



## Full Length Article

## 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, CO<sub>2</sub> 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.

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### 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 ground-water and in turn dissolved together because acetone does not absorb to soil but it is highly soluble in water; thus contamination of ground-water 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 (NO<sub>x</sub>), 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 CO<sub>2</sub> and H<sub>2</sub>O. 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 CO<sub>2</sub> and H<sub>2</sub>O 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 acetyl radical; after that, the acetyl 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 acetyl 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 range 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, CO<sub>2</sub>, UHC (unburnt hydrocarbons) and O<sub>2</sub> in four-digit displays. The measurements range of different gases is about 10% for CO, 20% for CO<sub>2</sub> 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

**Table 2**  
Fuel properties [34–40].

Properties	Acetone	Gasoline
Molecular formula	C <sub>3</sub> H <sub>6</sub> O	C <sub>8</sub> H <sub>15</sub>
Octane number	110	90–99
Oxygen content (wt%)	27.6	–
Density at 15 °C (g/mL)	0.791	0.745
Autoignition temperature (°C)	560	420
Flash point at closed cup (°C)	17.8	–45 to –38
Lower heating value (MJ/kg)	29.6	42.7
Boiling point (°C)	56.1	25–215
Stoichiometric AF ratio	9.54	14.7
Latent heat at 25 °C (kJ/kg)	518	380–500
Flammability limits (vol.%)	2.6–12.8	0.6–8
Saturation pressure at 38 °C (kPa)	53.4	31.01
Viscosity at 40 °C (mm <sup>2</sup> /s)	0.35	0.4–0.8

**Table 3**  
Specifications of the gas analyser.

Model	Infralyt CL
Power consumption (VA)	45
Range of apparatus heating (°C)	0–130 resolution 1 °C Accuracy ± 1 °C
Gases temperature range (°C)	5–45
Analysers heating range (°C)	0–130
Gases measurement ranges	CO 0–10% vol. CO <sub>2</sub> 0–20% vol. UHC 0–2000 ppm

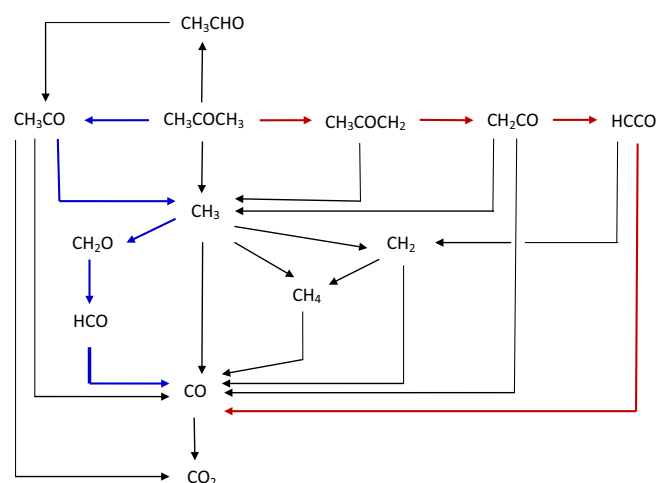
of the gas analyzer. The working principle of the gas analyzer is based on an interference filter correlation procedure; infrared energy is transmitted through the flow of exhaust gases to a filtered infrared detector; a rotating chopper wheel cyclically interrupts the infrared rays and produces a sequence of signals; the analysis of the measurement signals are done automatically by a microprocessor. Oxygen measurement takes place using an electrochemical cell. When carrying out emissions testing, cleanliness of the gas ways, especially in the case of hydrocarbons, is of great importance for accurate measurements. The measurements are seen on the front of the analyzer panel. For further details about experimental apparatus and procedure (see early publications [41–46]).

### 3. Results and discussions

Results demonstrate the emissions and performance characteristics of acetone–gasoline blends as well as pure gasoline fuel at steady state working conditions; consequently the use of acetone as a fuel in SI engine is evaluated and discussed. Combustion mechanism of acetone in SI engine is also highlighted for further understanding of engine performance and emissions. In the results, the three different blended rates of acetone–gasoline fuels are denoted as AC3, AC7 and AC10 where the “AC” designates acetone and the number next to “AC” designates the volume percentage of acetone. For example, the AC10 means that 10% acetone (99% purity) was blended with 90% gasoline by volume; AC0 represents the neat gasoline in the results. It is important to highlight that when acetone is added to gasoline fuel in the engine a lot of problems will show up not only to the environment and human health, but also to the engine itself, in case of incomplete burning of acetone. Accordingly, the study limits the acetone content in the blends to be up to 10 vol.%; more reasons for limiting acetone content in gasoline will be demonstrated later.

#### 3.1. Combustion mechanism

Since engine performance and pollutant emissions are products of the fuel combustion process, it is necessary first to understand

**Fig. 1.** Principal pathways of main species formation from acetone consumption/oxidation.

the mechanism of acetone combustion in SI engines if one makes use of it efficiently. Combustion of acetone in gasoline-fueled engines is very complex and until recently its detailed mechanism was not well understood, as demonstrated early. The chemical reaction scheme presented in this work was developed on the basis of previously available ones by Barnard and Honeyman [24,25], Chong [26], Heghe [47], Decottignies et al. [48], Black et al. [49], Tsuboi et al. [50], Dias et al. [51], Pichon et al. [52], Chong and Hochgreb [53], and Van Geem et al. [54]. Fig. 1 summarizes the main pathways of the acetone consumption/oxidation reactions at stoichiometric flame conditions. As seen, the thermal decomposition of acetone (CH<sub>3</sub>COCH<sub>3</sub>) leads to the direct formation of acetonyl radical (CH<sub>3</sub>COCH<sub>2</sub>), acetyl radical (CH<sub>3</sub>CO), methyl radical (CH<sub>3</sub>), acetaldehyde radical (CH<sub>3</sub>CHO) and very little of methoxide radical (CH<sub>3</sub>O) via reactions R01, R02, R03 and R04, as shown in Table 4. Subsequently, acetone is reacted with methyl radical to form acetonyl,

