EFFECT OF ALCOHOL ADDITIVES ON DIESEL ENGINE PERFORMANCE AND EMISSIONS

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Abstract

Alcohols have been used as an additive to diesel fuel. Two methods of alcohol addition have been considered: blending and fumigation. The effects of both methods on the performance and emissions of diesel engine have been studied and compared. The analysis was based on the fuel injection and combustion characteristics derived from indicator diagrams. The pros and cons of both methods have been emphasized and the recommendations of their application provided.

Keywords: *diesel engine, blending, fumigation, performance, emission*

1. INTRODUCTION

Diesel engines are widely used in transportation and industry due to their higher efficiency, durability and better economy than spark-ignition engines. Main regulated pollutants from diesel engine exhaust are nitrogen oxides (NO_x) and particular matter (PM) (Heywood, 1988). Several studies revealed that diesel engine PM emissions are the major cause of human respiratory tract and cardiovascular diseases. In addition to this, heavy fossil fuel consumption is leading towards the depletion of global oil reserves and becoming a serious problem to be dealt with. Much effort is being made globally in this regard for the adoption of alternate clean energy and sustainable fuel technology to decrease reliance over fossil fuels and to mitigate harmful emissions. Use of oxygenated fuels such as alcohols has recently become an important and vital method to substitute fossil fuels and to control the degrading environment by decreasing the PM, NO_x and greenhouse gas emissions from diesel engines.

Alcohols are used as a supplementary fuel with baseline fuels; use of pure alcohol requires modifications of the engine design. In order to avoid engine design modifications and to use alcohols in existing in service engines, dual fuel techniques are used. Addition of alcohols can be done by different techniques such as blending, fumigation, alcohol-base fuel emulsion and dual injection. Blending and fumigation are the most commonly and widely used techniques. It has been found that the method of alcohol addition significantly affects the engine combustion, performance and emission characteristics.

The goal of this paper is, based on the published research, to study, analyze and compare the effects of alcohol blending and fumigation on the performance and emissions of diesel engine.

2. ALCOHOLS AS A FUEL

Alcohols are considered as potential alternative fuels for IC engines because of their comparable fuel properties with that of baseline fuels (diesel, gasoline) which allows their usage in existing in service engines without or with minor modifications. Alcohols, as other oxygenated fuels, promote complete combustion and reduce emissions of PM, carbon monoxide (CO) and unburned hydrocarbons (HC). It has been found that lower viscosity of alcohols provides an easy injection and atomization with the air in the case of alcohol fumigation. The high heat of vaporization of alcohols produces cooling effect increasing air density and mass flow rate. These increase the volumetric efficiency and reduce compression work. During the combustion process, the high heat of vaporization of alcohols decreases peak cylinder temperature and results in the reduced NO_x emissions (Yano et al., 1983; Song et al., 2008). Physicochemical properties of primary alcohols are given in comparison with those of diesel fuel in Table 1.

Table 1. Comparison of properties of lower alcohols with those of diesel fuel (Kumar et al. 2013)

Property	Methanol	Ethanol	Butanol	Diesel
Density at 20ºC, kg/m^3	0.789	0.785	0.810	0.829
Cetane number	3.8	8	25	40-55
Heat of vaporization, MJ/kg	1.20	0.92	0.43	0.23-0.60
Lower heating value, MJ/kg	20.1	26.9	33.1	42.8
Boiling point, ºC	65	78	118	187-343
Flash point, ºC	12	13	35	74

2.1 Methanol vs. Ethanol vs. Butanol.

Primary alcohols (methanol, ethanol and butanol) are the most common and widely used alcohols in the internal combustion engines. According to the properties mentioned in Table 1, among these fuels the methanol has the lowest heating value which results in higher specific fuel consumption than the other alcohols. Methanol and ethanol when blended with diesel fuel reduce the cetane number (CN) of the blends, which result in the increased ignition delay and retarded start of combustion. Cetane improvers can be used to decrease ignition delay and to advance the start of combustion. Moreover, due to the polar nature of methanol, it is immiscible in diesel fuel. Certain additives may be used to make methanol-diesel stable blends. Miscibility problems of methanol with diesel fuel can be ignored by using the fumigation technique of alcohol addition. Ethanol with little water emulsions can be used with diesel fuel without any immiscibility problems. Flash point of methanol and ethanol is much lower than the diesel fuel and contains higher vapor formation potential in limited spaces; therefore extra safety precautions are required during their treatment and handling. Ethanol can react with rubber and leads to clogging inside the fuel pipe. However, this problem can be resolved by replacing the simple rubber fuel pipe with the high temperature and chemical resistant rubber pipe i.e. fluorocarbon rubber pipe. Butanol is considered as the most promising and attractive among these primary alcohols because of its superior properties. Due to the longer carbon chain than lower alcohols, butanol blends with baseline fuel (diesel, biodiesel) can be made at any concentration and does not cause any miscibility issues. Higher flash point of butanol makes it safer and it is less corrosive than other lower alcohols. In terms of combustion properties, heating value of butanol is higher than that of other lower alcohols, which provides improved specific fuel consumption. Cetane number of butanol is higher than lower alcohols which provide shorter ignition delay than that of methanol and ethanol.

3. TECHNIQUES OF ALCOHOL ADDITION

Alcohols can be added to the diesel engine as a supplementary fuel by different techniques such as blending, fumigation, alcohol-base fuel emulsion and dual injection. In blending mode, alcohol and baseline fuel are premixed and injected into the cylinder. Whereas in fumigation mode, alcohol is injected into the inlet manifold and mixed with entering air. In alcohol-base fuel emulsion method, an emulsifier (chemical additive that stabilizes emulsions) is used for the mixing of fuels to avoid immiscibility and separation. In dual injection method, a separate fuel injection system is needed for the operation of the engine. Among these techniques, blending and fumigation are the most common and widely used methods of alcohol addition.

