An Experimental Study on Aldehyde Emissions of a Hydrous Ethanol Fuelled Small SI Engine Generator Set

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Abstract

The objective of this study is to reveal quantitative analysis of aldehyde emissions, i.e. formaldehyde and acetaldehyde, from a modified SI engine equipped with maximum 6.5 kW generator set using hydrous ethanol. The load and engine speed of testing conditions are fixed at 4 kW and 3300 rpm, respectively. The studied parameters are 5 to 40% water contents in ethanol. The experimental results showed that BSFC for hydrous ethanol with 5 to 40% water contents is higher than gasohol about of 33 to 70%. The highest thermal efficiency occurred when used ethanol with 5 % water content (Eh95). At water content 5 and 20 % (Eh95 and Eh80), thermal efficiency is higher than that of gasohol approximately 25% and 5%, respectively. However, thermal efficiency in case of hydrous ethanol with 25 to 40 % water contents is lower than that of gasohol approximately 10 to 25%. The use of hydrous ethanol with 5 to 40% water contents (Eh95 to Eh60) can reduce 27 to 90% NO_x emissions, 75 to 83% CO emissions and 18 to 72% HC emissions while formaldehyde and acetaldehyde emissions are increased 50 to 300% and 200 to 1000%, respectively. In addition, the three-way catalytic converter can reduce NO_x emissions by 32 to 47 %, CO emission by 60 to 73%, HC by 8 to 36 %, formaldehyde by 8 to 35 % and acetaldehyde by 28 to 44 %. Therefore, the catalytic converter should be used when used ethanol as fuel.

***Keywords**:* Aldehyde, Hydrous Ethanol and SI Engine.

1. Introduction

Recently, the oil crisis and environmental pollutions are a serious problem worldwide. Continued and increasing use of petroleum fuels will cause local air pollution and the global warming problems. Therefore, many alternative fuels are interested. Bio-ethanol is an attractively alternative fuel for a spark ignition engine (SI engine). Actually, the use of ethanol as fuel in SI engine is not new concept [1]. First SI engine was designed to use ethanol as fuel.

Ethanol has several advantages. It has high octane number that is high anti-knock quality and high latent heat of evaporation. Thus the thermal efficiency of engine can be increased by increasing the higher compression ratio. In addition, the use of ethanol-gasoline blends and pure ethanol can reduce significantly CO and HC emissions in comparison to gasoline by 30-60% and up to 40%, respectively [2-5]. However, NO_x emission in case of ethanol-gasoline blends can be lower by 30% [4] and also higher by 50 % [5] as compared to gasoline.

In general, formaldehyde is produced as an intermediate product in the partial oxidation [9] of ethanol and acetaldehyde which are mainly produced from incomplete combustion of ethanol which depends on engine loads and ethanol contents [5] and oxygen concentrations [6]. As a result, the combustion of ethanol under the same operating conditions increases the formaldehyde and acetaldehyde emissions in comparison to gasoline. Formaldehyde has been classified by the EPA Group as B1, which is probable human carcinogen of medium carcinogenic hazard [10]. Acetaldehyde has been classified as B2, probable human carcinogen of low carcinogenic hazard [10]. The use of ethanol-gasoline blend has observed to increase markedly acetaldehyde by 100% to 200% [6-8] and some cases by 700% [7] and formaldehyde 15 to 50% [9]. In addition, formaldehyde and acetaldehyde contribute to the formation of nitric acid, peroxyacetyl nitrate (PAN), other smog components and ground-level ozone, which can harm lung function [7] and irritate the respiratory system [10].

In the previous works, ethanol for blend fuels has to be anhydrous ethanol, which is no water content or extremely low water content that is maximum water content by 1% (by volume) [11]. Nevertheless, anhydrous ethanol has higher cost of operation in purification process than hydrous ethanol.

