Influence of different alternative fuels on particle emission from a turbocharged common-rail Diesel engine

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Abstract

Influence of alternative fuels on diesel engine exhaust particle emission was investigated using an ultra-low sulfur diesel fuel as a baseline fuel where two biodiesels (canola & tallow), Fischer–Tropsch and bioethanol were used as alternative fuel. Both the biodiesels coming from canola and tallow feedstocks, as well as F-T were used as 100% to run the engine where up to 40% energy substitution by ethanol was achieved without any sacrifice of engine power output. It was found that up to 30% ethanol substitution reduced both particulate mass (PM) and particle number (PN) emission consistently for all load settings at 2000 rpm, highest 59% reduction in PM and 70% reduction in PN observed at 100% load. As previously suggested the possible mechanism for the observed reduction is the oxidation of particulate matter by OH radicals which are in excess with ethanol fumigation. For 40% ethanol substitution some inconsistency was observed for PM emission at different loads but consistent reduction was found for PN. Condensation of unburned/partially burned hydrocarbons that later condense on existing soot might be responsible for this, as the maximum increase of PM was observed at quarter load where low in cylinder temperature favour to nucleation of unburned hydrocarbons. PM emission was also reduced in case of using 100% FT, and 100% biodiesel and the highest 90% reduction in PM was observed for biodiesel at 100% load with almost no difference between the two biodiesels itself. On the other side a considerable difference was observed between canola and tallow biodiesel in case of PN emission. Canola biodiesel increased PN, due to the presence of the nucleation mode, for almost an order of magnitude for all load and speed settings where no such increase was observed for tallow biodiesel.

Keywords: Alternative fuel; ethanol fumigation; biodiesel; particulate matter; particle number; particle size distributions; Diesel engine

Nomenclature

\begin{tabular}{llll}
DPM & Diesel particulate matter & B100 & 100\% biodiesel \\
PM & Particle mass & FT & Fischer–Tropsch(Synthetic diesel) \\
PN & Particle Number & EXX & \% of energy substitution by ethanol fumigation \\
\end{tabular}

1. Introduction

Compression Ignition (CI) engine is in the pace of increasing popularity due to its higher thermal efficiency. It powers much of our land and sea transport, provides electrical power, and is used in farming, construction and industrial activities. Despite its significant advantages over Spark Ignition (SI) engines the tail pipe emissions from CI engines, especially...
particulate matter (PM) and NOx, are still a matter of great concern. Particulate matter emitted by diesel engine affects the Earth's temperature and climate by altering the radiative properties of the atmosphere[1]. All though Particles emitted from diesel engine contribute to the global climate both by direct heating and indirect cooling, the heating effect is dominant. So it is really important for climate change mitigation to reduce the diesel engine particulate matter emissions. Even, short atmospheric lifespan makes black carbon abatement one of the most attractive means to make a significant near-term impact on global warming.

In addition to climate change, chronic exposure of diesel exhaust particles (DEP) may lead to exacerbation of pulmonary diseases such as asthma and bronchitis as well as lung cancer. A few studies[2-4] have also described negative impacts of DEPs on reproductive systems i.e liver functions[3] and brain activity[4]. A recent epidemiological study on underground miners reported an increased risk of lung cancer mortality associated with DPM exposure[5]. By considering the health risk associated with DPM, International Agency for Research on Cancer (IARC), which is part of the World Health Organization (WHO), classified diesel engine exhaust as carcinogenic to humans. This adverse health effect of DPM is related to both the physical properties and chemical composition of particles. Physical properties of DPM that influence respiratory health include particle mass, number and size distribution, surface area and mixing status of particles[2]. As for example deposition of particles in different parts of the lung depends on their size, the smaller the particles the higher the deposition efficiency. Even small particle can penetrate deep into the lung. Furthermore, Smaller the particle, greater the chance of staying longer time in the atmosphere, so smaller particles have a higher probability that they will be inhaled and deposited in the respiratory tract and in the alveolar region. Due to the superiority of particle number over particle mass in determining its health and climate effect, European Union (EU) has already introduced particle number based emission standards for euro-v and euro-vi engines.

