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Experimental investigation of the effects of ammonia solution (NH_3OH) on engine performance and exhaust emissions of a small diesel engine

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ABSTRACT

In the present study, the effects of ammonia fumigation on the engine performance and exhaust emissions have been investigated experimentaly in a small diesel engine. Experiments have been performed for (2, 4, 6, 8, 10)% (by vol.) ammonia ratios at different engine speeds and loads. Here, 25% ammonia solution (25% ammonia + 75% water) have been used and this solution has been injected into intake air by a carburetor, which main nozzle section is adjustable. The test results showed that brake specific fuel consumption (bscf) increases at 2000 and 3000 rpms, but it decreases at 2600 rpm. The maximum reduction of bsfc has been determined as 7.28% for 5.48% ammonia ratio at 2600 rpm. Effective efficiency increases at all of the selected engine speeds and loads. However, the increase ratios of effective efficiency at 2600 rpm are higher than that of the other engine speeds. Exhaust emissions have been measured at 2200 rpm for different ammonia ratios and different loads and at 2600 rpm for different ammonia ratios, under only 6 Nm loads. It has been determined that carbon dioxide generally reduces at selected two engine speeds. However, nitrogen oxides, hydrocarbons and carbon monoxide generally increase. Total fuel cost for applied different ammonia ratios becomes lower than that of neat diesel fuel at 2600 rpm. At the other selected engine speeds; although total fuel cost decreases for some working conditions, it increases in some operating conditions. The maximum reduction of total fuel cost has been determined as 8.87% for 5.48% ammonia ratio at 2600 rpm.

1. Introduction

Instead of have being used alcohol and vegetables fuels in internal combustion engines, petroleum based fossil fuels have been the main fuels of these engines for nearly 130 years. Petroleum based fuels are being used in different areas and they have a significant place in our country's economy as well as in main other countries. In recent years, the risk of declining of petroleum sources, the increasing of environment pollution and also the rising of the levels of greenhouse gases force both governments and industries worldwide to mitigate the consumption and harmful effects of petroleum fuels. Especially the increase of environment consciousness stimulates the interest of researchers and engine manufacturers to search for alternative energy sources such as LPG, biodiesel, DME, natural gas and alcohol fuels. Among these, oxygenated fuels are critical importance due to their ability to reduce exhaust emissions and also increase engine performance [1–3].

Besides, oxygenated fuels, especially biodiesel and ethanol, can form a CO_2 life cycle and have a neutral effect on total carbon dioxide (CO_2) [4,5]. Although CO_2 is known a complete combustion product, it contributes to increase global temperature and it is regarded as greenhouse gases. It is estimate that CO_2 will increase with approximately 40% from the year 2007 to 2030 [6]. Therefore, reduction of CO_2 is as important as the reduction of the other exhaust emissions. It is known that ammonia and hydrogen, produced from renewable resources, can also be considered as carbon-free fuels [7–10]. Hydrogen is the most interesting fuel of the future, and it has been studied extensively in the literature [9–12]. However, the number of the studies on ammonia are limited compared to hydrogen and also the other alternative fuels [7]. In fact, ammonia has been used in busses in Belgium in 1942 during World War II [6,10]. Later, in the 1960's the U.S. Army also performed both theoretical and experimental studies to test the feasibility of ammonia as an alternative fuel source for internal combustion engines [6,10]. After the aforementioned, it can be said that ammonia studies as engine fuel are very limited until recent years.

Ryu et al. [8] investigated the engine performance of a spark ignition engine using direct injection of gaseous ammonia. In this study, gasoline was used as a second fuel to enhance combustion and an appropriate ammonia injection strategy was developed to obtain best

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engine performance. The test results showed the engine power increases by advancing ammonia injection timing. Also, the brake specific energy consumption with ammonia was very similar to that with neat gasoline. However, this study showed that the using ammonia increased nitrogen oxide (NO_x) and hdycarbon (HC) emissions and decreased carbon monoxide (CO) emission. After this study, Ryu et al. [9] studied the effect of combustion of hydrogen generated by an ammonia dissociation catalyst on engine performance and exhaust emissions in the same spark ignition engine. In their study, it was found that the conversion of ammonia into hydrogen increased engine power significantly and reduced fuel consumption, CO, HC, NH_3 and NO_x emissions considerably. This study showed that the ammonia dissociation catalyst can enable to use ammonia as a hydrogen carrier in internal combustion engines effectively [9]. Actually, ammonia is easily liquefied and stored under ambient temperature of 300 K at a pressure of approximately 10 bar and it is relatively easy to store as liquid or gas. Also, its infrastructure is well established and it can be regarded as a hydrogen carrier [7,10].

