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Performance and emission characteristics of an IC engine under SI, SI-CAI and CAI combustion modes

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ABSTRACT

Controlled auto ignition (CAI) or, also known homogenous compressed ignition, is an advanced combustion technology allowing a lower NO_x emission and fuel consumption that can relieve the energy demand based on petroleum. The objective of this study is to determine the effects of spark ignition (SI), spark assist controlled auto ignition (SI-CAI) and pure CAI combustion modes on the performance and emissions in a modified IC engine. For this purpose, the emissions, performance, and heat release analyses for these combustion modes were obtained at two different engine speeds (1500–2000 rpm) and various excess air ratio (EAR) in the range of 1.0–1.3 with 0.1 increments for both wide open throttle (WOT) and 50% opening throttle positions. The results showed that CAI combustion mode produced lower NO_x emissions, although it resulted in higher CO and HC emission than those under SI and SI-CAI combustion modes. In addition, brake mean effective pressures (BMEP) were obtained as higher values under SI-CAI combustion mode. Therefore, SI-CAI combustion mode provided a wider operational range than that of the CAI combustion mode. However, the SI-CAI combustion modes resulted in high NO_x emissions, but relatively lower values than those under SI combustion mode.

1. Introduction

With the requirements of the decrease in emissions emitted from internal combustion engine and, the reduction in fuel consumption based petroleum, the automotive industry is continuously looking for alternatives to spark ignition (SI) and compression ignition (CI) internal combustion (IC) engines. A promising alternative is CAI engine. In principle, the fuel and air in a CAI engine are mixed together as in a conventional SI engine. The mixed charge in the cylinder is, then, compressed, and at the end of the compression stroke, the combustion is initiated by an auto-ignition in a similar way to a conventional CI engine [1]. Furthermore, CAI combustion permits un-throttled operating of an IC engine which reduces pumping losses. Therefore, CAI combustion includes properties of both the SI and CI combustion engine processes [2]. However, unlike SI and CI combustions, the ignition timing in CAI combustion cannot be controlled directly since it relies heavily on chemical kinetic process [3,4]. The combustion phasing of a CAI engine is affected by various parameters; such as ignitable properties of the fuel, fuel concentration, residual rate, mixture homogeneity, intake temperature, compression ratio [5]. Hence, CAI combustion is achieved by controlling temperature, pressure and composition of the mixture so that it spontaneously ignites in the cylinder. The characteristic of CAI allows combustion to occur in very lean or diluted mixture, resulting in low combustion temperature that leads to reduce the NOx emissions [6]. On the other hand, CAI combustion resulting in much lower temperature in an ultra-lean or a diluted mixture may cause greater amounts of hydrocarbon (HC) and carbon monoxide (CO) emissions relative to conventional SI and CI engines [7]. The other drawback of CAI combustion is the limited operating region due to knock, misfire and partial burn regions [8]. In a CAI engine at high load range, the combustion reactions take place simultaneously at many points in the charge mixture, which lead to rapid heat release giving rise to knock region. Therefore, the charge mixture is diluted with the residual gas or excess air to control the heat release rate. However, misfire can

Abbreviations: ATDC, after top dead center; BMEP, brake mean effective pressure; BSFC, brake specific fuel consumption; CAD, crank angle degree; CAI, controlled auto ignition; CH_4, methane; CI, compression ignition; CO_2, carbon dioxide; CO, carbon monoxide; EAR, excess air ratio; ECU, electronic control unit; EGR, exhaust gas recirculation; GDI, gasoline direct injection; HC, hydrocarbon; HCCI, homogeneous charged compression ignition; IC, internal combustion; IMEP, indicated mean effective pressure; NO, nitric oxide; O_2, oxygen; SI, spark ignition; SI-CAI, spark assisted controlled auto ignition; WOT, wide open throttle.

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occur in the low load range with a very high level dilution [9].

In order to attain desirable CAI operation and extend the operating range, the effects of intake air temperature [10,11], compression ratio [10,12], EGR rate [13–15], and fuel additives or compositions [16–21] have been investigated. In addition, many researchers have reported the characteristics of CAI combustion, including auto-ignition timing and temperature, combustion duration, and heat release rate [10,13,17,18]. Zhoa et al. [22] achieved stable CAI combustion without increasing the compression ratio and intake charge heating. They used variable camshaft timings to adjust the EGR rate in the test engine fueled by gasoline. In order to take full advantage of the CAI combustion technology, detailed analyses were carried out on the engine performance, heat release and combustion characteristics, emissions and the effect of gas exchange processes. Their analyses showed that the engine's performance and emissions were mainly affected by the trapped residual fractions and residual temperature. Stokes et al. [23] studied on a modified gasoline engine to compare part load fuel consumption, emission and combustion characteristics under SI and CAI combustion modes using twin mechanical variable valve lift train. Cho et al. [24] investigated the effects of internal exhaust gas recirculation on CAI combustion with a rapid intake compression and expansion machine using methane as the fuel. They tested various supply timings rate and equivalence ratios for EGR rate to evaluate their effects on the CAI combustion. They showed that multi-point ignitions and faster combustion were observed along with realized CAI combustion and the supply timing of EGR correlates with its temperature which subsequently affects the auto-ignition timing and burning duration. They also stated that CAI combustion in a leaner mixture is more difficult and misfire occurred frequently even at high temperature. Zhang et al. [25] studied on a 2-stroke gasoline direct injection (GDI) engine equipped with a poppet valve train to extend the operating range of CAI combustion by means of using a certain ethanol concentration in a mixture. The results showed that the CAI combustion can be readily achieved and the range of CAI combustion can be significantly extended in the 2-stroke cycle of the poppet valve engine. Mack et al. [26] wet ethanol fuel on HCCI engine's operating limits, emissions and heat release rate using various fraction of ethanol into water. Liu et al. [27] performed the experimental studies on an *n*-butanol fueled HCCI engine to determine the effect of air dilution and effective compression ratio on the combustion characteristics. They reported that air dilution and the decrease of effective compression ratio can retard auto ignition timing of *n*-butanol and decrease maximum pressure rise rate.

