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REVIEW OF THE USE OF BIOETHANOL AS ALTERNATIVE FUEL FOR INTERNAL COMBUSTION ENGINES

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Abstract: The discovery of fossil fuels revolutionised the world, it caused rapid industrialisation and geometrical growth in transportation system globally. This growth however, is not without its disadvantages, chief among which is the change in global climate which is as a result of the increase in anthropogenic emission of greenhouse gases into the atmosphere. The need to stop the accelerated warming of the globe and its attendant consequences has led to the consideration of alternative sources to fossil fuels. Bioethanol is perceived as one of the viable alternative sources to fossil fuels, especially since it is renewable and is less contaminating. This study reviewed the suitability of bioethanol as alternative to fossil fuels for use in internal combustion engines. It was found that bioethanol is more suitable for use in spark ignition engines than in compression ignition engines. It was also found that the renewable nature of bioethanol and its low emission properties is its most outstanding advantage. It was however noted that despite the numerous literatures on biofuels and bioethanol, there is very limited literature on the nonautomotive use of biofuels in general and bioethanol in specific. There is also limited literature on properties of bioethanol obtained from different sources.

Keywords: bioethanol; spark ignition engine; compression ignition engine; greenhouse gas emissions; particulate matter

INTRODUCTION

Since the onset of the industrial age, fossil fuels have been the force driving the global economic growth and the consequential improvement in general standards of living. The high energy density of fossil fuels has been a major factor for its popularity and high demand for usage as fuel for domestic, industrial and transportation needs. This high demand for fossil fuels has not been without its impact on the environment. It is no longer news that climate change is as a result of anthropogenic emission of greenhouse gases (GHGs) into the atmosphere mainly from the burning of fossil fuels [1]. The attendant effects and consequences of climate change which include floods, accelerated desertification, drought, loss of biodiversity, reduction in soil fertility and a host of others have forced the hands of policymakers and governments to rethink the way and manner fossil fuels are used. This has made the idea of sustainable energy sources more appealing and a serious contender for replacement of fossil fuels. In recent years, the adoption and usage of electric vehicles has significantly improved globally [2], [3], this has encouraged vehicle manufacturers to give serious considerations to vehicles that run on alternative fuels.

Bioenergy has been among the sources of energy that has gained serious traction as an alternative to fossil fuels. In recent times, bioenergy and notably liquid biofuels have emerged as a suitable, renewable alternative to co-exist with fossil fuels as their quality constituents match petroleum-based products while less polluting (at combustion) and, if managed correctly, can contribute to rural development and economic growth [4].

Ethanol has been explored as a potential fuel since the creation of the internal combustion engines at the end of the 19th century. It is on record that in the early 19th century, Henry Ford designed a car that would run completely on ethanol [5]. Thus far, ethanol is one of the fuels that has shown promise as a substitute for gasoline, this has led to some countries choosing the path of less dependence on petroleum by developing their ethanol fuel technology. Brazil is a classic example of one of these countries where ethanol as an alternative fuel is a success story. This was encouraged by policies which encourage the usage of ethanol by making it cheaper than petrol [6].

Currently, ethanol is being used as a transportation fuel typically not in pure form but blended with gasoline in different proportions. A mixture of 90% gasoline, 10% ethanol is referred to as E10 and is the most common form since it can be used interchangeably with gasoline by vehicles without any special arrangement or modification of the fuel/air system on the vehicle. Even though bioethanol has proven to be a suitable replacement for petrol for use in vehicles, it has its inherent disadvantages, the major one among them being the corrosion of engine and auxiliary parts [7]–[9].

Bioethanol seems to be recognized as the best alternative to petroleum-derived transportation fuels and cooking fuels. This is justified by its ability of reducing air pollution, improving rural economies by creating job opportunities and raising farm income and diversifying energy portfolios. In this review paper on bioethanol as an alternative to petrol for internal combustion engines, a review of existing literature will be carried out so as to enumerate the advantages and possible problems associated with the uses of the bio ethanol in the internal combustion engine.