3.1 Alcohol Blending

In blending mode, alcohol is premixed with the baseline fuel (diesel, biodiesel) in a specific percentage and injected into the cylinder at the end of compression stroke. In this method large amount of alcohol cannot be added to the diesel fuel due to poor miscibility of alcohols-diesel blends. To overcome the immiscibility and phase separation issues, extra additives are required for the formation of the stable blends. However, use of these additives causes reduction in the amount of energy supply to the engine, and as a result, less amount of alcohol can be used on an energy basis in blending mode

as compared to the fumigation mode (Ecklund et al., 1984). Alcohol blending is the most commonly used technique because not even a minor engine modification is required in this method, which makes it a viable mode of alcohol addition for already in service diesel engines.

3.2 Alcohol Fumigation

In fumigation mode, alcohol is added to the air entering the inlet manifold through injection (Cheng et al. 2008) or through carburetion (Chauhan et al. 2011). Fumigation by carburetion has a drawback of increased flow resistance in the inlet manifold (Chauhan et al. 2011). That is why, fumigation by injection is commonly used, separate fuel delivery lines and control system are required in this method. In fumigation, alcohol is atomized and then mixed with the entering air, which decreases the temperature of the air-alcohol mixture and increases its density, as a result, a large amount of air-alcohol mixture can be delivered and more power can be obtained from the engine. Since alcohol is mixed with the intake air, no miscibility problems occur and hence no extra additives are required in alcohol fumigation. As discussed earlier use of additives decreases the amount of alcohol energy supply to the engine, thus fumigation provides almost double (50%) the amount of alcohol supply on an energy basis than the blending mode (25%) (Ecklund et al., 1984). This means, in fumigation, more quantity of baseline fuel can be replaced with the alcohols as compared to blending mode, which makes fumigation an attractive and potential option of alcohol addition.

4. EFFECTS OF ALCOHOL BLENDING ON DIESEL ENGINE PERFORMANCE AND EMISSIONS

Blending of oxygenated fuels such as alcohols with baseline fuel (diesel, biodiesel) is being considered worldwide as a potential solution of controlling harmful emissions as well as to fulfill the increasing global energy demands. Various studies have been done in this regard, to investigate the performance and emissions of the diesel engine. These studies proved alcohol blending to be useful in reducing some diesel engine emissions with satisfactory engine performance. The studies showing the effects of different alcohol-baseline fuel (diesel, biodiesel) blends on the diesel engine performance and emission characteristics are discussed below.

4.1 Effects of Methanol Blending

Huang et al. (2004) investigated the combustion characteristics of a CI engine operating on diesel–methanol blends and heat release analysis was carried out. It was found that by increasing the methanol mass fraction in the blend, the rate of heat release in the premixed combustion phase increases and, on the other hand, it shortens the duration of mixing-controlled combustion. Ignition delay was found to be increased with the increasing methanol mass fraction and this trend was more obvious at low engine loads and high speeds. The premixed combustion duration showed little variation and total combustion duration decreased as the methanol mass fraction increases. The heat release curve moved towards the top dead center (TDC), peak cylinder pressure and the maximum rate of pressure rise, all increased as the methanol fraction increased in methanol-diesel blends.

Huang et al. (2005) investigated the effect of the methanol-diesel blends on the performance and emissions characteristics of diesel engine at different fuel injection timings. It was found that the fuel conversion efficiency of the engine increases and brake specific fuel consumption (BSFC) decreases with advancing injection timing. For methanol-diesel blends, the NO_x emissions were increased with the advanced injection timing, although the NO_x emissions were decreased with increasing the amount of methanol in the blends for specific fuel injection timing. It was found that, at high engine loads, CO emissions were decreased by retarding the fuel injection timing, while at medium and low loads, the CO emissions showed a slight variation with fuel injection timing. In general, CO emissions were observed low for methanol-diesel blends. Unburned hydrocarbon emissions of the methanol-diesel blends were not affected significantly by the fuel injection timing. The smoke opacity was decreased with the advanced fuel injection timing.

Sayin et al. (2010) used 5% and 10% of methanol-diesel (M5, M10) and ethanol-diesel blends (E5, E10) and investigated the performance and emission characteristics of a direct-injection (DI) diesel engine. Experimentation was carried out at fixed torque and engine speeds of 1000 and 1800 rpm. Dodecanol was added to overcome the immiscibility of the blends. It was found for the blended fuel that smoke, CO and HC emissions were decreased whereas NO_x emissions were increased as compared to those of neat diesel fuel. Due to the lesser heating values of alcohols, BSFC of the blended fuel has been increased. The increase in BSFC was higher for the methanol blends than that of the ethanol blends. Fuel conversion efficiency of the blended fuels showed a decreasing trend with the increasing mass fraction of alcohols. This decline in efficiency was more obvious for methanol blends as compared to ethanol.

Zhang et al. (2012) studied the combustion and emissions characteristics of a turbocharged diesel engine operating on diesel-methanol blends with different additives. It was found that during premixed combustion phase the maximum cylinder pressure and the maximum heat release rate were increased as compared to neat diesel fuel. A slight increase has been found in NO_x emissions whereas the soot emission has been decreased in the case of blended fuel. It was also found that when M10 fuel was mixed with dimethyl ether as an additive, maximum cylinder pressure and the maximum heat release rate have been decreased in comparison with diesel fuel. NO_x, CO and soot emissions were reduced in this setup with the slight increase in HC emissions.

