# Demonstration of Compression-Ignition Engine Combustion Using Ammonia in Reducing Greenhouse Gas Emissions

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This study demonstrated the feasibility of ammonia combustion in compression-ignition diesel engines. Ammonia combustion does not produce carbon dioxide, a known greenhouse gas that contributes to global warming. Using this idea, a method was developed to introduce ammonia into the intake manifold and to inject diesel fuel or biodiesel directly into the cylinder to ignite the mixture. This dual-fuel approach was chosen because ammonia has a high resistance to autoignition. This approach was proven successful in a multicylinder, turbocharged diesel engine. The system developed required only a slight modification of the intake to implement the ammonia fuel line. The existing diesel fuel injection system remained unchanged. A liquid ammonia tank was used for fuel storage, and a high pressure relief valve regulated the ammonia flow rate. Engine combustion phasing (e.g., ignition) was controlled by diesel fuel injection. Both experiments and chemical kinetic studies were carried out for different diesel/ammonia ratios at various engine speeds and loads. Ammonia was used as an energy replacement for diesel fuel. The results showed that the peak engine torque could be achieved by using different combinations of diesel fuel and ammonia. During testing, a maximum energy replacement of 95% was measured. It should be noted that if more ammonia is added, a higher than rated power can be achieved depending on engine load conditions. This would be similar in practice to adding nitrous oxide to gasoline engines. It was also shown that $CO_2$ emissions were reduced monotonically for the same engine torque output as the amount of the ammonia in the fuel mixture increased. Additionally, burning ammonia in engines does not necessarily increase NOx emissions despite the fuel-bound nitrogen. Lower levels of NOx emissions were obtained as long as energy substitution by ammonia did not exceed 60%. This is thought to occur because of the lower combustion temperature of ammonia. This study also showed that the engine could be operated at different load conditions by using a small quantity of diesel fuel with the appropriate amounts of ammonia to achieve desirable loads. Biodiesel was also used with ammonia at different ratios resulting in successful engine operation. Results of using biodiesel−ammonia were similar to those of using diesel fuel−ammonia.

## 1. Introduction

Internal combustion engines are a major consumer of fossil fuels, and combustion of fossil fuels inevitably produces emissions of the greenhouse gas carbon dioxide ($CO_2$). During recent years, techniques have been developed to reduce life-cycle $CO_2$ emissions and to improve carbon sequestration. Such approaches include the use of hybrid vehicles, fuel cells, biorenewable fuels, and other alternative fuels that are not carbon-based. There are pros and cons with respect to each approach but all share the common theme of replacing the fossil fuel.

Among the many approaches to alleviating greenhouse gas emissions, the use of hydrogen as a fuel has gained public interest because the exhaust products do not include $CO_2$. It is worth noting that, like hydrogen, ammonia ($NH_3$) combustion with air also does not produce $CO_2$. Ammonia can be stored under moderate pressure at ambient temperatures and it can be oxidized under temperature conditions found in the engine cylinder. With proper modifications to the fuel system, the operative ability of the engine does not need to be compromised. Ammonia is presently abundant and the facilities for its production, storage, handling and distribution are available worldwide.

There are additional attractive features for using ammonia as an alternative energy source. Ammonia can be produced from renewable sources by electrolysis or solid-state synthesis. It is an important source for producing hydrogen and can serve as a means to help build the infrastructure of the hydrogen economy.[1] Before more convenient means for storing and transporting hydrogen are available, ammonia can be used as a hydrogen energy carrier.[2,3] In fact, ammonia can also be used as a fuel in fuel cells in which the ammonia is converted into a mixture of hydrogen and nitrogen by electrolysis[4] or by recycling the heat

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**Table 1. Comparisons of Thermodynamics Properties for Several Engine Fuels[a]**

| fuel | molecule | boiling point (°C) | stoichiometric (air/fuel) | latent heat (kJ/kg) | energy content (MJ/kg-fuel) | energy content (MJ/kg-stoichiometric mixture) |
|---|---|---|---|---|---|---|
| methanol | $CH_3OH$ | 64.7 | 6.435 | 1203 | 20 | 2.69 |
| ethanol | $C_2H_5OH$ | 78.4 | 8.953 | 850 | 26.9 | 2.70 |
| gasoline | $C_7H_{17}$ | | 15.291 | 310 | 44 | 2.58 |
| diesel | $C_{14.4}H_{24.9}$ | | 14.322 | 230 | 42.38 | 2.77 |
| ammonia | $NH_3$ | −33.5 | 6.0466 | 1371 | 18.61 | 2.64 |

[a] Note that ammonia has comparable energy content per unit mass of the stoichiometric mixture.

generated by the fuel cell.[5] Before the fuel cell vehicle becomes commercially available, it is of interest to investigate the feasibility and characteristics of engine combustion using ammonia as an alternative fuel.

In order to burn ammonia in engines successfully, several characteristics need to be considered. These include the high resistance to autoignition, high latent heat, low energy content, fuel-bound nitrogen, and a low boiling point. A storage pressure of approximately 10 bar is often used to store ammonia as a liquid. When ammonia reacts with air, nitrogen oxide (NOx) emissions could be a concern due to the fuel-bound nitrogen. Ammonia can also cause health concerns. It has a distinct odor at a low concentration level (as low as 7 ppm). Serious acute health effects are noted in humans for concentrations of approximately 150 ppm and 300 ppm is the threshold that is considered to be immediately dangerous to life and health. Ammonia can also be corrosive to certain materials such as copper, nickel and plastics. Nonetheless, ammonia combustion in engines can still be achieved by proper combustion strategies and fuel system modifications.

Ammonia was used to power buses in Belgium in 1942 when there was an extreme shortage of diesel fuel.[6] It was reported that the vehicle could achieve comparable performance using ammonia. During the 1960s, the U.S. military developed interest in using ammonia, rather than hydrogen and hydrazine ($N_2H_4$), as a fuel that can be used immediately in Army vehicles and devices. Such studies were motivated by extreme situations in areas where hydrocarbon fuels were not available and vehicles needed to rely on local generation of ammonia fuel.[7–9] Both theoretical and experimental studies were performed[7] and it was demonstrated that ammonia can be burned in both spark-ignition (SI) engines[8] and compression-ignition (CI) engines.[9] In the SI engine application,[8] ammonia vapor was partially decomposed to hydrogen and nitrogen, and the spark timing was adjusted to obtain a better engine performance. Results determined that hydrogen concentration was a critical factor for successful operation and a minimum concentration of 4−5% by weight was required. Engine test results also indicated an increase in specific fuel consumption and NOx emissions. In the CI engine application it was found that the successful approach was to supply ammonia vapor to the air intake system and use diesel fuel to provide ignition energy.[9] The other approach of directly injecting liquid ammonia into the cylinder without using diesel fuel was not successful despite the fact that the engine compression ratio was increased to 30:1.

