Detailed Modeling of HCCI and PCCI combustion and Multi-cylinder HCCI Engine Control

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We have developed and continue to improve the most advanced analysis tools for HCCI combustion

Through our collaborations we have applied these tools to a wide variety of industrially significant questions:

- What effect does turbulence have on HCCI combustion?
  - Completed study of Lund TD100 engine for low turbulence geometry, now conducting simulations on high turbulence geometry
- What are the low load limits to HCCI operation?
  - Study of HCCI low-load operation limits in Sandia engine
- Does mixing affect CO emissions in HCCI combustion?
  - Extended multi-zone model includes mixing effects – framework for general tool to analyze of HCCI, PCCI, SCCI
  - Analyzed post-combustion mixing and CO formation in HCCI engine

Our detailed chemical kinetics codes and optimization software guide our experimental control efforts

- **What control methods are viable for multi-cylinder HCCI engines?**
  - Designed and tested a generic control system for internal EGR control of cylinder by cylinder variation in 4-cylinder engine
  - Implementing closed loop feedback control for cylinder-by-cylinder phase balancing

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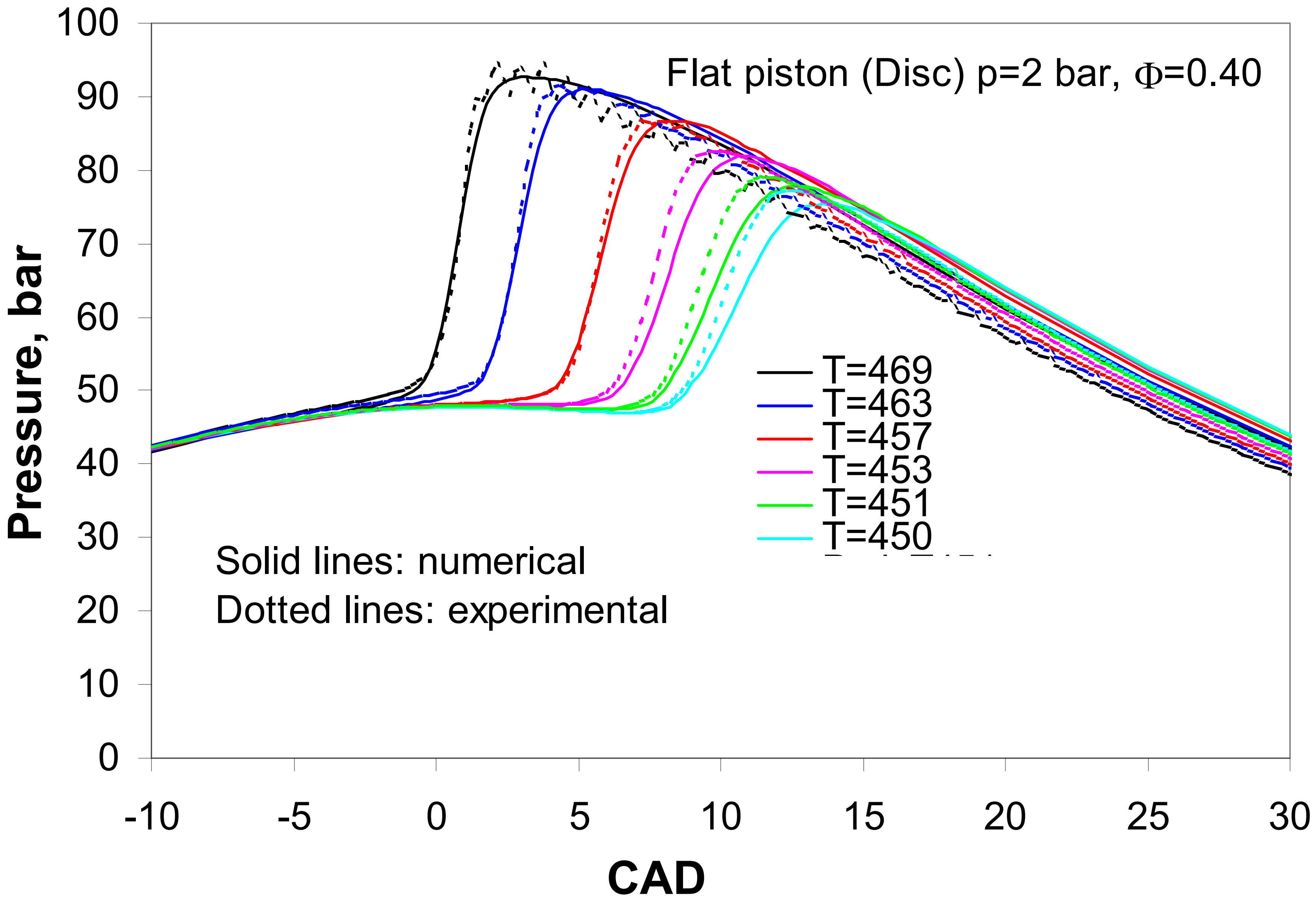
What is the role of turbulence in HCCI engines?

- Lund Institute studied HCCI operation in high and low turbulence engines
- These experiments showed that burn durations in higher turbulence configuration were significantly longer
- Debate raised about turbulence influence on the ignition process
- We conjecture that chemistry timescales are far too rapid to be affected by local turbulence timescales

