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SAMPLING OF UNREGULATED COMPONENTS OF A TWO-STROKE, STEPPED-PISTON ENGINE EMISSION

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ABSTRACT

High unburnt hydrocarbons (HC) emissions results in the case of carbureted two-stroke engine because of the scavenging process carried out by fresh mixture of air and fuel. Some of this air-mixture combines with the residual exhaust gas as it scavenges the cylinder. The use of lubrication oil present in the combustion process, inhibits the two-stroke engine as a mean engine to the environment. A two-stroke step-piston engine was developed to minimize these problems. The step-piston engine configurations incorporate a compression chamber which eliminates the use of crankcase compression. Therefore the usage of lubrication oil to lubricate the crankcase components could be stop. In this paper the unregulated gases namely benzene, 1,3-butadiene, toluene and methyl tertiary butyl ether (MTBE) were considered. Gas chromatography (GC) machine equipped with flame ionization detector (FID) was employed to detect the gases. A method was developed for analyzing hydrocarbon based gases. The test was fully computer guided using TotalChrom software where the results were displayed and logged automatically. Detected gas components arise from the GC were displayed qualitatively. Later the results were analyzed using Total Hydrocarbons Analysis (DHA) software for quantitative analysis. A conventional two-stroke engine was later chosen for comparative study.

***Keywords**: Engine emission, hydrocarbon analysis, unregulated gaseous concentration, two-stroke, stepped-piston.*

1.0 INTRODUCTION

High unburnt HC emissions results in the case of a carbureted two-stroke engine because of the scavenging process carried out by fresh mixture of air and fuel.

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Some of this air-mixture combines with the residual exhaust gas as it scavenges the cylinder. Part of it is lost is due to short circuiting, that is, some of the fresh air- fuel charge leaves the transfer port and goes out as the exhaust directly. The net effect is that 25-40% of the charge may be wasted resulting in high fuel consumption and high levels of unburnt hydrocarbons. Because of the internal exhaust gas recirculation, the fresh mixture is on the richer side compared to that of a four-stroke engine. In two-stroke engine, an air-fuel ratio of no more than 13:1 is required to achieve maximum power. A richer air-fuel ratio results in high monoxide (CO) emissions. Richer mixtures are also preferred in two-stroke engines to cool the engine.

Unregulated species is also a function of lubricant type, the ratio of oil-to-fuel, and the lubrication method. In two-stroke engines, oil is either premixed with fuel or injected into the fuel-air stream to lubricate the bearings and the cylinder wall. Part of the lubricant oil contributes to unregulated species and also makes its way into exhaust gases. Unlike in four-stroke engine, lubrication oil that enters the crankcase is not recovered but goes out into the atmosphere as particulate matter and other products of combustion.

2.0 CAUSE OF UNBURNED HYDROCARBON

For many reasons, a complete combustion of the hydrocarbon fuel does not occur within the internal combustion engine. Consequently, some unburned hydrocarbons are exhausted into the atmosphere. One of the causes of these unburned HC emissions is known as quenching, a phenomenon which occurs when a flame in the internal combustion chamber approaches any relatively cool metal surfaces. The flame does not burn close to these cool surfaces consequently it goes out or is 'quenched' by the cool areas. As a result this leaves a small amount of unburned fuel or hydrocarbons in this area, which passes out of the combustion chamber during the exhaust stroke.

Another cause of unburned hydrocarbons in the emission is the combustion chamber deposits. These deposits are porous. Therefore, as the piston moves up on the compression stroke, it forces some fuel into these deposits. The absorbed fuel never burns, and it comes out of these deposits late in the power stroke or during the exhaust stroke where it passes into the atmosphere. Another cause of unburned hydrocarbon in the emission is the quantity of air/fuel mixture reaching the individual combustion chambers. For example, if too rich a mixture, one containing more fuel than necessary, reaches the combustion chambers, there will not be sufficient oxygen present to allow a complete combustion. Consequently unburned hydrocarbons contained in the partially burned mixture escape through the emission and into the atmosphere.

2.1 Formation of Unburned Hydrocarbons

The emission of unburned hydrocarbons or organic substances, in general, results from the incomplete combustion of the hydrocarbons. Contrary to CO and NO_X, which are formed in a homogeneous phase at high temperature in the fluid, the hydrocarbons result from heterogeneous effects in the mixture and in the neighborhood of the cylinder walls, hence at lower temperature.

Unburned hydrocarbons include a wide variety of hydrocarbons (as shown in Table 1) which are harmful at varying degrees to human health or have different reactivities in the tropospheric chemical conversions. Emissions such as aldehydes account for only a few percent of the HC emissions of a spark ignition engine.

Table 1: Example of Hydrocarbons Classes in Exhaust Gas [1]

Carbon, percent of total HC			
Paraffin	Olefins	Acetylenes	Aromatics
33	27	8	32

2.2 Regulated and Unregulated Components

Commonly there are two kinds of emission that emitted from two-stroke engine, that is regulated and unregulated. This emission classified base on their impact to environment and human. Nitrogen oxide (NO), carbon monoxide (CO) and sulphur dioxides are classified under regulated emission. While unburned HC which is benzene, 1,3-butadiene, toluene and methyl tertiary butyl ether, (MTBE) and a lot more are classified under unregulated emission.

