ID: 2016-ISFT-356

Butanol as a CI Engine Fuel: A Review

Sidharth[1], Yougender Singh[2], Parvesh Kumar[3], Harveer Singh Pali[4], Naveen Kumar[5]

[1]*Maharaja Agrasen Institute of Technology, Delhi, India*
[2]*Asst. Commandant, Indian Coast Guard*
[3,5]*Delhi Technological University, Delhi, India*
[4]*Noida Institute of Engineering and Technology, Noida, India*
[1]*sidraje2002@yahoo.com*

Abstract: *Oxides of nitrogen and smoke are the most critical emissions from diesel engines which cause serious environmental degradation when liberated in atmosphere. Fuels like alcohol contains large oxygen content and have enormous potential to reduce exhaust emissions. Butanol is a very promising alcohol covered in this survey, namely n-butanol. Based on the published literatures available up today, the study focuses on all major exhaust emissions of butanol blends in compression ignition (CI) engine, i.e., carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x) and smoke. The study also describes the effects of butanol blends discussed in various literatures on the performance of the CI engine which comprises of brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC). Exhaust gas temperature effects were also analyzed for the butanol content in the fuel blends.*

Keywords: Butanol, Exhaust emissions, Thermal efficiency

1. INTRODUCTION

In the present era of energy crisis, the world is crumbling to find the ways that can help in satisfying the current demand. The fuels which are available to us will be exhausted soon and the entire machinery dependent upon them will come to a halt. Various alternatives are available in the market; however, most of them are not easy to be commercialized. Since compression ignition (CI) engines have been employed in most of the heavy applications, the main focus of the researchers is to find the substitute that can stabilize the demand and also help in finding the solution for global concern of environmental degradation.

There are various biofuels that have been developed in the past including vegetable oils, different methyl and ethyl esters (biodiesels), bio-dimethylether, bio-hydrogen, bio-alcohols etc. Biodiesel is one of the best suited alternatives for the current diesel fuel as it possesses comparable properties to diesel fuel and can also be blended with diesel fuel in any proportion, without any changes in the existingsetups[1,2].

Biodiesel still posses many disadvantages which includes poor atomization, incomplete combustion, fuel system clogging and higher NOx formation. A simple approach that is employed in spark ignition engineis by the addition of alcohols. Alcohols assist in proper atomization and a replacement of fuel in a gasoline engine. Usage of alcohols in CI engine is supposed to provide the same benefits.

The major problem faced in a CI engine for blending with diesel engine fuel is its non miscibility nature. The use of alcohol blended with diesel was a subject of research in the 1980s and it was shown that alcohol–diesel blends were technically acceptable for existing diesel engines [3].

The relatively high cost of ethanol production at that time meant that the fuel could only be considered in cases of fuel shortages. Butanol is one of a primary alcohol type and found to be a very attractive fuel for diesel engine because of its renewable nature. The other benefits include its miscibility in diesel fuel and its oxygenated nature which hereby results in reduction in emissions in a compression ignition engine [4].

In this review, the engine performances of blends are discussed. The paper focuses on the performance parameters namely, brake thermal efficiency, brake specific fuel consumption and regulated exhaust emissions i.e. carbon monoxide (CO), nitrogen oxides (NOx), and unburned hydrocarbons (HC), smoke and exhaust gas temperature.

2. PROPERTIES OF N-BUTANOL

Butanolis a mainly arenewable fuel derived from biomass that can be produced by fermentation of sugar cane, corn and wheat. Secondary source of butanol is petroleum. Butanol ($CH_3(CH_2)_3OH$) is a 4-carbon structure and is a higher-chain alcohol which can form a straight chain or a branched structure, thus resulting in different properties. Consequently, it exists as different isomers depending on the location of the hydroxyl group (–OH) and carbon chain structure, biomass tending to yield mainly straight chain molecules. 1-butanol, better known as n-butanol (normal butanol), has a straight-chain structure with the hydroxyl group (–OH) at the terminal carbon [5].

