EFFECT OF BUTANOL ADDITION TO DIESEL ON THE CI ENGINE CHARACTERISTICS: A REVIEW

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ABSTRACT

This paper presents a brief review of the effect of butanol addition to mineral diesel on the engine performance and exhaust emissions of a compression ignition engine. This study is based on the reports available in the existing literature on using various butanol-diesel blends as CI engine fuels by different researchers. Alcohol based fuel such as butanol is being considered as an alternative fuel for use in diesel engines due to their advantages of being renewable and environment friendly. Butanol can be produced by fermentation of commonly used agricultural wastes. The analysis of different experimental results shows that butanol diesel blends as fuels enhance the thermal efficiency, lower the exhaust gas temperature (EGT), emit less soot and lower NO_x (at low blend percentages) compared to pure diesel. However, the NO_x emission increases when the percentage of butanol is increased in the blended fuel. Thus the use of butanol is advantageous considering both engine performance and exhaust emissions.

KEYWORDS: IC Engine, Alternative Fuel, Butanol, NO_x, EGT.

It is a well-known fact that fuel is the backbone of modern transportation system of the world. Almost every automobile uses conventional fuels as their primary source of energy. However, with the recent rise in the population, development in the field of science and urbanization of the world the demand for fuels is constantly increasing. These conventional fuels being a non-renewable source of energy are constantly being depleted and are in a process of extinction

Diesel engines are the most popular well known efficient prime mover among the internal combustion engines because of their simple robust construction coupled with high thermal efficiency and specific power output with better fuel economy, much longer life span and reliability which results in their widespread use in transportation, thermal power generation and many more industrial and agricultural applications [Sahin and Aksu, 2015 & Zhang and Balasubramanian, 2014]. Compared with gasoline engines diesel engines have higher efficiency so they have become more and more popular at present. Engine manufacturers worldwide have been able to develop diesel engines with high thermal efficiency and specific work output keeping inside the limits of the imposed regulations that everyday has become more stringent [Rakopoulos et. al., 2010]. However diesel engines emit larger volumes of nitrogen oxides (NO_X) and smoke (soot) which are hard to be discovered or eliminated simultaneously due to non-uniformity of fuel/air ratio and temperature distribution in cylinder. With respect to the increase of diesel engine based vehicles the shareof pollutants in atmospheric pollution caused by these vehicles is increasing as well.

Significant achievements for the development of cleaner diesel engines have been made, over the last decades, by following various engine-related techniques, e.g. the use of common-rail systems, fuel injection control strategies, exhaust gas recirculation, exhaust gas after-treatment etc. [Rakopoulos et. al., 2010].Increasing concerns of fossil fuel depletion, oil-price volatility, burgeoning energy demands, global warming by GHG (green-house gases) emissions, toxic pollutants (smoke and NO_X) and rigorous emission regulations are driving the scientific community to find alternative renewable bio-fuels for use in diesel engines [Zhang and Balasubramanian, 2014]. Furthermore, especially concerning the reduction of pollutant emissions, researchers have focused their interest on the domain of fuel-related techniques, such as for example the use of alternative gaseous fuels of renewable nature, which are environment-friendly or oxygenated fuels, which are able to reduce particulate emissions [Rakopoulos et. al., 2010].

Biofuels made from agricultural products (oxygenated by nature) not only offer benefits in terms of exhaust emissions, but also reduce the world's dependence on oil imports, with local agricultural industries supported and farming incomes enhanced. Among those, liquid bio-fuels, such as vegetable oils and there derived bio-diesels (methyl or ethyl esters), ethanol, butanol, and ethers are considered as very promising bio-fuels for diesel engines [Rakopoulos et. al., 2011]. The advantages of vegetable oils as diesel fuel are the minimal sulfur and aromatic content, and the higher flash point and lubricity. Their disadvantages include primarily the very high viscosity, the higher pour

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point, and the lower cetane number, calorific value and volatility [Choi and Jiang, 2015]. The advantages of bio-diesels as diesel fuel are the minimal sulfur and aromatic content, and the higher flash point, lubricity and cetane number. Their disadvantages include the higher viscosity (though much lower than the vegetable oils one), the higher pour point, the lower calorific value and volatility, the hygroscopic tendency, and the lower oxidation stability [Choi et. al., 2015]. Owing to the above disadvantages researchers are now concentrating on alcohol based fuels.

