Increasing Engine Efficiency through Extreme Compression

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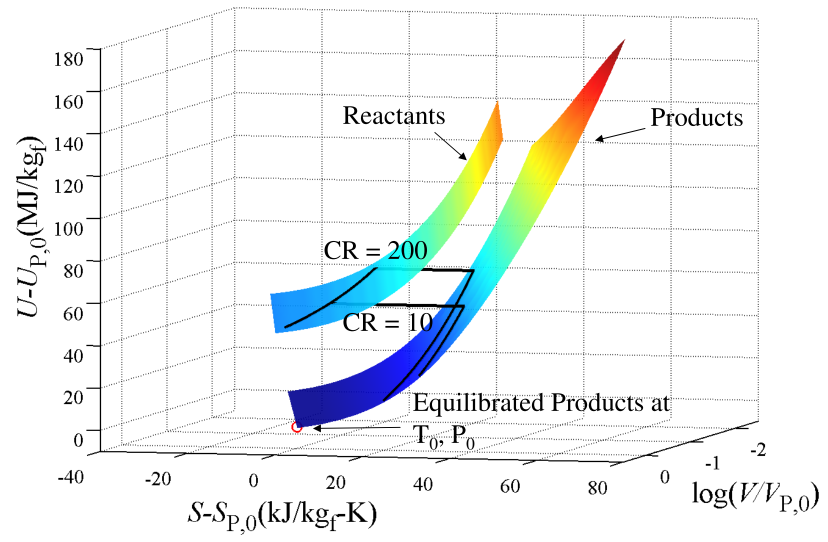
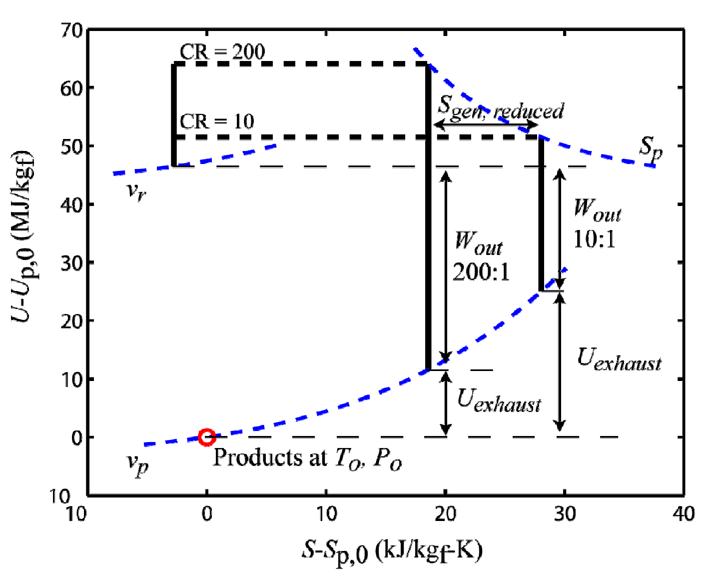
Motivation

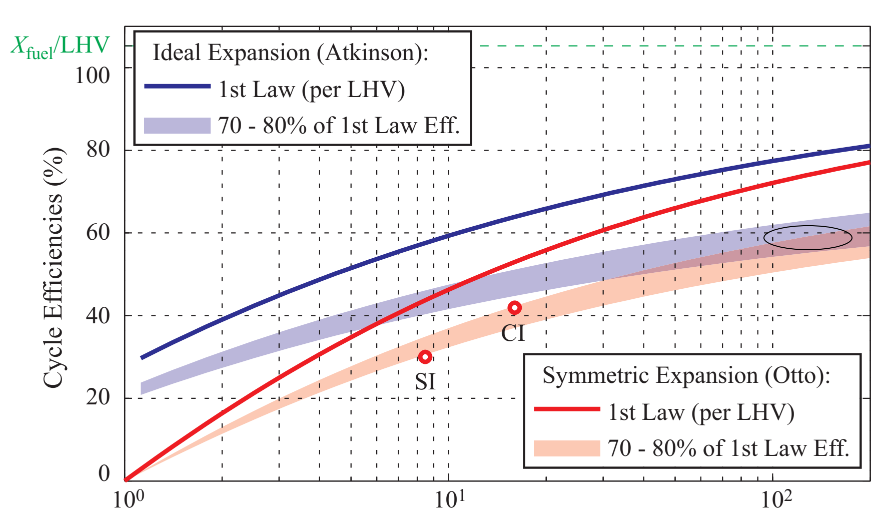
One of the most substantial loss mechanisms in current, simple-cycle, unrestrained, reactive engines is combustion irreversibility. A large fraction (~20%) of the exergy of the fuel resource can be destroyed during the combustion process. The goal of this project is to substantially reduce the combustion irreversibility thereby increasing the overall efficiency.