**Table 4**  
Main acetone consumption/oxidation reactions [24–26,47–57].

Reactions	No.	References
$CH_3COCH_3 \rightarrow CH_3COCH_2 + H$	R01	[24–26,49–51,54]
$CH_3COCH_3 \rightarrow CH_3CO + CH_3$	R02	[24–26,49–51,54]
$CH_3COCH_3 + OH \rightarrow CH_3CHO + CH_3O$	R03	[49–51]
$CH_3COCH_3 + H \rightarrow CH_3CHO + CH_3$	R04	[49–51]
$CH_3COCH_3 + CH_3 \rightarrow CH_3COCH_2 + CH_4$	R05	[26,54]
$CH_3COCH_3 + CH_3 \rightarrow CH_2CO + CH_3 + CH_4$	R06	[48]
$CH_3COCH_2 \rightarrow CH_2CO + CH_3$	R07	[49,50]
$CH_3CHO + H \rightarrow CH_3CO + H_2$	R08	[47,51]
$CH_3CO \rightarrow CH_3 + CO$	R09	[49–54]
$CH_3CO + O \rightarrow CH_3 + CO_2$	R10	[48]
$CH_3CO + OH \rightarrow CH_3 + CO + OH$	R11	[48]
$CH_3CO + HO_2 \rightarrow CH_3 + CO_2 + OH$	R12	[48]
$CH_3 \rightarrow CH_2 + H$	R13	[26,47]
$CH_3 + O \rightarrow CH_2O + H$	R14	[26,47,51]
$CH_3 + OH \rightarrow CO + 2H_2$	R15	–
$CH_2O + OH \rightarrow HCO + H_2O$	R16	[47,51]
$HCO \rightarrow CO + H$	R17	[26,47,51]
$CH_2CO + H \rightarrow HCCO + H_2$	R18	[26,51]
$CH_2CO + OH \rightarrow HCCO + H_2O$	R19	[26,51]
$CH_2CO + OH \rightarrow CH_3 + CO$	R20	[26,51]
$HCCO + H \rightarrow CO + CH_2$	R21	[26,47,51]
$CH_2 + O \rightarrow CO + H_2$	R22	[47]
$CH_2 + H_2 \rightarrow CH_4$	R23	–
$CH_4 + O \rightarrow CO + 2H_2$	R24	[55]
$CO + O \rightarrow CO_2$	R25	[47,55–57]
$H_2 + O \rightarrow H_2O$	R26	[55–57]

methane, methyl and very little of ketene radicals ( $\text{CH}_2\text{CO}$ ) via two different pathways reactions (R05 and R06), as shown in Table 4. Acetonyl radical then decomposes to form methyl radical and ketene via reaction R07. Next, the ketene decomposes to ethynyloxy radical ( $\text{HCCO}$ ), carbon monoxide ( $\text{CO}$ ) and methyl via reactions R18, R19 and R20. The ethynyloxy radical then decomposes to ethylene ( $\text{CH}_2$ ) and carbon monoxide via reaction R21. From the acetaldehyde pathway, it decomposes to the acetyl via reaction R08. Some researchers [24–26,54] neglected this pathway and considered that the acetone produces acetyl directly; however, others [47,49–51] showed that it is important and, in turn, it is included here. The acetyl afterward decomposes to carbon monoxide, carbon dioxide and methyl (reactions R09–R12); and methyl decomposes in turn to ethylene, methanal ( $\text{CH}_2\text{O}$ ) and carbon monoxide via reactions R13, R14 and R15, respectively. Methanal decomposes to hydrogen carbonate ( $\text{HCO}$ ) (reaction R16) that, in turn, decomposes to carbon monoxide via reaction R17, as shown in Table 4. Both ethylene and methane are oxidized to carbon monoxide via reactions R22 and R24, respectively. Besides, ethylene contributes methane via reaction R23. Finally, carbon monoxide is oxidized to carbon dioxide ( $\text{CO}_2$ ) via reaction R25, and hydrogen ( $\text{H}_2$ ) is oxidized to water ( $\text{H}_2\text{O}$ ) via reaction R26 in case of enough air conditions (stoichiometric or lean acetone flame). These are the key pathways for acetone oxidation/decomposition mechanism. The differences between this chemical mechanism and others are that Barnard and Honeyman [24,25] and Chong [26] showed that acetone mechanism contains three main acetone initiation reactions, namely R01 (as two reaction pathways) and R02 (as one reaction pathway), as shown in Table 4. However, Black et al. [49], Tsuboi et al. [50] and Dias et al. [51] showed that acetone is also decomposed into acetaldehyde via reactions R03 and R04 where such reactions are important and they should be included. On the other hand, Black et al. [49], Tsuboi et al. [50] and Dias et al. [51] had not considered some other important pathways in their acetone mechanisms. For example, Black et al. [49] did not consider the formation pathway of ethynyloxy ( $\text{HCCO}$ ) from ketene ( $\text{CH}_2\text{CO}$ ); but this pathway is the dominate path for the ethynyloxy formation (see Chong [26] and Dias et al. [51]). Tsuboi et al. [50] and Dias et al. [51], on the other hand, have not considered the formations and oxidations pathways of  $\text{CH}_4$  and  $\text{CH}_2$ ; in addition, they had not considered the  $\text{CO}_2$  formation from  $\text{CH}_3\text{CO}$ . However, such pathways are showed by other researchers to be included. The  $\text{CH}_4$  and  $\text{CH}_2$  formation pathways are showed by Chong [26], Heghe [47], Decottignies et al. [48] and Van Geem et al. [54]. The  $\text{CH}_4$  and  $\text{CH}_2$  oxidation pathways are showed by Black et al. [49]. The  $\text{CO}_2$  formation from  $\text{CH}_3\text{CO}$  is showed by Decottignies et al. [48] and Black et al. [49].

In general, the acetone oxidation/decomposition mechanism proposed here may cover the principal pathways of main formed species. By analyzing such mechanism, one can highlight only two main pathways for acetone combustion: one for oxidation and another for decomposition. The key pathway for acetone oxidation is:  $\text{CH}_3\text{COCH}_3 \rightarrow \text{CH}_3\text{CO} \rightarrow \text{CH}_3 \rightarrow \text{CH}_2\text{O} \rightarrow \text{HCO} \rightarrow \text{CO} \rightarrow \text{CO}_2$ . However, the decomposition pathway of acetone could be identified as:  $\text{CH}_3\text{COCH}_3 \rightarrow \text{CH}_3\text{COCH}_2 \rightarrow \text{CH}_2\text{CO} \rightarrow \text{HCCO} \rightarrow \text{CO}$ . By further evaluation of such two main pathways, one may conclude that the decomposition pathway of acetone is the main consumption pathway rather than the acetone oxidation pathway (see the relations in Table 4). This conclusion is consistent with Chong [26]. As a final point, it is important to clarify that this study did not provide a systematic validation of the acetone reaction mechanism in terms of ignition delay or engine simulation validations since each path is already validated by others (e.g., References [24–26,47–57]) and, in turn, it could be trusted (see Table 4). In addition, the skeletal mechanism for acetone combustion is consistent with the performance and emissions measurements of acetone blended fuel in combustion engine, i.e., this provides further belief in the mechanism.

### 3.1.1. Mechanism of CO formation

Since carbon monoxide is a harmful and poisonous gas, it is important to reduce its level within acetone combustion. The proposed acetone chemical mechanism described above is able to define CO emission pathways. The CO is formed from the decomposition/oxidation of  $\text{CH}_3\text{CO}$  via R09 and R11,  $\text{CH}_3$  via R15,  $\text{HCO}$  via R17,  $\text{CH}_2\text{CO}$  via R20,  $\text{HCCO}$  via R21,  $\text{CH}_2$  via R22 and  $\text{CH}_4$  via R24, as shown in Table 4. However, the principle intermediate formation reaction of CO from acetone is mainly through two main pathways as follows:

Path 1:  $\text{CH}_3\text{COCH}_3 \rightarrow \text{CH}_3\text{CO} \rightarrow \text{CH}_3 \rightarrow \text{CH}_2\text{O} \rightarrow \text{HCO} \rightarrow \text{CO}$

Path 2:  $\text{CH}_3\text{COCH}_3 \rightarrow \text{CH}_3\text{COCH}_2 \rightarrow \text{CH}_2\text{CO} \rightarrow \text{HCCO} \rightarrow \text{CO}$

Path 2 is more dominate than path 1, for the CO formation. Hence, if one aims to reduce CO emission, it should be oxidized to  $\text{CO}_2$ , e.g., using enough air at high temperature environment to precede complete oxidation, which means complete combustion of acetone.

