



RECENT ADVANCES IN THE APPLICATION AND CHALLENGES OF METHANOL FUELS IN SPARK IGNITION ENGINE

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ABSTRACT

Alternative fuels on internal combustion engine (ICE) recently becomes an attention due to the concern on environment protection, needs on reducing dependency on fossil fuels and meets current stringent regulation. Methanol is one of the attractive alternative fuel due to its ability to produce from a renewable resources and it is oxygenated, therefore it has the potential to achieve better engine performance and emission in spark ignition engine. Currently, only few of research paper discuss the methanol fuel in the collective form of information including adverse effect of methanol usages and responses in spark ignition engine performance and emissions. Due to this reason, this paper will focus on the applications and challenges with recent literature data of methanol fuel specifically for spark ignition engines. The first part of this review will be discuss on the advantages and disadvantages of the application of methanol fuels. Also discuss is the published research result on the engine performance and emission using methanol-gasoline fuel blends. The second part will focus on the recent trends and challenges in the research of methanol fuels for the past ten years. The findings show further improvements need to be done on current methanol fuel in areas such as; specifying acceptable range for current gasoline engine operation, ensuring safety in storing and handling methanol-gasoline blends, and validating the long term effects of the fuel compatibility.

Keywords: engine performance, combustion characteristics, exhausts emission, methanol, alcohol-gasoline fuels, spark ignition engine.

INTRODUCTION

Demand on petroleum fuels is keep on increasing nowadays due to the phenomenal growth in the industrialization and transportation sector. Approximately about 58% of energy is consumed by transportation sector from the total of 80% fossil fuel which is the primary energy consumed in the world (Escobar *et al.*, 2009; Gill, Tsolakis, Dearn, and Rodríguez-Fernández, 2011; Nigam and Singh, 2011). Gasoline is one of the available fossil fuels for transportation sector and widely used for on-road vehicle worldwide. Increasing number of vehicles, rapid development for fuel efficiency and hybrid engine has made gasoline a continually demanding fossil fuel (Mohamad and How, 2014). Besides that, many researches also have been conducted on blending gasoline with additives to investigate the engine combustion, performance and emissions without any modification on the gasoline engine. Some of these additives are aromatics (benzene and toluene), methyl tertiary butyl ether (MTBE) and alcohols which serve as octane boosters and to increase fuel volatility in the gasoline engine (Surisetty, Dalai, and Kozinski, 2011). This ever increasing demands especially in the transportation sector has caused several problems including emission of harmful pollutants that can cause human health problem and global warming.

Therefore, interest on searching alternative fuels for transportation sectors has significantly grown recently due to the concern on environment pollution, reducing reliance on current existing fossil fuels and stringent regulations from the combustion of the fuel. Some alternative fuel is introduced for small scale or specific use only, while other take alternative fuel as a potential substitutes for existing fuels. Number of research paper published on alternative fuel also has grown exponentially

for the past 20 years as per shown in Figure-1 (Dutta, Daverey, and Lin, 2014). Meanwhile, Figure-2 shows energy densities and weight efficiency for the available energy sources on transportation sector such as fossil fuels, biofuels and batteries (Connolly, Mathiesen, and Ridjan, 2014). It indicates that fossil fuels having energy densities approximately 85 times larger and biofuels were having around 40 until 70 times larger compared to batteries. In addition, all conventional fossil fuels and biofuels have a much higher difference in weight efficiency compared to batteries.

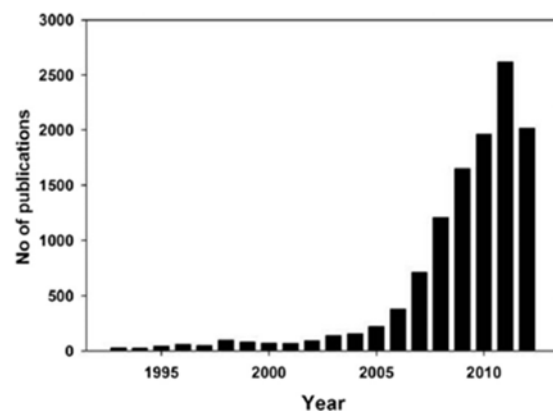


Figure-1. Statistic of paper had being published related to alternative fuel for the past 20 years (Dutta *et al.*, 2014).

