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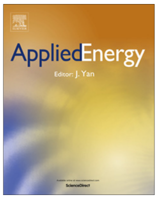

Performance characteristics of compression-ignition engine using high concentration of ammonia mixed with dimethyl ether

Kyunghyun Ryu [a], George E. Zacharakis-Jutz [b], Song-Charng Kong [b,*]

[a] *School of Mechanical and Automotive Engineering, Kunsan National University, South Korea*
[b] *Department of Mechanical Engineering, Iowa State University, USA*

HIGHLIGHTS

- Performance of a diesel engine using direct-injection ammonia-DME is investigated.
- Stable engine operation can be achieved by using early injection timings.
- Combustion of high concentration of ammonia exhibits HCCI characteristics.
- High load operations favor the use of high concentration of ammonia.

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ABSTRACT

Combustion and emissions characteristics of a compression-ignition engine using ammonia (NH_3) and dimethyl ether (DME) mixtures were investigated in this study. The experiments were conducted using three different mixtures, including 100%DME, 60%DME–40%NH_3, and 40%DME–60%NH_3 (by weight). The injection pressure was maintained at approximately 20.6 MPa and engine combustion and exhaust emissions were measured in order to analyze and compare the performance of different mixture compositions. Results show that engine performance decreases as ammonia concentration in the fuel mixture increases. Significant cycle-to-cycle variations are observed when 40%DME–60%NH_3 is used. The injection timing for best torque needs to be advanced with increased ammonia concentration in the fuel mixture due to the high resistance to autoignition of ammonia. Moreover, with the increase in ammonia concentration, both engine speed and engine power exhibit limitations relative to 100%DME cases. For 40%DME–60%NH_3, the appropriate injection timing was found to range from 90 to 340 BTDC and the engine exhibits homogeneous charge compression ignition (HCCI) combustion characteristics due to the highly advanced injection timing. 40%DME–60%NH_3 conditions also results in higher CO and HC emissions due to the low combustion temperature of ammonia. Soot emissions for 40%DME–60%NH_3 remain extremely low. When ammonia is used, NOx emissions are increased due to the formation of fuel NOx. Exhaust ammonia emissions also increase as ammonia concentration in the fuel mixture increases from 40% to 60%. Overall, in this study appropriate strategies are developed to enable the use of ammonia in direct-injection compression-ignition engines and the corresponding engine performance is evaluated.

1. Introduction

It is important to explore the use of alternative engine fuels for reasons of environmental protection and energy conservation. The use of alternative fuels, such as biorenewable fuels, can help reduce the life-cycle carbon emissions. Studies on internal combustion engines using biorenewable fuels have increased steadily in recent years [1–4]. In addition to tradition biofuels such as biodiesel and ethanol, it is also of critical importance to evaluate the use of non-carbon-based fuels to further reduce carbon dioxide (CO_2) emissions, an important greenhouse gas, in urban areas. Hydrogen (H_2) is recognized as a carbon-free fuel with favorable combustion characteristics. Hydrogen-fueled internal combustion engines and fuel cells have also received much attention and attracted significant public interest [5–7]. However, there are many challenges in using hydrogen for transportation due to various infrastructural issues such as production, storage, and transport.

Abbreviations: ATDC, after top-dead-center; BMEP, brake mean effective pressure; BSEC, brake specific energy consumption (MJ/kW h); BSFC, brake specific fuel consumption (g/kW h); BTDC, before top-dead-center; CAD, crank angle degree; DME, dimethyl ether (CH_3OCH_3); EPA, Environmental Protection Agency; GDI, gasoline direct injection; IMEP, indicated mean effective pressure.

[*] Corresponding author. Tel.: +1 515 294 3244.
E-mail address: kong@iastate.edu (S.-C. Kong).

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Ammonia (NH_3) can be also regarded as a carbon-free fuel and does not produce CO_2 emissions when it is used in internal combustion engines. Furthermore, ammonia is one of the world's most synthesized chemicals and is easy to store, handle, and distribute with pre-existing infrastructure. Ammonia can be easily liquefied and stored under room temperature (300 K) at a pressure of approximately 10 bar, allowing for efficient onboard application. In addition to the traditional Haber–Bosch process [8], ammonia can also be produced from renewable sources such as solar, wind, geothermal, and ocean energy [9] or from waste heat or electricity with water, biomass or organic waste, and air as the primary feedstock for production [10–11]. Moreover, the cost of ammonia is also comparable to the cost of diesel fuel on energy basis [12]. Thus, ammonia can be an attractive alternative fuel for engines. The possibility to produce ammonia from renewable sources and the desire to use non-carbon fuel further promote the potential use of ammonia as a fuel.

Numerous studies on using ammonia for engines have been performed, driven by the need for alternative fuels, dating back to the use of ammonia to power busses in Belgium in 1942 during World War II due to the fuel shortage [13]. In the 1960's the U.S. Army also performed both theoretical and experimental studies to evaluate the feasibility of ammonia as an alternative fuel source for internal combustion engines [14–16]. After the aforementioned literature, there has not been significant engine research using ammonia as a fuel until recently [17–20].

