Energy Conversion and Management 95 (2015) 248–258

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Effect of main injection timing for controlling the combustion phasing of a homogeneous charge compression ignition engine using a new dual injection strategy

Pranab Das *, P.M.V. Subbarao, J.P. Subrahmanyam

Department of Mechanical Engineering, Indian Institute of Technology-Delhi, New Delhi 110016, India

ARTICLE INFO

Article history:
Received 18 September 2014
Accepted 6 February 2015
Available online 27 February 2015

Keywords:
Homogeneous charge compression ignition
Dual injection
Heat release rate
Main injection
Pilot injection

ABSTRACT

Homogeneous charge compression ignition combustion of diesel fuel is implemented using a novel dual injection strategy. A new experimental technique is developed to modify a single cylinder direct injection diesel engine to run on homogeneous combustion mode. Effect of main injection timing is investigated covering a range from 26 to 8 crank angle degrees before top dead center with an interval of 3°. Retarded main injection timing is identified as a control strategy for delaying combustion phasing and a means of controlled combustion phasing of direct injection homogeneous charge compression ignition combustion. Two load conditions were investigated and it was observed that at higher load, start of combustion depends more on fuel air equivalence ratio than main injection timing, whereas at low load, it significantly varies with varying main injection timing. Significant improvements in smoke and oxides of nitrogen emissions are observed when compared with the baseline conventional combustion. By studying different combustion parameters, it is observed that there is an improvement in performance and emissions with marginal loss in thermal efficiency when the main injection timing is 20° before top dead center. This is identified as the optimum main injection timing for such homogeneous combustion under the same operating condition.

1. Introduction

Homogeneous charge compression ignition (HCCI) combustion is a concept that combines both the strategies of conventional SI and CI combustion. A lean homogeneous air fuel mixture undergoes compression and auto ignites simultaneously resulting in very low smoke and NO_X emissions [1]. Studies have shown that HC and CO emissions dramatically increase when compared to conventional diesel combustion and the maximum attainable IMEP is limited because of knock and this remains a major problem in HCCI combustion. HCCI combustion strongly depends on in-cylinder mixture quality. Control of combustion phasing is the major issue that needs to be defined over a wide range of load and speed [2]. Effect of early single injection and double injection configurations on combustion and emission characteristics was investigated [3] in a single cylinder four stroke high speed DI diesel engine using a conventional jerk pump and a high pressure electronic injection system. The results showed a significant improvement in NO_X and smoke emissions with very early and split injection strategy. However, ISFC in two-stage injection was higher. For direct injection HCCI combustion, an early introduction of fuel is desirable [4] for better mixing and a low pressure injector is preferred to avoid wall impingement. The spontaneous auto-ignition of the charge resulted in very low emission of NO_X and smoke. Three different independent combinations of early-main (EM), pilot-main (PM) and early-pilot-main (EPM) were investigated in another study [5]. A little early injection helps in obtaining a very lean mixture throughout the entire cylinder both globally and locally and thus it significantly reduces smoke and NO_X simultaneously which are generally high in conventional diesel combustion due to locally rich mixture. Variation in single injection timing and spray included angle were investigated [6] and reported that a narrow spray angle is preferred to avoid wall wetting that in turn reduce HC emissions. Premixed equivalence ratio plays a predominant role

Abbreviations: TDC, after top dead center; BDC, bottom dead center; BSFC, brake specific fuel consumption; BTE, brake thermal efficiency; BTDC, before top dead center; CAD, crank angle degree; CI, compression ignition; DI, direct injection; HCCI–DI, homogeneous charge compression ignition–direct injection; MIT, main injection timing; PRR, pressure rise rate; RI, ringing intensity; RPM, revolutions per minute; SFC, specific fuel consumption; SI, spark ignition; TDC, top dead center.

* Corresponding author. Tel.: +91 955970910/8800267347.
E-mail address: iampranab.iitd@gmail.com (P. Das).

http://dx.doi.org/10.1016/j.enconman.2015.02.018
0196-8904/

Nomenclatures

ϕ	fuel air equivalence ratio	M_m	mass of the main fuel
γ	ratio of specific heats	°	degrees
M_p	mass of the pilot or premixed fuel		

