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Energy Analysis of a Single Cylinder 4-Stroke Diesel Engine Using Diesel and Diesel-Biodiesel Blends

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Abstract

In today's scenario, the energy crisis has become the global challenge for sustainable growth. The conventional fuels are depleting day by day and hence it becomes necessary to switch towards alternative fuels. These alternative fuels are still in their developing stage as the cost of production is high and technological advancement is not enough to match the existing gaps. One of the most popular alternative fuels that is grabbing attention for a diesel engine is Biodiesel. Although many researchers have done a lot of work on the performance and emission analysis of a diesel engine using biodiesel and diesel-biodiesel blends, still there are many concerns which require attention. In this paper, energy analysis of single cylinder water cooled 5 HP diesel engine has been done. Based on energy analysis, a comparison has been done for diesel and diesel-biodiesel blends. At different loading condition, the performance of the engine has been investigated. The percentage energy utilized in each component of the engine at the various loads for each fuel blends are presented. A smooth characteristic for each performance parameter has been observed when pure diesel was used in the engine. Whereas energy lost in the case of diesel-biodiesel blends in exhaust gases and in unaccounted losses do not maintain a smooth trends. At higher engine load, all the fuel blends show a lower value of brake specific fuel consumption (BSFC) while the fuel blend with their ratio as 20% biodiesel and 80% diesel by volume (B20) gives the lowest value. The brake thermal efficiency for B20 is highest when the engine worksat maximum loading condition. The present analysis reveals that lower the biodiesel content in the fuel blends lower the value of heat release rate (HRR) for all loading conditions. Whereas, B20 gives the lowest value of HRR when the engine working in higher loading condition.

Keywords: Engine, Diesel, Biodiesel, Combustion, Energy analysis, Performance analysis.

Nomenclature

BP	*Brake Power*
FP	*Friction Power*
IP	*Indicated Power*
BTE	*Brake Thermal Efficiency*
ITE	*Indicated Thermal Efficiency*
CR	*Compression Ratio*
m_a	*mass flow rate of air*
m_f	*mass flow rate of fuel*
A/F	*Air fuel ratio*
NCV	*Net Calorific Value*
BSFC	*Brake Specific Fuel Consumption*
HRR	*Heat Release Rate*

Symbols

H	*Heat/Energy*
η	*Efficiency*
T	*Torque*

Subscripts

bp	*Brake power*
w	*Water*
un.	*Unaccounted loss*
ex	*Exhaust*

INTRODUCTION

Energy is the most necessary part of day to day life for sustainable development. Although energy can't be created as the first law states, it can be converted from one form to other. The better the conversion process, lower will be the loss of energy. Hence, the conversion process is very important from efficiency point of view. The availability of the fuel for conversion is depleting rapidly and hence, it becomes necessary to reach out towards some alternatives. Different alternative fuels have been developed to overcome the present energy crisis. For diesel engine, biodiesel is one of the most popular options available nowadays. The existing diesel engine creates issues while operating using pure biodiesel as a fuel. From the literature, it has been observed that pure biodiesel does not show better performance and emissions. Felipe Soto et al. [1] evaluated the behavior of biofuels and fossil fuel using thermal analysis, thermogravimetry and performance tests of the engine. Both the tests were conducted in different conditions; it was observed that for best combustion performance at the lower heating rate and at atmospheric pressure, diesel-biodiesel blend should be used. The B20 blend was concluded to be the best. Raheman et al. [2] conducted experiments on a 10.3 kW direct injection water cooled single cylinder diesel engine to check its performance with blends of diesel and biodiesel (B10 and B20). Biodiesel was used to decrease harmful emissions and hence performance analysis was done to check its effect on engine wear. By increasing concentration of biodiesel blends, it was found that BSFC and EGT increased by 2.49% and 4.44% respectively, and BTE decreased by 1.48%. Venkateswara Rao [3] investigated the possibility of utilizing biodiesel produced using ethanol and methanol by conducting experiments on a diesel engine. They concluded that pure diesel gave a higher value of brake thermal efficiency as compared to that when diesel-biodiesel blends were burned. Hoseini et al. [4] reviewed the strategies which were already proposed for reducing emissions in a diesel engine. Combustion management, usage of fuel additives, and after-treatment technology are few of the most effective strategies. Using biofuels is seen as the best-proposed solution for reducing the emissions. It was also recommended that higher compression ratio and an increased fuel injection pressure must be considered when the engines with turbochargers are used. JinlinXue et al. [5] reviewed various reports in 2011, to check the effect of biodiesel on engine performance, durability, economy and emissions. Biodiesel reduces PM, CO and HC emissions, decreases carbon deposit and wear of the engine components but leads to power loss, increased fuel consumption, and increased NOx emissions from conventional diesel engines. Usage of biodiesel blends with a small volume of biodiesel, instead of using pure diesel, can help in curbing pollution. Buyukkaya [6] analyzed and compared the effects of rapeseed oil and its blends on an unmodified engine, and that of pure diesel on the performance and combustion characteristics of the engine. At a higher speed, the torque for B5 was higher than diesel. Through tests, it was observed that low concentration blends would be the best solution for the engines. Qi et al. [7] have done experimental analysis for combustion and emission characteristics. At higher engine load a large decrease in smoke and CO emissions was observed. Combustion of diesel-biodiesel blends gives a higher value of peak heat release rate and peak pressure rise rate at lower engine loads. Vijay et al. [8] studied the results of diesel and mahua biodiesel blended fuel, indirectly injected into a diesel engine by making modifications in the nozzle orifice diameter. The performance and emissions were analyzed for nozzles with three different aperture diameters of injection holes. It was observed that smaller orifice diameter gives better brake thermal efficiency and BSFC. The emission characteristics show that HC, CO and smoke capacity decreases with a decrease of hole diameter, but NOx emission increased. Smaller orifice resulted in highest MGT on increasing BP, due to good atomization, increased cone angle and air-fuel amalgamation. Maximum peak pressure was increased for smallest orifice due to high MGT. Ozer et al. [9] investigated the effects of blending canola biodiesel with diesel on a single cylinder direct injection diesel engine, at four load values and at 2200rpm speed. Canola biodiesel showed slightly earlier SOI and SOC, but shorted ID periods, due to the higher value of cetane number and lesser aromatic content. Increasing canola biodiesel volume decreases the maximum heat release rate at previous locations. For B20, BSFC improved to reach 6.56% and BTE decreased to 4.2% at high load. But the NOx emission values gradually increased (max 8.9%) with increasing volume of canola biodiesel, and emissions in the form of CO and HC decreased (max 32%), with blends B20 fuel at higher engine load. Smoke emissions reduced by a maximum of about 53.5%. Patel et al. [10] performed experimental analysis to study performance and emission characteristics of the diesel-biodiesel blend on an engine with a single cylinder, at varying compression ratios (14, 16 and 18). It was seen that with an increase in compression ratio BTE increased and BSFC reduced, while brake power remained unchanged. Emission of CO, CO2, and HC decreased with an increase in compression ratio, whereas NOx emission increased. Thus, best result was obtained with B20 biodiesel blend at a compression ratio of 18. It was also recommended that use of biodiesel blends would require modification in the injection system of the engine as biodiesel is more viscous as compared to diesel.

