Exergy and energy analysis of 4-stroke single cylinder CI engine using Pongamia-ethanol-butanol fuel blends

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Abstract: Depleting sources of fossil fuels and environmental issues like air pollution and harmful toxic emissions from the combustion of these fossil fuels have made the search for their potential substitutes essential. Biodiesel is found to be one such widely accepted viable option as seen from literature. In this work, Pongamia oil biodiesel, Bioethanol and Biobutanol have been selected for blending with diesel. The analysis of exergy and energy of varying proportions of Pongamia-Ethanol-Butanol blends and diesel as fuels for a 4-stroke, single-cylinder CI engine has been carried out. Further, based on the formed equations, a computer program has been written to obtain the final output characteristics. Four blends namely, D100 (neat diesel), P50E50 (50:50 Pongamia-Ethanol blend), P45E45Bu10 (45:45:10 Pongamia-Ethanol-Butanol blend), P40E40Bu20 (40:40:20 Pongamia-Ethanol-Butanol blend) have been considered for the analysis. P50E50 blend shows a significant decrease in heat loss due to exhaust gases, net energy loss, destructive availability, and increase in energy efficiency, exhaust availability, and available efficiency output characteristics as compared to neat diesel. Hence, it is concluded to be the best potential replacement for diesel fuel from all the considered blends.

Keywords: Biodiesel, Pongamia, energy analysis, exergy analysis, bioethanol, biobutanol.

1. Introduction

Increasing environmental problems and to be able to meet the required energy demand has always been a major concern and challenge for a lot of countries. This is owing to the rapid industrialization and continuous growth of the transport sector. One of the biggest contributors to air pollution are emissions from vehicles and industries. Hence, to counter these problems a replacement or alternative for petroleum fuels is necessary, which would produce lesser emissions and provide better performance characteristics. Some commonly used alternatives for the same by literature are hydrogen, biodiesel, biogas, etc.

Biodiesels have a lot of advantages such as being renewable, non-toxic, high oxygen content, biodegradable and lesser sulphur content, etc., that make them suitable to be used as a substitute to petroleum fuels. But higher viscosity is one of the few problematic properties of biodiesel. Hence, bio
alcohols are widely used as additives to nullify the negative effects of biodiesel. Bioethanol and butanol are commonly used for the same reasons. Ethanol is considered as one of the best fuels for SI engines because of its high-octane number. Also, it is a satisfactory alternative as fuel when mixed with diesel for the CI engines. Improved performance and emission characteristics are observed with this fuel. The major problem that stands in the way of commercial use of ethanol as fuel is its production being dependent on the edible sources which are of high importance and its usage in the healthcare and chemical field. [1]. Butanol is a renewable fuel like ethanol which is based on biomass. Properties like hydrophilic nature, high energy content, high cetane number, low vapor pressure, high miscibility in diesel, high flash point make it a suitable option for being used as a renewable energy source. Butanol also acts as a solution to the issue of corrosion which occurs in the case of ethanol [2].

Production of biodiesel from edible sources has always been a good option. But it has not been commercially feasible since the world population has been exponentially increasing which further has led to the problem of food shortages. Therefore, the inedible feedstock is generally used for biodiesel production. This ultimately leads to a reduction in the cost and usage of petroleum fuels without causing any major changes to the already existing engines. Various feedstocks available for ethanol/butanol biofuel production are: Sugar Feedstocks, Starchy Feedstocks, Cellulose Feedstocks, Lignocellulosic Feedstocks.

Straight Vegetable Oils (SVO) can’t be utilized directly in diesel engines due to its high viscosity which leads to fuel injector choking, reduced atomization of fuel, incomplete combustion, etc. Other issues related to such crude vegetable oils are low volatility, and unsaturated polymer chains. These problems can be lessened by four ways for preparation of biodiesel: pyrolysis, transesterification, dilution with hydrocarbons blending, and Micro-emulsion [3]. Of these methods, transesterification is one of the easiest and most cost-effective way and is widely used to produce biodiesel. In the setup, the reaction between a triglyceride ester and an alcohol which is a glycerin occurs to produce an ester that has a chain of the consequent alcohol. The products obtained from the reaction are glycerol and crude biodiesel. After the reaction time if the layers of biodiesel and glycerol are separable, the process of transesterification can be assumed to be effective. Glycerol being heavier should settle and be used in different enterprises and sold according to its worth. The main advantages of transesterification are that it reduces the viscosity of the biodiesel, lowers the boiling point, flash point, and pour point, and leads to complete removal of glycerides from biodiesel.