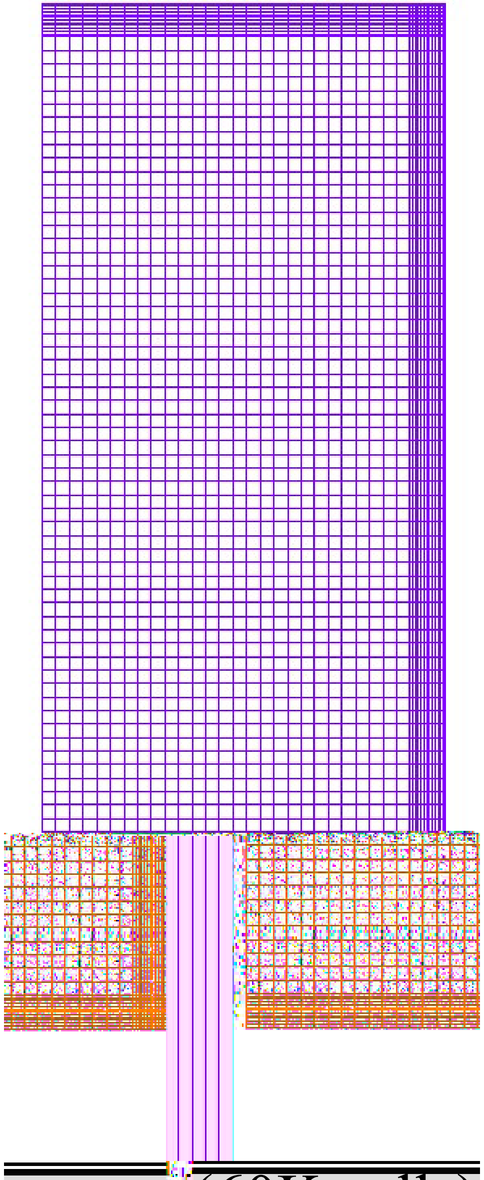
Lower turbulence piston crown

Higher turbulence piston crown

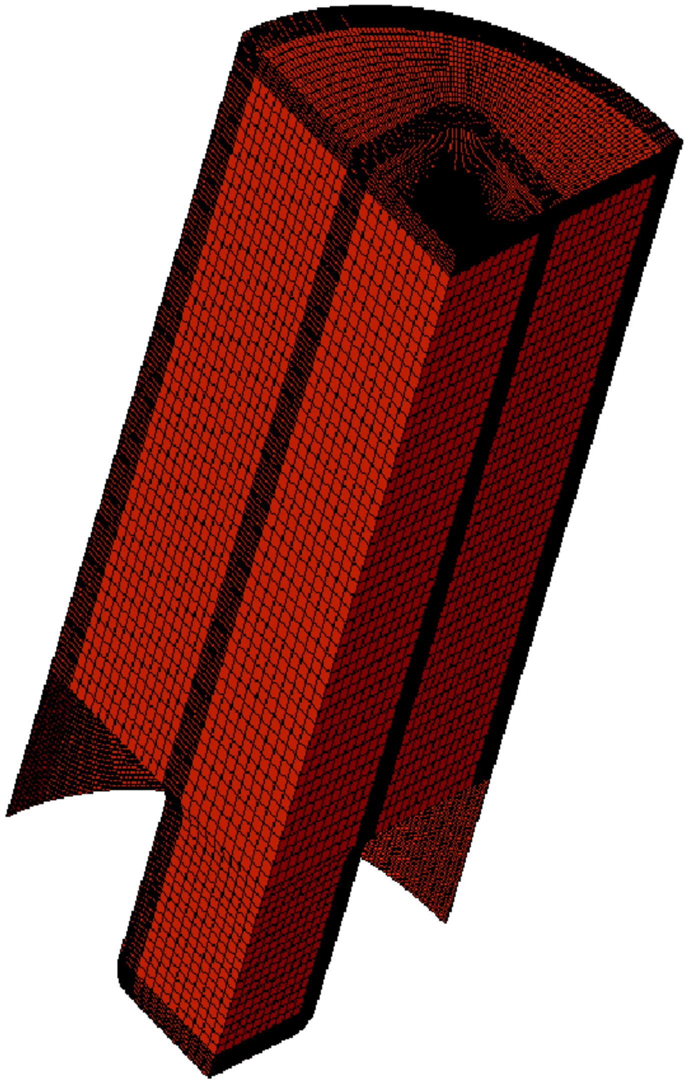
We have completed simulations with the flat-top (lower turbulence) geometry that agree very well with experiments



Simulations have been completed for the low turbulence case, high turbulence case is in progress



Flat crown (60K cells)



Square Bowl Crown (400K cells)

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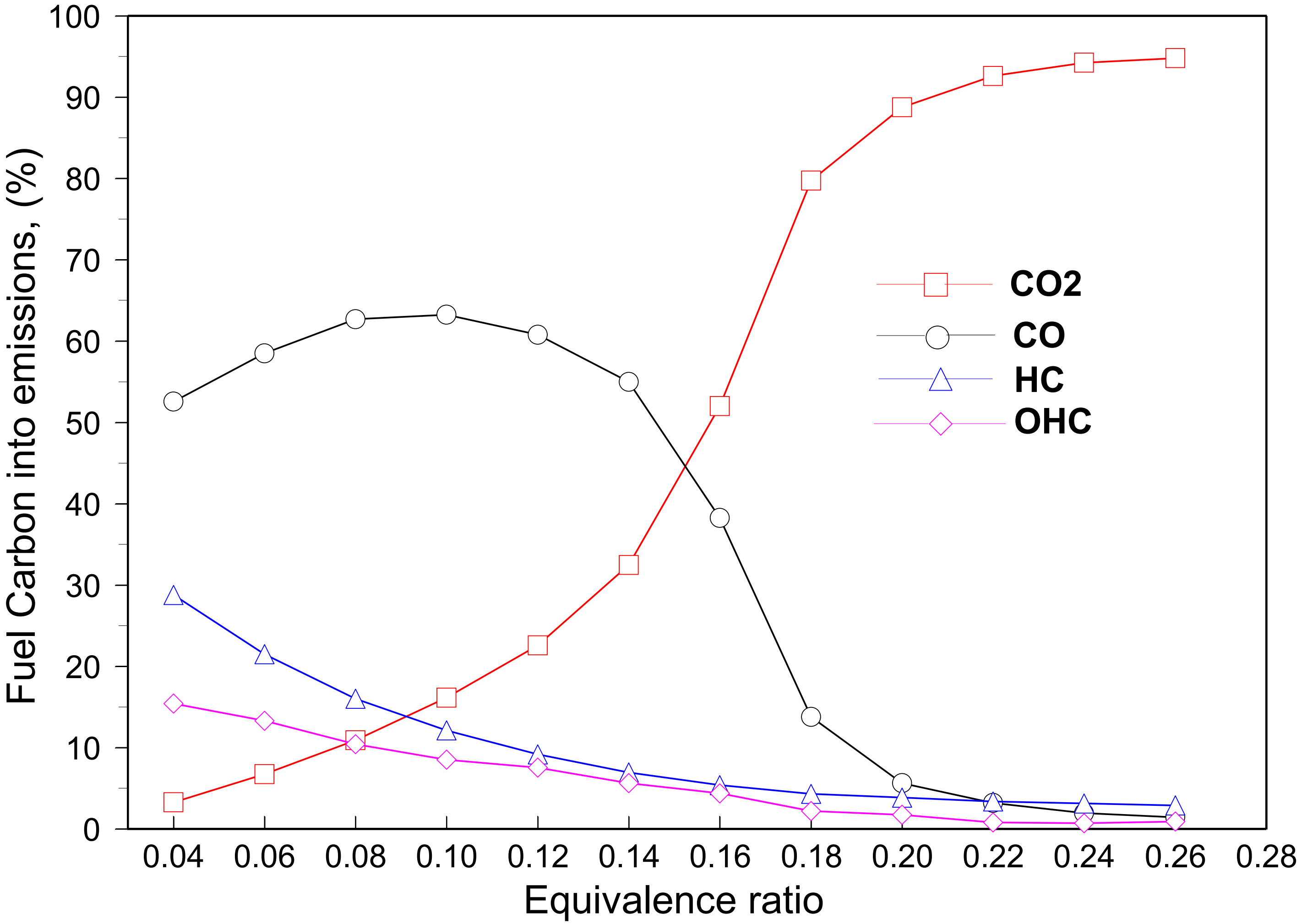
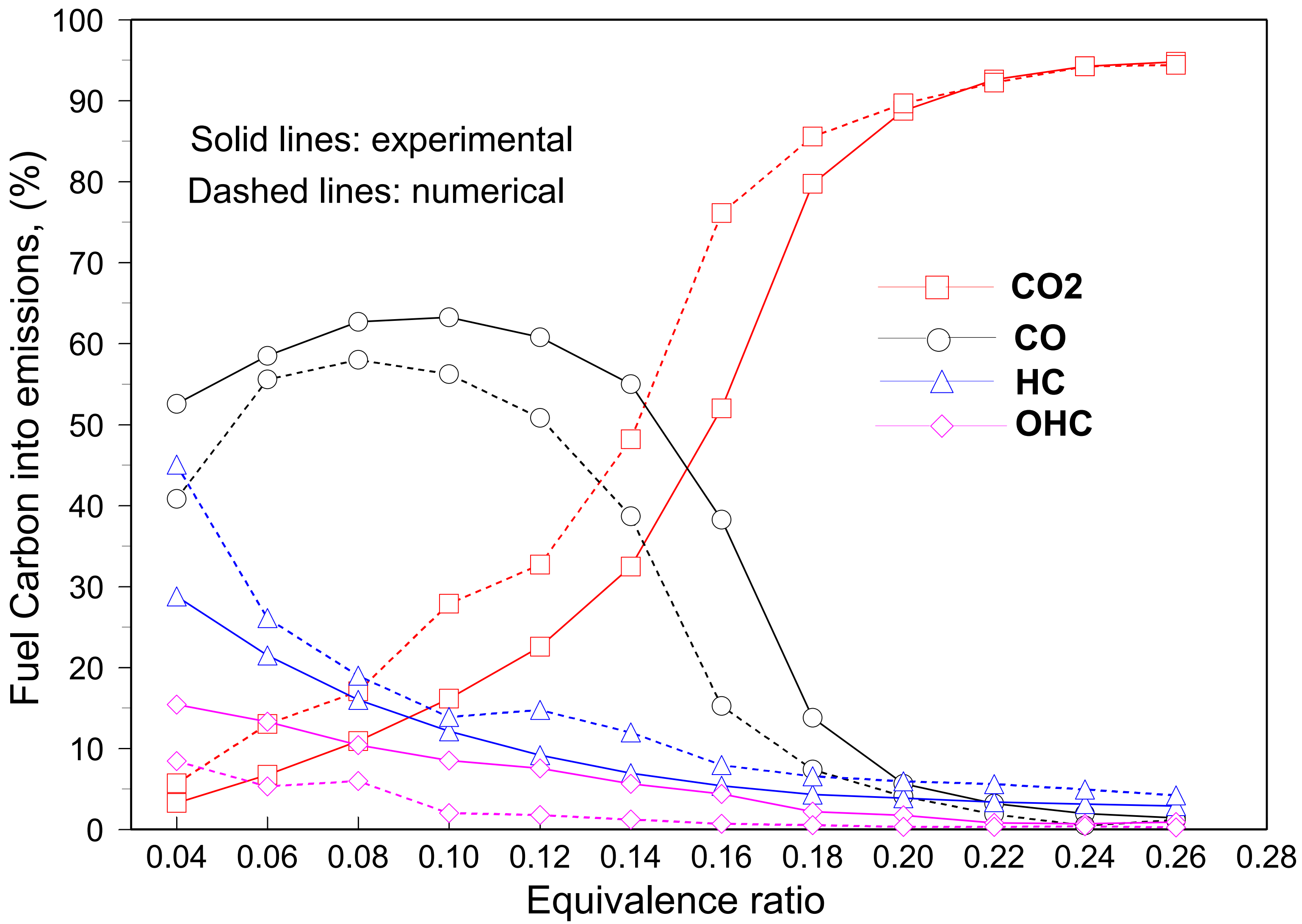
Experiments in the Sandia HCCI engine show very inefficient combustion as equivalence ratio is reduced