Shahmirzae et al. [11] used irreversible heat transfer conditions to investigate an air-standard cycle for a diesel engine. The model estimated and analyzed the output work and thermal efficiency values of this cycle with diesel, biodiesel and B20, under different values of cut-off ratio and compression ratio. As the engine design parameters were changed, the output work of the engine increased with compression ratio, and the maximum work output was observed at certain compression ratio. Hike in the value of compression ratio beyond this value decreased the output work. When the cut-off ratio of the engine increased uniform characteristics were observed for all fuels, which show a decrease in output work and in thermal efficiency of the engine. It was concluded from simulations that the performance of B20 blend fuel is same as that of diesel fuel and hence B20 is recommended as an alternative fuel for conventional diesel engines. Therefore, diesel engines are not needed to be modified to burn diesel-biodiesel blends, especially for B20. Tomas et al. [12] stated that for full engine load at rated speed, the auto-ignition delay period increased by 0.6%, 1.2%, 4.6% and 13.5% respectively. The minimum BSFC increased by 0.4%, 4.6%, 7.1%, and 14.9%, respectively, when the engine was operating on biodiesel fuel blends B10, B20, B40 and B60 in comparison to diesel fuel. Maximum BTE was unaffected when the engine is operating at full load condition. Kumaresh et al. [13] performed an experiment at various loads using rubber seed oil (RSO) and its diesel blends in a 4-stroke direct injection single cylinder diesel engine running at constant speed. The conclusions from their experimental work show that diesel has a much better performance than pure RSO and its blends. The optimum blend of RSO is B20 due to 6.5% increase in BTE as compared to pure RSO in full load condition. Due to lower combustion rate of vegetable oil, higher exhaust gas temperature was observed in full load condition for all RSO blends as compared to pure diesel. Small decrease in BTE of

0.1% and 1.1% were investigated at brake mean effective pressures of 1.160 bar and 5.320 bar respectively by replacing diesel with blends of biodiesel [14]. Ashish et al. [15] experimentally investigated that with increase in biodiesel content in diesel-biodiesel blend, BSFC increases. Whereaspure biodiesel gives highest BSFC at all loads. From the detailed literature survey it was concluded that the optimum blend is B20 which can be used successfully in a CI engine without modification but with a marginal compromise in the engine performance.

MATERIALS AND PROPERTIES

Biodiesel

The fuel was prepared in the laboratory using Jatropha seeds. After fuel preparation, some important properties of biodiesel were measured which are listed below.

Table I. Various properties of biodiesel

S. N.	Property	Value
1	Net Calorific Value	38.829 MJ/kg
2	Density	886.34 kg/m^3
3	Specific gravity	0.887
4	Kinematic Viscosity	5.05 x 10^-6 m^2/sec

Diesel

Following properties of diesel are listed below.