Creation of Biodiesel through Transesterification Reaction follows the given step: Blending of alcohol and catalyst, Separation, Alcohol Removal, and Methyl ester wash. There are many vital variables which are called process variables that influence the rate of conversion and reaction. They can be the temperature of the reaction, the proportion in which oil and alcohol are used, or the type of catalytic action.

Because, Alcohol and Biodiesels are not significantly miscible liquids, multiple ways have been derived to prepare their homogenous mixtures to obtain better properties. These are namely: Dual injection method, use of ignition Improvers, Surface Ignition, Spark Ignition methods and Fumigation [4]. Due to irreversibility in the combustion process of fuel in an engine, it is not possible to fully convert the fuel energy to work output due to various mechanical and thermal losses that occur during the whole conversion process. Available energy i.e., the energy left for conversion to work after various losses is known as exergy. Maximum extractable amount of energy available in a system when equilibrium is being maintained with the environment is known as exergy. Calculation of all energy losses, locations where they exist, and the reasons because of which they occur are the focused areas while carrying out energy analysis. Hence, to have better information about the irreversibility during the conversion process and engine efficiency, exergy analysis is performed. It helps in suggesting the possible engine modifications to make the performance characteristics better.

Various work has been done on studying the performance and emission characteristics of CI engine. Manibharathi et al. [5] had shown the characteristics of performance and emission of Pongamia biodiesel with nano-additives at varying load situations for different proportions like 10%, 20%, 30%, and 100% blends. Recently, many authors have worked on energy and exergy analysis of biodiesel blend. Kumar
et al. [6] analyzed the study of biodiesel prepared from Pongamia oil for its characteristics of emission and performance, with cobalt oxide nano additives for B-100 blend on a CI engine. Further, Sravani et al. [7] studied the effect of ZrO2 additive on B20 Pongamia biodiesel blend by varying the proportion of nano additive to 120 ppm, 80 ppm, and 40 ppm. Naveen Kumar et al. [8] also analyzed the impact of titanium oxide nano-additive, on the performance of B20 Pongamia biodiesel blend by varying the proportion of nano additives to 150 ppm, 250 ppm, and 350 ppm. Parvez et al. [9] analyzed the energy of a 4 stroke, single-cylinder engine using diesel- jatropha biodiesel mixtures. The different blends considered in the study were B0, B10, B20, B30, and B40. Balasubramanian et al. [10] studied the energy & exergy for a four-stroke, single-cylinder engine using blends of Pongamia and neem biodiesel as dual biodiesels. Later, Meisami et al. [11] did an economic study on energy & exergy for a diesel engine fueled with castor oil biodiesel of six different mixture blends (B0, B5, B10, B15, B20, B30) on a commercial engine. Kavitha et al. [12] performed the analysis of exergy-energy on jatropha biodiesel with diesel- ethanol blends in a CI engine. The blends included in the study were D100, D90J7.5E2.5, D95J3.75E1.25, D98J1.5E0.5. Panigrahi et al. [13] studied the analysis of exergy, and energy for a CI-engine using Polanga-oil methyl ester as a fuel on CI engine with blends of PB20 (20%polanga biodiesel and 80% diesel) and diesel. Jannatkhah et al. [14] demonstrated mathematical modelling including chemical reactions, energy conservation, and complete exergy analysis. Blends of sunflower, corn, canola, and restaurant waste oil biodiesels were produced and the results were compared for the exergy and energy parameters for these fuels. Panigari et al. [15], determined the mathematical model based on chemical reactions of energy-analysis for a steady flow system, energy-analysis for considered study experiment, breakdown of fuel energy exergy analysis, and breakdown of fuel exergy. Comparative results of B20 blend of Simarouba oil biodiesel and neat diesel were considered to draw the results. A study by Ramalingam et al. [16] deals with the analysis of the impact of butanol on engine performance and emission characteristics of a CI engine using Pongamia biodiesel blend with Ethanol. Later, Kul et al. [17] performed the energy-exergy analysis on a mono- cylinder CI engine using Safflower biodiesel, diesel, and bioethanol blends.

