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Cold start idle emissions from a modern Tier-4 turbo-charged diesel engine fueled with diesel-biodiesel, diesel-biodiesel-ethanol, and diesel-biodiesel-diethyl ether blends

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HIGHLIGHTS

- Diesel-biodiesel blends with additives ethanol and diethyl ether are tested at idle.
- In biodiesel blends, B20 with ethanol additive had cloud points below −25 °C.
- Biodiesel blends with additives emitted much lower CO emissions than diesel.
- Additives were found effective to reduce the increase in NOx from biodiesel blends.
- Ethanol additives reduced HC emissions in B100 blends significantly at idling.

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ABSTRACT

This study investigated the emissions of a modern (Tier 4) 4-cylinder direct injection (DI) diesel engine at idling with no load conditions. Three idling speeds: low (800 rpm), medium (1000 rpm) and high (1200 rpm), respectively are considered. Two additives (5% and 15% by volume), ethanol and diethyl ether (DEE) were mixed with biodiesel-diesel blends B20, B50 and B100. B100 was produced from canola oil. Engine was tested from cold start to warm up in real world conditions. Emissions analysis was conducted for carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), nitrogen dioxide (NO_2), oxides of nitrogen (NO_x), and unburned hydrocarbons (HC). Investigation results show that, CO and NO_x emissions decrease, but HC emissions increase after warm-up than cold start. Diesel-biodiesel blends with additives produce lower CO emissions then neat diesel; ethanol and DEE additives can reduce NOx emissions in diesel-biodiesel blends, and increasing biodiesel content reduced HC emissions.

1. Introduction

Extensive use of the compression ignition (CI) engine in mining, construction and transportation as well as new emissions regulations has increased interest in developing cleaner diesel engines. Biodiesel has become a promising alternative to convention diesel fuel due to its ability to run in CI engines with little to no modification [1]. Biodiesel feedstock includes up to 350 oil producing crops globally, animal by-products, waste grease, and various other sources [2]. Over the last decade biodiesel output has grown from 0.8 to 14.7 billion litres annually [3]. In 2010, the Canadian Environmental Protection Act Bill C-33 mandated 5% renewable content in gasoline by 2020 and 2% renewable content in diesel fuel and heating oil by 2012 [3]. Most renewable fuel in Canada comes from the production of Ethanol from corn and wheat [4]. Vaillencourt et al. [5] developed the Times-Canada model which predicts that energy consumption is expected to increase by 42% by 2050. Canola oil is the major source of biodiesel production in Canada. Canola oil is converted using the process of transesterification. Transesterification or alcoholises is a process by which fat or oil reacts with an alcohol in the presence of a catalyst to form an ester and glycerol [6,7]. The increasing number of diesel passenger, and heavy duty diesel vehicles have resulted in regulation of CI combustion emissions [8]. The most commonly regulated emissions are CO, HC, particulate matter (PM), and NO_x. Biodiesel are attractive because they have the potential to decrease PM, CO, and HC emissions [9].

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Due to the extended idling periods that heavy-duty vehicles exhibit, idling emissions have been the subject of increasing laws, and regulations from policy makers [10]. In Canada, the Department of Natural Resources has posted idling reductions campaign strategies and by-law strengths/weaknesses for municipalities [11]. Natural Resources Canada has also released a campaign for commercial shipping fleets titled FleetSmart, which is aims to reducing idling time of transport trucks [12]. Regulations are left up to municipalities to develop and enforce. In Ontario (Canada), 37 municipalities have regulated idling to some extent [11]. In the city of Kingston (Ontario), all vehicles must not idle for more than 3 min out of every hour, with exceptions for cold weather, parades, emergency vehicles, etc. [13]. In contrast the city of Thunder Bay (Ontario) only regulates idling at gas stations where three or more axel vehicles can idle for 5 min out of every hour and all other vehicles for 2 min out of every hour [14]. The study in [10] compared the emissions of medium duty diesel engines to gasoline trucks, and previously studies heavy-duty diesel engines. As typically reported the study found that the diesel engines exhibited lower fuel use, higher NO_x emissions, and PM emissions while idling. The medium sized diesel engines exhibited lower fuel use and idle emissions than the heavy-duty diesel engines.

While operating in mining, construction, and transportation, diesel engine can experience periods of low operation efficiency. A study in [15] examined equipment operational efficiency, which is the ratio of which a piece of equipment is in use vs running idle. Operation efficiency of construction equipment can range from 85% to 41%. As operational efficiency decreased the percentage of unnecessary CO_2 emissions increases [15]. This study only looked at CO_2; unnecessary emissions for other regulated emissions would follow a similar pattern. Another study in [16] explored the relationship between emissions from mechanical fuel injection (MFI) and electronic fuel injection (EFI) of heavy-duty diesel vehicles during idle; it was found that overall EFI diesel engines emitted less CO, HC, and PM than MFI engines. However, EFI engines emitted higher NO_x emissions due to advanced timing in idle condition. Similarly, transport trucks can idle up for extensive periods of time. For example Frey and Kuo [17] examined the use of auxiliary power units (APU) for idling reduction in long haul trucks. Long-haul trucks can idle for more than 2000 h per year. Idling reduction strategies are especially important in long-haul trucks that experience extreme hot or cold temperatures, where diesel engines are used as power units for cabin air conditioning and heating. The use of APU's was found to significantly decrease fuel use, and emissions of CO_2, NO_x, and PM in mild climates. In more extreme climates observed in much of Canada, idling rates must increase when temperatures drop well below freezing.