INTERNAL COMBUSTION ENGINES

Internal combustion engines (ICE) are heat engines that convert chemical energy in a fuel into mechanical energy. The mechanical energy is usually made available for use in the forms of a rotating output shaft which is connected to the engine. The sequence of activities that occur within the ICE involves first conversion of the chemical energy of the fuel into thermal energy by means of combustion or oxidation with air inside the engine. This thermal energy raises the temperature and pressure of the gases within the engine and the high-pressure gas then expands against the mechanical mechanisms of the engine. This expansion is converted by the mechanical linkages of the engine to a rotating crankshaft, which is the output of the engine. The crankshaft, in turn, is connected to a transmission and/or powertrain to transmit the rotating mechanical energy to the desired final use. For engines this will often be the propulsion of a vehicle (i.e., automobile, truck, locomotive, marine vessel, or airplane). Other applications include stationary engines to drive generators or pumps, and portable engines for things like chainsaws and lawn mowers [10], [11].

BIOFUELS

Biofuels by definition are fuels that are generated from biological material, a concept that has recently been narrowed down to renewable sources of carbon [12]. They can complement and/or replace fossil fuels and reduce carbon emissions in the transport sector with only modest changes to vehicle technology (i.e. engines) and to existing infrastructure for fuel distribution. The difference between fossil fuels and biofuels is that fossil fuels were produced millions of years ago when plants and other organisms died, became buried and were subjected to high temperatures and pressures forming coal, oil or natural gas. Biofuels, on the other hand, are produced from biological material that has been living recently. There are a number of ways in which biofuels can be produced, some biofuels can be produced from waste material, such as recycled plant oils, whilst others can be produced from plants specially grown for the purpose. Both liquid and gaseous forms of biofuels can be produced from crops that either have a high sugar content, such as sugar cane or sugar beet, or contain starch that can be converted into sugars, such as maize. Plants containing high levels of plant oils, such as oil palm or soybean, can also be used. Wood and its by-products can be converted into a variety of biofuels. Depending on the feedstock type and the maturity and sustainability of the production process, biofuels can be classified as conventional (1st generation) or advanced (2nd and 3rd generation) biofuels.

Conventional biofuels are biofuels produced from commercial feedstock (such as corn, sugar cane and other sucrose and starchy crops) using the well-known processes currently in use in many countries. They include liquid fuels, such as bioethanol from sugar- and starchy crops, biodiesel from oil crops and waste oil, and biogas for anaerobic digestion and other processes. The main disadvantage of first-generation biofuels is the food-versus-fuel debate, which may cause rise in food prices. There are concerns about environmental impacts and carbon balances, which sets limits in the increasing production of biofuels of first generation [13].

Second-generation biofuels are defined as fuels produced from a wide array of different feedstocks, especially but not limited to non-edible lignocellulosic biomass. Biomass used for production of second-generation biofuels is usually separated in three main categories: homogeneous, such as white wood chips; quasi-homogeneous, such as agricultural and forest residues; and non-homogeneous, including low value feedstock as municipal solid wastes as reported [14]. The price for 2nd generation biofuels is significantly less than the price for vegetable oil, corn, and sugarcane, which is an incentive. On the other hand, such biomass is generally more complex to convert and its production is dependent on new technologies.

Third generation biofuels are biofuels that are produced from algal biomass, which have a very distinctive growth yield as compared with classical lignocellulosic biomass [15]. Production of biofuels from algae usually relies on the lipid content of the microorganisms. Usually, species such as Chlorella are targeted because of their high lipid content and high productivity [16], [17]. There are many challenges associated with algal biomass, this includes the need for large volumes of water.