In this study, energy-exergy analysis of various blends of Pongamia biodiesel–Diesel has been done for a diesel engine. Pongamia oil possesses properties like high flash point, calorific and cetane number which are similar to that of diesel. Also, karanja seeds are easily accessible and the oil extracted falls in the category of non-edible oils, all these factors make it an excellent choice for the production of biodiesel as the use of these oils are limited. To nullify the negative effects of biodiesel, additives in the form of alcohols are widely used. Ethanol is considered as one of the best fuels for SI engines because of its high-octane number. Just like ethanol, properties like hydrophilic nature, high energy content, high cetane number, low vapor pressure, high miscibility in diesel, high flash point make butanol a suitable option for being used as a renewable energy source. Based on the literature available on ‘biodiesel blends analysis for energy and exergy’, it was observed that very few studies for energy and exergy analysis on alcoholic biodiesel fuels have been carried out. No energy-exergy analysis for Pongamia-Ethanol-Butanol blended biodiesel has been done. Dependence of heat energy, energy loss, and energy-exergy efficiency on exhaust gas temperature for the considered blends have not yet been taken into consideration. Therefore, work on energy-exergy characteristics of Pongamia-Ethanol-Butanol blended biodiesel of ratios (P50E50, P45E45B10, P40E40B20) on a CI engine with has been undertaken. Parameters including heat energy lost, energy efficiency, input availability, exhaust gas availability, destructive availability, and available efficiency will be determined and depicted through graphs. Calculations using equations based on chemical reactions are demonstrated in this energy-exergy analysis. P50E50 blend was observed as the optimum blend ratio since it gave the highest energy and exergy efficiencies for all the brake power values. Further, the deviation of mean values of the other properties considered for P50E50 blend compared to neat diesel is 20.39% decrease, 15.29% decrease, 11.34% decrease, 1.97% increase, 19.50% decrease in \( Q_{\text{exhaust}} \), \( Q_{\text{loss}} \), \( A_{\text{input}} \), \( A_{\text{exhaust}} \) and vs BP respectively.

In the present work, exergy-energy analysis has been carried out by considering D100 (neat diesel),
P50E50 (50:50 Pongamia-Ethanol blend), P45E45Bu10 (45:45:10 Pongamia–Ethanol-Butanol blend), P40E40Bu20 (40:40:20 Pongamia-Ethanol-Butanol blend) fuel blends for a 4-stroke, single-cylinder CI engine.

2. Methodology

2.1. Analysis

Analysis of energy and exergy of has been performed in this section. Assumptions taken for the calculation of energy- exergy, equations for calculating the various parameters of energy and exergy for each blend have been mentioned below.

2.1.1. Energy Analysis

Energy is the capacity of doing work. It can be of two types in thermodynamics, energy in transit, and energy in storage. It can also be called as the first law analysis and to analyse, certain assumptions must be made,

1. The process of combustion in an engine is a steady flow process.
2. A control volume system has been assumed.
3. The potential and kinetic energies of fluid are ignored.
4. Air and exhaust gas are the ideal mixture of gases [18].

2.1.1.1 Energy Balance in a Steady Flow Process

From conservation of energy, it can be considered that the total entering flow of all energy streams in a control volume will be equivalent to the energy rate streams leaving a controlled volume as there is no energy accumulation. According to the assumptions, kinetic and potential energies need to be ignored. So, the equation becomes, [19]

\[ q - w = m(h_2 - h_1) = m\Delta h = m \int_{1}^{2} C_p (T) = C_p (T_2 - T_1) \]  

where \( h \) is enthalpy, specific heat capacity at constant pressure is \( C_p \), \( q = Q/m \) equals specific heat transfer, \( w = W/m \) equals specific work done and \( T \) equals temperature compatible to it.

2.1.1.2 Heat Supplied (\( Q_s \))

\( Q_s \) is the fuel supplied to the engine (in kW). [19]

\[ Q_s = m_f \times \text{L.C.V.} \]  

Where L.C.V. equals lower calorific value of heat source or fuel (kJ/kg), \( mf \) equals mass flow rate of fuel input given (kg/sec).