Table II. Various properties of diesel

S. N.	Property	Value
1	Net Calorific Value	42.6 MJ/kg
2	Density	825.6 kg/m^3
3	Specific gravity	0.826
4	Kinematic Viscosity	4.0 x 10^-6 m^2/sec

Diesel-Biodiesel Blends

There are four different blends which have been prepared using diesel and biodiesel. B10, B20, B30 and B40 are considered as the sample fuel blends for experiments. These blends are produced based on volumetric ratio such as 90 ml of diesel and 10 ml biodiesel were kept in 100 ml sample of B10. Similarly B20, B30 and B40 were also produced. These blends are shown below in Fig. 1.

Figure 1. Photograph of Diesel-biodiesel blends, B10, B20, B30 and B40 fuel sample

EXPERIMENTATION ON SETUP

Engine Setup

In this paper, an experimental setup has been used for the analysis. The setup consists of a vertical 4-stroke water cooled single cylinder diesel engine mounted on a rugged frame. A counter flow heat exchanger type calorimeter is installed at the exhaust to evaluate the mass flow rate of exhaust gases. Brake dynamometer is used to apply load on the engine. An orifice meter is attached to the supply line of air to calculate its mass flow rate required for combustion. Water is used as working fluid in both the cases i.e. calorimeter and cooling system. A burette is fitted with the fuel tank for measuring the mass flow rate of fuel. A line diagram of this setup is given below.

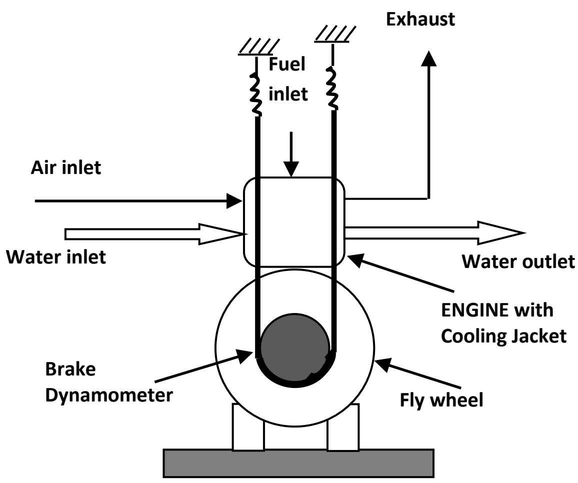

Figure 2. Line diagram for Engine with Brake Dynamometer

Table III. Specifications of the Diesel Engine used in the experiment

Name	**Details**
Made by	Eicher (5 HP)
Engine type	Single cylinder 4-stroke water cooled Diesel Engine
Loading Device used	Belt type Brake Dynamometer
Rated Power	3.73 kW
Rated speed	1500 rpm
Cylinder bore	80 mm
Stroke Length	110 mm
Swept Volume	553 cc

Figure 3. Photograph of Engine Setup

EXPERIMENTAL TEST PROCEDURE

The experiments were performed using diesel and diesel-biodiesel blends at different loading conditions. In addition to pure diesel, there are four blends which were prepared for experimentation i.e. B10, B20, B30 and B40 (40% biodiesel and 60% diesel by volume). For evaluation of the performance of the engine, certain important parameters of the engine such as air flow rate, fuel consumption, engine speed, temperatures at the inlet and outlet of water cooling system as well as calorimeter were noted. Once the observations were recorded major performance parameters of the engine such as brake power, specific fuel consumptions and brake thermal efficiency etc. were calculated. Further, based on energy analysis, a heat balance sheet was developed for each case of the blends. Initially, the engine runs for more than half an hour to achieve steady state, and then all the readings under no load condition were noted. Subsequently, a set of data was also recorded for all the loading conditions by using different fuels such as pure diesel, B10, B20, B30 and B40.

Using B10, B20, B30 and B40 fuel blends in the engine, performance characteristics were analyzed and then the same were compared with that of the engine fueled with pure diesel. In addition to performance analysis, separate heat balance sheet was prepared to check the location of maximum energy loss. The heat balance sheet was developed based on energy analysis.

FORMULATION AND ENERGY ANALYSIS

a. Brake Power (kW) $BP = \frac{2\pi NT}{60*1000}$ …………… *(4.1)*

b. Brake thermal efficiency (%) $\eta_{bth} = \frac{BP*100}{mf*CV}$ ….*(4.2)*

c. Friction Power: A graph between fuel consumption and brake power (kW) has been plotted for different readings. A line has been found and this line is further extended in negative power axis. The power in negative axis at which fuel consumption is zero becomes friction power. This plot is popularly known as Willian's line.

d. Brake Specific fuel consumption (kg/kW-hr) $BSFC = \frac{mf}{BP}$ ………………..*(4.5)*

e. Heat Balance Sheet: Based on first law analysis a heat balance sheet has been prepared for each fuel blend. All the values in terms of power have been converted to corresponding energy values, to ensure that we have energy units for each component. For the energy unit, it was considered that the engine was running for an hour and the energy released by the fuel is taken as the total energy input to the system. Subsequently, HRR and energy exchange by other components such as heat equivalent to BP, heat carried away by Cooling water, heat carried away by exhaust gases, radiation, and unaccounted losses were also calculated.

