Fuel 188 (2017) 427–441

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Experimental investigations of the effects of pilot injection on combustion and gaseous emission characteristics of diesel/methanol dual fuel engine

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HIGHLIGHTS

- Effect of pilot injection on DMDF combustion characteristic and gaseous emissions were analyzed.
- Regulated and unregulated gaseous emissions from the engine with DMDF system were examined.
- Compared with single injection, pilot injection strategy could reduce most of gaseous emissions.
- Increasing pilot quantity could reduce HC, CO and most of unregulated emissions of DMDF engine.
- Advancing pilot injection timing caused an increase in some unregulated emissions on M50 mode.

ARTICLE INFO

Article history:
Received 2 July 2016
Received in revised form 27 August 2016
Accepted 9 October 2016
Available online 15 October 2016

Keywords:
Pilot injection
Diesel/methanol dual fuel
Combustion characteristics
Gaseous emissions
Unregulated emission

ABSTRACT

A diesel engine with 6-cylinder, turbocharged intercooling and common rail system was modified to operate on diesel/methanol dual fuel (DMDF). To optimize combustion process at high methanol substitution ratio (MSR) and further decrease exhaust emissions of DMDF engine at low load condition, pilot injection strategy was applied on it and the combustion, regulated and unregulated gaseous emission (included NOx, CO, THC, carbon dioxide (CO_2), nitrous oxide (N_2O), unburned methanol (CH_3OH), formaldehyde (HCHO), formic acid (HCOOH), 1,3-butadiene (1,3-C_4H_6), benzene (C_6H_6) and toluene (C_7H_8)) characteristics were experimentally investigated. Experimental results reveal that the application of pilot injection could improve combustion stability and fuel economy at high MSR, and it can also reduce regulated emissions CO, THC except NOx, and unregulated emissions tested in this study except CO_2 on M0 and M10 mode and toluene on M50 mode when compared with single injection cases. Increase pilot injection quantity and advance pilot injection timing both cause an increase in in-cylinder temperature and pressure before main combustion. The variations of pilot injection quantity and timing have less effect on regulated and unregulated gaseous emissions except NOx on M0 and M10 mode than higher MSR mode. With the rise of pilot quantity and the advance of pilot injection timing, HC and CO emissions decrease gradually but NOx emissions ascend; almost all unregulated emissions tested in this study on M30 mode reduce gradually; but when the MSR continues to rise to 50%, increasing emissions in unburned methanol, 1,3-butadiene and benzene are observed.

1. Introduction

The more and more strict emission regulations and the depletion of petroleum resources drive people to look for alternative fuels of engine [1,2]. Methanol has become into a diesel alternative fuel that shows great application prospects because of its high oxygen content and also can be generated from biomass [3]. Due to its low cetane number, methanol is quite difficult to ignite directly in diesel engine. Domestic and foreign scholars have carried out many researches on the application of methanol in diesel engine, and several methods such as fuel blends [3–8], methanol fumigation

Abbreviations: DMDF, diesel/methanol dual fuel; CO_2, carbon dioxide; N_2O, nitrous oxide; CH_3OH, methanol; HCHO, formaldehyde; HCOOH, formic acid; 1,3-C_4H_6, 1,3-Butadiene; C_6H_6, benzene; C_7H_8, toluene; DMCC, diesel/methanol compound combustion; MSR, methanol substitution ratio; DI, direct injection; DME, dimethyl ether; COV_{IMEP}, the coefficient of variation of indicated mean effective pressure; ECU, electronic control unit; CA, crank angle; TDC, top dead center; BTDC, before top dead center; HRR, heat release rate; MFB, mass fraction burned; FTIR, Fourier transform infrared spectroscopy; NO, nitric oxide; PAH, polycyclic aromatic hydrocarbon.

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http://dx.doi.org/10.1016/j.fuel.2016.10.056
0016-2361/

Nomenclature

$\dot{m}_{Dneat}$	the diesel fuel consumption on pure diesel mode, kg/h
$\dot{m}_{Ddual}$	the diesel fuel consumption on DMDF mode, kg/h
H_{LD}	the lower heating value of diesel, MJ/kg
H_{LM}	the lower heating value of methanol, MJ/kg
$\dot{m}_{Mdual}$	the methanol fuel consumption on DMDF mode, kg/h
b_{eq}	equivalent fuel consumption rate, g/kW h
P_e	the engine power, kW
Φ_D	equivalence ratio of diesel
Φ_M	equivalence ratio of methanol
Φ_T	total equivalence ratio
$\dot{m}_D$	mass flow rate of diesel fuel, kg/h
$\dot{m}_M$	mass flow rate of methanol fuel, kg/h
$\dot{m}_{air}$	mass flow rate of intake air, kg/h
λ_D^{st}	the stoichiometric air-fuel ratio of diesel fuel
λ_M^{st}	the stoichiometric air-fuel ratio of methanol fuel