Ammonia combustion in a constant-volume chamber has been demonstrated experimentally by partial dissociation into hydrogen to overcome the low burning speed and high ignition energy.[10] A study on modeling the burning velocity and flame temperature of ammonia under SI engine conditions has also been performed.[11] Other studies on ammonia oxidation have been written. However, these studies are mainly on NOx reduction or biomass conversion.[12–15] Literature on ammonia combustion in engines is very limited. Nevertheless, the environmental concern in recent years has renewed interest in using ammonia as an engine fuel to reduce greenhouse gas emissions.[1,2]

There are technical and economic aspects of adopting ammonia as an engine fuel. This study is focused on the technical aspect of demonstrating the feasibility and strategy of burning ammonia in a modern diesel engine. In this paper, combustion characteristics of ammonia in the engine environment were studied by using thermochemical analysis and chemical reaction mechanisms. A method based on the chemical kinetic study for inducting ammonia into the engine was designed and used for successful operation. The results of fuel consumption and gaseous emissions will be presented based on experimental engine tests.

## 2. Ammonia Combustion Characteristics

**Thermochemical Properties.** The ammonia molecule does not consist of carbon atoms and thus does not produce $CO_2$ when burned. A complete reaction for the stoichiometric ammonia−air mixture can be written as $NH_3 + 0.75(O_2 + 3.76N_2) \rightarrow 1.5H_2O + 3.32N_2$.

Table 1 lists several thermochemical properties of various fuels that are relevant to engine combustion.[16] The energy content of ammonia is lower than that of the typical hydrocarbon fuel on a mass basis. However, the stoichiometric air/fuel ratio for ammonia is significantly lower than that of a typical hydrocarbon fuel. In other words, more ammonia can be burned

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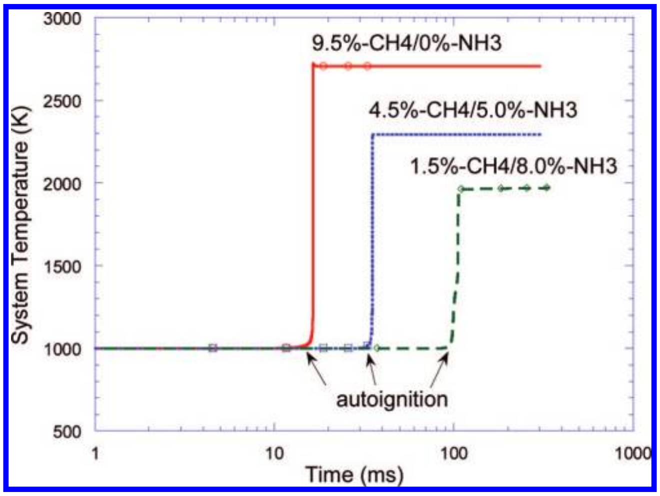


**Figure 1.** Temperature histories of cases with different $CH_4$ and $NH_3$ compositions during autoignition.

with the same amount of air. The greater amount of ammonia can make up for its lesser energy content per unit mass. As a result, the ammonia−air mixture has a comparable energy content per unit mass of stoichiometric mixture (i.e., sum of the fuel and air mass) as listed in Table 1. Air is a limiting parameter in normal engine operation. Based on the same amount of air, appropriate amounts of ammonia can be inducted into the engine to supply comparable fuel energy.

**Chemical Kinetic Study on Ignition Delay.** Because ammonia has a high resistance to ignition, it is important to understand its chemical kinetic characteristics in the engine environment. Chemical kinetic analyses were performed to study the effect of ammonia concentration on the ignition of a $CH_4$−$NH_3$−air system. The CHEMKIN code[17] was used with a detailed reaction mechanism. The mechanism consists of 53 species and 325 reactions and has been well validated for many different applications.[18] Different initial compositions were simulated and effects of ammonia concentration on ignition delay were investigated. The simulation was performed under constant pressure conditions at 50 atm. The initial mixture was assumed to be perfectly mixed.

Figure 1 shows the temperature histories of various cases with an initial temperature of 1000 K. It can be seen that, as ammonia concentration increases, the mixture is more difficult to autoignite. In fact, ammonia has a high autoignition temperature, 651 °C, as compared to 225 °C for diesel fuel, 440 °C for gasoline and 540 °C for methane.[16] This characteristic implies that if ammonia is used as a fuel, careful planning is required to prevent engine misfire.

The concentration histories of several major species during ignition are shown in Figure 2. It can be seen that at 100 ms (ms), nearly all the methane has been depleted while a majority of ammonia still exists. Clearly ammonia is less easy to autoignition than methane, which is less easy to autoignition than diesel fuel. Therefore, in the present engine experiment, it was decided to use a dual-fuel approach, i.e., diesel fuel−ammonia, in which diesel fuel was used to initiate the combustion of the ammonia−air mixture in the cylinder. Different ratios of diesel fuel−ammonia will be tested.

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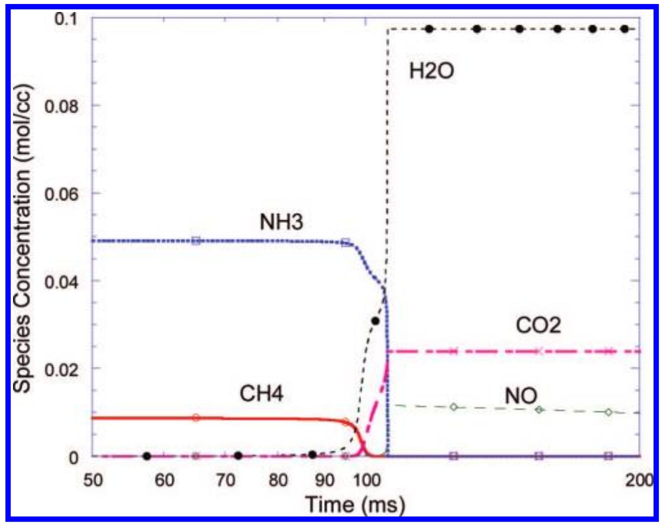


**Figure 2.** Concentration histories of selected species during ignition for the system with 1.5%-$CH_4$/8.0%-$NH_3$.

Since ammonia and diesel fuel have different heating values, different fuel mixture compositions will result in different energy levels. Table 2 lists the corresponding energy ratios based on different molar percentages of the two fuels. In the following analysis, the performance of the dual-fuel system will be discussed in terms of the energy ratio of the two fuels.

