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Effects of diesel/ethanol dual fuel on emission characteristics in a heavy-duty diesel engine

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Abstract. In order to reduce emissions and diesel consumption, the gas emissions characteristics of diesel/aqueous ethanol dual fuel combustion (DFC) were carried out on a heavy-duty turbocharged and intercooled automotive diesel engine. The aqueous ethanol is prepared by a blend of anhydrous ethanol and water in certain volume proportion. In DFC mode, aqueous ethanol is injected into intake port to form homogeneous charge, and then ignited by the diesel fuel. Results show that DFC can reduce NOx emissions but increase HC and CO emissions, and this trend becomes more prominent with the increase of water blending ratio. Increased emissions of HC and CO could be efficiently cleaned by diesel oxidation catalytic converter (DOC), even better than those of diesel fuel. It is also found that DFC mode reduces smoke remarkably, while increases some unconventional emissions such as formaldehyde and acetaldehyde. However, unconventional emissions could be reduced approximately to the level of baseline engine with a DOC.

1 Introduction

As public concern about environmental pollution and energy security increase, alternative fuels are receiving more and more attention. Ethanol is a biomass based renewable fuel, which contains no sulfur in itself and has higher latent heat of vaporization than diesel and gasoline fuels. Since late 1990s, ethanol blended diesel fuel has been used on diesel engines. Andrzej [1] conducted research on a single cylinder diesel engine to reduce the smoke and NOx pollutants. Previous experiments [2] were carried out on a naturally aspirated, four-cylinder traditional mechanical injection diesel engine, while ethanol was injected into the air intake of each cylinder to form a homogeneous mixture, which could reduce the smoke and NOx emissions, so we introduced a diesel/ethanol blended with water dual fuel combustion (DFC). It is great significance to study alternative diesel fuels, such as ethanol blended with water. On the one hand, it can reduce production costs of ethanol; on the other hand, the evaporation latent heat of the ethanol blended with water is much higher than that of diesel, thus reducing the temperature inside the cylinder during the mixture formation and avoiding the increase of NOx emissions as ethanol injected increases at medium and high loads [3]. Moreover, increasingly the injection amount of ethanol will make the engine mechanical load too high and easily lead to rough work. There are some advantages to blend some water with ethanol. Firstly, water will lower the heating value of ethanol to reduce mechanical load. Secondly, due to larger evaporation latent heat of water, the NOx emissions are reduced effectively.

Investigation was performed on a common-rail diesel engine, and the ECU control strategy was not open compared with that of previous mechanical pump diesel engines. In order to evaluate the effects of DFC on a common-rail diesel engine and achieve the same objective function, engine speed and torque were set as independent variables without communicating with original engine electronic control unit (ECU). Under DFC mode, ethanol will be injected into the intake port of each cylinder to form a homogeneous mixture with air for combustion, while the original diesel fuel injection system will be retained but slightly modified to limit diesel quantity. At engine start and low speed, the engine will operate on diesel alone to ensure cold starting capability and to avoid aldehydes production under these conditions. At medium and high loads, the engine will operate on a homogeneous air/ethanol blended with water mixture ignited by pilot diesel to reduce particulate matter and NOx emissions and the amount of ethanol injected is controlled by a dedicated ECU. Keep engine power constant and take economical and discharging performances into account, then calculate the spray ethanol map.

2 Experimental setup and procedure

2.1 *DFC engine*
The experimental investigation was conducted on a four-cylinder, common-rail, turbocharged, inter-cooled diesel engine, which was modified for DFC operation. An ethanol fuel rail and four fuel injectors were added to the air intake manifold of the engine. Ethanol blended with water (hereinafter referred to as ethanol) was introduced through four fuel injectors into the intake port of each cylinder at a pressure of 0.5MPa to form a homogeneous ethanol/air mixture. The injection time and the amount of ethanol injected are controlled by an ECU. The fuels used in this study include diesel in which sulfur content is less than 50ppm, anhydrous ethanol and distilled water. The ethanol with a purity of 99.9% was used and blended with 30%, 40% and 50% volume fractions of water. The fuel is designated as EW fuel for the ethanol-water blends (EW30, EW40, EW50).

2.2 *Testing equipment*
During the tests, an electric dynamometer (AVL 504/4.6SL) and an engine control system (PUMA Open) were used to control the engine speed and torque; diesel and ethanol consumptions were measured by two intelligent fuel consumption meters (AVL 735s), respectively. Regulated gas emissions including THC, NOx, CO and unregulated gas emissions including formaldehyde and acetaldehyde were measured by the AVL SESAM-FTIR. It is capable to determine up to 25 gaseous exhaust components simultaneously. The smoke emission was measured by the AVL 415s smoke meter.

