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Methanol fumigation in compression-ignition engines: A critical review of recent academic and technological developments

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ABSTRACT

The expanding energy demand, surging oil prices, depleting oil reserves, environmental pollution and climate change problems associated with the utilization of fossil fuels have revived interest to find out clean alternative fuels. Methanol is one of the most competitive alternative fuels due to its liquid nature, high oxygen contents, and high octane number and could produce from renewable sources. In this review, recent engine experimental and computational studies concerned with methanol fumigation on diesel engine were summarized. Technical and safety issue such as physical and chemical effect, environmental and health risk associated with the use of this technology were discussed. Modeling and simulation, engine performance and emissions, and recent advanced concept for methanol fumigated diesel engine were then reviewed respectively. At the beginning, the chemical and physical effect by the addition of methanol on the diesel fuels combustion were analyzed. The results showed that the fumigation of methanol could significantly prohibit the formation of PAHs. Then, for engine experiments, the effect of methanol fumigation on performance, combustion and emission characteristics of DMDF diesel engines were analyzed. It is examined that the fumigation of methanol fuel could reduce diesel engine emissions without adverse impacts on the performance of diesel engines. Further, new engine concepts such as RCCI operated with methanol fumigated diesel engine has also been summarized. Finally, this article puts forward some suggestions for the researches of diesel methanol dual fuel engine in the future.

1. Introduction

Methanol is a very flexible fuel for IC engines and can be made from a wide variety of both renewable and fossil fuel resources: natural gas, coal, wood, agricultural and municipal waste, and so on, at a cost generally lower than that for ethanol [1]. The use of alcohol (methanol and ethanol) as a fuel is as old as the IC engine itself. Some of the earliest IC engine models, developed at the end of nineteenth century were actually designed to run on alcohol. However, the interest in alcohol-based fuels did came to extensively use until 1970s due to the ready availability of large quantities of cheap oil. With the first OPEC oil crisis of the 1970s and concerns about pollution did the interest in alcohol fuels grow again. Thomas Reed [2] was one of the first to advocate methanol as a fuel in the United States, publishing in 1973 a paper in Science that explained some of its advantages. He stated that adding 10% methanol to gasoline improved performance, gave better mileage and reduced pollution. Similar results obtained in Germany by Volkswagen, with the support of the West German government [3]. To the end of 1990s, the number of methanol fueled vehicles in use in the United States reached a maximum of 20000 units (containing flexible fuel vehicles) [4]. During the 1990s, different technological advances were achieving wide acceptance in the automobile industry electrical

Abbreviations: PAHs, Polycyclic Aromatic Hydrocarbons; DMDF, diesel methanol dual fuel; RCCI, reactive controlled compression ignition; CFD, Computational Fluid Dynamics; NO_x, nitrogen oxides; HC, hydrocarbon; CO, carbon monoxide; IC, internal combustion; OPEC, Organization of the Petroleum Exporting Countries; BSFC, brake specific fuel consumption; CI, compression ignition; LHV, low heat value; PM, particulate matter; DI, direct injection; EGR, exhaust gas recycling; DMCC, diesel methanol compound combustion system; NO_2, nitrogen dioxide; DOC, diesel oxidation catalyst; BTX, benzene, toluene and xylene; SOF, soluble organic fraction; RON, research octane number; MON, motor octane number; OSHA, Occupational Safety and Health Administration; CO_2, carbon dioxide; AA, air atmosphere; MAA, methanol–air mixture atmosphere; LIF, laser induced fluorescence; LES, Large Eddy Simulation; PDPA, Phase Doppler Particle Analyzer; SMD, Sauter Mean Diameter; CPU, Central Processing Unit; RANS, Reynolds-averaged Navier–Stokes; RBFN, radial basis function network; NSGA II, Non-dominated Sorting Genetic Algorithm II; HD, Heavy duty; PPRR, Peak Pressure Rise Rate; IVC, intake valve closing; SOI, start of injection; RI, ringing intensity; ATDC, after top dead center; BTE, brake thermal efficiency; EPU, electronic unit pump; MSR, methanol substitution ratio; PCP, peak cylinder pressure; UED, unevenness degree; COVpp, coefficient of variation of peak pressure; BMEP, brake mechanical effective pressure; PN, particulate number; CA, crank angle; ATDC, $BSNO_x$, brake specific nitrogen oxides; DMCC, diesel/methanol compound combustion; IMEP, indicated mean effective pressure; HCCI, homogeneous charge, compression ignition; SR_m, substitution ratio; AFR, air fuel ratio; SR, Substitution Ratio; PR_m, premixed ratio of methanol; MDO, marine diesel oil