Due to the lower energy content of ammonia, the flame temperature will be reduced as the ammonia ratio is increased. Thermodynamics calculations were performed for the adiabatic flame temperature as a function of the fuel composition and equivalence ratio. Figure 3 shows the flame temperature is reduced from 2320 to 2100 K for the stoichiometric condition (PHI = 1.0) as ammonia energy fraction is increased from 0 (entirely diesel fuel) to 1 (entirely ammonia). The above flame temperature can provide indications on the in-cylinder temperature level when ammonia is used.

The adiabatic flame temperature is evaluated by assuming the reaction system reaches equilibrium, i.e., infinite time for chemical reactions. In diesel engines, reaction time is a limiting factor and its implication needs to be considered. Fuel must ignite and combust within a few milliseconds (ms). Thus, ignition delay is an important parameter in diesel engines. The engine will misfire if the ignition delay is too long. The ignition delay of the diesel−ammonia mixture at various proportions was computed using a chemical reaction mechanism that also considers the oxidation of diesel fuel.[19] In this mechanism, diesel fuel was represented by *n*-heptane since both diesel fuel and *n*-heptane have a similar cetane number. Results of ignition delay for different fuel compositions and initial temperatures are shown in Figure 4. As can be seen, for the same initial temperature, ignition delay increases as more diesel fuel is replaced by ammonia. The overall system also exhibits the peculiar feature of 'negative temperature coefficient' that is encountered in the typical hydrocarbon fuel. The reason is due to the dominance of diesel fuel during the ignition process. Figure 5 shows the temperature histories of cases with different fuel compositions. The initial temperature was 1000 K for all cases. It can be seen that the ignition delay time increases as the percentage of ammonia is increased.

In summary, ammonia can potentially be used as a diesel engine fuel. By replacing part of diesel fuel with ammonia, the

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**Table 2. Corresponding Energy Ratios for Different Molar Percentages of Diesel Fuel and Ammonia**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| molar percentage (diesel−$NH_3$) | 100−0 | 90−10 | 80−20 | 60−40 | 50−50 | 40−60 | 20−80 | 10−90 | 0−100 |
| diesel energy (%) | 100 | 99.2 | 98.2 | 95.3 | 93.1 | 89.9 | 77.0 | 59.8 | 0 |
| $NH_3$ energy (%) | 0 | 0.8 | 1.8 | 4.7 | 6.9 | 10.1 | 23.0 | 40.2 | 100 |

mixture is less easy to ignite and the combustion temperature will be lower. The relative proportion of diesel fuel and ammonia needs to be determined carefully to ensure the successful engine operation.

## 3. Experimental Setup

Engine tests were performed on a multicylinder, turbocharged diesel engine manufactured by John Deere (Model 4045). Table 3 lists the engine specifications[20] and operating conditions used in this study. Due to its high resistance to ignition, ammonia was introduced into the air intake system of the engine and diesel fuel was directly injected into the cylinder to initiate combustion.

The intake system of the engine was slightly modified to integrate the ammonia fuel line, whereas the diesel fuel injection system remained unchanged. A pressurized liquid ammonia tank, containing 150 lbs of liquid ammonia, was implemented and a high-pressure relief valve was used to regulate the ammonia flow rate. Liquid ammonia will become vapor once it leaves the fuel tank. A 1/4-in. stainless steel pipeline was used to connect the ammonia tank and the engine intake. The induction point is located immediately after the compressor to prevent corrosion to the turbocharger. The induction location is strategically placed before the intake manifold for a better mixing of ammonia and air prior to entering the cylinder. Combustion phasing (e.g., ignition) was controlled by diesel fuel injection.

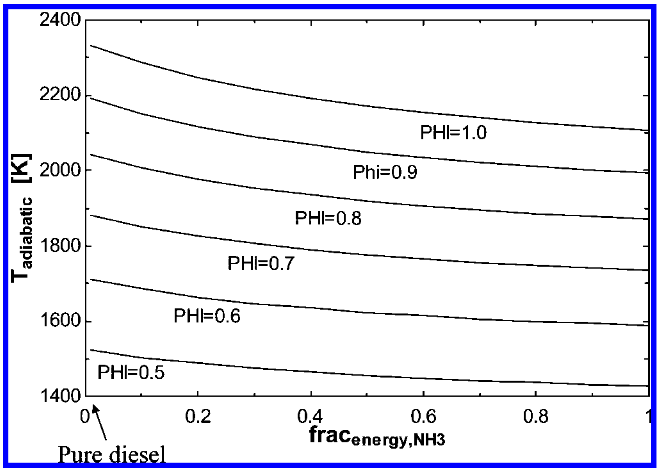


**Figure 3.** Calculated adiabatic flame temperature for the diesel fuel−ammonia mixture as a function of the equivalence ratio (PHI) and the fuel composition (described by the fraction of total energy provided by ammonia).

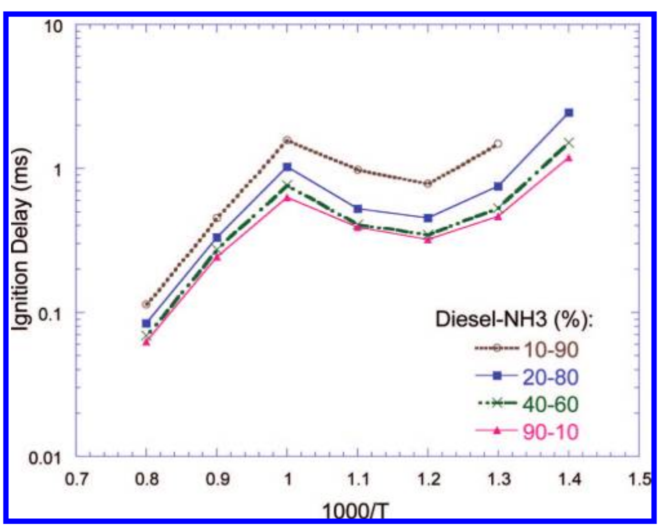


**Figure 4.** Ignition delay time versus the inverse of the initial temperature for various fuel compositions.

Experiments were carried out for different diesel fuel−ammonia ratios at various engine speeds and loads. Different sets of tests were performed including (1) constant ammonia flow rates, (2) constant engine torque with different diesel−ammonia flow rates, (3) constant diesel fueling with variable ammonia flow rates, and (4) ammonia with *soy-based* biodiesel. Engine torque, brake specific fuel consumption (BSFC), and emissions of $CO_2$, HC and NOx were measured. The exhaust ammonia was not recorded because the ammonia measurement (e.g., wet chemistry) involves a very different technique than that for other gaseous emissions. The present study focuses on the feasibility of ammonia combustion in diesel engines and the comparative engine performance. Detailed investigations of the exhaust ammonia will be performed in a future study.