The result from the research on alternative fuel for transportation vehicles has introduced some possible alternative fuel such as biodiesel, methanol, ethanol, butanol, synthetic natural gas (SNG) and many more.



Current available alternative fuel should be environmental friendly, able to produce in large quantity, low cost and capable to apply with or be added to gasoline fuel in order to have better engine performance and lower emissions. Based on these criteria, methanol can be considered as one of the attractive alternative fuels for transportation sectors because it is oxygenated and renewable. Methanol

contains oxygen that enables the fuel to combust more completely which boost combustion efficiency and reduces air pollution. Methanol also have higher energy content compare to other alternative fuels such as liquefied petroleum gas (LPG) or compressed natural gas (CNG) with minor modifications on the fuel system (Ramadhas, 2010).

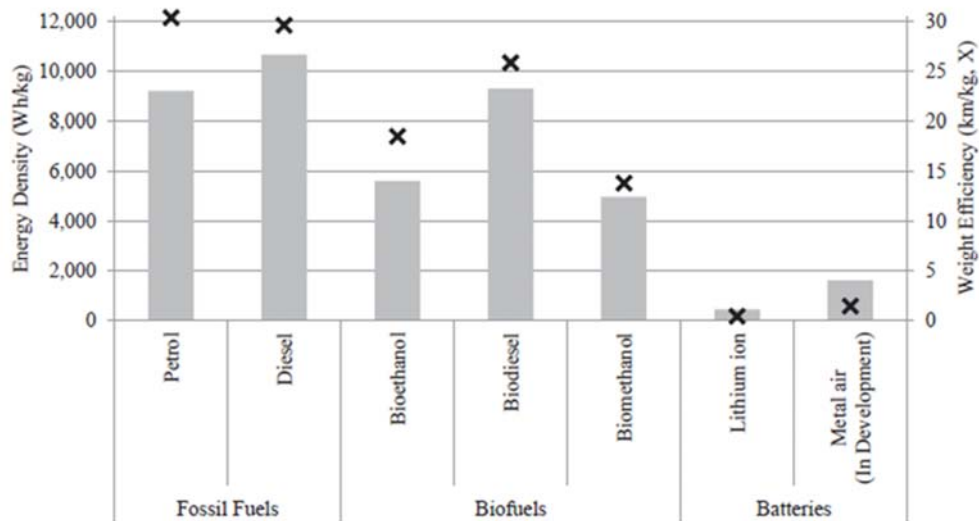


Figure-2. Selection of fossil fuels, biofuels and batteries on energy density and weight efficiency (Connolly *et al.*, 2014).

In terms of production, methanol can be produce from a wide variety of renewable sources such as gasification of wood, waste products and agricultural by-products (Al-Farayedhi, Al-Dawood, and Gandhidasan, 2002). In addition, methanol also able to produce from alternative fossil fuel based feed stocks such as natural gas and coal (Bromberg & Cheng, 2010; Harrington and Pilot, 1975). Either one production is considered feasible in the context of alternative fuels. However, methanol production from coal in long term is crucial due to coal is the most abundant energy resource in the world that able to meet future fuel demands (Harrington and Pilot, 1975). In terms of the application on internal combustion engine, methanol can be applied with little modification for material compatibility and have better engine performance compared to gasoline (Yuen, Villaire, and Beckett, 2010). Besides application of methanol fuel in internal combustion engine, methanol also being used as conversion to dimethyl ether, ingredient for biodiesel production and hydrogen for the fuel cell vehicles (Ramadhas, 2010). There are lot of researches and published works related to methanol especially on the drawbacks of methanol, its response on spark ignition engine performance and emissions, but only some works are found related to the methanol fuels in the collective form of information. In this paper, it will mainly discuss on the methanol fuel application in spark ignition engine including its benefits, drawbacks and solutions to overcome the problems arise. The next part of this paper

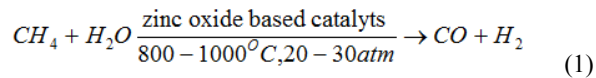
will discussed the trends and challenges in recent research on methanol fuels for the past ten years.