In some studies, spark-assisted CAI combustion, also known as spark-assisted compression ignition (SACI), has been studied to extend the operation range of CAI combustion engine [28–30]. In the SACI or SI-CAI combustion mode, the spark produces a propagating flame that burns a certain amount of the mixture and with the heat released by the fuel energy the temperature increases, which leads to auto ignition of the remaining mixture [31]. Wang et al. [32] investigated spark induced compression ignition in a gasoline HCCI engine using combustion visualization and engine experiments. They stated that the SICI combustion mode can be controlled by spark timing and an EGR rate and utilized as an effective method for high load extension on the gasoline HCCI engine. Urushihara et al. [33] studied on the test engine, having a compression ratio of 15 to perform the SI and CAI hybrid combustion by igniting a stratified charge near the spark plug first at the engine speed of 1200 and 2400 rpm. As a result, they reported that the maximum imep value could be increased but it was accompanied with higher NOx emissions than pure CAI operation. Wang et al. [34] investigated the effect of thermal stratification on the SI-CAI combustion characteristics. They found that intake temperature has a greater effect on the initial combustion, while coolant temperature has more significant effect on later combustion stage.

Previous studies have shown that CAI or HCCI and SI-CAI combustion has still remained with its drawback in practical use despite provided significant developments, which can bring about a multi-combustion modes IC engine.

As CAI combustion allows un-throttle operating as mentioned earlier, the results of the previous studies were reported for un-throttle operating to eliminate pumping losses. In this study, the effects of SI, SI-CAI and pure CAI combustion modes on the engine's emissions and performance were investigated for both wide open throttle (WOT) and, 50% WOT positions. The combination of hot external exhaust gas recirculation and heating intake air strategies were used to achieve SI-CAI and pure CAI combustion. The experimental studies for the combustion modes were performed at different engine speeds and excess air ratios (EAR) to compare the effects. In addition, the combustion characteristics were also analyzed with the heat release rates obtained from the first principle of thermodynamics during a cycle.

2. Experimental apparatus and test procedure

All experiments were carried out on a Lombardini LGW 523 four-stroke gasoline engine, which was modified to attain CAI with/without spark-assisted combustion in Erciyes University. The technical specification of the engine is given in Table 1. For CAI combustion, an 1800 W air heater was used for heating intake air to reach a certain value of temperature in the intake manifold and, an EGR line from the exhaust manifold to the intake manifold was also installed to increase the charge temperature in cylinder and utilize dilution effect of the exhaust gases. The standard gasoline of RON 95 fuel was used in this study and the value of auto ignition for gasoline is 1050–1100 K [1]. Therefore, with polytrophic approach, the intake manifold temperature was kept the value of 200 ± 2 °C ($\approx$473 K) to reach auto ignition temperature of gasoline in the vicinity of top dead center during (TDC) during a compression stroke. All engine temperatures were monitored using K type thermocouples and the intake temperature was controlled by an on-off controller. The EGR rate was controlled manually with an EGR valve considering the proportion of CO_2 emissions measured on intake manifold to exhaust manifold as in given the book by Stone [35]. A moderate EGR rate of 30% was kept constant in order to determine clearly the effect of EAR values and to avoid a misfire combustion region that may occur with a high level EGR rate during the experiments. An electronic card was developed to control the instant fuel consumption during CAI operation. The emulator, providing the adjustment of the fuel rate when the spark plug is cut off, was also designed for transition to CAI combustion mode.

The engine was coupled to a 50 kW hydraulic dynamometer that

Table 1
Engine specifications.

Engine type	4 Stroke – 2 cylinder
Model	LGW 523
Bore	72 mm
Stroke	62 mm
Displacement	505 cm^3
Compression ratio	10
Fuel injection	Port fuel injection
Injection pressure	3.5 bar
Fuel	Gasoline 95 RON
Coolant temperature	90 °C
Engine speed	1500, 2000 rpm