Applied Energy xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A novel split cycle internal combustion engine with integral waste heat recovery ☆

Guangyu Dong *, Robert Morgan, Morgan Heikal

School of Computing, Engineering and Mathematics, University of Brighton, BN2 4GJ, United Kingdom

HIGHLIGHTS

- A novel engine thermodynamic cycle is proposed.
- Theoretical analysis is applied to identify the key parameters of the thermodynamic cycle.
- The key stages of the split cycle are analysed via one-dimensional modelling work.
- The effecting mechanism of the split cycle efficiency is analysed.

ARTICLE INFO

Article history:
Received 29 August 2014
Received in revised form 17 December 2014
Accepted 5 February 2015
Available online xxxx

Keywords:
Split cycle
Isothermal compression
Isobaric combustion
Heat recuperation
Waste heat recovery

ABSTRACT

To achieve a step improvement in engine efficiency, a novel split cycle engine concept is proposed. The engine has separate compression and combustion cylinders and waste heat is recovered between the two. Quasi-isothermal compression of the charge air is realised in the compression cylinder while isobaric combustion of the air/fuel mixture is achieved in the combustion cylinder. Exhaust heat recovery between the compression and combustion chamber enables highly efficient recovery of waste heat within the cycle. Based on cycle analysis and a one-dimensional engine model, the fundamentals and the performance of the split thermodynamic cycle is estimated. Compared to conventional engines, the compression work can be significantly reduced through the injection of a controlled quantity of water in the compression cylinder, lowering the gas temperature during compression. Thermal energy can then be effectively recovered from the engine exhaust in a recuperator between the cooled compressor cylinder discharge air and the exhaust gas. The resulting hot high pressure air is then injected into a combustor cylinder and mixed with fuel, where near isobaric combustion leads to a low combustion temperature and reduced heat transferred from the cylinder wall. Detailed cycle simulation indicates a 32% efficiency improvement can be expected compared to the conventional diesel engines.

1. Introduction

The internal combustion engine (ICE) has been the incumbent power source for road transport applications for over 100 years. The high power density, good transient response and low cost make the ICE an excellent fit with the needs of road vehicles in an environment with an abundant supply of low cost liquid fossil fuels [1–3]. However, climate change and diminishing stocks of petroleum have led to a drive for higher efficiency solutions [4,5]. Alternative power converters such as fuel cells and batteries and increased electrification of the transmission between the prime mover and the wheels and downsizing of the ICE have also been proposed to improve the vehicle system performance [6]. Fuel cells and electrification are attractive for the passenger cars, but the high load factor of commercial vehicles is particularly challenging to such alternative powertrains [7,8]. Recent research [9] has shown improvements to the thermal efficiency of the ICE offers the most effective means of reducing energy consumption when compared to other solutions on the basis of both cost and overall efficiency (including fuel processing and logistics chain efficiencies).

Incremental improvements in the ICE efficiency through friction reduction and improvements in the combustion system will continue but savings will become increasingly difficult and costly [10]. Waste heat recovery such as organic Rankine cycles [9] and open gas and steam cycles [11] have been proposed and could deliver improvements of the order of 2–5%. Alternative combustion

☆ This paper is included in the Special Issue of Clean Transport edited by Prof. Anthony Roskilly, Dr. Roberto Palacin and Prof. Yan.

* Corresponding author. Tel.: +44 1273641950.
E-mail address: G.Dong@brighton.ac.uk (G. Dong).

http://dx.doi.org/10.1016/j.apenergy.2015.02.024
0306-2619/

Nomenclature

a	droplet surface area (m^2/kg)
atdc	after top dead centre
AFR	air fuel ratio
C	isothermal index
CA	crank angle
C_v	specific heat under constant volume
C_p	specific heat under constant pressure
CR	compression ratio
ER	expansion ratio
EVC	exhaust valve close timing
EVO	exhaust valve open timing
h	enthalpy (kJ/kg)
IVC	intake valve close timing
IVO	intake valve open timing
k	isentropic exponent
p	pressure
Q_{LH}	fuel heat release amount (kJ)
Q_{RE}	recuperated heat (kJ)
S	entropy
T	temperature (K)
T_{in}	intake air temperature (K)
T_{out}	outlet air temperature (K)
Δ	difference
u	heat transfer coefficient
V	volume

Greeks

γ	specific heat ratio
σ	recuperator effectiveness
η	thermal efficiency

Subscripts

LH	fuel lower heating value
RE	heat recuperation

systems, such as low temperature combustion to reduce heat losses [12] could also improve efficiency. However, these approaches, even when combined with waste heat recovery are likely to yield a maximum system efficiency of 45–50% [13]. Further improvements to efficiencies beyond 50% require a fundamental change to the ICE cycle.

