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Impact of low temperature combustion attaining strategies on diesel engine emissions for diesel and biodiesels: A review

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ABSTRACT

Simultaneous reduction of particulate matter (PM) and nitrogen oxides (NO_x) emissions from diesel exhaust is the key to current research activities. Although various technologies have been introduced to reduce emissions from diesel engines, the in-cylinder reduction techniques of PM and NO_x like low temperature combustion (LTC) will continue to be an important field in research and development of modern diesel engines. Furthermore, increasing prices and question over the availability of diesel fuel derived from crude oil have introduced a growing interest. Hence it is most likely that future diesel engines will be operated on pure biodiesel and/or blends of biodiesel and crude oil-based diesel. Being a significant technology to reduce emissions, LTC deserves a critical analysis of emission characteristics for both diesel and biodiesel.

This paper critically investigates both petroleum diesel and biodiesel emissions from the view point of LTC attaining strategies. Due to a number of differences of physical and chemical properties, petroleum diesel and biodiesel emission characteristics differ a bit under LTC strategies. LTC strategies decrease NO_x and PM simultaneously but increase HC and CO emissions. Recent attempts to attain LTC by biodiesel have created a hope for reduced HC and CO emissions. Decreased performance issue during LTC is also being taken care of by latest ideas. However, this paper highlights the emissions separately and analyzes the effects of significant factors thoroughly under LTC regime.

1. Introduction

The diesel engine is the most efficient type of internal combustion engine, offering good fuel economy and low carbon dioxide (CO_2) emission [1]. Unfortunately, it is also a source of particulate matter (PM) and nitrogen oxides (NO_x), both of which are now subjected to legislative limits because of their adverse effects on the environment and human health [2]. In the last few years, diesel engines have been subjected to progressively stringent emission control standards; especially as far as NO_x and PM emissions are concerned. Fig. 1 shows this trend for Europe (Euro 2, 1996–Euro 5, 2008), the United States (US04–US10) and Japan. In order to meet the requirements of future emission standards, emission of these substances, as well as carbon monoxide (CO) and hydrocarbon (HC) emissions must be reduced significantly. Three general methods can be applied to the engines to meet lower regulated emission limits, viz. alternation of fuels [3,4], alternation of combustion processes and after-treatment of the exhaust [5]. Considerable progress has been made on both combustion and catalyst control pathways to reduce emission. Diesel particulate filters (DPF) for PM filtration and selective catalytic reduction (SCR) of NO_x are now available for after-treatment of engine out emissions. Nevertheless, to minimize the cost and complexity of exhaust after-treatment systems as well as for potential fuel economy penalties—considerable research efforts have also focused on the in-cylinder control of emissions through the application of low-temperature combustion (LTC) techniques.

LTC is now widely demonstrated covering light-duty [7–11] to heavy-duty [12–14] engines. It is the concept at the heart of advanced diesel combustion. LTC is a general term for Homogeneous Charge Compression Ignition (HCCI) combustion, and Premixed Charge Compression Ignition (PCCI) combustion [5]. To explain the theory of LTC, Akihama et al. [15] simulated combustion by a compression ignition (CI) 3D-CFD KIVA2 model and plotted local equivalence ratio (Φ) vs. flame temperature (T) for the stratified combustion process. This particular figure showed the NO_x–PM trade-off related to conventional diesel combustion, where at the edge of spray flame, fuel lean zones produce abundant NO_x and fuel rich zones inside the spray flame produce abundant soot (an

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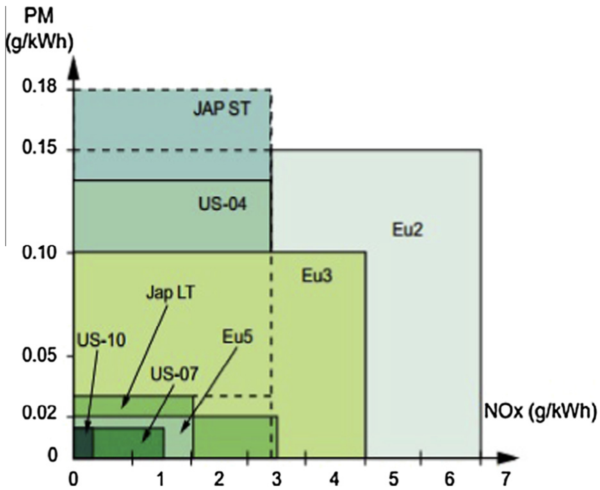

Fig. 1. Decreasing limit of NO_x and PM [6].