## 4. Results and Discussion

**Constant Ammonia Flow Rates.** The first objective of the engine test was to demonstrate that ammonia could be burned in the modern diesel engine using the present dual-fuel approach. During the test, diesel fueling rates were adjusted to reach desirable load conditions, i.e., 20, 40, 60, 80, 100% of the full load at the respective engine speed using diesel fuel alone. At each load point, a constant flow rate of ammonia was introduced into the engine. As soon as the relief valve was open, the dynamometer indicated an increase in the engine torque. Figure 6 shows the results for the engine speed at 1400 rpm. It can be seen that a constant increase in the engine torque was obtained resulting from ammonia combustion. Based on the two fuel flow rates, the energy contribution from ammonia was calculated as seen also in Figure 6. At a low diesel fueling rate of 20% load, the energy contribution from ammonia was as high as 50% of the total energy. A similar increase in the engine torque was also observed for the engine speed at 1800 rpm as shown in Figure 7. Since the diesel fueling rate was increased for the higher engine speed, the percentage of energy contribution from ammonia was reduced. Nonetheless, it was demonstrated that ammonia can be used for diesel combustion without major modifications to the engine's geometrical specifications.

**Constant Engine Torque.** Engine tests were performed using ammonia to compensate diesel fuel energy so that the engine could reach it peak torque output regardless of the diesel fuel flow rate. During the test the diesel fuel flow rate was controlled so that the engine only produced a specific percentage of the peak torque. At a specific load condition based on diesel fuel (i.e., from 5% to 80%), the ammonia flow rate was adjusted until the engine generated a torque that was comparable to that of 100% diesel load (280 ft-lb). The torque curves are shown in Figure 8 for 1000 rpm conditions. Assuming the combustion efficiency of diesel fuel in the dual-fuel setup is the same as that in the pure diesel setup, the difference in the two torque curves will be the contribution of ammonia combustion. Notice that at low diesel fueling, the demand in ammonia was large and there was a decrease in engine torque output due to insufficient ammonia supply under the current setup. Nonethe-

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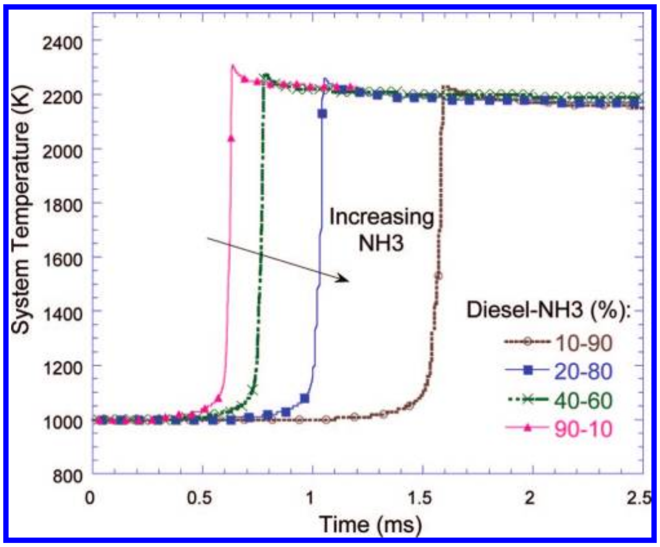


**Figure 5.** Temperature histories for different fuel mixtures. As the amount of ammonia increases, the system may have the risk of failing ignition within the allowable reaction time in engines.

**Table 3. Specifications of the test engine and operating conditions**

| | |
|---|---|
| engine | John Deere 4045 4-cylinder, 4-valve, direct injection |
| bore and stroke (mm) | 106 × 127 |
| total engine displacement (L) | 4.5 |
| compression ratio | 17.0:1 |
| valves per cylinder intake/exhaust | 2/2 |
| firing order | 1-3-4-2 |
| combustion system | direct injection |
| engine type | in-line, 4-stroke |
| aspiration | turbocharged (located on engine) |
| injection system | common rail |
| piston | bowl-in-piston |
| engine speed (rev/min) | 1000−1800 |
| load | 5−100% |
| fuel | ammonia<br>No. 2 diesel<br>biodiesel (B100) |

less, it was demonstrated that the present engine was able to use 5% diesel energy with 95% ammonia energy to achieve a nearly peak engine torque.

Figure 9 shows the mass flow rates of ammonia and diesel fuel corresponding to the conditions in Figure 8. As can be seen, the ammonia flow rate was considerably higher than the diesel flow rate at low diesel loads to provide sufficient energy. At the 50% diesel load condition, i.e., the other 50% of energy from ammonia, a higher quantity of ammonia was required due to its lower energy content on a mass basis.

The brake specific fuel consumption of each fuel was evaluated based on the respective fuel flow rate and contribution to engine power, as shown in Figure 10. In general, the BSFC for ammonia and diesel fuel had an opposite trend with respect to the diesel load. For low diesel load (e.g, less than 15%), diesel BSFC was high due to the poor part-load efficiency as in a regular diesel engine. As the diesel load increased beyond 60%, the amount of ammonia supplied to the engine was relatively small and the premixed ammonia−air mixture in the cylinder could be too lean to be burned effectively. Thus, combustion efficiency for ammonia was low resulting in high ammonia BSFC. Therefore, in practical applications, operating the engine at extremely high or low ammonia levels needs to be avoided to prevent poor efficiency.

The fuel conversion efficiency (defined as work output divided by fuel energy input) was also calculated. The "work

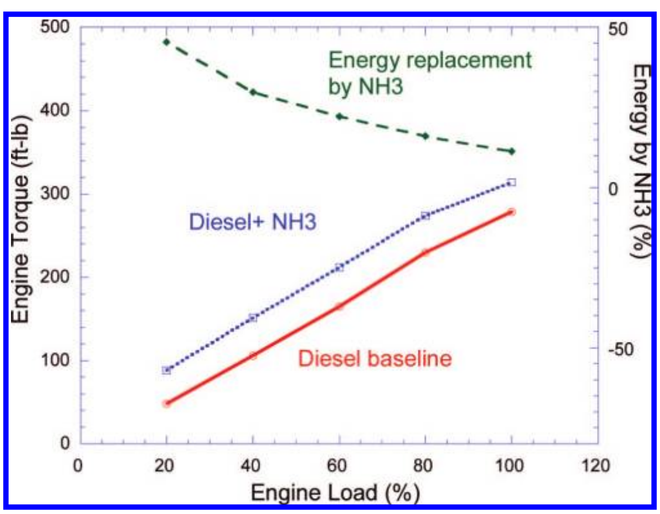


**Figure 6.** Engine torque curves and the percentage of energy replacement by ammonia for constant ammonia flow rate with the engine speed at 1400 rpm. The engine torque was increased as a result of ammonia combustion.

