

The Recuperated Split Cycle - Experimental Combustion Data from a Single Cylinder Test Rig

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ABSTRACT

The conventional Diesel cycles engine is now approaching the practical limits of efficiency. The recuperated split cycle engine is an alternative cycle with the potential to achieve higher efficiencies than could be achieved using a conventional engine cycle. In a split cycle engine, the compression and combustion strokes are performed in separate chambers. This enables direct cooling of the compression cylinder reducing compression work, intra cycle heat recovery and low heat rejection expansion. Previously reported analysis has shown that brake efficiencies approaching 60% are attainable, representing a 33% improvement over current advanced heavy duty diesel engine. However, the achievement of complete, stable, compression ignited combustion has remained elusive to date. The challenge is to induct hot high pressure charge air close to top dead centre into the combustion cylinder and then inject and burn the fuel before the piston has travelled significantly down the expansion stroke. In this paper, we report results from a single cylinder split cycle combustion research engine. Stable, rapid combustion was achieved at 800 rpm and 1200 rpm at the retarded timings required for a split cycle engine. The calculated rate of heat release was more rapid than typically observed on conventional compression ignition engine suggesting good mixing of the fuel and air during induction. One dimensional cycle analysis was used to calculate the implications of the test results on the full engine cycle which indicated class leading brake efficiencies approaching and possibly exceeding, 60% are possible from a split cycle engine.

CITATION: Morgan, R., Jackson, N., Atkins, A., dong, G. et al., "The Recuperated Split Cycle - Experimental Combustion Data from a Single Cylinder Test Rig," *SAE Int. J. Engines* 10(5):2017, doi:10.4271/2017-24-0169.

INTRODUCTION

Long range - high load factor applications such as long haul freight transportation present a challenge in delivering a low carbon transport system. Light duty vehicles predominantly operate under transient, stop/start conditions over short journeys where the total energy required to reach the destination is within the practical limits of battery technologies. However, heavy duty powertrains commonly operate at much higher loads for longer periods of time. The storage of sufficient electrical energy in a battery for such missions and delivery of a practical re-charging solution would require technological breakthroughs that are currently not projected from fundamental research in the field. Significant benefits through vehicle

and system measures, such as kinetic energy recovery and improved aerodynamics are expected to deliver substantial improvements but the primary source of loss in the system, the prime mover, is more challenging. Reductions in powertrain friction and improvements in combustion efficiency are likely to deliver brake efficiencies as high as 50% from conventional compression ignition technologies [1]. The addition of waste heat recovery will also drive performance beyond 50%, but there is a broad consensus that brake efficiencies in the range of 50-55% represents the technology limit from an advanced compression ignition propulsion system with waste heat recovery.

To achieve higher efficiencies, new thermodynamic cycle concepts beyond the Diesel cycle are needed and have been highlighted by several roadmaps, such as those published by the UK Autocouncil [2]. Advanced, low heat rejection combustion systems such as Reactivity Controlled Compression Ignition (RCCI) [3] and alternative engine cycles, such as the double expansion cycle [4] and opposed piston cycles [5] have been suggested, but the authors review of the literature suggests efficiencies of 55% are the maximum that can be expected from these concepts. The recuperated split cycle engine was first proposed by Coney [6] and further developed by Jackson [7] and Dong [8, 9] as a radical departure from the conventional Otto and Diesel cycles. In the split cycle engine, the combustion and compression processes are separated into different chambers with intracycle waste heat recovery. Direct cooling of the charge air during compression to achieve isothermal compression is the key enabler to intracycle waste heat recovery and the high overall efficiency of the cycle. Several authors have predicted cycle brake efficiencies of over 55% and as high as 60% for large scale systems.

Splitting the internal combustion engines cycle into separate cylinders is not new; it was probably first described by Harry Ricardo in the 1908 Dolphin engine. Perhaps the most well-known split cycle concept has been the Scuderi engine [10] which reached an experimental prototype stage and successfully ran as a spark ignited light duty gasoline engine. A substantial project was undertaken in the 2000's by National Power in partnership with Ricardo to develop a 3 MW engine, referred to as the ISOENGINE. Very encouraging results from the compression part of the cycle were reported [11]. However, stable and rapid combustion had not been achieved when the project ended [12].

