COMPARISON OF THE IMPACT OF INTAKE OXYGEN ENRICHMENT AND FUEL OXYGENATION ON DIESEL PARTICULATE EMISSIONS

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Introduction

Addition of oxygen to assist the diesel combustion process is by no means a new idea. Significant work has been ongoing for some years regarding oxygenation of diesel fuel through additives and alternative fuels [1,2,3,4]. Oxygen enrichment of intake air has also been considered as a measure to control the PM emission and to improve thermal efficiency. Argonne National Laboratory has developed a membrane that efficiently separates standard air into oxygen and nitrogen. Motivated by this novel method, recent work at University of Wisconsin-Madison has explored the impact of intake composition [5] and compared the impact of fuel oxygenation and intake oxygen enrichment [6]. This recent work shed some light on the effects of intake charge composition, but left many unanswered questions. The work presented here compares oxygenated fuels with oxygen enrichment of intake air. In this case, we are examining the application of Air Products' VSA type A-040/120L Oxygen Generator to improving diesel engine operation.

Experimental

The experimental system consists of an engine test cell (dynamometer, controller), an engine, combustion analysis instrumentation, and emissions analyzers. Figure 1 presents a schematic diagram of the VW TDI 1.9L turbodiesel engine and test cell instrumentation. Steady-state engine operation at 75 % load and 1900 rpm was chosen for this study because oxygenates effect was known as rather pronounced than at low load condition. A pressure transducer, mounted in the glow-plug hole in the first cylinder was used with a shaft encoder to provide time-resolved pressure traces for heat-release rate calculation. Emissions of particulate matter, NO_x, CO, CO_2, HC were measured respectively via BG1 dilution tunnel, FTIR and HFID.

The intake air flow rate was directly measured via an electronic mass air flow sensor. Fuel consumption rate was recorded via fuel tank weight loss using a precision weighing scale and real-time fuel consumption rate was also measured using two separate flowmeters (Micromotion D06) on the fuel flow to the engine and fuel return from the engine. For oxygen enrichment of the intake air, modification to intake air supply line was required. The oxygen was supplied by the oxygen generator (Air Products' VSA type A-040/120L) into the intake air surge tank through a pressure regulator, a metering valve and flowmeter. Fumigation in to the intake surge tank was chosen to allow the thorough mixing of oxygen-air mixture through the subsequent devices such as the air filter, turbocharger and intercooler before entering the intake manifold. With known air flow rates at the desired engine operation condition, the required oxygen flow rate was pre-calculated and was set to obtain the desired volume percent oxygen enrichment. To verify this oxygen enrichment, the oxygen-air mixture was sampled at the air filter by using the Rosemount O_2 analyzer (Model 755R).

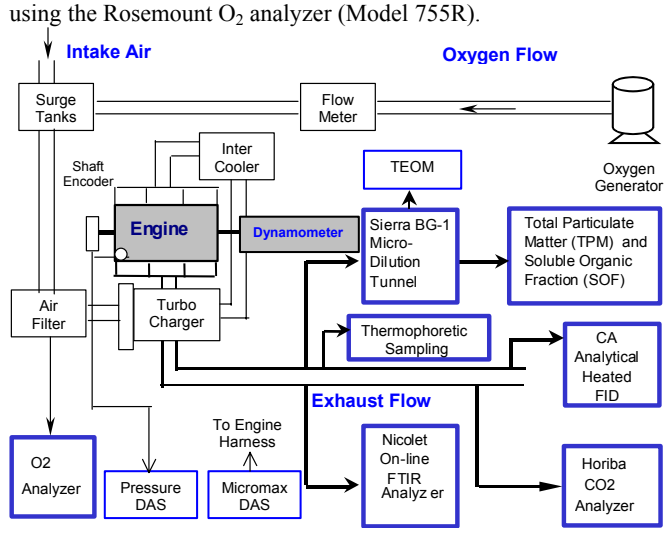

Figure 1. Schematic diagram of the experimental setup

Fuel oxygenation was accomplished using two compounds with widely different cetane number. A mixture of glycol ethers, 20 vol.% monoglyme and 80 vol.% diglyme (referred to as CETANER^{TM}), with a cetane number of 100 represented a cetane-improving oxygenate. In contrast, 1,3-dioxolane with a cetane number of 30 represented a cetane suppressing oxygenate. Both compounds were soluble in diesel fuel and provided a means of identifying the cetane number and oxygen addition effects.