N-butanol is of particular interest as a renewable biofuel as it is less hydrophilic, and possesses higher energy content, higher cetane number, higher viscosity, lower vapor pressure, higher flash point and higher miscibility than ethanol, making it more preferable than ethanol for blending with diesel fuel [5]. Therefore, the problems associated with lower alcohols of non miscibility are solved to a considerable extent when using n-butanol [6].

However, at the moment, its production rate by ABE (acetone butanol ethanol) fermentation is much lower than that of the yeast ethanol fermentation process, a fact explaining the much more vigorous research on ethanol compared with n-butanol during the last decades, particularly after the petroleum crisis in the 1970s [5].

The literature concerning the use of n-butanol/diesel fuel blends in diesel engines and its effects on their steady-state performance and (exhaust) emissions is limited, but with a steadily rising trend. An early study by Yoshimoto et al. [7] dealt with the performance and exhaust emission characteristics of a diesel engine fueled with vegetable oils blended with oxygenated organic compounds, including n-butanol. Rakopoulos et al. published results from an experimental investigation on a high-speed DI diesel engine [8], and on a medium-duty diesel engine [9] during steady-state conditions.

These studies revealed the beneficial effects of using various blends of n-butanol with diesel fuel on smoke and CO emissions at various loads, however at the expense of higher NOx and HC emissions. Again, it is the high oxygen content of n-butanol that leads to enhanced in-cylinder soot oxidation, which is responsible for the decrease in smoke emissions. Similar results were reached by Yao et al. [10], Lujaji et al. [11] (croton oil was included in the fuel blend) and Dogan [12], all referring to steady-state experimentation. As is also the case with biodiesel and ethanol blends, engine operation with n-butanol/diesel fuel has been found to have slightly higher specific fuel consumption as well as a slight increase in brake thermal efficiency.

TABLE 1. Properties of ethanol, n-butanol and diesel fuel (13, 14)

Properties	Diesel Fuel	n-butanol	Ethanol
Chemical Formula	$C_{14.09}H_{24.78}$	C_4H_9OH	C_2H_5OH
Specific Gravity	0.85	0.81	0.79
Boiling Point (°C)	190-280	108.1	78.3
Net Heating Value (MJ/kg)	42.6	33	27
Heat of Vapourisation (KJ/kg)	600	578.4	900
Octane Number	N.A.	94	92
Cetane Number	42.6	< 15	< 15
Stochiometric air/ fuel ratio	14.6	11.1	9
Molecular Weight	193.9	74	46
% of Carbon (wt.)	86.7	64.9	52.1
% of Hydrogen (wt.)	12.7	13.5	13.1
% of oxygen (wt.)	0	21.5	34.7
C/H ratio	6.8	4.8	4.0

Table 1 summarizes the most important physical and chemical properties of n-butanol and ethanol considered in this review against those of the reference diesel fuel.

From the data provided in Table 1 it can be concluded that butanol, with respect to the diesel fuel, contain/have:

- Much lower cetane number (CN) (and higher octane number, accordingly). CN represents the ignitability of the fuel, with higher CN leading to shorter ignition delay. The increase in the premixed-phase of combustion originating in the longer ignition delay period of the alcohol-blends results also in a proportionately higher amount of fuel burned under constant volume conditions, which entails higher cycle efficiency but also elevated combustion noise radiation. The ignitability issues associated with the use of alcohols in diesel engines are more prominent during cold starting.
- Lower heating value owing to the oxygen content (greater mass needs to be injected in order to achieve the same engine power output).
- Lower density, so that volumetrically-operating fuel pumps inject smaller mass of alcohol than conventional diesel fuel.
- Lower flash point, which is a measure of the temperature to which a fuel must be heated such that the mixture of vapor and air above the fuel can be

ignited. Ethanol is way less safe than diesel fuel in that respect.

- Smaller carbon to hydrogen atom ratio (C:H), particularly for ethanol. This affects (reduces) the adiabatic flame temperature.
- Higher heat of vaporization, particularly for ethanol. Thus, larger amount of heat is needed to evaporate the liquid alcohol, which eventually leads to smaller amount of heat remaining for the increase of gas temperature.
- In general, the higher the number of carbon atoms in the alcohol molecule, the lower its oxygen content and hence its potential for soot reduction (as will be discussed later in the text), but also the higher its cetane number, LHV, density, stoichiometric air–fuel ratio and viscosity, thus rendering it more compatible with diesel fuel [15]. Consequently, based on the physical and chemical properties alone, as these are documented in Table 1, n-butanol seems more appropriate than ethanol to be used in a diesel engine. In support to this argument.