METHANOL-GASOLINE FUEL; TRENDS AND CHALLENGES

Methanol received public attention due to its low-polluting future fuels and considered as highly efficient through their lean operating ability (Ingamells and Lindquist, 1975; Liao, Jiang, Cheng, Huang, and Zeng, 2006). This is due to methanol has a higher octane number, oxygen ratio, flammability limit and low carbon to hydrogen ratio compared to gasoline. Methanol also is the most common alcohol fuels that was used as a fuel additive or alternative with gasoline in the spark ignition engine because they are fluid and have several physical and combustion properties similar to gasoline (Abu-Zaid, Badran, and Yamin, 2004; Hu, Wei, Liu, and Zhou, 2007). In terms of production of methanol, it involves generation of syngas by steam reforming reaction and water-gas reaction. Syngas can be produced from both fossil fuels (natural gas, crude oil) and renewable resources (municipal solid waste and wood). The final stage to form methanol is the methanol synthesis reaction in the presence of zinc oxide based catalysts and high temperature of 800 - 1000 °C (Salvi, Subramanian, and Panwar, 2013). Refer to equation (1) - (3) for the reaction involved for the methanol production via synthesis gas.



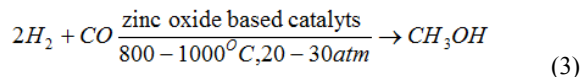
Steam reforming reaction:



Water-gas shift reaction:



Methanol synthesis reaction:



In terms of methanol fuel properties, it has higher heat of vaporization which gives fuel conversion efficiency. It enables to cool the air entering into engine and increase the volumetric efficiency with the power output compared to gasoline (Bilgin and Sezer, 2008; Hsieh, Chen, Wu, & Lin, 2002). These cooling effects also enable to increase knock resistance on the engine operation. However, having high latent heat of vaporization has caused methanol to give a cold start problem to the engine and greater emissions of NO_x at very lean operation condition (Harrington and Pilot, 1975; Ingamells and Lindquist, 1975). It is suggested that using fuel blends with low content of methanol is mostly practical for engine operation to overcome cold start problem (Abu-Zaid *et al.*, 2004; Gorse *et al.*, 1992; Lin and Chao, 2002). An additional factor that makes methanol attractive is the oxygenated atoms in their molecular compounds which provide significant reduction in the CO and HC emissions, but it may be adversely affect NO emissions. In terms of combustion characteristics, methanol fuel have high flame speed that allows qualitative load control by varying amounts of EGR or mixture richness. Methanol also is less hazardous than gasoline in terms of fire safety which makes it a suitable choice for racing fuel in the US for many years (Vancoillie *et al.*, 2013).

However, usage of methanol will also have some drawbacks on the application of methanol fuel in spark ignition engine. Methanol well known of its corrosiveness, highly toxic, colorless, odorless and tasteless (Ingamells & Lindquist, 1975; MacLean and Lave, 2003). This is due to the presence of oxygen which having high atomic weight, its energy density is lower than base gasoline. The corrosion problem can be avoided by not using materials from copper, brass, aluminum or rubber materials for the fuel delivery system. It is advisable to use fluorocarbon rubber as a replacement for rubber (Hsieh *et al.*, 2002). Methanol also has high volatility rate which increase in aldehyde emissions and cause phase separation. Methanol volatility also cause increase in Reid vapor pressure which will effect in giving high temperature in the combustion cylinder and drivability problems such as vapor lock. In order to avoid phase separation, only blend the methanol and gasoline at the service pump station in order to

prevent phase separation in the fuel distribution system. In another approach, many research was conducted such as fuel reforming, fuel heating, intake air heating, blend fuel and supplementary fuel in order to overcome volatility of methanol (Liao, Jiang, Cheng, Huang, and Wei, 2005; Prieto-Fernandez, Luengo-Garcia, and Ponte-Gutierrez, 1999; Yanju *et al.*, 2008).

SPARK IGNITION ENGINE PERFORMANCE AND EMISSION TEST

Many researchers has studied the influence of methanol fuel especially on engine performance and emissions. However, need to take note that results obtained can be different from each other due to different test conditions and engine technologies being used in the experiments. Liu *et al.* (Liu, Cuty Clemente, Hu, and Wei, 2007) have used gasoline and methanol-gasoline blends as fuel on a three-cylinder experiment engine. They have added methanol at the volumetric rates of 10%, 15%, 20%, 25% and 30% to gasoline. According to the obtained experiment results, it has been seen that the increasing of methanol ratio in the gasoline has caused the decreasing of engine torque and power and increasing of BTE. Especially it has been determined while the first study emissions (HC, CO and NO) have decreased; the formaldehyde and methanol emissions have increased significantly.