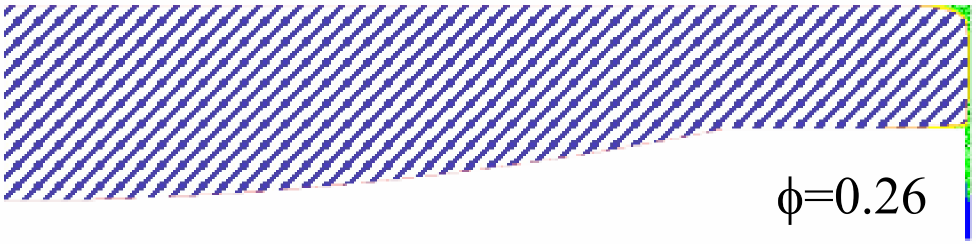
Experimental isooctane HCCI data from the Sandia Engine



Simulations agree well with experiment



Our multi-zone model gives insight into the reduced combustion efficiency as equivalence ratio decreases



Complete Combustion

High CO

Fuel, IHC, CO

Unburned fuel

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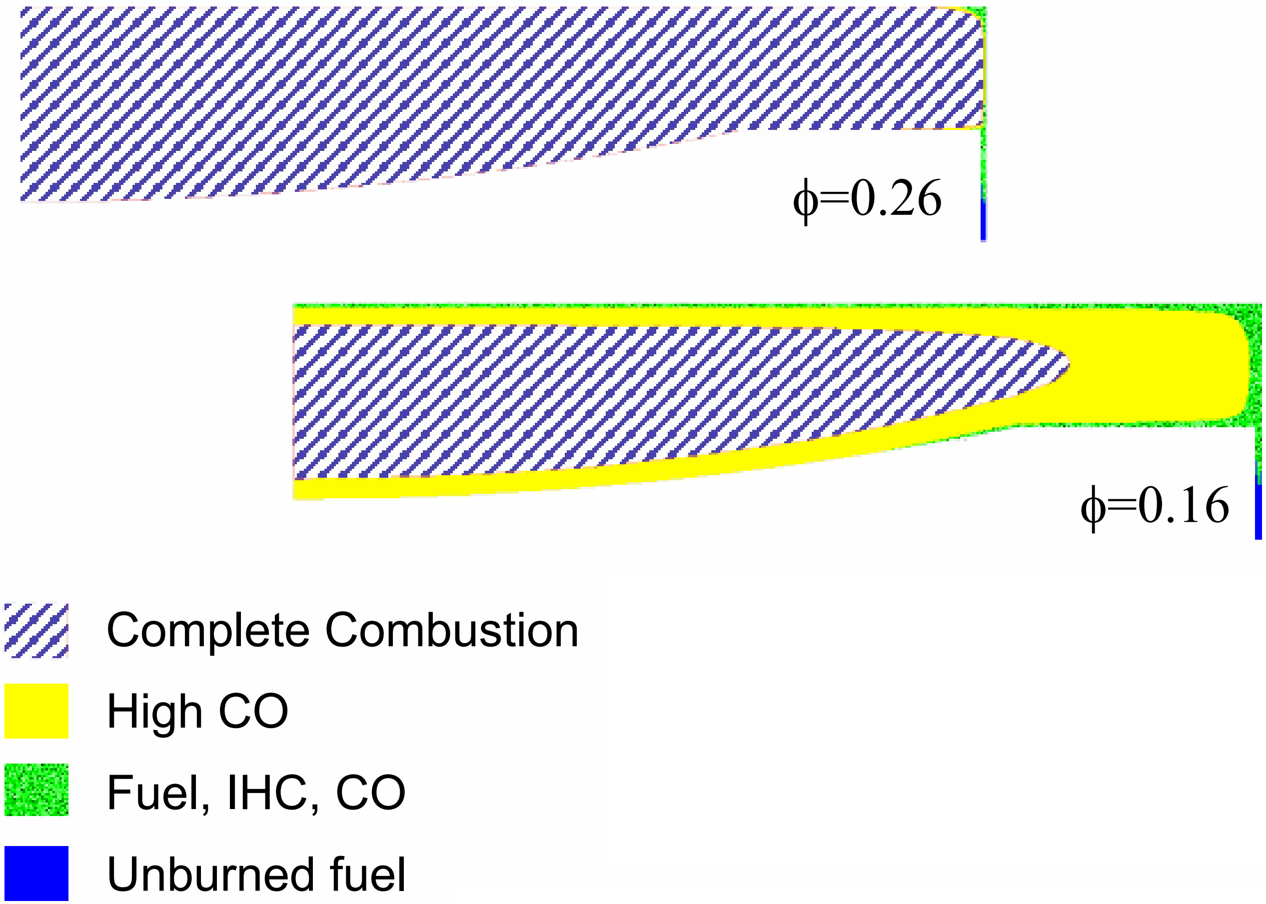

