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Combustion characteristics of a common rail direct injection engine using different fuel injection strategies

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ABSTRACT

Fuel injection parameters such as fuel injection pressure (FIP) and start of injection (SOI) timing significantly affect combustion, performance, emission and durability of a common rail direct injection (CRDI) diesel engine. In this study, a state-of-the-art single cylinder research engine was used to investigate the effects of FIP and SOI timings on engine combustion characteristics, which affects heat transfer and soot formation as well. The experimental setup consisted of an instrumented single cylinder engine with provision to vary the fuel injection parameters along with online high speed combustion data acquisition and analysis system. Experiments were conducted at constant engine speed (1500 rpm) at four different FIPs (300, 500, 750 and 1000 bar), four different SOI timings and different fuel injection quantities. Combustion characteristics of the engine were analyzed using exhaustive heat release analysis based on in-cylinder pressure data. In direct injection compression ignition (DICI) engines, fuel vaporization and heat transfer characteristics affect fuel-air mixing, which is also influenced by the FIP and SOI timings. These injection parameters significantly control the rate of pressure rise (ROPR), and heat release rate (HRR), which in-turn affect the heat transfer from the engine cylinder as well as the engine power output. Therefore, it is necessary to optimize the fuel injection parameters to develop efficient and clean combustion diesel engines.

1. Introduction

Internal combustion (IC) engines are the major power plants for transportation sector as well as for stationary applications. These engines are widely used in automotive, agricultural and industrial applications due to their high-energy conversion efficiencies and robustness [1]. Current compression ignition (CI) engines are operated by mineral diesel derived from crude petroleum refining. Higher particulate matter (PM) and oxides of nitrogen (NO_x) in emissions and the resulting trade-offs between them are the major drawbacks of conventional diesel engines. Many researchers have shown that PM emitted from diesel engines are generally 10–100 times higher than gasoline fueled SI engines [2–4]. PM emitted from diesel engines significantly affect performance and durability as well as they cause harmful environmental and health effects. Higher PM emissions lead to lower fuel economy due to incomplete combustion, and cause fuel loss. Interaction of PM with engine components also results in increased wear of the engine components. Currently, researchers are focusing on further improvement of diesel engines in terms of both emissions and combustion, along with utilization of various alternate fuels [5]. To comply with increasingly stringent emission norms, optimization of engine operating parameters is required with the objective of reduced emission and improved engine performance. Until now, various advanced technologies have been developed such as common rail direct injection (CRDI) system, turbocharged system, diesel particulate filter (DPF) and diesel oxidation catalysts (DOCs) to obtain superior engine performance along with lower emissions from the diesel engines. These techniques demand sophisticated and expensive electronic sensors and actuators for use in passenger/commercial vehicles.

The combustion, emissions and performance characteristics of a CRDI diesel engine are directly affected by several factors including fuel injection pressure (FIP), start of injection (SOI) timing, fuel quantity injected, number of injections, combustion chamber design, number of nozzles, spray pattern, etc. However, some of these parameters also affect engine power output indirectly, and heat transfer is one such important parameter. Heat transfer is closely related to different in-cylinder phenomenons namely flame quenching due to cold cylinder walls, knocking due to excessive rate of pressure rise (ROPR) and

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frictional losses due to degradation of lubricating oil at high temperatures [6]. At high loads, in-cylinder temperature exceeds the design limits, leading to reduction in lubricating oil viscosity, resulting in higher frictional losses. Overheating of the piston, exhaust valve, cylinder head, valve seats and other components is also harmful because this may lead to piston burnout and cracks in the combustion chamber walls, eventually leading to catastrophic destruction of the engine [7]. Heat transfer also affects charge and wall surface temperatures, which have important influence on the formation of pollutants such as NOx, carbon monoxide (CO) and unburned hydrocarbons (HCs) [8,9]. In-cylinder fluid motion and heat transfer play an important role in controlling the temperature of these components [10]. To gain insights into how flow-field interacts with fuel injection and combustion and how this interaction influences wall heat transfer coefficient, Tanov et al. [11] performed optical measurements of different fuel injection strategies to investigate differences between the turbulent kinetic energy (TKE) field and how it differs from the motored engine case. They reported that in-cylinder thermodynamic states at the time of fuel injection and start of combustion (SOC) are critical parameters, which govern the heat transfer from the engine cylinder. Therefore, SOI timing is an important parameter, which not only affects the combustion but also controls the heat transfer from the engine cylinder.

Combustion and emissions of a diesel engine are significantly influenced by the quality of fuel atomization/sprays; therefore improvement in fuel atomization significantly affects the engine performance [12,13]. FIP in a diesel engine varies from 200 to 1600 bar, largely due to innovations in the CRDI system development landscape. In order to atomize the liquid fuel into small droplets, very high pressure difference across the injector nozzle is necessary in order to enable rapid atomization/evaporation of fuel and high spray jet penetration in the combustion chamber. Small droplets and high penetration of fuel jet improves the fuel-air mixing, which is necessary for shorter ignition delay and more complete combustion. When FIP is relatively lower, fuel droplet diameters tend to become larger, therefore ignition delay increases. This leads to higher in-cylinder pressure and ROPR during the premixed combustion phase. When FIP is increased, fuel droplet diameters become smaller and the physical delay shortens. This leads to improved fuel-air mixing, therefore smoke level and CO emission become lower. However, too high a FIP causes shorter ignition delay, which leads to in-homogeneity in fuel-air mixture, resulting in relatively lower combustion efficiency [14,15]. Increasing FIP also increases the premixed phase combustion heat release and early part of mixing controlled phase combustion heat release, which raises the steady state heat transfer [16].