### 3.1.2. Mechanism of $\text{CO}_2$ formation

In the acetone mechanism, three main  $\text{CO}_2$  formation reactions pathways are illustrated, namely R10, R12 and R25, as presented in Table 4 and shown in Fig. 1. As seen,  $\text{CO}_2$  formation mechanism is a result of oxidation of both CO and  $\text{CH}_3\text{CO}$ . However, the oxidation of CO (reaction R25) is the main pathway for the  $\text{CO}_2$  formation.

### 3.1.3. Mechanism of UHC formation

It is known that complete reaction mechanism for hydrocarbons may consist of thousands of elementary reactions [47]. In this work, the entire hydrocarbons obtained from acetone oxidation/decomposition might be classified into methyl ( $\text{CH}_3$ ), ethylene ( $\text{CH}_2$ ) and methane ( $\text{CH}_4$ ), as shown in Fig. 1. However, the main hydrocarbon formed from acetone combustion is mostly  $\text{CH}_3$ . Such hydrocarbons are oxidized afterward into carbon monoxide and hydrogen, and subsequently to carbon dioxide and water (in case of enough air) with concomitant release of energy.

## 3.2. Performance

Examining the blended fuels on engine performance is carried out using different performance issues, as shown in Figs. 2–6. Fig. 2 shows the exhaust gases temperature versus engine speeds; Fig. 3 shows the pressure of the gases inside the cylinder; Fig. 4 shows

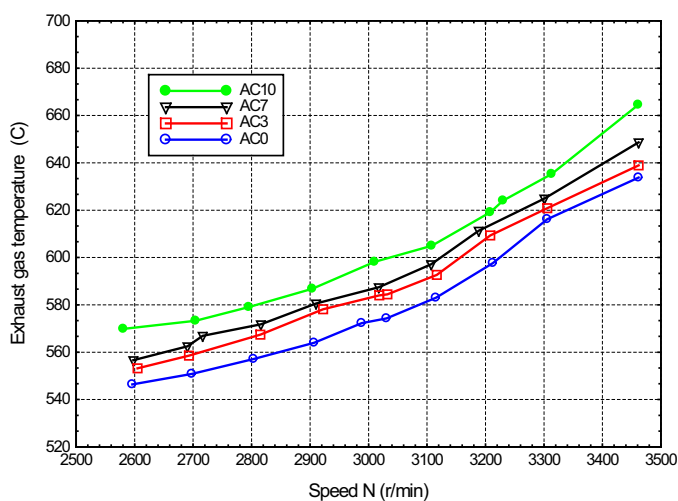


Fig. 2. Exhaust gases temperature versus engine speed for 10 vol.% acetone (AC10), 7 vol.% acetone (AC7), 3 vol.% acetone (AC3) and 0 vol.% acetone (AC0) in gasoline.

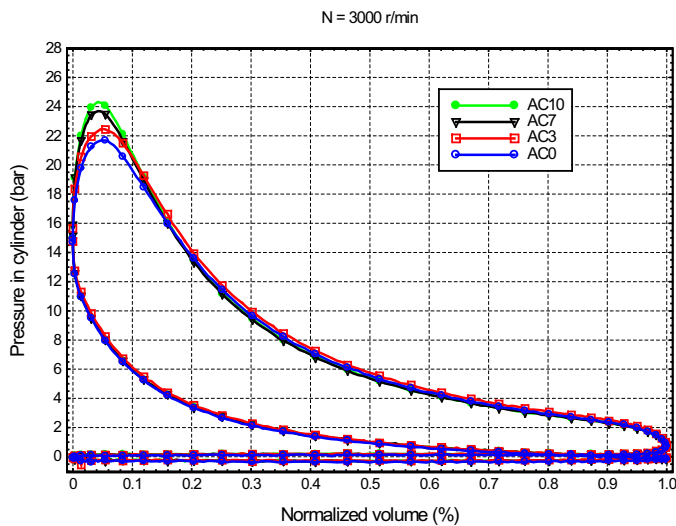


Fig. 3. P-V diagram. Captions are similar to those in Fig. 2.

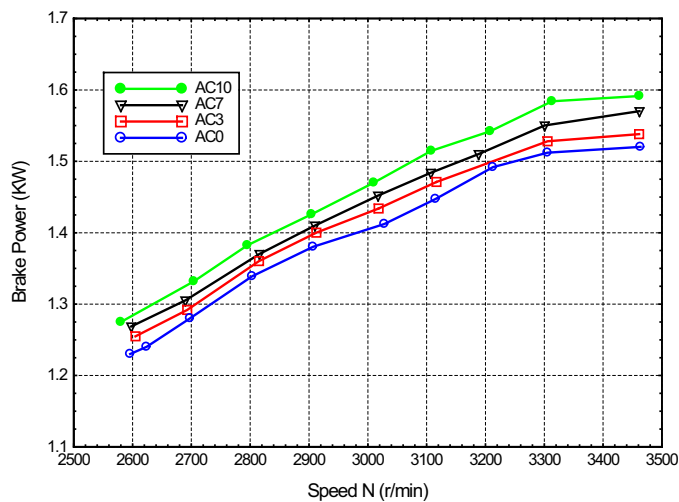


Fig. 4. Brake power versus engine speed. Captions are similar to those in Fig. 2.

the power generated from the engine at different speeds; Fig. 5 shows the torque versus engine speeds; and Fig. 6 shows the volumetric efficiency versus engine speeds for the three blended fuels and neat gasoline. It can be demonstrated from the figures that the greater the rate of acetone in the blends, the higher the engine power, torque, volumetric efficiency, temperature of the exhaust gases and in-cylinder pressure, i.e., better engine performance. The best performance was obtained in this study at the blended fuel of AC10. In particular, the temperature of the exhaust gases compared to neat gasoline fuel increases by 0.8%, 2.3% and 5% when using blends of AC3, AC7 and AC10, respectively. Pressure in-cylinder increases by 2.3%, 9.1% and 10.5% when using blends of AC3, AC7 and AC10, respectively, compared to gasoline fuel. Engine power increases by 1.3%, 3.9% and 5.2% when using blends of AC3, AC7 and AC10, respectively, compared to gasoline fuel. Torque increases by 0.45%, 1.36% and 2.1% when using blends of AC3, AC7 and AC10, respectively, compared to gasoline fuel. Finally, volumetric efficiency increases by 0.9%, 1.6% and 3.2% when using blends of AC3, AC7 and AC10, respectively, compared to gasoline fuel.