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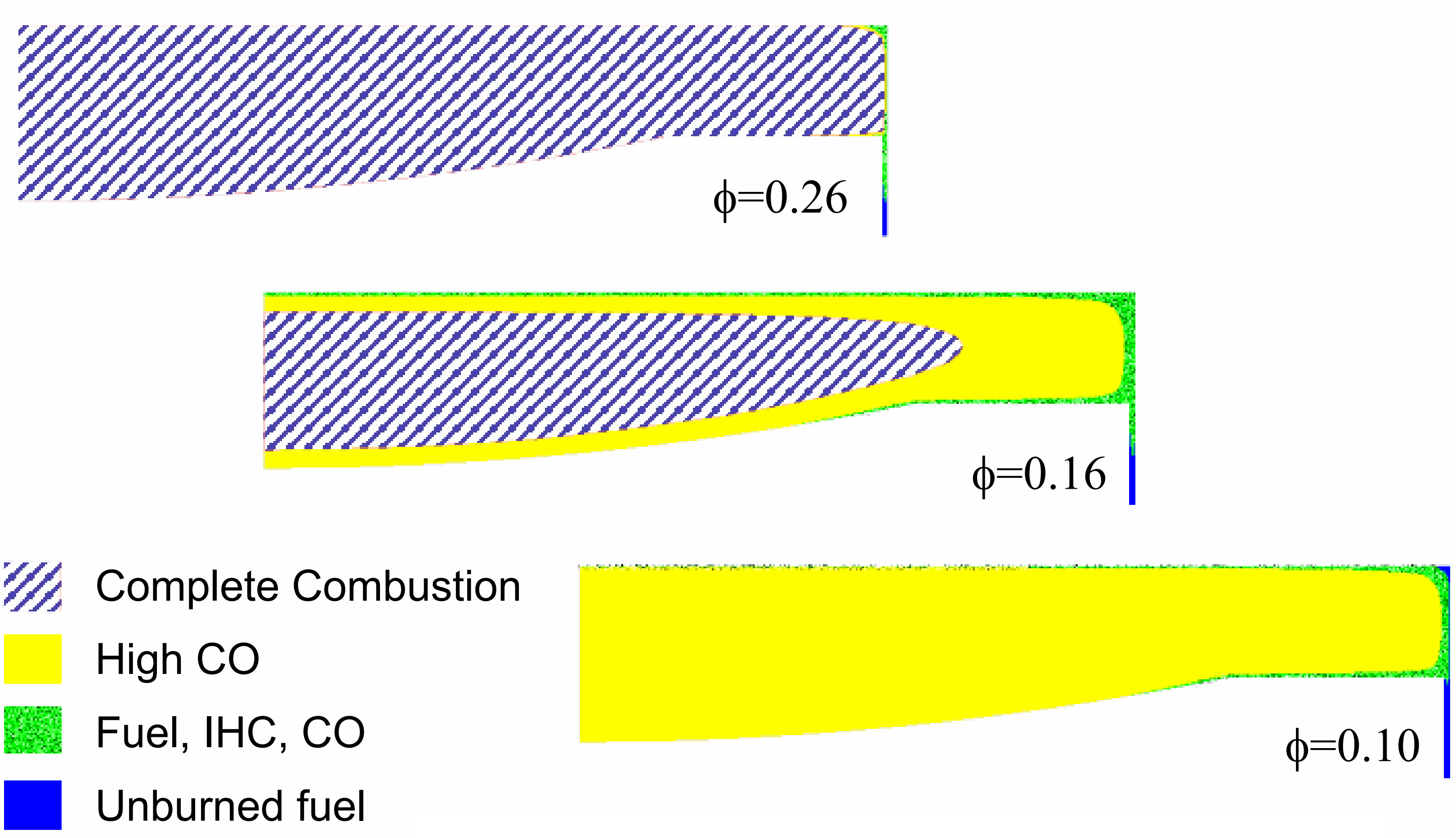

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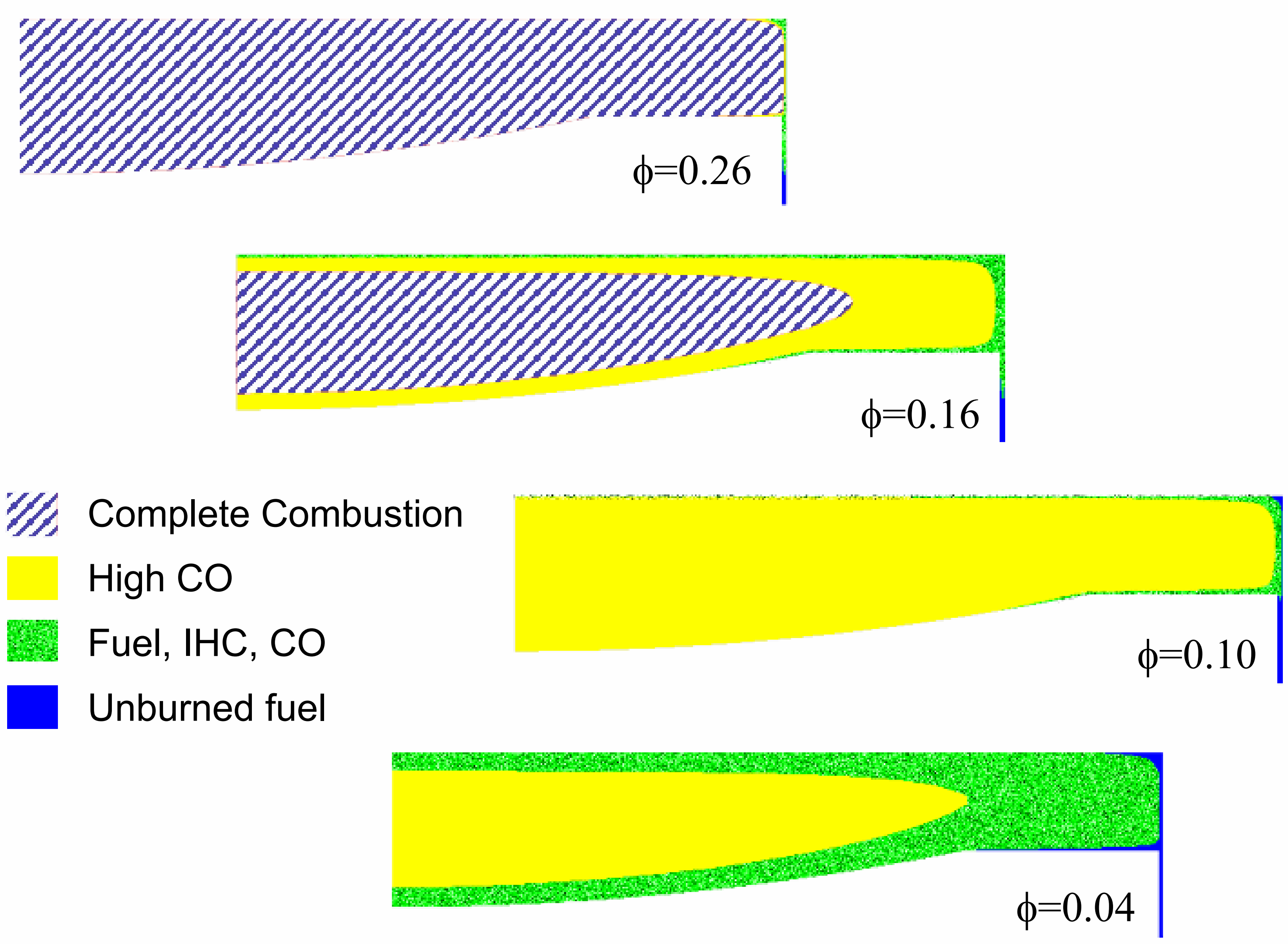