Canakci et al. (2009) investigated the effect of injection pressure on the performance of the single-cylinder DI diesel engine fueled with methanol-diesel blends (M5, M10 and M15). The tests have been conducted at the injection pressures of 180, 200 and 220 bar at different loads and speed of 2200 rpm. It has been shown that at the design injection pressure of 200 bar the heat release rate, maximum cylinder pressure, fuel conversion efficiency, smoke, HC and CO emissions were reduced with increasing mass fraction of methanol, while an increase in BSFC and NO_x emissions has been observed. When injection pressure was reduced to 180 bars, NO_x emissions were decreased, whereas CO, HC and smoke emissions were increased and the other parameters remained unchanged. It has been found that when the injection pressure was increased to 220 bars, CO, smoke and HC emissions were decreased while heat release rate, maximum cylinder pressure and NO_x emissions were increased. Considering the BSFC and fuel conversion efficiency, optimum results were observed at the injection pressure of 200 bars (design injection pressure). Sayin and Canakci (2009) assessed the effects of injection timing on the engine performance and emission characteristics. Methanol-diesel blends were tested at different injection timings. The tests results showed that by retarding the injection timing, minimum NO_x and CO_2 emissions were obtained, while BSFC and fuel conversion efficiency were found to be maximum at the design injection timing.

Qi et al. (2010) used biodiesel-diesel–methanol blends and investigated the performance and emission characteristics of a single cylinder DI diesel engine. Different blending percentages were used for the experimentation such as methanol 5% (M5), 10% (M10) and 50% biodiesel and 50% diesel (BD50). They have made BDM5 (biodiesel-diesel-methanol) and BDM10 by adding M5 and M10 to the BD50. It was found that, at low engine loads, combustion started later for the BDM5 and BDM10 as compared to BD50, whereas for high engine loads, start of combustion was unchanged. At rated load BDM5 and BDM10 effectively reduced smoke emissions while CO emissions were reduced up to some extent and NO_x and HC emissions were observed the same as that of BD50.

Anand et al. (2011) performed experimentation on a multi-cylinder turbocharged DI diesel engine fueled with neat Karanji biodiesel and methanol-biodiesel blends. Tests were performed at different loading conditions under constant speed and injection timings. A slight increase in the ignition delay (maximum 1 crank angle degree) was observed for methanol-biodiesel blends than that of neat biodiesel. It was found that, the maximum rate of pressure rise followed variations of the ignition delay at different operating conditions. However, the maximum cylinder pressure and the maximum heat release rate were decreased for biodiesel-methanol blends. Moreover, start of combustion was delayed and a reduction in combustion duration was observed for the blended fuel and an increase of 4.2% in the fuel conversion efficiency was obtained due to the addition of 10% methanol in the biodiesel. It was found that for methanol-biodiesel blends NO_x and smoke emissions were

significantly reduced while HC and CO emissions varied with the engine load. At low loads HC and CO emissions were slightly increased while at high loads HC emissions were almost unchanged, but a significant reduction in CO emissions was observed for the methanol-biodiesel blend.

4.2 Effects of Ethanol Blending

Ajav et al. (1999) experimentally evaluated the effects of ethanol-diesel blends on the performance and emission of a stationary diesel engine at a constant speed. The tests were performed using 5%, 10%, 15% and 20% ethanol–diesel blends (E5, E10, E15 and E20) and engine power, BSFC and fuel conversion efficiency were investigated. The obtained results showed an increase of 9% in BSFC for E20 blend as compared to that of neat diesel fuel. It was found that without any significant power reduction, exhaust emissions were reduced with ethanol–diesel blends as compared to neat diesel fuel. Moreover, for ethanol-diesel blends, CO emissions reduced up to 62% and 24% reduction was observed in NOx emissions.

Ren at al. (2008) studied the combustion characteristics of a DI diesel engine operating on ethanol-diesel blends along with the CN improver. It was found that by increasing the mass fraction of ethanol in the blends, the ignition delay and the premixed combustion duration were increased, whereas the mixing-controlled combustion duration and the total combustion duration were decreased. Moreover, by increasing the ethanol percentage, the center of the heat release curve approached to the TDC. In addition to this, the brake specific fuel consumption was found to be increased due to the increased oxygen content of the blended fuel. It was found that for specific fuel injection timing, the smoke opacity was significantly reduced and NOx emissions were slightly decreased with ethanol addition.

Rakopoulos et al. (2008) experimentally investigated the effects of ethanol-diesel blends (E5 and E10) on the performance and emissions of a six-cylinder, turbocharged and after-cooled, heavy duty, direct injection diesel engine. It was found that with the use of ethanol blends, smoke opacity was significantly reduced while NO_x and CO emissions were slightly decreased, whereas an increase in HC emissions were observed. Moreover, as the ethanol percentage in the blended fuel increases, the BSFC was increased and the fuel conversion efficiency also showed a slight increase.

Rakopoulos et al. (2008) further performed the experimentation to study the combustion characteristics of a DI diesel engine fueled with ethanol-diesel blends (5%, 10% and 15%) operating at a constant speed and different loads. It has been found that the ignition delay of the ethanol blended fuel was increased with slightly increased injection pressure. The rate of maximum pressure rise was increased and peak cylinder pressure was slightly affected. Moreover, using analysis of cylinder pressure relative to ignition delay, it was found that the fuel pump system has no effect on the cyclic pressure variations. It was also concluded that the type of fuel used up to low content such as 15% blend with the diesel fuel has a slight influence on engine characteristics and will not cause any degradation in the performance or emissions.