Since Diesel engines typically experience high periods of idling, biodiesel research must also consider the idle condition. Biodiesel could be used in conjunction with other idling/emission reduction strategies to optimize vehicle fleet use. Rahman at al. [18] examined the effect idling had on Jatropha biodiesel emissions. Biodiesel was found to be an attractive CO, and HC emission reduction strategy. These reductions come at the expense of increased NO_x emissions. In a study [19], the performance and emissions of a diesel engine when fueled with biodiesel produced from waste cooking oil were examined. Lowest engine rpm tested was 1500 rpm, study found that HC emissions vary greatly with engine speed, however CO and PM emissions depend more on engine load. NO_x emissions were slightly increased with biodiesel blends. Singh et al. [20], tested the emissions from a diesel engine fueled with biodiesel and hydro processed renewable diesel (HRD). Using the European stationary cycle an idle condition was tested as one of thirteen modes. B100 was found to be more effective in reducing PM, CO, and HC emissions, but HRD reduced NO_x by 29% and brake specific fuel consumption. A study on waste cooking oil [21], included multiple idle states at 800 and 1200 rpm. The tests found that increases of HC and NO_x emissions were present at idle conditions but not at high rpm conditions, concluding that low engine speed has significant effect on emissions when using biodiesel. An additional study from An et al. [22] also concluded that partial load and idle conditions have significant impact on CO emissions, brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC). These studies support that when considering changing fuel blends the idle condition emissions must also be studied. The next step for moderate climates is to test the full range of engine condition emissions on biodiesel with good low temperature properties.

Alcohols can be used in CI engine's as alternative fuels when blended with diesel or biodiesel. Alcohol can also improve the low temperature properties of biodiesel and biodiesel blends. Yilmez et al. [23] tested biodiesel with ethanol as an additive at 3%, 5%, 15% and 25% in a diesel engine generator. Engine tests were conducted from 0% (no load) to 90% load from two resistive heating units. Cooling effects and oxygen content of alcohols were primary factors that affected emission reduction. Test results showed that the blends increased CO emissions compared to diesel at low load conditions, but there is no significant change in CO emissions at high loads based on fuel types or blends. Ethanol blended fuels reduced NOx emissions for all concentrations. HC emissions were found to depend heavily on operating conditions. Up to about 40% load, HC with blends is much higher than that of diesel fuel, and at loads higher than 40%, the HC levels of blends and diesel fuel is pretty much similar. 2.5%, 5%, and 7.5% ethanol by volume was added to waste pork lard biodiesel [24]. Single cylinder diesel engine was tested at 1500 rpm for 0%, 20%, 40%, 60%, 80%, and 100% load conditions. Ethanol addition was found to reduce CO, HC and smoke emissions when compared to neat biodiesel, and the reduction is higher at high loads. It was found that HC emission reductions would decrease with increase in ethanol additive. Ethanol was found to increase NO_x emissions for all biodiesel-ethanol blends, and higher the load, the higher the NOx emissions was. Biodiesel with ethanol additive was tested on a supercharged DI diesel engine in [25] at a speed of 1500 rpm with loads from 20% to 100%. It was found that NOx emissions increase with loads, and addition of ethanol in the blends helps reducing the NOx emissions. Test results also showed that ethanol was able to increase CO and HC emissions at all loads, whereas these increases were reduced when supercharged. Ethanol-biodiesel blends were tested in a multi-cylinder diesel engine and a single-cylinder low temperature combustion diesel engine in [26]. Three test conditions were examined: 1500 rpm at 3 bar Brake Mean Effective Pressure (BMEP); 2500 rpm and 6 bar of BMEP; and 4000 rpm at full load. In general, higher NOx and smoke and lower CO and HC were obtained at

Table 1
Test results of biodiesel according to ASTM 6751.

Test name	Test method	ASTM Limit	Results
Free glycerin (mass%)	ASTM D6584	Max. 0.02	0
Total glycerin (mass%)	ASTM D6584	Max. 0.24	0.112
Flash point, closed cup (°C)	ASTM D93	Min. 130	169
Water & sediment (vol.%)	ASTM D2709	Max. 0.505	0
TAN (mg KOH/g)	ASTM D664	Max. 0.5	0.14
Sim. dist., 50% recovery (°C)	ASTM D2887	N/A	359.8
Cetane index	ASTM D976 (2 variables formula)	N/A	50
Copper corrosion, 3 h @ 50 °C (rating)	ASTM D130	Max. 3a	1a