The in-cylinder pressure and exhaust gases temperatures are indicators for the completeness of fuel combustion when comparing

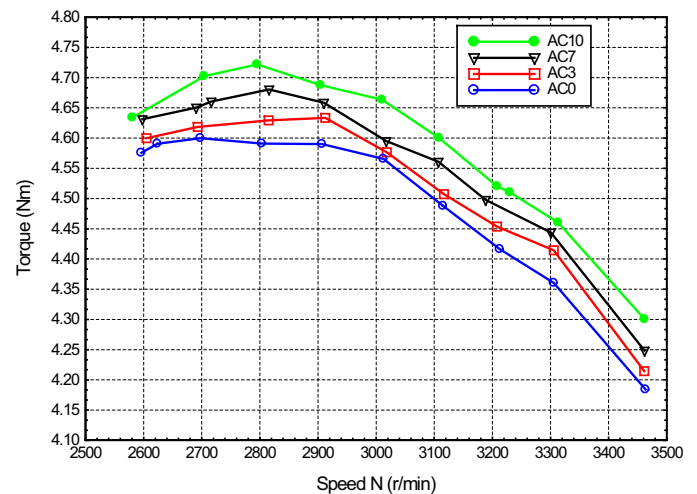


Fig. 5. Torque versus engine speed. Captions are similar to those in Fig. 2.

different fuels at same operating conditions. The reactants get into the combustion chamber (CC) at room pressure/temperature while products demonstrate an elevated pressure/temperature. The pressure/temperature of the products in the CC depends on the energy released from the combustion reactions and heat loss through the boundary of the CC. The pressure/temperature of combustion products is depleted for propelling the piston, and afterward the exhaust gases leave the CC at a temperature called exhaust gases temperature. Comparison of exhaust gases temperature of test fuels when operated at same engine conditions, is shown in Fig. 2. Results indicated an increase in exhaust gases temperature when engine operated with the fuel blends. The higher latent heat of vaporization for acetone leads to temperature drop in cylinder and, in turn, a decrease in the exhaust gases temperature. But there are other factors that increase the temperature in the cylinder. The lower latent heat of acetone compared to gasoline leads to improve volumetric efficiency (as it will be shown later), which leads to such increase in exhaust gases temperature of fuel blends. In addition, the oxygen in the acetone structures enhances the blended fuels combustion and, in turn, increases the exhaust gases temperature since the exhaust gases temperature is a mirror of the combustion efficiency and other parameters, like combustion timing, mixture strength

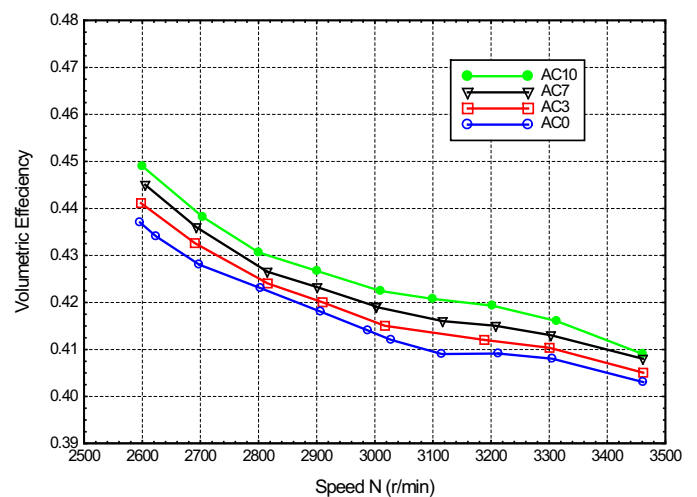


Fig. 6. Volumetric efficiency versus engine speed. Captions are similar to those in Fig. 2.

etc. Heat release analyses can also show that the combustion of acetone–gasoline blends produce a noticeable high temperature heat release behavior, whereas the 10 vol.% acetone in gasoline shows the highest heat release among all test fuels. For the same reasons, the high in-cylinder pressure of blended fuel (AC10) is the highest, compared to neat gasoline, as shown in Fig. 3. Such high heat release rate of fuel blends is a result of the immediate pathway of CO formation, as shown in Fig. 1. The CO formation mechanism shows a direct forming path, which means fast combustion of acetone in the form of gas phase. In addition, such direct path plays an important role in the ignition delay time of the fuel blends.

The high volumetric efficiency of the blended fuels (as acetone rate increases in the blended fuels, volumetric efficiency increases) is attributed to the high latent heat of acetone (518 kJ/kg) compared to gasoline (380–500 kJ/kg), as shown in Table 2, where the higher the heat capacity, the lower fuel evaporation and thus the higher volumetric efficiency occurred. Acetone evaporates much slower than anything in gasoline where it is in liquid phase at atmospheric pressure and room temperature, unlike gasoline. Acetone could be vaporized at low pressure and temperature (27 bar and at 303 K [51]) or at 1 bar and 329 K (boiling point 56 °C, as shown in Table 2). Added to this is the high saturation pressure of acetone compared to gasoline; the saturation pressure of acetone is 53.4 kPa, whereas for gasoline it is 31.01 kPa (at 38 °C), as shown in Table 2. One more reason for advantage of acetone volumetric efficiency is that the surface tension for acetone is about 22.3 mN/m but it is about 20.9 mN/m for gasoline (at 90% octane and 20 °C) [58]. Consequently, acetone needs a longer induction time to be decomposed and vaporized due to its high surface tension characteristics. But as soon as acetone vaporized, it speeds up the combustion once the reaction started. This may be explained based on the reaction mechanism as follows. Generally, the decomposition path of acetone is slower than the oxidation one. Hence, acetone takes longer time to be decomposed, but after a while, oxidation takes a place and, in turn, reaction speeds up the combustion process. The acetone's higher volumetric efficiency leads to obtain higher engine torque, power, in-cylinder pressure and combustion temperature (e.g., exhaust gases temperature). Generally, the use of acetone–gasoline blends directs to improve both fuel conversion efficiency and engine performance, compared to neat gasoline, as shown in Figs. 2–6.

The boost of engine performance of blended fuels may also refer to the fact that significant leaning of blended fuels was obtained when acetone (AF = 9.54) was mixed with gasoline (AF = 14.6) in certain concentrations. This can partially explain the leap of fuel conversion efficiency due to its more complete combustion. Another reason is that acetone fuel contains oxygen (27.6 wt.%), as shown in Table 2, which leads to an increase in fuel conversion efficiency. Moreover, acetone has high octane number by about 110, as shown in Table 2, because of its high flame speeds. The higher the flame speed is, the lower the tendency of knock occurs and, in turn, better performance obtained.

One hypothesis of acetone as a fuel, as explained above, is that its droplet slows down the evaporation but speeds up the combustion of gasoline vapor to allow for a more complete combustion. But adding too much acetone to gasoline will speed up the flame burning too much, and adding too little will not influence, or speed up a little, the fuel burning. This work examined the addition of 3–10 vol.% of acetone and it works well; but the maximum limit of acetone addition to gasoline needs to be defined (this would be presented in another research work). Besides, with the increase of acetone content in the blends, the specific fuel consumption (the figure is not presented) increases due to its lower energy density compared with the neat gasoline, as shown in Table 2. Moreover, due to the higher latent heat of vaporization of acetone than that of gasoline, fuel blends showed higher specific fuel consumptions, as expected. However, specific fuel consumption is affected by many

factors, such as fuel properties and engine operating parameters. As the load/power is gradually increased, specific fuel consumption reduces gradually. It is important to highlight that the specific fuel consumption is not measured at all speed range to be presented as other figures in the work.