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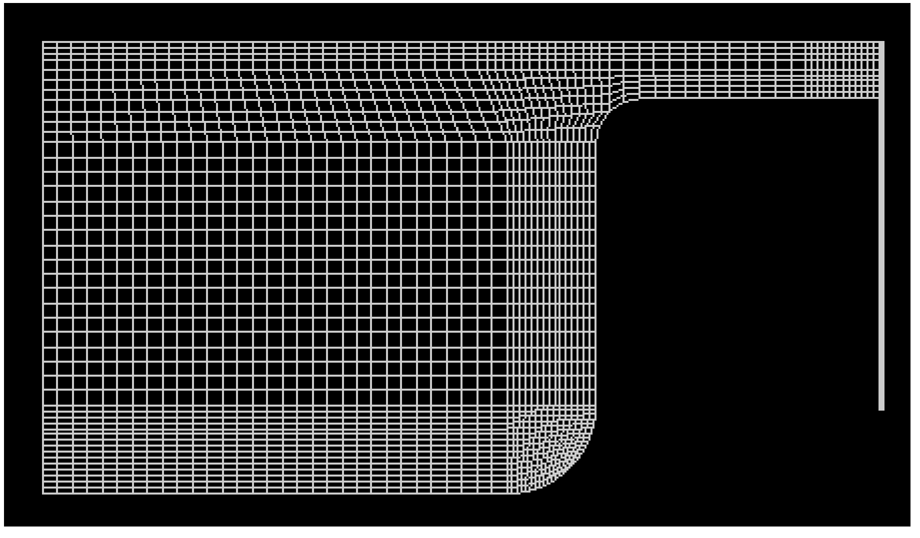
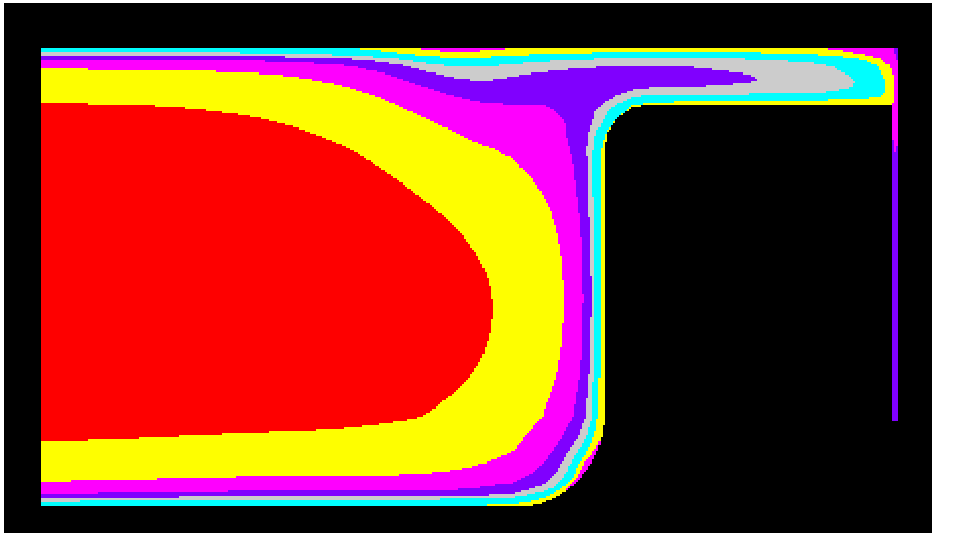
The original design of the multi-zone model is appropriate for modeling truly homogeneous HCCI combustion

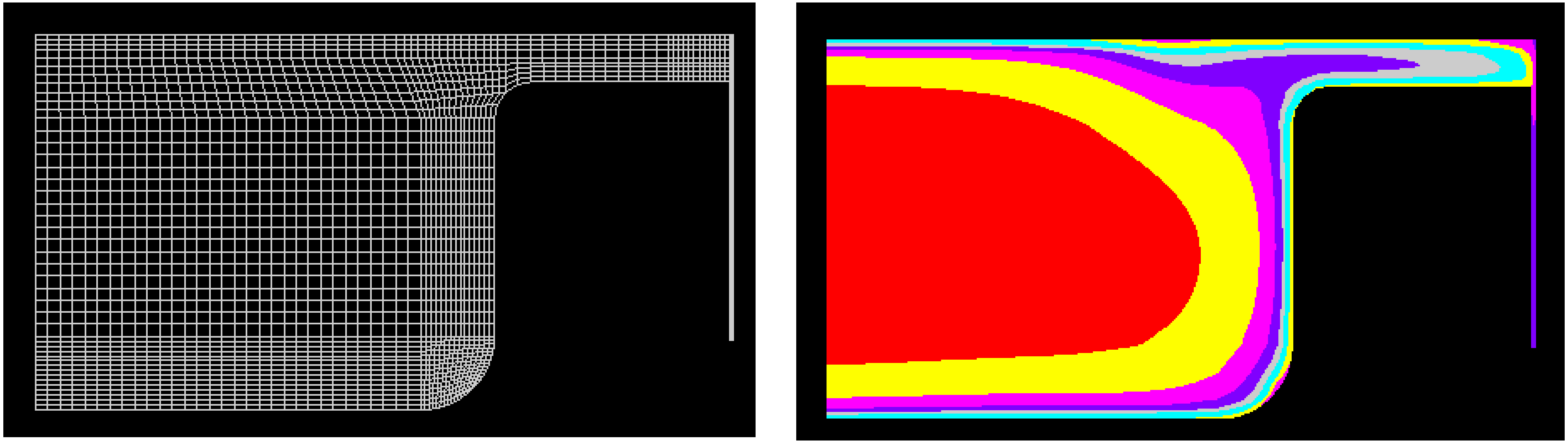




Original Multi-zone Model: One-way mapping from Kiva to Kinetic Solver

Enhancement to multi-zone model gives us the capability to handle stratified combustion (PCCI, SCCI)