Ideal Otto cycles at CR =10 and 200. Exergy is destroyed due to unrestrained reaction by jumping surfaces from reactants to products.



Ideal Otto cycles for stoichiometric propane/air on a *U-S* diagram. Entropy generation and energy left in the exhaust are significantly reduced with higher compression.



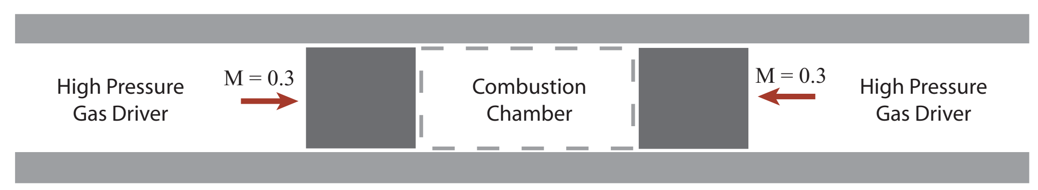
At 100:1 compression ratio we can potentially realize simple cycle efficiencies near 60% – significantly higher than current devices[1]. The goal of this project is to design and build a device that will test the feasibility of increasing efficiency by using extreme compression.

[1]Heywood, Internal Combustion Engine Fundamentals, 1988. p.196

Basic Design

New design choices are required to construct a device capable of these high compression ratios. Post-combustion pressures are greater than 1000 bar, while post-combustion temperatures are greater than 3000 K. A few of the obstacles and their design implications include:

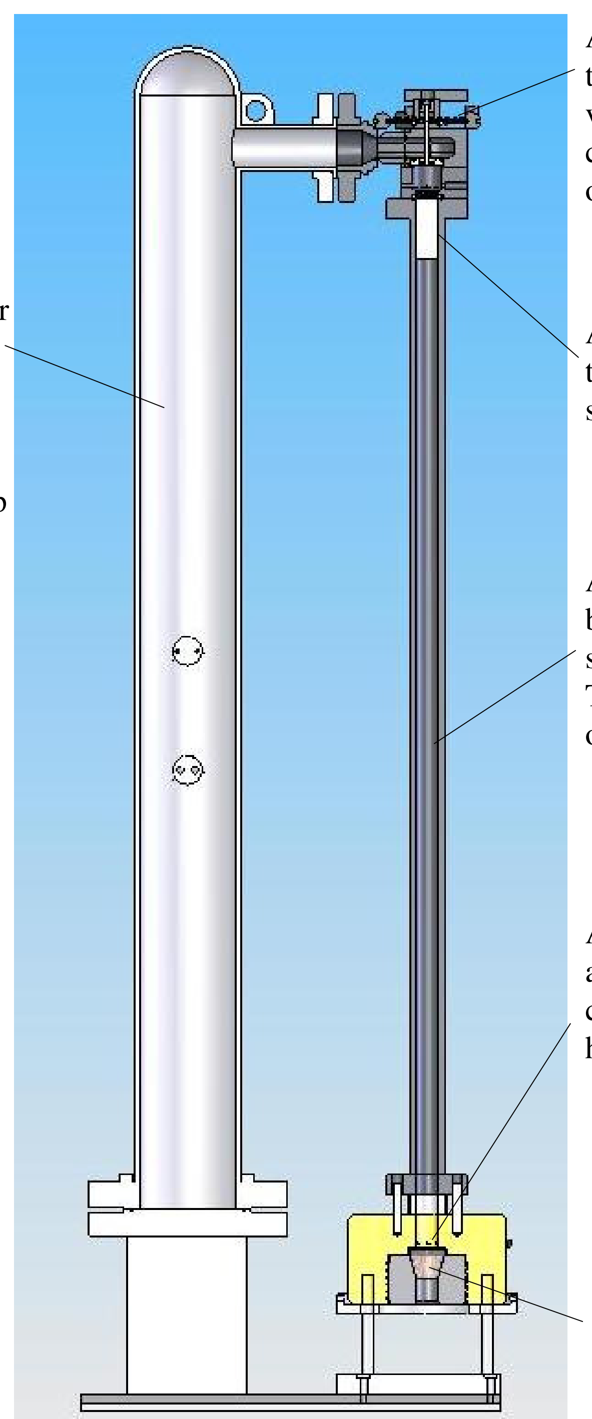
- Typically the higher temperatures lead to greater heat transfer losses
  - → Design engine with a low surface-to-volume ratio at 100:1 CR (e.g. a long stroke)
  - → Increase expansion speed to extract work before it is transferred out as heat
- High pressures lead to high forces
  - → Use two pistons to balance the forces and increase expansion rate
- Pre-mixed or early injection strategies will react too early
  - → Use high-pressure direct injection system to phase combustion



Basic concept drawing of device design

Experimental Design

We have designed an experimental apparatus to study the feasibility of achieving reduced combustion irreversibility by performing the reaction at high internal energies. The apparatus contains:



A large, high-pressure air reservoir, capable of providing driver air pressure up to 68 bar

A fast (~20 ms opening time) air-driven poppet valve to allow repeatable, controllable introduction of driver air to cylinder

A free-piston architecture that allows for high piston speeds

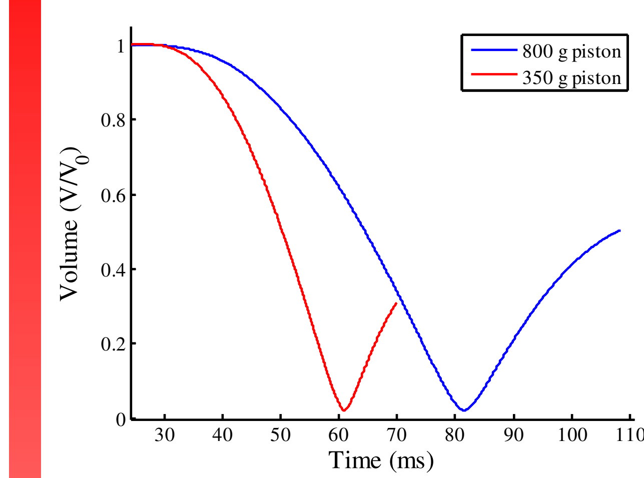
An ~ 2.5m long cylinder bore to achieve low surface to volume ratios at TDC, reducing the effects of heat transfer

A high-pressure combustor attached to the end of the cylinder to withstand the high pressures at TDC.

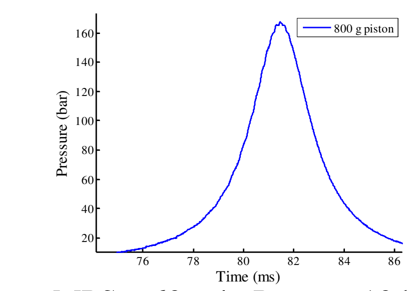
Sapphire window port for optical access to combustion.

