Comparison of Ethanol and n-Butanol Blends with Gasoline: A Computational Study

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Abstract – This study investigates the effect of blending ethanol and n-butanol with gasoline on performance and emissions of a four cylinder four stroke spark ignited MPI engine. AVL BOOST was used to simulate the combustion process for different blends of ethanol and n-butanol with gasoline (25%, 50%, 75%, and 100% by volume). The simulation results showed the unburned Hydrocarbon (HC) and Carbon monoxide (CO) emissions have reduced drastically and the oxides of Nitrogen (NOx) emitted is reduced for higher concentration of alcohols when compared with gasoline.

Keywords – AVL BOOST, CFD, Ethanol Blend, n-Butanol Blend.

I. INTRODUCTION

The ability to produce alcohols from renewable resources has made it a potential fuel to replace Gasoline. Ethanol blended fuels are being studied extensively by the researchers and with the advent of advanced technologies in butanol production, Butanol blended fuels are gaining prominence. [1]

Advances in Computational methods and the availability of high speed computers have made it possible for the researchers to simulate and analyse combustion processes in an IC Engine. Experimental study requires enormous time, manpower, material and financial resources. However, the use of Computational Fluid Dynamics (CFD) as a research tool to simulate the process has made it advantageous over experimental study [2].

The present study uses AVL BOOST, a CFD package to simulate the combustion process of different ethanol and n-butanol blends in four stroke, four cylinder MPI engine. The simulation is carried out for different blends of ethanol and butanol (25%, 50%, 75% and 100% by volume) with varying speed at full load condition.

II. METHODOLOGY

The pre-processing steps of AVL Boost enables the user to model a 1-Dimensional engine test bench setup using the predefined elements provided in the software toolbox. The various elements are joined by the desired connectors to establish the complete engine model using pipelines.

In Fig.1, E1 represents the engine C1, C2, C3, C4 represent the four cylinders of the engine. MP1 to MP14 represent the measuring points, PL1, PL2 represent the plenum. SB1, SB2 are for the system boundary and the flow pipes are numbered 1 to 32. CL1 represents the cleaner and R1 to R10 represent flow restrictions.

Fig. 1: AVL BOOST 1D Engine model
The various configurations and parameters are set for each element. The system boundary conditions are specified. It is important to make a correct estimate of the boundary conditions as it directly affects the accuracy of the results.

For the current study Vibe two zone model was selected for the combustion analysis. This model divides the combustion chamber into unburned and burned gas regions [3]. The first law of thermodynamics is applied to each of the zones to predict the rate of fuel consumed with respect to crank angle.

The following equations (1, 2) govern the Vibe two zone model [4]:

\[
\frac{dm_{ub}}{da} = -p_c \frac{dv}{da} + \sum \frac{dq_{wb}}{da} + h_u \frac{dm_b}{da} - h_{gb} \frac{dm_{ub}}{da}
\]

\[
\frac{dm_{ub}}{da} = -p_c \frac{dv}{da} - h_u \frac{dm_b}{da} - h_{gb} \frac{dm_{ub}}{da}
\]

Where
- \( dm_{ub} \) Denotes change of the internal energy in the cylinder
- \( p_c \) Denotes piston work
- \( dq_{f} \) Denotes fuel heat input
- \( dq_{wb} \) Denotes wall heat losses
- \( h_u \) Denotes enthalpy flow from the Unburned to the burned zone
- \( h_{gb} \) Denotes enthalpy due to blow by u and b in the subscripts denote unburned and burned gas.

Prediction of NOx generated by combustion was based on the model by Pattas and Häfner which incorporates the well-known Zeldovich mechanism [5]. The rate of NOx production was estimated by using the following equation (3):

\[
r_{NO} = C_{PPM} \cdot C_{KM} \cdot (2.0) \cdot (1 - \alpha^2) \cdot \frac{r_1}{1 + \alpha K_2} \cdot \frac{r_4}{1 + \alpha K_4}
\]

\[
\alpha = \frac{c_{NO,act}}{C_{NO,eq}} \cdot \frac{1}{C_{PPM}}
\]

Where
- \( C_{PPM} \) Denotes Post Processing Multiplier
- \( C_{KM} \) Denotes Kinetic Multiplier
- \( c \) Denotes molar concentration in equilibrium
- \( r_i \) Denotes reactions rates of Zeldovich mechanism

The amount of CO emissions was predicted using the following equation (4) which was taken from a model presented by Onorati et al[6].

\[
r_{CO} = C_{const} \cdot (1 - \alpha) \cdot (r_1 + r_2)
\]

\[
\alpha = \frac{c_{CO,act}}{c_{CO,eq}}
\]

Where
- \( c \) Denotes molar concentration in equilibrium
- \( r_i \) Denotes reactions rates based on the model

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The mass of CO emissions at any time period is given by equation (5):

\[
m_{crevice} = \frac{V_{crevice} M}{RT_{piston}}
\]