2.3 *Experimental procedure*
The experiments were performed on the pure diesel and then on the DFC mode which represents diesel/ethanol blended with 30%, 40% and 50% volume fractions of water dual fuel combustion (DFC (EW30), DFC (EW40) and DFC (EW50)). This study aims to investigate the effects of ethanol blended with water on emissions characteristics of diesel engine with a DOC added to further reduce emissions. Experiments were first carried out on the diesel engine using diesel alone to build up a database for comparison with those obtained with DFC modes. In the DFC modes, the engine was first fueled with diesel fuel to 85% engine load while ethanol was then injected to top up the other 15% engine load. In this study, emission testing was mainly performed at steady states for different loads at the speed of 2500 r/min. Besides all sorts of conventional gas emissions such as NOx, CO, HC and smoke, the effects of ethanol blended with different proportion of water on unregulated gaseous pollutants such as formaldehyde and acetaldehyde were also studied. At each engine load, experiments were carried out with and without DOC in the engine exhaust system. In this study, experiments were performed at the speed of 2500 r/min and engine loads of 25%, 50%, 75% and 100%, corresponding to brake mean effective pressures (BMEPs) of 0.183, 0.366, 0.549 and 0.732MPa, respectively. At each engine load, experiments were carried out with pure diesel mode and DFC modes. Make sure that the engine speed, torque, water and lubricating oil temperature and intake temperature under DFC mode stay the same with pure diesel combustion mode, to ensure the comparability of the test results. At each mode, the engine was allowed to run for a few minutes until the exhaust gas temperature attained a steady state value before data were measured.

3 Results and discussion

3.1 *Regulated emissions*

The emissions of NOx before and after DOC at different engine loads of 2500 r/min are shown in Figure 1. As shown in Figure 1a, NOx emissions increases with engine load increasing for all modes. Compared with diesel fuel, the NOx emissions in DFC modes are reduced. When running at DFC (EW50) mode, the maximum reduction of NOx was 37.1% at load of 0.183MPa.

The formation of NOx highly depends on the oxygen concentration, in-cylinder temperature and residence time for the reaction. There are several mechanisms that affect the NOx when ethanol is ignited by the injected diesel fuel. Firstly, there is an increase in oxygen supply which might enhance NOx emission. Secondly, the cooling effect of aqueous ethanol, due to its high latent heat of evaporation (more than 4 times of diesel), ethanol tends to absorb more heat than diesel fuel and thus cools down the intake temperature and lowers the combustion temperature, leading to lower NOx emissions [4]. Thirdly, it is commonly known that ethanol can lead to an increase in ignition delay because of its lower cetane number, resulting in an increase in fuel burned in the premixed combustion phase and hence an increase in the combustion temperature [5], meantime it will decrease the combustion time. These positive and negative effects compete with each other and lead to the variation of NOx emissions. As shown in Figure 1a, the decrease in NOx for DFC become more significant with the increase of water blending ratio. Compared to diesel fuel, reductions of NOx are about 8.9%, 18.5% and 25.3% for DFC (EW30), DFC (EW40) and DFC (EW50), respectively, at load of 0.732MPa.

As shown in Figure 1b, after passing through the DOC, the NOx emission almost has no change at DFC (EW40) mode, indicating that there is no obvious conversion of NOx using this kind of fuel component with the DOC, but at other modes DOC still have certain effects in decreasing the NOx emissions.

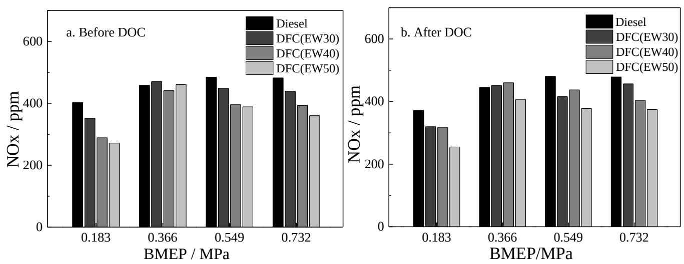

Figure 1. NOx emissions before and after DOC versus engine loads.

Figure 2a shows the HC emissions before DOC at different engine loads of 2500 r/min. There is an increase in HC emission of DFC mode compared with that of diesel and this trend becomes more obvious with the increase of water proportion. The increase of HC with DFC is higher at low load, and lower at high load, which is reported by almost all investigators on various types of engines and conditions [4]. Comparing with diesel fuel, the highest increase of HC is about 15 times for DFC (EW50) at low load.