More recently, Ricardo, the University of Brighton and subsequently Hiflux Ltd. have completed several projects developing elements of the recuperated split cycle engine, to the point in which when the technology is ready for integration into a full demonstration engine. The work reported in this paper covers an extensive programme to investigate the air induction and combustion processes in the combustor cylinder of the engine. The paper first describes the recuperated split cycle engine and the challenges presented in achieving efficient combustion. The experimental test facility is then described and results from the test programme presented. Finally, analysis of the combustion data to determine the rate of heat release and the implications of the results on cycle efficiency are presented. The paper concludes with remarks on the implications of the results regarding the potential of the split cycle engine to support the delivery of a high efficiency clean engine, or more accurately; the integration of thermal energy recovery a 'thermal propulsion system' as described by the UK Automotive Council for the low carbon transport systems of the future.

THE SPLIT CYCLE ENGINE

The split cycle engine uses a variant of the recuperated Brayton cycle with two main differences; the compression process is near isothermal and reciprocating compressors and expanders are used rather than the turbomachines more commonly used in gas turbine prime movers. As such, the combustion process is intermittent, enabling higher combustion temperatures to be sustained within

material limits which typically cap the efficiency potential of a gas turbine. Referring to Figures 1 and 2 and indicative valve timings presented in table 1, the split cycle can be described as follows:

- 1-2 Induction of air into the compressor cylinder and isothermal compression.
- 2-3 Constant pressure heat transfer in a recuperator, recovering exhaust heat.
- 3-4 Induction into the combustor cylinder, (addition of fuel and heating through combustion.)
- 4-5 Expansion in the combustion cylinder.
- 5-6 Exhaust and heat recovery in the recuperator, recovering exhaust energy to the pre-combustion charge air.

The isothermal compression process in stage 1-2 could be achieved in several ways; (a) multi stage compression with intercooling (b) the addition of a non-evaporating heat transfer fluid such as water during the compression stroke, or (c) introduction of an evaporating fluid such as liquid nitrogen directly into the compression cylinder during the compression stroke. In the second option, the fluid is kept in the liquid phase to facilitate separation post compression and enable a closed fluid cycle. A significant mass flow of fluid is required to minimize the temperature rise, typically three times the charge air flow to prevent excessive temperature rise and boiling of the water [11]. Option 3 is particularly interesting as the liquid nitrogen will boil during the compression process and does work on the working fluid. The nitrogen will also act as a diluent and contribute to the control of NO_x emissions from the engine. This concept was investigated as part of the Cool R and Cryopower Innovate UK projects [13].

Table 1. Indicative split cycle valve timings

Compressor cylinder inlet	35° ATDC to 180° ATDC
Compressor cylinder discharge	-5° ATDC to 2° ATDC
Combustion cylinder inlet	-5° ATDC to 15° ATDC
Combustion cylinder exhaust	180° ATDC to -40° ATDC

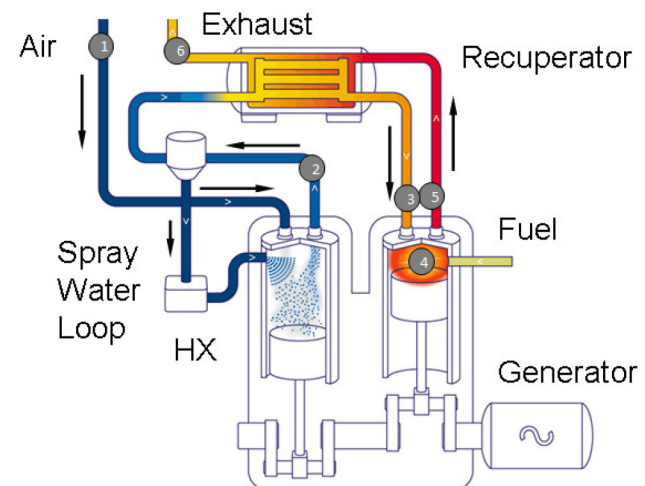


Figure 1. Schematic of the recuperated split cycle engine. [Downloaded from ascelibrary.org by AA Document Sharing Hub](#)

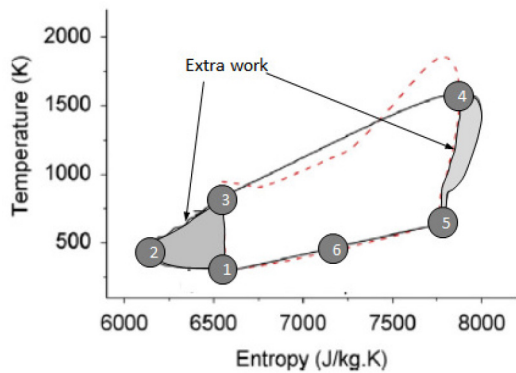


Figure 2. Temperature - Entropy diagram of a conventional diesel engine (red dashed line) and split cycle engines (solid black line) Numbers refer to the positions on the cycle described in Figure 1.