Heat equivalent to brake power; $H_{bp} = BP \times 3600$

Similarly, all the power units were converted into corresponding energy units.

$H_{un.} = H_{fuel} - (H_{bp}+H_w+H_{ex})$

RESULTS AND DISCUSSIONS

Based on the experiments conducted on a single cylinder 4-stroke water cooled diesel engine, detailed calculations have been done to compute engine performance parameters. The performance parameters which have been calculated in the present analysis are brake power, friction power, indicated power, brake thermal efficiency, BSFC and heat release rate. Later, a comprehensive energy analysis for the same engine has been performed to check the possibility of saving energy and to identify the possible improvements that can be done in the existing setup. Energy analysis of the system was performed using the first law of thermodynamics and various graphs have been plotted to get a better understanding of the system performance. Brake power has been calculated using the equation (4.1) under various load conditions. For each fuel blend, Willian's line has been plotted to get friction power. The graphs mentioned below (Fig 4-13) show the percentage energy consumption at various loads. The loads applied to the engine during experiments are 0% (no load), 20%, 40% and 60%.

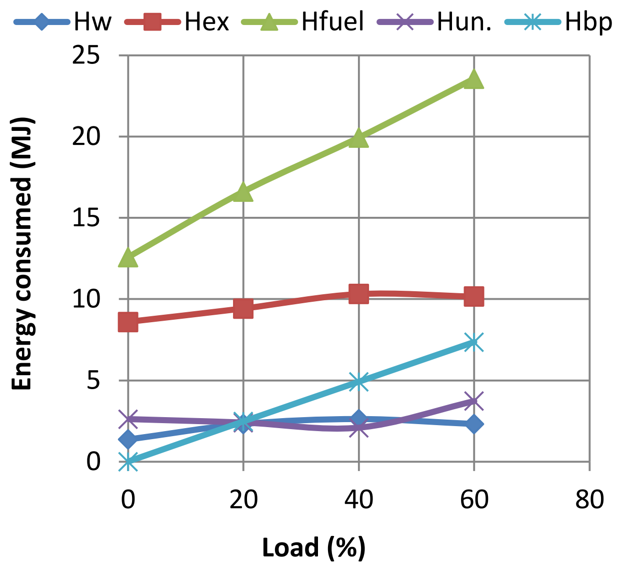

Figure 4. Energy consumption for pure Diesel (B0)

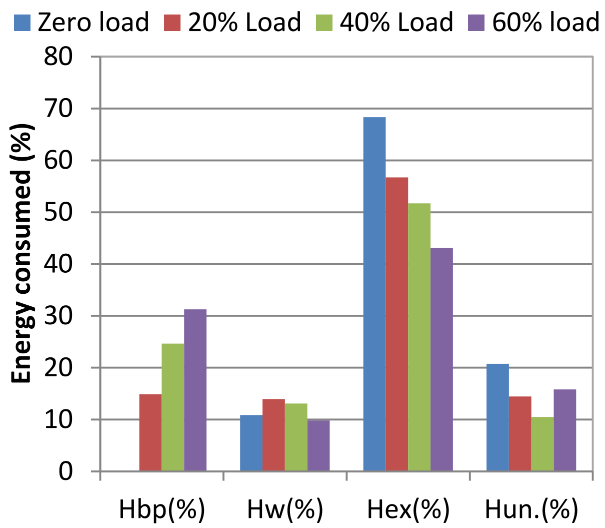

Figure 5. % Energy consumption for pure Diesel (B0)

As the load increases, the heat release rate of the engine increases. It is well-known that the brake power increases with increasing engine load. A smooth characteristic curve for each parameter has been observed when the engine runs on pure diesel. But the curves obtained for energy losses in exhaust gases and as unaccounted losses do not maintain a smooth trend. It is highly fluctuating as shown in graphs (Fig. 6, 8, 10 and 12).

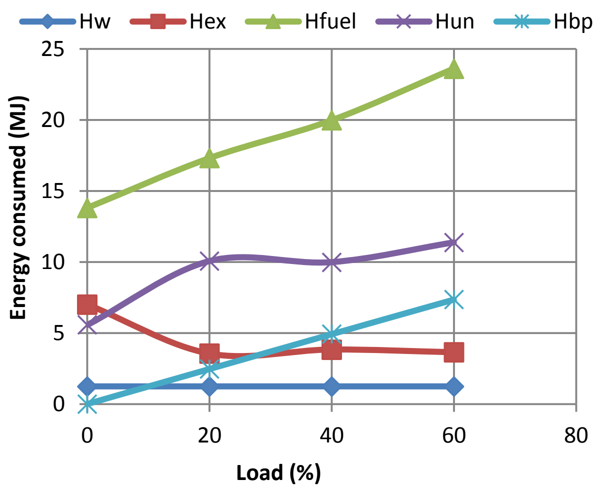

Figure 6. Energy consumption for Diesel-biodiesel blend (B10)

