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Experimental investigation of the influence of internal and external EGR on the combustion characteristics of a controlled auto-ignition two-stroke cycle engine

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HIGHLIGHTS

- Investigate the effect of In-EGR, Ex-EGR and octane number on a CAI 2-stroke engine.
- Effect of In-EGR, Ex-EGR and octane number on combustion phasing of the engine.
- Effect of In-EGR, Ex-EGR and octane number on cyclic variability of the engine.
- Identify the CAI combustion upper and lower boundary for operating regions.

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ABSTRACT

A two-stroke cycle engine incorporated with a controlled auto-ignition combustion approach presents a high thermodynamic efficiency, ultra-low exhaust emissions and high power-to-weight ratio features for future demand of prime movers. The start of auto-ignition, control of the auto-ignition and its cyclic variability, are major concerns that should be addressed in the combustion timing control of controlled auto-ignition engines. Several studies have been performed to examine the effect of internal exhaust gas recirculation utilization on auto-ignited two-stroke cycle engines. However, far too little attention has been devoted to study on the influence of external exhaust gas recirculation on the cyclic variation and the combustion characteristics of controlled auto-ignition two-stroke cycle engines. The purpose of this study is to examine the influence of external exhaust gas recirculation in combination with internal exhaust gas recirculation on the combustion characteristics and the cyclic variability of a controlled auto-ignition two-stroke engine using fuel with different octane numbers. In a detailed experimental investigation, the combustion-related and pressure-related parameters of the engine are examined and statistically associated with the coefficient of variation and the standard deviation. The outcomes of the investigation indicates that the most influential controlled auto-ignition combustion phasing parameters can be managed appropriately via regulating the internal and external exhaust gas recirculation and fuel octane number. In general, start of auto-ignition and its cyclic variability are predominantly affected by external exhaust gas recirculation variation rather than internal exhaust gas recirculation. Furthermore, although the magnitude of low temperature heat release is substantially influenced by external exhaust gas recirculation variation, timing of low temperature heat release is more influenced by internal exhaust gas recirculation approach.

1. Introduction

Concerns about sustainable energy supply and environmental protection are exerting rigorous demands on modern internal combustion engines (ICEs) to improve fuel efficiency [1–4]. Controlled auto-ignition (CAI) combustion, also known as homogeneous charge compression ignition (HCCI), combines two major stages in ICE cycles, including preparation of premixed air and fuel and the compression of the homogeneous charge until the commencement of auto-ignition [5–7]. Accordingly, there will be no longer flame front (e.g., SI engine) and diffusion burning (e.g., diesel engine) [8–12]. To achieve CAI/HCCI combustion, high intake charge temperatures and substantial amount of charge dilution have to be present. In-cylinder gas temperature must be

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Nomenclature

Abbreviations

A/BTDC	after/before top dead center
CO_2	carbon dioxide
CAI	controlled auto-ignition
CI	compression ignition
COV	coefficient of variation
DOC	duration of combustion
Ex-EGR	external exhaust gas recirculation
HCCI	homogeneous charge compression ignition
In-EGR	internal exhaust gas recirculation
NO_X	nitric oxides
NTC	negative temperature coefficient
ON	octane number
PW	pulse width
STD	standard deviation
SOA	start of auto-ignition
SI	spark ignition
uHC	unburned hydrocarbon
WOT	wide-open throttle

Greek symbols and variables

θ_{HRRmax}	crank angle at HRR_{max}
θ_{LTHR}	crank angle at LTHR
θ_{Pmax}	crank angle at P_{max}
γ_{inh}	inherent residual gas ratio
γ_{ap}	applied residual gas ratio
$(\eta_{sc})_{inh}$	inherent scavenging efficiency
$(\eta_{sc})_{ap}$	applied scavenging efficiency
K_0, K_1, K_2	scavenging coefficients
k	heat capacity ratio
L_{ap}	applied corrected delivery ratio
L_{inh}	inherent corrected delivery ratio
m_{fuel}	fuel mass flow rate
T_{epc}	in-cylinder gas temperature at exhaust port closure
T_{epo}	in-cylinder gas temperature at exhaust port opening
T_{in}	intake gas temperature
T_{sc}	scavenging gas temperature
T_r	residual gas temperature
P_{epc}	in-cylinder pressure at exhaust port closure
P_{max}	maximum in-cylinder pressure

sufficiently high to initiate and sustain chemical reactions leading to auto-ignition processes [13–18]. In a typical two-stroke engine, the average charge temperatures at low and high loads are not high enough to maintain stable CAI combustion [19–21].