During experiments, it was observed that reasonable engine noise was obtained when using acetone blends although high in-cylinder pressure usually induces high level of noise (acetone blends provide high in-cylinder pressure, as shown in Fig. 3). One more advantage of using acetone as a blended fuel in SI engines is that the engines set up can be maintained without any necessary modifications/adjustments when acetone content is below 10% by volume. In addition, acetone is showed to be very soluble in gasoline fuel, which in turn supports a high quality of the blends combustion. However, acetone can also dissolve in water to form emulsion, which causes corruptions of metals. Consequently, the engine fuel system as well as gasoline must be completely free of water, otherwise corruptions will happen quickly to the fuel line, leading to wide-ranging reform in the fuel system, and perhaps worst of so if corrosion/damage occurred while driving. Add to that, the acetone is an effectual corrosive to rubber and plastic; when the acetone comes into contact with any rubber/plastic fuel system components, they will be dissolved away, which leads to extensive repairs/replace/damage of such components. Thus, fuel system must not contain any rubber or plastic components whether there is water in the system/fuel or not. As a recommendation, the fuel system components must be made of high quality metals before using acetone in the engine, otherwise there will be serious problems that cannot be remedied.

### 3.3. Emissions

Figs. 7–9 illustrate the effects of the acetone–gasoline blends on engine emissions. As shown, 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. Such reductions in emissions are changed with changing engine speeds or blend rate. When the engine speed is fixed to be about 2600 r/min, the AC3 produces amount of emissions less than the neat gasoline by about 40%, 29.5% and 35% for CO, CO<sub>2</sub> and UHC, respectively; when using AC7, the emissions, compared to the neat gasoline, are reduced by about 44.5%, 34% and 33% for CO, CO<sub>2</sub> and UHC, respectively; when using AC10, the emissions, compared to neat gasoline, are reduced by about 46.7%, 35.5% and 31.8% for CO,

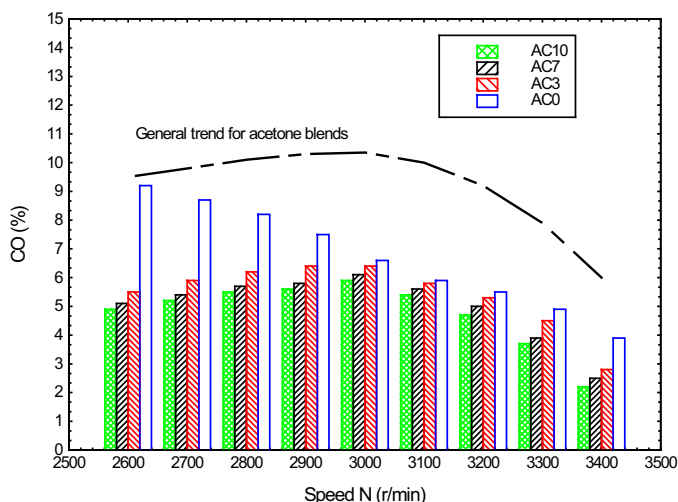


Fig. 7. Carbon monoxide versus engine speed. Captions are similar to those in Fig. 2.

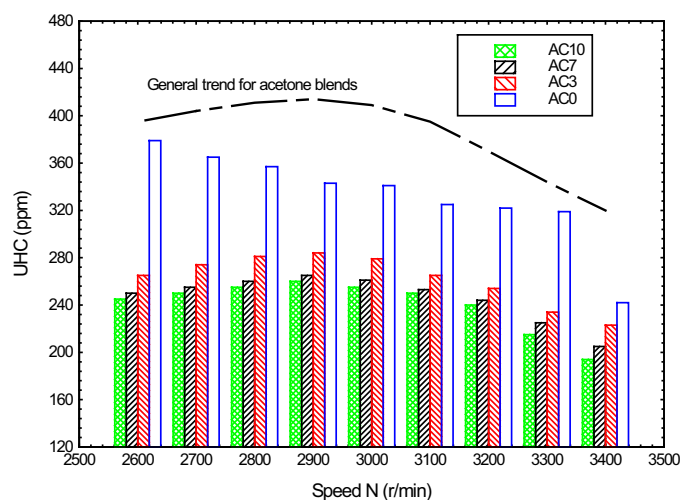


Fig. 8. Unburnt hydrocarbon (UHC) versus engine speed. Captions are similar to those in Fig. 2.

CO<sub>2</sub> and UHC, respectively. This means that an increase in the proportion of acetone in the blended fuel reduces engine emissions (CO and UHC) significantly. But the rate of reduction in CO and UHC emissions is decreased by increasing acetone content where you may compare the changes from AC3 to AC7 and/or from AC7 to AC10 at same speed, as it will be shown later. On the other hand, the engine speeds influence significantly on the pollutant emissions. The influence of engine speeds and acetone rate on emissions is numerically identified as follows. The CO emission of AC10 is lower than that of AC7 by 2.2%, while CO of AC7 is lower than CO of AC3 by 4.5%, at 2600 r/min; however, at speed of 3400 r/min, CO of AC10 is lower than CO of AC7 by 5.5%, while CO of AC7 is lower than CO of AC3 by 7.7%, as shown in Fig. 7. Similarly, in the case of UHC, as shown in Fig. 8, the AC10 is lower than AC7 by 1.3%, while the AC7 is lower than AC3 by 4.7% at speed of 2600 r/min; however, at speed of 3400 r/min, the AC10 is lower than AC7 by 6.3%, while the AC7 is lower than AC3 by 8.25%. As well in the case of the CO<sub>2</sub> emissions, as shown in Fig. 9, the AC10 is higher than AC7 by 1.1%, while AC7 is higher than AC3 by 2.3% at speed of 2600 r/min; however, at speed of 3400 r/min, AC10 is larger than AC7 by 1.6%, while AC7 is larger than AC3 by 2.5%. From these numbers and their analysis,

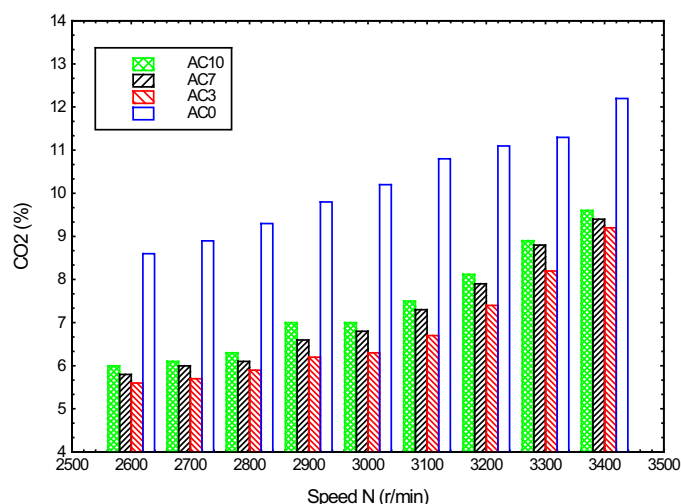


Fig. 9. Carbon dioxide versus engine speed. Captions are similar to those in Fig. 2.

one may notice that the behavior of blends at high speeds is more efficient at getting less pollution emissions than that in the case of low speeds conditions. Besides, by increasing the acetone rate in the mixture, its effectiveness to decrease emissions is not the same as in the low rate conditions.