BIOETHANOL

Ethanol (C_2H_5OH) is a high performance, biomass fuel. It is considered the most suitable alcohol to be used as a fuel for spark ignition engines. Ethanol is a biodegradable, high-octane motor fuel derived from renewable energy sources such as sugars, starches, and cellulosic matter found in plants. It has been used as a fuel or additive since the days of Henry Ford's Model T. Ethanol is used as transportation fuel typically not in pure form but blended with gasoline in different proportions. The term, "Exx", is used to describe ethanol-gasoline blends, also known as gasohol, where xx indicates the fraction of ethanol present in the fuels. For instance, E15 means blends of ethanol and gasoline that contain 15% ethanol. It is considered the most suitable alcohol to be used as a fuel for spark ignition engines, it is the most widely used fuel among biofuels in the world. More than 95% of bioethanol production is obtained by processing agricultural products. In many countries of the world, the use of bioethanol in vehicles has become compulsory and the rate of this has been diversified in each country according to their own production sizes. There is also a requirement to use biofuels in EU countries, the minimum bioethanol addition was increased from 2% to 5.75% in 2010, it is expected to increase to 10% in 2020 and 25% in 2030 [18].

Bioethanol is obtained by transforming organic substances, whose origin is sugar, by microorganisms in the fermentation medium. The content properties of the raw material used and the sugar content it contains significantly affects the bioethanol yield to be obtained at the end of fermentation. Bioethanol production steps are carried out from three different raw materials, mainly sugar compounds, starchy compounds and cellulosic materials. While sugar and starch containing products are generally handled in the common area, cellulosic raw materials are kept separate as they require longer and more complex processes as pretreatment. Since the basic structure of starchy substances is based on sugar, the sugar they contain can be easily revealed with several different pre-treatments. Examples of these are corn, which is used in many parts of the world. Apart from this, grains such as wheat and barley also contain high levels of sugar. Sugar is directly released in agricultural products such as sugar cane and sugar beet [19]. A major advantage of bio-ethanol is that the feedstock (agricultural materials) is varied, renewable and can be produced in many places. Feasibility of growing lignocellulosic material for ethanol production has been explored around the world depending upon availability (including Nigeria). According to Abdullahi *et al* [20], switch grass could be cultivated under irrigation both in lowland and upland conditions in Sokoto state of Nigeria with manure and nitrogen fertilizer supplementation.

Even though bioethanol is receiving more attention as a potential transportation fuel of the future, its cost is still proving to be the major hindrance to its success as the next petrol is its cost. Its cost is still high due to the manufacturing and processing required. The conversion of lignocellulosic feedstock into bioethanol is based on two main processes: biochemical and thermochemical processes. The biochemical process relies on enzymatic or acidic hydrolysis to convert cellulose and hemicellulose into sugars, followed by fermentation and distillation to extract the ethanol. The thermochemical processing involves the conversion of biomass into a range of products, by thermal decay and chemical reformation, this essentially involves heating biomass in the presence of different concentrations of oxygen which generates synthesis gas or syngas. This syngas can be directly burned or further processed for other gaseous or liquid products. In this sense, thermal or chemical conversion of biomass is very similar to that of coal. The clear advantage of thermochemical processing is that it can essentially convert all the organic components of the biomass compared with biochemical processing which focuses mostly on the polysaccharides [21].

ETHANOL AS ALTERNATIVE FUEL FOR INTERNAL COMBUSTION ENGINES

Bioethanol is currently the most commonly used biofuel for spark ignition (gasoline) engine applications due to similar auto-ignitability properties to those of gasoline fuel. Ethanol can also be used as an additive in diesel engines to enhance combustion and reduce some emissions in spite of differences in auto-ignitability as compared to diesel fuels. Since most small engines are spark ignition, the future of bioethanol in small engine applications appears to be very promising [22]. Ethanol contains 35% oxygen, which results in a complete combustion of fuel and thus lowers the emission of harmful gases. Bioethanol when blended with gasoline, increases the octane number, decreases the Reid vapour pressure and produces fuel with clean burning characteristics. Ethanol also reduces smog formation because of low volatility; its photochemical reactivity and low production of combustion products. In addition, bioethanol possesses a property of low flame temperature that results in good engine performance and durability [23]. Bioethanol in spark ignition engine applications is currently the most practical and widely used biofuel and is potentially the most feasible renewable replacement for small gasoline engine applications. Using bioethanol in spark ignition engines with higher values of the compression ratio becomes possible due to its higher octane number which can go as high as 106. Also, the higher combustion rate of bio-ethanol is directly related to engine efficiency improvement.