After analyzing various physical and chemical properties of the alcohols concluded that n-butanol can be blended with diesel fuel practically at any rate without concerns over stability (above 0°C), viscosity or cold-flow properties, whereas blends up to 35% should only be applied based on potential lubricity problems. On the other hand, various blending limitations occur for ethanol apart from lubricity [15].

3. PERFORMANCE PARAMETERS

3.1 BRAKE THERMAL EFFICIENCY

Rakopoulos*et.al.* [9] observed that for all the butanol/diesel fuel blends, the BTE is slightly higher than that for the corresponding neat diesel fuel case, with the increase being higher the higher the percentage of butanol in the blend. This means that the increase of brake specific fuel consumption (BSFC) for the butanol/diesel fuel blends is lower than the corresponding decrease of the lower calorific value of the blends. This can be attributed to the higher premixed combustion part possessed by the butanol blends because of the lower cetane number of butanol, leading to higher percentage of ‘constant volume’ combustion, and to the lower heat losses (due to the lower average cylinder gas temperatures) and to ‘leaner’ combustion.

Dogan[12] has conducted the experiments on n-butanol-diesel fuel blends and concluded that the brake thermal efficiency (BTE)of the blends was found to be higher than normal diesel fuel. The oxygen content of the fuel blends contributes higher BTE. The improvement in BTE can be referred to the enhanced oxygen content, which aids improvement in combustion, especially during the diffusion combustion phase. Another factor that affects the BTE is cetane number. Lower cetane number of the n - butanol/diesel fuel blends causes to longer ignition delay, thereupon a wider range fraction of fuel burned in the premixed mode, which elevates the BTE. Furthermore, flame/burning speed of fuels is having an important effect on the brake thermal efficiency.

Rakopoulos*et.al*[16] observed that the BTEforn-butanol diesel fuel blends is a little higher than the corresponding one for the diesel fuel case, with this increase being higher the higher the percentage of the bio-fuel in the blend. It is to be noted that the mixture in the case of the n-butanol blends is effectively leaner with respect to the corresponding neat diesel fuel case, as involving the same amount of (naturally) aspirated air and on top of that the fuel-bound oxygen in the bio-fuel. One is hesitant to provide (speculative) explanations for the small differences involved among the four bio-fuels diesel fuel blends showing increased brake thermal efficiency, as there are many unknown factors with usually counteracting effects (spray details, fuel properties, etc) inside the framework of uncertainties in this measurement.

Zhang and Balasubramanian[17] performed an experimental study and concluded that the increase in BTE following the butanol addition can be attributed to the oxygen enrichment coupled with the longer ignition delay associated with butanol’s lower cetane number, which enhances the combustion process and promotes the premixed burning phase. The integrated result shows that butanol addition slightly increased the BTE at medium and high engine loads, but showed a similar level of BTE between B20 and the ternary blends at low engine load

According to the results of Sharon *et.al.* [18],butanol content in the diesel-palm oil–butanol blends increased, BTE increased because of the efficient combustion caused by the presence of oxygen molecule in butanol.

Valentino *et.al.*[19] used 20 % butanol and 40 % butanol with diesel and concluded that the joint effect of higher resistance to auto ignition and higher volatility of n-butanol blends with a some penalty on fuel consumption which in turn decreased the thermal efficiency of the system.

3.2 BRAKE SPECIFIC FUEL CONSUMPTION

Rakopoulos*et.al.* [9] found that for the butanol/diesel fuel blends, the specific fuel consumption is a little higher than the corresponding diesel fuel case, with the increase being higher the higher the percentage of butanol in the blend. This is the expected behavior due to the lower calorific value of the butanol compared to that for the neat diesel fuel, given that the comparison is effected at the same load.