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fuel injection, three-way catalytic converters, reformulated gasoline, and so on, reducing dramatically the emission problems associated with gasoline-powered vehicles but decreasing at the same time the interest in methanol based fuels. However, the recent dramatic increase in oil prices, combined with growing concerns about human caused climate changes, has revived interest in alternative fuels, among which methanol can play an important role.

The diesel engine has the highest thermal efficiency of any practical internal or external combustion engine due to its high expansion ratio and inherent lean burn. But the combustion of diesel engine also brings along a row of well-known disadvantages. There are, for one, the higher emissions of nitrogen oxide (NO_x) and soot pollutants, which has both been identified as significant health hazard. Methanol does not produce smoke, soot and particulates during combustion process. This, and the fact that methanol produces very low emissions of NO_x because it burns at lower temperatures, make methanol attractive as a substitute for diesel fuel [1,4]. However, methanol's cetane rating is only about 3, while diesel fuel has a cetane ratings that range from 40 to 55. To overcome the low cetane rating of methanol, diesel motors must be adapted, such as higher compression ratio or ignition through spark plugs [5–8]. Additives can be included to increase the cetane rating of methanol to levels close to diesel fuels [9]. However, these ignition improvers, are typically composed of nitrogen-containing compounds such as octyl nitrate and tetrahydrofurfuryl nitrate, many of which are toxic and or carcinogenic.

With methanol and diesel fuels being substantially immiscible, the possibility of using any blends of methanol and diesel fuel in diesel vehicles is difficult. The use of methanol as a blend of diesel or as an additive coupled with other alternative fuels has been investigated in plenty of previous studies. Huang et al. [10] noted that smoke, CO and THC emissions decreased while NO_x emissions increased as methanol content in fuel blends increases. Methanol-diesel fuel blends resulted in increased BSFC and ignition delay, as the combustion duration of methanol–diesel blends was found to be shorter than those of neat diesel fuel. Further, Huang el al. [11] prepared the fuel blends by adding oleic and *iso*-butanol as a solvent to diesel methanol blend. Their results also showed that the NO_x concentration increased with increasing oxygenate mass fraction, while the amount of smoke decreased. And the addition of oxygenate in the diesel fuel had a strong influence on the NO_x concentration at high engine load, whereas it had little influence at low engine load. Bayraktar et al. [12] using a diesel-methanol-dodecanol blends on a CI engine to investigate the performance at different compression ratios. They concluded that among different blends, the blend including 10% methanol (M10) is the most suited one for CI engine performance point of view. Sayin et al. [13] assessed the performance and exhaust emissions of a direct injection diesel engine, using methanol-diesel and ethanol diesel blends. Dodecanol was added to stabilize the blends. The use of fuel blend also caused decrease in the emission of smoke, CO and THC, and increase in NO_x emissions. The BSFC was also increased for both blends mainly due to the lower heating value (LHV) of methanol and ethanol. Yilmaz [14] investigated the performance and emissions of a compression ignition engine running on four fuel concentrations of biodiesel-methanol blends (M15, M10, M5, and M0). The results indicated biodiesel–methanol blends could potentially reduce emissions but the change would greatly depend on engine load, intake air temperature and blend ratio. That is recommended that biodiesel–methanol be used with low alcohol concentration at loads higher than part load and in warm environment (or preheated intake air) to achieve complete, efficient combustion. However, the miscibility problem remain, the presence of a very small amount of water can cause methanol–diesel mixture to separate into diesel and water-methanol phases [15]. And the ratio of methanol to diesel has to be low to avoid adverse effects on combustion [16].