Increased HC emissions are caused mainly because of incomplete combustion. The lower gas temperature of DFC makes it difficult to burn completely, especially when the amount of ethanol injected is small, which results in a lean air/ethanol mixture to burn at low load. In addition, the clearance between the piston and the liner may store some ethanol mixture that could not be burned until it escaped from these places in the exhaust stroke. All these would increase HC emission for the DFC engine. HC emissions of different fuels after DOC are shown in Figure 2b. The DOC is effective in reducing HC emissions below that of diesel fuel, while HC emissions of the baseline engine are also reduced after DOC.

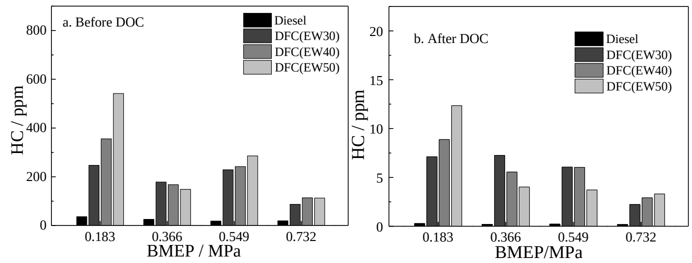

Figure 2. HC emissions before and after DOC versus engine loads.

CO emission is toxic and an intermediate product in the combustion of hydrocarbon fuels, and it results from incomplete combustion. CO emissions before and after DOC at different engine loads of 2500 r/min are shown in Figure 3. With the increase in engine load, CO emission in general decreases, due to the increase of combustion temperature. There is a significant increase in CO emission from the DFC engine compared with that of the baseline engine. CO emission increases by three or more times when operating at DFC mode. However, the increase in CO emission is not strongly related to the percentage of water.

The results showed that, before DOC, the drastic increase in CO emission at low load for blends is due to decrease in-cylinder gas temperature and the delayed combustion process. With lower flame temperature, a thickened quench layer is formed and a larger fraction of ethanol may be found in a rich air/fuel ratio range or even liquid state in the quench layer, as the flame front spreads too slowly to reach them. Another reason for the increase in CO emission is the increase in ignition delay. This results in combustion of a proportion of the fuel in the expansion stroke, which lowers the gas temperature and reduces the CO oxidation reaction rate, resulting in incomplete combustion and causing relatively high CO emission. However, Figure 3b shows that the DOC is effective in reducing CO emission from the DFC engine to a level much lower that of diesel fuel.

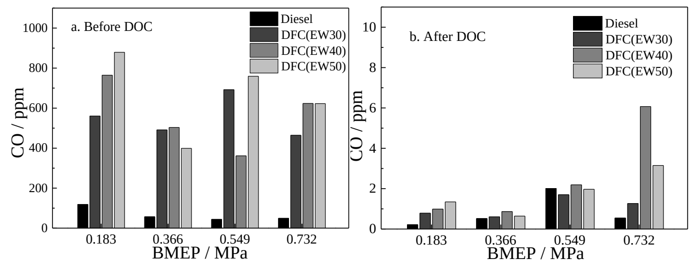

Figure 3. CO emissions before and after DOC versus engine loads.

Figure 4a depicts an increase in smoke emission with the increase of engine load before DOC at 2500 r/min. The increasing load makes injection quantity increased, the excess air ratio reduced, thereby increasing the amount of fuel cracking and reducing the oxidation of early carbon smoke, which leading to the increase of smoke emission.

EW30 has the most obvious effect on the improvement of smoke emissions. With the increase in proportion of water, the smoke emission increases. High proportion water blended with ethanol means high vaporization latent heat, which will lower the temperature of the mixture, then may inhibit the fuel atomization, increase the unevenness of fuel and air mixture, extend the flame retardant period, and lead to an increase in pyrolysis carbon smoke. The increase of HC also means fuel cracking increases.

Smoke emissions of different fuels after DOC are shown in Figure 4b, and the variation trend is same with the result before DOC. After DOC, the smoke emission declines slightly. At medium and high loads, the oxidation efficiency of DOC for smoke is high. This may due to the appropriate exhaust temperature, oxygen content and retention time.