In another study (Szybist *et al.*, 2010), combustion and emission characteristics of methanol-gasoline blends was further investigated using three cylinder port fuel injection (PFI). The results shown that when volume of methanol percentages increase, the flame development and combustion period is shortened and indicated mean effective pressure increases during first 50 cycles. With some modification done on the engine in order to study engine emission during cold start and warm up, the result shown that hydrocarbon (HC) gives 40% reduction and carbon monoxide (CO) gives 70% reduction when fuelled with 30% methanol volume in the blends. In addition, there is increase in exhaust gas temperature at 140°C after 200s operation started compared with base gasoline.

Investigation also have been performed on blending only low alcohol content(methanol) with gasoline to investigate its effect on spark ignition engine performance and exhaust emission (Ahmed; Yanju *et al.*, 2008). The results shown that as the volume percentage of blending is increasing, the emitted regulated emission is decreasing especially on carbon monoxide (CO) and Oxides of Nitrogen (NO_x). By increasing the methanol percentage in the blends, the brake power and brake thermal efficiency will also increase due to higher cylinder temperature. Eyidogan *et al.* (Eyidogan, Ozsezen, Canakci, and Turkcan, 2010) have experimentally analyzed the effects of the unleaded gasoline, ethanol-gasoline and methanol-gasoline blends at the low ratios on the engine performance, combustion characteristics and exhaust emissions. According to the results obtained from chassis dynamometer, it has been observed that the usage of blend fuel has increased the BSFC and the cylinder gas



pressure (CGP) and heat release rate (HRR) have started to rise earlier. Also, it has been determined that with the usage of alcohol mixtures, the exhaust emissions have also decreased.

In another study was performed an experiment engine that having low efficiency, single cylinder and variable compression ratio, the effects of methanol usage on the performance and emissions have been analyzed (Çelik, Özdayan, & Alkan, 2011). The compression ratio has been increased from 6:1 to 10:1 and the studies made with methanol at high compression ratio have been compared with the gasoline study realized at original compression ratio (6:1). According to the obtained data, it has been determined in the study with the methanol fuel that while the engine power and CO, CO₂ and NO emissions have decreased, brake thermal efficiency (BTE) and HC emission have increased. Together with the increasing of the compression ratio, while engine power, BTE and CO₂, NO_x, and HC emissions have increased, it has been observed that BSFC and CO emissions have decreased.

Ozsezen *et al.* (Ozsezen and Canakci, 2011) have examined the effects of usage of the gasoline and low ratio ethanol-gasoline and methanol-gasoline blends as fuel on a vehicle having a four cylinder gasoline engine on the vehicle performance and exhaust emissions. According to the results of the experiment made in the chassis dynamometer, a slight increase has been observed in the wheel power and BSFC in the alcohol-gasoline blends when compared to the gasoline study. Pourkhesalian *et al.* (Pourkhesalian, Shamekhi, and Salimi, 2010) studied the effects of gasoline, and alternative fuels including hydrogen, propane, methane, ethanol and methanol to understand the performance and emission characteristics of an SI engine using the fuels. According to the results, the engine power and the emissions of CO and NO_x decreased, and fuel consumption increased when pure ethanol and methanol were used instead of gasoline. In another study (Price, Twiney, Stone, Kar, and Walmsley, 2007), the effects of blending methanol and ethanol with gasoline on unburned hydrocarbon and its particulate emissions were examined in a spray guided direct injection engine. The results were that the particulate emissions had decreased with E85, and had increased with M85 for stoichiometric air fuel mixtures. Nevertheless, the highest increase of unburned hydrocarbon emission was observed with using E85, and M85 compared to gasoline.

Cay *et al.* (Çay, Korkmaz, Çiçek, and Kara, 2013) theoretically investigated the effects of methanol fuel on the performance and exhaust emissions. The results showed that the emission characteristics improved with the use of methanol compared with the gasoline. Knocking combustion under various engine operating conditions in a high compression ratio SI methanol engine were investigated theoretically by Zhen *et al.* (Zhen, Wang, Xu, and Zhu, 2013). The results demonstrated that it could not fully put down engine knock only by retarding spark timing methods because of the high Compression Ratio, with the increase of EGR (exhaust gas recirculation)

rate, the knock intensity was found to be greatly suppressed and the peak pressure was reduced.