Alcohol fuels can be used as oxygenated fuel additives with fossil- based fuels for diesel engines as a clean alternative fuel source to reduce the greenhouse gas emissions, renewable energy utilization in various areas [Karabektas and Hosoz, 2009]. Alcohol fuels such as ethanol, methanol and butanol can be used as oxygenated fuel additives in fossil-based fuels for diesel engines as alternative fuel sources [Siwale et. al., 2013]. Alcohol–diesel fuel blends in diesel engines extend ignition delay period of the combustion process and this period depends on the kind of alcohol blended and becomes longer as the content of the alcohol in the blends is increased [Hajba et. al., 2011].

Properties and Advantages of using Butanol as Fuel

Butanol is one of the primary alcohols, which has more advantages than ethanol and methanol as an alternative fuel for internal combustion engines, because its fuel properties are closer to those of fossil-based fuels [Rakopoulos et. al., 2011]. Ethanol is hygroscopic or less miscible when mixed with diesel over a wide range of conditions especially at low temperatures. Butanol is less hydrophilic and has a higher miscibility factor in diesel than ethanol. Due to high carbon content and good inter-solubility with diesel without addition of any co-solvents or emulsifiers n-butanol makes it easier to blend with diesel [Szulczyk, 2010]. Butanol has a lower vapour pressure than ethanol, thus the diesel butanol blends are potentially suitable for transport and the need for additional transportation and storage infrastructure can be avoided and hence reduces costs [Dogan, 2011]. Apart from this butanol has a higher heating value, and higher cetane number. The energy content of butanol is 33.1 MJ/Kg whereas ethanol energy content is 26.8 MJ/Kg [Karabektas and Hosoz, 2009]. Thus butanol fares much better in energy content and is closer to diesel in terms of energy value. Pure butanol has a cetane number of 25 which is comparable to that of cetane number of diesel. Ethanol on the other hand has a very low cetane number approximately close to 8. Higher cetane fuel causes an engine to run smoothly and quietly as because higher cetane fuels have shorter ignition delay compared to lower cetane fuels (minimizing of ignition delay results in less unburned fuel in the cylinder and less intense knock) [Tingbo et. al., 2012]. The flash point of butanol is quite high (30°C) compared to ethanol (13-14°C) making it a safer fuel to use than ethanol. Thus considering the superior qualities of butanol over ethanol, butanol would be preferable to ethanol for blending with conventional diesel and more so than methanol.

Table1 Comparison of properties of diesel fuel, n-butanol and ethanol [3, 4]

Fuel properties	Diesel fuel	n-butanol C_4H_9OH	Ethanol C_2H_5OH	iso-butanol C_4H_9OH
Density at 20°C, (kg/m^3)	837	810	788	802
Cetane number	50	~25	~8	~15
Lower calorific value (MJ/kg)	43	33.1	26.8	33.64
Kinematic viscosity at 40 ^{0}C (mm^2/s)	2.6	3.6	1.2	2.63
Boiling point (°C)	180-360	118	78	107.9
Latent heat of evaporation (KJ/kg)	250	585	840	684
Oxygen (%wt)	0	21.6	34.8	21.62
Flash point (°C)	70	28	14	27.8
Boiling Point (°C)	227	117.7	79	107.9
Self Ignition Temperature (°C)	254	343	363	415.6

Effect of butanol-diesel blend on engine performance

Performance parameters like brake specific fuel consumption, brake thermal efficiency, power output which have been evaluated by different researchers after experimental studies are reported in this section. Data points for graphs have been extracted using x-y extract and then plotted in origin.

