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Performance and emissions analysis on using acetone–gasoline fuel blends in spark-ignition engine

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ABSTRACT

In this study, new blended fuels were formed by adding 3–10 vol. % of acetone into a regular gasoline. According to the best of the author's knowledge, it is the first time that the influence of acetone blends has been studied in a gasoline-fueled engine. The blended fuels were tested for their energy efficiencies and pollutant emissions using SI (spark-ignition) engine with single-cylinder and 4-stroke. Experimental results showed that the AC3 (3 vol.% acetone + 97 vol.% gasoline) blended fuel has an advantage over the neat gasoline in exhaust gases temperature, in-cylinder pressure, brake power, torque and volumetric efficiency by about 0.8%, 2.3%, 1.3%, 0.45% and 0.9%, respectively. As the acetone content increases in the blends, as the engine performance improved where the best performance obtained in this study at the blended fuel of AC10. In particular, exhaust gases temperature, in-cylinder pressure, brake power, torque and volumetric efficiency increase by about 5%, 10.5%, 5.2%, 2.1% and 3.2%, respectively, compared to neat gasoline. In addition, the use of acetone with gasoline fuel reduces exhaust emissions averagely by about 43% for carbon monoxide, 32% for carbon dioxide and 33% for the unburnt hydrocarbons. The enhanced engine performance and pollutant emissions are attributed to the higher oxygen content, slight leaning effect, lower knock tendency and high flame speeds of acetone, compared to the neat gasoline. Finally the mechanism of acetone combustion in gasoline-fueled engines is proposed in this work; two main pathways for acetone combustion are highlighted; furthermore, the CO, CO2 and UHC (unburnt hydrocarbons) mechanisms of formation and oxidation are acknowledged. Such acetone mechanism is employed for further understanding acetone combustion in spark-ignition engines.

1. Introduction

Modern industrial processes depend heavily on acetone as one of the extensive organic solvents [1,2]. Acetone is an extensive solvent for synthetic fibers and most plastic materials such as bottles made of polystyrene, polycarbonate, polypropylene and others. Acetone is also used as a basic ingredient in paints and varnishes industries as well as many industrial applications (see e.g. References [3–7]). This multi-industrial use of acetone results, without a doubt, in large quantities of acetone containing wastes. Unfortunately, when disposing of such wastes many environmental problems appear. By burying the wastes underground, acetone can penetrate to groundwater and in turn dissolved together because acetone does not absorb to soil but it is highly soluble in water; thus contamination of groundwater occurs due to the high toxicity of acetone. On the other hand, disposing of such wastes through burning is also known to express, in some conditions, for releasing of acetone into the atmosphere [8]. Acetone in the atmosphere is known to play an important role in changing the chemistry of the environment and it is also found to be the most oxygenated organic in the upper troposphere [9–11]. In addition, acetone in the atmosphere can cause serious health problems in the central nervous system, kidneys, reproductive system, liver, skin and others. Repeated exposure to acetone may cause organ damages. Recently, the level of acetone in water and air is reported to be about 20 parts per million (ppm) and 13 to 20 ppm, respectively, and such levels should be minimized [12].

Various techniques have been developed for acetone emission disposal. One of the most promising techniques is using catalytic combustion of acetone (after separation from other mixed components) to convert it into carbon dioxide and water. This technique mainly depends on the catalytic performance of the catalyst, which is the most important factor determining the effectiveness of this technique. Generally, two types of catalysts are commonly used: noble metal and transition metal oxides. The noble metal oxide type is very costly, which limits its broad applications. The transition metal oxide type, on the other hand, is less costly but its stability under some operating conditions is poor where its deactivation is frequently

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observed [13–15]. In the current study a new technique is applied, which is based on the combustion of acetone in the spark-ignition (SI) engines. Such new technique is very challenging since little is known about acetone chemical behavior in a hot oxidizing environment and therefore its practical combustion in SI engines.

Combustion of acetone in internal combustion engines is reviewed in literatures and few publications are found concerning combustion of acetone in compression ignition (CI) engines. Chang et al. [16,17] studied acetone–butanol–ethanol–diesel blends in CI engines. The researchers applied a mixture of 20 vol.% acetone–butanol–ethanol (ABE) and 80 vol.% diesel fuel; results demonstrated a better combustion efficiency and a reduction in particulate matter, nitrogen oxides (NOx), PAHs (polycyclic aromatic hydrocarbons), unburnt hydrocarbon and almost zero soot formation, compared to neat diesel fuel. The results also reported that energy efficiency of ABE–diesel was higher than the neat diesel, which means that ABE–diesel blend is a promising green fuel. Lin et al. [18] carried out a study using 1–3 vol.% acetone in diesel and showed that fuel blends can improve combustion efficiency and reduce pollutant emissions, compared to neat diesel fuel. Based on such available few literatures, acetone–diesel blended fuel is a promising alternative in compression ignition engine, especially acetone could be obtained from biomass and, in turn, it is considered as renewable fuel, as to be discussed later. However, similar studies on acetone–gasoline blended fuel were not found in the literature, according to the best knowledge of the author. Hence, there is a need for fundamental understanding on the feasibility of acetone–gasoline blend in SI engine. The goal of this study is to investigate the combustion characteristics of acetone and affirm its potential and environmental applications as a blended fuel in SI engines; furthermore, the study aims at investigating a new technique for disposal of acetone wastes, which were produced during different industrial processes (after separated from other disposals).