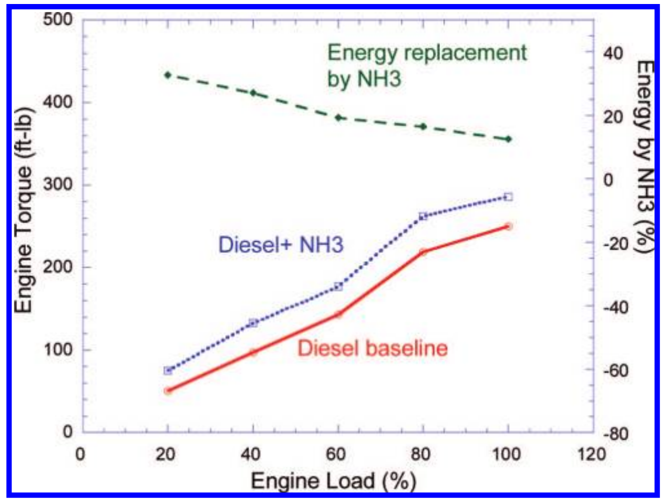


**Figure 7.** Engine torque curves and the percentage of energy replacement by ammonia for constant ammonia flow rate with the engine speed at 1800 rpm. The engine torque was increased as a result of ammonia combustion.

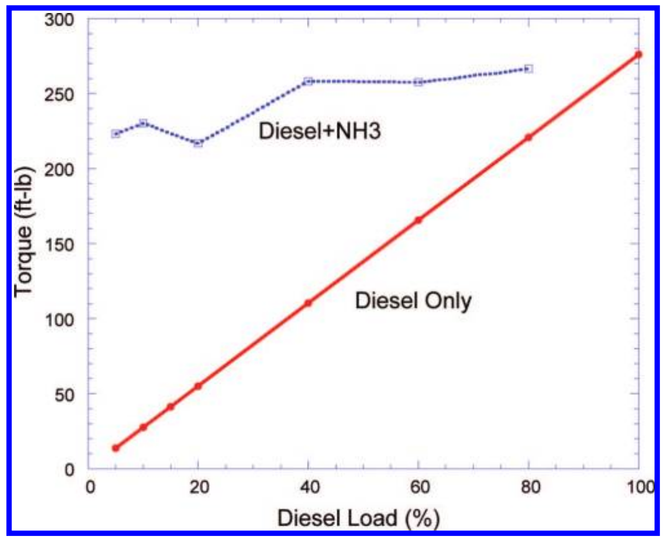


**Figure 8.** Engine torque output using (1) diesel fuel only (solid line) for different load conditions, and (2) diesel fuel with the appropriate amount of ammonia to reach the high torque conditions (dotted line). The engine speed was at 1000 rpm.

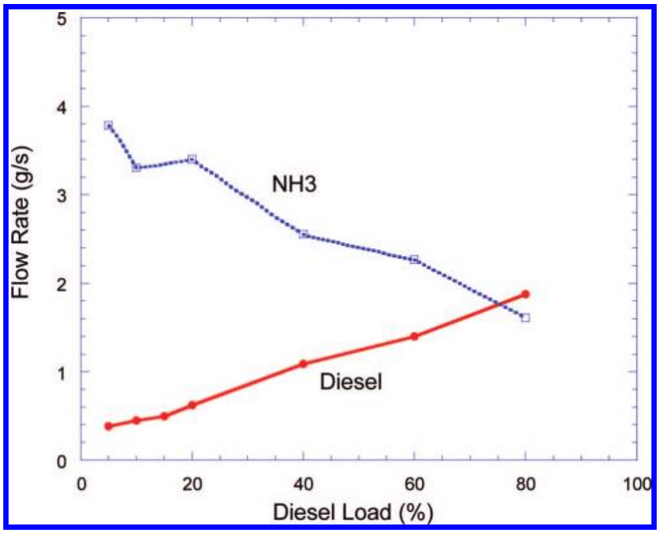


**Figure 9.** Flow rates of both diesel fuel and ammonia to reach the high torque output, corresponding to the torque curve (dotted line) in Figure 8.

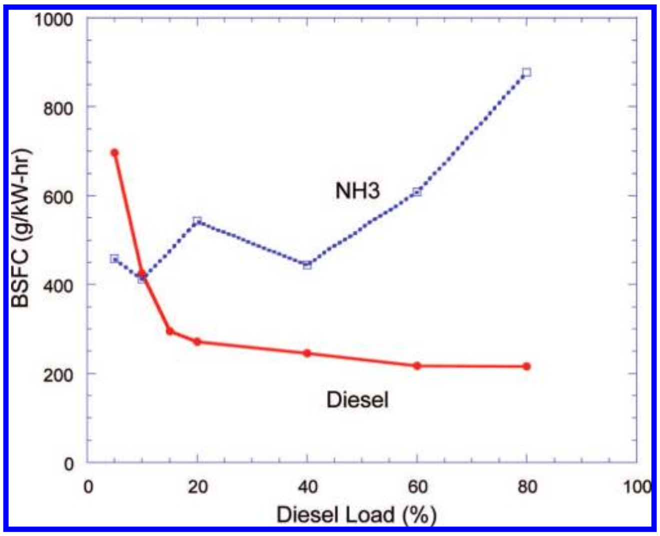


**Figure 10.** Brake specific fuel consumption based on diesel fuel and ammonia, respectively, under the high torque output conditions, corresponding to the torque curve (dotted line) in Figure 8.

**Table 4. Fuel Efficiency of the Operating Conditions Corresponding to Figure 10**

| diesel load (%) | 5 | 10 | 15 | 20 | 40 | 60 | 80 |
|---|---|---|---|---|---|---|---|
| efficiency based on diesel fuel alone (%) | 12.2 | 19.9 | 28.8 | 31.1 | 34.5 | 39.0 | 39.2 |
| efficiency based on $NH_3$ alone (%) | 42.2 | 46.9 | 31.2 | 35.6 | 43.6 | 31.8 | 22.0 |
| overall fuel efficiency (%) | 18.9 | 28.0 | 29.9 | 33.2 | 38.5 | 35.0 | 28.2 |

output by using diesel fuel alone" divided by "diesel fuel energy supplied" is 3600/(42.4 × BSFC_diesel). For ammonia, the formula is 3600/(18.6 × BSFC_$NH_3$). For instance, at the 40% diesel load point in Figure 10, the diesel fuel efficiency is 34.5% and the ammonia fuel efficiency is 43.6%. Consequently, the overall fuel efficiency is the ratio of the total work output to total fuel energy, and is equal to 38.5%. Table 4 listed the respective and the overall fuel efficiency. As can be seen, good overall fuel efficiency can be achieved between 20% and 60% diesel load range.