In the late 70s initial attempts concerning auto-ignited two-stroke engine resulted in significant improvements in the combustion stability, fuel efficiency and exhaust emissions [22–29]. Numerous investigations have performed using exhaust port throttling to increase the amount of trapped residual gas in the combustion chamber [15,30–37]. Duret et al. developed this technique in an air-assisted direct fuel injection two-stroke engine using computational and numerical approaches [38–40]. Transfer ports throttling was also attempted to improve the mixing between the fresh charge and the hot reactive residual gases (i.e., charge stratification) [41,42]. Several studies were also undertaken to examine the influence of the fuel formulation on two-stroke CAI combustion [43–45]. The effect of exhaust gas recirculation (EGR) on the CAI combustion characteristics was examined using exhaust port throttling strategy when the engine was run under WOT condition [46,47]. The effect of utilizing internal EGR by means of the negative valve overlap strategy (rebreathing) has been investigated in a switchable two/four-stroke engine [48–50]. The effect of EGR employed in the CAI combustion process was investigated numerically and experimentally [29,32,51]. In general, the overall effect of EGR utilization can be described as: (i) charge heating effect, (ii) heat capacity or Thermal effect, (iii) dilution effect and (iv) chemical effect [12,52]. The combined effect of these factors is assumed to regulate the ignition timing of combustion. Accordingly, the ignition timing will be advanced if the first effect is substantial, but will be retarded if the other three effects are more dominant. Cyclic variation in a CAI/HCCI combustion engine is attributed to (i) thermal stratification, (ii) charge inhomogeneity, (iii) AFR fluctuation and (iv) diluent fluctuation [12,17,18].

This experimental study aims to investigate the influence internal EGR, external EGR and fuel octane number (ON) on the control of CAI combustion phasing and its cyclic variability to better understanding of the engine operating ranges. The reports to date have focused on internal EGR rather than external EGR as far as the CAI two-stroke cycle engine is concerned. This investigation is the first of its kind undertaken to examine the effect of external EGR in comparison with internal EGR and fuel octane number changes on the combustion phasing and cyclic variability in a CAI two-stroke cycle engine.

2. Experimental apparatus setup

2.1. Test engine specifications and instrumentation

A single-cylinder, two-stroke, naturally aspirated, liquid-cooled engine was modified and used to meet the CAI experimental engine test rig requirements. The detailed specifications of the engine are shown in Table 1.

An electronically controlled port fuel injection system is used, in which an injector's pulse width (PW) regulates the flow rate of the injected fuel (control of AFR) into the intake port of the engine. In addition, the fuel injection system is equipped with an exhaust lambda sensor (i.e., closed loop control) to monitor the real-time AFR of the engine. The intake airflow temperature can be regulated via an electric heater device. Combustion-burned gases can be retained in the combustion chamber by exhaust port area restriction. These high temperature gases will be mixed with the incoming fresh fuel–air mixture, resulting in increase temperature and pressure after completion of the scavenging process. This strategy for burned gas utilization is known as internal exhaust gas recirculation (In-EGR). Consequently a ball-type valve (38 mm diameter) is installed in the exhaust pipe, i.e., 50 mm away from the exhaust port downstream side. Immediate after the In-EGR valve, a T-joint

Table 1
Specifications of modified single cylinder CAI two-stroke cycle engine.

Engine type	Single cylinder two-stroke case reed valve
Bore × stroke	59 × 54.5 (mm)
Displacement	149 (cm^3)
Scavenging type	Schnurle (Loop Scavenging)
Scavenging port timing	117.5 CAD A/BTDC
Exhaust port timing	82.5 CAD A/BTDC
Exhaust system	Expansion Chamber
Geometric compression ratio	11.3
Cooling system	Liquid cooled
Fuel supply system	Electronically controlled port fuel injection
Scavenging coefficients	K_0 = 0.02904, K_1 = −1.0508, K_2 = −0.34226