Effect on brake specific fuel consumption (bsfc)

Karabektas and Hosoz, 2009 compared thebrake specific fuel consumption for neat diesel and 5%, 10%, 15% and 20% isobutanol diesel blends. They observed that with increasing isobutanol caused higher brake specific fuel consumption compared to neat diesel. Similar results were also obtained by Rakopolous et al. who compared 8%, 16% and 24% of n-butanol diesel blends with neat diesel fuel. Zhang et al. also observed the same trend when they compared the brake specific fuel consumption of n-butanol, iso-butanol and octanol to that of neat diesel.

Increasing brake specific fuel consumption with higher butanol content can be explained by the fact that more is the butanol content lower is the energy content of the fuel and hence more amount of fuel is required to produce the same brake power. Findings of Rakopolous et al. have been shown as under.

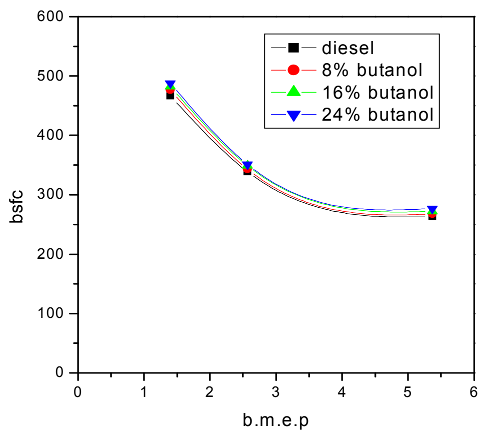


Figure 1: Variation of brake specific fuel consumption for various mean effective pressures.

Effect on brake thermal efficiency

Kumar et al. 2015 investigated the effects n-butanol and iso-butanol on the brake thermal efficiency of a four stroke direct injection diesel engine and compared it to that of neat diesel fuel. Blends used were of 10%, 20% and 30% each of n-butanol and iso-butanol. They observed that 20% n-butanol gave maximum brake thermal efficiency at higher loads among various blends. At partial load no significant change in brake thermal efficiency was observed for both the blends, but at higher loads n-butanol blends gave higher brake thermal efficiency than iso-butanol blends. This may be attributed to the higher cetane number and density of n-butanol. Chen et al. 2013 investigated the effect of 20%, 30% and 40% n-butanol addition to diesel and compared it to that of neat diesel fuel case on a passenger car diesel engine. They observed that butanoldiesel blends showed higher brake thermal efficiency thanneat diesel. The higher the percentage of butanol in the blend more is the brake thermal efficiency. Thismay be attributed to the enhanced oxygen content and higherlaminar flame speed of the butanoldiesel blends.

Balamurugan and Nalini, 2014 studied the impact of various alcohol blends (propanol and butanol) on diesel engine performance and compared it to that of neat diesel fuel. Test fuels used were 4% & 8% each of propanol and n-butanol diesel blends and 100% neat diesel. They observed that at low and medium loads brake thermal efficiency for alcohol blends was nearly similar to that of neat diesel. But at higher loads alcohol blends showed higher brake thermal efficiency than diesel. When butanol and propanol are compared butanol showed higher efficiency. Higher brake thermal efficiency can be attributed to the fact that mixing of alcohol with diesel reduced density and cetane number of blended fuels, which in turn improved the spray characteristics and prolonged ignition delay.