In an attempt to overcome the miscibility and ignition problems, methods such as methanol fumigation or dual injection system have also been employed. The methanol delivery system is an isolated low pressure fuel deliver system, and special materials like Teflon could be used, which could also avoid the corrosive problem of methanol. Heisey et al. [17] investigated a single-cylinder DI Diesel engine fumigated with aqueous alcohol (ethanol and methanol) in amounts up to 55% of the total fuel energy. They noted that alcohol fumigation improved thermal efficiency slightly at moderate and heavy loads, but increased ignition delay at all operating conditions. Carbon monoxide emission generally increased with alcohol fumigation and showed no dependence on alcohol type or quality. Oxides of nitrogen emission showed a strong dependence on alcohol quality; relative NO_x levels decreased with increasing water content of the fumigant. Particulate mass loading rates were lower for ethanol-fueled conditions. Another study by Houser et al. [18] examined methanol fumigation on a light duty automotive diesel engine. Results are presented for a test matrix consisting of twelve steady state operating conditions chosen to reflect over-the-road operation of a Diesel engine powered automobile. Generally methanol fumigation was found to decrease NO emission for all conditions, to have a slight effect on smoke opacity, and to have a beneficial effect on fuel efficiency at higher loads. Also at higher loads the methanol was found to induce what was defined as "knock limited" operation. Baranescu et al. [19] studied fumigation of alcohols in a multi-cylinder diesel engine. Alcohol fumigation was achieved by injection in the crossover pipe of the engine downstream the turbocharger. The results showed that alcohol fumigation substantially increases the maximum rate of pressure rise and peak cylinder pressure, which might cause heavy knock. With the fumigation of alcohol, the carbon monoxide and hydrocarbon emissions were dramatically increased. Odaca et al. [20] made an attempt to optimize NO_x and smoke emissions of a DI diesel engine with EGR and methanol fumigation. The results indicated that the smoke concentration is decreased and total fuel consumption is improved according to the increase in methanol energy ratio. The method was applied to Japanese 13 mode test procedure and it was recognized that NO_x mass emission were reduced to almost one half without increase in particulate emissions. However, drastic increase in CO, HC and aldehyde emissions were also observed. Yao et al. [21,22] proposed a diesel methanol compound combustion system (DMCC) in an attempt to reduce smoke and NO_x from diesel engines. In the DMCC system, single diesel fuel mode is used for engine cold starting and for low load operation. After engine warmed up, at medium to high load, the engine switched to dual fuel mode: a fixed amount of diesel fuel is maintained while extra energy is acquired by injecting methanol into the intake manifold to form a homogeneous methanol/air mixture. The system was tested on two 4-cylinder diesel engines: one naturally aspirated and the other turbocharged. In both cases, the DMCC system is found to reduce brake specific equivalent fuel consumption (the consumption of both methanol and diesel were converted into the equivalent diesel fuel based on their lower heating values), reduce smoke emission, and reduce NO_x emission but increase CO and HC emissions. Further, Yao et al. [22–25] used the DMCC method coupled with an oxidation catalyst, and the CO, HC, NO_x and soot emissions could all be reduced. Zhang et al. [25,26] evaluated the effect of DMCC scheme and the DOC on the unregulated emissions (unburned methanol, formaldehyde, methane, ethyne, ethene, 1,3-butadiene and the BTX (benzene, toluene and xylene), based on the Japanese 13 Mode test cycle. The results also showed that the DMCC scheme can effectively reduce NO_x, particulate mass and number concentrations, ethyne, ethene and 1,3-butadiene emissions but significantly increase the emissions of THC, CO, NO_2, BTX (benzene, toluene and xylene), unburned methanol, formaldehyde, and the proportion of SOF in the particles. After the DOC, the emission of THC, CO, NO_2, as well as the unregulated gaseous emissions, can be significantly reduced when the exhaust gas temperature is sufficiently high while the particulate mass concentration is further reduced due to oxidation of the SOF. The fumigation method seems potentially since the energy fraction of premixed fuel and reactivity of mixture could vary depending on actual requirements, which could achieve advanced