Experimental Data

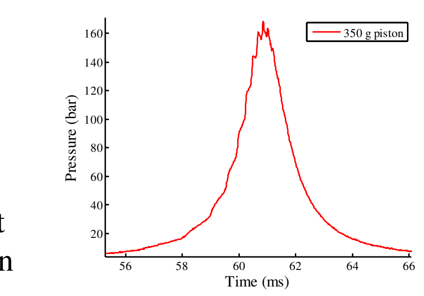
Air Compression Data



Air compression data for CR = 50 with different piston masses. Lower masses have higher piston accelerations, generating acoustic waves.

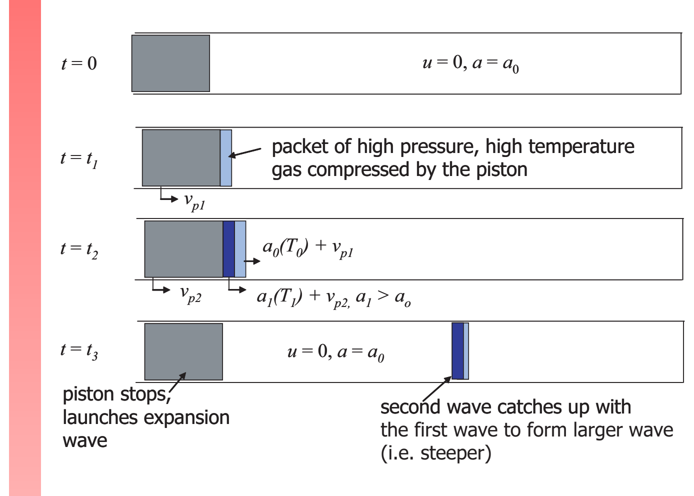


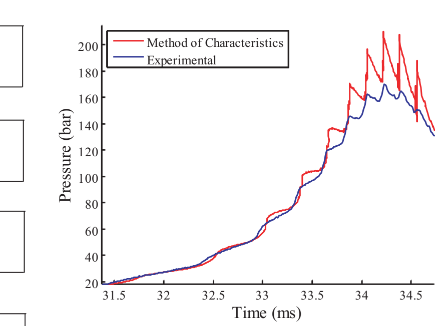
MPS ~ 60 m/s, P_{driver} = 10 bar



MPS ~90 m/s, P_{driver} = 12 bar

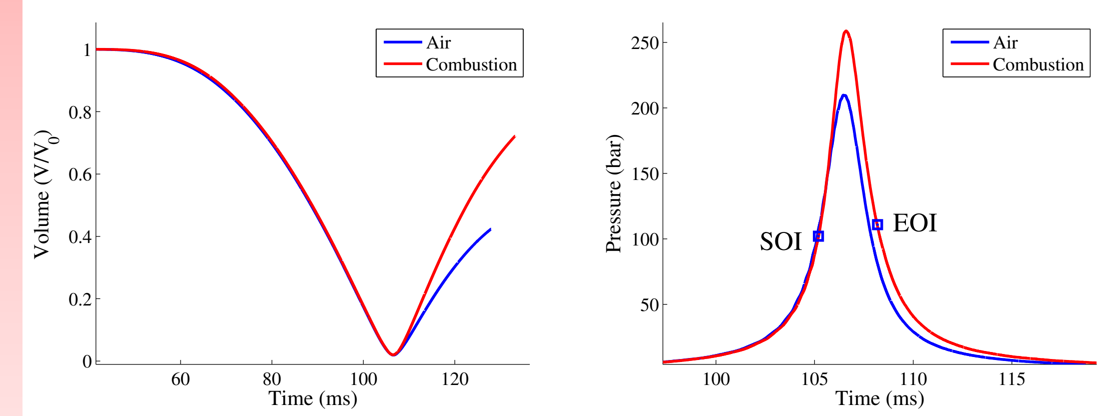
Acoustic Wave Formation and Method of Characteristics





