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Experimental investigation on methanol auto-ignition in a compression ignition engine under DMDF mode

Bin Wang, Anren Yao, Chunde Yao*, Chao Chen, Han Lu, Jun Feng

State Key Laboratory of Engines, Tianjin University, Tianjin 300072, China

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ABSTRACT

At high loads, Diesel-Methanol Dual Fuel (DMDF) engines strongly rely on high methanol substitution for diesel proportion (MSP) to achieve high efficiency combustion and reduce nitrogen oxides (NOx) and soot emissions. However, high MSP is limited by the probability of methanol auto-ignition. The experimental study was conducted to investigate into the influence factors of methanol auto-ignition under diesel engine conditions at 50% of full load. Meanwhile the testing results concerning combustion characteristics and emissions have been analyzed. Experimental results showed that if there was apparent heat release before TDC, which was earlier than diesel fuel injection, it indicated that methanol auto-ignition occurred. In order to avoid methanol auto-ignition which is very easily to cause knock or rapid pressure rise, the in-cylinder mean temperature should be less than 990 K (at this case, the intake temperature was 338 K) before diesel injection timing. As intake temperature increased, methanol heat release timing was advanced and the heat release rate (HRR) was gradually accelerated. If the injection timing of diesel was later than that of methanol auto-ignition, almost all diesel fuel would be burned in the form of diffusion combustion in the methanol flame, leading to the increase of soot emissions. Methanol auto-ignition would be inhibited by EGR gas. The EGR and MSP had a great impact on both the ignition timing and the peak HRR of methanol auto-ignition. As EGR ratio increased, so did the incomplete combustion loss of methanol. As long as methanol auto-ignition occurred, the increase of MSP would result in a decrease in NOx emissions, but soot emissions were increased instead.

1. Introduction

Recent years, in order to simultaneously reduce high NOx and Particulate Matter (PM) emissions of diesel engine, the current researches mainly focus on Premixed Charge Compression Ignition (PCCI) [1,2]. PCCI mode could not only achieve ultra-low emissions [3], but also achieve higher thermal efficiency [4]. Premixed fuel is ignited by direct injection fuel, so the ignition timing determined by the injection timing of diesel could be realized, and the operating range could be extensively expanded [5]. However, at high load, PCCI engines are faced with the problem of the auto-ignition of premixed fuel before diesel is injected [6,7]. Chintala et al. [8] experimentally investigated the auto-ignition of hydrogen-air charge in a compression ignition engine under hydrogen-diesel dual-fuel mode. They found that with 18.8% (about 19%) hydrogen energy share, combustion started earlier than diesel fuel injection, which indicated that auto-ignition of hydrogen-air charge occurred without any external ignition source (pilot diesel fuel) and they found that the auto-ignition temperature of hydrogen-air charge was 953 K ± 8 K. Pedrozo et al. [9] experimentally investigated ethanol-diesel dual-fuel combustion at high load. They found that there was an early auto-ignition process of the premixed charge, which took place prior to the diesel injection, and the mean in-cylinder gas temperature was above 950 K before ethanol auto-ignition.

The occurrence of premixed charge auto-ignition may cause following issues: firstly, the proportion of premixed fuel will be restricted, and it is because that if auto-ignition of premixed charge occurs, the start of combustion will be advanced. Meanwhile, with increasing premixed energy fraction, the HRR of auto-ignition is significantly

Abbreviations: DMDF, diesel methanol dual fuel; MSP, methanol substitution percent; EGR, exhaust gas recirculation; NOx, nitrogen oxides; THC, total hydrocarbons; CO, carbon monoxide; PM, particulate matter; PCCI, premixed charge compression ignition; NO, nitrogen oxide; DMCC, diesel methanol compound combustion; FID, flame lionization detector; CLD, chemiluminescence detector; BTE, brake thermal efficiency; ECU, electronic control unit; CA, crank angle; HRR, heat release rate; TDC, top dead center; ATDC, after top dead center; BTDC, before top dead center; IMEP, indicated mean effective pressure; SI, spark-ignition; HCCI, homogeneous charge compression ignition; LTC, low temperature combustion; PRR, pressure rising rate; MPRR, the maximum pressure rising rate

* Corresponding author at: Tianjin University, No. 92 Weijin Road, Nankai District, Tianjin, 300072, China.
E-mail address: arcdyao@tju.edu.cn (C. Yao).