Most research activities have been focused on utilizing ammonia in spark-ignition engines due to its high octane rating [16,20]. Engine tests were conducted in a spark-ignition Cooperative Fuel Research (CFR) engine with the compression ratio varying from 6:1 to 10:1 [16]. Results show that in order to burn anhydrous ammonia in a SI engine, ammonia must be introduced as a vapor and be partly decomposed into hydrogen and nitrogen. The minimum amount of ammonia to be decomposed needs to be 4–5 percent by weight of the total ammonia. In another study, gaseous ammonia was used with gasoline in a CFR engine [20]. Results show that operation on 100% gasoline was required at idle and a mixture of 70% ammonia–30% gasoline (on energy basis) could be used at the normally aspirated, wide-open throttle conditions. The introduction of ammonia could allow the use of a higher compression ratio due to its high octane number.

Ammonia combustion was investigated in a compression-ignition CFR engine equipped with a pre-chamber [14]. Test results show that in order to achieve successful ignition of ammonia, the engine required a compression ratio of 35:1 with both water jacket and intake air at 150 °C using diesel fuel (CN 53) as a pilot fuel. However, another study using premixed ammonia in a compression-ignition engine utilizing a short diesel pilot injection was unsuccessful even at a compression ratio of 30:1 [15]. The resistance to autoignition of ammonia poses challenges for use in a compression-ignition engine [21].

Recently ammonia has been recognized by many as a potential combustion fuel and recent research results were published [22–25]. An economic study suggests that the feasibility of using ammonia as a fuel can greatly benefit from the well-established infrastructure and existing knowledge [26]. Despite the high resistance of ammonia to autoignition, it is still worth investigating ammonia combustion in diesel engines since diesel engines dominate heavy-duty transportation, stationary power generation, and heavy machinery applications. In order to overcome the demerits of ammonia, different fueling methods such as dual-fuel combustion systems have been attempted in conjunction with appropriate engine compression ratios [12,27].

Our previous research was performed with the goal to achieve equal engine power between solely diesel fuel and dual-fuel operation using ammonia-diesel fuel [17,27]. Ammonia vapor was continuously introduced into the intake manifold together with directly-injected diesel fuel. However, in the above approach, ammonia in the exhaust (i.e., ammonia slip) was relatively high. The subsequent challenge was to reduce ammonia slip by using a direct liquid injection strategy [12]. Due to ammonia's high resistance to autoignition, DME was chosen to mix with ammonia due to the similarity in vapor pressure of both fuels and the high cetane number of DME. Additionally, both fuels are miscible. It was found that ammonia causes longer ignition delays and can limit the engine load range under the conditions studied. Moreover, only moderate levels of ammonia concentration in the fuel mixture were tested using limited injection pressure. Thus, it is worth further investigating effects of fuel mixture composition and operating parameters on diesel engine combustion using ammonia as a primary fuel.

In this study, the effect of fuel mixture composition on the combustion and emission characteristics of a DI diesel engine using blends of ammonia and DME is investigated. Especially, a method to effectively run the engine at a mixture of 40%DME–60%NH_3 was explored. The combustion characteristics and exhaust emissions are presented.

2. Experimental apparatus and procedure

2.1. Test engine and stand

A Yanmar L70V single-cylinder, direct-injection diesel engine (Table 1) was used in this study. The engine test stand consisted of a heavy-duty steal frame to which the engine and dynamometer were mounted. A Klam K10C electromagnetic retarder was used to load the engine. The engine and retarder were coupled directly utilizing a vibration damping flexible tire shaft coupling.

The engine required significant modifications to the injection system for this research. The original injection system was replaced by an electronically controlled injection system in order to utilize ammonia and to allow greater control of the injection event. A Bosch fuel injector designed for use in gasoline direct-injection (GDI) engines was installed using the pre-existing injector port. To accommodate the unit, a few modifications to the cylinder head were also made. The new injector, a glow plug, a cylinder pressure sensor, and thermocouples to measure cylinder head temperature and intake air temperature were installed in the cylinder head.

The cylinder pressure for combustion analysis was measured using a Kistler 6125B piezo-electric pressure transducer together with a Kistler 5010 charge amplifier. The cylinder pressure was measured every 0.1 crank angle degrees and averaged over 250 engine cycles.

Intake air was drawn from the room and the consumption was measured using a Meriam laminar flow element equipped with a surge air tank, which was mounted below the engine. A computer-controlled single tubular heating element with a nominal power output of 1.1 kW was installed along the centerline of the surge tank and was used to heat the intake air up to 90 °C to help counter heat loss due to the high latent heat of vaporization of ammonia.

The gaseous emissions were measured using a combination of a Horiba MEXA 7100DEGR, Horiba MEXA 1170NX, and DeJaye emissions analyzers, which have been widely used in industry for studying diesel exhaust emissions as well as the performance of selective catalytic reduction (SCR) systems utilizing urea injection. The emissions data recorded included CO, CO_2, NOx, HC, O_2, and NH_3. In particular, exhaust ammonia emissions were measured using a Horiba MEXA 1170NX analyzer and a DeJaye analyzer, both of which are capable of measuring ammonia and NOx emissions