From point of view of the advantages of ethanol and the economics of ethanol production, the use of hydrous ethanol with high water content for SI engine can reduce not only emission but also the operating cost of production of ethanol. For these reasons, the water content in ethanol fuel is an interesting parameter. The water contents in ethanol are expected to change working conditions of the engine and affect on tail pipe emissions.

Therefore, this study investigates the effect of water content in ethanol on emissions, especially aldehydes, from a modified SI engine equipped with maximum 6.5 kW generator set. Specific fuel consumption and thermal efficiency results are also revealed.

2. Experimental setup

2.1 Experiment apparatus

The schematic diagram of the experiment is shown in Fig. 1. Experiments were carried out on a SI engine equipped with 6.5 kW generator set. The SI engine was modified to control optimized operating condition for hydrous ethanol. The fuel injection system was controlled by an electronic control unit (ECU), which optimized the mixture equivalence ratio and ignition timing for all the tests. Technical specifications of the modified engine are described in Table 1.

Fuel consumption was recorded by continuous mass measurement, ONO SOKKI model FM-2500. The intake air pressure was measured by digital manometer, SOKKEN model PZ-77, which is located after the air filter and before the throttle valve. K-type thermocouples were used to measure the temperatures of the intake air, engine oil, exhaust gases and the catalytic converter.

Table 1 Specifications of modified engine

Modified engine	
Engine type	4-stroke overhead valve single cylinder
Displacement	389.2 cm^3
Bore x Stroke	88x64 mm
Compression ratio	10.2:1 (OEM 8:1)
Engine speed	2400-3600 rpm
Cooling system	Forced air
Fuel supply	Electrical fuel injection (OEM carburetor)

The regulated emissions, which are CO, HC and NO_x, were measured from exhaust pipe before and after catalytic converter when reach satisfying engine speed and load. The engine was operated for a sufficient time to achieve thermal stability which is checked by temperature of cylinder, engine oil and exhaust.

The schematic diagram of exhaust gas sampling for aldehyde analysis is shown in Fig. 2. For aldehyde measurement, the procedures for sampling followed the California Air Resource Board (CARB) Method No. 1004. The sampling gas was trapped by DNPH cartridge with exhaust gas flow rate of 150 ml/min for five minutes. The sampled material was diluted from the cartridges with 5 ml of acetonitrile. The solution of acetonitrile 50 µl was analyzed by high performance liquid chromatography (HPLC), Shimadzu UV-HPLC wavelength 365 nm. A mobile phase, which is HPLC grade, of 60% acetonitrile and 40% water was used in operation with a flow rate of 1 ml/min.