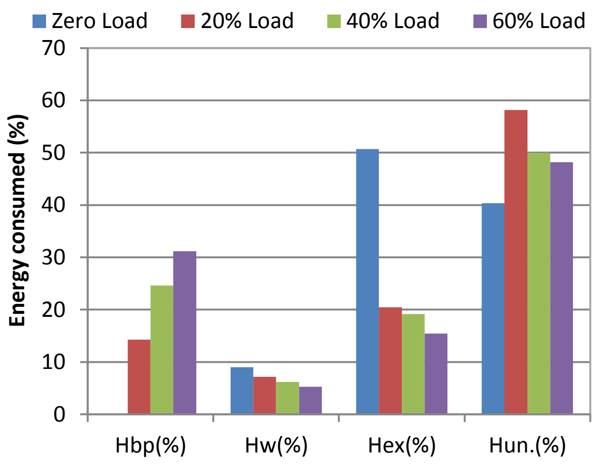

Figure 7. % Energy consumption Diesel-biodiesel blend (B10)

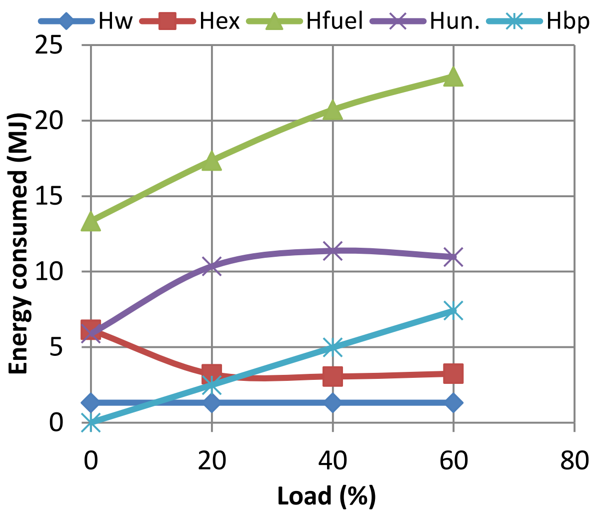

Figure 8. Energy consumption for Diesel-biodiesel blend (B20)

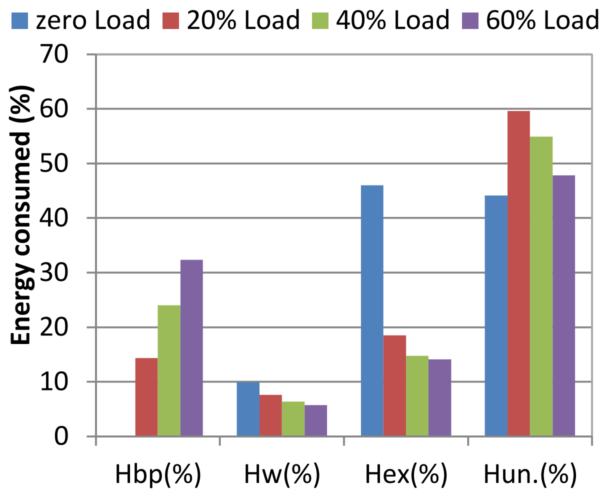

Figure 9. % Energy consumption Diesel-biodiesel blend (B20)

The percentage energy consumption in each component of the engine at the various loads for each fuel blend is shown in figures (Fig. 5, 7, 9 and 11). Initially, when the brake power was zero at the no-load condition of the engine, maximum energy content was observed in exhaust gases. As the engine runs, the temperature of the engine increases which leads to an increase in the energy lost to the surroundings through radiation. In the present analysis, radiation losses are considered as an unaccounted loss. Initially, the experiments were performed for pure diesel and then the engine was run at various blends of diesel and biodiesel, namely B10, B20, B30, and B40. After the completion of the experiment with each blend, the engine was stopped for around an hour to cool it down and bring it back to a lower temperature. Shown below are the line graphs and bar graphs for the blends that have been tested. All the graphs have the % energy consumed as the ordinate and load % as the abscissa.

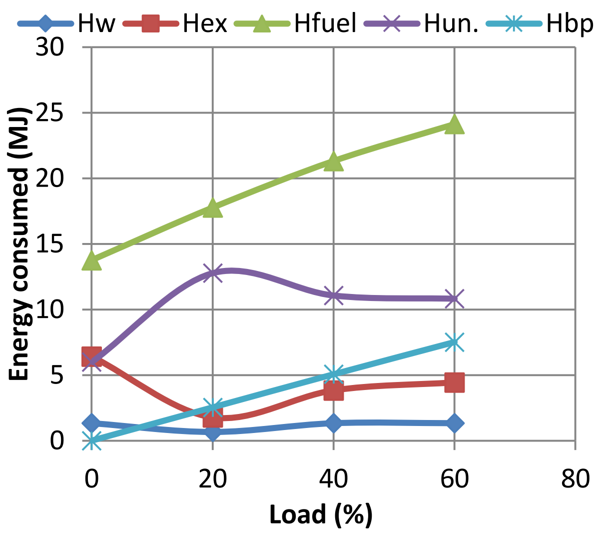

Figure 10. Energy consumption for Diesel-biodiesel blend (B30)