INFLUENCE OF METHANOL ON ENGINE COMBUSTION PROCESS

For the combustion process, there are two common areas that always related and give valuable information which are heat release rate and peak cylinder pressure. These parameters will indicate how the combustion of fuel affects the engine design, fuel injection system and engine operating condition. Investigation done by (Hu *et al.*, 2007) shows that rapid burning phase was reduces and start of combustion (SOC) was advances with the addition of methanol to gasoline. Besides that, the methanol-gasoline blends also recorded high peak cylinder pressure compare to base gasoline (Hu *et al.*, 2007; Liu *et al.*, 2007). In addition, high engine speeds also recorded advanced start of combustion due to rapid burn phase and addition of methanol (Liu *et al.*, 2007). Another same experimental done also show that peak pressure cylinder increases as the methanol concentration in the gasoline blends is increases (Yanju *et al.*, 2008). The blends of M85 shows advanced in both combustion duration and ignition delay by CA of 5-6° and 4-5° each compared to gasoline (Yanju *et al.*, 2008).

Experimental work has been carried out on the effects of the base gasoline, methanol-gasoline and ethanol-gasoline blends to the combustion characteristics, engine performance and exhaust emissions (Eyidogan *et al.*, 2010). The results obtained from chassis dynamometer shows that cylinder gas pressure and heat release rate has increase earlier for blended fuel compare to base gasoline. Besides that, combustion characteristics of methanol at lower blending ratio have also been investigated (Fan, Xia, Shijin, Jianhua, and Jianxin, 2010). The results shows that no significance variation in cylinder pressure and heat release rate with the increase of methanol ratio with gasoline.

Investigation also has been performed on the effects of optimal injection and ignition timings on performance and emissions from the usages of methanol in spark ignition engine (Li, Gong, Su, Dou, and Liu, 2010). The result shows maximum in-cylinder pressure and maximum heat release rate was obtained in the optimal injection and ignition timings with engine speed of 1600 rpm and full load condition. Investigation by A.K. Agarwal *et al.* (Agarwal, Karare, and Dhar, 2014) using 10% and 20% methanol blended with gasoline in spark ignition transportation engine and compare with baseline gasoline. The results shows that only minor difference in cylinder pressure and heat release rate started late for gasohol blends with peak of heat release rate were wider compared to gasoline. Another experimental analysis done by using ultralow sulfur gasoline with methanol blends were tested on multipoint port injection gasoline engine (Geng, Zhang, and Yang, 2015). The result shows that the heat release rate and cylinder gas pressure increase and happen earlier with the present of methanol fuel.



CURRENT RESEARCH AND POTENTIAL OF METHANOL FUEL

Recent development studies of alcohol application especially on methanol present a wide range of outstanding improvement which adds difficult challenge for new concepts. Besides than application of methanol in gasoline blends, other recent research on methanol are

blending diesel with methanol, introduction of dimethyl ether, involvement in the ingredient of biodiesel production and application in fuel cells. Figure-2 shows the published research paper for the past ten years related on the usage of methanol as an alternative fuel. This figure indicates that methanol receives more attention for transportation and generation sectors.

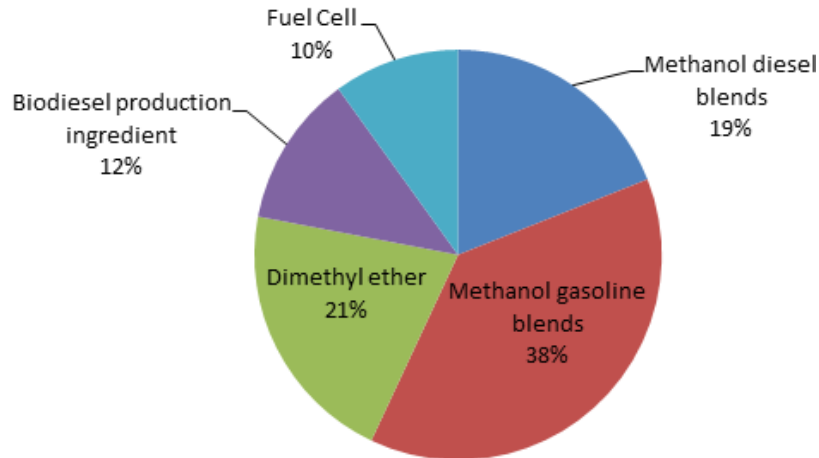


Figure-2. Number of published paper related to methanol for the past 10 years (based on literature survey by using the ISI Web of Knowledge on August 2015).

