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Particulate emissions from laser ignited and spark ignited hydrogen fueled engines

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A B S T R A C T

Exponentially increasing energy demand and stricter emission legislations have motivated researchers to explore alternative fuels and advanced engine technologies, which are more efficient and environment friendly. In last two decades, hydrogen has emerged as promising alternative fuel for internal combustion (IC) engines and vehicles. For gaseous fuels, laser ignition (LI) has emerged as a novel ignition technique due to its superior characteristics, leading to improved combustion, engine performance and emission characteristics. Numerous advantages of LI system such as flexibility of plasma location, lower NO_x emissions and capability of igniting ultra-lean fuel–air mixture makes LI system superior compared to conventional spark ignition (SI) system. This study experimentally compares particulate emissions from hydrogen fueled engine ignited by LI and SI systems. Experiments were performed in a constant speed engine prototype, which was suitably modified to operate on gaseous fuels using both LI as well as SI systems. Particulate were characterized using engine exhaust particle sizer (EEPS) spectrometer. Results showed that LI engine resulted in relatively higher particulate number concentration as well as particulate mass compared to SI engine. In both ignition systems, particulate emissions increased with increasing engine load however rate of increase was relatively higher in LI system. Relatively larger count mean diameter (CMD) of particulate emitted from SI engine compared to LI engine was another important observation. This showed emission of relatively smaller particles in larger numbers from LI engine, compared to baseline SI engine.

Introduction

Conventional diesel engines are used in various light and heavy-duty applications due to higher power output, higher brake thermal efficiency (BTE) and greater robustness compared to their gasoline counterparts. However, emission of different toxic gaseous species and carbonaceous particulate matter (PM) limit their applications. To control harmful emissions and to comply with prevailing emission regulations, automotive industry is exploring the possibility of deploying advanced combustion techniques such as homogeneous charge compression ignition (HCCI) [1], premixed charge compression ignition (PCCI) [2] etc., in addition to using after-treatment devices such as diesel oxidation catalysts

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(DOC) [3], diesel particulate filter (DPF) [4] etc. and deploying alternative fuels such as biofuels [5–9], gaseous alternate fuels [10–13] etc. in IC engines. These steps reduce engine out emissions significantly however increased complexity and cost of vehicles remain the major issues of these techniques. On the other side, rapid depletion of non-renewable petroleum reserves is alarming and automotive industry needs to explore alternative energy resources for sustaining the burgeoning transport sector. To resolve this, researchers are focusing on using alternative fuels in transport sector such as biodiesel [5–8], straight vegetable oils (SVOs) [9], primary alcohols [8], compressed natural gas (CNG) [10], hydrogen [11], hydrogen-CNG (HCNG) mixtures [12], liquefied petroleum gas (LPG) [13], etc. Amongst these alternative fuels, most fuels have a common concern of particulate emissions, which have harmful effects on the human health [14,15].