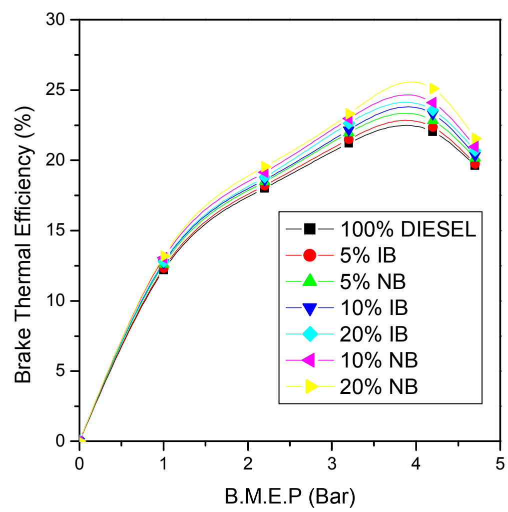


Figure 2: Variation of brake thermal efficiency for various butanol and iso-butanol blends.

Effect on Exhaust gas temperature (EGT)

Yusri et al. 2015 used 10% blend of n-butanol with diesel and tested it in a 4-cylinder, 4-stroke common rail direct injection CI engine at two different engine speeds of 1000 and 2500 rpm. He observed that addition of n-butanol resulted in lowering of exhaust temperature by 7.5% and 5.2% at engine speeds 1000rpm and 2500 rpm respectively compared to diesel. Al-Hasan and Momany, 2008 investigated the effect of iso-butanol addition to diesel fuel on a single cylinder four stroke CI engine. They observed that with increasing butanol content exhaust gas temperature decreases and the lowest exhaust gas temperature was observed for 40% butanol diesel blend. Dogan, 2011 evaluated the influence of n-butanol/diesel fuel blends using five-test fuels of 5%, 10%, 15% and 20% n-butanol diesel blends and neat diesel fuel in a single cylinder, four stroke naturally aspirated DI high speed diesel engine. They observed that n-butanol/diesel fuel blends gave lower exhaust gas temperature compared to neat diesel. Decreasing exhaust gas temperature with increasing butanol content can be attributed to the low energy content and higher latent heat of evaporation of the n-butanol/diesel fuel blends which lowers the temperature in the combustion chamber.

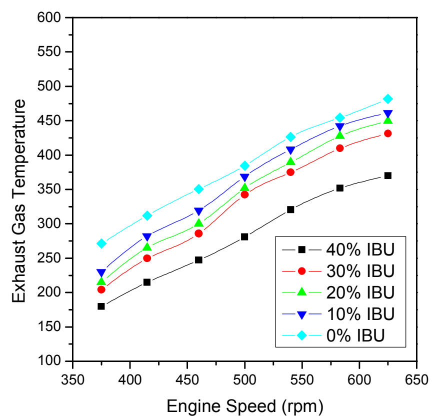


Figure 3: Effect on exhaust gas temperature for different butanol blends at various engine Speeds.

Effect of Butanol addition to diesel on Exhaust Emissions

The effect of butanol addition to mineral diesel on the pollutants emissions will be briefly discussed in the following section.

Effect on CO emission

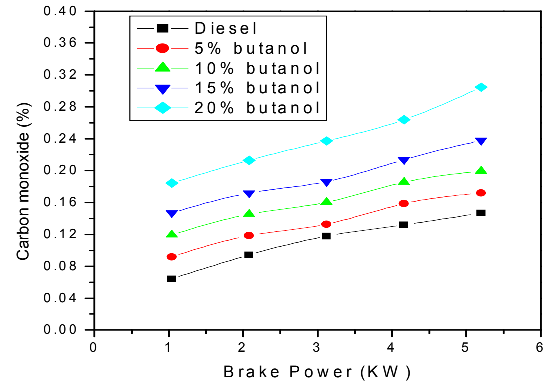


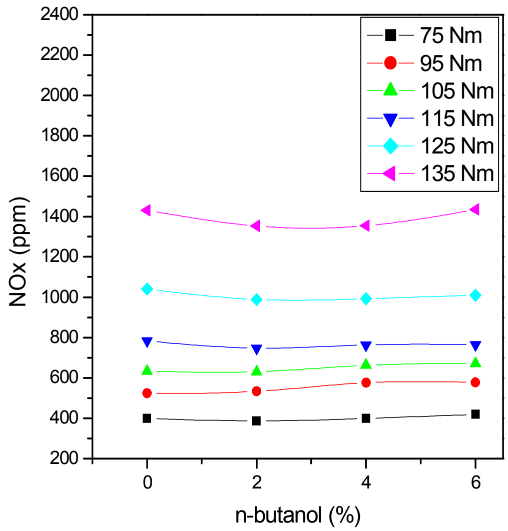
Figure 4: Variation of CO emission for various butanol blends with brake power.