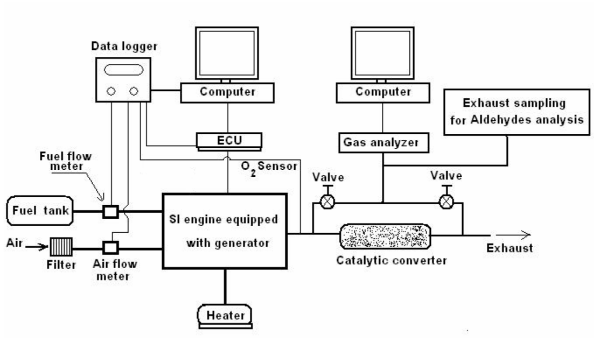

Fig. 1 schematic diagram of the experiment

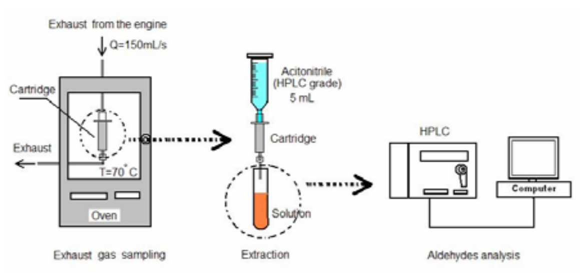

Fig. 2 schematic diagram of exhaust gas sampling for aldehyde analysis

2.2 Experimental condition

In this study, the variation of water contents in ethanol are setted as parameters. Water contents are varied between 5 to 40% v/v, to investigate the effect of water contents in ethanol. For example, the ethanol with water content of 5 % v/v or 40 % v/v is called Eh 95 or Eh 60. The experimental conditions are shown in Table 2. The engine was tested at a constant engine speed of 3300 rpm and a constant electric power output of 4 kW at stoichiometric A/F ratio (λ=1). In each tests, specific fuel consumptions, thermal efficiency and emission are measured and compared to those of gasohol octane 91 (E10), which is a mixture of 90% gasoline and 10% ethanol.

Table 2 Experimental conditions.

No.	Fuel	Water content (%)	Load (kW)	Engine Speed (rpm)	λ
1	Gasohol (E10)	-	4	3300	1
2	Eh95	5			
3	Eh80	20			
4	Eh75	25			
5	Eh70	30			
6	Eh65	35			
7	Eh60	40			

3. Results and discussion

3.1 Brake specific fuel consumption

Fig. 3 shows brake specific fuel consumption (BSFC) when used ethanol with different water contents in SI engine. To obtain the same operating condition, BSFC of all hydrous ethanol are higher than that of gasohol because heating value of ethanol fuel is reduced on adding more water. The results also show that, BSFC for hydrous ethanol increase around 33 to 70% with increasing of water content 5 to 40% (Eh95-Eh60).

3.2 Thermal efficiency

Thermal efficiency of ethanol with various water content and reference fuel are showed In Fig. 4. The results show that thermal efficiency on using hydrous ethanol is 15 to 24 % while thermal efficiency in case of gasohol is 21 %. The highest thermal efficiency is at the condition of ethanol with 5 % water content (Eh95) and gradually decreased with increased water content.

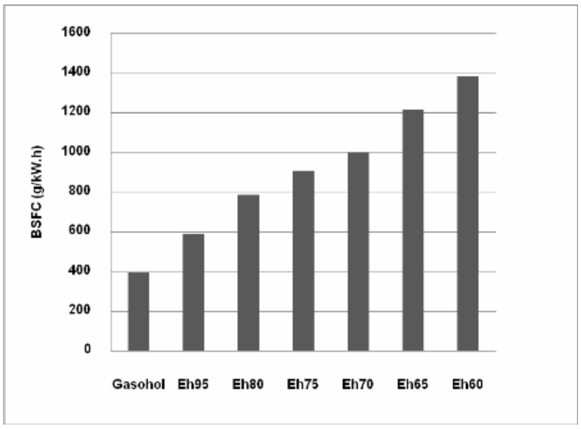

Fig. 3. Brake specific fuel consumption with various water contents in ethanol at 3300 rpm, 4 kW load and stoichiometric A/F (λ=1).

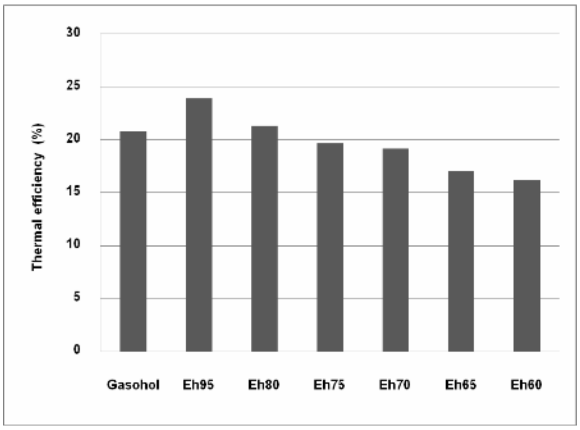

Fig. 4 Thermal efficiency with various water contents in ethanol at 3300 rpm, 4 kW load and stoichiometric A/F (λ=1).