Huang et al. (2009) experimentally examined the diesel engine performance and emission characteristics fueled with E10, E20, E25 and E30 ethanol-diesel blends. To avoid the immiscibility of ethanol-diesel blends, n-butanol (5%) was used as an additive. It was found that with the increasing percentage of ethanol in the blended fuel, the fuel conversion efficiency was decreased. Moreover in terms of exhaust emissions, it was observed that smoke emissions were significantly decreased, whereas, CO emissions varied with loading conditions i.e. increased at low loads and decreased at higher loads as compared to neat diesel fuel. The HC emissions were reduced at higher speeds and full loads, while NO_x emissions were decreased at low speeds when fuelled with the blends. Up to 87.5% reduction in smoke emissions has been observed with blended fuel as compared to that of diesel fuel.

Barabas et al. (2010) presented the experimental results of performance and emission of a diesel engine fueled with ethanol-biodiesel-diesel blends and compared with neat diesel fuel. Up to 32.4% increase in BSCF up to 21.7% decrease in fuel conversion efficiency has been observed with the blends at lower engine loads as compared to diesel fuel. From exhaust analysis it was observed that at high engine loads CO emissions have been reduced up to 59%, while CO_2 emissions have been

increased. At partial and high loads, NOx emissions were slightly increased, whereas HC and smoke emissions were reduced at all loads for the blended fuel as compared to diesel fuel.

Hulwan et al. (2011) used Jatropha biodiesel as an additive to improve the ethanol-diesel fuel miscibility. The engine fueled with the blend A (D70-E20-B10), blend B (D50-E30-B20), blend C (D50-E40-B10) and neat diesel (D100) was tested at the design injection timing of 13 crank angle degrees BTDC. Advanced injection timing was required for higher ethanol blends to run the engine. It was found that with advance injection timing, the NO (nitric oxides) emissions were almost doubled and maximum cylinder pressure was increased. The heat release rate and indicator diagrams showed that at low loads a delayed combustion process was observed for blended fuel, while at high loads it reaches to that of diesel fuel. For blends BSFC was significantly increased, fuel conversion efficiency was slightly improved and a dramatic reduction in smoke opacity was observed at high loads. The NO_x emissions showed variation with the operating conditions whereas at low loads, a drastic increase in CO emissions was observed. It was concluded that blend B (D50-E30-B20) has given satisfactory performance with minimum emissions.

4.3 Effects of Butanol Blending

Rakopoulos et al. (2010) conducted experimentation to evaluate the effects of *n*-butanol-diesel blends on the performance and emission characteristics of a turbocharged DI diesel engine. Blends used for tests contain 8% and 16% (by volume) of n-butanol with neat diesel fuel. The series of tests were conducted for each blend, with the engine operating at two speeds and three loads. It was found that when butanol fraction in the blended fuel was increased, higher BSFC was observed along with a slight increase in fuel conversion efficiency. The NOx emissions were slightly reduced and HC emissions were increased whereas the CO emissions of the blended fuel were either remained unchanged or reduced as compared to neat diesel fuel.

Ozsezen et al. (2011) inspected the effects of iso-butanol-diesel blends on the diesel engine performance, combustion and emission characteristics. Tests were performed under three different loads and at a constant engine speed. Three different iso-butanol-diesel fuel blends i.e. B5 (5% iso-butanol), B10 (10% iso-butanol) and B15 (15% iso-butanol) were used in the experiments. It was found that BSFC was increased for the blended fuel but it was reasonable when B5 and B10 were used while BSFC was highest for B15. Fuel conversion efficiency was decreased with the increasing iso-butanol percentage in the blend. The heat release rate and maximum cylinder pressure were reduced in comparison with neat diesel fuel, whereas CO emissions, NOx and smoke opacity were significantly decreased with iso-butanol blended fuel. However, a slight increase in HC emissions was observed.

Rakopoulos et al. (2011) studied the combustion and performance characteristics of a Hydra diesel engine fueled with n-butanol-diesel fuel blends, consisted of n-butanol up to 24% by volume. With butanol-diesel blends an increase in the ignition delay was observed, peak cylinder pressure was almost remained unchanged, and the cylinder temperature was slightly decreased as compared to that of neat diesel fuel. The fuel conversion efficiency of the blended fuel was slightly increased; NO_x and smoke emission were reduced significantly.

Altun et al. (2011) experimentally studied the effects of addition of n-butanol to the biodiesel-diesel blends on the diesel engine characteristics. Tests were performed on a single cylinder DI diesel engine operating under three different engine loads and at a constant speed. It was found that the addition of n-butanol to the 20% diesel-biodiesel fuel blend (B20) slightly increases the BSFC and fuel conversion efficiency as compared to that of the B20 fuel blend. HC and CO emissions were reduced, whereas no change was observed in NO_x emissions at low engine loads. On the other hand a reduction in NO_x emissions was found at high engine loads. The smoke opacity of the fuel blends heavily decreased for all the operating conditions.

Recently Lujaji et al. (2011) studied the performance and emission of the diesel engine fueled with croton oil-diesel-butanol blends. It was found that at higher engine loads, with the increasing butanol fraction, the BSFC of the blend was increased while on the other hand fuel conversion efficiency was

decreased. Moreover, the cylinder pressure was increased and heat release rate was improved when butanol was added to croton oil-diesel blend. The NO_x emissions were remained unchanged, whereas the reduction in CO and smoke emissions were observed for the butanol blended fuel.