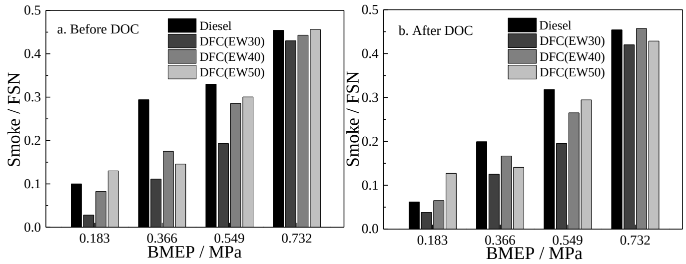

Figure 4. Smoke emissions before and after DOC versus engine loads.

3.2 *Unregulated emissions*

Figure 5a depicts acetaldehyde emissions before DOC at different engine loads of 2500 r/min. Since acetaldehyde is an intermediate product from partial oxidation of quenched fuel, maybe more acetaldehyde emission is converted from ethanol under different conditions. It is also seen that acetaldehyde emission has close relations with loads and water content. With the increase of loads acetaldehyde gradually decreases to minimum at medium loads, then increases again at high loads. With the increase of water content, acetaldehyde emission increases. [6] revealed an increase in acetaldehyde when using ethanol blended diesel. Under DFC mode, with increase of water proportion, acetaldehyde emission increases especially at low load.

Figure 5b shows that the DOC is effective in reducing acetaldehyde emission from the DFC engine to a level that of the baseline engine. However, acetaldehyde emission does not reduce after DOC at low load. Firstly, this is attributed to low combustion temperature and exhaust temperature at low load, which does not meet the appropriate light-off temperature of DOC. Secondly, with the increase of engine speed, the residence time of exhaust gas in DOC is shortened, so less acetaldehyde emissions have time to be oxidized. In order to significantly reduce the acetaldehyde emission through using DOC, a small amount of ethanol should be injected at high speed and low load conditions.

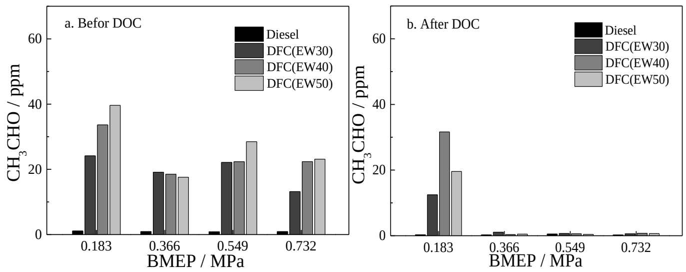

Figure 5. Acetaldehyde emissions before and after DOC versus engine loads.

Figure 6 describes formaldehyde emissions before and after DOC at different engine loads of 2500 r/min. Formaldehyde emission from baseline engine is less than 5 ppm, then increases with the addition of ethanol and decreases with increase in engine load, as shown in Figure 6a. It can be seen from Figure 6b, after DOC formaldehyde emission reduces to a very low level, even lower than that of the baseline engine. Formaldehyde emissions decrease with increase of exhaust temperature, as aromatics do not participate in their formation; these pollutants are produced at lower temperatures. It can be concluded that the DOC can effectively reduce the regulated and unregulated pollutants in DFC mode, including the air toxics: acetaldehyde and formaldehyde.

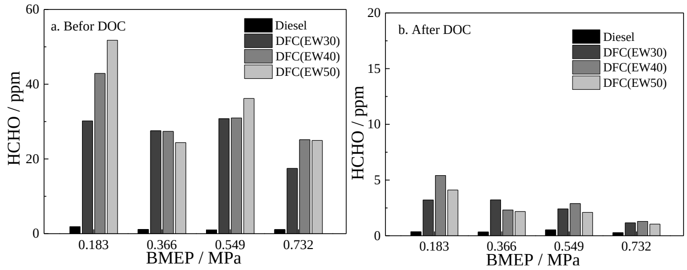

Figure 6. Formaldehyde emissions before and after DOC versus engine loads.

4 Conclusions

(1) The common-rail, turbocharged, inter-cooled diesel engine with diesel/ethanol blended with water dual fuel can run stable under different engine loads.

(2) DFC mode can remarkably reduce NOx emissions (up to 37.1%) compared with the baseline diesel engine.

(3) The DOC can reduce unburned HC and CO emissions effectively (up to 99.9% and 98.7% compared with the baseline diesel engine, respectively), but there is no obvious conversion of NOx.

(4) DFC mode has higher unregulated pollutants such as acetaldehyde and formaldehyde, however, the DOC can effectively eliminate acetaldehyde and formaldehyde, even better than that of diesel fuel.

Acknowledgement

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