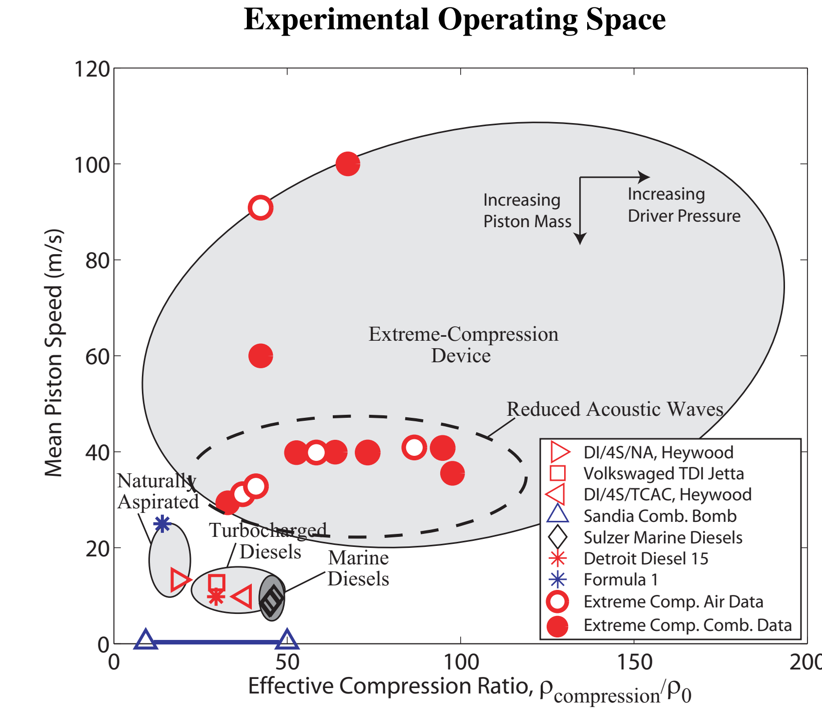
Experimental data vs. method of characteristics simulation. Shocks form in the simulation due to lack of dissipation in the model.

Volume and Pressure Profiles for CR = 50, Air and Combustion Data



Volume and pressure profiles for CR =50. Squares mark the start and end of injection.

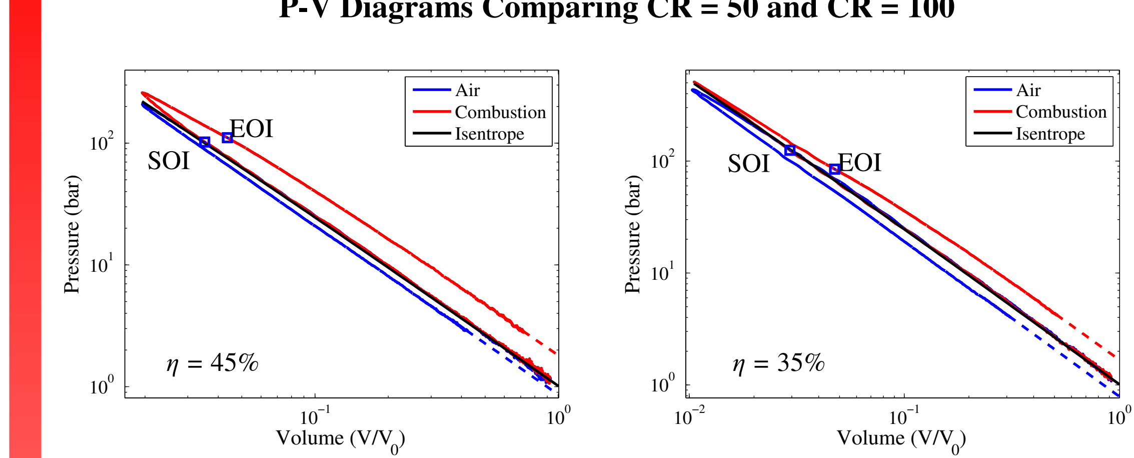
Experimental Operating Space



Operating space of device as well as more recent operating space given constraints due to piston acceleration.