2.1.1.3 Heat Equivalent of Brake Power (\( Q_{bp} \))

Basically, it is the ratio of brake power output to power input. It is measured in kW. [19]

\[ Q_{bp} = 2\times\pi \times N \times T_e \]  

here, \( N \) gives crank revolution/sec and \( T_e \) gives torque produced (kNm).

2.1.1.4 Heat in Exhaust Gases (\( Q_{ex} \)).

It is measured in kW. [19]

\[ Q_{ex} = m_{ge} \times C_{pe} \times (T_5 - T_a) \]
where the mass flow rate of exhaust gas = mass flow rate of fuel + mass flow rate of air (Kg/sec). 
C.pe gives specific heat of exhaust gases (kJ/kg K). T5 gives exhaust gas temperature (Kelvin). Ta equals 293.15 K.

2.1.1.5 **Unaccounted Energy Losses (Q_u)**
Heat lost in the surroundings, friction losses, gas leakage, etc. are some examples of unaccounted losses. It is measured in kW. The difference between the Q_s and the sum of Q_bp and Q_ex gives us the unaccounted losses of the engine. [20]

\[ Q_u = Q_s - (Q_bp + Q_ex) \] (5)

2.1.2. **Exergy Analysis**
For a system, exergy is a property depending on both the system and surroundings. It is the maximum extractable useful work till thermodynamic equilibrium with surroundings are obtained.

The maximum work that can be obtained in a heat engine by providing it a certain heat input is called the available energy i.e. A.E. or the available portion of the energy supplied. According to the second law of thermodynamics, minimum energy which is rejected is called unavailable energy i.e. U.E. or the unavailable portion of the energy supplied [21].

2.1.2.1 **Exergy Balance in Steady Flow Process**
Generally, exergy is not conserved, unlike energy. The difference between exergy in and exergy out is equal to the exergy destroyed for a steady flow process, whereas, in energy, the difference equals zero due to the conservation principle., turbines, etc. are also the control volume systems.

![Figure 1. Available and unavailable energy in a cycle [18]](image)

\[ E_{x, in} - E_{x, out} = E_{x, destroyed} \] (6)

Total exergy of a system is the sum of two types of exergies i.e., thermo-mechanical exergy (e_{tm}) and chemical exergy (e_{ch}).[21]

2.1.2.2 **Chemical Exergy of Liquid Fuel**
Maximum extractable useful work which can be done by a substance till the dead state is reached is called the chemical exergy. It can also be called as the availability in fuel (A_{in}). [21]
ef_{ch} = \{L.H.V. [1.0401 + 0.1728 (H/C) + 0.0432 (O/C) + 0.2169 (S/C)×(1 - 2.0628 (H/C))])

H, C, O and S are the fractions by mass of hydrogen, carbon, oxygen, and sulphur respectively and LHV refers to lower heating value of the fuel used. etm of fuel is zero.

2.1.2.3 Exhaust Gas Exergy
Exhaust gas is assumed to be the mixture of ideal gases, which also means, there is no room for water vapours in it. [19]

\[ e_{etm} = \sum_{i=1}^{n} ai \{h_i(T) - h_i(T0) - T0×[\text{^\text{°}s}(T) - \text{^\text{°}s}(T0) - R \ln (P/P0)]} \]  

(8)

where ai equals coefficient corresponding to component in equation of combustion reaction, \text{^\text{°}s} is the absolute entropy at 1 atm, and R equals gas constant i.e. 8.314 kJ/kmol·K, h is enthalpy (exhaust gas component) at the particular exhaust gas temperature (EGT). etm of the exhaust gas can be written as, [11]

\[ e_{ch} = RT0 \sum_{i=1}^{n} Yi \ln \left( \frac{Yi}{Yie} \right) \]  

(9)

Where, Yi denotes molar ratio (i\text{th} element) in exhaust gas, Yie denotes the molar ratio (i\text{th} element).