[9,10] and dual fuel emulsion [11] have been applied. Sayin et al. [6] carried out an experiment on a naturally aspirated DI diesel engine fueled with diesel methanol dual fuel to investigate the performance and emission characteristics of engine. Research showed that the application of methanol blend led to an increase in CO, HC and smoke emissions but a decrease in NOx emissions. Yao et al. [12] investigated the effect of methanol fumigation on a turbocharged inter-cooling diesel engine. They found that the CO, HC emissions were increased but NOx and soot emissions were significantly reduced. They explained that the decreased emissions in soot were mainly because methanol does not have C-C bond and could not be easy to produce obvious PAH and aromatic species. Meanwhile, the high oxygen content and the lack of aromatics and sulfur provided by methanol resulted in the reduction of soot formation while diesel engine operated on DMDF mode. The research results of Prashant et al. [8] showed that with increasing amount of methanol in diesel fuel, the ignition delay of diesel methanol dual fuel mode was longer than that of pure diesel mode.

Though there are so many methods to solve the difficulty of the direct application of methanol in diesel engine, the fumigation of methanol seems to be a promising method that could flexibly switch from pure diesel mode to relatively high methanol substitution mode [13,14]. Researches showed that the fumigation of methanol could reduce PM, NOx and soot emissions, but meanwhile, the addition of methanol caused an increase in HC, CO and unregulated emissions such as unburned methanol, formaldehyde and 1,3-butadiene, especially at low load where the temperature of cylinder and exhaust gas is relatively low compared with high load conditions [1,10,15–17]. Zhang et al. [16] conducted an experiment on a diesel methanol dual fuel engine which methanol fumigation method was used to investigate the regulated and unregulated emissions of it. Results showed that the NOx emissions, PM number and mass concentrations of the dual fuel engine were decreased, but HC, CO, formaldehyde and unburned methanol emissions ascended significantly. Pan et al. [17] investigated the effect of intake air temperature on emission and combustion characteristics of DMDF engine. They found that the HC, CO, unburned methanol and formaldehyde emissions of DMDF engine ascended with increasing proportion of fumigated methanol, but HC, CO and both of these two unregulated emissions were decreased with the rise of intake air temperature. Additionally, the research by Wang et al. [13] showed that high MSR applied at low load condition could cause instable combustion of DMDF engine: misfire and roar combustion happened alternately, leading to increased emissions of unburned hydrocarbons and deteriorated fuel economy due to misfire combustion. To improve combustion stability and reduce the regulated and unregulated gaseous emissions of methanol fumigation engine at low load operation, intake charge heating [17] and methanol heating before supplying to the intake manifold are effective methods. It is because these two methods help to promote the vaporization of methanol before entering into cylinder, thus reduce the cooling effect of methanol on in-cylinder charge and finally promote the complete combustion of fuel. But the application of these two methods to vehicle increases the complexity of air-intake and fuel supplying systems, so it is better to solve this problem by other methods.

The common rail system allows to precisely control the fuel supply system, and the application of pilot injection in an operating cycle could optimize combustion process and reduce emissions [18,19]. Compared with single injection operation, the combustion of pilot injection fuel could increase the temperature and pressure in cylinder before main combustion, thus promotes the complete oxidation of fuel and finally reduces HC emissions [20–22]. Roh et al. [21] carried out an experiment to investigate the impact of diesel, biodiesel-diesel and biodiesel-DME fuels on the emission characteristics of a compression ignition engine to single and pilot injection strategies. Results showed that after the application of pilot injection, the combustion process tended to be smoother as the peak heat release rate was significant lower. Additionally, the HC emissions of conditions with pilot injection were lower than that of single injection. To investigate the effect of multiple injection on combustion and emission characteristics from a low compression ratio engine, Suh [22] conducted an experiment on a single-cylinder compression ignition engine. It was observed that the COV_{IMEP} of one pilot injection case reduced by 33.5% compared with single injection case, indicating that the operation of engine became more stable. The HC emissions of multiple injection (included one pilot injection and two pilot injection) strategies were both lower than that of single injection strategy, and the author explained that it was because the combustion of pilot-injected fuel ignited the main-injected fuel and finally promoted the complete combustion of main-injected fuel. However, the CO emissions increased when multiple injection strategies application. The application of pilot injection on DMDF engine could be an effective method to reduce the cooling effect of methanol on in-cylinder charge in high MSR under low load due to higher in-cylinder temperature before main combustion, thus avoids misfire combustion and efficiently promotes the oxidation of fuel. As a result, there may be a reduction in HC, CO and some of the unregulated emissions as they belong to unburned hydrocarbon or incomplete combustion products. Therefore, pilot injection seems to be an effective method to improve combustion stability and incomplete combustion products emissions under low load (especially at high MSR) which does not increase system complexity.

The emission limits of regulated components (included HC, CO, NOx, PM and soot) are specified in the emission regulations of China and Europe, but unregulated emission components such as methanol, formaldehyde and benzene have not been limited. It is well known that various unregulated emissions present in the engine exhaust gases undergo secondary chemical reactions in the environment and form secondary and tertiary pollutants, meanwhile, their negative influences on environment and human health are nonnegligible. Methanol has a great effect on the nervous system and blood system of human beings. The intake of