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Study of cylinder-to-cylinder variation in a diesel engine fueled with diesel/methanol dual fuel

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HIGHLIGHTS

- The UED of engine increases with the MSP under various engine loads.
- The MSP within 40% is preferable.
- It is helpful to decrease the UED as intake air temperature within 35–80 °C.
- Increasing of engine speed can decrease cylinder-to-cylinder variation and UED.

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ABSTRACT

The methanol fuel used in diesel engine can reduce the emissions effectively, while the performance of engine keeps unchanged or even improved, the study of methanol used in diesel engine is paid more and more attention. Experiments were conducted in a 4-cylinder, turbocharged direct injection diesel engine fueled with diesel/methanol dual fuel (DMDF). In the experiment, methanol was injected into inlet duct by two low-pressure injectors, and directly mixed with intake air before entering the engine. The diesel fuel was directly injected in cylinder. The methanol substitution percent (MSP), intake air temperature and engine speed were changed to investigate the unevenness degree (UED) cylinder-to-cylinder. The experimental results show that the UED of engine increases with the increase of MSP under various engine loads, the COV_{pp} increases with MSP under low engine load, and the COV_{pp} curves vary very little under low MSP under 75% and 100% engine load, but a significantly rise appeared when MSP further increases. The UED gradually increases with the increase of intake air temperature, and it is usually less than 8% when intake air temperatures lower than 80 °C under 40% MSP. It suggests it is helpful to decrease the UED when the intake air temperature is in the range of 35–80 °C as MSP less than 40%. In addition, the difference of pressure between cylinder-to-cylinder decreases with the increase of engine speed, it can be considered raising MSP at high engine speed in order to gain better engine economy.

1. Introduction

Diesel engines are widely used in industrial, transportation and agricultural production. However, due to the non-uniformity of mixture air/fuel ratio and temperature distribution in the combustion chamber, it is very difficult to reduce both NO_x and soot simultaneously for diesel engines. Moreover, NO_x and soot belong to the pollutants that are targeted for reduction because they are harmful to human health and environment [1–3]. With the depletion of oil resources and increasingly strict environmental regulations, looking for alternative engine fuels become a pressing task [4–8]. The methanol which can be easily synthesized from coal has been paid more and more attention by China because of its abundant source and low cost, meanwhile it can be easily used in engine and reduce both NO_x and soot emissions [9–11]. In previous studies, the main applications of methanol on the diesel engine include methanol–diesel blend method and methanol fumigation method. The methanol–diesel blend method injects methanol and diesel blend fuel which are premixed into cylinder directly through the fuel injector, this way has disadvantage that the mixing proportion of methanol is restricted and need to add additives to prevent methanol stratification [12]. The fumigation method uses low-pressure methanol injectors introducing methanol into air intake duct, and mixes with air to form carbureted mixture and then enters

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Nomenclature

DMDF	diesel methanol dual fuel	N	cycle index ($N = 100$)
MSP	methanol substitution percent	$\overline{P_{max}}$	mean value of peak pressure of N cycles (MPa)
COV_{pp}	coefficient of variation of peak pressure (%)	P_i	peak pressure of each cycle (MPa)
UED	unevenness degree	P_{max}	maximum peak pressure valve of the 4 cylinders (MPa)
EGR	exhaust gas recirculation	P_{min}	minimum peak pressure valve of the 4 cylinders (MPa)
TDC	top dead center	$\overline{P_{mean}}$	mean peak pressure valve of 4 cylinders (MPa)
NO_x	nitrogen oxides	CA05	the crank angle where 5% of mass fraction burned (°CA)
ECU	electronic control unit	CA90	the crank angle where 90% of mass fraction burned (°CA)
CA50	the crank angle where 50% of mass fraction burned		
σ	the standard deviation of peak pressure		