4.4 Summary of Alcohol Blending

The majority of experimental studies concluded that specific fuel consumption of all the alcohols (methanol, ethanol, and butanol) increases and fuel conversion efficiency decreases with the increasing alcohol content in the blend. The lower heating value of alcohols is responsible for the increase in specific fuel consumption i.e. methanol specific fuel consumption will be maximum among all the alcohols due to its lowest heating value. At the same time some studies showed a slight increase in fuel conversion efficiency through the addition of alcohols to biodiesel blends (Anand et al,. 2011). The analysis of combustion characteristics of alcohol-base fuel blends revealed that the maximum cylinder pressure and ignition delay were increased while the start of combustion was delayed and the total combustion duration was decreased in comparison with the neat diesel fuel. The ignition delay of the blended fuel increases due to the lower CN of alcohols. Longer ignition delay increases the rate of pressure rise, which may cause the diesel knock. CN improvers such as alkyl nitrates can be used to reduce ignition delay and cyclic variations of the blended fuel. In terms of exhaust emissions, literature review showed that for methanol blending smoke content, CO, CO_2 and HC emissions decrease significantly with an increase in NO_x emissions. However, this increase in NO_x emissions can be countered by adding methanol to biodiesel-diesel blends. It was observed in numerous studies that for ethanol blending, PM, NO_x, and CO emissions were significantly reduced with a slight increase in HC emissions. However, with the increasing ethanol fraction, some studies shown a decrease in HC emissions with a corresponding increase in other emissions at different engine operating conditions.

In particular, for butanol blending, increasing the butanol content in the blend, NO_x, CO and soot emissions significantly decrease while HC emissions shows an increasing trend as compared to that of diesel fuel. Contrary to this, some studies also showed reduced HC emissions of the blended fuel. In most of the cases, NO_x emissions depend upon engine operating conditions and percentage of butanol added. It was found that use of butanol in diesel-biodiesel blends enhanced the blend properties; CO and HC emissions were decreased with a slight increase in NOx emissions.

Finally, it can be concluded that alcohol blends with baseline fuels (diesel, biodiesel) decreases the engine emissions with satisfactory engine performance. The blend stability and miscibility issues can be solved by the use of additives and CN improvers.

5. EFFECTS OF ALCOHOL FUMIGATION ON DIESEL ENGINE PERFORMANCE AND EMISSIONS

Alcohol addition through fumigation is a widely used technique because alcohol and baseline fuel is not premixed in this method; this avoids the miscibility and stability issues of lower alcohols which are faced in alcohol blending. Different experimentation and studies have been performed in this regard to analyze the effects of alcohol fumigation on diesel engine combustion, performance and emission characteristics.

5.1 Effects of Methanol Fumigation

Houser et al. (1980) evaluated the effects of methanol fumigation on the emissions of a diesel engine and was considered as one of the pioneer studies on alcohol fumigation. Experimentation was performed on a four stroke DI diesel engine, fueled with diesel fuel and 40% fumigated methanol. It was found that with methanol fumigation, NO_x emissions were decreased for all operating conditions, smoke opacity was slightly affected, and fuel conversion efficiency was improved slightly at higher loads.

Zhang et al (2011) conducted experimentation on a four-cylinder DI diesel engine with methanol injection. The effects of fumigation on engine performance and emissions were investigated under different engine loads and at a constant speed. It was found that with methanol fumigation, the BSFC was increased at all the loads while fuel conversion efficiency varies with loading conditions. At low engine loads, fuel conversion efficiency was decreased and improved at high engine loads. The emission analysis of methanol fumigation showed decreased PM and NO_x emissions in comparison to those of neat diesel fuel. This reduction in PM and NO_x emissions was more obvious with the increasing fumigation ratio of methanol. The CO and HC emissions were increased with the increasing fumigation ratio; this increase was more noticeable at low engine loads due to the retarded combustion, lean air-alcohol mixture and cooling effect of the alcohols. However, in general, methanol fumigation increased the HC and CO emissions, with the reduction in NO_x emissions.

Cheng et al. (2008) experimentally studied methanol fumigation with biodiesel and compared the results with ultra-low sulfur diesel (ULSD) fuel in a DI diesel engine. Tests were performed at a constant speed with 10% fumigated methanol at five different engine loads. It was found that CO_2, NO_x, and PM emissions were reduced with the methanol fumigation as compared to that of ULSD fuel. The fuel conversion efficiency was observed higher at medium and high loads. As compared to diesel fuel, HC, CO and NO_x emissions were increased with methanol fumigation.

Zhang et al (2013) recently investigated the effects of methanol fumigation on the combustion and emission characteristics of a diesel engine operating at constant speed, different loading conditions and fumigation ratios. The combustion analysis revealed that the peak cylinder pressure was decreased at low and medium engine loads and increased at high loads with methanol fumigation. The ignition delay and maximum heat release rate were increased, but the combustion duration remained almost unchanged. It was found that increasing the engine load from medium to high, methanol fumigation made a significant reduction in PM emissions. These reductions were due to the higher heat release in the premixed mode and decreased diesel fuel consumption.

5.2 Effects of Ethanol Fumigation

Abu-Qudais et al. (2000) studied the effects of ethanol fumigation and blending on the performance and emissions of a DI diesel engine. The tests were performed to select an optimum percentage of ethanol that gives satisfactory engine performance and lower emissions. Alcohol fumigation was done by simply injecting the ethanol into the inlet port of the engine. It was found that at 20% ethanol fumigation gave optimum results than the other fumigation percentages. An increase of 7.5% in fuel conversion efficiency, 55% of CO emissions, 36% of HC emissions were obtained, whereas, a reduction of 51% in soot concentration and 48% in engine smoke was obtained.