Enhanced Model:
Kinetic solver results are mapped back onto Kiva Grid

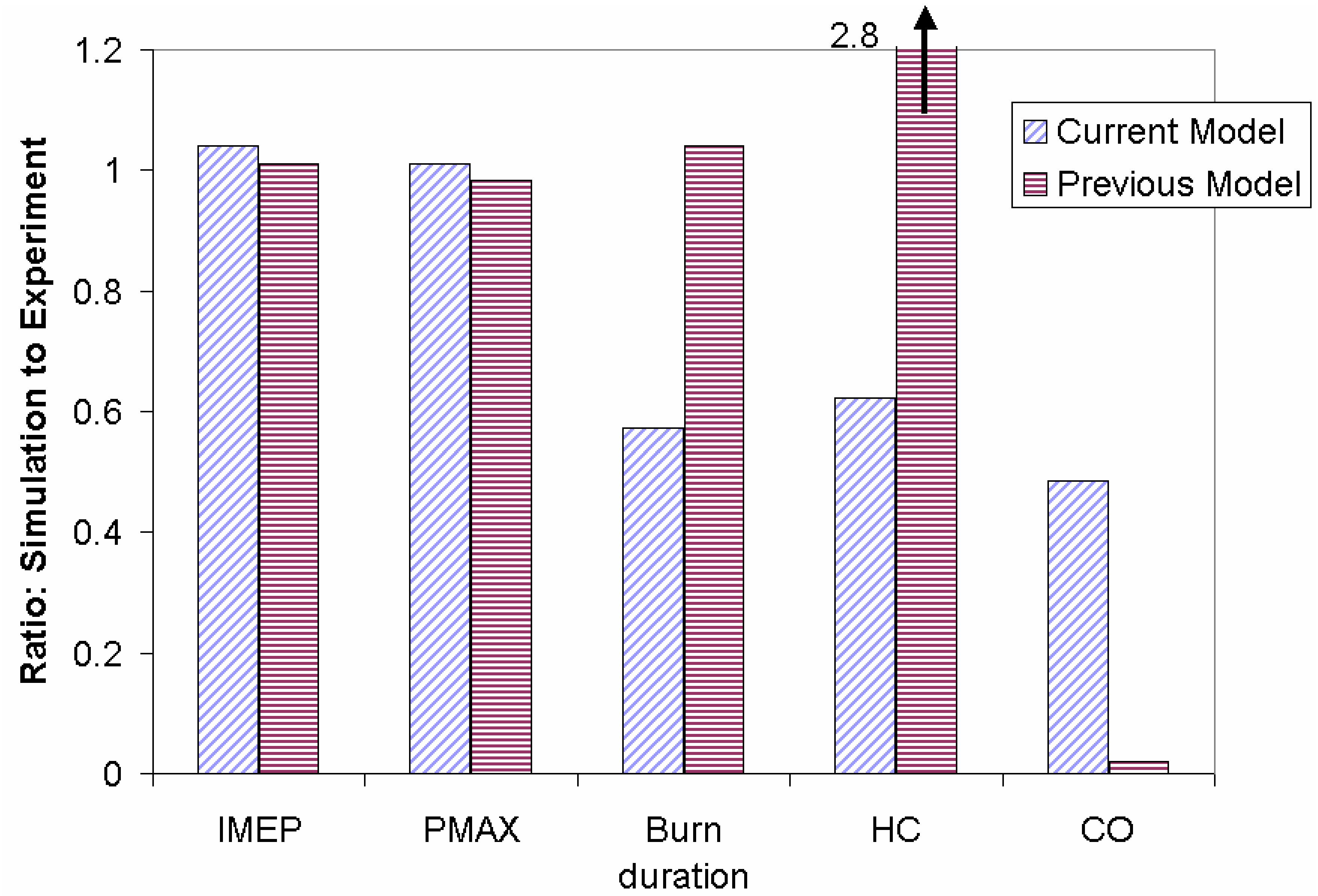


Kiva can now be used to account for mixing and heat transfer between zones for the whole cycle

The enhancements in the model allow us to move beyond "truly homogeneous" HCCI combustion

- **Model is generally applicable to cases where heat release and mixing are weakly coupled**
  - PCCI = Premixed Charge Compression Ignition
    - High Internal EGR
  - SCCI = Stratified Charge compression Ignition
    - Early Direct Injection

Accounting for mixing in multi-zone model yields much improved CO and HC emissions (SAE 2003-01-1821)