It is interesting to highlight that by increasing the engine speeds, the recital of gasoline fuel is different from blended fuels. In case of gasoline fuel, the CO and UHC are decreased while CO<sub>2</sub> increased by increasing the engine speeds. While in the case of blended fuels, the emissions of CO and UHC are increased by increasing engine speeds until they reach the peak and then they decrease continually until reaching the lowest value at the speed of 3400 r/min (limit speed of the experiment). In case of CO<sub>2</sub> emissions, the behavior of gasoline is similar to that of blended fuels where CO<sub>2</sub> increases by increasing the engine speeds for both types of fuels (gasoline and blends) but with different rates (as showed earlier).

One important observation is that the worst emissions of the blends are at medium speed (2900–3000 r/min), where the highest levels of CO and UHC are gained. Besides, the emissions at low speeds (<2900 r/min) tend to increase by increasing engine speeds; but it should be noted that the emissions of blended fuels at low and medium speeds are still better than those of gasoline fuel. The trends of CO and UHC at low and medium speeds may attribute to the fact that the CO and UHC productions/formations pathways are dominant than the consumption/oxidation pathways, e.g., fast productions/formations and slow consumption/oxidation of both CO and UHC. This can be shown clearly from the several pathways for CO and UHC formation but less ones for the consumption/oxidation pathways, as shown in Table 4. By increasing the temperature inside the combustion chamber (more generated power) at high speeds conditions, the consumption/oxidation pathways become more activated and, in turn, CO and UHC are decreased. In addition, the decomposition/oxidation of hydrocarbons via carbon dioxide reaction path (hydrocarbons can produce carbon dioxide directly without going through CO, as shown in Fig. 1) may be dominant in the presence of high heat and, hence, formation of CO partially drops off. In view of that, CO and UHC are decreased dramatically at high power/speeds. On the other hand, continuous growing of CO<sub>2</sub> may be tentatively assigned to (C–O) and/or (UHC–O) reactions pathways. The growing intensity of the CO<sub>2</sub> suggests that CH<sub>3</sub>COCH<sub>3</sub> is decomposed/oxidized perfectly at high temperature/pressure/speeds conditions. Despite the coverage continually increase of CO<sub>2</sub> with speeds, but its value remains always below neat gasoline.

By further analyzing the pollutant emissions results with the help of acetone mechanism discussed earlier, one can emphasize that the CO, CO<sub>2</sub> and UHC emissions are highly depending on the intermediate compounds. Such compounds from acetone decomposition/oxidation were typically enlarged and growing at lower temperature/pressure/speeds because of the reaction rate scheme. The reactivity of such intermediate compounds is varied with engine speeds/powers. Anikeev et al. [59] stated that the reaction rate constantly increases exponentially with increasing pressure/temperature. In addition, reaction rate depends on the oxygen concentration, pressure, temperature and nature of compounds, e.g., differing by the number of C and H atoms and the related bonds between them. Furthermore, these intermediate compounds are either not thermodynamically stable at high reaction temperatures or has high effective reaction pathways that lead to stable CO<sub>2</sub> products. In addition, the role of oxygen in the acetone fuel may be less activate at low and medium speeds, rather than to oxidize the fuel. Finally, it is important to clarify that the influence of temperature and pressure on the chemistry of acetone decomposition/oxidation is quite complicated and the analysis needs further support by a modeling study. In conclusion, one may emphasize that the gas-phase reactions have a large impact on engine

pollutant emissions and this is very related to engine speed. As a recommendation, one can optimize pollutant emissions produced from engine at using acetone–gasoline blended fuels by working at speeds greater than or equal to 3400 r/min.

In general, the pollutant emissions of SI engine using blended fuel are much lower than those in the neat gasoline fuel at all engine speeds. This may refer to the fact that the acetone fuel contains oxygen as part of its content, while gasoline does not contain any oxygen. This allows the combustion of acetone to be more complete with less pollutions (CO and UHC). As well, it is observed that the acetone fuel contains less carbon atoms than those in gasoline fuel by about 62% (3 and 8 carbon atoms for acetone and gasoline fuels, respectively, as shown in Table 2), and this leads to generate much less CO and CO<sub>2</sub> emissions than those in gasoline (for the carbon conservation point of view). In addition, the overall fuel consumption might be improved since the blends burn in significant lean conditions (fuel consumption is affected by engine operating parameters, as mentioned earlier). This can add advantages of using acetone fuel widely without causing such high emissions as in gasoline. From this study, one can draw that acetone is a promising fuel in SI engines because of its friendly environment. Adding acetone is a sort of activating the combustion of fuel or tonic.

By analyzing the factors influencing engine emissions, the following factors may be proposed in this work as playing a primary role in SI engine pollutant emissions of the acetone–gasoline blended combustion process: inducted charge of air, fuel type and engine speeds. The charge of air influences the completeness of combustion. Increasing acetone content in the fuel blends or engine speeds (>3000 r/min) shows to improve the pollutant emissions of CO and UHC. Consequently, one can gain high engine performance and low pollutant emissions by optimizing the engine speeds and/or increasing acetone rate in the fuel blends.

#### 4. Conclusions

While no evaluation of the combustion characteristics of acetone in a gasoline-fueled engine is presented in early studies, several factors are identified in this work to significantly investigate the performance and pollutant emissions of acetone–gasoline blended fuels. Experiments have been carried out with fuel blends containing 3, 7 and 10 vol.% acetone in gasoline as well as the neat gasoline fuel. Engine was operated with each blend at 2600–3500 r/min. Based on this work, the following conclusions may be drawn:

- The use of acetone–gasoline blends leads to a boost in both fuel conversion efficiency and engine performance.
- The greater the rate of acetone in the blends (up to 10 vol.%), the higher the engine power, torque, volumetric efficiency, exhaust gases temperature and in-cylinder pressure.
- Adding acetone to gasoline leads to an initial increase in CO and UHC emissions followed by a steady decrease with increasing engine speeds. However, the emissions (CO and UHC) decrease continually with increasing engine speeds for neat gasoline.
- At high speeds conditions, fuel blends are more effective at reducing pollution emissions than those at low speeds conditions.
- The worst (highest) emissions of the fuel blends are at medium speed (2900–3000 r/min) but they are still lower than those of the neat gasoline.
- Two main pathways for acetone combustion are highlighted: one for oxidation and the other for decomposition. The decomposition pathway is dominant than the oxidation pathway.
- Acetone needs a longer induction time to be decomposed, but as soon as vaporized, it speeds up the combustions once the reaction started.
- As acetone content increases in the blends, specific fuel consumption increases.

