Micro-Homogeneous Charge Compression Ignition (HCCI) Combustion: Investigations Employing Detailed Chemical Kinetic Modeling and Experiments

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5 December 2001

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Micro-Engines

- Objective:
  - Replace batteries with engine-generators.
  - Energy Density:
    * Hydrocarbon: $40\,\frac{\mathrm{MJ}}{\mathrm{kg}}$; Battery: $1\,\frac{\mathrm{MJ}}{\mathrm{kg}}$
    * Only need 4% fuel conversion efficiency.
  - Goal: 10 W from a packaged volume of $1\,\mathrm{cm}^3$.
- Programs:
  - Micro-Gas Turbine Engine (MIT)
  - MEMS Rotary Engine (University of California Berkeley)
  - MEMS Free-Piston Engine-Generator (Georgia Tech.)
  - MEMS Free-Piston Knock Engine (Honeywell International)

Micro-Engines

- Problems:
  - Practical:
    - Materials
    - Fabrication
    - Friction
    - Sealing
  - Micro-Combustion:
    - Enhanced heat transfer—Flame quenching.
    - Strategies:
      - Fuel selection (e.g., Hydrogen) and catalysts. (MIT).
      - Adiabatic boundary (University of California Berkeley).
      - Multiple Ignition points (Georgia Tech.).
      - Knock Combustion, i.e., HCCI (Honeywell International).

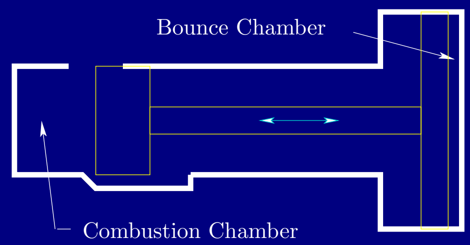
Homogeneous Charge Compression Ignition (HCCI)

- A premixed charge is compressed until it explodes.
- Features:
  - Rapid combustion with non-traditional propagation, i.e., no flame front.
  - Multiple simultaneous ignition.
  - No external ignition.
  - Can ignite extremely lean mixtures.
  - Fuel flexibility.
- Closely related to engine knock.
- Intimately linked to the compression process and fuel oxidation kinetics.
- Hot research area, but control is a serious problem.

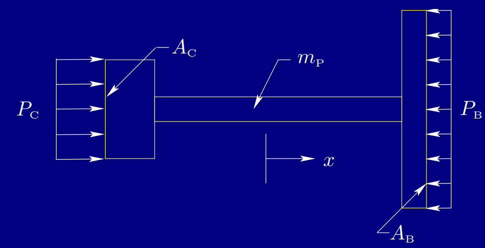
Free-Piston Dynamics

- Thermodynamic-dynamic balance:

Free-Piston Configuration



Free Body Diagram

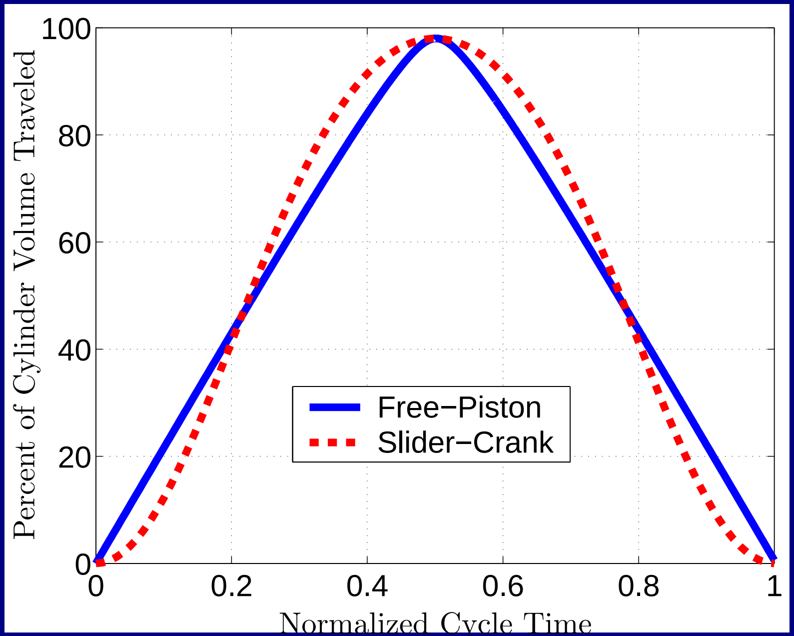


$$\Sigma F_x = m_{\mathrm{P}} \frac{d^2 x}{dt^2} = P_{\mathrm{C}} A_{\mathrm{C}} - P_{\mathrm{B}} A_{\mathrm{B}}$$