The splitting of the compression and expansion strokes into separate cylinders has the potential to greatly improve the overall cycle efficiencies through:

(1) Reduction of the compression work by induction into a cool cylinder or direct cooling of the charge air during compression.
(2) Decoupling of the compression and expansion strokes effectively enabling a Miller cycle.
(3) High pressure waste heat recovery between the compression and combustion cylinders.

The concept of splitting the ICE cycle into separate cylinders is not new, and was first described by Ricardo in 1908 [14]. Coney [15] evolved the cycle to add isothermal compression and high pressure recuperation for stationary power applications. Water injection into the compression cylinder was proposed to achieve isothermal compression. A break efficiency of 60% was predicted using cycle simulation, but the contribution of the various features of the cycle was not described. Sud [16] proposed an alternative concept for road transport applications, that utilised a cool compressor cylinder and separate combustion cylinder with a close coupled transfer port. Both concepts were taken to lab demonstration, but were not commercialised. More recently, Atkins [17] has suggested a variant of the Coney engine that uses liquid nitrogen to cool the compressor, exploiting both the latent and sensible heat of the cryogenic fluid. It is claimed this overcomes the difficulties of carrying a water handling system on a road vehicle. Based the previous research, the split cycle engine has the potential to achieve a step improvement in efficiency comparing to convention IC engines. However, the dominate mechanisms, and the key parameters of the new thermodynamic cycle have not been investigated in previous studies.

To understand the efficiency potential of the split cycle under ideal and practical conditions, a parametric analysis of this novel cycle is conducted. This fundamental understanding is required to identify the optimal configuration of a split cycle engine. The contribution of various features of the cycle to the overall efficiency is discussed in detail in this paper. Classical analysis is first used to investigate the global trade offs of compression ratio and waste heat recovery on a reciprocating split cycle engine. Full cycle analysis is then used to investigate in detail key features of the cycle and the impact on the engine architecture. The paper concludes with a discussion on the potential of a split cycle engine in road transport and stationary applications.

2. Engine structure and theatrical thermodynamic cycle analysis

2.1. Description of the split engine cycle

A schematic of the 'isoengine' type of split cycle engine is shown in Fig. 1. Ambient air at stage point 1 is pre-compressed in the turbocharger, and then sent to the reciprocating compression cylinder (2). A certain amount of water is injected into the cylinder to cool down the air during compression, resulting in a quasi-isothermal compression process. After the compression stage (3), a high-pressure two-phase water/air mixture leaves the isothermal compressor, and the water is recovered in a separator. The liquid water is cooled and sent back to a water tank (5). A recuperator is installed downstream the separator to heat the high-pressure air (4). Within the recuperator, the air is heated by the exhaust flow (7), and then an intra-cylinder heat recovery process is achieved.

After the recuperation process (6), the fully preheated compressed air is fed to the combustion cylinders. As the combustion chamber intake valve opening time (IVO) is near to top dead centre (TDC), the diffusion of the combustion flame occurs in the expansion stroke of the cylinder. As a result, the combustion peak pressure is not increased significantly and a quasi-isobaric combustion process can be assumed. At the end of the expansion stage, the cylinder pressure is very close to the pressure in the exhaust pipe (7), so the exhaust stroke can be assumed as nearly isobaric as well. Based on the above processes, a complete split cycle is achieved.

2.2. Thermodynamic cycle analysis of the split cycle engine

The introduction to the split cycle engine indicates that both the combustion and exhaust stroke are nearly isobaric, and the

Please cite this article in press as: Dong G et al. A novel split cycle internal combustion engine with integral waste heat recovery. Appl Energy (2015), http://dx.doi.org/10.1016/j.apenergy.2015.02.024