Dogan [12] observed that during engine testing n-butanol/diesel fuel blends slightly increased the BSFC. At the highest engine load for B20 fuel blend, BSFC is increased. The increment in BSFC becomes smaller as the engine load is increased. Generally, the engine consumes more fuel with n-butanol/diesel fuel blends than with reference diesel fuel to generate the same engine output torque because of the lower heat content of the fuel blends. As would expect, the BSFC increases with the increasing n-butanol content in the fuel blends because of the decreased energy content. In addition, lower blending percentages there is not much have significant influence on BSFC

Rakopoulos*et.al.* [16] observed that the bsfc for the butanol blends is higher than the corresponding one for the diesel fuel case, with this increase being higher the higher the percentage of the butanol in the blend. This is the most expected behavior, due to the lower calorific value of all bio-fuels tested compared to that of the neat diesel fuel, thus requiring higher fuel mass flow rates for achieving the same power output as that produced by the corresponding neat diesel fuel case.

Zhang *et.al*. [17] reported that there was a marginal increase in BSFC when the blends contained 5% and 10% butanol. However, it increased to 3.7%, 3% and 2.7% from low to high engine load, respectively, when 15% butanol was added. The high proportion of butanol in the blends reduces the calorific values of blends significantly, resulting in an increased fuel mass needed to obtain the same power output

Sharon *et. al.*[18] used diesel-palm oil–butanol blends and seen that as the butanol content in the blend increased BSFC decreased which might be due to the increased oxygen content of the blend which helps in better combustion of the fuel during premixed combustion phase.

Valentino *et.al.*[19] blended 20 % butanol and 40 % butanol with diesel and concluded that the joint effect of higher resistance to auto ignition and higher volatility of n-butanol blends with a some penalty on fuel consumption.

A comprehensive investigation into n-butanol/diesel fuel blend effects during transients was conducted by Choi *et.al.* [20] and stated that the BSFC of BU20 (i.e. 20 % n-butanol-80% diesel) increases at low load conditions. BSFC of BU20 increase significantly at the higher loads, because of locally incomplete combustion. However, the BSFC values of BU5 (i.e. 5 % n-butanol-95% diesel), BU10 (i.e. 10 % n-butanol-90% diesel) were a little decreased at all loads. The engine consumed less fuel with BU5 and BU10 fuel blends than with D100 (i.e. 100% diesel) reference fuel to generate the same engine output torque, but it increases with BU20. It was confirmed from this experiment that an optimum blending ratio of the butanol in the diesel fuel exists.

Yoshimoto *et.al.*[21] used Palm oil methyl ester and 1-butanol blends. The BSFC (brake specific fuel consumption) increases with the addition of n-butanol in the blend. This order is due to the lower heating value of palm oil methyl ester and 1-butanol, because much larger injected fuel quantities are necessary to maintain the specified output conditions

Sahin and aksu [22] concluded that as lower heating value of n-butanol is smaller than that of diesel fuel, sobsfc takes higher values as n-butanol ratio increases. That is, the engine consumes more fuel to produce the same effective power and consequently bsfc increases. However, in the present study, very large increments in bsfc have not been observed due to using low n-butanol percentages.

4. EMISSION PARAMETERS

4.1 CARBON MONOXIDE

Rakopoulos*et.al.*[9] concluded that the CO emissions were either equal or reduced with the use of the butanol/diesel fuel blends with respect to those of the neat diesel fuel, with this reduction being in general higher the higher the percentage of butanol in the blend.

Dogan [12] compared CO emission levels of n - butanol/diesel fuel blends as a function of engine load. The CO emissions emitted by diesel engine were high at higher engine loads.Iin the present study it is evident that CO emissions reduced with the increasing n -butanol content in the fuel blends. The higher oxygen content of n-butanol/diesel fuel blends can pro-mote the oxidation condition of CO and enhance the complete combustion, resulting in lower BSCO emissions.