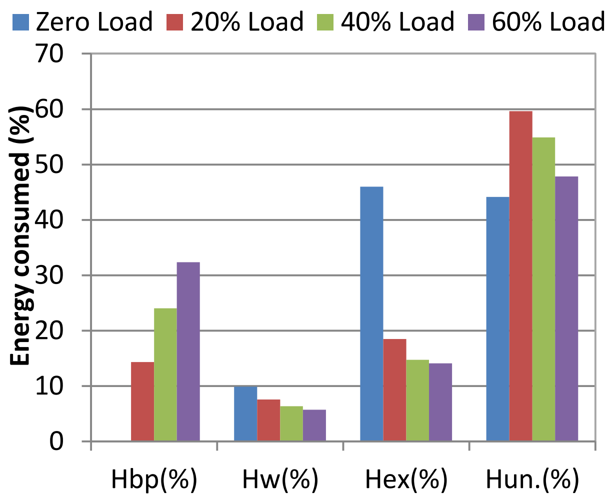

Figure 11. % Energy consumption Diesel-biodiesel blend (B30)

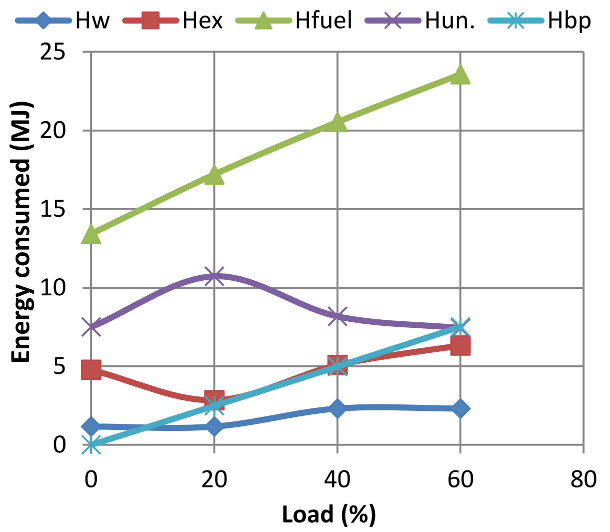

Figure 12. Energy consumption for Diesel-biodiesel blend (B40)

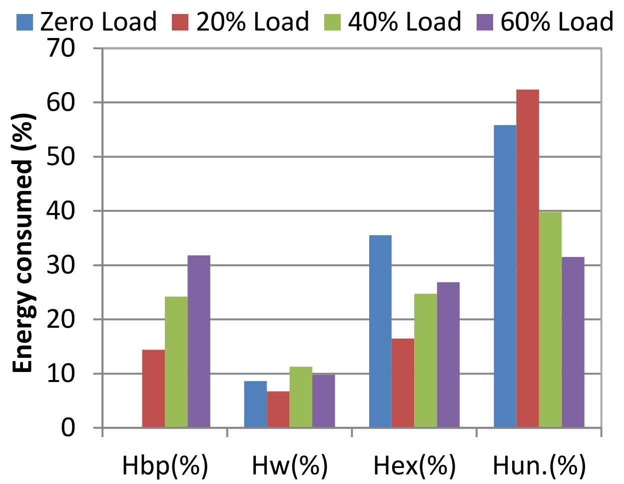

Figure 13. % Energy consumption Diesel-biodiesel blend (B40)

Brake thermal efficiency

From Fig. 14, a similar nature is seen for the plot of BTE with respect to the engine load. The trend of brake thermal efficiency increases as the engine load increases. Initially, the engine was operating at no load condition; combustion of diesel fuel gives highest BTE; equal to 14.87%. Since the biodiesel is more viscous it does not vaporizes quickly and hence it does not release enough energy when the engine is operating in a no-load condition, whereas at higher engine load engine temperature is more which helps in atomization as well as vaporization of the fuel. Due to the presence of oxygen in the biodiesel, it shows improved combustion. This oxygen promotes complete combustion of the fuel blend which tends to release more heat. The BTE for B20 is found to be 32.32% which shows the highest value when the engine is working on maximum loading condition.