Although ammonia has high self-ignition temperature, the use of ammonia in diesel engines have also examined by using different techniques [7,10,12–14]. Anhydrous ammonia was investigated experimentally and theoretically in Cooperative Fuel Research (CFR) engine by Starkman et al. [14]. In this study, a new injection system and also a spark ignition system were added to their test engine. Results indicated that ammonia decreased engine power and it increased bsfc approximately (1–1/2) fold. This study showed that liquid ammonia may be burn satisfactorily as a fuel in diesel engine at normal compression ratios by using spark ignition to ignite the injected fuel. Later, Reither et al. [10] were investigated the use of ammonia by applying dual-fuel approach or fumigation method, by making a minor modifications in normal diesel engine. In their study, ammonia was injected in the intake air (AF) by using an adapted injection system as an additional fuel and various combinations of ammonia and diesel fuel were successfully tested. From their experimental results showed that AF increased HC, CO, NO_x and bsfc. On the other hand, it reduced soot emissions significantly. Another ammonia fumigation study was performed by Gill et al. [12]. In their study, ammonia gas, dissociated ammonia (a mixture of H_2, N_2 with small percentages of NH_3) and pure hydrogen was injected into intake air in a diesel engine and they found that by substituting only 3% of the intake air by ammonia, the diesel fuel consumption and the CO_2 decreased at the levels of 15%. Also, they determined that AF increased HC, NO_x emissions but it decreased CO emission. There are also different fuels – ammonia mixtures studies in literature. Such a study was performed by Ryu et al. [10]. They was tested various mixtures of ammonia (NH_3) and dimethyl ether (DME) in a diesel engine. The original diesel fuel injection system of their test engine was replaced with a new system for injecting ammonia-DME mixtures into the cylinder directly. Emissions data showed that soot emissions remained extremely low for the fuel mixtures tested. On the other hand, as ammonia concentration increased, CO and HC and NO_x emissions increased. It can be understood from the above informations that the use of ammonia generally increases fuel consumption and CO, HC and NO_x emissions and it reduces CO_2 and soot emission.

For the fulfilling of international emission standards of internal combustion engines, after-treatment technologies are also used apart from alternative fuels and combustion improvement studies etc. [15,16]. For example, various additives, patented by various companies, are used in exhaust systems of diesel engines which used on truck, buses and passanger cars. These additives are mixtures of water and urea which have similar structure and specific characteristics. This mixture is decomposed into exhaust gases and transformed into ammonia. This ammonia reacts with the incomplete combustion products such as NO_x, CO and HC coming out of the engine and it converts them to complete combustion products such as N_2 and H_2O and CO_2. It was thought by authors that ammonia can improve combustion process and thus it can prevent to produce incomplete combustion products by its using as an additive considering its the above-mentioned feature. Evaluating of these effects of ammonia, it is intended to investigate the use of ammonia in a small diesel engine. Furthermore, it can be seen in the relevant literatures that detailed experimental studies on ammonia include cost analysis are not reported. Furthermore, in recent years, studies on ammonia have also been increased. As a result, ammonia as a fuel is becoming an interesting area for researchers.

It is well known that ammonia is in the gas phase under normal ambient air conditions. Consequently, there may be arisen some difficulties for using gas ammonia in engines. For this reason, ammonia solution (25% ammonia + 75% water) was used in the present study. Ammonia solution does not mix with diesel fuel homogeneously. Furthermore, due to the poor auto-ignition capability of ammonia and corrosive effect of water content on fuel system, the use of diesel-ammonia solution blends are not feasible [17,18]. Hence, ammonia solution was injected into intake air by using an adapted simple carburetor and diesel fuel injected on this mixture at end of the compression process. Here, at the application of this method any change has not been made in original injection system of the test engine and the engine mainly operates due to diesel principle. As a result, as above explained, the main objective of the present work is to investigate experimentally the effects of addition of ammonia solution at low ratios such as (2, 4, 6, 8, 10%, by vol.) on performance and emission characteristics of a small diesel engine at different loads and engine speeds. Furthermore, cost analysis has been conducted and the obtained ammonia solution results were compared to NDF.

2. Experimental study

2.1. Experimental apparatus

The test engine used in the present study is one-cylinder, four-stroke, air-cooled direct injection diesel engine (Palmera, model PA-HP170F). Table 1 presents the main specifications of the test engine. The experimental system was produced by TecQuipment (model TD114) and its photograph was given in Fig. 1. Exhaust gases composition was determined by DiGas 4000 gas analyzer produced by AVL. The accuracies of CO_2 and CO are within ± 0.1% vol. and ± 0.01% vol., respectively. Also, the accuracies of HC and NO_x measurement are within 1 ppm.

2.2. Ammonia addition system

In the present experimental study, for adding appropriate amounts of ammonia solution into inlet air an elementary carburettor, which gas and air throttles were dismantled and the other auxiliary equipments were left out of order, was mounted on the inlet manifold of the test engine. The air inlet of this carburetor was connected to the air consumption measuring box by using a flexible hose. Furthermore, ammonia solution flow rate was controlled by a fine threaded adjustment screw which can change the carburetor main fuel jet section. Fig. 2 presents photograph of the adapted carburettor.

2.3. Operating conditions

In the present study; a new engine, produced for agricultural applications, was mounted in the experimental system. It is well known

Table 1
Main technical specifications of the test engine.

Engine	Palmera PA-HP170 F direct injection diesel engine
Displacement	211 cm^3
Number of cylinder	1
Bore & stroke	70 & 55 mm
Compression ratio	20: 1
Maximum power	3.1 kW @ 3600 rpm