Heat from the combustion gases is transferred to the cylinder bore by convection, followed by conduction through the piston rings and skirt [7]. In the process of heat transfer from the combustion gases to the coolant through metallic components, all the three modes of heat transfer are involved. From the gases to the metallic components, heat is transferred mainly by forced convection with some contribution by radiations. Radiative heat transfer is mainly governed by the quantity of soot produced during combustion, which is significantly affected by FIP and SOI timings. In diesel engines, radiations may account for > 20% of the total in-cylinder heat transfer [7]. However, in modern engines, the fraction of heat transfer by radiations has significantly reduced due to formation of lower number of soot particles [13]. Bruneaux [17] investigated spray characteristics of a CRDI fuel injection system in a high pressure, high temperature experimental test cell by creating conditions similar to the ones that exist in a diesel engine at the time of fuel injection. It was observed that higher FIP enhanced atomization at the nozzle exit and resulted in higher fuel distribution in the vapor phase, leading to improved fuel-air mixing. To date, several studies have been conducted to improve diesel combustion and emission characteristics by enhancing spray atomization via suitable optimization of fuel injection parameters for alternate fuels [18–28]. It has been shown that, change in SOI timing altered the in-cylinder pressure and temperature at time of injection. Consequently, important factors, which influenced emissions such as ignition delay, fuel adherence to walls, and squish were also significantly affected [24]. In other studies, it was shown that earlier SOI timing caused lower in-cylinder air temperatures and pressures; therefore ignition delay increased and vice-versa. It was concluded that variation in SOI timing strongly influenced exhaust emissions, especially NOx emissions due to changing maximum in-cylinder temperature [29–32]. Hountalas et al. [29] performed experiments using advanced SOI timing and EGR to assess their effect on engine efficiency. A range of SOI timings for efficiency improvement was calculated without affecting NOx and soot levels significantly. Tao et al. [30] performed experiments using retarded SOI timings and reported significant reduction in emissions of NO_x. Parlak et al. [33] investigated the effect of SOI timings on the brake specific fuel consumption (BSFC) and NOx emissions in a low heat rejection (LHR) indirect injection (IDI) diesel engine. In the experiments, small variation in SOI timing (38° bTDC to 34° bTDC) led to 40% reduction in NOx emissions along with 6% reduction in BSFC. Similarly, Nwafor [34] studied the effect of advanced SOI timings on engine performance and exhaust emissions in a dual-fuel CI engine and reported a measurable reduction in CO_2 and CO emissions. Further, it was shown that advanced injection timings led to slightly increased BSFC and reduced BTE [27]. Yang et al. [35] carried out experiments to investigate the effect of fuel injection timing on particulate emissions using a dual-fuel engine. They reported that in-cylinder gas density at the instant of start of fuel injection plays an important role in the fuel-air mixing process. At the time of fuel injection, higher gas density helps in spray disintegration, resulting in more homogeneous fuel-air mixture formation. However too retarded SOI timing tilted the combustion more towards mixing controlled combustion phase, which led to higher soot formation and consequently higher heat losses.

Effect of heat transfer on engine power output has been investigated by many researchers however a qualitative correlation between the heat transfer and combustion characteristics of a modern engine has not been thoroughly investigated. Optimization of FIP and SOI timings is necessary in order to obtain lower BSFC; lower heat losses, superior combustion and lower emissions. This study was carried out in a research engine with varying FIP and SOI timings, which showed the effect of these parameters on engine combustion characteristics.

2. Experimental setup

Experiments were performed in a single cylinder research engine (AVL, 5402) coupled with an transient dynamometer (Wittur Electric, 2 S B 3). Schematic of the experimental setup is shown in Fig. 1. Technical specifications of the test engine are given in Table 1. In IC engines, an improved cooling system can potentially reduce thermal stresses on various engine components, resulting in longer engine life however engine cooling must be controlled optimally. Fast transient heat flux from the combustion products to the cylinder liner and transient heat loss to the cooling passages affects the overall engine efficiency and pollutant formation. The experimental setup was equipped with lubricating oil, fuel and coolant conditioning systems, which maintained the respective temperatures constant at 90 °C, 30 °C and 60 °C respectively for the entire test duration.

The engine was fitted with a CRDI system with provision for control and measurement of FIP and SOI timings and a Bosch common rail system capable of pressurizing fuel up to 140 MPa. Fuel was supplied to the common rail via a high-pressure fuel pump. This high pressure rail was connected to a Bosch injector with a 5-hole nozzle (0.18 mm hole diameter) and spray cone angle of 142°. The needle lift of the injector was 0.2 mm with steady flow rate of 12.5 ml/s. An intake air flow measurement system (ABB, Sensy-flow P), gravimetric fuel flow meter (AVL, 733 S.18) and piezoelectric pressure transducer (AVL, QC34C) were used to measure air-flow rate, fuel quantity and in-cylinder pressure respectively. For measuring the SOI timing, a current clamp

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