into cylinders when inlet valve opening, this method has a high MSP that can reach more than 70% [11,13]. Series of studies [8,11,13,14] showed that fumigation method should be paid more and more attention because of practical use, convenient installation and high MSP. However, the methanol fumigation mainly use low-pressure methanol injectors which installed in the intake manifold in previous studies, the temperature of intake manifold decreases significantly because of the evaporation of methanol which the latent heat of evaporation is about 4.53 times that of diesel fuel, especially when MSP increases [8]. In addition, the evaporation of methanol is not sufficient and the engine start difficultly under low ambient temperature, especially when the ambient temperature fall below 16 °C [14,15]. Meanwhile, the intake manifold of diesel engine is simpler than that of gasoline engine, and the time of methanol mixing with air after injection is short. After a long time of injection, the methanol will be introduced into cylinder in the form of droplet especially at high MSP, and studies [16,17] have found that a small explosion will occur when the droplet which methanol and diesel merged under high temperature environment. Experiments also showed that it is very easy to cause engine knock when MSP increases at high engine load, thus the operating range of methanol/diesel engine is limited [13]. Moreover, the air–fuel ratio in combustion chamber is non-uniform when methanol droplet was introduced into cylinder which may cause incomplete combustion and increasing of HC emission.

In order to promote the atomization of methanol completely and mix homogeneously with air under high MSP, the methanol is injected into inlet duct by two low pressure methanol injectors in this paper, and the two low-pressure methanol injectors used in the experiment has the same injection parameters such as injection pulse width, timing and injection pressure to provide adequate methanol fuel to engine and ensure the atomizing quality of methanol. In this way, methanol can mix with air through a long pipe to form homogeneous charge and methanol droplet disappeared after turbulence flow. However the cylinder configuration of diesel engine is usually in-line-type, the inlet duct of diesel engine guides homogeneous charge into cylinder from one side that may causes the methanol quantity different in 4 cylinders, and then results in cylinder-to-cylinder variation of combustion. Previous studies mainly focused on mean performance of all engine cylinders, while the imbalance that methanol entered into each cylinder will pull down the whole engine performance such as decrease of engine power and torque, increase of exhaust emission. This work first proposed the definition of UED of DMDF engine calibrated by peak pressure and paid more attention to pressure comparison of each cylinder. In order to investigate the effect on UED cylinder-to-cylinder, the inlet duct injection of methanol is studied on a 4-cylinder turbocharged direct injection diesel engine and the cylinder pressure, COV_{pp}, CA05, CA50 and CA90 of 4 cylinders are analyzed under different engine speeds and loads with the change of intake air temperature and MSP, the engine test combination is given in Table 1. The effect of above parameters on the UED of DMDF engine are analyzed to ensure high MSP used in diesel engine with each cylinders work more evenly.

2. Experimental set up and method

2.1. Engine system and fuels

The experiments are performed in a 4-cylinder, in-line, turbocharged, direct injection diesel engine, the specifications of the test engine are shown in Table 2. The engine was modified with a methanol rail and two low-pressure methanol injectors were added to the air inlet duct. A methanol pump was used to supply methanol to the methanol rail, and the methanol was injected into air inlet duct with a pressure of 0.4 MPa to form methanol/air premixed mixture. The injection quantity and timing of methanol were controlled by a methanol electronic control unit (ECU). The pressure of in-cylinder was measured respectively using 4 Kistlerpiezo-electric type pressure sensors (6052CU20) installed at the head of the 4 cylinders. The pressure sensors were connected to four AVL charge amplifiers, and then the pressure signals were input in the AVL combustion analyzer to obtain the combustion data. The diesel engine was coupled with a dynamometer, the engine torque and speed were controlled by the FST2E engine test system. The schematic diagram of the experimental setup is shown in Fig. 1.

The methanol (99.9% purity) and diesel used in this study are commercial fuels and are same with the literature [8,11] used.

Table 1
Engine test combination.

Item	Engine load (%)	MSP (%)	Engine speed (r/min)	Temperature in front of methanol injector (°C)
Variation of MSP	25	0, 10, 20, 30	1660	35
	75	0, 10, 20, 30		
	100	0, 10, 15, 20, 25		
Variation of intake air temperature	50	30, 40	1660	35, 50, 65, 80, 95, 110
Variation of engine speed	50	0, 10, 25, 40	1260, 1460, 1860	35