Swamy et al., 2009 observed that with increasing load CO emissions increases. Also as the butanol content in the blend increases the CO emissions decreases. Yao et al., 2010 observed a similar trend. They tested four butanol diesel blends containing 0%, 5%, 10% and 15% n-butanol. But the reduction effect of CO was found to be less prominent as butanol content was increased beyond 5%. Decreasing CO emission with increasing butanol content can be attributed to the fact that butanol being an oxygenated fuel oxidizes CO into CO_2 and hence reduces its emission.

A contrasting trend was observed by Wu et al., 2014 who found that CO emission increased with addition of n-butanol at low loads but at higher loads CO emission for blends and pure diesel were nearly the same. At low loads due to lower in-cylinder temperature, quenching layer gets enlarged and hence CO emission increases

Effect on NO_X emission

Chen et al., 2012 observed that at high load conditions due to an increase in mean in-cylinder temperature NO_X emission increased for butanol diesel blends compared to neat diesel. However at low load conditions higher butanol content could decrease NO_x emission. Sahin et. al. observed decrease in NO_X emission at 2% butanol content whereas for 4 and 6% butanol content higher NO_X emission compared to diesel fuel was observed.



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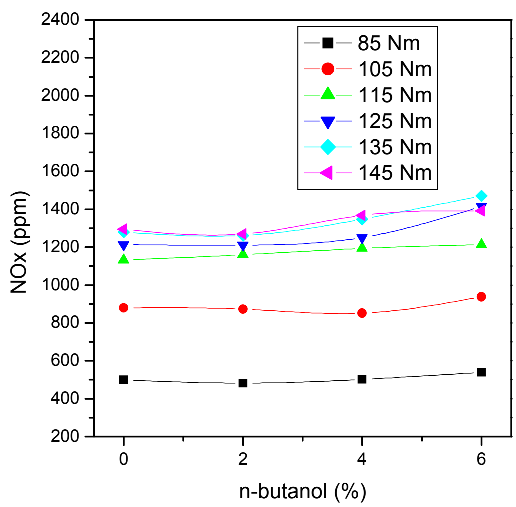
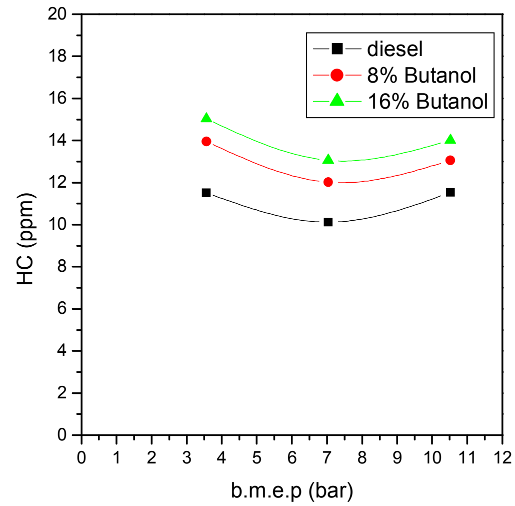


(b)

Figure 5: Variation of NO_X emission for various butanol percentages at 3000 rpm and 1500 rpm respectively.