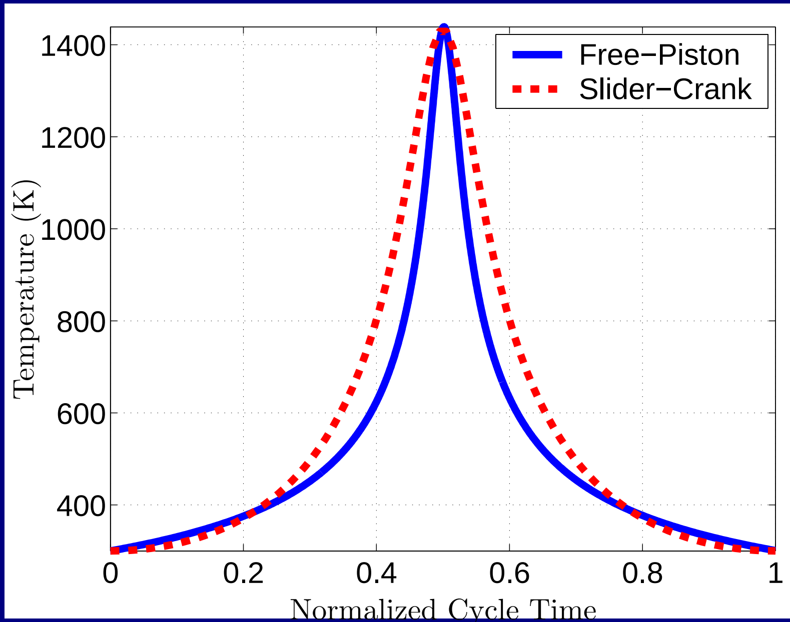
- Advantages:
  - Mechanically simple.
  - Virtually infinitely variable compression ratio—may solve HCCI control problem.
- Disadvantages:
  - Difficult to design due to combustion-piston coupling.
  - Limited work output options exist.

Free-Piston vs. Slider-Crank (No Combustion)

Volume



Temperaure (γ=1.4)

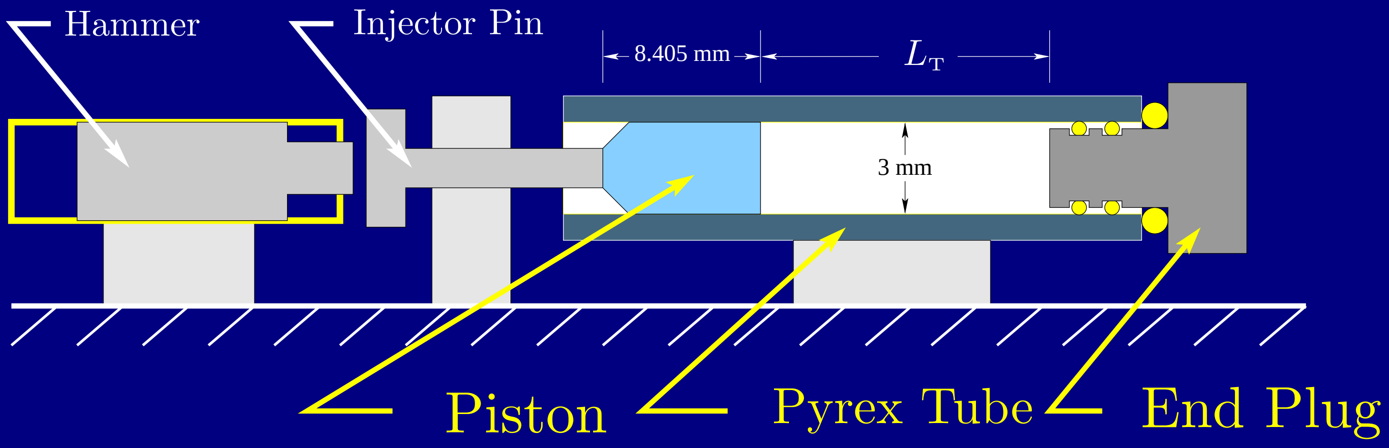


- Free-piston compression process differs from slider-crank.
- Significant implications for HCCI.

Micro-HCCI Modeling Efforts: How small can an HCCI engine be?

- Performance estimation to devise operating conditions for 10, 1, and 0.1 Watt engines.
- Determine operational maps by checking for ignition with:
  - Detailed kinetic mechanism (C4) in a variable-volume batch reactor (SENKIN).
  - SENKIN modifed to include conduction heat transfer model.
  - Slider-crank piston motion assumed.
  - Heat transfer determines minimum engine size (reduces effectiveness of compressive heating). Mostly a factor for engines 1 W and smaller.