Kowalewicz, A. (2007) experimentally studied the performance, combustion and emissions of single cylinder DI diesel engine operating on the rapeseed methyl esters (RME) with ethanol fumigation. Experimentation was done with a constant speed and at two loads: high and low load. Combustion analysis showed an increase in ignition delay with the increasing ethanol fraction. This results in the shorter total combustion time. It was found that at low engine load, the increasing fraction of ethanol resulted in lower pressure and heat release rates, low efficiency, lower NO_x emissions, and higher HC and CO emissions. Whereas at high load the increasing fraction of ethanol resulted in higher pressure and temperature and higher efficiency. CO_2 and smoke emissions were decreased while NO_x emissions were increased.

Chauhan et al. (2011) investigated the effects of ethanol fumigation on the diesel engine emission characteristics. Experimentation was performed on a small capacity, naturally aspirated, single-cylinder four-stroke, DI diesel engine. Fumigation was achieved by carburetion. It was found that with ethanol fumigation CO_2 emissions and exhaust temperature were reduced with increasing ethanol percentage. NO_x and CO emissions varied with the engine load. NO_x emissions were decreased up to 16% at full load and CO emissions were decreased at the engine loads above 70%. But this decrease in CO emissions was limited up to 15% ethanol fumigation, after that with the increasing the ethanol fraction, CO emissions were increased. On the other hand, HC emissions were increased for the entire

load range. It was concluded that 15% ethanol fumigation is an optimum fumigation percentage for better engine emissions.

Bannikov et al. (2013) experimentally evaluated the effects of ethanol fumigation on the performance and emissions of four stroke, single-cylinder, DI diesel engine operating on Jatropha biodiesel. It was found with 23% ethanol fumigation, the engine efficiency was increased by 5% as compared to that of neat biodiesel. Start of combustion was delayed by 1.2 crank angle degrees as compared to Jatropha biodiesel. Heat release rate and pressure curves were observed closer to that of neat diesel fuel. Moreover, due to ethanol fumigation the burn duration was decreased by 6.4 crank angle degrees that led to increase in efficiency. Smoke opacity, CO_2 and CO emissions were decreased by an amount of 50%, 5% and 30% respectively while HC and NOx emissions were increased.

5.3 Effects of Butanol Fumigation

Limited number of research has been published for butanol fumigation. Chen et al. (2013) has conducted an experimental investigation on a DI diesel engine with exhaust gas recirculation (EGR) in combination with port fuel injection (PFI) of n-butanol. Effects of butanol concentration and EGR rate on combustion, performance and emissions were evaluated. It was found that butanol concentration and EGR rate have a combined impact on the combustion process. At low EGR rate, the maximum heat release rate and the maximum cylinder pressure were increased with increasing butanol concentration while ignition delay remained unchanged. However, at high EGR rate the maximum heat release rate and maximum cylinder pressure both were decreased with the increasing butanol concentration with a longer ignition delay and longer combustion duration. CO and HC emissions were increased with the increasing butanol concentration. That was accompanied by the higher indicated specific fuel consumption (ISFC) and lower fuel conversion efficiency. It was also found that butanol PFI in combination with EGR simultaneously reduced NO_x and soot emissions.

Lopez et al. (2013) studied the impact of n-butanol and hydrous ethanol fumigation on the combustion, performance and emission characteristics of an automotive diesel engine and compared the experimentation results with that of ULSD fuel. It was found that premixed combustion was increased and the total combustion process was observed fast for both alcohols, while the maximum in-cylinder temperature was decreased as compared to ULSD. The fuel conversion efficiency and BSFC were decreased for butanol as well as ethanol in comparison with ULSD fuel. Emission characteristics of both alcohols showed increased CO and HC emissions and reduced NOx and PM emissions, in comparison with ULSD fuel. However, the magnitude of this reduction was significantly affected by engine operating conditions.

5.4 Summary of Alcohol Fumigation.

With alcohol fumigation BSFC increases with the increasing alcohol injection rate at all engine loads. However, some studies shown a decreased BSFC with alcohol fumigation (Lopez et al. 2013). Change in the fuel conversion efficiency with alcohol fumigation depends upon the engine load; efficiency increases at low load and increases at medium and high engine loads. It may also be concluded that fuel conversion efficiency slightly improves by applying alcohol fumigation to the diesel engine operating on biodiesel. Combustion characteristics show that cumulative effect of the alcohol fumigation is retarded start of combustion. According to some studies, alcohol fumigation decreases NO_x emissions as compared to diesel fuel; reduction in NO_x emission significantly depends upon engine load. At the same time, an increase in NO_x emissions has also been reported in some studies. CO and HC emissions also vary with the engine load but are generally reduced with the alcohol fumigation. CO_2, smoke opacity and PM emissions significantly decrease with alcohol fumigation at all engine loads.