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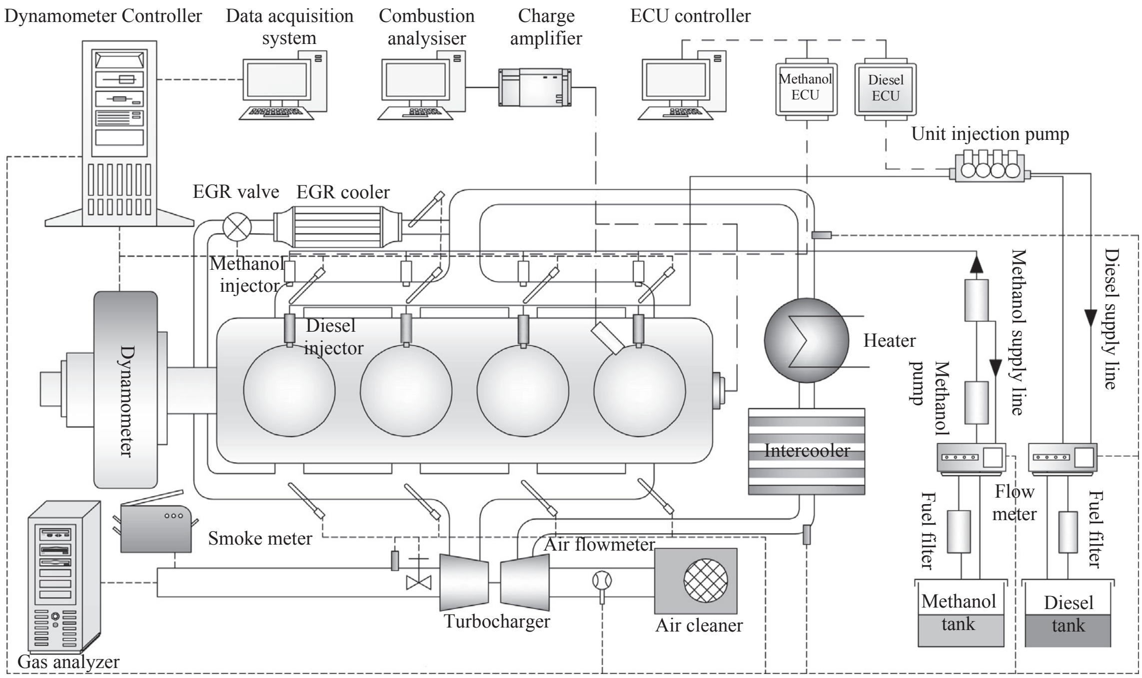

Fig. 1. Schematic of the experimental setup.

increased [10]. The auto-ignition timing of premixed fuel is ahead of compression TDC. Thus, with increasing premixed fuel substitution, the in-cylinder pressure and pressure rise rate (PRR) will be increased, which could exceed the engine design limits. Secondly, the knock problem becomes severer when there is the occurrence of premixed charge auto-ignition [11]. The combustion mode of premixed charge auto-ignition is homogeneous charge compression ignition [12], and there is the possibility of knock in the uncontrolled homogeneous charge compression ignition. If knocking occurs, the engine might suffer severe damages including breakage of piston rings, piston melting, and cracking of cylinder head [13]. Finally, the oxygen in the cylinder will be partly consumed by premixed charge auto-ignition, so the oxygen concentration will be locally decreased, leading to the increase of soot emissions [14].

DMDF combustion mode is actually an exclusive kind of PCCI combustion mode. The former one is only dealing with diesel and methanol, but the later one can cover various kinds of fuel, such as diesel and gasoline, diesel and natural gas and so on. The premixed fuel is ignited by direct injection fuel which can be defined as PCCI mode. In our experiences, DMDF is a complex combustion mode among PCCI modes, due to the fact that the vaporization latent heat of methanol was 4.3 times that of diesel, and the ignition temperature of methanol was twice that of diesel. When diesel spray penetrates into methanol mixture, there are two fuels interaction as engine condition varies. Whichever will be first ignited, the other one must be influenced, which will cause different PRR, HRR and consequent engine performance. DMDF combustion mode can achieve ultra-low emissions and high thermal efficiency. Wang et al. [15] investigated the operating range of DMDF. They found that the appearance of knock provided the upper bound of the operating range, which was due to the auto-ignition of premixed methanol charge. Wang et al. [16] found that the knock tendency was reduced into an unobservable magnitude at high MSP by using suitable combustion control strategy, and methanol is smokeless and flameless while burning. Thus soot production could be reduced when the engine fueled with more methanol fuel.

Due to the high compression ratio of diesel engine, the temperature and pressure near the TDC are high, which results in the methanol auto-ignition before diesel is injected [17]. However, current researches on methanol auto-ignition did not focus on diesel engine. Kumar et al. [18] used a heated rapid compression machine to investigate the auto-ignition of methanol under high-pressure and low-to-intermediate temperature conditions. They found that the ignition delay was strongly influenced by temperature, pressure, fuel loading, and oxygen concentration. Fieweger et al. [19] investigated self-ignition of several spark-ignition (SI) engine fuels including methanol, and the experiments were carried out under relevant engine conditions by the shock tube technique. They found that the self-ignition of methanol was characterized by a very pronounced initial deflagration, and the chemical ignition delay time showed an approximately linear dependence of the Arrhenius plot for temperature higher than 800 K. Aranda et al. [20] had an experiment in a flow reactor in the temperature range 600–900 K and in the pressure interval 20–100 bar as a function of stoichiometry, which was conducted to investigate methanol oxidation. Research results showed that the temperature for onset of reaction was largely independent of stoichiometry, and it decreased with increasing pressure.

If methanol ignites before diesel fuel does, engine knock may occur [21]. In this case, the in-cylinder temperature will be quite high when diesel is injected, and the ignition delay of diesel will be shortened. Thus diesel combustion mode will be diffusion-dominated heat release patterns, which also promotes soot formation [8,22]. In light of those, uncontrollable methanol auto-ignition is abnormal combustion in DMDF mode and needs to be suppressed. Although the auto-ignition research in PCCI mode has been carried out in several literatures[23], the physical properties and the ignition performance of methanol are different from other fuels[24]. Compared with ethanol and hydrogen, methanol has higher heat of vaporization and oxygen content [25]. Thus, it is essential to investigate the auto-ignition of methanol on diesel engine. In this paper, the experimental study was conducted to investigate the influence factors of methanol auto-ignition under compression ignition engine conditions, which was to extend the operation range of DMDF. The influence factors mainly concentrated on intake temperature, diesel injection timing, exhaust backpressure, EGR ratio and MSP. What we have done in the study focus on making clear the relationship and interaction between diesel and methanol while engine is working to extend the operation range of fuel economy.