- Three factors have been identified to significantly influence on SI engine performance and emissions at using acetone–gasoline blends: inducted charge of air, rate of acetone in the fuel blends and engine speeds.
- The SI engine set up could be maintained without any necessary modifications/adjustments when acetone content is below 10% by volume.
- Acetone is a very promising alternative fuel to be directly used in SI engines. Adding acetone is sort of activating the combustion of gasoline fuel. But engine systems must be of high quality before using acetone in the engine.

#### References

- [1] L. Zhengang, F.S. Zhang, Effects of various solvents on the liquefaction of biomass to produce fuels and chemical feedstocks, *Energy Conv. Manage* 49 (2008) 3498–3504.
- [2] Y. Alhassan, N. Kumar, I.M. Bugaje, H.S. Pali, P. Kathkar, Co-solvents transesterification of cotton seed oil into biodiesel: effects of reaction conditions on quality of fatty acids methyl esters, *Energy Conv. Manage* 84 (2014) 640–648.
- [3] L. Rong, D. Yang, H. Lou, M. Zhou, X. Qiu, Influence of sulfonated acetone–formaldehyde condensation used as dispersant on low rank coal–water slurry, *Energy Conv. Manage* 64 (2012) 139–144.
- [4] I.K. Soda, P. Piumsomboon, Isopropanol–acetone–hydrogen chemical heat pump: a demonstration unit, *Energy Conv. Manage* 48 (2007) 1200–1207.
- [5] M. Zhou, X. Qiu, D. Yang, W. Wang, Synthesis and evaluation of sulphonated acetone–formaldehyde resin applied as dispersant of coal–water slurry, *Energy Conv. Manage* 48 (2007) 204–209.
- [6] Y. Xu, J. Long, Q. Liu, Y. Li, C. Wang, Q. Zhang, et al., In situ hydrogenation of model compounds and raw bio-oil over Raney Ni catalyst, *Energy Conv. Manage* 89 (2015) 188–196.
- [7] H. Peng, L. Juan, X. Ling, Study on heat transfer performance of an aluminum flat plate heat pipe with fins in vapor chamber, *Energy Conv. Manage* 74 (2013) 44–50.
- [8] M. Szweczyńska, E. Dobrzyńska, M. Posniak, Qualitative analysis of highly toxic organic compounds emitted from uncontrolled combustion sources using GC-MS/MS, *Chem. Anal.* 53 (2008) 59–70.
- [9] H.B. Singh, D. O'Hara, D. Herlth, W. Sachse, D.R. Blake, J.D. Bradshaw, et al., Acetone in the atmosphere: distribution, sources and sinks, *J. Geophys. Res. Atm.* 99 (1994) 1805–1819.
- [10] M. Yujing, A. Mellouki, J. Photochem, The near UV absorption cross sections for several ketones, *J. Photochem. Photobiol. A Chem.* 134 (2000) 31–36.
- [11] H. Singh, Y. Chen, A. Staudt, D. Jacob, D. Blake, B. Heikes, et al., Evidence from the Pacific troposphere for large global sources of oxygenated organic compounds, *Nature* 410 (2001) 1078–1081.
- [12] C. Klaassen, *The Basic Science of Poisons*, McGraw-Hill, New York, 2013. ISBN 978-0071769235.
- [13] C. Hu, Enhanced catalytic activity and stability of Cu 0.13 Ce 0.87 Oy catalyst for acetone combustion: effect of calcination temperature, *J. Chem. Eng.* 159 (2010) 129–137.
- [14] X. Qi, M. Stephanopoulos, Activity and stability of Cu–CeO<sub>2</sub> catalysts in high-temperature water–gas shift for fuel-cell applications, *Ind. Eng. Chem. Res.* 43 (2003) 3055–3062.
- [15] B. Wen, M. He, Study of the Cu–Ce synergism for NO reduction with CO in the presence of O<sub>2</sub>, H<sub>2</sub>O and SO<sub>2</sub> in FCC operation, *Appl. Catal. B Environ.* 37 (2002) 75–82.
- [16] Y.C. Chang, W.J. Lee, S.L. Lin, L.C. Wang, Green energy: water-containing acetone–butanol–ethanol diesel blends fueled in diesel engines, *Appl. Energy* 109 (2013) 182–191.
- [17] Y.C. Chang, W.J. Lee, T.S. Wu, C.Y. Wu, S.J. Chen, Use of water containing acetone–butanol–ethanol for NO<sub>x</sub>–PM (nitrogen oxide–particulate matter) trade-off in the diesel engine fueled with biodiesel, *Energy* 64 (2014) 678–687.
- [18] S.L. Lin, W.J. Lee, C.F. Lee, S.J. Chen, Energy savings and emission reduction of nitrogen oxides, particulate matter, and polycyclic aromatic hydrocarbons by adding water-containing acetone and neat soybean oil to a diesel-fueled engine generator, *Energy Fuels* 24 (2010) 4522–4533.
- [19] M. Baldi, E. Finocchio, F. Milella, G. Busca, Catalytic combustion of C<sub>3</sub> hydrocarbons and oxygenates over Mn<sub>2</sub>O<sub>4</sub>, *Appl. Catal. B Environ.* 16 (1998) 43–51.
- [20] A.M. El-Nahas, J.W. Bozzelli, J.M. Simmie, M.V. Navarro, G. Black, H.J. Curran, Thermochemistry of acetylonyl and related radicals, *J. Phys. Chem.* 110 (2006) 13618–13623.
- [21] K. Sato, Y. Hidaka, Shock-tube and modeling study of acetone pyrolysis and oxidation, *Comb Flame* 122 (2000) 291–311.
- [22] M. Chaos, Z. Zhao, A. Kazakov, F.L. Dryer, An experimental and kinetic study of acetone oxidation in a flow reactor. 31st Int Sym on Combust, Heidelberg, 6–11 August, 2006.
- [23] C.D. Chang, J. Anthony, The conversion of methanol and other O-compounds to hydrocarbons over zeolite catalysts, *J. Catal.* 47 (1977) 249–259.
- [24] J.A. Barnard, T.W. Honeyman, The gaseous oxidation of acetone, I: the high-temperature reaction, *Proc. R Soc. London Ser. A* 279 (1964) 236–247.