ENGINE PERFORMANCE

The properties of bioethanol which makes it suitable for use as replacement for gasoline in spark ignition engines are numerous, these properties are intricately linked to the performance of a spark ignition engine. Table 1 shows a comparison of the fuel properties of bioethanol as compared to gasoline [24], [25]:

Table1: Comparison of Physical and Chemical Properties of Bioethanol and Gasoline

The fuel properties	Gasoline	Bio-ethanol
Density at 15 °C [kg/m3]	735...760	792
Boiling point (at 1.013 bar) [°C]	30...190	78
Specific heat (at 20 °C, 1.013 bar) [kJ/kgK]	2.01	2.369
Dynamic viscosity at 0°C [mPa s]	0.42	1.20
Heat of combustion [kJ/kg]	43500	26800
Theoretical combustion air quantity [kg/kg]	14.9	9
Heat of vaporization [kJ/kg]	290...380	904
Autoignition temperature [°C]	257...327	420
Octane number, MON/RON	90/98	87/106
Flame temperature (λ =1) [°C]	2290	1930
Lower Heating Value (MJ/kg)	`44	26.9
Ignitability range (°C, 1.013 bar): Φs....Φi	0.4...1.4	0.3...1.56
Composition: C/H/O [%mass]	85/15/0	52/13/35
Flame velocity (λ =1, at 20 °C, 1.013 bar) [m/s]	0.41	0.56
Ignitability point [°C]	<20	12.5
Reid vapor pressure [daN/cm^2]	0.8...0.9	0.14
Temperature reduce at vaporization (λ =1) [°C]	28	96.5
Heat of combustion for stoichiometric mixture [kJ/kg]	0.8...0.9	0.14
Temperature decrease when vaporizing a theoretical mixture [ºC]	28...31	96.5
Molecular weight [kg/kmol]	98	46.070
Melting point at 1.013 bar [ºC]	<-30	-114.6

From the properties shown in Table 1 above, the higher heat of vaporization of ethanol indicates that the volumetric efficiency of ethanol blends is higher than that of pure gasoline, improving power output [26]–[28]. It was determined that a 5% increase in the portion of ethanol in the mixtures can enhance the octane number of fuels by 10% [29]. This allows ethanol blends to operate in engines with higher compression ratios than gasoline. The higher laminar flame speed of ethanol makes ethanol blends combust quicker than gasoline, improving efficiency and power [25]. Jankowski and Sandel [30] found that the use of bioethanol can influence a spark ignition engine's performance thus:

a. Evaporative cooling of the charge in the inlet manifold and during the intake stroke, increasing charge density, and thus increasing the effective volumetric efficiency and power output.
b. The combined effect of the stoichiometric air/fuel ratio and the heat of combustion enable alcohols to release

more heat of combustion for a given air charge, thus increasing power output.

c. Changes in the timing, rate, and duration of combustion thus influencing the cycle efficiency, which influences the power output and specific fuel consumption.