Results and Discussion

The experiments was intended to investigate and compare the relative effect of two oxygen addition methods on emission and combustion, via intake air enrichment and oxygenation of the fuel. To directly compare both intake air oxygen enrichment and oxygenated fuel under the same extent of oxygen addition, oxygen to carbon ratio in the overall mixture was kept constant. An elementary analysis was performed to match the oxygen to carbon ratio on the basis of the overall in-cylinder gas compositions in the same way as Donahue et al. [6].

In Figure 2, oxygen addition, whether it comes from intake air enrichment or via oxygenated fuel, reduces soot even though the extent of PM reduction varies remarkably with oxygen addition method. For the equivalent level of oxygen addition based on oxygen to carbon ratio=5.1, intake air oxygen enrichment was more effective for reducing soot than fuel-bound oxygen addition, such as CETANER^{TM} blends and 1,3-dioxolane blends.

This significant effectiveness of intake air enrichment might be explained by the synergistic effects of the thermal and chemical interaction arising from intake oxygen addition. The heat release rate in Figure 3 indicates that oxygen enrichment lowered the peak premixed burn, which leads to lower soot precursor formation through reduced fuel pyrolysis without any shift in combustion phase from the baseline. The resulting increased heat release in the mixing-controlled combustion phase will also contribute to increased soot oxidization. A similar trend of heat release characteristics has been observed previously for intake air enrichment by Donahue et al. [6].

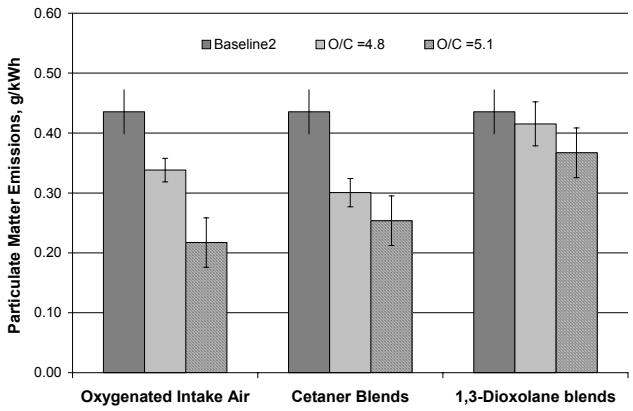

Figure 2. Particulate Matter Emissions for different oxygen addition methods, g/kWh basis.

The other possible explanation is that the presence of OH and O in the mixing-controlled phase will more likely attack the soot precursors, which results in a lower acetylene concentration as postulated by Gülder [7]. The free oxygen supplied by the intake air can be the key species affecting the soot formation chemistry, thereby reducing soot formation and increasing the oxidation of the soot.

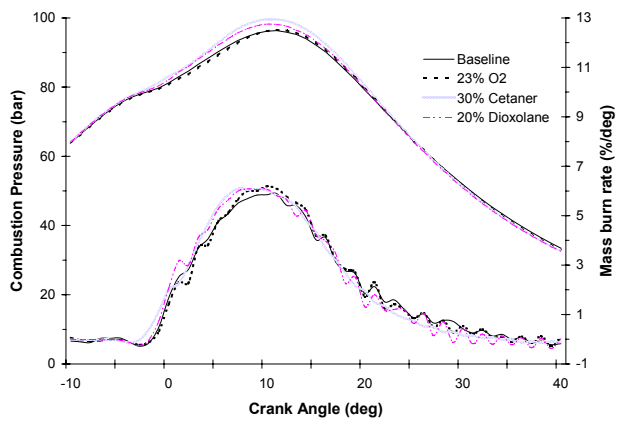

Figure 3. Heat release rate for different oxygen addition methods at O/C=5.1.