Exhaust emissions of $CO_2$, HC and NOx were measured for various conditions using both dual-fuel and pure diesel setups. Engine tests were performed under the constant engine torque conditions (i.e., 280 ft-lb). The emissions data using 100% diesel fuel were recorded for comparisons. Different combinations of diesel−ammonia energy ratios were tested. It was initially speculated that ammonia combustion would produce high NOx emissions due to the fuel-bound nitrogen. However, ammonia combustion results in a lower flame temperature that could suppress NOx production. These two effects will compete with each other and the net result may not be certain.

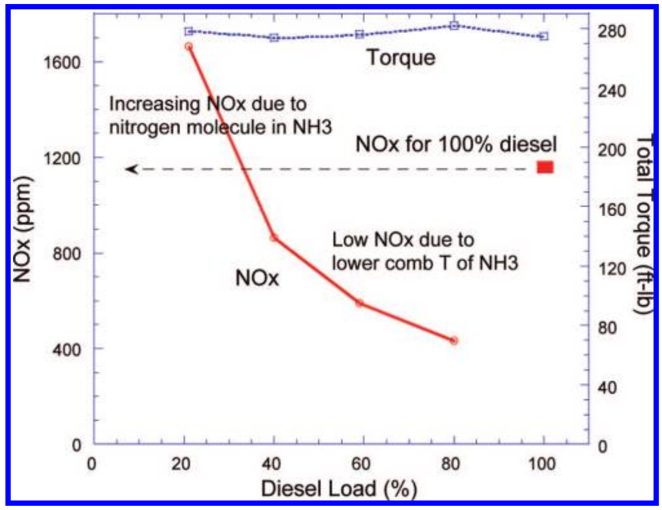


**Figure 11.** NOx emissions for diesel−ammonia combustion at 1000 rpm under peak torque conditions at various diesel loads. At low diesel load conditions, more ammonia is introduced in order to achieve the peak engine torque output. Emissions are compared to tests using pure diesel fuel.

As can be seen from Figure 11, when a moderate amount of diesel fuel was replaced by ammonia, NOx emissions were reduced as compared to the pure diesel combustion for the same torque. It seems that the decrease in NOx is due to the reduction in overall combustion temperature due to the participation of ammonia. The effect of fuel-bound nitrogen appears to be less significant for the overall NOx production. The other possible reason is the effect of ammonia in NOx reduction reactions as used in the modern diesel aftertreatment devices. In the Selective Catalytic Converter (SCR), a catalyst is needed for NOx reduction using ammonia. In the engine cylinder, the combustion temperature could be high enough that a catalyst is not needed for NOx reduction reactions. Thus, the net NOx emissions could be reduced. Clearly further research is required to clarify effects of ammonia on NOx emissions under diesel in-cylinder conditions.

Results in Figure 11 also show that, as the amount of ammonia increased (i.e., moving toward lower diesel load conditions), NOx emissions also increased. If a significant amount of diesel fuel is replaced by ammonia (e.g., 20% diesel load condition), NOx emissions increase significantly due to the effect of fuel-bound nitrogen. The present results indicate that low NOx emissions can be obtained if the diesel energy level is higher than 30%. In other words, if the energy substitution by ammonia does not exceed 70% of the total energy, NOx emissions will not be a problem.

Figure 12 shows that HC emissions had an opposite trend to NOx emissions. When diesel fuel started to be replaced by ammonia, lower combustion temperature resulted in incomplete combustion of diesel fuel and produced higher HC emissions. As a significant amount of diesel fuel was replaced by ammonia, low HC emissions were obtained since the source of HC, i.e., diesel fuel, was reduced significantly.

The emission data of $CO_2$ are shown in Figure 13. As can be expected, $CO_2$ emissions decreased steadily as more diesel fuel was replaced by ammonia. The $CO_2$ emission data at each dual-fuel condition can be compared with that of using 100% diesel

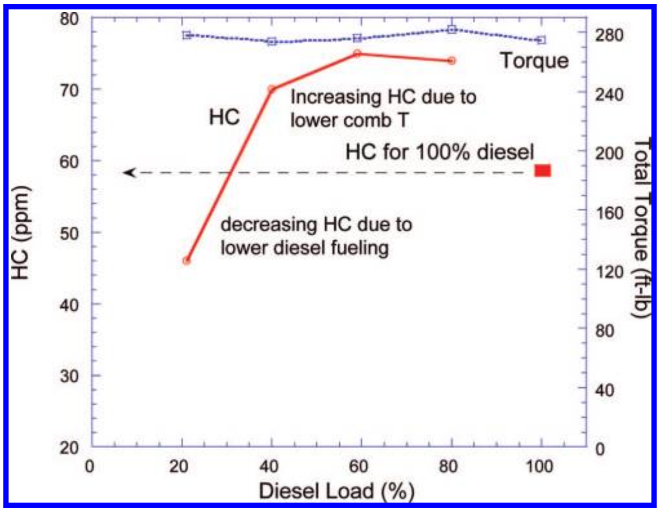


**Figure 12.** HC emissions for diesel−ammonia combustion at 1000 rpm under peak torque conditions at various diesel loads. Emissions are compared to tests using pure diesel fuel.

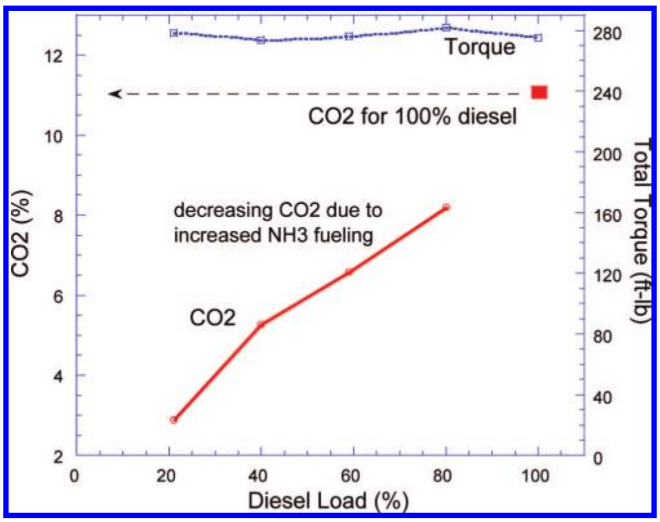


**Figure 13.** $CO_2$ emissions for diesel−ammonia combustion at 1000 rpm under peak torque conditions at various diesel loads. Emissions are compared to tests using pure diesel fuel.