Benzene is an aromatic hydrocarbon that is present in gas form both in exhaust and evaporative emissions from motor vehicles. This gas is emitted under the low load condition, because it is easily oxidizes in high temperature. Formaldehyde is other kinds of unregulated component, which tends to be emitted under the low load condition [2]. The non-road mobile sources contribute 23 % to the formaldehyde inventory. Meanwhile 1,3-butadiene is formed in engine exhaust by incomplete combustion of fuel [2]. It is not present in any evaporative and refueling emissions, because it is not present in any appreciable amount in gasoline fuel. While 1,3-butadiene is emitted at the low engine speed condition, because 1,3-butadiene decompose in a short time, and the exhaust gas stays much longer in a cylinder under the low speed condition than under high engine speed one [2]. The study done by Takada et al. [2] also shows that non-road mobile source contribute 15.2 % to the 1,3-butadiene inventory.

2.2.1 Nitrogen Oxide

Nitrogen oxides are formed during combustion as a result of high temperature and pressure as found in the internal combustion engine. The high temperatures necessary to form NO_x above 2,500°F (1371°C) only occur during some phases of engine operation [1].

During the combustion process, temperatures may exceed 4,500°F (2482°C). At temperatures above approximately 2,500°F [1], oxides of nitrogen form very rapidly from the nitrogen and oxygen in the air. Consequently, the formation of NO_x is dependent upon temperatures, and any variable that causes an increase in temperatures above 2,500°F will cause an increase in NO_x emissions.

The oxides of nitrogen have a composition of about 98 % nitric oxide and 2 % nitrogen dioxide. Nitric oxide itself is a colorless gas but when it combines with oxygen to form nitrogen dioxide, a gas with brownish colors. Then nitrogen dioxide combines with certain active hydrocarbon with presence of sunlight to form photochemical smog.

One of the negative aspects of this combination is the formation of ozone (O_3). The sunlight breaks apart some of the nitrogen dioxide to form nitric oxide and oxygen atom with diatomic oxygen forms ozone. At the same time this nitrogen oxides causes changes in lung function in asthmatics and also contribute to acid rain [3].

2.2.2 Carbon Monoxide

Carbon monoxide (CO) is another regulated component produced by the two-stroke engine during its combustion process. Carbon monoxide is an invisible gas that results from incomplete combustion of the engine air/fuel mixture. If complete combustion of the fuel charge occurs, the process would produce carbon dioxide (CO_2) instead of carbon monoxide. Carbon monoxide produced by the engine because there is insufficient oxygen available to completely burn all the air/fuel mixture.

Carbon monoxide can create several problems. For instance, carbon monoxide itself is an odorless, colourless, poisonous gas. When people inhale carbon monoxide into their lungs, it transfers into the bloodstream. There it takes the place of the place of oxygen within the red blood cells, resulting in a reduction of the oxygen supply to the body. This lack of oxygen can cause headaches, reduction in mental alertness [4] and even death if the carbon monoxide concentration is high enough [3].

2.2.3 Sulphur

Another form of regulated gases that emitted from exhaust emission is that of oxides of sulphur (SO_x). Oxides of sulphur result from the small amount of sulphur present in the gasoline itself. Under normal conditions the sulphur content of the fuel less than 0.1 %. However, this small amount of sulphur is emitted from an engine's exhaust into the atmosphere in the form of oxides of sulphur.

The production of a sulphuric acid mist is the major problem arising from SO_x emissions from motor vehicles. However, this particular problem primarily occurs with motor vehicles equipped with catalytic converters. The reason is that these converters provide an oxidizing atmosphere that enhances the formation of sulphuric acid from the sulphur compounds within the fuel.

In the catalytic converter sulphur dioxide (SO_2) is converted to sulphur trioxide (SO_3) within the oxidizing atmosphere of the unit (as shown in Eq. (1)).

$$SO_2 + O \rightarrow SO_3 \tag{1}$$

Next, sulphur trioxide (SO_3) unites with water (H_2O) vapor and forms a sulphuric acid (H_2SO_4) mist. This sulphuric acid mist is very corrosive. Consequently, it will, upon contact, deteriorate textiles, building materials, and vegetation [4]. Moreover, it is a well-known fact that sulphuric acid in any form is very harmful to living tissue [3].

2.2.4 Benzene

Benzene is a clear, colorless, aromatic hydrocarbon which has a characteristic sickly, sweet odor. It is both volatile and flammable. Benzene contains 92.3 % carbon and 7.7 % hydrogen with the chemical formula C_6H_6. [5]. The benzene molecule is represented by a hexagon formed by six sets of carbon and hydrogen atom bonded together with alternating single and double bonds. The amount of benzene and the length of time of the exposure determine whether harmful health effects will occur and the type and severity of these health effects.