- [25] J.A. Barnard, T.W. Honeyman, The gaseous oxidation of acetone, II: the Low-temperature reaction, *Proc. R. Soc. London Ser. A* 279 (1964) 248–259.
- [26] C. Chong, Combustion characteristics of alternative liquid fuels (Ph.D. thesis), Cambridge Univ, Cambridge, UK, 2011.
- [27] T. Tsuboi, K. Ishii, S. Tamura, Homogeneous thermal oxidation of acetone behind reflected shock wave, *Trans. Japan Soc. Mech. Eng. Ser. B* 67 (2001) 2797–2804.
- [28] T.M. Lee, A. Ishizaki, S. Yoshino, K. Furukawa, Production of acetone, butanol, and ethanol from palm oil mill effluent using *C. saccharoperbutylacetonicum* N1-4, *Biotechnol. Lett.* 17 (1995) 649–654.
- [29] A.M. Lopez-Contreras, P.A.M. Claassen, H. Mooibroek, W.M. De-Vos, Utilisation of saccharides in extruded domestic organic waste by *Clostridium acetobutylicum* ATCC 824 for production of acetone, butanol and ethanol, *Appl. Microbiol. Biotechnol.* 54 (2000) 162–167.
- [30] M.S. Madihah, A.B. Ariff, M.S. Khalil, A.A. Suraini, M.I.A. Karim, Anaerobic fermentation of gelatinized sago starch-derived sugars to acetone–1-butanol/ethanol solvent by *Clostridium acetobutylicum*, *Folia Microbiol.* 46 (2001) 197–204.
- [31] N. Qureshi, M.M. Meagher, J. Huang, R.W. Hutkins, Acetone butanol ethanol (ABE) recovery by pervaporation using silicalite–silicone composite membrane from fed-batch reactor of *Clostridium acetobutylicum*, *J. Memb. Sci.* 187 (2001) 93–102.
- [32] A. Ishizaki, S. Michiwaki, E. Crabbe, G. Kobayashi, K. Sonomoto, S. Yoshino, Extractive acetone–butanol–ethanol fermentation using methylated crude palm oil as extractant in batch culture of *Clostridium saccharoperbutylacetonicum* N1-4 (ATCC 13564), *J. Biosci. Bioeng.* 87 (1999) 352–356.
- [33] M. Ozcan, S. Öztürk, Y. Oguz, Potential evaluation of biomass-based energy sources for Turkey, *Eng. Sci. Tech. JESTECH* 18 (2015) 178–184.
- [34] N. Zhou, M. Huo, H. Wu, K. Nithyanandan, C.F. Lee, Q. Wang, Low temperature spray combustion of acetone–butanol–ethanol (ABE) and diesel blends, *Appl. Energy* 117 (2014) 104–115.
- [35] M. Lapuerta, R.G. Contreras, J.C. Fernandez, M.P. Dorado, Stability, lubricity, viscosity, and cold-flow properties of alcohol–diesel blends, *Energy Fuels* 24 (2010) 4497–4502.
- [36] Y.C. Lin, W.J. Lee, H.R. Chao, S.L. Wang, T.C. Tsou, G.P. Chang-Chien, Approach for energy saving and pollution reducing by fueling diesel engines with emulsified biosolution/biodiesel/diesel blends, *Environ. Sci. Tech.* 42 (2008) 3849–3855.
- [37] G. Chen, Y. Shen, Q. Zhang, M. Yao, Z. Zheng, H. Liu, Experimental study on combustion and emission characteristics of a diesel engine fueled with 2,5-dimethylfuranediesel, n-butanol–diesel and gasoline/diesel blends, *Energy* 54 (2013) 333–342.
- [38] J. Freeman, J. Williams, S. Minner, C. Baxter, J. DeJovine, L. Gibbs, Alcohols and Ethers: A Technical Assessment of Their Application as Fuels and Fuel Components, 2nd ed., API Publication, New York. American Inst of Phy, 1988.
- [39] J.A. Dean, Lange's Handbook of Chemistry, 14th ed., McGraw-Hill, New York, 1992.
- [40] A.S. Hamadi, Selective additives for improvement of gasoline octane number, *Tikrit J. Eng. Sci.* 17 (2010) 22–35.
- [41] A. Elfasakhany, The effects of ethanol–gasoline blends on performance and exhaust emission characteristics of spark ignition engines, *Int. J. Automot. Eng.* 4 (2014) 608–620.
- [42] A. Elfasakhany, Investigation on performance and emissions characteristics of an internal combustion engine fuelled with petroleum gasoline and a hybrid methanol–gasoline fuel, *Int. J. Eng. Tech.* 13 (2013) 24–43.
- [43] A. Elfasakhany, Experimental study on emissions and performance of an internal combustion engine fueled with gasoline and gasoline/n-butanol blends, *Energy Conv. Manage* 88 (2014) 277–283.
- [44] A. Elfasakhany, Experimental investigation on SI engine using gasoline and a hybrid iso-butanol/gasoline fuel, *Energy Conv. Manage* 95 (2015) 398–405.
- [45] A. Elfasakhany, Investigations on the effects of ethanol–methanol–gasoline blends in a spark-ignition engine: performance and emissions analysis, *Eng. Sci. Tech. JESTECH* 18 (2015) 713–719.
- [46] A. Elfasakhany, Experimental study of dual n-butanol and iso-butanol additives on spark-ignition engine performance and emissions, *Fuel* 163 (2016) 166–174.
- [47] C.I. Heghe, C1–C4 Hydrocarbon oxidation mechanism (Ph.D. thesis), Chem Faculty, Carola Univ, Heidelberg, Germany, 2006.
- [48] V. Decottignies, L. Gasnot, J.F. Pauwels, A comprehensive chemical mechanism for the oxidation of methylethylketone in flame conditions, *Combust. Flame* 130 (2002) 225–240.
- [49] G. Black, S. Pichon, H. Curran, J. Simmie, R. Donohue, N.D. Chaumeix, An Experimental and modeling study of the combustion of acetone, 3rd Eur Comb Meeting, 2007.
- [50] T. Tsuboi, K. Ishii, S. Tamura, Thermal oxidation of acetone behind reflected shock wave, *Proc 17th conf ICDERS*, Hakone, Japan, 1999.
- [51] V. Dias, J. Vandooren, H. Jeanmart, Flame structure studies of acetone, 23rd Journées d'Etude of the Belgian Section, Brussels, May 27–28, 2014.
- [52] S. Pichon, G. Black, N. Chaumeix, M. Yahyaoui, J.M. Simmie, H.J. Curran, et al., The combustion chemistry of a fuel tracer: measured flame speeds and ignition delays and a detailed chemical kinetic model for the oxidation of acetone, *Combust. Flame* 156 (2009) 494–504.
- [53] C.T. Chong, S. Hochgreb, Measurements of laminar flame speeds of acetone/methane/air mixtures, *Combust. Flame* 158 (2011) 490–500.
- [54] K.M. Van Geem, A. Cuoci, A. Frassoldati, P. Steven, G.B. Marin, E. Ranzi, An experimental and kinetic modeling study of pyrolysis and combustion of acetone–nButanol–ethanol (ABE) mixtures, MCS7, Sardinia, Italy, 2011.
- [55] L. Tao, N. Berge, A. Elfasakhany, X.S. Bai, Experimental and numerical studies of a pulverised wood flame, 6th Europ Conf on Ind Furnaces and Boilers, Lisbon, Portugal, 2002.
- [56] A. Elfasakhany, X.S. Bai, Modeling of pulverised wood combustion: a comparison of different models, *Prog. Comp. Fluid Dyn.* 6 (2006) 188–199.
- [57] A. Elfasakhany, T. Klason, X.S. Bai, Modeling of pulverised wood combustion using a functional group model, *Comb. Theory Model.* 12 (2008) 883–904.
- [58] D.M. Koenhen, C.A. Smolders, The determination of solubility parameters of solvents and polymers by means of correlations with other physical quantities, *J. App. Poly Sci.* 19 (1975) 1163–1179.
- [59] V.I. Anikeev, A. Ermakova, M. Goto, Decomposition and Oxidation reactions of aliphatic nitro compounds in supercritical water, *Kinet. Catal. Springer* 46 (2005) 821–825.