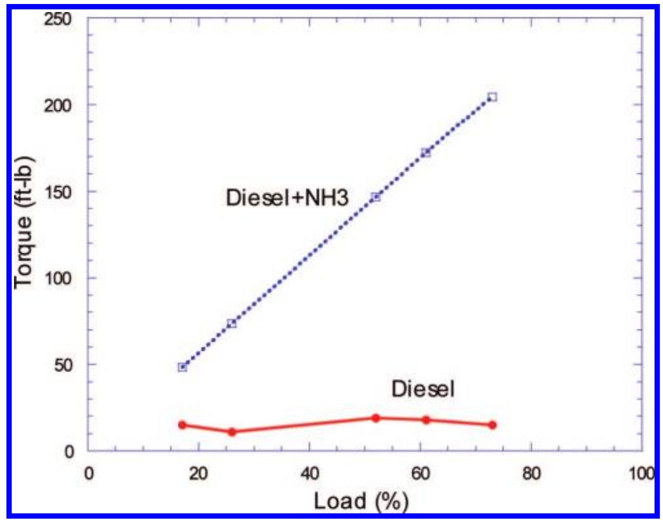


**Figure 14.** Engine torque output of using (1) a small amount of diesel fuel alone (solid line), and (2) the corresponding small amount of diesel fuel with the appropriate amount of ammonia to reach a desirable engine torque (dotted line). The engine was at 1400 rpm.

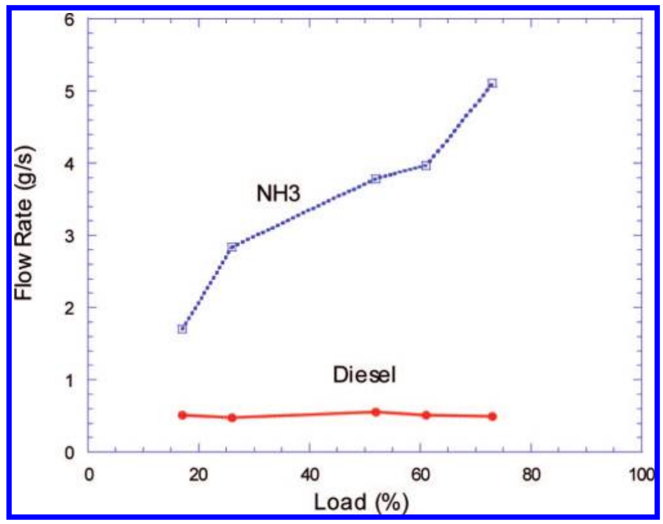


**Figure 15.** Flow rates of both diesel fuel and ammonia to reach the desirable torque output, corresponding to the torque curve (dotted line) in Figure 14.

fuel, and the difference is the reduction resulting from burning ammonia. For instance, $CO_2$ emissions were reduced from 11% to 3% if 80% of the total energy came from ammonia combustion. Note that the engine torque outputs were the same for all the operating points shown in Figure 13.

**Minimum Diesel Fueling with Variable Ammonia Flow Rates.** The above results have demonstrated that a large quantity of ammonia can be burned with a small quantity of diesel fuel to achieve a high engine power output. In the following tests, the diesel fueling rate was maintained at a constant level that was equivalent to the amount for producing 5% engine load. The ammonia flow rate was varied so that different engine loads were achieved. Figure 14 shows the torque curves of using diesel fuel alone and the dual-fuel approach. At each operating point, the diesel fuel flow rate was specified to obtain 5% engine load. The ammonia flow rate was then adjusted to achieve desirable engine torque, e.g., from 20% to 75%. As can be seen in Figure 15, the diesel flow rate remained constant and the ammonia flow rate increased as the engine load increased. The test results indicated that variable engine torque can be obtained using ammonia as the main fuel with the ignition energy provided by diesel pilot injection.

Figure 16 shows the respective BSFC based on diesel fuel and ammonia. It can be seen that the fuel efficiency was relatively low for the above test conditions. The diesel BSFC was high due to the poor part-load efficiency, and the results are consistent with those in Figure 10 for low diesel fueling conditions. At low engine loads, the ammonia BSFC was high due to the poor combustion efficiency of the lean ammonia−air mixture, and is also consistent with results in Figure 10 for high diesel fueling conditions. As the amount of ammonia increased, ammonia BSFC was decreased to a level similar to that in Figure 10 for low diesel fueling conditions (i.e., high ammonia fueling). Note that the engine speeds were different for conditions in Figures 10 and 16 but the results are consistent. In a future study, the flow rates of both fuels can be optimized for achieving a better fuel efficiency with respect to the desirable engine load.

**Engine Tests Using Biodiesel.** Engine tests using different combinations of biodiesel (B100) and ammonia were also performed. The same experimental conditions for the tests of ammonia−diesel fuel were used, including constant ammonia flow rates, constant engine torque, and 5% biodiesel energy with variable ammonia flow rates to reach desirable engine loads. Results of using ammonia−biodiesel were similar to those of using ammonia−diesel fuel and thus are not shown here in

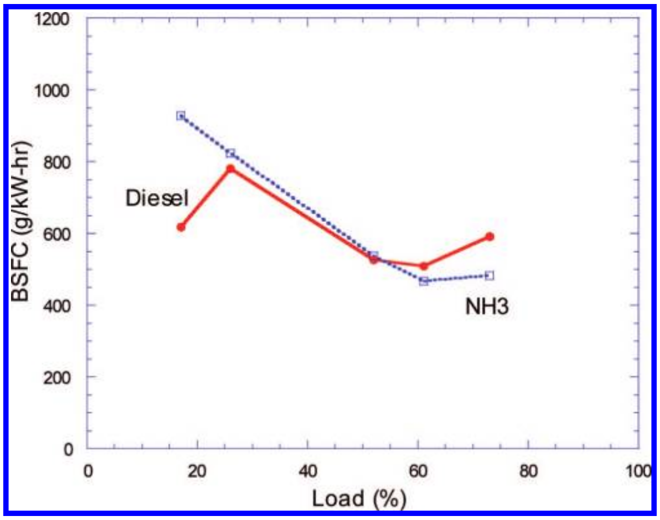


**Figure 16.** Brake specific fuel consumption based on diesel fuel and ammonia, respectively, under different torque conditions, corresponding to the torque curve (dotted line) in Figure 15.

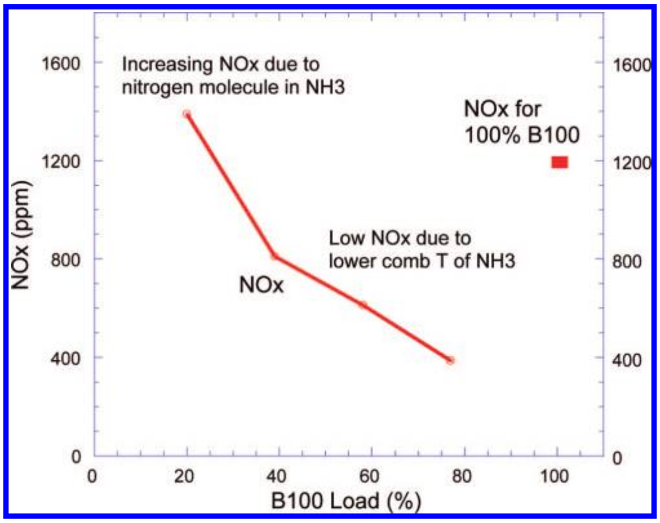


**Figure 17.** NOx emissions for biodiesel−ammonia combustion at 1000 rpm under peak torque conditions for various biodiesel loads. At low biodiesel load conditions, more ammonia was used to achieve the peak engine torque output. Emissions are compared to tests using pure biodiesel.