Where
- \( m_{crevice} \) Denotes mass of unburned charge in the Crevices [kg]
- \( p \) Denotes cylinder pressure [Pa]
- \( V_{crevice} \) Denotes total crevice volume [m3]
- \( M \) Denotes unburned molecular weight [kg/kmol]
- \( R \) Denotes gas constant [J/(kmol K)]
- \( T_{piston} \) Denotes piston temperature [K]

n-butanol and Ethanol properties are not pre-defined in AVL BOOST. Hence coefficients for calculating thermodynamic properties of n-butanol were taken from thermodynamic database [8] were added to the BOOST fuel database to simulate the engine fuelled with the blends.
III. RESULTS AND DISCUSSION

The present study concentrates on the emission and performance characteristics of different blends of ethanol and n-Butanol (25%, 50%, 75%, and 100% by volume) with gasoline. E25, E50, E75, E100 denote ethanol blends and B25, B50, B75, B100 denote n-butanol blends. The blends were analyzed using AVL BOOST code at different engine speeds varying from 1000rpm to 5000rpm in steps of 1000rpm. The results are divided into different sub-sections based on the parameter analyzed.

A. Brake Power

The fig. (2) Shows that B25 has the highest power output and E25 has a power output approximately equal to that of gasoline. The gain of the engine power can be attributed to the increase of the indicated mean effective pressure for alcohol blended fuels [9]. With the increase in alcohol percentage, the density of the mixture and the engine volumetric efficiency increases and this causes the increase of power [10]. The heat of evaporation of these alcohols is higher than that of gasoline. Further, n-Butanol has a higher Heating value compared to ethanol and thus we observe a higher power output. But with increase in concentration of alcohols, power reduces, which can be attributed to lower heating values of alcohols.

![Fig. 2: Variation of Brake Power with Engine Speed](image)

![Fig. 3: Variation of Brake Specific Fuel Consumption with Engine Speed](image)
Fig. 4: Variation of Carbon Monoxide emissions with Engine Speed

Fig. 5: Variation of Unburned Hydrocarbon emissions with Engine Speed

Fig. 6: Variation of Nitric Oxide emissions with Engine Speed
B. BSFC

The fig. (3) shows that the Brake specific fuel consumption (BSFC) is higher for the alcohol blends compared to gasoline. This behaviour can be attributed to the fact that ethanol and n-butanol have lesser heat content compared to gasoline. BSFC increases with increase in the percentage of alcohol. The heating value of ethanol is approximately 35% less than the values of gasoline [11]. Hence more amount of fuel is required to generate the same amount of power. Further it can be seen that the BSFC is lesser for n-Butanol blends compared to ethanol blends for the same reason that n-butanol has higher heat content than ethanol.

C. CO emissions

The results in Fig. (4) indicate a drastic reduction in the Carbon monoxide (CO) emissions when alcohol blends were used. The generation of CO mainly depends on the operating conditions of the engine and the equivalence ratio [3]. When alcohols are blended with gasoline, the combustion process is enhanced because of the availability of extra oxygen molecule in the fuel and therefore CO emissions are reduced [12]. However, CO emissions are always present in the exhaust due to dissociation of combustion products and the concentration reduces with decreasing combustion temperature [13]. n-Butanol blends have higher CO emissions compared to ethanol blends because they require more oxygen than ethanol blended fuel for complete combustion.

D. HC emissions

The unburned hydrocarbon (HC) emissions indicate the completeness of the combustion process. It depends on many design and operating variables [13]. The Fig. (5) indicates a significant reduction in HC emissions. Experimental studies by Bahattin et al has also showed a similar trend for HC emissions when ethanol was blended with gasoline. This significant reduction in HC emissions is due to the leaning effect and oxygen enrichment caused by alcohol addiction [12].

Also, it can be observed that there is a decrease in HC emissions with increasing speed for all cases. This increased speed results in improved turbulence intensity within the cylinder, which aids for more complete combustion.

E. NOx emissions

Fig. (6) shows the NOx emitted with variation in speed at full load conditions. NOx emissions are higher than Gasoline for E25, E50, B25, and B50. This is due to the availability of oxygen molecule in the fuel which leads to complete combustion and thus rise in peak temperature. However, at higher concentrations (E75, E100, B75, B100) NOx emission decreases. This can be attributed higher heat of vaporization and the decrease in combustion stability with increase in concentration of alcohols [14].

Experimental results have shown that there was an increase in NOx emissions with increase in speed [15]. Similar trend was obtained for all alcohol blends during the simulation.

IV. CONCLUSIONS

The following conclusions can be made from the investigation.

1. Ethanol and n-butanol can be effectively used as oxygenates, which enhance the performance and emission characteristics of SI engine.
2. Using pure ethanol and n-butanol increases the BSFC of the engine.
3. Considerable reduction in HC and CO is observed on using alcohol blends.
4. NOx emissions increase initially and later decrease with increase in concentration of alcohols.

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VI. REFERENCES