At water content 5 and 20 % (Eh95 and Eh80), thermal efficiency is higher than that of gasohol approximately 25% and 5%, respectively. These results can be explained that the cooling effect of hydrous ethanol, which has the latent heat higher than that of gasohol, decreases the temperature of the working charge in the cylinder. The cooling effect of temperature can reduce the compression work [11], and improve volumetric efficiency and anti-knock behavior [5]. In addition ethanol has higher laminar flame speed, yielding a reduction in heat loss through cylinder wall. Hence, the thermal efficiency can be improved.

In contrast, thermal efficiency is lower than gasohol around 10 to 25% when the water content increases in the range 25 to 40 % (Eh75-Eh60). It is believed that heat from combustion is lost through water content.

3.3 Regulated emissions

NO_x emissions are illustrated in Fig 5 with 95% confidence interval. It can be seen that hydrous ethanol use can reduce NO_x emissions approximately 27 to 90% with increasing of water content 5 to 40% (Eh95-Eh60). The results are similar trend to [4]. Since hydrous ethanol has water contents and has higher latent heat than that of gasohol, it can be understood that the combustion temperature is decreased by cooling effect from evaporative process in intake stroke [4]. Moreover, heat release from combustion loses to the addition of water. These effects cause the reduction of combustion temperature which is observed from spark plug temperature as shown in Fig. 6. As a result, NO_x emissions decrease. In addition, the results showed that the catalytic converter can reduce NO_x by 32 to 47 % (Fig. 5).

In Fig. 7, CO emission is significantly lower than gasohol approximately 75 to 83% when the water content increases in 5 to 40 % (Eh95-Eh60). It can be explained that the oxygen atom in ethanol molecule enhances complete combustion. However, the addition of water content enhances incomplete combustion which caused an increase in CO value. The result also shows that catalytic converter can reduce CO emission by 60 to 73%.

The results of hydrocarbons in Fig. 8 show that the use of ethanol with 5 to 40% water content (Eh95-Eh60) can reduce significantly HC emissions in comparison to gasohol approximately 18 to 72%. Since the molecules of ethanol are polar molecules, it is not easily absorbed by engine oil layer, which is non-polar molecules, on the cylinder wall [12]. However, total hydrocarbon increases again with increasing water content of more than 25% (Eh 75). It may be explained that higher hydrocarbon emission is caused from incomplete combustion due to flame quenching effect of water mixture in cylinder. The combustion temperature is reduced which can be observed by spark plug temperature as shown in Fig. 6. Moreover, Fig. 8 showed that HC was reduced by 8 to 36 % when the exhaust passed catalytic converter.

3.4 Unregulated emissions

Fig. 9 shows formaldehyde emission from combustion of hydrous ethanol. Firstly, its trend, which has similar to total hydrocarbon trend, slightly decreases with increasing of water content 20 and 25 % (Eh80 and Eh75). It is expected that the increasing of small water contents can enhance combustion. Nevertheless, when water content is higher than 30% (Eh70), formaldehyde levels increased. It is same reason as hydrocarbon, because of quenching effect, causing incomplete combustion and formation of formaldehyde. The result also shows that formaldehyde emissions from combustion of hydrous ethanol are higher than gasohol approximately 50 to 300% when the water content increases from 5 to 40 % (Eh95-Eh60). The catalytic converter can reduce formaldehyde by 8 to 35 %.

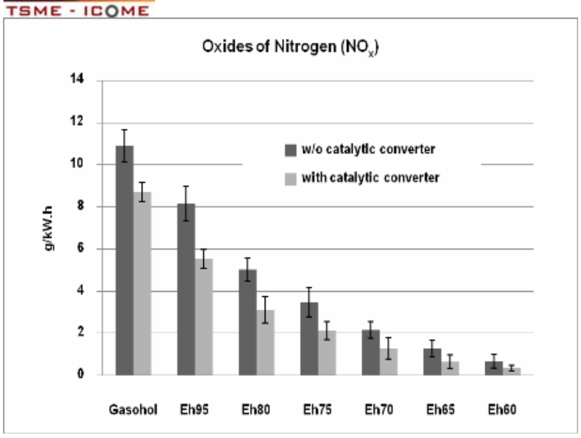

Fig. 5. Oxides of nitrogen from combustion of hydrous ethanol with various water contents at 3300 rpm, load 4 kW and stoichiometric A/F.

