

- **In-cylinder fuel blending enables improved control of premixed combustion event**
  - Two fuels with different reactivity (e.g., gasoline and diesel) to form in-cylinder reactivity gradients

- **Benefits**
  - Diesel-like or higher brake thermal efficiency
  - Low NOx and particulate emissions (less aftertreatment requirements)

- **Multi-cylinder engine challenges**
  - Two fuel systems with precise control
  - High dilution (for some conditions)
  - Precise control of intake conditions
  - Combustion feedback control
  - ....

**Figure Source:** Sandia National Laboratories, “Optical Engine Research Rapidly Reveals How High-Efficiency RCCI Combustion Controls Burning Rates”, U.S. DRIVE Highlights of Technical Accomplishments 2011.

**For more information:**
New control opportunities: Previous observations of structure in cyclic dispersion once thought of as academic curiosities

- **Lean Combustion Limit**

- **HCCI Instabilities**

*Simulation example of cycle-to-cycle variations for lean-burn SI combustion*

*Repeating patterns observed near the stability limit of spark assisted HCCI combustion*
Opportunity is through the prediction and control for the forced stabilization of inherently unstable systems

- Stability potential roadblock to many advanced combustion implementations
- Current approach is distance from the edge of stability to avoid unintended excursions
- Driven by stochastic (in-cylinder variations) and deterministic (cycle-to-cycle coupling) processes
- Further complicated by cylinder imbalances

**TAKEAWAY:** Dynamic instabilities are short-term predictable and conducive to control

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Stable Combustion

Transition Region

“Safe” Operation

Acceptable Cyclic Dispersion  Unstable  Complete Misfire

“Edge of Stability”
Understanding of instability mechanisms coupled with advances in sensors and ECUs will enable unprecedented control opportunities

- **Operation near the “edge of stability”**
  - Avoid unintended excursions which may damage or destroy engine and aftertreatment systems
  - Example showing the “edge of stability” for lean burn SI combustion

- **Transition and stabilization of LTC modes**
  - Multi-mode operation may require transition between combustion modes
  - Operation under inherently unstable conditions may provide benefits
  - Example of complex but short-term predictable patterns in spark assisted HCCI combustion

- **Avoiding abnormal combustion events**
  - Pre-ignition potential roadblock to extreme down-sizing
  - Advanced time-series methods used for prediction and avoidance
  - Example phase-space reconstruction which is one method that has potential for prediction and avoidance of abnormal combustion events
Parameter space is growing rapidly and expected to continue to grow

- **Challenge**
  - Conventional design methods may not be possible for optimal solution
  - Massive calibration space is difficult to manage

- **Opportunity**
  - Enable new high efficiency combustion strategies for real-world applications
  - Improved fuel flexibility – ability to make use of a more diverse fuel supply?

**TAKEAWAY:** On path to fully own the engine for new levels of optimization

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**Source:** Adapted from Atkinson et al., DEER 2011.
Better simulation is critical to engine design and calibration optimization

- **Three levels of simulation with different purposes**
  - **Predictive combustion:** combustion optimization and methods development
  - **Full engine simulation:** engine system optimization and model-based controls
  - **Full vehicle simulation:** technology interactions, component optimization and supervisory controls

- **Each scale requires different level of fidelity**
  - High fidelity combustion on vehicle scales computationally impossible (at the moment)

- **Exponential increase in parameter space translates to exponential increase in simulation space and computational requirements**

**TAKEAWAY:** Need for faster simulation, faster optimization methods, and reduced models for on-board controls
Leadership High Performance Computing* (HPC) has potential to accelerate design and development at an unprecedented scale

- ORNL applying unique combination of engine and catalysis expertise with world-class HPC expertise to address design and engineering challenges

- Example ORNL projects in progress with industry
  - **Large Infrastructure computing for Multi-cycle Instability and Transient Simulations** (LIMITS)
    - Addresses limits of fuel economy benefit of dilute combustion
    - Focus on stochastic and deterministic processes that drive cycle-to-cycle instabilities
    - Major challenge is scaling serial problem (cycle-to-cycle variations) to parallel architecture
  - **Injector design optimization**
    - Improve understanding and design optimization of fuel injector hole patterns for improved engine efficiency and reduced emissions


*Leadership HPC: DOE provides a portfolio of national high-performance computing facilities housing some of the world’s most advanced supercomputers.*
HPC speeds will increase 1000x over the next decade

**ORNLS Leadership Computing Roadmap**

- **Leadership technology of today provides foundation for desktop computers and small clusters of tomorrow**

- **Interesting factoids:**
  - Current laptop technology would have ranked in top 500 supercomputers of the late 1990s
  - System at bottom of current top 500 list equivalent to aggregate of all machines on 1999 list
  - An iPad 2 would have made the early lists of the top 500 machines in the world

*PF = Petaflop = 1 quadrillion floating point operations/second; EF = Exaflop = 1 quintillion floating point operations/second

**OLCF = Oak Ridge Leadership Computing Facility**
HPC challenges and opportunities going forward

- Improved large scale modeling and simulation is critical to addressing evolving science and engineering problems to make the most of advances in engine and catalyst technologies

- Resources becoming more readily available
  - HPC technology continues developing at fast pace
  - Multi-core systems now readily available and affordable
  - New hybrid architectures are combining traditional CPUs with GPUs to deliver new capabilities

- Major challenge is many simulation codes not ready for large scale parallel and/or hybrid architectures

- Large scale simulation critical to understanding and developing reduced models for small clusters and eventually onboard computers

Jaguar, a Cray XK6 supercomputer housed at ORNL is a DOE flagship supercomputer and one of the fastest in the world for unclassified research
Takeaways

- Engines are undergoing a paradigm shift in flexibility
- New control opportunities will push the boundaries of high efficiency operation
- New approaches to calibration will be necessary for optimization of the next generation of engines
- Predictive simulation is essential for optimal design and controls
- HPC is available and should be considered when developing new models and simulation codes
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