According to a study by Sharon *et.al.* [18], at low loads, increased CO emission for blends were due to the high viscosity of used palm oil, low in-cylinder temperature and high latent heat of evaporation of butanol causing quenching effect over the piston and cylinder wall resulting in poor oxidation of CO. At high loads reduced CO formation for the blends was mainly due to the effective oxidation of CO due to the high in-cylinder temperature in combination with the presence of oxygen molecule in fuel blends

Sujit*et.al.* [23] revealed that the CO emissions are lower for the butanol blends at the same oxygen content. This benefit in CO emissions using butanol blends could be due to the lower C/H ratio of alcohols compared to diesel engine fuel. It is further suggested by the authors that this effect compensates for the potential increase in CO with butanol blends due to the higher heat of vaporisation and as a consequence of reducing the in-cylinder temperatures.

Armas*et.al.* [24] found that CO emissions observed with butanol blends were lower than those corresponding to diesel fuel in all the cycles. These trends were mainly due to the presence of oxygen in the composition of the blends. CO values corresponding to the first urban cycle were always the highest for all the tested fuels whereas those obtained in the extra urban cycle are the lowest.

Atmanl.*et.al.* [25] indicated that CO emissions for n-butanol fuels decreased with increasing the engine speed. This could be explained that combustion efficiency increases via higher volumetric efficiency and vortexmotion in the combustion chamber.

4.2 NITROGEN OXIDES

Rakopoulos*et.al.*[9] stated that the NOx emitted by the butanol/diesel fuel blends are slightly lower than those for the corresponding neat diesel fuel case, with the reduction being higher the higher the percentage of butanol in the blend or in half of the cases leveling off. This may be attributed to the engine running overall 'leaner' and the temperature lowering effect of the butanol (due to its lower calorific value and its higher heat of evaporation) having the dominant influence, against the opposing effect of the lower cetane number (and thus longer ignition delay) of the butanol leading possibly to higher temperatures during the premixed part of combustion.

Dogan [12] observed that NOx emissions were decreased with n -butanol/diesel fuel blends during all engine loads. It is well known that the oxygen presence and the temperature in the cylinder have main effect on NOx formation. The increasing oxygen content and lower cetane number of the n-butanol/diesel fuel blends can help to the formation of NOx emissions. The lower cetane number of the n -butanol/diesel fuel blends causes to longer ignition delay, and so leads to higher com-bustion temperature in the premixed combustion mode. Whereas, n-butanol/diesel fuel blends generally have lower flame temperature, due to lower energy content and higher heat of evaporation.As a result of these conflicting factors, the emitted NOX of n-butanol/diesel fuel blends is lower than that reference diesel fuel.

An comprehensive observation by Rakopoulos*et.al.* [16] found that the NOx emitted by all butanol blends are lower than the ones for the corresponding neat diesel fuel case, with this decrease being higher the higher the percentage of the bio-fuel in the blend. This is attributed to the lower temperatures during the combustion period that do not favor NOx formation, which dominate over the extra fuel-bound oxygen bringing possibly more 'zones' near to stoichiometric conditions and little to the lean where NOx formation is favored. The absence of aromatics from the bio-fuels also contributes to less NOx formation

Sharon *el.al.*[18] blended containing butanol with diesel and palm oil which showed reduced NOx emission inspite of their higher oxygen content. This might be due the temperature lowering effect of butanol caused by its high latent heat of evaporation

Valentino *et.al.* [19] compared fuels namely 80% of the baseline diesel and 20% n-butanol by volume, denoted BU20, and 60% in baseline diesel and 40% n-butanol by volume, denoted BU40 and have stated that the addition of butanol in the blends have allowed to reduce NOx. The reason is longer ignition delay is attained using BU20 and BU40 with respect to diesel fuel, leading to a better mixing rate before start of combustion.

Sukjit*et. al.* [23] reported butanol, NOx emissions are higher for butanol than in the case of normal diesel fuels. This difference is due to the lower heat of vaporisation of butanol which is not high enough to compensate for the cetane number effect.

4.3 HYDROCARBONS

Rakopoulos*et. al.* [9] concluded that the total HC emissions were increased with the use of the butanol/diesel fuel blends with respect to those of the neat diesel fuel, with this increase being higher the higher the percentage of butanol in the blend. These may predominantly include: slower evaporation and so slower and poorer fuel–air mixing due to the higher heat of evaporation of the butanol blends, and increase with butanol of the so called 'lean outer flame zone' where flame is unable to exist.