2.1.2.4 Shaft Availability (A_s)
This is the power available on the shaft, equal to the brake power developed in the engine (kW). [22]

\[ A_{ex} = Q_{ex} - \{mge ×Ta×\{C_{pe} ln (T5/Ta)- R ln (Pe/Pa)} + ech \} \]  

(10)

Here, R refers to specific gas constant in kJ/kg K. Pa is the atmospheric pressure which equals to 1 atm in N/m². Pe, which is final pressure of exhaust gas in N/m², is 293.15K. mge denotes the mass (exhaust gas measured in kg/s). T5 denotes exhaust gas temperature (EGT) in Kelvin, C_{pe} (average specific heat of exhaust gas) which can be evaluated by adding the product of the molar fraction of the particular exhaust gas and their specific heats at particular exhaust gas temperature [21].

2.1.2.5 Exhaust Gas Availability (A_{ex})
This is also measured in kW. [21]

\[ A_{ex} = Q_{ex} - \{mge ×Ta×\{C_{pe} ln (T5/Ta)- R ln (Pe/Pa)} + ech \} \]  

2.1.2.6 Destructive Availability (A_d)
It is measured in kW. [20]

\[ A_d = A_{in} - (A_s + A_{ex}) \]  

(11)

2.1.2.7 Exergy Efficiency
It tells us how effective the system is when compared with its performance is compared with that in reversible conditions. It is calculated in %. [20].

\[ \eta_A = \{1 - (A_d/A_{in})\} \]  

(12)

3. Solution Procedure
The first step towards finding the solutions for the particular set of blends was to determine the chemical formula of each blend i.e. P50E50, P45E45Bu10, and P40E40Bu20 for which the composition of fatty acids in Pongamia oil and then their esters were considered. According to the composition of Pongamia, ethanol and the butanol in the blends, the chemical formula for each blend was calculated. Then, the
combustion reaction equation for each blend was established and balanced in each case like the given example below [18].

\[
X_{0.192}Y_{0.225}Z_{1.45} + 14.55(O_2 + 3.76N_2) \rightarrow 10.219XO_2 + 10.12Y_2O + 56.74N_2 \tag{13}
\]

The next step was to calculate AFR and specific heat of exhaust gases. \(m_f\) and \(m_a\) were calculated by calculating mass of fuel and air by [23],

\[
ma = 68.9(C - O/2 + H/4) \tag{14}
\]
\[
mf = 12C + 16O + H \tag{15}
\]
\[
AFR = \frac{ma}{mf} \tag{16}
\]

\(C_{pe}\) was calculated through the formula,

Specific heat of flue gases = molar fraction of exhaust gases / specific heat of exhaust gases \(\tag{17}\)

All the engine specifications, calorific value, EGT, BP and BSFC values for the blends were taken from a research paper [23]. By putting all these values in the formulas used in the energy analysis, \(Q_s\) (heat supplied), \(Q_w\) (work done), \(Q_{ex}\) (heat in exhaust gases) and \(Q_u\) (unaccounted energy losses) can be found. Mass fraction of C, H, O in fuel is calculated by the formula [23],

Mass fraction of the element = Mass of element in the chemical formula / Sum of mass of all elements in formula (C, H, O) \(\tag{18}\)

For the exergy analysis, specific enthalpies and entropies were calculated at exhaust gas temperatures for each case along with their reference environment values. (Specific enthalpy = standard enthalpy at the particular temperature /mass and similar for the specific entropy). Putting all these values in exergy formulas, \(e_{ch}, A_{in}, A_s, A_{ex}, A_d\) can be calculated.

A C++ program was made according to the following steps which are also described in the flow chart below.

1. Input values for composition of fuel (C, H and O) and calorific value or LHV of fuel (inKJ/kg).
2. Calculate AFR, establish stoichiometric equation, mole fraction of exhaust gases, molecular weight of exhaust gas, mass fraction of C, H and O in fuel.
3. Start loop to input four different brake powers (KW) and the corresponding BSFC (Kg/KW-Hr) and EGT (in Celsius).
4. Calculate EGT in kelvin, Mass flow rate of fuel, air and exhaust gases in kg/s and average specific heat of exhaust gases.
5. Calculate heat supplied, work done, heat in exhaust gases, unaccountable energy losses and energy efficiency.
6. Calculate availability in fuel (\(A_{in}\)), shaft availability (\(A_s\)), chemical exergy in exhaust gases (\(e_{ch}\)), total availability in exhaust gas (\(A_{ex}\)), destructive availability (\(A_d\)) and availability efficiency.
7. Display calculated results in tabular form for each brake power for the fuel.
**Figure 2: Process Flow Chart**
4. Results and Discussion

In this study, neat diesel and blends of Pongamia oil biodiesel are used as test fuels. The energy and exergy analysis led to the results shown in figures 3-5 and 6-9 respectively. The trend of input availability, exhaust gas availability, destructive availability, and the exergy efficiency, constituting to exergy distribution for fuels are shown in them.