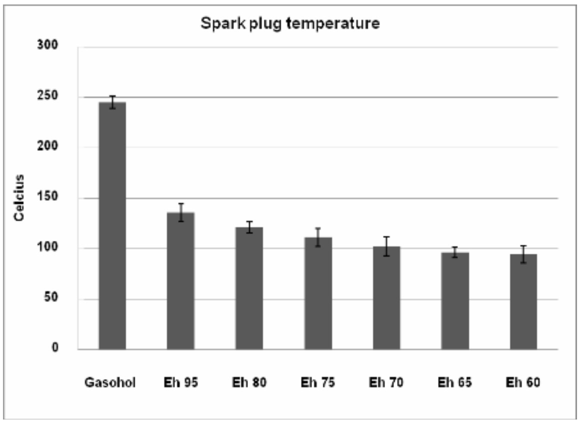

Fig. 6. Spark plug temperature at 3300 rpm, load 4 kW and stoichiometric A/F.

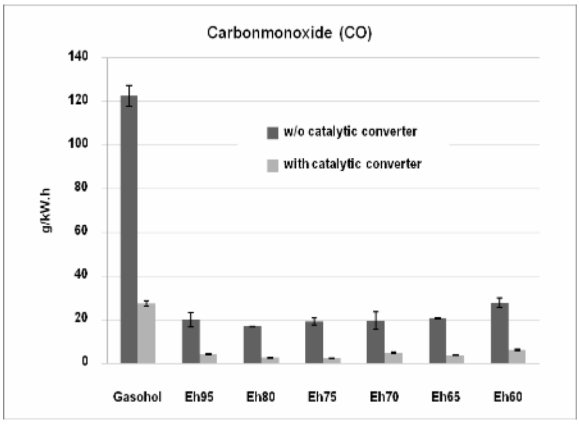

Fig. 7. Carbonmonoxide from combustion of hydrous ethanol with various water contents at 3300 rpm, load 4 kW and stoichiometric A/F.

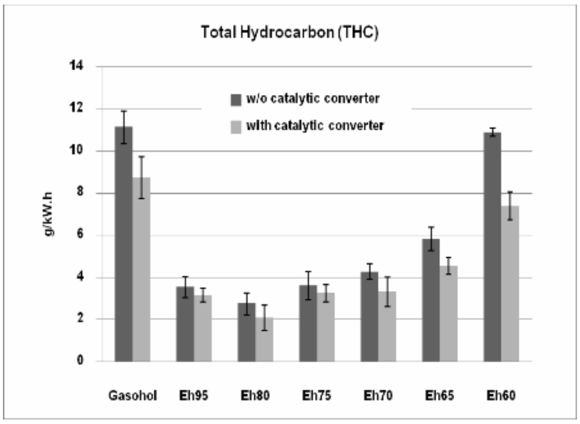

Fig. 8. Total hydrocarbon from combustion of hydrous ethanol with various water contents at 3300 rpm, load 4 kW and stoichiometric A/F.