6. COMPARISON OF ALCOHOL BLENDING AND FUMIGATION

Alcohol blending and fumigation have their own pros and cons. Alcohol blending is considered an easier method to implement than fumigation but it has some problems to be dealt with, such as poor miscibility of lower alcohols (methanol, ethanol) in diesel fuel. On the other hand fumigation technique requires certain modifications (separate injection system) in the engine, which is a drawback of this method. With alcohol blending NO_x emissions significantly decrease while with alcohol fumigation NO_x emissions vary with the engine load. With the alcohol blending CO and HC emissions increase for the entire range while with fumigation, they also increase but depending upon the engine operating conditions; in some studies reduction of CO and HC with fumigation is also reported. The fuel conversion efficiency and specific fuel consumption are neither better for alcohol blending nor for alcohol fumigation. The temperature of the blends also affects their stability; additives may be used to counter this issue. In turn, there are no stability problems with fumigation technique; no additives are used due to which fumigation can provide double the amount of alcohol on an energy basis as compared to blending. It has been found that use of lower alcohols in the blends causes corrosion in the fuel delivery systems. Alcohol blending significantly reduces the CN of the blend. CN improvers may be used for overcoming this problem if required. Apart from technique of alcohol addition, the type of alcohol used also influence the engine performance and emissions.

7. CONCLUSION

Majority of the studies reported better exhaust emissions for both the methods of alcohol addition, but improvement of the performance characteristics were not achieved to the desired extent. Among other alcohols the butanol has been declared as having better fuel properties and providing better performance and emission characteristics. Moreover, butanol fumigation is a field in which very limited published data is available, but its results are so far more promising than others. Therefore, butanol fumigation can be considered as a viable option of alcohol addition to the base fuels in diesel engines. Further research is required to determine the rate of butanol fumigation for the optimum engine efficiency and emissions over the range of engine speed and load.

REFERENCES

Ajav, E.A., Singh, B. and Bhattacharya, T.K. (1999), ‘Experimental study of some performance parameters of a constant speed stationary diesel engine using ethanol–diesel blends as fuel’, Biomass and Bioenergy, Vol. 17 No. 4, pp. 357–365.

Abu-Qudais, M., Haddad, O. and Qudaisat, M. (2000), ‘The effect of alcohol fumigation on diesel engine performance and emissions’, Energy Conversion and Management, Vol. 41 No. 4, pp. 389–399.

Anand, K., Sharma, R.P. and Mehta, P.S. (2011), ‘Experimental investigations on combustion, performance and emissions characteristics of neat karanji biodiesel and its methanol blend in a diesel engine’, Biomass and bioenergy, Vol. 35 No. 1, pp. 533–541

Altun, S., Oner, C., Yasar, F. and Adin, H. (2011), ‘Effect of n-butanol blending with a blend of diesel and biodiesel on performance and exhaust emissions of a diesel engine’, Industrial & Engineering Chemistry Research, Vol. 50 No. 15, pp. 9425–9430

Bannikov, M., Bajwa, A.U., Iftikhar, M.B., Moghal, N.I. and Zeb, U. (2013), ‘OPTIMIZATION OF THE PERFORMANCE OF DIESEL ENGINE RUNNING ON JATROPHA BIODIESEL THROUGH ETHANOL FUMIGATION.’, Journal of International Scientific Publications: Materials, Methods & Technology, Vol. 7 No. 1.

Barabas, I., Todoruţ, A. and Băldean, D. (2010), ‘Performance and emission characteristics of an CI engine fueled with diesel–biodiesel–bioethanol blends’, Fuel, Vol. 89 No. 12, pp. 3827–3832.

Cheng, C.H., Cheung, C.S., Chan, T.L., Lee, S.C., Yao, C.D. and Tsang, K.S. (2008), 'Comparison of emissions of a direct injection diesel engine operating on biodiesel with emulsified and fumigated methanol', Fuel, Vol. 87 No. 10, pp. 1870–1879.

Chen, Z., Liu, J., Wu, Z. and Lee, C. (2013), 'Effects of port fuel injection (PFI) of n-butanol and EGR on combustion and emissions of a direct injection diesel engine', Energy Conversion and Management, Vol. 76, pp. 725–731.

Canakci, M., Sayin, C., Ozsezen, A.N. and Turkcan, A. (2009), 'Effect of injection pressure on the combustion, performance, and emission characteristics of a diesel engine fueled with methanol-blended diesel fuel', Energy & Fuels, Vol. 23 No. 6, pp. 2908–2920.

Chauhan, B.S., Kumar, N., Pal, S.S. and Du Jun, Y. (2011), 'Experimental studies on fumigation of ethanol in a small capacity diesel engine', Energy, Vol. 36 No. 2, pp. 1030–1038.

Ecklund, EE., Bechtold, RL., Timbario, TJ., McCallum, PW., (1984) 'State-of-the-art report on the use of alcohols in diesel engines. Paper no. 840118. Warrendale, PA: Society of Automotive Engineers, Inc.

Heywood, JB 1988, *Internal Combustion Engine Fundamentals*, McGraw-Hill, New York.

Huang, Z.H., Lu, H.B., Jiang, D.M., Zeng, K., Liu, B., Zhang, J.Q. and Wang, X.B. (2004),'Combustion characteristics and heat release analysis of a compression ignition engine operating on a diesel/methanol blend', Proceedings of the institution of mechanical engineers, part D: Journal of Automobile Engineering, Vol. 218 No. 9, pp. 1011–1024.

Huang, ZH., Lu, HB., Jiang, DM., Zeng, K., Liu, B., Zhang , JQ., et al. (2005), 'Performance and emissions of a compression ignition engine fueled with diesel/oxygenate blends for various fuel delivery advance angles'. Energy and Fuel 2005;19:403–10

Huang, J., Wang, Y., Li, S., Roskilly, A.P., Yu, H. and Li, H. (2009), 'Experimental investigation on the performance and emissions of a diesel engine fuelled with ethanol–diesel blends', Applied Thermal Engineering, Vol. 29 No. 11, pp. 2484–2490.