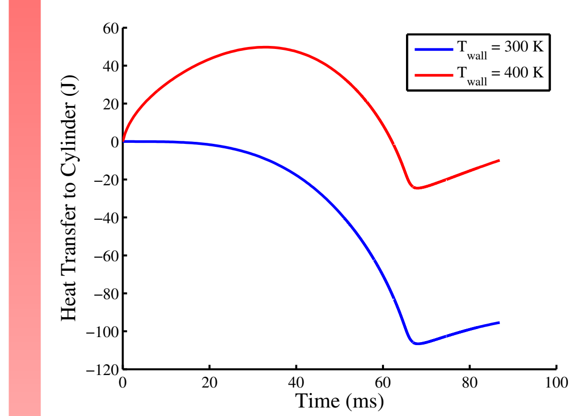
Experimental Efficiency

P-V Diagrams Comparing CR = 50 and CR = 100

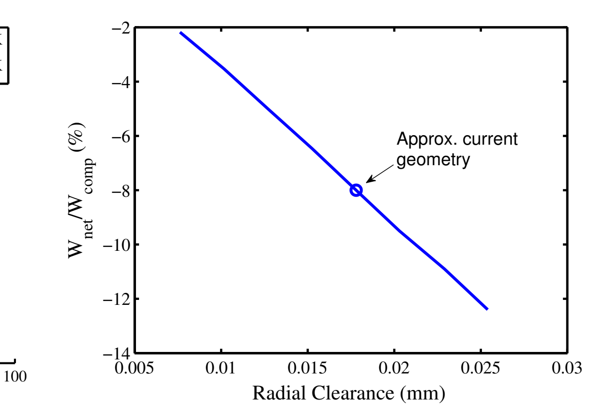


P-V diagrams for air and combustion data at CR = 50 on the left and CR = 100 on the right. Additional mass and heat transfer losses as well as poor combustion phasing are apparent at the higher compression ratio which accounts for the loss in efficiency.

Heat and Mass Transfer Losses

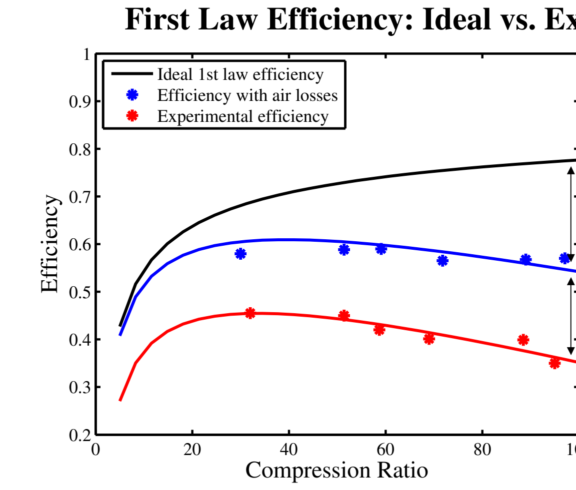


Heat transfer models show that heat transfer during the compression stroke could be reduced if wall temperatures were 400 K as they are in most IC engines.



Mass transfer models show that by using active clearance control, mass losses could be reduced.

First Law Efficiency: Ideal vs. Experimental



Efficiency vs. compression ratio comparing experimental data with the ideal cycle. Efficiency with air losses shows that heat and mass transfer losses as a percentage of a fixed amount of fuel increase with compression ratio. Combustion data losses include additional heat and mass transfer over the air losses as well as combustion inefficiency.

Future Work

- Assess Combustion Performance
  - Combustion efficiency
  - Extent of turbulent mixing vs. laminar flow
  - Injector spray performance at high densities
  - Ignition delay timing
- Install window to visualize spray dynamics and combustion
- Install exhaust gas analysis system for measuring NOx and reaction efficiency
- Analyze and experimentally test ring design to understand and reduce blowby

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