If one plans to use acetone in gasoline engines, it is necessary first to understand its mechanism of combustion. Reaction mechanism provides an understanding of acetone oxidation kinetics in combustion conditions based on describing how reactions take a place at the molecular level and which bonds are broken or formed and in which order. By reviewing literatures, little but varied works were found concerning acetone combustion mechanism. Baldi et al. [19] showed that acetone was incompletely oxidized (at 200 °C) to form acetic acid and acetaldehyde, but completely oxidized (at 270 °C) to form CO2 and H2O. El-Nahas et al. [20] argued that acetone may undergo pyrolysis reactions with partial oxidation of acetone to form acetyl radical. Sato and Hidaka [21] developed a mechanism for pyrolysis and oxidation of acetone, which consists of 164 reactions and 51 species. Chaos et al. [22] measured the time histories for stable species concentrations under acetone oxidation conditions and proposed a mechanism consisting of 248 reactions and 46 species. Chang and Anthony [23] showed that acetone is chemically transformed into hydrocarbons and subsequently into CO2 and H2O through decarboxylation and dehydration. Barnard and Honeyman [24,25] presented acetone oxidation in the gas-phase and showed that the first chain-initiating step in acetone oxidation was by attacking acetone via oxygen to form acetonyl radical; after that, the acetonyl radical is decomposed into methyl radical and ketene. Chong [26] studied acetone oxidation mechanism and pointed out that acetone is mainly reacted through three main reactions, which formed methyl radicals in one reaction and acetonyl radical in the other two reactions. Tsuboi et al. [27] evaluated the oxidation/decomposition of acetone in combustion conditions and presented a mechanism that includes the main pathways for acetone oxidation/decomposition. From the above literatures, one comes up with the idea that combustion of acetone in gasoline-fueled engines is very complex and until recently its confidence mechanism is not well understood. In the current study, the chemical reaction scheme of acetone is developed and new mechanism is proposed where such chemical mechanism is used to understand emissions pathways of acetone combustion in SI engines. The importance for such mechanism is magnified with the advent of the recent possibility of obtaining acetone in large quantities during biomass fermentation processes from several biomass types such as palm oil waste, domestic waste and abundant agricultural crops (see e.g. References [28–33]). Consequently, bio-acetone as a renewable might be proposed in a near future as a substitute or supplement of gasoline as a transportation fuel.

2. Experimental apparatus and method

The experiments are conducted using spark-ignition engine, which has a single-cylinder and four strokes placed on a chassis and connected with a dynamometer. The engine is air cooled with a 7:1 compression ratio and without catalytic converter unit. The displacement volume is 147.7 CC with 2 valves per cylinder. The engine was operated with the throttle plate wide open at speed rang of 2600–3400 r/min and load of 1.3–1.6 KW. ECU (electronic control unit) was used in the engine setup for controlling air/fuel ratio, which is changed with engine speed/power but it is not tuned for different fuels. Engine specifications are summarized in Table 1. Different sensors and apparatuses are equipped with the engine to carry out the engine performance measurements as: temperature sensor, pressure sensor, speed sensor etc. Different connectors are employed to feed signals from different sensors to the amplifier and then to the data acquisition card that is connected with a personal computer (PC). The PC allows for data recording and displaying in various forms via the PC monitor. The experimental procedure is applied as following: (1) filling the system with fuel, (2) commissioning apparatus and sensors, (3) starting the engine using DC motor, and (4) operating the engine in steady state conditions. After starting up the engine, it works without load for few minutes to warm up and, afterward, measurements take place. Four different fuels are measured, which are neat gasoline (as base fuel), 3 vol.% acetone in gasoline, 7 vol.% acetone in gasoline and 10 vol.% acetone in gasoline. Properties of acetone and gasoline used in this study are presented in Table 2, from References [34–40]. The experiments of all fuels were applied at same engine working conditions without tuning.

In addition to engine, an exhaust gas analyzer is used to measure the exhaust emissions. The sampling probe of the analyzer is connected to a water trap by a length of flexible hose. To avoid excessive amounts of condensate entering the filters, one should avoid suddenly raising the hose above the level of the analyzer. The gas analyzer is housed with displays and controls via the front panel. The front panel shows the measurements of CO, CO2, UHC (unburnt hydrocarbons) and O2 in four-digit displays. The measurements range of different gases is about 10% for CO, 20% for CO2 and 2000 ppm for UHC. Table 3 presents the measurements range and specifications

Table 1
Specifications of the engine.

Engine	SI engine
Manufacturer/model	GUNT, Hamburg, Germany/CT 150
No. of cylinders/cycle	One/4 stroke
Ignition system	Spark ignition
Bore × stroke	65.1 mm × 44.4 mm
Connecting rod length	79.5 mm
Displacement volume	147.7 CC
Compression ratio	7: 1
Rated power	1.5 kW
Cooling medium	Air cooled
Lubrication system	Pressurized lubrication
Oil sump capacity	0.6 L
Number of valves	2

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