Use of after treatment technology is one way of reducing diesel exhaust emissions[6] where alternative fuels can be another potential way[7]. Among different types of alternative fuels biodiesel and synthetic diesel fuel, such as Fischer–Tropsch (F–T), are considered to be the most promising options for CI engines as they can be used in CI engines without engine modification[8]. Ethanol, as an alternative fuel, also has the potential to be used in CI engines[9], but its very low cetane number and poor solubility in diesel, especially at low temperature, is key barrier on its way of implementation. Fumigation of ethanol into the intake manifold of the engine where vaporized ethanol mixes with incoming air can resolve the issue of poor solubility when blending ethanol with diesel. In this study, a six cylinder 6 liter turbocharged heavy duty Cummins diesel engine was used to investigate the effect of afore mentioned alternative fuels on diesel emission with a special emphasis on particle emission.

2. Experimental methods

PM and NOx emission measurement was performed from the exhaust of a 6 cylinder, turbocharged-after cooled, common rail diesel engine. Specification of the engine has shown in table-1. Engine was soupled to an ECU controlled hydraulic dynamometer for adjusting the engine load and speed. An ultra low sulphur diesel fuel was used as a baseline fuel to run the engine where two biodiesel (canola & tallow), a synthetic diesel F-T (Fischer–Tropsch) and bio ethanol were used as alternative fuel. Both the biodiesels coming from canola and tallow feedstocks, as well as F-T were used as 100% basis to run the engine where up to 40% energy substitution by ethanol was achieved without any sacrifice of engine power output. Energy substitution by ethanol was accomplished by fumigating the ethanol into engine intake air.

![Fig. 1. Schematic diagram of experimental set up](image-url)
Figure 1 displays the experimental setup used to sample exhaust from diesel engine exhaust pipe. An ejector diluter made by Dekati was used to dilute the raw exhaust from the engine exhaust pipe, where raw exhaust is mixed with particle free compressed air. The purpose of the dilution is to bring down the temperature as well as the concentration of gases and PM within the measuring range of the instrument. A HEPA filter was used to provide particle free compressed air for the diluter. Diluted exhaust was then sent to different gaseous and particle measuring instrument for measurement. A CAI 600 series CO\textsubscript{2} analyzer was used to measure the CO\textsubscript{2}, and CO concentration directly from the raw exhaust. A second CO\textsubscript{2} meter (SABLE, CA-10) was used to record the CO\textsubscript{2} from the diluted exhaust. Dilution ratio was calculated from two CO\textsubscript{2} measurements by using the following formula.

\[
\text{Dilution Ratio (DR) } = \frac{\text{CO}_2(\text{Raw}) - \text{CO}_2(\text{Background, CAI})}{\text{CO}_2(\text{Diluted}) - \text{CO}_2(\text{Background, SABLE})}
\]

A CAI 600 series CLD NO\textsubscript{x} analyzer was used to measure the NO\textsubscript{x} and NO\textsubscript{2} from diluted exhaust. PM\textsubscript{2.5} emissions was measured by a TSI DustTrak(Model 8530). DustTrak readings were converted into a gravimetric measurement by using the tapered element oscillating microbalance to DustTrak correlation for diesel particles published by Jamriska et al[10]. Particle number and size distribution was measured by scanning mobility particle sizer (SMPS) consists of TSI 3080 classifier and TSI 3025 butanol base condensation particle counter (CPC).

3. Results and discussions

3.1. PM 2.5 emission from different alternative fuels

Figure-2 shows the brake specific PM2.5 emission at engine speed 2000 rpm. For 25% and 100% load, PM reduced consistently with the increase of ethanol percentage and maximum 59% reduction was observed for 30% ethanol substitution at 100% Load. For 40% ethanol substitution PM increased slightly at 100% load which was well below the PM of neat diesel but around 44% increase was observed at 25% load resulted in highest PM emission among all fuels and engine load settings. On the other hand, no such reduction in PM was observed due to ethanol substitution for 50% and 75% load. The most significant reduction in PM2.5 was achieved when using biodiesel and this trend was consistent regardless of the load and speed settings of the engine. Highest 93% reduction was achieved for 100% canola biodiesel while it was 91% for tallow biodiesel. A considerable reduction in PM is also observed for synthetic diesel which was higher than both of the biodiesels but lower than neat diesel and all ethanol substitutions.