Benzene causes problems in the blood. People who breathe benzene for long periods may experience harmful effects in the tissues that form blood cells [5], especially the bone marrow. These effects can disrupt normal blood production and cause a decrease in important blood component. A decrease in red blood cells can lead to anemia. Reduction in other components in the blood can cause excessive bleeding. Blood production may return to normal after exposure to benzene stops. Excessive exposure to benzene can be harmful to the immune system, increasing the chance for infection and perhaps lowering the body's defense against cancer [5]. Benzene also can cause cancer of the blood-forming organs and also known as human carcinogen. Long-term exposure to relatively high levels of benzene in the air can cause cancer of the blood-forming organs which is called as leukemia.

Exposure to benzene has also been linked with damage to chromosomes which are the parts of cells that are responsible for the development of hereditary characteristics. Exposure to benzene may also be harmful to the reproductive organs. Women who exposure high levels of benzene had irregular menstrual periods. When examined, these women showed a decrease in the size of their ovaries.

2.2.5 1,3-Butadiene

1,3-butadiene is a flammable, colorless gas with a pungent odor. The chemical formula of 1,3-butadiene is C_4H_6. 1,3-butadiene has a molecular weight of 54.09 grams per mole [6]. At 25°C, 1 part per billion by volume (ppbv) of 1,3-butadiene equals 2.21 micrograms per cubic meter of 1,3-butadiene.

Health effect when breath very high level of 1,3-butadiene for short time can cause central nervous system damage, blurred vision, nausea, fatigue, headache, decreased blood pressure and pulse rate and unconsciousness, meanwhile when breath lower levels can cause irritation of the eyes, nose and throat [6].

2.2.6 Toluene

Toluene is a clear colorless fuming liquid with a pungent, fruity odor. The chemical formula for toluene is $C_6H_5CH_3$, [6] and it has a molecular weight of 44.06 g/mol. Vapors are heavier than air and can travel considerable distance and cause flashback from combustion source. When heated to decomposition toluene emits acrid smoke and toxic fumes of carbon monoxide and carbon dioxide.

At medium concentrations toluene can cause an irritant of the skin, eyes, mucous membranes, throat and respiratory tract. Symptoms of short-term exposure to higher levels of this compound include nausea, vomiting, headache, dermatitis and pulmonary edema (fluid in the lungs) [7].

2.2.7 Methyl Tertiary-Butyl Ether (MTBE)

MTBE is a component which is blended with gasoline to replace lead as an octane enhancer (helps prevent the engine from "knocking"). This component is mixed for the purpose of lean combustion. MTBE is a chemical compound that is manufactured by the chemical reaction of methanol and isobutylene. MTBE is produced very large quantities and is almost exclusively used as a fuel additive in motor gasoline. It is one of a group of chemicals commonly known as "oxygenates" because they raise the oxygen content of gasoline. At room temperature, MTBE is a volatile, flammable and colorless liquid that dissolves rather easily in water. Routes of human exposure to MTBE can include inhalation, ingestion, and dermal contact. Non-Cancer acute exposure of humans to high concentrations of MTBE can result in nausea, vomiting, dizziness, and sleepiness. Direct exposure to the skin and eyes can cause drying and irritation [8].

3.0 STEPPED-PISTON ENGINE

Figure 1 illustrates the stepped-piston engine design presented in a half-cut view. The engine was proposed to be a prime mover for many platforms. Major design contribution is additional auxiliary ports that will increase the charge efficiency and subsequently the engine performance. It was specially designed to incorporate with a direct fuel injection system and electronic control unit (ECU). These devices are expected to eliminate the drawback of two-stroke engine.

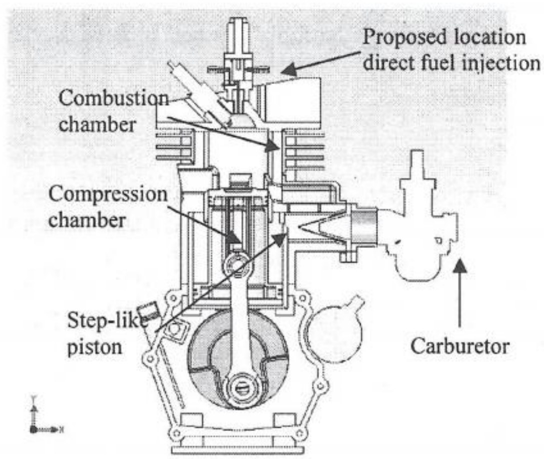

Figure 1: Inner geometry of the engine

The stepped-piston engine design consists of two surfaces namely the combustion and compression surface. The combustion surface (piston crown) is exposed to the combustion chamber while the compression surface (which is lower) act as the compression chamber for the supercharger thus eliminates the used of crankcase compression. With this design the usage of conventional two-stroke lubrication oil for crankcase mechanism can be eliminate, and for the top piston ring set it can be reduce to eradicate the white smoke produce by the engine. For the lower piston ring set, the four-stroke lubrication oil can be used, hence improve the quality of lubrication system.