4.1 Heat Carried Away by Exhaust Gases ($Q_{\text{exhaust}}$):

The general trend from figure 3 shows a steady increase in thermal energy carried away by exhaust gases with an increase in Brake power. $Q_{\text{exhaust}}$ value is dependent on the EGT (exhaust gas temperature), which is higher for complete combustion. Therefore, D100 gives the highest output i.e., 0.329, 0.551, 0.771, 1.033 kW @ 1.256, 2.512, 3.768, 5.024 kW Brake Power respectively. Increasing the ratio of Ethanol and Butanol shows a slight decrease in this property as compared to D100. Due to the difficulty in vaporization of butanol in diesel blend, P50E50 exhibits the maximum output values of all the considered biodiesel—alcohol blends while P40E40B20 gives the lowest output values. They show a decrease of 11.46, 19.28, 25.90, 19.707% and 42.38, 43.84, 42.01, 29.04% respectively, relative to D100 at all BP conditions.

![Figure 3. $Q_{\text{exhaust}}$ v/s Brake Power variation](image)

4.2 Heat Energy Lost ($Q_{\text{loss}}$):

Heat loss in a CI engine is the summation of all energy losses during the combustion process, including the heat carried away by the exhaust gases. Hence, from a general approach, the two characteristics should follow a similar trend. But as can be observed from figure 4, it is not the case. $Q_{\text{loss}}$ shows a steady increase for all blends with an increase in Brake Power. D100 shows the highest $Q_{\text{loss}}$ and the output values increase with increasing butanol ratio in the fuel blend. The unaccounted heat losses in the cylinder are increased because they are dependent on the energy of unburnt fuel and the addition of Butanol promotes the unburnt fuel mass as the frictional losses increase. D100 has the highest energy loss at all BP values 7.894532, 9.359859, 9.912943, 10.920645 kW respectively. Followed by P40E40B20 and the least output is obtained for the P50E50 blend. The percentage decrease in $Q_{\text{loss}}$ values as observed are9.87, 9.40, 18.33, 2.40, and 13.23, 11.58, 22.83, 13.15 respectively, relative to D100 at all BP conditions.
4.3 Energy Efficiency:
There is an increase in the energy efficiency as the brake power for all blends are increased. As is seen from figure 5, for D100, as BP increases the energy efficiency increases to a maximum of 29.591639% @5.024kW while, the highest efficiency for a biodiesel-alcohol blend is found to be of P50E50 blend i.e., 32.754665%, and the lowest is that of P45E45Bu10 which is 30.350193% at the same brake power. It can also be observed that at higher Brake Power values ~ 3.768kW, the curve starts to flatten. The variation of efficiency of biodiesel-alcohol blends relative to D100 is due to the low volatility, marginally lower viscosity, and high density of alcohols as well as lower vaporization that negatively affects homogenous formation of the fuel mixture and causing to incomplete combustion.