Specific PM2.5 Emissions for different alternative fuels

![Graph showing PM2.5 emissions for different alternative fuels.](image)

Fig. 2. Brake specific PM2.5 emission for different alternative fuels at 2000 rpm engine speed
3.2. Particle number and size distribution from different alternative fuels

The reduction in PM due to alternative fuel is further revealed in particle number and size distribution as shown in figure-3, figure-4(a) and figure-4(b). With the increase of ethanol substitution, brake specific particle number concentration decreased consistently at 25%, 50%, 75% and 100% load, and highest reduction happened for 40% ethanol substitution at 100% load. For 25% load, total particle number concentration at 10% ethanol substitution was higher than neat diesel and 30 nm increase of particle median diameter was found for 40% ethanol substitution. This increase of particle median diameter indicates why highest PM2.5 emission was observed for 40% ethanol substitution at 25% load. Tallow biodiesel decreased the total particle number concentration with the reduction of 15 nm median diameter. For canola biodiesel, accumulation mode particles reduced but the presence of 20 nm nucleation mode particles are constantly observed during all load and speed settings as shown in figure-4(b) separately. The presence of nucleation mode particle in case of canola biodiesel increased specific particle number emission almost by an order than neat diesel. Particle size distribution for synthetic diesel fuel was found almost similar to that of fossil diesel with slight reduction in total number concentration at 100%, 75% and 50% load, while a small increase in nanoparticle emission was observed at 25% load.
The presence of fuel bound oxygen in the ethanol was the driving force behind the reduction of both PM and PN due to ethanol substitution. As previously suggested[11] the possible mechanism for the observed reduction is the oxidation of particulate matter by OH radicals which are in excess with ethanol fumigation. Higher ratio of hydrogen to carbon, higher volatility and absence of aromatics and sulphur in ethanol also favoured suppression of in cylinder PM formation. For 40% ethanol substitution some inconsistency was observed for PM emission at different loads but consistent reduction was found for PN. Condensation of unburned/partially burned hydrocarbons that later condense on existing soot might be responsible for this, as the maximum increase of PM was observed at quarter load where low in cylinder temperature is favourable to nucleation of unburned hydrocarbons. For biodiesels, the massive reduction of PM is also due to its oxygen content and higher cetane value. Difference in specific PN emission between two biodiesels might be due to its chemical composition. Canola biodiesel composed of 30% more double unsaturated compound than tallow biodiesel which might favour formation of nucleation mode particles. In addition viscosity of and density of canola biodiesel also found higher than tallow biodiesel which may also favour smaller particle emission. For FT, the absence of aromatics and sulphur supposed to be responsible for low PM emission as they act as precursor for PM.

3.3. Effect of different alternative fuels on specific NOx emission

Figure 5 shows the brake specific NOx emission for different alternative fuels at 2000 rpm. For ethanol fumigation, NOx emission decreased from the reference diesel fuel with the increase of energy substitution by ethanol for each engine load. Highest 25% NOx reduction was observed for 40% energy substitution (E40) by ethanol at 100% load where it was 14%, 12% and 9% for E30, E20 and E10 respectively. Same trend was found in NOx reduction at other engine load as well. Low heating value of ethanol which causes low in cylinder temperature is mainly responsible for reduced NOx emission for ethanol fumigation On the other hand brake specific NOx emission increased for both biodiesels and synthetic diesel. Between two biodiesels tallow biodiesel produced less NOx than canola biodiesel. NOx emission increased 25%, 11%, 47% and 32% at 25%, 50%, 75% and 100% load respectively for canola biodiesel while it was 4%, 6%, 5% and 11% for tallow biodiesel at the same engine load. Higher degree of unsaturation of canola biodiesel is found to be responsible for higher NOx emission by canola biodiesel than tallow biodiesel, similar result is also reported by[12] Finally, NOx emission from synthetic diesel was also found higher than neat diesel but lower than biodiesel.

Specific NOx emission for different alternative fuels

![Fig. 5. Brake specific NOx emission for different alternative fuels at 2000 rpm engine speed](image-url)
4. Conclusions

- In general energy substitution by ethanol fumigation reduced both PM and PN emission compared to petroleum diesel and maximum 59% reduction in PM and 70% reduction in PN observed at full load. Up to 30% energy substitution by ethanol reduced PM and PN consistently regardless of the engine operating condition where some inconsistency was observed for 40% ethanol substitution due to nucleation at some engine operating speeds and loads. Ethanol substitution also reduced NOx emission.
- Biodiesel reduced PM most among all used alternative fuels and the highest 93% reduction was observed at full load. But canola biodiesel increased PN almost an order than diesel due to the presence of nucleation mode particles where tallow biodiesel reduced PN significantly with 15 nm reduction in particle median diameter.
- PM emission for FT was found lower than neat diesel and all ethanol fumigation but higher than biodiesel, where no considerable difference was observed for PN.
- Both biodiesel and FT increased specific NOx emission. Between two biodiesels NOx emission from canola was higher than tallow due to the presence of more unsaturated compound in canola biodiesel which may cause prolonged premixed combustion favorable for thermal NOx production.

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