The oxygenated fuels were seen to advance the start of injection timing in Figure 3 because the engine maintains power at the requested level through injection timing adjustment to compensate for the higher density and lower heating value of oxygenated fuel as compared to the baseline fuel. Specifically, injection timing of the CETANER^{TM} blend was more advanced than that of 1,3-dioxolane, but the high cetane number of CETANER^{TM} compensates this advanced injection timing so that ignition delay was similar to the baseline and 23% intake air enrichment. Under the same ignition delay, the CETANER^{TM} blend was also observed to lower peak premixed burn as in an intake air enrichment case, which leads to the lower soot formation through reduced fuel pyrolysis. The heat release characteristics of CETANER^{TM} are consistent with the observations reported by Beatrice and coworkers, that premixed burn rate decreases while diffusion heat release rate increases at high load. That high diffusion heat release was attributed to increased oxidation of the combustion intermediates by oxygen present in the additive [8].

The unfavorable effect of oxygen addition on NO_x emissions becomes greater in the order of 1,3-dioxolane, CETANER^{TM} and intake air enrichment as shown in Figure 4. This trend does agree with typical PM-NO_x trade-off behavior, i.e. the lower the PM, the higher the NO_x. In other words, the increased oxygen concentration causes a NO_x increase in all cases, but the extent of the increase depends strongly on how the oxygen is added. Intake air enrichment leads NO_x emissions to increase by 53 and 126 (%) with respect to baseline for 22 (vol.%) and 23 (vol.%) oxygen concentration, respectively. Considering that NO_x is more likely to form in a post flame zone where the mixing controlled regime dominates, heat release in the mixing controlled phase of combustion might be one of the key factors. Under the present engine operation where mixing controlled combustion occurs, the higher heat release rate of the mixing controlled combustion phase leads to higher temperatures for the intake air enrichment case shown in Figure 4. This thermal effect contributes to a NO_x increase in combination with local ϕ (equivalence ratio) effect. According to local ϕ theory, the available oxygen in the high-temperature flame region may shift this locally rich mixture toward a slightly lean mixture where the maximum equilibrium O-atom mole fraction lies [6]. Consequently, the high equilibrium concentration of oxygen atom along with super-equilibrium O-atom results in higher kinetically formed NO_x. The incorporation of the fuel-bonded oxygen mitigates the adverse impact of leaner combustion conditions compared to free oxygen atom from intake air enrichment, causing a smaller NO_x increase compared to oxygen enriched intake air.

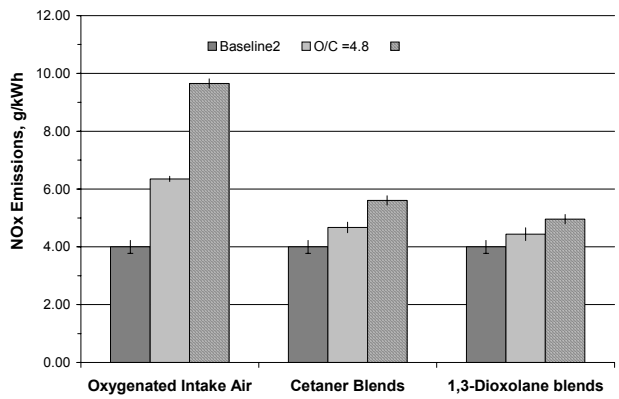

Figure 4. NO_x Emissions for different oxygen addition methods, g/kWh basis

Conclusions

While oxygen enrichment of intake air reduces diesel PM significantly more than fuel oxygenation, fuel oxygenation can provide PM reduction with only a modest affect on NO_x emissions. With their linear structure, the glycol ethers that comprise CETANER^{TM} were shown to be far more effective for soot reduction than equivalent oxygen addition via Dioxolane with its ring structure.

References

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