Single-Shot Micro-HCCI Experiments



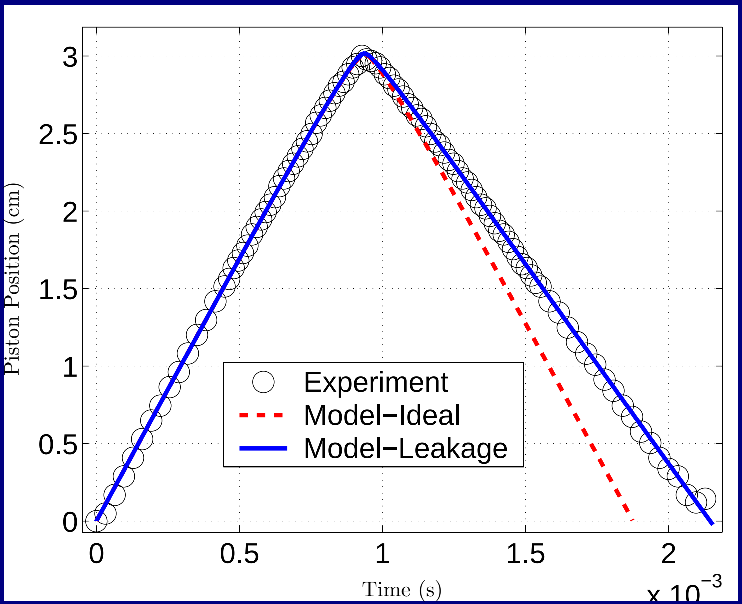
- Setup:
  - Piston: 3 mm Diameter × 8.4 mm; mass 0.435 g
  - Precison Pyrex tubes, L_T varys from 32 mm to 57 mm.
  - Piston rides on air cushion; gap approximately 5 μm.
- Measurements:
  - Record piston motion with Phantom v4.0 Digital camera. $\left(16 \frac{\mu s}{\text{Frame}}\right)$
  - Determine position and velocity from movies.

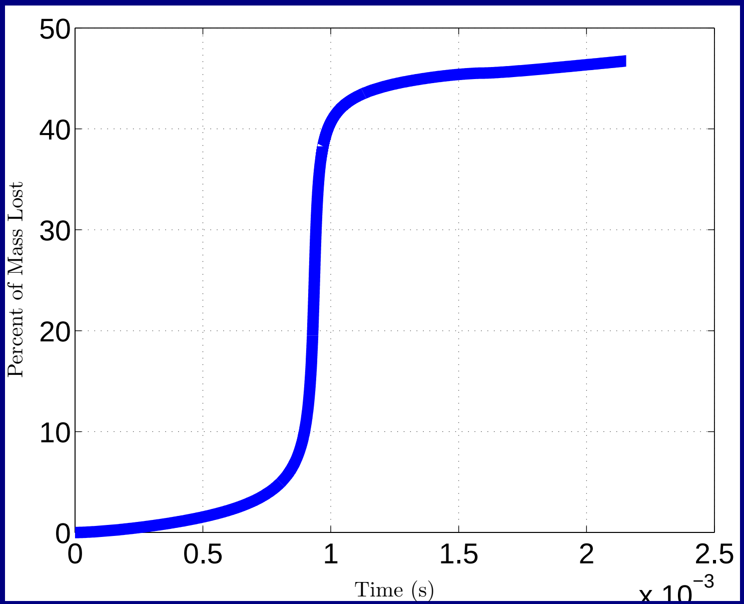
Significant Results

- HCCI combustion in volume 3 mm in diameter and < 0.3 mm.
- Charge initially at ambient conditions.
- No external ignition system.
- Very lean (0.25 equivalence ratio) combustion is possible.
- Combustion is quenched during expansion and not at the walls.
- Evidence that:
  - HCCI is initiated at multiple locations.
  - Traditional flame propagation does not occur.

Single-Shot Experiment Concerns

- Developed models of piston motion—no combustion.
- Blow-by, or leakage through the piston-cylinder gap is significant:
  - Exaggerates the compression ratio.
  - Decreases outgoing velocity.
  - Almost 50% of fresh charge is lost.





Conclusions and Future Work

- HCCI holds promise for micro-engines.
- Micro-engines may be limited by factors other than combustion.
- Future work:
  - How small can it go? Reduce crevice volume and test shorter tube lengths.
  - Chemical analysis of the products.
  - Model piston motion and HCCI coupling with detailed chemical kinetics.
  - Validate model with single-shot experiments.

Acknowledgement

This project was sponsored by Honeywell International under DARPA contract No. F30602-99-C-0200. The authors would also like to thank Dr. Wei Yang and Mr. Tom Rezachek of Honeywell International for designing and providing equipment for the single-shot experiments.

For More Information:

For this presentation and the paper upon which it is based:

http://www.menet.umn.edu/~haich/