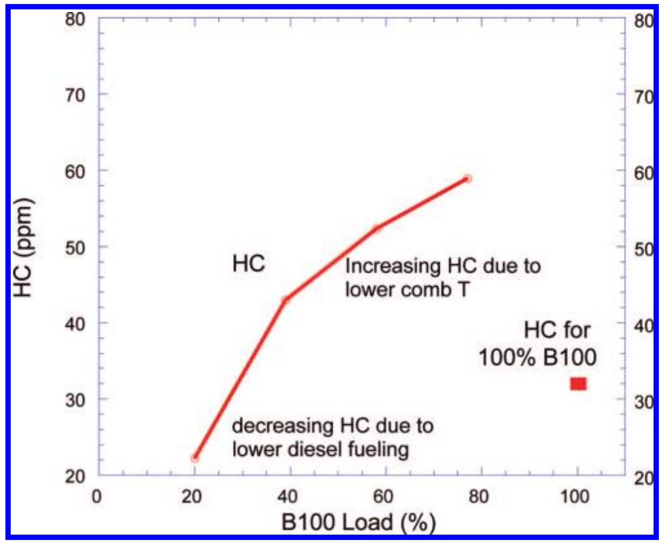


**Figure 18.** HC emissions for biodiesel−ammonia combustion at 1000 rpm under peak torque conditions for various diesel loads. Emissions are compared to tests using pure biodiesel.

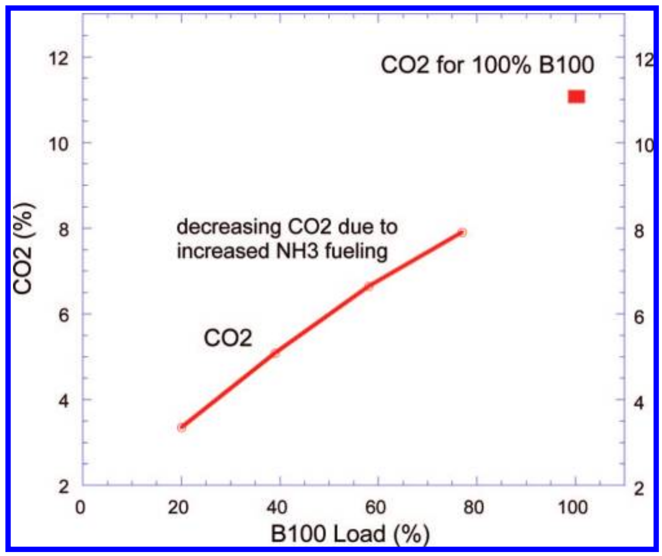


**Figure 19.** $CO_2$ emissions for biodiesel−ammonia combustion at 1000 rpm under peak torque conditions for various diesel loads. Emissions are compared to tests using pure diesel fuel.

detail. Therefore, this study has demonstrated that the engine can be operated using a combination of ammonia and biodiesel that can greatly benefit the environmental $CO_2$ sequestration.

It is known that biodiesel combustion will result in different emission characteristics than regular diesel fuel. Figures 17–19 show emissions of NOx, HC and $CO_2$, respectively, for constant engine torque conditions at 1000 rpm. At different operating points, appropriate combinations of ammonia−biodiesel were used to achieve the same torque. As the biodiesel fueling rate was increased, the ammonia flow rate was decreased.

The trends in emissions data were the same between ammonia/biodiesel and ammonia−diesel fuel. In particular, lower NOx emissions can be obtained unless a significant amount of biodiesel is replaced by ammonia, e.g., higher than 70% of the total energy. Hydrocarbon emissions increased when biodiesel started to be replaced by ammonia unless the biodiesel energy only accounts for 30% or less of the total energy. A significant reduction in $CO_2$ emissions could be obtained by replacing biodiesel with ammonia while achieving the same engine torque. By comparing the emission results when using biodiesel and regular diesel fuel, it was found that biodiesel produced slightly higher NOx but significantly lower HC emissions. These results were also consistent with the common understanding of biodiesel combustion characteristics.

## 5. Summary and Conclusions

This study investigated the feasibility of using ammonia as a direct diesel engine fuel. Ammonia can be potentially used as an engine fuel, and it has similar energy content per unit mass of stoichiometric mixture as other hydrocarbon fuels. Ammonia is less easy to autoignite and its combustion will result in a lower flame temperature. Thus, ignition energy needs to be provided to the in-cylinder ammonia−air mixture in order to prevent engine from misfiring.

Engine tests were performed using a dual-fuel approach with diesel fuel and ammonia. The intake system of the engine was slightly modified to implement the ammonia fuel line, whereas the diesel fuel injection system remained unchanged. Combustion of the ammonia−air mixture was initiated by the ignition of diesel fuel. Test results demonstrated that ammonia can be successfully burned in a modern diesel engine at various engine speeds and loads. Different combinations of diesel fuel and ammonia flow rates were tested.

Test results showed that different diesel fuel−ammonia ratios can be used to achieve the same engine torque. The energy replacement by ammonia can be as high as 95% for successful engine operation. Reasonable fuel economy can be obtained when ammonia is adjusted to provide 40−80% of the total energy.

Exhaust emission measurements indicated that NOx emissions were not necessarily a concern for ammonia combustion despite the fuel-bound nitrogen. Test results showed that NOx emissions were reduced if the ammonia energy ratio does not exceed 60%. The possible reasons for the decrease in NOx include the lower flame temperature and the effect of ammonia in NOx reduction reactions as observed in the modern diesel after-treatment system.

It is believed that combustion of the present diesel fuel−ammonia mixture generally produced higher HC emissions due to low combustion temperatures except at low diesel fueling conditions. It was also found that a significant reduction in $CO_2$ emissions can be achieved by replacing diesel fuel with ammonia. The reduction in $CO_2$ emissions was nearly proportional to the ammonia energy ratio.

Engine tests using biodiesel with ammonia were also performed, and the results were similar to those using diesel fuel with ammonia. By using the combination of biodiesel and ammonia as in this study, the life-cycle $CO_2$ emissions can be greatly reduced.

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