Experimental work

- **What control methods are viable for multi-cylinder HCCI engines?**
  - Designed and tested a generic control system for internal EGR control of cylinder by cylinder variation in 4-cylinder engine
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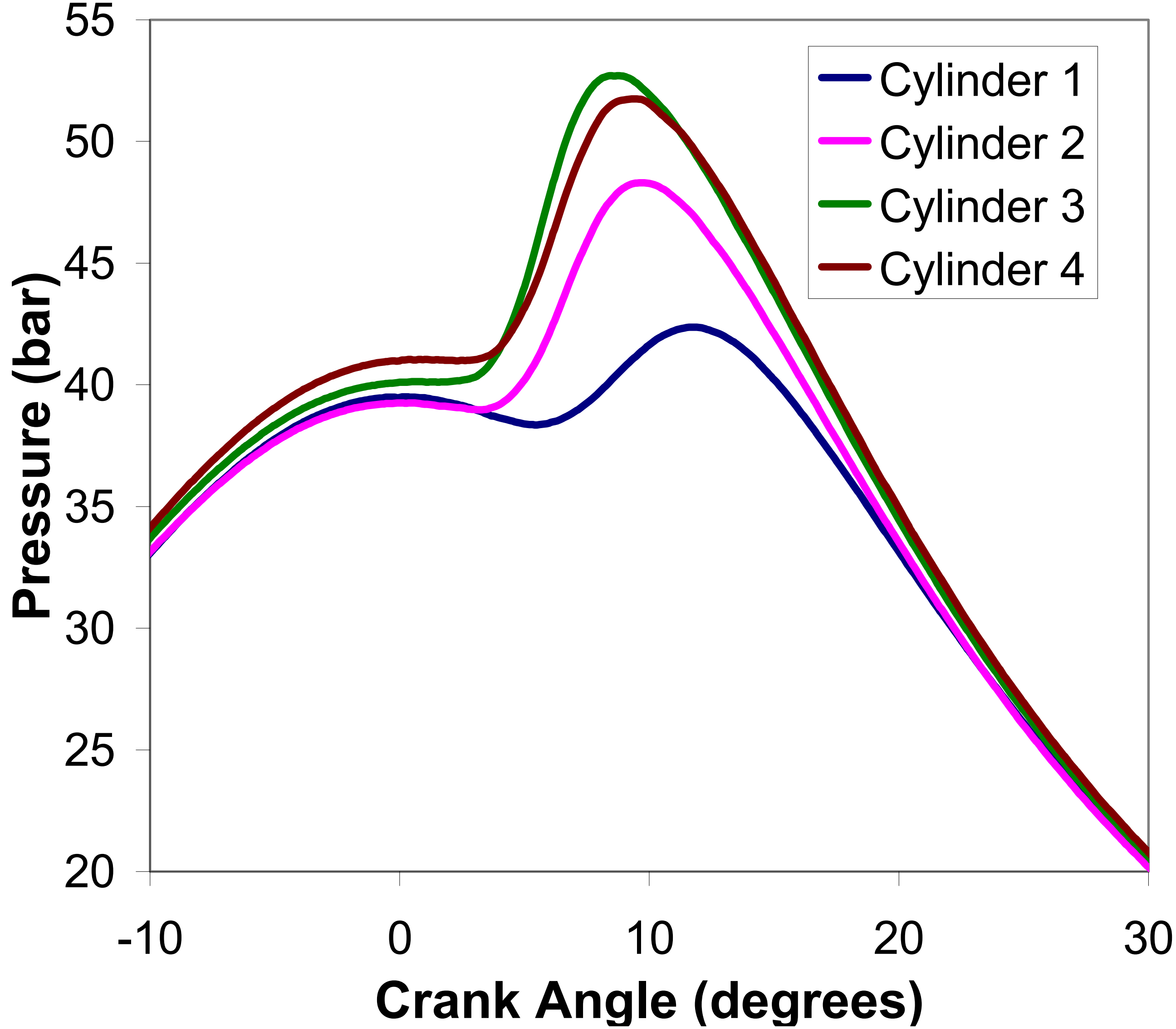
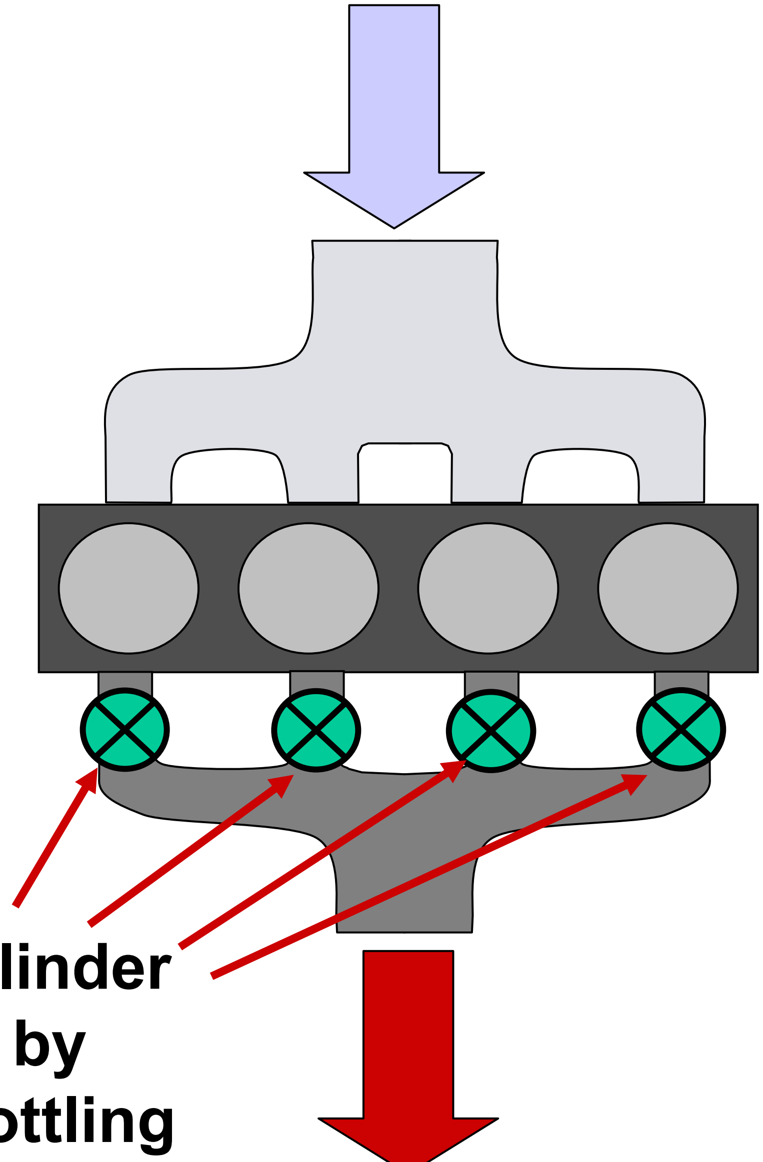
Controlling cylinder-by-cylinder combustion timing is very important for multi-cylinder HCCI engines



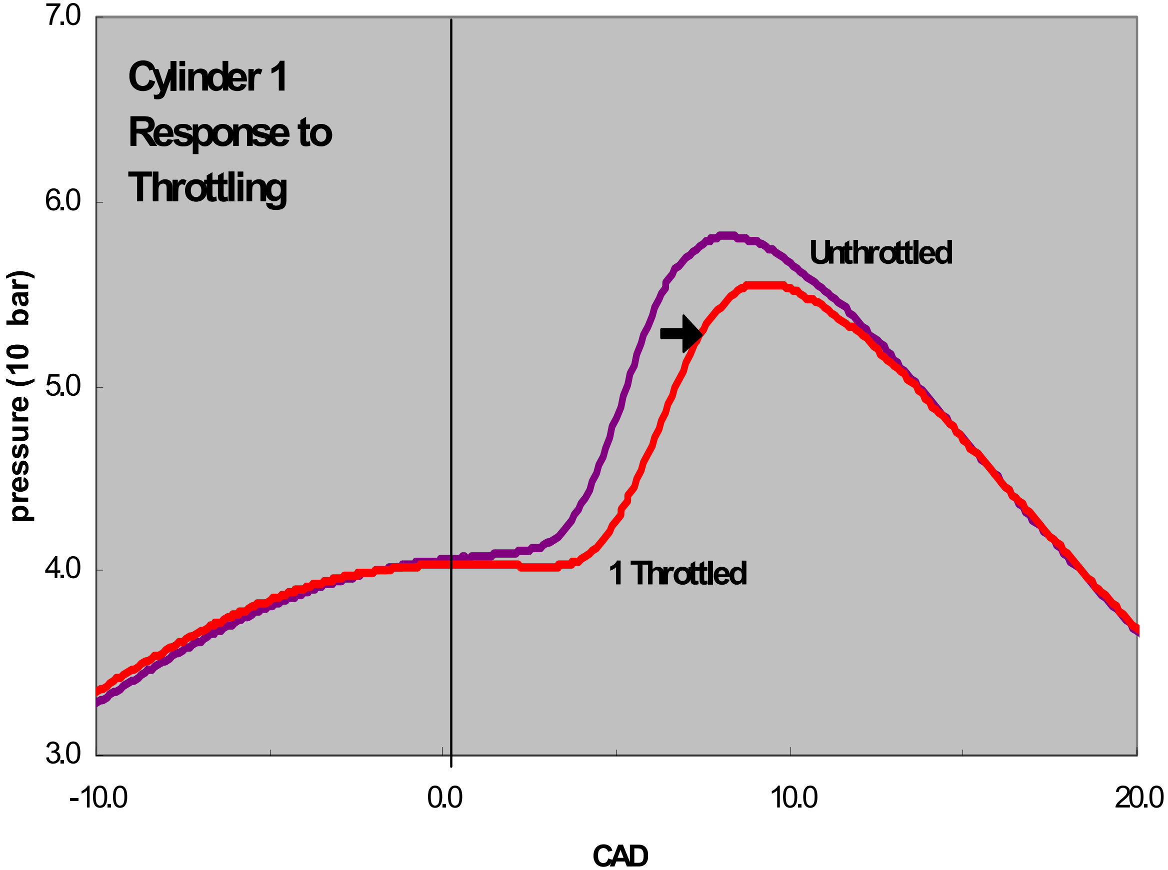
A generic, low cost surrogate to variable valve timing is being used for controlling cylinder to cylinder variations