The benefit of isothermal compression can be shown by considering the ideal work of the two processes:

$$\text{Isothermal Process } W = RT \ln P_r$$

$$\text{Adiabatic Process } W = \frac{RT}{\gamma-1} (P_r^{\frac{\gamma-1}{\gamma}} - 1)$$

Where P_r is the pressure ratio, T the inlet temperature and R the gas constant and γ the ratio of specific heats. The potential work saving is therefore proportional to the pressure ratio and at representative diesel compression ratios, savings of over 20% are possible. But how can the benefits of isothermal compression be integrated into a power cycle? Previous analysis has shown brake efficiencies of more than 55% [9] and approaching 60% [6] are possible from the split cycle. Inspection of Figure 2 shows clearly where the savings arise:

- Firstly, the isothermal compression process significantly reduces the work of compression. By recovering exhaust heat, the thermodynamic conditions post recuperator (position 3 in Figure 1) are similar to those at ignition in a conventional diesel engine. The extra 'area' under the T-S diagram (see Figure 2) shows the extra work (for a given fuelling rate) recovered by combining isothermal compression with recuperation. It should be noted that isothermal compression alone will not deliver a substantial improvement in efficiency, as additional fuel must be burnt to achieve equivalent peak temperatures and pressures and hence, work recovery.
- Secondly, the expansion cylinder can operate at near adiabatic conditions and at a different expansion ratio to the compression cylinder compression ratio in a split cycle engine, without the pumping losses incurred in an Otto or Diesel cycle engine [14]. This is because the charge air is introduced at high temperature and pressure close to TDC to the combustion cylinder, therefore the combustion cylinder can be operated with a high chamber wall temperature without the normal penalty in volumetric efficiency observed on conventional engines through charge heating. The high wall temperature reduces heat losses and increases expansion work recovery. The reduction of heat loss combined with the higher expansion ratio results in more expansion work being recovered, further enhancing efficiency.

The relative contributions of the above factors in delivering a brake efficiency of over 50% were quantified by Dong [9]. The analysis assumed non-evaporative water cooling of the isothermal compressor and the findings are summarised below:

1. Separating the compression and combustion strokes into different cylinders and isothermal compression - 10%.
2. Exhaust recuperation - 20% improvement.
3. Low heat loss expansion and compression - expansion ratio optimization - 20%.

However, the realisation of a practical split engine cycle is not without challenges. Concentrating on challenges relating to the combustion cylinder, these can be summarised as:

- Induction of the charge air close to top dead centre, requiring rapid intake valve opening and closure with a short dwell period of about 30° crank angle.
- Unconventional air motion, with the intake air being choked across the inlet valves and very high in-cylinder air velocities during induction and fuel injection.
- Achieving stable complete combustion with retarded ignition timing (15-20° ATDC).
- High temperatures in the combustion chamber due to the loss of the charge air cooling observed in conventional engines.

The challenge of the split cycle combustion system can therefore be summarised as: get the air into the chamber in the shortest possible time, mix with the fuel and initiate combustion before the piston begins the expansion stroke.

EXPERIMENTAL TEST FACILITY

The experimental programme reported in this paper focused on the demonstration of the basic principles of split cycle combustion. A single cylinder Ricardo Titan engine was modified to replicate the combustion cylinder of a split cycle engine. The facility therefore represented only half the cycle, with the high temperature charge air being supplied by a separate air supply system.

The intake and exhaust valves were controlled using custom high speed electro-hydraulic actuators. Hydraulic control was selected to provide independent valve motion control during this earlier research phase of the project. The system used was a total loss hydraulically driven actuator. A flexible mechanical solution would be expected for a production engine and has been demonstrated in work by Scudari [15]. The cylinder head was modified to include a separate flame deck, with intensive cooling via drillings in areas of high thermal load. A two-piece piston with aluminium lower half and steel shallow open combustion chamber was used to (a) improve the temperature tolerance of the piston and (b) insulate the crown from the ring pack and under crown cooling, thereby reducing heat losses. It should be noted that at the start of the programme, how the fuel would burn in such an unusual combustion system was unknown and so the combustion chamber was not extensively analysed and the design was based on engineering judgement. A photograph of the engine installation is shown in Figure 3 and key engine data in table 2.