element of PM). With their model and Φ–T map they explained that LTC takes place at temperatures below the formation regime of NO_x and at local equivalence ratios below the formation regime of diesel soot. As mentioned earlier, these systems can be divided into two categories [16]. Those in which the combustion phasing is decoupled from the injection timing and the kinetics of the chemical reactions dominate the combustion, are in the first category which is known as HCCI mode. In the second category, combustion phasing is closely coupled to the fuel injection event which is termed as PCCI mode. In the former category, air and fuel are thoroughly premixed in such a way that at the start of the combustion, the mixture is nearly homogeneous and characterized by an equivalence ratio, which is lower than 1 everywhere. For the second category, pre-mixing occurs between the fuel injection and start of combustion event, but significant regions exist where the equivalence ratio is greater than unity at the start of the combustion. Fig. 2 shows the plot of local equivalence ratio (Φ) vs. flame temperature (T) with different combustion mechanisms. It can be seen that, NO_x forms in the lean mixture zone where flame temperature is above 2200 K, whereas soot forms in the rich mixture zone above 1800 K. Conventional combustion overleaps the formation zones of NO_x and soot, but LTC techniques like HCCI and PCCI avoid these zones and reduce NO_x and soot simultaneously. Recently, a new approach of LTC, Reactivity Controlled Compression Ignition (RCCI) has been proposed by several authors [17–19]. This technology has the potential to overcome some of the limitations of HCCI and PCCI.

The objective of this article is to present the state of the art of the effects of different LTC mode (HCCI, PCCI, RCCI) attaining

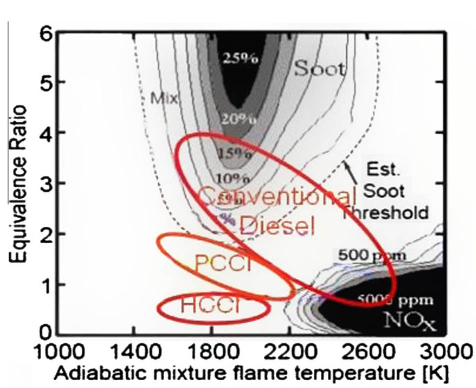

Fig. 2. Plot of local equivalence ratio vs. flame temperature with different combustion mechanisms [17].

strategies on particular diesel emissions (NO_x, PM, CO, UHC) using both petroleum diesel and biodiesel. The attainment of these strategies primarily depends on some factors like, application of exhaust gas recirculation (EGR), change in injection timing (IT) & injection pressure (IP), variation in compression ratio (CR) hence operating load, changes in fuel blends, etc. Therefore the analysis has been governed by these significant factors surely. To provide a complete overview of the whole scenario, more than 150 technical articles have been reviewed to collect significant information related to this article's objective. At first, the article briefly introduces the LTC strategies and then analyzes how the attainment of these strategies may affect the emissions for petroleum diesel and biodiesel respectively. Though LTC mode has a positive impact on NO_x and PM emissions but many of the researchers have reported reduced performance during LTC modes [20,21] due to higher rates of EGR and incomplete combustion. Impact of LTC modes on engine performance is also briefly presented here in this article.

2. LTC strategies

2.1. Homogeneous Charge Compression Ignition (HCCI)

HCCI engine is a combination of SI (homogeneous charge spark ignition) and CI (stratified charge compression ignition) engines with a sense that it uses premixed charge like SI engine but depends on autoignition like CI engine [22]. In HCCI, fuel is injected well before the combustion event which allows the homogeneous mixture of air–fuel. This homogeneous mixture initiates combustion simultaneously at different sites of the combustion chamber unlike SI (flame propagation) or CI (locally rich flame front) engines. With diesel fuel, HCCI combustion shows two-stage heat release. The first stage is low temperature kinetic reactions and the second stage is main heat release regime [23]. HCCI autoignition is controlled by low temperature chemistry and the main heat release is dominated by CO oxidation [24]. The main advantage of the HCCI combustion over conventional combustion mode is the reduction of NO_x and soot in the exhaust. Though the concept gives higher indicated thermal efficiency, inability to control the combustion phasing has led the researchers to try different combustion control strategies e.g. port fuel injection [25,26], early direct injection [27,28], multiple fuel injection [29,30], compound combustion technology [31,32], narrow angle injection [33–35], late direct injection [36,37], variable inlet temperature, variable valve timing, internal or external EGR, etc. [22]. In addition, use of alternative fuels and fuel blends according to compression ratios and operating conditions have much potential to control the combustion phasing [22,38,39]. Actually, fuels with different autoignition points can be blended at varying ratios to control the ignition point at various load–speed regions [40]. This has yield alternative fuels to be tested in HCCI engines [41–51]. In diesel–fueled HCCI engines, these combustion control technologies are not often used alone. The combination of several strategies helps in achieving better effects on the combustion mechanism.

2.2. Premixed Charge Compression Ignition (PCCI)

Premixed charge compression ignition or the partially premixed charge compression ignition (PPCI) evolved from the HCCI combustion mode for the sake of better control over the start of combustion (SOC). In-cylinder homogeneity causes rapid combustion by simultaneous ignition throughout the cylinder space and produces great combustion noise in the HCCI mode. It is also very tough to control the combustion phases in HCCI mode. PCCI process is introduced to solve these problems. It is not fully homogeneous like HCCI. It achieves desired ignition delay through enhanced charge motion,