EMISSIONS

An important engineering aspect of the internal combustion engine involves decreasing the quantity of undesirable emissions created by the combustion process. Exhaust emissions are dependent on fuel composition, air/fuel equivalence ratio, operating conditions, oxygen content, and the chemical structure of additives power [25]. The increased water contents results in an increase in the specific heat of the combustion products. The increased charge mass and specific heat can significantly reduce temperatures throughout the cycle, which would tend to reduce NO_x emissions. Using bioethanol in SI engines can reduce emissions through the following thus [30]:

a. Reduced stoichiometric air/fuel ratio, thus leaning out unless closed loop air/fuel ratio control is used.
b. Differences in the actual chemical reactions related to the combustion of alcohols, influencing the composition and reactivity or toxicity of the exhaust gasses
c. Changes in fuel distribution owing to the different evaporative characteristics of alcohols.
d. Changes in charge temperature owing to evaporative cooling properties of alcohols.
e. Increased gas specific heat and increased charge mass when closed loop air/fuel ratio control is used, leading to reduce combustion temperatures

ADVANTAGES OF USING BIOETHANOL AS ALTERNATIVE FUEL IN SI ENGINES

The advantages of using bioethanol as alternative fuel for SI engines are numerous, chief among them includes the emission of lower quantities of GHGs when compared to gasoline [31,32]. Still on emissions, bioethanol as fuel for SI engines instead of gasoline have been proven to have lower particulate emission [33,34]. Also, as ethanol content increases, benzene levels in the emissions from bioethanol reduces. Still on emissions from combustion of bioethanol laced fuels, emissions from such fuels contain less ozone damaging substances compared to pure gasoline or diesel. In addition to these, bioethanol has no sulphur content and is wholly biodegradable. When compared to other biofuels like biomethanol, bioethanol is less toxic [35].

Since bioethanol has a higher octane number compared to gasoline, this feature allows SI engines to run more efficiently. Also, its high-octane performance makes operating SI engines that run on bioethanol relatively cheaper than SI engines that run on gasoline. Likewise, SI engine vehicles retrofitted to run on bioethanol have been found to have higher energy efficiency than their equivalent gasoline run vehicles.

DISADVANTAGES OF USING BIOETHANOL AS ALTERNATIVE FUEL IN SI ENGINES

The nature of bioethanol having low vapour pressure and high latent heat of vapourization makes cold starting in cooler climates more difficult. This makes the use of ethanol exclusively in place of gasoline as fuel for SI engines unsuitable, especially in cold climates [13,30]. When bioethanol is burnt as fuel in SI engines, it leads to increased formation of acetaldehyde but lower emissions of formaldehyde compared to the combustion of gasoline in SI engines.

The low lubricity of bioethanol means higher friction among engine parts as such wearing and corrosion of engine parts are more common when SI engines use bioethanol as their preferred fuel. Another problem encountered when vehicles use ethanol as fuel is that of phase stability especially when water is present in the mixture. On the safety aspect, whenever neat ethanol is burnt, an invisible flame is given off, this can cause serious safety concerns since the flame cannot be spotted in good time.

BIOETHANOL AS ALTERNATIVE FUEL IN COMPRESSION IGNITION (CI) ENGINES

The Compression Ignition engine is currently considered the most fuel-efficient engine for industrial and transport applications, but it has the major disadvantage of being a significant contributor to air pollution caused by the combustion of diesel. Therefore, using bioethanol fuels in CI engines reduces emissions of particulate matter and GHGs. Ethanol use in CI engines represents a more efficient ethanol application because of the higher efficiency of the combustion, which on average is about 30% higher than in SI engines.

One of the major reasons why ethanol is added to diesel is to enhance combustion efficiency and reduce emissions of particulate matter and GHGs. The ethanol-diesel blend is also referred to as e-diesel. The main drawback is that ethanol is immiscible with diesel fuel over a wide range of temperatures, leading to phase separation. Consequently, in many cases the presence of a surfactant and cosolvent additive in the e-diesel blend becomes necessary [36,37].

EFFECTS OF BIOETHANOL FUEL IN COMPRESSION IGNITION ENGINES

Diesel oil has an energy content of about 36MJ/litre, whereas that of ethanol is 21 MJ/litre, this means that the engine needs injection of relatively larger volumes of fuel, compared to diesel oil, in order to have the same power output. Therefore, if bioethanol is to be used in compression ignition engines, then larger injectors, pumps, and fuel tanks are required [36].

