Energy Conversion and Management 86 (2014) 8–19

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Investigation on gasoline homogeneous charge compression ignition (HCCI) combustion implemented by residual gas trapping combined with intake preheating through waste heat recovery

Hui Xie [a,*], Le Li [a], Tao Chen [a], Hua Zhao [a,b]

[a] State Key Laboratory of Engines, Tianjin University, No. 92, Weijin Road, Nankai District, Tianjin 300072, PR China
[b] Centre for Advanced Powertrain and Fuels, Brunel University, London, UK

ARTICLE INFO

Article history:
Received 27 March 2014
Accepted 5 May 2014

Keywords:
HCCI
CAI
Gasoline engine
Residual gas trapping
Intake preheating
Waste heat recovery

ABSTRACT

Homogeneous charge compression ignition (HCCI) combustion achieved by residual gas trapping suffers from the limitation of the low load extension and fuel economy penalties whilst achieved by intake preheating alone is limited by the high intake thermal requirement and waste heat recovery. In the presented research, systematic engine experiments were carried out on a single cylinder engine on the combined use of residual gas trapping and intake preheating to achieve optimized combustion and better fuel conversion efficiency in the HCCI operational range. The effect of different combinations between residual gas trapping and intake preheating on HCCI combustion was explored and analyzed. It was indicated that the implementation transition from residual gas trapping to intake preheating significantly influenced the fuel economy and emissions. The decreased loss resulting from changed valve configuration contributed much more than half of the fuel economy improvement. The variation in emissions depended both on the combustion temperature influenced by dilution charge and the in-cylinder distribution affected by implementation form. It was also demonstrated that the increased benefit became less when the intake temperature further went up. Thus a relatively reasonable compromise between intake thermal demand and engine efficiency could be achieved to optimize the HCCI combustion by combining waste heat recovery and residual gas trapping. Compared to negative valve overlap method alone, the supplementary of intake preheating by waste heat recovery provided 8–12% fuel economy improvement throughout the typical load range of HCCI combustion. Also the low load boundary was effectively extended to 0.8 bar, without suffering excessive increase in CO and HC emissions.

1. Introduction

Homogenous charge compression ignition (HCCI), also known as Controlled Auto-Ignition (CAI), has been recognized as one of important ways of achieving high thermal efficiency and ultra-low nitric oxides (NOx) emission [1]. As for gasoline engines, significant improvements in efficiency acquired by HCCI are mainly coming from the elimination of the pumping loss caused by intake throttling and the acceleration of heat release process.

In order to achieve the desired high in-cylinder temperature required for the multi-site auto-ignition, the use of high compression ratio and/or high charge temperature before compression is necessary [2]. A higher compression ratio reduces the high charge temperature requirement or even directly renders the air–fuel mixture to auto-ignition without charge preheating [3–5], together with the benefit of a higher thermal efficiency. But a higher compression ratio results in a higher pressure rise rate, which reduces the HCCI/CAI high load limit [5–7] and causes knocking combustion at full load in the spark ignition (SI) mode. Hence, a variable compression ratio (VCR) device is needed to meet the requirements of the gasoline engine across its entire operation [3,8]. However, the complexity, cost, and durability of the VCR mechanism have so far hindered its practical implementation in production gasoline engines.

Elevating in-cylinder temperature before compression is the most direct way to achieve controlled auto-ignition and it had used to investigate the basic characteristic of HCCI combustion by means of an electrical heater [9,10]. In addition, a fast thermal management (FTM) system has been proposed and tested to obtain HCCI combustion and SI operation in the same engine [11–15].

* Corresponding author. Tel.: +86 22 27406842x8009; fax: +86 22 27406842.
E-mail addresses: xiehui@tju.edu.cn (H. Xie), lile@tju.edu.cn (L. Li), chen_tao@tju.edu.cn (T. Chen), hua.zhao@brunel.ac.uk (H. Zhao).

http://dx.doi.org/10.1016/j.enconman.2014.05.022
0196-8904/

Nomenclature

CA10	crank angle at 10% burned mass
CA50	crank angle at 50% burned mass
CA90	crank angle at 90% burned mass
CO	carbon monoxide
COV	coefficient of variation
CV_{co}	calorific value of carbon monoxide
CV_{hc}	calorific value of unburned hydrocarbon
CV_{fuel}	calorific value of fuel
HC	hydrocarbon
HCCI	homogenous charge compression ignition
IMEP	indicated mean effective pressure
$IMEP_g$	gross indicated mean effective pressure
ISFC	indicated specific fuel consumption
ISHC	indicated specific hydrocarbon
ISCO	indicated specific carbon monoxide
ISNOx	indicated specific oxides of nitrogen
NOx	oxides of nitrogen
NVO	negative valve overlap
PVO	positive valve overlap
PMEP	pumping mean effective pressure
RGF	residual gas fraction
SI	spark ignition
TDC	top dead center
WHR	waste heat recovery

