Mechanical Engineering Design of a Split-Cycle Combustor

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University of Brighton, March 2015
“mechanical design considerations for a heat engine where rapid combustion is required”

The split-cycle concept has been identified as a potential, and now perhaps practical, means of improving the thermodynamic cycle efficiency of a heat engine intended for use in a hybrid powertrain town car.

This engine requires rapid air and fuel delivery, rapid mixing and rapid combustion; what should the hardware look like?
Agenda

The following topics will be considered

• What is the function of the combustor in a split cycle engine?
• What do we mean by rapid combustion?
• Air admission mechanisms
• In-cylinder air motion for the promotion of rapid combustion
• CEREEV proof of concept combustor machine
What is the function of the combustor in a split cycle engine?
Function of Combustor – **What is a Split-Cycle Engine?**

Brayton split engine, 1876
Function of Combustor – What is a Split-Cycle Engine?
Function of Combustor – What is a Split-Cycle Engine?

http://upload.wikimedia.org/wikipedia/commons/8/8b/Scuderi_Split_Cycle_Engine_-_Cycle.gif
What do we mean by rapid combustion?
Rapid Combustion – A Working Definition

Preliminary target values (to suit hybrid powertrain micro car)

• 10 kW
• 127 / 135 cc
• 4 stroke
• Gasoline

• Mass of inlet air: 1 gram / event (approximately)

• Inlet / ignition period (angle): 20 crankshaft degrees (approximately)

• Inlet / ignition period (time): assuming 20 crankshaft degrees; 6.6 ms @500 rev/min; 3.3 ms @1000 rev/min  Note: F1 engine = 2.9 ms assuming 310 degrees @18,000 rev/min

• Upstream pressure conditions: 10 bar, 300 K (approximately)
Air admission mechanisms

Flow routing
Valve shrouding
Valve motion
Flow Routing – Port Shape and Surface Finish

Inlet surface finish ≈ 320 grit abrasive paper (Honda F1)
Flow Routing – Surface Finish Study (CK Karun)

- CFD study of surface texture effects on boundary layer flows
- ANSYS / Fluent axisymmetric duct model (*Inlet BC: velocity; Exit BC: pressure*)
- K-omega turbulence model (*turbulence intensity; dissipation scale*)
- Real port geometry surface finish data (from 3D scanner)
Flow Routing – Surface Finish Study (CK Karun)

- Inlet plane: $U = 11 \text{ m/s}; \text{Re } 1500$ (laminar case)
- Axial location where surface texture is included in model
- Direction of flow

$U = 31 \text{ m/s}; \text{Re } 4200$ (transition case)

$U = 73 \text{ m/s}; \text{Re } 10,000$ (turbulent case)
Valve Shrouding – Effective Area vs. Path Disturbance


https://groups.yahoo.com/neo/groups/soaringvoyagers/conversations/topics/102
Valve Shrouding – Trajectory Nozzles

http://www.google.com/patents/US7398748

http://www.google.com/patents/US4355604

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Valve Shrouding – Rotary Valves

Coates Engine (spherical rotary valves)

Lotus rotary calve 2 stroke (1990s)

Aspin vertical axis electric-actuation rotary valve (1970s)
Valve Shrouding – **Effective Area vs. Path Disturbance**

Honda V10 F1 engine (15 k rev/min), dual plane valve inclination (reduced bore shrouding), pneumatic valve actuation

Honda V8 F1 engine (18 k rev/min) sectioned cylinder head (mean piston speed at 18 k rev/min = 24.8 m/s); \(V_{\text{chamber}} = 300 \text{ cm}^3\); bore/stroke = 2.3; rod/stroke = 2.7
Valve Motion – Positive Valve Closing Mechanisms

Valve Motion

Fig. 4.22. Desmodromic valve gear operating four valves per cylinder from two camshafts on G.P. Delage engine.

http://www.taringa.net/posts/autos-motos/1119657/El-Motor-Desmodromico.html
Air Admission – Air Injector Concept

- Injector: Bosch HDEV 4/4.1 Hollow Cone; DI piezoelectric; 140 to 200 bar fuel pressure
- High flow rate (fuel) ≈ 42 mg/ms @ 200 bar (277 mg for 6.6 ms or 20 CA @ 500 rev/min)
- Multiple injection