Table 2: Engine specifications

Parameter	Size/ Feature
Cylinder type	Single cylinder, piston ported
Displacement	125 cm^3
Bore x Stroke	53.8 x 56 mm
Scavenging Concept	Multi-port Loop Scavenged
Exhaust Port opening/ Closing	93 CA ATDC/ 267 CA ATDC
Intake port opening/ closing	110 CA ATDC/ 250 CA ATDC
Rated power (kW @ rated RPM)	9.2 @ 6500 RPM
Ignition Timing	-20 BTDC

4.0 TESTING METHODOLOGY

The stepped-piston engine was installed on an engine test-bed and all the necessary standard testing equipment was set. The first stage was to take samples of emission at different engine speed without any load given to it. Next at constant engine speed with load and finally at constant speed with and without load while, the lubrication oil (2-T) content varies. For comparative purposes a conventional two-stroke engine with the same capacity was chosen and undergoes the same testing procedure.

4.1 Testing Equipment

In this experiment a gas analyzer, which is built into Clarus 500 Gas Chromatograph, utilizes a split injection port, capillary column and Flame Ionization Detector (FID), which are combined into a channel for detailed analysis of individual hydrocarbon component. Data is acquired with Totalchrom software, which generates a text format file of the processed data. The Detailed Hydrocarbon Analysis (DHA) software is then used to process the text format file and then to identify, quantify and report the individual components detected.

As for loading the engine, standard engine test-bed was engaged with eddy-current dynamometer. A Magtrol DSP6001 Dynamometer Controller provides the load control. With 120 readings per second the controller provides superior resolution for data acquisition and curve plotting.

5.0 CHROMATOGRAPHY METHOD

Knowledge of the individual hydrocarbon compound composition of petroleum distillates and refinery products identification are useful in the evaluation of feedstock and product materials and process operations control. The test method provides for the determination of individual hydrocarbon components of light liquid hydrocarbon mixtures typically encountered in petroleum refining operations with boiling point ranges up to approximately 250°C [9]. Component concentrations are determined in the range of 0.001 to 100 mass percent.

The method developed is then used for the hardware and software mentioned earlier. The test method should be used together with the gas chromatography operating conditions. The chromatography method is as tabulated in Table 3. As a result, the retention time given by the gas chromatography for each component is as shown in Table 4.

Table 3: Column temperature program

Event	Parameter
Initial Temperature	5°C
Initial Time	10 min
First Program Rate	5°C/min
First Hold Temperature	50°C
First Hold Time	50 min
Second Program Rate	1.5°C/min
Final Temperature	200°C
Final Hold Time	5 min

A syringe of 20 ml and 10 μl were used for collecting samples. 20 ml syringe was used to collect sample in gas form while 10 μl was used for sample in liquid form.

Table 4: Component retention time

Component Name	Component Type	Retention Time (min)
1,3-Butadiene	Single Peak Component	9.391
MTBE	Single Peak Component	19.566
Benzene	Single Peak Component	27.486
Toluene	Single Peak Component	43.721

6.0 RESULTS AND DISCUSSIONS

The DHA software provides the concentration reading for each specimen. The plotted graph is concentration versus engine variable that contribute towards the emissions such as load, percentage of 2-T and so on. The chromatogram shows the conditions for each species that emitted at high concentration. Samples of chromatogram are as shown in Figure 2.