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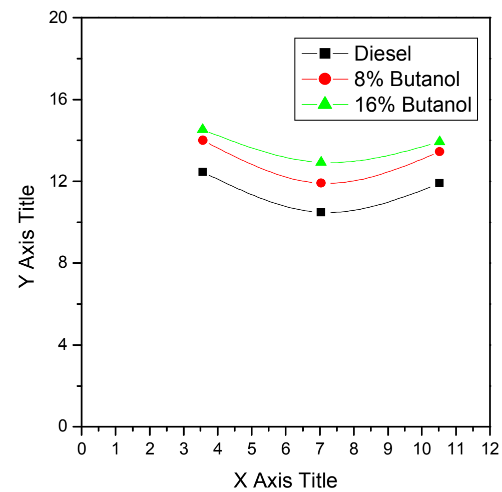

(b)

Figure 6: Variation of HC emission for various butanol percentages at 1200 rpm and 1500 rpm respectively.

Tingbo et al., 2012 observed a decrease in NO_X emission with increasing butanol percentage. Decreasing NO_X emission may be attributed to the higher heat of evaporation of leading to lower in-cylinder temperature and shortened burning duration. Whereas increased NO_X emission can be explained by the fact that addition of oxygen makes the overall mixture leaner and increases excess air coefficient.

Effect on Hydrocarbon emission

Choi et al., 2015 observed that at 10% butanol content hydrocarbon emission was found to be lower than pure diesel due to increased combustion temperature. However higher butanol content containing 20% butanol in the blend showed higher hydrocarbon emission than neat diesel at low load engine conditions. An interesting trend was observed by Siwale et al., 2013. They reported that at 1500 rpm with increasing butanol content hydrocarbon emission increases. But at 3000 rpm beyond 25% load the hydrocarbon emission is generally reduced. At low loads due to lower cetane number, lower evaporation and higher heat of evaporation of butanol blends improper fuel air mixing occurs. This leads to formation of 'lean outer flame zone' leading to enhanced formation of hydrocarbons. Improvement in air fuel mixing as in higher loads reduces hydrocarbon emission. Rakopolous et al., 2010 observed that increase of butanol content in the blend increases hydrocarbon emissions at all load conditions

Effect on Smoke emission

Rakopolous at al., 2011 compared the smoke emissions of 5% and 10% ethanol diesel blends and the same percentages of butanol diesel blends with neat diesel. They observed that increasing percentages of either biofuel decreased the smoke emissions compared to diesel. This may be attributed to the presence of oxygen molecule in local fuel rich zones which enhances combustion and reduced smoke.

Kumar et al., 2016 compared the smoke emissions of ultra low sulfur diesel to each of 30% blend of octanol, heptanol, pentanol and isobutanol. He observed that 30%isobutanol blend showed the lowest smoke emission compared to diesel and other higher alcohols. Kumar and Sarvanan, 2015 investigated the effect of iso-butanol addition to diesel fuel on smoke emissions of a single cylinder direct-injection diesel engine. Test fuels used were four iso-butanol/diesel blends containing 10%, 20%, 30%, and 40% iso-butanol prepared on volume basis. They observed that smoke opacity decreasedasiso-butanol content increases in the blends. This may be attributed to the oxygenated nature of iso-butanol blend. The presence of oxygen in iso-butanol aids the combustion by enhancing fuel–air mixing in fuel-rich zones and also lowers chances of soot-nuclei formation during diffusion combustion period.

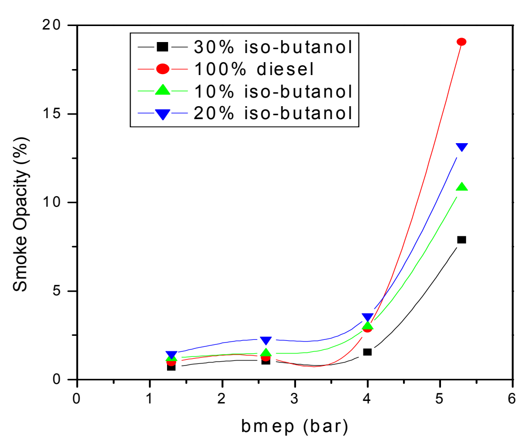

Figure 7: Variation of Smoke Opacity for pure diesel and various percentages of iso-butanolblend.