Particulate formation in the engine combustion chamber can be reduced by homogeneous fuel–air mixing [16]. Therefore researchers performed experiments using gaseous fuels, which resulted in homogeneous fuel–air mixture due to their higher diffusivity [10–13]. They reported that use of gaseous fuels results in lower particulate mass emission however particulate number concentration still cannot be neglected. They suggested that presence of carbon atoms in the fuels is the main reason for particulate formation. Therefore zero/low carbon fuels such as hydrogen, dimethyl ether (DME) and CNG are very attractive and have also been explored [17]. Amongst these test fuels, hydrogen has been found to be most suitable fuel for IC engines due to its superior properties and ultra-low emission potential. Hydrogen is an odorless, non-toxic and renewable alternative fuel, which can be produced through electrolysis of water, gasification of coal, biomass and steam reformation of natural gas [18]. Hydrogen combustion produces only water vapors as combustion product therefore it can be a potentially a promising sustainable alternative fuel candidate for next generation engines. Several researchers experimentally verified improved combustion, engine performance and emission characteristics of hydrogen. Gatts et al. [19] reported that addition of hydrogen along with conventional fuels led to improved performance and ultra-low emissions at high loads. Singh et al. [20] carried out engine experiment using mineral diesel, gasoline, CNG, HCNG and hydrogen and reported that hydrogen fueled engine emitted the lowest particulate numbers as well as particulate mass amongst all test fuels. However, significant number of particulate emitted by gaseous fuels is another concern because relatively smaller size particles emitted by gaseous fuels increase the associated health risk. To investigate the source of particulate from zero-carbon fuels, Singh et al. [20] carried out a comprehensive study and suggested that all particulate were not formed due to combustion of fuel alone. Significant amount of particulate were formed due to incomplete combustion of lubricating oil as well. Organ-metallic additives in the lubricating oil undergo evaporation during combustion and they condense during cooling of exhaust gas, resulting in formation of various organic and inorganic compounds getting adsorbed on particulate surfaces [21]. During post-combustion reactions, these compounds act as soot precursors and promote particulate formation. Khalek et al. [21] reported that engines with lower particulate emissions favored by re-nucleation of lubrication oil additives in the exhaust, lead to higher particulate emissions. Significant contribution to the particulate emission from lubricating oil pyrolysis was also reported by Zielinska et al. [22]. They reported that the polycyclic aromatic hydrocarbons (PAHs) emissions from gasoline engines showed greater similarity with the composition of PAHs present in the lubricating oil rather than gasoline. Influence of particle size on human health has also increased scientific curiosity in other measures of particulate emissions such as their size, number and surface area. Relatively smaller particles (D_p < 50 nm) have more severe impact on human health compared to relatively larger particles (D_p > 100 nm). Smaller particles have higher probability to be inhaled and deposited in the human respiratory tract and alveolar region by diffusion [23]. Toxicological studies have shown that fine particles (D_p < 2.5 μm) have higher toxicity per unit mass of particulate, compared to coarse particles (D_p < 10 μm) [23].

Apart from particulate emissions, Pal et al. [24], Dharamshi et al. [25], and Das [26] reported that pre-ignition and backfire of hydrogen engine leads to excessive noise at higher engine loads. These issues could be resolved by using an electrode-less ignition system for igniting the hydrogen–air mixtures in the engine combustion chamber. Previous studies showed that the slight variation in fuel properties, method of ignition and engine operating conditions significantly affect particulate characteristics [20]. Therefore it becomes necessary to investigate particulate emission characteristics of laser ignited (LI) engines. LI system is a novel concept used for ignition of fuel–air mixture inside the combustion chamber. LI is an electrode-less ignition system, which inhibits probability of auto-ignition and backfire in hydrogen fueled engine. In LI, a pulsating laser beam is converged at the focal point using a converging lens. This focused laser beam with high energy density at the focal point of the converging lens creates plasma. Plasma is formed only when the energy density at the focal point breaches the threshold value. Other than controlling backfire and auto-ignition, LI has emerged as a superior ignition technique capable of delivering superior engine performance and emissions. In previous studies, advantages of LI system such as lower NO_x emissions, higher power output and ignition capability of ultra-lean fuel–air mixture have been reported [24–28]. However particulate emission characteristics of hydrogen fueled LI engines have not been investigated thoroughly. Therefore this study aims to explore differences in particulate characteristics of a hydrogen fueled engine ignited with LI system and a conventional spark plug. The experiments were performed in a constant speed engine prototype at five different engine loads (5, 10, 15, 20 and 25 Nm) using hydrogen as test fuel. All other parameters such as spark timing and engine compression ratio were kept constant for both ignition systems.

Experimental setup

In this study, experiments were performed on a constant speed diesel engine (Kirloskar; DM10) prototype suitably modified to operate in SI and LI modes. For all experiments, compression ratio was kept constant at 11.0. Ignition timing

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