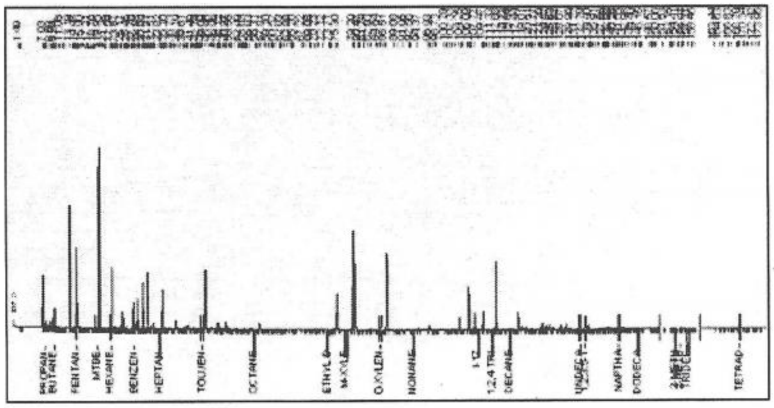

Figure 2(a): Chromatogram of stepped-piston engine at 2000 rpm

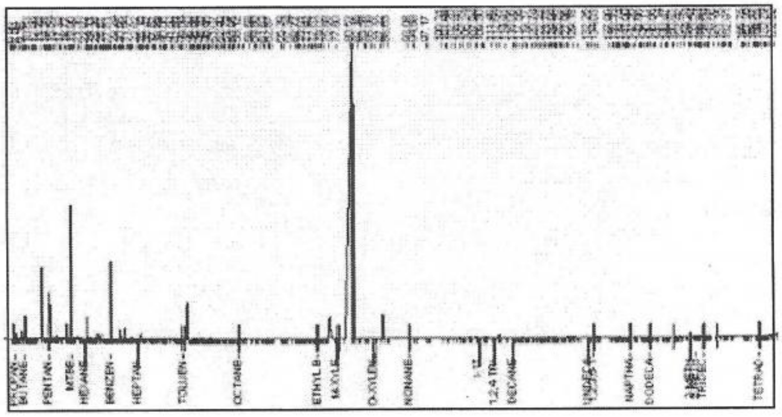

Figure 2(b): Chromatogram of comparative engine at 2000 rpm

6.1 Variable Engine Speed Test

At these conditions the engine will operate with varied speed from 500 rpm to 4000 rpm. At these operating conditions, the percentage of 2-T will remain constant and no load is given to the engines. This parameter is set to relate the pattern of species concentration with engine speed.

Figure 3 shows the concentration of benzene, MTBE, toluene and 1,3-butadiene. In general, maximum concentration is toluene for low speed engine condition. While MTBE shows the highest concentration for high speed engine conditions. Benzene, toluene and 1,3-Butadiene have negative slope between 500 rpm to 3000 rpm. The value of slope for toluene is greater compared to benzene and 1,3-butadiene. But benzene and toluene have a positive slope between 3000 rpm to 4000 rpm. While MTBE has an opposite trend compared to the other three components.

Figures 3 and 4 exhibit the concentration patterns are about the same between these two engines where the minimum concentration occurred at 3000 rpm except for MTBE. Figures 5, 6, 7 and 8 are the individual plot of each gas element for both engines showing the relationship between concentration and engine speed. Referring to the quantities obtained from the experiment, the stepped-piston engine illustrates lower concentration for benzene and MTBE. As for toluene and 1,3-butadiene the profiles are lying close to each other.

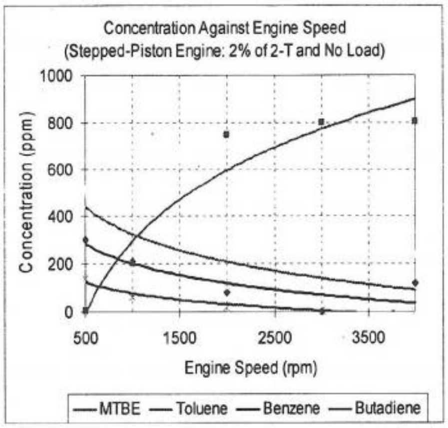

Figure 3: Stepped-piston engine with 2% of 2-T without load

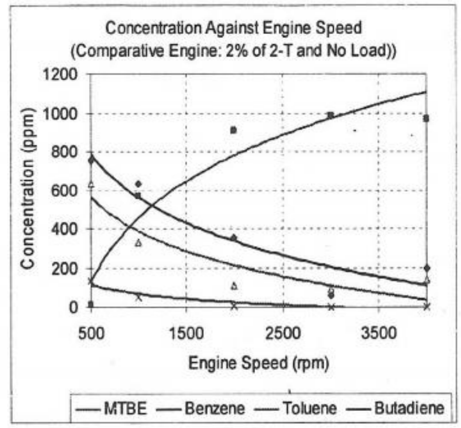

Figure 4: Comparative engine with 2% of 2-T without load

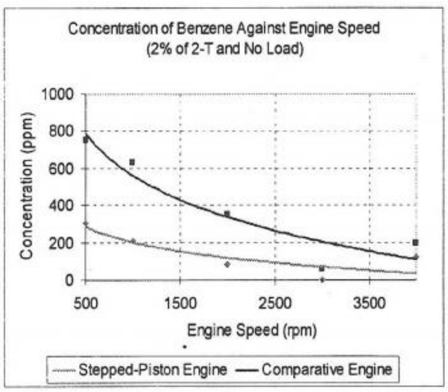

Figure 5: Concentration of benzene with 2% of 2-T and without load

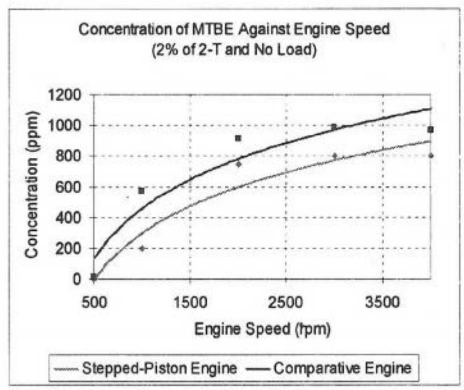

Figure 6: Concentration of MTBE with 2% of 2-T and without load

6.2 Constant Speed and Variable Load Test

At constant speed test the torque will be applied ranging from 3 to 5 Nm while the speed and percentage of lubrication will remain constant. This parameter is set to relate the pattern of species concentration with torque.