Hulwan, D.B. and Joshi, S.V. (2011), 'Performance, emission and combustion characteristic of a multicylinder DI diesel engine running on diesel–ethanol–biodiesel blends of high ethanol content', Applied Energy, Vol. 88 No. 12, pp. 5042–5055.

Houser, K.R., Lestz, S.S., Dukovich, M. and Yasbin, R.E. (1980), Methanol fumigation of a light duty automotive diesel engine, SAE Technical Paper, available at: http://papers.sae.org/801379/

Kowalewicz, A. (2007), 'ECO-DIESEL ENGINE FUELED WITH RAPESEED OIL METHYL ESTER AND ETHANOL', International Journal of Energy for a Clean Environment, Vol. 8 No. 4, availableat:http://www.dl.begellhouse.com/journals/6d18a859536a7b02,3c9d65aa19a8f577,31b69acb3874d91b.html

Kumar, S., Cho, J.H., Park, J., Moon, Il., (2013) 'Advances in diesel–alcohol blends and their effects on the performance and emissions of diesel engines', Renewable and Sustainable Energy Reviews, Volume 22, Pages 46-72, ISSN 1364-0321.

Lujaji, F., Kristóf, L., Bereczky, A. and Mbarawa, M. (2011), 'Experimental investigation of fuel properties, engine performance, combustion and emissions of blends containing croton oil, butanol, and diesel on a CI engine', Fuel, Vol. 90 No. 2, pp. 505–510.

Lopez, A.F., Cadrazco, M., Agudelo, A.F., Corredor, L.A., Vélez, J.A. and Agudelo, J.R. (2015), 'Impact of n-butanol and hydrous ethanol fumigation on the performance and pollutant emissions of an automotive diesel engine', Fuel, Vol. 153, pp. 483–491.

Ozsezen, A.N., Turkcan, A., Sayin, C. and Canakci, M. (2011), 'Comparison of performance and combustion parameters in a heavy-duty diesel engine fueled with iso-butanol/diesel fuel blends', Energy, Exploration & Exploitation, Vol. 29 No. 5, pp. 525–541.

Qi, D.H., Chen, H., Geng, L.M., Bian, Y.Z. and Ren, X.C. (2010), 'Performance and combustion characteristics of biodiesel–diesel–methanol blend fuelled engine', Applied Energy, Vol. 87 No. 5, pp. 1679–1686.

Rakopoulos, D.C., Rakopoulos, C.D., Kakaras, E.C. and Giakoumis, E.G. (2008), 'Effects of ethanol–diesel fuel blends on the performance and exhaust emissions of heavy duty DI diesel engine', Energy Conversion and Management, Vol. 49 No. 11, pp. 3155–3162.

Rakopoulos, D.C., Rakopoulos, C.D., Giakoumis, E.G., Papagiannakis, R.G. and Kyritsis, D.C. (2008), 'Experimental-stochastic investigation of the combustion cyclic variability in HSDI diesel engine using ethanol–diesel fuel blends', Fuel, Vol. 87 No. 8, pp. 1478–1491.

Rakopoulos, C.D., Rakopoulos, D.C., Giakoumis, E.G. and Kyritsis, D.C. (2011), 'The combustion of n-butanol/diesel fuel blends and its cyclic variability in a direct injection diesel engine', Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, Vol. 225 No. 3, pp. 289–308.

Rakopoulos, D.C., Rakopoulos, C.D., Hountalas, D.T., Kakaras, E.C., Giakoumis, E.G. and Papagiannakis, R.G. (2010), 'Investigation of the performance and emissions of bus engine operating on butanol/diesel fuel blends', Fuel, Vol. 89 No. 10, pp. 2781–2790.

Ren, Y., Huang, Z.H., Jiang, D.M., Li, W., Liu, B. and Wang, X.B. (2008), 'Effects of the addition of ethanol and cetane number improver on the combustion and emission characteristics of a compression ignition engine', Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, Vol. 222 No. 6, pp. 1077–1087.

Song, R., Liu, J., Wang, L., Liu, S., (2008)'Performance and emissions of a diesel engine fuelled with methanol'. Energy & Fuels; 22:3883–p8.

Sayin, C. (2010), 'Engine performance and exhaust gas emissions of methanol and ethanol

diesel blends', Fuel, Vol. 89 No. 11, pp. 3410–3415.

Sayin, C. and Canakci, M. (2009), 'Effects of injection timing on the engine performance and exhaust emissions of a dual-fuel diesel engine', Energy Conversion and Management, Vol. 50 No. 1, pp. 203–213.

Yano, T., Ito, K., 'Behavior of methanol and formaldehyde in burned gas from methanol combustion: a chemical kinetic study' (1983). Bulletin of JSME; 26: p94–101.

Zhang, Z.H., Cheung, C.S. and Yao, C.D. (2013), 'Influence of fumigation methanol on the combustion and particulate emissions of a diesel engine', Fuel, Vol. 111, pp. 442–448.

Zhang, Z.H., Tsang, K.S., Cheung, C.S., Chan, T.L. and Yao, C.D. (2011), 'Effect of fumigation methanol and ethanol on the gaseous and particulate emissions of a DI diesel engine', Atmospheric Environment, Vol. 45 No. 11, pp. 2001–2008.

Zhang, C.P., Zhai, X.M., Li, Y.J. and Sun, Z.G. (2012), 'Research on Combustion Characteristics and Emissions of Methanol-Diesel Fuel with Different Additives', Advanced Materials Research, Vol. 354, pp. 462–467.