Injector: Denso Fan / Denso 10 Hole Alphabet / Bosch C270 (70° cone) / Bosch HDEV4 (Piezo, 200 bar, ≈ 40 cm³/s)
Air Admission – F-Air Injector (chamber experiments)

Air motion ‘look-see’ study
Quiescent environment; seeded air (powder suspended in chamber a priori of injection)
Air Admission – F-Air Injector (crossflow experiments)

Particle Image Velocimetry (PIV) study of injection into a crossflow. Part of feasibility study for using an fuel injector as an air injector (F-Air Injector)

(Tiago Carvalho, Dr de Sercey)

Experiments informed by research engine engine specifications:

• 80 mm duct section (74 mm bore)
• Mean bulk air motion associated with 500 rev/min
Air Admission – **F-Air Injector (crossflow experiments)**

Results at 4 bar and -500 μs ASOI (static crossflow):
Experiments were carried out with 4 different image measurement times, After Start of Injection (ASOI) and 4 different cross-flow speeds.

Images were post-processed using the Adaptive PIV method.
Air Admission – F-Air Injector (crossflow experiments)

Results for injection into crossflow (increasing crossflow velocity)

- Display options set to show U and V components of the flow velocity
- The U (horizontal) component is displayed with a contour plot
- The V (vertical) component is displayed with vertical blue vectors
In-cylinder air motion for the promotion of rapid combustion

Primary motion
Combustion chamber layout
Mixture preparation
In-Cylinder Air Motion – **Primary Motion**

**Tumble Dominated Motion**

http://fr.wikipedia.org/wiki/Piston_(m%C3%A9canique)#mediaviewer/File:Swirl_and_Tumble.svg

**Swirl Dominated Motion**

http://www.avtonline.co.uk/theworkshop/theworkshop/tumbleflapsandswirlflaps#_Ud04Hpm1Fhw
In-Cylinder Air Motion – **Chamber Layout**

Austin A-series (1990s)  

M-B 113 (2000s)  

Chrysler twin spark semi-hemi (in production)  

ALFA Romeo hemi; 10° CA ignition advance reduction (1990s)
In-Cylinder Air Motion – DI Gasoline

High fuel pressure (up to 200 bar) for rapid atomisation / evaporation

Reduced penetration (multiple fuel injections, 0.1 to 3 ms injection duration)

In-cylinder gas absolute pressure at injection up to 40 bar
In-Cylinder Air Motion – **DI Gasoline (Ford Ecoboost)**

**Typical leading edge technology for production SI engines**

In-Cylinder Air Motion – Disruptive Technology?

- Traditional high speed SI engines suggest ‘multi’ input hardware (fuel; spark; air)

- With the combustor of the split-cycle engine, we retain a fundamental chemistry governed flame speed / combustion time requirement, AND, lose the air motion contribution of the piston, which is a significant source of mixing inducing tumble motion. These both present challenges to rapid combustion

- What next?

http://www.spherelab.gatech.edu/
‘Strato-geneous’ (Vector Guided F-Air Injection)

Multiple stratified combustion fields are ignited ‘simultaneously’ to mitigate the time required for flame front propagation.
CEREEV proof of concept combustor machine

Experimental facility
Proof of concept(s) combustor machine
Proof of Concept – Experimental Facility

Hydra single-cylinder research engine; mean piston speed at 1 k rev/min = 2.5 m/s; $V_{chamber} = 325$ cm$^3$; bore/stroke = 0.98; rod/stroke = 2.1
Proof of Concept – Revised Geometry (phase 1)

Existing Inlet / Exhaust

Existing Inlet / Exhaust (or window)

‘Cassette’ concept
Proof of Concept – **MPP Head**

- Concept chamber and piston design for maximum compression (expansion) ratio
- Pre-chamber two stage combustion process
Prototype cylinder head and twin air injector assembly

- Design of injection ports air and fuel, piston crown, spark plug pocket
- Integration of standard or low lift camshafts in addition to EHV
- Exhaust manifold
- In-cylinder pressure transducer recess
Proof of Concept – **MPP Head**

- Concept piston crown with piston crown pre-chamber for two-stage combustion
Proof of Concept – MPP Head

- Concept chamber and piston design for maximum compression (expansion) ratio
- Layout features
Proof of Concept – MPP Head

Prototype engine kit / Ensemble de la concept !
Thank you – Merci Beaucoup!

The University of Brighton team, circa 2014