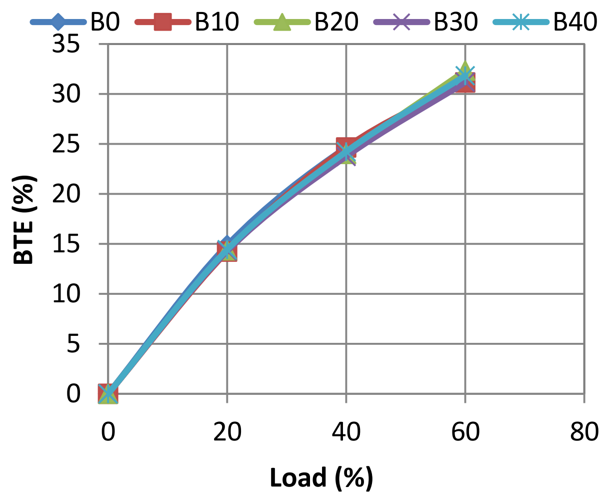

Figure 14. Brake thermal efficiency vs Loads (%)

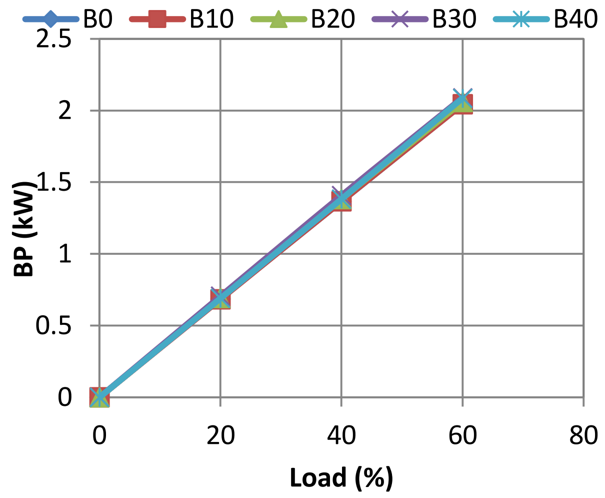

Figure 15. Brake power vs Loads (%)

From fig 15 we can see that the brake power increases with increase in engine load. The graphs for A/F ratio with respect to load for each blend have been illustrated in fig 16. At no load condition, maximum A/F ratio has been observed for all the blends. At higher engine load all the curves in the graph coincide, and hence engine requires almost same fuel-air mixture. Whereas, pure diesel and B20 require an almost equal air-fuel ratio when the engine operating in maximum load condition.

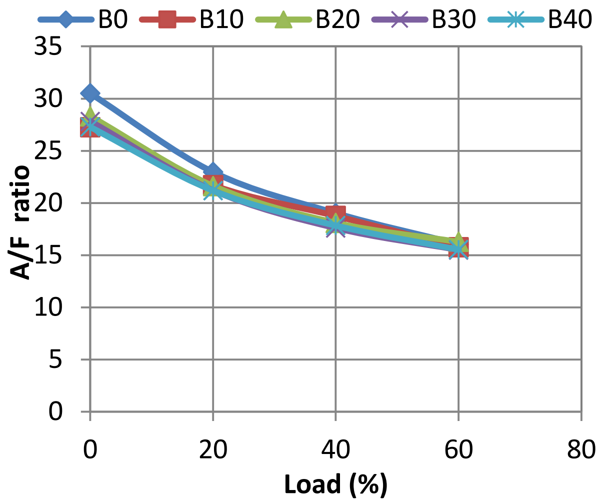

Figure 16. Air fuel ratio vs Loads (%)

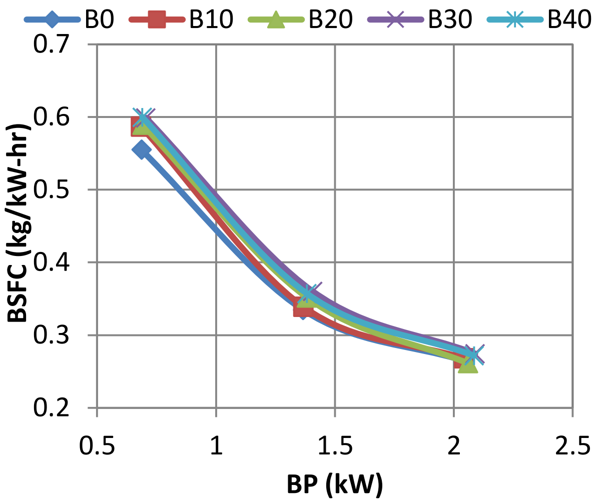

Figure 17. BSFC vs Brake power

Brake specific fuel consumption

The variation of BSFC with brake power for each blend has been illustrated in Fig. 17. A uniform trend has been observed for all the blends. As the load increases BSFC drastically decreases. At no load condition, combustion of pure diesel shows the minimum value of BSFC whereas, with the increase in biodiesel content, BSFC also increases. The BSFC value of an engine mainly depends on the viscosity, density and chemical composition of the fuel. Since the heating value of biodiesel is lower than that of pure diesel, hence as we increase the biodiesel content, BSFC also increase for same engine loading. At higher engine load, all the fuel blends show a lower value of BSFC, while B20 gives the minimum value.