CONCLUSION

In the present study we have investigated the effect of butanol blends with diesel on the engine performance and emission of a compression ignition engine. From the above investigation it can be inferred that

- Brake specific fuel consumption increases with increase in percentage of butanol in the blend. This is mainly due to lower energy content of butanol compared to that of diesel fuel hence more consumption.

- Brake thermal efficiency increases as we increase the butanol content in the blend. This occurs due to presence of oxygen thatenhances combustion, leading to complete combustion of fuel. Lower cetane number can also be considered a significant factor for increase of brake thermal efficiency.

- Increase of butanol percentage in blend decreases soot emission. Butanol being an oxygenated fuel, oxygen atoms enter fuel rich region and consume soot precursor by formation of hydroxyl radicals. Also the higher latent heat of vaporization of butanol than diesel and higher ignition delay of prolongs combustion, resulting in reduction of soot emission.

- NOx emission may increase or decrease depending on the butanol content of the fuel. Presence of low amount of butanol decreases NOx emission due to lower cetane numberand lower heating value of butanol-diesel blend, along with higher latent heat of. However increase of butanol content beyond certain percentage increases NOx emission. The oxygenated fuel enhances combustionleading to intensive premixed combustion causing an increase of NOx emission.

- CO emission will increase or decrease is still uncertain. Some authors found an increase in CO emission with increasing butanol content whereas some observed the reverse.

- Exhaust gas temperature decreases with increasing butanol content in the blend but a significant decrease was not noted in many cases. Decrease of exhaust gas temperature with increasing butanol content can be explained by the fact that due to the lower energy content of the blends the released heat is lower for the same quantity of fuel which leads to reduced EGT. The higher latent heat of evaporation of the fuel is also responsible for reduction of exhaust gas temperature.

- THC emission increases with increasing concentration of butanol in butanol diesel fuel blend. Theories given in favour of increasing THC emission are slower evaporation and poorer fuel–air mixing due to the higher heat of evaporation of the butanol blends.

REFERENCES

Sahin Z. and Aksu O.N., 2015. "Experimental investigation of the effects of using low ratio n-butanol/diesel fuel blends on engine performance and exhaust emissions in a turbocharged DI diesel engine," Renewable Energy, **77**:279-290.

Zhang Z.-H. and Balasubramanian R., 2014. "Influence of butanol–diesel blends on particulate emissions of a non-road diesel engine," Fuel, **118**:130–136.

Rakopoulos D.C., Rakopoulos C.D., Giakoumis E.G., Dimaratos A.M. and Kyritsis D.C., 2010. "Effects of butanol-diesel fuel blends on the performance and emissions of a high-speed DI diesel engine," Energy conversion and management, **51**:1989-1997.

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, **89**:2781–2790.

Rakopoulos D.C., Rakopoulos C.D., Papagiannakis R.G. and Kyritsis D.C., 2011. "Combustion heat release analysis of ethanol or n-butanol diesel fuel blend in heavy-duty DI diesel engine," Fuel, **90**:1855–1867.

Choi B. and Jiang X., 2015. "Individual hydrocarbons and particulate matter emission from a turbocharged CRDI diesel engine fueled with n-butanol/diesel blends," Fuel, **154**:188–195.

Choi B., Jiang X., Kim Y.K., Jung G., Lee C., Choi I. and Song C.S., 2015. "Effect of diesel fuel blend with n-butanol on the emission of a turbocharged common rail direct injection diesel engine," Applied Energy, **146**:20–28.

Karabektas M. and Hosoz M., 2009. 'Performance and emission characteristics of a diesel engine using isobutanol–diesel fuel blends," Renew Energy, **34**:1554–1559.

Siwale L., Kristof L., Adam T., Bereczky A., Mbarawa M., Penninger A. and Kolesnikov A., 2013. "Combustion and emission characteristics of n-butanol/diesel fuel blend in a turbo-charged compression ignition engine," Fuel, **107**:409–418.