However the power consumed by the electrical heater is usually up to several kilowatts especially for a multi-cylinder engine, which accounts for a substantial part of the engine output and in turn sacrifices the improved fuel economy brought about by the HCCI combustion. On the other hand, two thirds of the thermal energy from combustion of fuel in average is dissipated to the coolant and carried away by hot exhaust gases. Therefore, it would be a more efficient way to preheat the intake charge with heat exchangers through waste heat recovery [3,11,12,16–19]. However, with a moderate compression ratio (9.5–11.5) of the gasoline engine, it would require an intake temperature up to 250–320 °C to achieve auto-ignition combustion of gasoline [9,20,21], which can hardly be attained through exhaust–intake heat exchangers due to the low exhaust temperature of HCCI combustion. The imbalance between the available exhaust heat and charge heating required becomes even more acute at low load, at which auto-ignition combustion demands more intake thermal supply as the burned gas and exhaust temperature decreases. Although, it is possible to improve such imbalance by more advanced exhaust valve opening and the use of intake throttling, the less expansion work and additional pumping loss associated with such measures will lead to a deteriorated fuel economy [22]. In addition, in view of the limited space in the engine bay and additional weight of heat exchangers, it would be advantageous to use a smaller heat exchanger by reducing the intake heating requirement for HCCI/CAI combustion.

Residual gas trapping typically achieved by the negative valve overlap (NVO) strategy is widely adopted to realize HCCI/CAI combustion in 4-stroke gasoline engines [23], which retains part of the hot burned gas in the cylinder by early exhaust valve closing. The trapped residual gas is characterized with high heat availability to heat the intake charge and high heat capacity to dilute the combustion [24]. The use of residual gas provides a more feasible and convenient way to achieve HCCI/CAI combustion, but it still faces some drawbacks. The trapping and recompression of burned gas result in pumping loss due to heat loss and hence lower fuel economy than the fully unthrottled combustion at some part load conditions, such as the stratified-charge lean-burn DISI combustion [25,26], and HCCI combustion obtained by other means [4,27]. In particular, the net indicated specific fuel consumption of HCCI/CAI combustion achieved by residual gas trapping deteriorates noticeably when compared with the intake charge heating that was assumed available from waste heat recovery [21]. In addition, the low load extension of HCCI/CAI combustion achieved with residual gas trapping is limited by instability and misfire, due to both the high dilution effect and insufficient heating of residual gas at low loads [28].

The above discussion indicates that the HCCI/CAI combustion achieved by residual gas trapping suffers from fuel economy penalties whilst achieved by intake preheating alone is limited by waste heat recovery. In order to overcome their limitations, it would be advantageous to combine both intake preheating and residual gas trapping. On the one hand, residual gas trapping provides a charge heating effect resulting in lower required inlet temperature [20,29]. On the other hand, replacing part of hot burned gas with preheated air would benefit for fuel economy improvement and low load extension.

Some researches on HCCI combustion have already employed both the two implementations. It is demonstrated that assisted by residual gas trapping by the positive valve overlap (PVO) method, the operation range of HCCI combustion achieved by intake preheating has been successfully extended to idle condition [30]. However, the quantity of residual gas captured by PVO was very limited and it was achieved at the expense of higher exhaust back pressure. Its low load extension was mainly contributed by the higher compression ratio. In another study [31], intake preheating was employed to maintain the combustion phasing of propane HCCI combustion obtained with residual gas trapping. A few studies were performed on the influence of the intake temperature on HCCI/CAI combustion obtained by the NVO method, it was found that the effect of inlet air temperature variation on HCCI combustion was insignificant when the intake air temperature was varied within the range of typical intake conditions [32], whilst at higher intake temperature it was found the intake charge heating could be used to control the maximum pressure rise rate [33] and combustion phasing limitation [34]. Recent research also revealed the effect of diluent composition on the rates of HCCI combustion [35]. In a systematic study of CAI combustion with PVO, Yang et al. [36] and Yang and Zhao [37] concluded that the highest fuel conversion efficiency would be obtained when the waste heat could be utilized to supply the intake air heating together with internally recycled burned gases through PVO. This was also confirmed by an analytical study on low load HCCI/CAI combustion operations [38].

However, few investigations have been reported on the implementation optimization in terms of fuel economy and low load extension regarding the HCCI/CAI combustion achieved with both residual gas trapping and intake preheating, and there is no related research carried out on the same engine with wide residual gas concentration and relative air/fuel ratio ranges to clarify this issue. In the presented work, systematic engine experiments were carried out on a single cylinder engine on the combined use of residual gas trapping and intake preheating to investigate the influence of implementation form and to optimize the combined implementation for better fuel conversion efficiency and lower load extension. Firstly, a set of experiments with a constant injected fuel