Lujaji*et. al.* [11] observed high Total HC emission at lower loads and maximum loads. The reason for this could be the slightly higher percentage of hydrogen and viscosity values for the blends mainly because of presence of butanol in the blends contributes to an increase in THC emissions.

Dogan [12]showed that n -butanol/diesel fuel blends emitted higher hydrocarbon (HC) emissions than reference diesel fuel. This is mainly due to the combined effects of the lower cetane number and higher heat of evaporation of the blends. Lower cetane number of the n-butanol/diesel fuel blends prolongs the ignition delay, allowing more time for fuel blends to evaporate. Higher heat of evaporation of n -butanol/diesel fuel blends causes slower evaporating, which leads to increase the BSHC emissions. Therefore, the BSHC emission increases with increasing n -butanol content in the diesel fuel blends

Rakopoulos*et. al.* [16] reported that there are higher HC emissions for the butanol diesel fuel blends. It is possibly be attributed to the broadening of the lean spray flame-out region (due to existence of the fuel-bound oxygen) during the relatively higher ignition delay, having the dominating influence. This is the region in which the fuel has already mixed beyond the lean limit of combustion, without then being able to auto-ignite and sustain a fast reaction front.

Sharon *et. al.* [18] revealed that the presence of butanol with low cetane number in the fuel blends, during ignition delay period fuel impingement occurs over engine cylinder wall causing quenching effect resulting in increased HC emission for the blends in comparison to diesel fuel. Increased HC emission for the blends containing butanol might be due to their lower cetane number.

Sahin and Aksu [22] reported that the addition of n- butanol into diesel fuel reduces the viscosity which has great influences on the atomization and spray formation of the injected fuel. Lower viscosity typically results in smaller size of the fuel droplets. Also, the addition of n-butanol may result in microexplosions in the injected fuel, which is attributed to the higher volatility of n-butanol than diesel fuel. These factors could improve the fuel air mixing, which results in over-mixing of fuel. Thus, HC formation could increase.

Sukjit*et. al.* [23] while comparing the butanol blends to diesel fuel, observed that total HC emissions for both ethanol and butanol blends are higher. This means that butanol addition produces higher total HC emissions, mainly due to heat of vaporisation of alcohols, as it is obtained by others especially in low load engine conditions. The higher heat of vaporisation of alcohols results in incomplete combustion. This effect is more influential at low load conditions because the combustion temperature is itself lower than at high load.

Armas*et.al.* [24] concluded the total HC emissions are similar for all ethanol butanol diesel blends, indicating that the higher enthalpy of vaporization of alcohols did not have a great influence on total HC emissions when combustion conditions are not cold. The values of total HC obtained during the 1st urban cycle are higher for all the fuels in comparison with the rest of the urban cycles. These differences in total HC emissions between the cycles were due to the thermal conditions associated to the tests.

Armas*et. al.* [26] found that the total HC concentrations derived from the test of butanol blends were clearly higher than those produced by diesel fuel. The high enthalpy of vaporization of alcohols leads to a great hydrocarbon emission. Fuel evaporation reduces the in-cylinder mean temperature and, in consequence, the temperature during the combustion process, this effect being much more noticeable during cold start.

4.4 SMOKE

Rakopoulos*et. al.* [9] observed that the soot emitted by the butanol/diesel fuel blends is significantly lower than that for the corresponding neat diesel fuel case, with the reduction being higher the higher the percentage of butanol in the blend with the exemption of the low load where it is the same. This may be attributed to the engine running effectively overall 'leaner', since the aspirated air mass remains the same , with the combustion being now assisted by the presence of the fuel-bound oxygen of the butanol even in locally rich zones, which seems to have the dominant influence.