Auto-ignition property of diesel fuel is designated by its cetane rating, diesel engines at the moment are designed to run on fuel that has cetane numbers of 40 and 51. Unfortunately, the cetane rating of ethanol is quite low, it ranges 5 to 15. This means that the fuel will likely not auto-ignite under the conditions existing in standard diesel engines. This problem can be remedied by the addition of certain ignition improvers, applying an ethanol fuel with too low cetane number in CI engines can among other things, result in poor cold starting, rough idling, and excessive NOx emissions [36].

The fuel system of the diesel engine is such that the fuel injectors and fuel pump rely on the lubricating properties of diesel to reduce friction and wear. Ethanol is considered a low lubricity fluid, and this effect may cause failure of some parts of the fuel system. These lubrication problems can be overcome by using additives or improving the properties of these parts such that they become more resistant to wear and tear.

FINDINGS AND DISCUSSION OF FINDINGS

Several researches have been carried out in order to identify the effects of bioethanol as alternative fuel for internal combustion engines and many of the literature have shown the advantages of bioethanol as well as the problems associated with its production, marketing and usage (among others) from different perspectives. However, gaps in knowledge still exist, as some aspects need to be investigated to be able to draw proper conclusions about the use of the bioethanol in internal combustion engines.

These gaps in knowledge includes (but not limited to) the followings:

≡ Analysis of the composition of ethanol (according to the type of processing and the source). The composition of ethanol produced from different sources and processing methods is significant because the ethanol produced from biomass may be different from the one obtained from grains. So also, the ethanol processed using the thermochemical process may differ from the one processed using the biochemical process. This factor may affect the proper mixing and blending the ethanol and other fuels

≡ The impact of mixing of bioethanol from different sources is unknown, this makes the possibility of phase separation occurring when bioethanol from different sources is mixed and used as fuel. Such possible phase separation may affect the emission and the performance characteristics of the engine.

≡ The impacts of neat bioethanol and bioethanol blends used in non-automotive applications is unknown. There is very limited data available with regards to the usage of bioethanol non-automotive engines such as power generators, lawn mowers etc.

≡ Corrosion test is regarded as vital for any successful engineering design, ethanol blends with different ethanol concentrations may have different corrosion properties on materials, and these properties are unknown. There is a need to study these properties in order to find out which of the blends has the highest corrosion property.

≡ It was found that there are no proper specifications by manufacturers on the type of ethanol blend to be used in different automotive engines. It is expected that internal combustion engines from different manufacturers should specify the of gasoline/diesel-ethanol blends to be use in their respective products

CONCLUSIONS

This study which is a review of the use of bioethanol as alternative fuel for internal combustion engines considered the suitability of bioethanol as alternative fuel by reviewing data available in literature. It was found that a number of qualities makes it suitable, among which are renewable nature and emission characteristics. However, there are also problems associated with its usage such as relatively higher cost of production and corrosive effect on engine parts. In summary, the following conclusions can be drawn based on the literature reviewed in this paper.

≡ Bioethanol is more suitable to be used in spark ignition engines than in compression ignition engines considering its wider differences with diesel than with gasoline.

≡ Bioethanol can deliver more power output (due to higher volumetric efficiency) but has lower volumetric fuel economy when compared with gasoline.

≡ Bioethanol can be produced virtually everywhere due to wide ranges of its raw materials

≡ Bioethanol is less toxic than gasoline as it is considered to be bio friendly, but it is corrosive to several materials. Extra measures need to be taken when selecting materials for engines with bioethanol compatibility.

≡ When bioethanol is to be used in conventional diesel engines, some modifications are needed such as larger injectors etc.

≡ There is a greater reduction in the emission of greenhouse gases when ethanol is used compared to gasoline and diesel.

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