Methanol - diesel blends

Due to separation issues, methanol and diesel fuel is difficult to mix together as a diesel engine fuel. However, according to Shi *et al.* (Shi, Zhao, Fu, Wang, and Sun, 1983) methanol – diesel blends can give good performance when not more than 30% volume of methanol blends in the fuel. In the same time, having maximum amount of methanol mass fraction by 20% by weight can improve combustion characteristics (Huang *et al.*, 2004). There is precaution step need to be taken care especially in the design of the fuel system of the engine due to its corrosive nature in methanol – diesel blends. Moreover, researchers need to pay more attention to this fuel due to its ability to forms aldehyde compound and forms a strong acid from the burning of methanol (Tzeng, Lin, and Opricovic, 2005).

Dimethyl ether

In general, dimethyl ether (DME) is the product from synthesis gas through methanol synthesis and methanol dehydration which known as two-step process (Jia, Tan, & Han, 2006). It known as ultra clean fuel and highly desirable alternative fuel due to its ability to effectively reduce emission and particulate matter (Arcoumanis, Bae, Crookes, & Kinoshita, 2008; Semelsberger, Borup, & Greene, 2006). DME can be use in diesel engines, power generation, households and other purposes. At the same time, more attraction and interest have being developed on the research of DME synthesis and its utilization due to huge market potential (Farsi, Eslamloueyan, & Jahanmiri, 2011; Kiss & David, 2012). DME have high cetane number and positive combustion

characteristics which make it a practical fuel for diesel engines. Besides that, DME also blends well with gasoline which applicable for electrical generators or internal combustion engine.

Biodiesel production ingredient

Methanol will play a role in a transesterification process involving reaction with large variety of animal fats and vegetable oils to produce biodiesel. It is known that biodiesel can blended with regular diesel oil in any proportion without major problems (Olah, 2005). Therefore, many of the products derived from methanol such as DME and biodiesel can act as replacement for diesel fuel with minor modification on the diesel engine and fuel system (Olah, 2005).

Fuel cell

The recent advancement in fuel cell was using methanol for their production and known as direct methanol fuel cells (DMFC). The role of methanol in direct methanol fuel cells (DMFC) is when air is directly oxidized by methanol to form carbon dioxide (CO₂) and H₂O while producing electricity (Olah & Prakash, 2012). Moreover, DMFC also function as a system that being developed to replace battery for future portable power market. Interestingly, there will be no NO_x emissions from the vehicle due to ability of DMFC to breaks methanol into oxygen and hydrogen directly without require partial oxidation or steam reforming (Ramadhas, 2010). Thus, fuel cell can be defined as the best alternatives for transportation field on internal combustion engine.



CONCLUSIONS

Research on alternative fuels has been vitally important for quite some time. In the search on alternative fuel for transportation vehicles, engine constraint, economic issues and environmental concerns must be considered in developing sustainable and viable fuel. Methanol fuel is one the attractive fuels for the gasoline engine due to its ability to produce from renewable sources and it is oxygenated fuel. Better engine performance, improve combustion characteristics and reduction of emissions was recorded when using methanol - gasoline blends due to improvement in fuel properties. Meanwhile for the past ten years, methanol - gasoline fuel has become the most published research work compared to other usage of methanol fuel such as methanol - diesel blends, ingredient to biodiesel and dimethyl ether production and application in the fuel cell vehicles. Corrosion is the main problem faced by methanol - gasoline fuels on internal combustion engine. However, this problem can be overcome with simple modification to the vehicles or adding additives to improve fuel properties of alcohols. Further investigations should be carried out on the current existing methanol - gasoline fuels in order to have improved engine performance and reducing emission. Some of the area of improvement needs to investigate on methanol - gasoline fuels are its fuel properties and combustion process. This valuable information will help future researchers to understand and to studies the details on the nature of combustion process of methanol - gasoline fuels that related to the fuel properties of methanol. Improvements also need to be done on the current resources and technologies in order to meet and satisfy the fuel requirement of internal combustion engine.

ACKNOWLEDGEMENT

The authors of this review paper would like to express their sincere gratitude to Universiti Teknologi MARA (UiTM) under scheme of Tenaga Pengajar Muda (TPM) on this research.

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