4.4 Input Availability ($A_{input}$):
Input availability is directly dependent on better combustion of fuel which is why neat diesel in comparison to the Pongamia biodiesel blends has better output characteristics i.e., 10.13, 13.28, 15.45, 18.15kW @ 1.256, 2.512, 3.768, 5.024 kW Brake Power respectively. Further, due to the higher oxidation property of alcohol additives that leads to better combustion, its increase in fuel blend causes the $A_{input}$ Characteristic output to increase. Among the biodiesel-alcohol blends considered, P40E40Bu20 shows the highest output characteristics and P50E50 gives the lowest. A decrease in output values is found to be 8.97, 8.30, 14.13, 2.54%, and 10.80, 8.95, 16.47, 9.03% respectively for all valves of BP relative to D100.
4.5 Exhaust Gas Availability ($A_{\text{exhaust}}$):
Exhaust gas exergy is the useful portion of the heat carried by exhaust gases. This graph hence follows a similar trend as that of $Q_{\text{loss}}$. D100 shows almost a linearly varying graph of exhaust gas availability. It is observed from figure 7 that by adding Ethanol to biodiesel, a relatively higher output characteristic as compared to D100 is obtained. Whereas, the trend starts decreasing as the ratio of Butanol in the blend is increased. This is because exhaust gas availability is also affected by the EGT and as explained in a prior section, which is why P50E50 shows the highest output among the considered biodiesel-alcohol blends and while P40E40Bu20 shows the least. The increase in the percentage of output values is calculated to be 3.61, 2.50, 1.21, 0.75, and 2.04, 0.34, -1.09, -1.50 respectively relative to diesel for all considered Brake Powers.

4.6 Destructive Availability ($A_{\text{availability}}$):
Destructive availability varies depending on factors like the number of irreversible processes, blending of the reactants during the chemical processes, friction between parts, nature of the combustion-processes, uncontrolled gas expansion, or turbulence inflow in the cylinder, etc. Availability thus is quite a complicated term that varies directly with Brake Power values. From figure 8 it can be observed that D100 shows the highest destructive availability, followed by the P50E50 blend, and the least is shown
by the P40E40Bu20 blend. Decrease in output values for P50E50 and P40E40Bu20 relative to D100 blend is found to be 18.40, 15.17, 28.34, 15.91% and 14.91, 13.46, 23.72, 4.03% respectively for all considered BP values.

Figure 8. $A_{\text{destructive}}$ v/s Brake Power variation

4.7 Available Efficiency ($A_{\text{efficiency}}$):
Available efficiency is majorly dependent on the nature of combustion-processes, engine and fuel atom interaction at different phases of combustion processes. Figure 9 reveals that the least $A_{\text{efficiency}}$ was calculated for D100 at all brake power conditions. Pongamia biodiesel promotes incomplete combustion in comparison to diesel. The addition of alcohol increases the number of oxygen atoms available for combustion thereby increasing the available efficiency. Higher latent heat of vaporization causes poor vaporization in Butanol. Therefore, the increase of Butanol in the fuel causes incomplete combustion and hence we obtain the trend as observed. P50E50 blend gives the highest available efficiency among all the considered fuel blends with the output being 41.96, 42.10, 49.54, and 46.86% at 1.256, 2.512, 3.768, and 5.024 kW Brake Power respectively.

Figure 9. $A_{\text{efficiency}}$ v/s Brake Power variation

5. Conclusions
The performance of fuel blends has been evaluated in terms of $Q_{\text{exhaust}}$, $Q_{\text{loss}}$, energy efficiency, $A_{\text{input}}$, $A_{\text{exhaust}}$, Availability, and $A_{\text{efficiency}}$ characteristics and compared to neat diesel. It has been observed from the results that because of low flame temperatures due to butanol, P50E50 fuel blend shows the lower values of heat lost ($Q_{\text{loss}}$) and destructive availability (Availability) for the constant value of brake power
in comparison to other fuel blends. The energy efficiency as well as availability efficiency has been observed maximum at brake powers in the case of P50E50 fuel blend than other fuel blends. P50E50 blend showed best performance values for $Q_{ex}$, $Q_{loss}$, $\eta_{\text{efficiency}}$, $A_d$ and $A_{\text{efficiency}}$ characteristics. The observed changes in these properties were: 0.203618kW decrease in $Q_{ex}$, 1.435879kW decrease in $Q_{loss}$, increase of 3.163026%, in efficiency, 1.659778kW decrease in $A_d$ and increase of 4.344685% in $A_{\text{efficiency}}$ at 5.024kW BP as compared to performance of D100 under similar operating conditions. The variation of efficiency of biodiesel-alcohol blends relative to D100 is due to its low volatility, higher density and marginally higher viscosity which leads to slow combustion of the fuel due to their impact on mixture formation. It is further observed that the P50E50 blend can be considered the best fuel blend among other blends. This work shows the potential of alcoholic fuel blends which are cleaner and renewable energy sources to replace diesel partially.

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