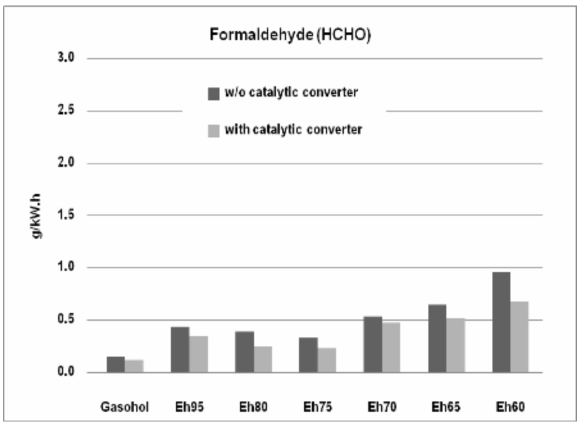

Fig. 9. Formaldehyde from combustion of hydrous ethanol with various water contents at 3300 rpm, load 4 kW and stoichiometric A/F.

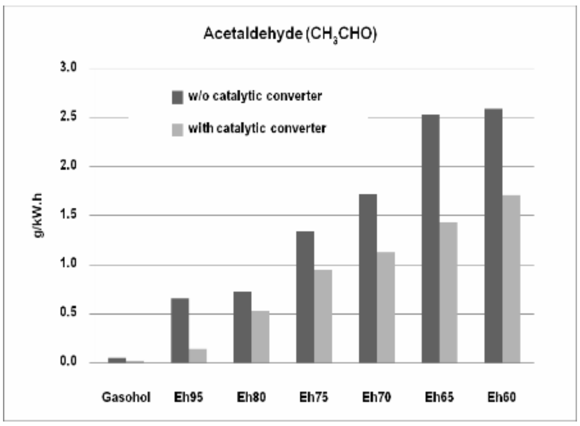

Fig. 10. Acetaldehyde from combustion of hydrous ethanol with various water contents at 3300 rpm, load 4 kW and stoichiometric A/F.

Acetaldehyde emissions are shown in Fig. 10. It is clear that acetaldehyde emissions increase as the water content in ethanol increases. It can be explained that it has low oxidation rate at high water content due to low combustion temperature. The result also shows that acetaldehyde emissions from combustion of hydrous ethanol are higher than gasohol around 200-1000% when the water content increases in 5-40 % (Eh95-Eh60). The catalytic converter can reduce acetaldehyde by 28-44 %.

4. Conclusions

This study discusses the results obtained by experiments carried out on a SI engine equipped with generator. All tests were performed at 3300 rpm engine speed, load 4 kW and λ = 1. The main conclusions are:

- BSFC for hydrous ethanol is higher than gasohol about of 33-70% with increasing of water content 5-40% (Eh95-Eh60) at the same desired operating condition.
- The highest thermal efficiency occurred when used ethanol with 5 % water content (Eh95). At water content 5 and 20 % (Eh95 and Eh80), thermal efficiency is higher than that of gasohol approximately 25% and 5%, respectively. In contrast, thermal efficiency is lower than gasohol approximately 10-25% when the water content increases more than 25%.
- The regulated emissions are reduced when hydrous ethanol is used in comparison to gasohol. The use of ethanol with 5-40% water content (Eh95-Eh60) can reduce 27-90% NO_x emissions, 75-83% CO emissions and 18-72% HC emissions.
- The unregulated emissions are increased when hydrous ethanol is used in comparison to gasohol. The use of ethanol with 5-40% water content (Eh95-Eh60) increase 50-300% for formaldehyde emissions and 200-1000% for acetaldehyde.
- For hydrous ethanol fuels, the three-way catalytic converter can reduce NO_x emissions by 32-47 %, CO emission by 60-73%, HC by 8-36 %, formaldehyde by 8-35 % and acetaldehyde by 28-44 %. Therefore, the catalytic converter should be used when ethanol is used as fuel.

It can be concluded from point of view of pollutant emission and thermal efficiency that ethanol blend with water less than 20% (Eh 95-Eh 80) can be used as the optimum fuel for SI engine. However, some interesting topic should be further studied, for example:

- The effect of water content in ethanol on engine oil durability and material corrosion of fuel system.
- Others unregulated emission, especially carbonyl group.
- The effect of catalytic converters on unregulated emissions.

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