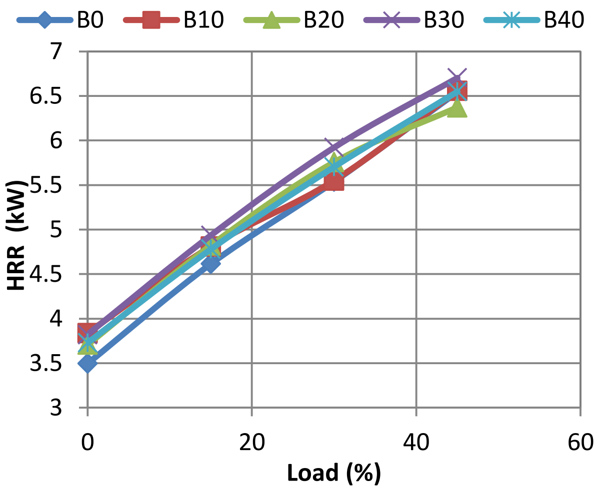

Figure 18. Heat release rate vs % load for each blend

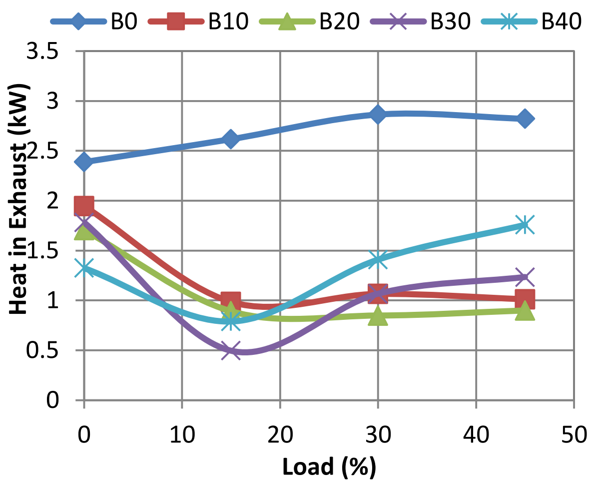

Figure 19. Energy in exhaust vs Load (%)

Heat Release Rate

The variation of HRR with different loading conditions for each blend has been illustrated in Fig. 18. The heat release rate mainly depends on the heating value of the fuel and fuel-air mixing. The trend shows that HRR increases with increase in engine load. Higher is the engine load, lower is the air-fuel ratio which leads to increase in HRR. It has been observed from the graph that the lower the content of biodiesel in the fuel blends, lower the value of HRR for all loading conditions. Whereas B20 blend gives the lowest value of HRR when the engine is working in maximum loading condition.

The graph in Fig. 19 clearly shows the energy lost in exhaust gases when the engine is run using different blends at different load conditions. When the engine was operating at no load condition, a large amount of energy was being wasted in the exhaust. Around 30%-40% of the energy supplied from the fuel is liberated into the environment as exhaust. The smoothest trend in the graph is observed for pure diesel with no content of bio-diesel. For lower percentages of bio-diesel content in the blend, the energy in exhaust reduces with higher load % and then becomes almost constant. The temperature of the exhaust gases is around 100°C which shows that it has quite high energy content. It is a well-known fact from the second law of thermodynamics that higher is the temperature at which the energy is available, higher is the quality. Hence, the high-temperature exhaust gases will have higher exergy content. Further, the present work can be extended in future for a detailed exergy analysis that would be more helpful to check the scope of improvement in the existing system.

CONCLUSIONS

Each of the blends, such as B0 (pure diesel), B10, B20, B30 and B40 fuels, have been used for the experimental analysis. A detailed heat balance sheet for the engine has been drawn for each blend. The main conclusion based on detailed literature survey on diesel-biodiesel blends and from the experimental results is summarized as follows:

- At no load condition, combustion of pure diesel shows the minimum value of BSFC whereas, with the increase in biodiesel content, BSFC also increases. At higher engine load, all the fuel blends show a lower value of BSFC while B20 gives the minimum value.
- The brake thermal efficiency increases as the engine load increases. Initially, the engine was operating at no load condition; combustion of diesel fuel gives highest BTE; equal to 14.87%. Due to the presence of oxygen in the biodiesel, combustion of the biodiesel blend fuel releases more heat. At higher engine load engine temperature is more which helps in atomization as well as vaporization of the fuel. The BTE for B20 is found to be 32.32% which shows highest when the engine is working on maximum loading condition of the experiment.
- At higher engine load, although all the blends show lowest value of BSFC, B20 gives the minimum value of BSFC. At higher engine load, engine requires almost same fuel-air mixture. While pure diesel and B20 require an almost equal air-fuel ratio when the engine is operating at maximum load condition.
- The present analysis reveals that lower the biodiesel content in the fuel blends lower the value of HRR for all loading conditions. Whereas, B20 gives the lowest value of HRR when the engine is working in maximum loading condition.

For lower percentages of bio-diesel content in the blend, the energy in exhaust reduces with higher load and then becomes almost constant. A smooth pattern (around 0.89 kW) of energy in exhaust has been obtained when the B20 blend was used for combustion. From the present analysis, one can conclude that the high-temperature exhaust gases will have enough energy content to utilize. A detail exergy analysis can also be desirable to check the exergy exchange in each component of the system. The exergy analysis would give a clear picture of the existing setup to check the scope of improvement in the existing system.

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