Figures 9 and 10 show the concentration of emissions for 1000 rpm and 3000 rpm with load. From both figures, it can be seen that the concentration of benzene, 1,3-butadiene and toluene are high at low load but for the MTBE is has the opposite trend. At low load, the concentrations of benzene are more compared to toluene and 1,3-butadiene. However the concentrations of toluene are negligible for 1000rpm and 3000rpm. Meanwhile for 1,3-Butadiene the concentration are nearly the same for both engine conditions.

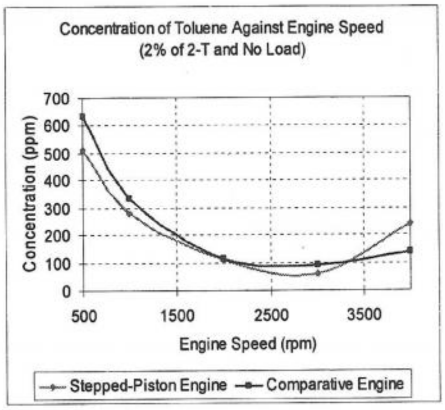

Figure 7: Concentration of toluene with 2% of 2-T and without load

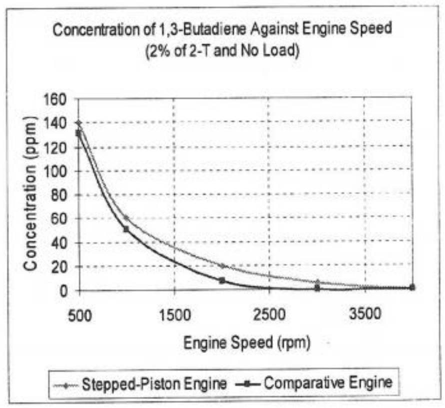

Figure 8: Concentration of 1,3-butadiene with 2% of 2-T and without load

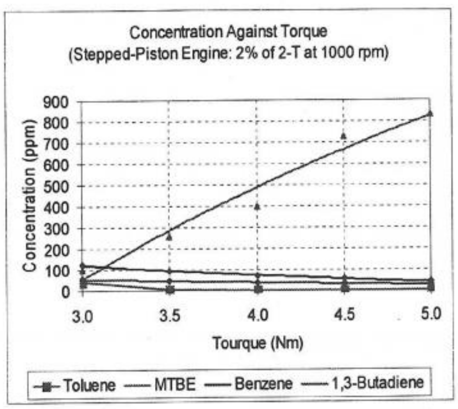

Figure 9: Stepped-piston engine with 2% of 2-T and with load at 1000 rpm

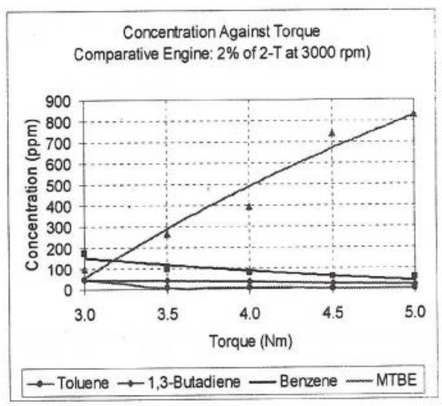

Figure 10: Stepped-piston engine with 2% of 2-T and with load at 3000 rpm

Figures 11, 12, 13 and 14 show the individual concentration of emission at 1000 rpm and 3000 rpm. The variations of emission concentration are not so obvious for the four elements. As for benzene, toluene and 1,3-butadiene the concentrations are decreasing with load increment. Meanwhile for MTBE the increasing trend is observable from Figure 12.