than injection timing in the formation of the major pollutants. This study showed that a longer spray travel distance gives lower soot emissions; however CO increased. Late split injection [7] showed that a very low NO_X emissions of the order of 10 ppm can be achieved at medium load but soot, HC and CO would increase which needs to be controlled using after treatment devices. Multiple direct injections (MDI) are suggested [8] as one of the promising methods to achieve simultaneous reduction in smoke and NO_X emissions. The second injection helps in prolonging the heat release which reduces the knock propensity of the engine and thereby extend the load range of the HCCI combustion regime. Effect of fuel spray angle using double injection strategy was investigated [9] and showed that a wide spray angle and higher injection pressure significantly reduced smoke emission but NO_X emission increased. On the other hand, due to locally rich mixture narrow spray angle helps in reducing NO_X emission but this dramatically increases smoke emissions. A different combination of pilot and main injection timings were tried [10] and showed that retarded second injection significantly suppressed NO_X emissions from such engines with a penalty in CO emission and the same can be controlled by adjusting injection timings. Another study [11] reported that dual injection strategy has the potential of achieving low temperature combustion. They showed that early pilot injection and higher injection pressure results in very low smoke emissions. A range of early single Injection timings were investigated [12] and ultra low soot formation was identified with advanced combustion strategy. The major conclusions derived that BSFC, HC and CO emissions were generally higher due to early fuel injection. At higher load or higher equivalence ratio, SOC was found to advance noticeably and this can be delayed using cooled EGR. This in turn reduces peak temperature and pressure of the cylinder gas and thus helps in reducing NO_X emissions. Studies on single late injection technique [13] showed that NO_X and PM reduced simultaneously at low load conditions. Multiple pulse injection strategy was investigated [14] where seven early pulse injections followed by a main injection were used. It reported that at low load, PM and NO_X reduced simultaneously even without EGR but for higher load, EGR was a must. Multiple injection strategy was investigated in a study using CRDI electronic injection system [14] to achieve HCCI like combustion. They studied the effect of two pilot injections followed by a main injection at TDC in their experiments. They showed that a small quantity of early injected fuel and higher injection pressure is preferable for low temperature combustion in order to achieve low soot and NO_X Emissions. Another study [15] reported that with two pilot injections, combustion efficiency improved and IMEP obtained was 2.1% higher than baseline performance. Zhang et al. [16] investigated HCCI combustion using combination of port injection and direct injection technique. Ying et al. [17] investigated HCCI–DI combustion using similar experimentation technique to that of [16]. They [17] concluded that HCCI–DI mode of operation could increase load range of the engine when compared with HCCI operating mode. A similar experimentation technique (combination of port and direct injection) is adopted by Ma at al [18] and Hou et al. [19] to investigate effect of premixed ratio is in detail. Ganesh et al. [20] investigated external mixture formation technique to achieve HCCI combustion. A further study [21] by Ganesh et al. reported that EGR plays a significant role in extending the load range of HCCI combustion. Biogas fuelled HCCI combustion [22] is investigated in detail and ultra low emissions were achieved. The effect of internal EGR on HCCI combustion is investigated [23] and significant improvements were observed. A study as BD-HCCI [24] showed the effect of energy ratio of biogas and diesel fuel. They covered an intake temperature range of 100–135 °C and reported extremely low NO_X and smoke emissions were achieved. Exhaust heat recovery to achieve controlled intake air heating system for HCCI combustion is demonstrated in [25]. A comprehensive review on various aspects of Diesel fuelled HCCI combustion is presented in [26]. The NADI concept [27] demonstrated a technique to extend the HCCI load regime maintaining very low emissions. A recent study [28] showed that split injection timing and the split ratio largely affects emissions and combustion behavior of diesel low temperature combustion (LTC). Fang et al. [29] studied effect of main injection timing on HCCI combustion using a CRDI injection system. The range of main injection timing covered was from 10.6° to −5° ATDC in their investigation. An experimental and theoretical attempt [30] reported that injection timing has a significant role in mixture preparation, combustion and emission behavior of PCCI combustion engine. CRDI technique to achieve in-cylinder multi injection is most commonly used to achieve stratified controlled HCCI/DI combustion [31]. Our own study [32] on development of a novel experimentation technique to achieve HCCI combustion suggests that HCCI load range can be extended by controlling split ratio. The developed technique can be potentially used to develop HCCI–DI combustion engine without any serous engine geometry modification. This study [32] concluded that higher premixed equivalence ratio or higher engine load significantly advanced the combustion phasing of HCCI combustion.

After a comprehensive review of literature, it is realized that injection timing plays a significant role in HCCI–DI combustion. It is identified that very little information is available on main injection timing. It is well understood from available literature that, for a lean homogenous charge main injection timing initiates the combustion and therefore, a controlled HCCI–DI combustion phasing can be maintained. Several studies suggested that load range is much higher for HCCI–DI combustion as compared to HCCI combustion (fully premixed). But no HCCI–DI combustion studies are available on the understanding of the relation between engine load and main injection timing when a constant split ratio (highly premixed) is maintained. Furthermore, how knocking intensity is influenced by main injection timing is not available in literature.

Present study focused on combustion control strategy for HCCI–DI combustion using a new experimentation technique. 80% of the fuel was injected (Pilot injection) early during suction stroke (270 CAD BTDC) and rest 20% (main) fuel was introduced near TDC during compression stroke to trigger the combustion. The effect of main injection timings (MIT) for a wide range (26–8° BTDC) is investigated and analyzed in this paper. Two different load conditions are also compared to understand the effect of equivalence ratio. A detailed combustion, performance and emission behavior of HCCI–DI combustion is investigated. After a detailed analysis, optimum main injection is identified. Effect of main injection timing on knocking combustion is not at all available in literature. This study also covers this issue and interesting results were drawn.