Dogan [12] concluded that smoke emissions are produced by oxygen deficiency, and they are suspended particles in the exhaust system. Smoke opacity of n-butanol/diesel fuel blends as a function of engine load. Generally, soot emissions follow CO trend. It was observed that the smoke opacity was reduced with the increasing n-butanol content in the fuel blends. This trend is due to higher oxygen and lower carbon content of the n-butanol/diesel fuel blends. Since, smoke emissions decrease when the oxygen content of the fuel is increase

Rakopoulos*et. al.* [16] shows the emitted (soot) smoke opacity, where one can observe that the soot emitted by butanol/diesel fuel blends is lower than the one for the corresponding neat diesel fuel case, with this reduction being higher the higher the percentage of butanol in the blend. This is attributed to the combustion being now assisted by the presence of the fuel-bound oxygen even in locally rich zones, which seems to dominate over the lower temperatures (where existent) that render difficult the combustion of the formed soot.

Sharon *et. al.* [18] reported that the blends containing butanol reduced smoke opacity throughout the test because of the presence of oxygen molecule in butanol which would make the fuel to burn in the lean side.

Yoshimoto *et. al.* [21] blended fuel in 40 mass% 1-butanol showed reducing smoke effects mainly due to promotion of soot oxidation reactions, promoted by the oxygen contained in the 1-butanol.

These results discussed by Sahin*et. al.* [22]concluded that n-butanol/diesel fuel blend is a very efficient technique to reduce smoke. The influences of n-butanol addition on soot emission can be explained as follows: (a) adding n-butanol enhances the fueleair mixing, which tends to reduce the formation of soot. (b) adding n-butanol reduces the sulfur content of the fuel, which decreases the soot emission. (c) as an oxygenated fuel, n-butanol has a lower tendency to form soot precursors, such as benzene and poly cyclic aromatic hydrocarbons (d) The use of n-butanol provides leaner running of the engine than that of normal diesel fuel and thus combustion process assisted by the presence of the fuel-bound oxygen of the n-butanol even in locally rich zones.

Armas*et. al.* [24] showed the lower values of smoke opacity with butanol blends indicate that the presence of oxygen in the fuel is the main factor that favors the lower soot generation, especially in local rich zones.

4.5 EXHAUST GAS TEMPERATURE

Dogan [12] concluded that exhaust gas temperature was reduced with increasing n-butanol content in fuel blends with respect to those of the reference diesel fuel.

Rakopoulos*et. al.* [16] observed that the exhaust gas temperatures for the n-butanol diesel fuel blends are a little lower than the corresponding ones for the neat diesel fuel case, with this decrease being higher the higher the percentage of the n-butanol in the blend. It is mainly because of the cylinder temperature histories during the late diffusion combustion period.

Sharon *et. al.* [18] foundthataddition of butanol result in reduction in exhaust gas temperature.This is mainly because of high latent heat of evaporation and lower calorific value of butanol.

Choi *et. al.* [20] compared with the neat diesel fuel, butanol-blended fuel show a little lower exhaust temperatures. Combustion temperatures can be estimated from exhaust temperatures and determined by the heat release rate and the vaporization latent heat of fuels. However, the heat release rate of butanol tends to increase because of its oxygenation.

Rakopoulos*et. al.* [27] reported for the case of n-butanol lower exhaust temperature. It may be attributed also because of n-butanol lower calorific value and higher heat of evaporation, although these can somehow be offset by the opposing effect of the lower cetane number of the n-butanol.

5. SUMMARY

- The summary of the compressive literature review in the former section is discussed below:
- Butanol addition in diesel engine fuel results in reduction of calorific value, kinematic viscosity and density by increasing the blending percentage.
- The BTE of the engine was higher and increases by increasing the percentage of butanol in the blend with any diesel engine fuel and the BSFC of the engine was lower as compared to diesel fuel due to presence of enriched oxygen in the blends.
- The emission of CO, NOx, smoke opacity and exhaust gas temperature were decreased; however, there was slight increase in HC emissions on adding butanol to diesel engine fuel.
- On the strength of comprehensive literature review, it can be concluded that the performance characteristics of butanol-diesel engine fuel blends were nearly similarto that of neat diesel and almost all emissions were lower on these blends.
- The review indicated that higher alcohol namely butanol is a very promising extender to diesel fuel for use in CI engine.

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