Hajba L., Eller Z., Nagy E. and Hancsok J., 2011. "Properties of diesel-alcohol blends. Hungarian Journal of Industrial Chemistry," VESZPREM. **39**(3):349-352.

Szulczyk K.R., 2010. "Which is a better transportation fuel- butanol or ethanol? International Journal of Energy and Environment," **1**(1).

Dogan O., 2011. "The influence of n-butanol/diesel fuel blends utilization on a small diesel engine performance and emissions," Fuel, **90**:2467–2472.

Tingbo Z., Zhiyu H., Zheng C., Biao J. and Yun L., 2012. "A Study on a Passenger Car Diesel Engine Fueled with Butanol-Diesel Blend under Typical Operating Condition," Applied Mechanics and Materials, **190-191**:1345-1350 © (2012) Trans Tech Publications, Switzerland.

Zhang T., Munch K. and Denbratt I., 2015. "An experimental study on the use of butanol or octanol blends in a heavy duty diesel engine,"SAE Int. J. Fuels Lubr., **8**(3).

Kumar V., Gupta D., Siddiquee M.W.N., Nagpal A. and Kumar N., 2015. "Performance and Emission Characteristics of n-Butanol and Iso-Butanol Diesel Blend Comparison," SAE Technical Paper 2015-01-2819, 2015, doi:10.4271/2015-01-2819.

Chen Z., Liu J., Han Z., Du B., Liu Y. and Lee C., 2013. "Study on performance and emissions of a passenger-car diesel engine fueled with butanol-diesel blends," Energy, **55**:638-646.

Balamurugan T. and Nalini R., 2014. "Experimental investigation on performance, combustion and emission characteristics of four stroke diesel engine using diesel blended with alcohol as fuel," Energy, **78**:356-363.

Yusri M., Mamat R., Ali O. M., Aziz A., Akasyah M. K., Kamarulzaman M. K., Ihsan C. K., Mahmadul H. M. and Rosdi S. M., 2015. "Combustion and emissions characteristics of a compression ignition engine fueled with n-butanol blends," 3rd International Conference of Mechanical Engineering Research (ICMER 2015).

Al-Hasan M.I. and Al-Momany M., 2008. “The effect of iso-butanol-diesel blends on engine performance,” Transport, **23**:306–310.

Swamy R.L., Chandrashekar T.K., Banapurmath N.R. and Khandal S.V., 2009. “Impact of Diesel-butanol Blends on Performance and Emission of Diesel Engine,” Oil Gas Res., **1**:101.

Yao M., Wang H., Zheng Z. and Yue Y., 2010. “Experimental study of n-butanol additive and multi-injection on HD diesel engine performance and emissions,” Fuel, **89**:2191–2201.

Wu J., Zhu L., Wang Z., Xu B. and Wang H., 2014. “The Study about Combustion and Emission Characteristics of n-Butanol/Diesel Fuel Mixture,”Applied Mechanics and Materials, **492**:335-340 c© (2014) Trans Tech Publications, Switzerland.

Chen G., Yu W., Li Q. and Huang Z., 2012. “Effects of n-Butanol Addition on the Performance and Emissions of a Turbocharged Common-Rail Diesel Engine,” SAE Technical Paper 2012-01-0852, 2012, doi: 10.4271/2012-01-0852.

Kumar B.R., Saravanan S., Rana D. and Nagendran A., 2016. “A comparative analysis on combustion and emissions of some next generation higher-alcohol/diesel blends in a direct-injection diesel engine,”Energy Convers. Manag., **119**:246–256.

Kumar B.R. and Saravanan S., 2015. “Effect of iso-butanol addition to diesel fuel on performance and emissions of a DI diesel engine with exhaust gas recirculation,” ProcIMechE Part A: J Power and Energy, **230**(1):112–125.