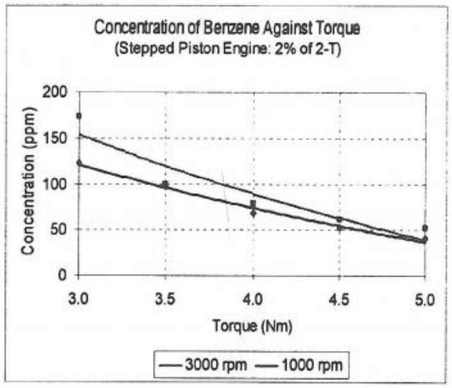

Figure 11: Concentration of benzene with 2% of 2-T and with load

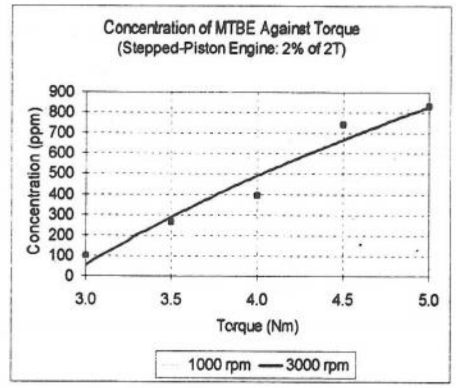

Figure 12: Concentration of MTBE with 2% of 2-T and with load

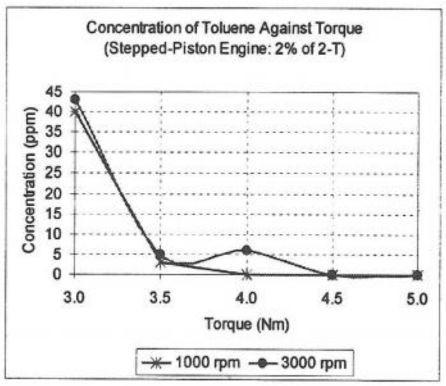

Figure 13: Concentration of toluene with 2% of 2-T and with load

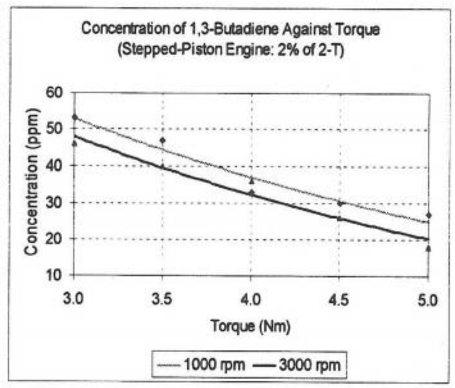

Figure 14: Concentration of 1,3-butadiene with 2% of 2-T and with load

6.3 Constant Speed and Variable Lubrication Oil (2-T) Content

At these conditions the engine will operate with varied percentage of 2-T from 1% to 5%. At these operating conditions, the speed and load will remain constant. This parameter is set to relate the pattern of species concentration with percentage of 2-T.

Figures 15 and 16 show the concentration of emissions for 1000 rpm with and without load while the percentage of 2-T varies. From both figures, it can be seen that the concentration of benzene, 1,3-butadiene, toluene and MTBE increased with the percentage of 2-T used. Engine running without load shows a high concentration of benzene and toluene compared to 1,3-butadiene and MTBE. However, at 1000 rpm with 5 Nm load, the concentration of MTBE is high.

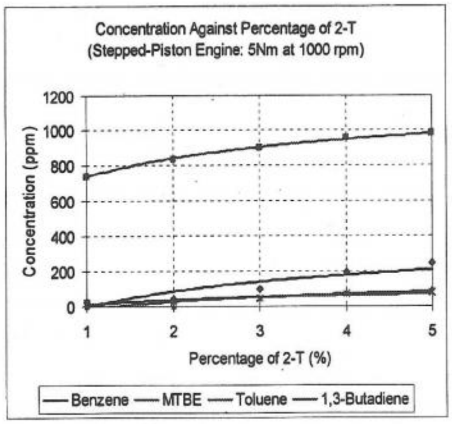

Figure 15: Stepped-piston engine at 1000 rpm with 5 Nm load

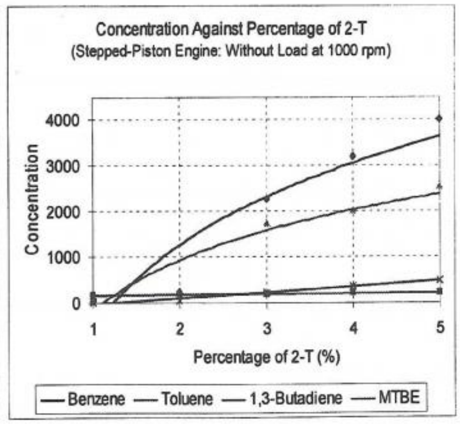

Figure 16: Stepped-piston engine at 1000 rpm without load

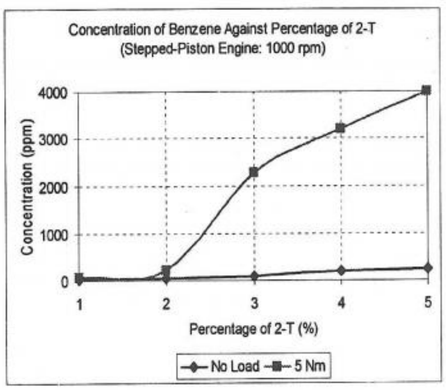

Figure 17: Concentration of benzene with variable 2-T content at 1000 rpm

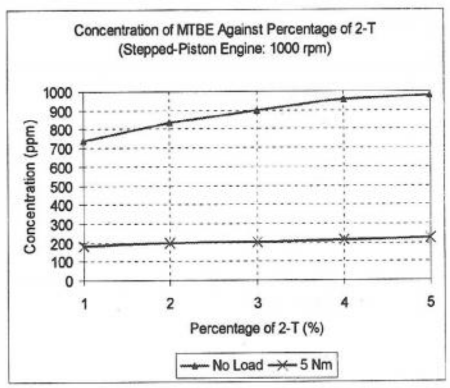

Figure 18: Concentration of MTBE with variable 2-T content at 1000 rpm

Figure 17 shows the relationship between concentration and percentage of 2-T. In general, the concentration of benzene is greater without load compared to with load condition. It can be seen, that the benzene concentration is proportion to percentage of 2-T. Between 1% - 2% of 2-T the concentration of benzene is low for both engine conditions. However, without load engine conditions, the concentration increased rapidly from 210 ppm at 2% to 2261ppm at 3%. From this point onwards, concentration increased gradually to 4000ppm. In contrast, between 2% to 5% of 2-T, the concentration of benzene rose slowly for 1000 rpm with 5 Nm load engine conditions.