Individual cylinder EGR Control by Exhaust Throttling

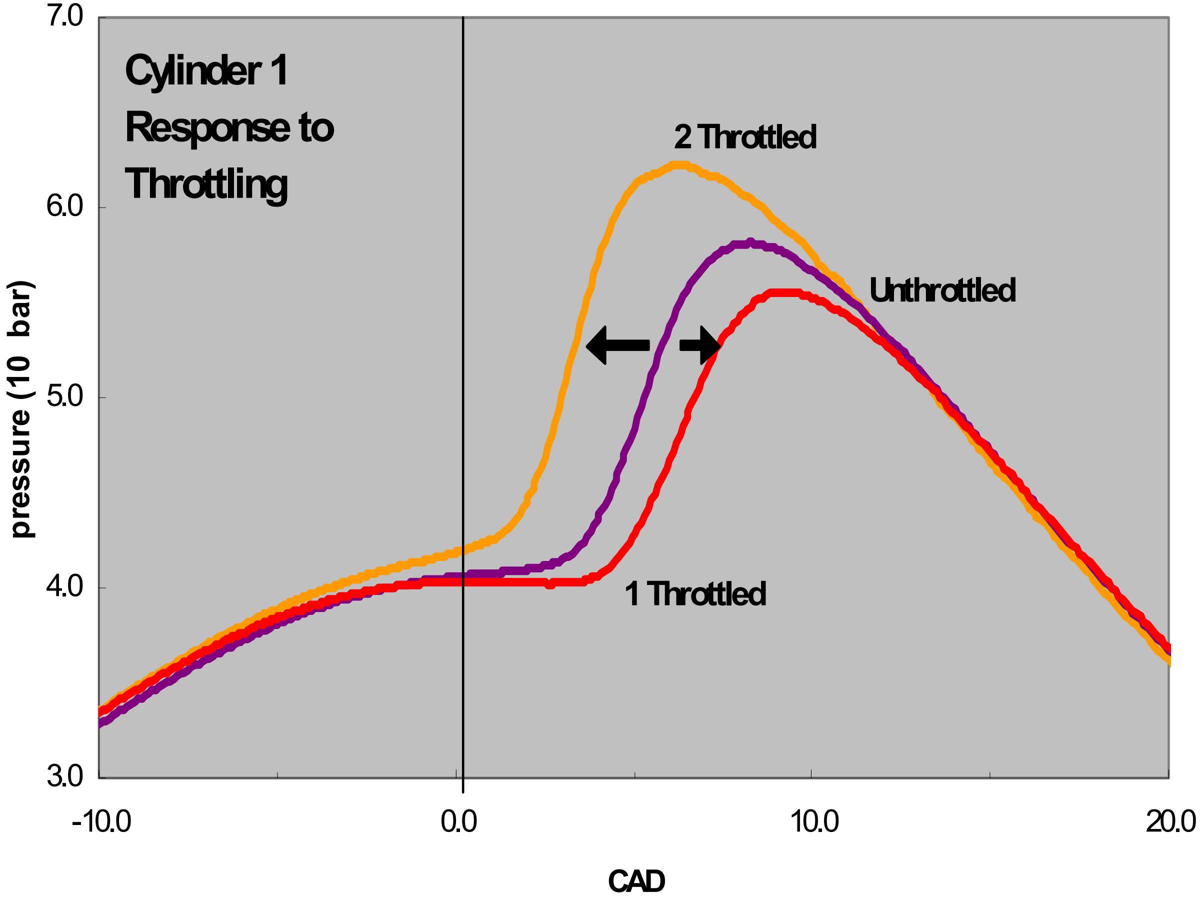
Surprising Exhaust Throttle Effects on start of combustion (SOC)

1. SOC delayed by backpressure of cylinder !
2. Constant fuel flow intake (non injected), and naturally aspirated air intake may explain SOC retardation.



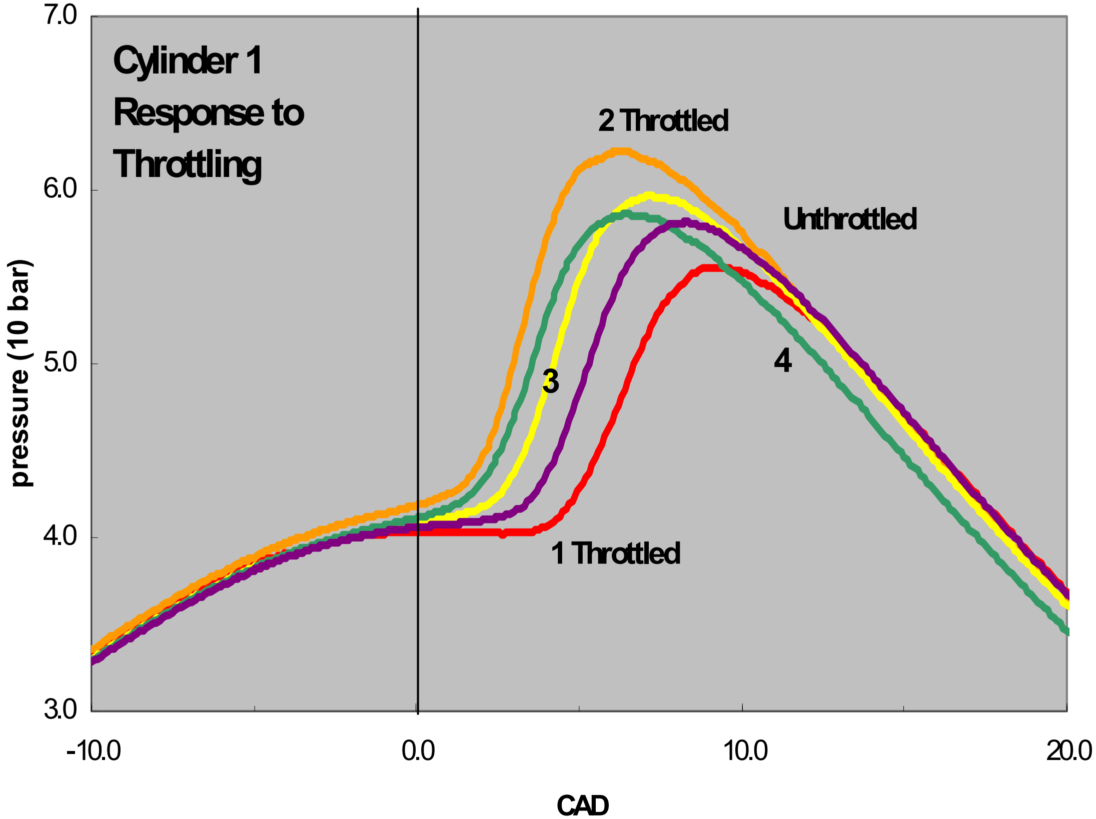
Surprising Exhaust Throttle Effects on SOC

Amazingly, throttling of other cylinders advances SOC of cylinder 1 !?!



Any Exhaust Throttle affects SOC in Cylinder 1

Backpressure of cylinders 3 and 4 also increases the SOC in cylinder 1



Future analysis and experimental work will focus on cylinder interactions and how to control them