Figure 18 shows the results of MTBE analysis and it revealed that the concentration of MTBE for 1000 rpm with 5 Nm load is more compared to no load conditions. The concentration of MTBE for both engine conditions is proportion to percentage of 2-T. The concentration of MTBE for 1000 rpm with 5Nm load, increased gradually from 738 ppm at 1% to 979ppm at 5% of 2-T. Meanwhile for no load engine conditions the concentration of MTBE also rose slowly.

Overall, the increment of MTBE concentration is very small compared to other three species for both engine conditions. This is because the concentration of MTBE is not much depending on the percentage of 2-T. But it depends on the load and engine speed. Meanwhile MTBE is not formed by others combinations of species, but it is formed during the combustion process due to incomplete combustion. Therefore, it can be concluded that the concentration of MTBE is not much dependent on percentage of lubrication oil but it depends on the load and engine speed.

The concentration between the percentage of 2-T and emission quantity of toluene is shown in Figure 19. In general, it shows that higher concentration of toluene occurred for no load conditions and the concentration is proportional to percentage of 2-T for both engine conditions.

The toluene concentration for no load conditions increased gradually between 1% - 2%, and increased rapidly from 280 ppm at 2% to 1740 ppm at 3% of 2-T. however from 3%, it started to increase gradually to 2018 ppm and continued to increase rapidly to 2550 ppm. Meanwhile for load conditions, toluene concentration remain constant between 1% - 2% and from this point, it increase steadily.

The correlation between the percentage of 2-T and emissions quantity of 1,3-butadiene is shown in Figure 20 . It was observed that the concentration of 1,3-butadiene are more for no load conditions compare to load conditions.

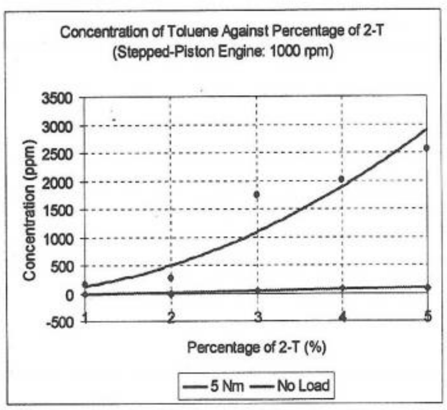

Figure 19: Concentration of toluene with variable 2-T content at 1000 rpm

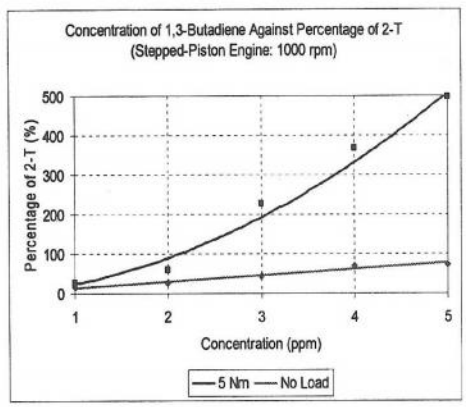

Figure 20: Concentration of 1,3-butadiene with variable 2-T content at 1000 rpm

The concentration of 1,3-butadiene for no load engine conditions increase gradually from 28 ppm at 1% to 60 ppm at 2% of 2-T. Beyond that, the concentration of 1,3-butadiene increase rapidly, reaching a peak of 496 ppm at 5%

of 2-T. Between 2% - 5% the concentration of 1,3-butadiene is proportional to percentage of 2-T. In contrast, the concentration of 1,3-butadiene for load engine conditions rise slowly from 17 ppm to 69 ppm and remain constant at 74 ppm. From Figure 20, it also shows that concentration is greater for no load engine conditions.

7.0 CONCLUSIONS

Engine testing was carried out to investigate the emission characteristics of four unregulated component which are benzene, MTBE, toluene and 1,3-butadiene. The ultimate interest is to observe these emissions emitted from the stepped-piston engine and compare it with a conventional two-stroke engine. Conclusions were drawn based on the experimental results.

Benzene was emitted under the high speed and low load conditions, because benzene is easily oxidized in a high temperature. Toluene was emitted under low loads. This is because toluene is formed under low temperature.1,3-butadiene emitted more under low speed, at this conditions 1,3-butadiene decomposes in a short time, and the exhaust gas stays much longer in a cylinder under low speed conditions. The concentration of MTBE is elevated at high speed and high load. This is because MTBE is not formed by others combinations of species, so at this conditions more air- fuel mixture goes into combustion chamber and formed during combustion process because of incomplete combustion.

Finally the concentrations for stepped-piston engine are lower for some species compared to the comparative engine at ideal engine conditions.

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