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Exergy analysis of diesel engine powered by diesel- mustard biodiesel blend with diethyl ether as additive

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ABSTRACT

In this paper, the thermodynamic analysis of the existing diesel engine was conducted to evaluate the effects of using diethyl ether (DEE) as additive to mustard and diesel. The mustard biodiesel and DEE blending with diesel in the ratio of 0:0:100, 20:0:80, 30:0:70, 40:0:60, 15:5:80, 25:5:70 and 35:5:60 by volume were tested in diesel engine. The aim of exergy analysis is to estimate the exergy destruction in each module as well as exergetic efficiencies. In the thermodynamic performance, 3.5 kW diesel engines coupled with eddy current dynamometer. From the thermodynamic analysis, the maximum thermal efficiency of the engine is 29.6% for biodiesel blend at higher load.

Keywords: Diesel, mustard oil, DEE, energy, exergy.

INTRODUCTION

The increasing energy demand, raising oil prices, depleting oil resources and environmental pollution problems associated with the use of fossil fuels have sparked renewed interest to find sustainable, economically feasible and environmentally friendly bio-fuels [1,2]. According to its soil and climate conditions, each country has grown oil-productive plants with respect to its available landscape. Groundnut oil, which is classified as edible, is widely grown in India [3]. The world demand for diesel engines projected about 6.9% per year. However it emits higher level of particulate matters (PM) and oxides of nitrogen emissions (NOx) which emissions are mainly due to the engine combustion with heterogeneous fuel-air mixture. NOx emissions form at higher temperature could decrease by reducing the in-cylinder temperature and also decreases maximum available work [3-5]. Energy is fundamental requirement for economic development for countries. Many sectors in Indian economy such as agriculture, transportation, commercial, manufacturing and domestic need inputs of energy. The utilization of energy in all sectors has been steadily increases all over the country [6]. The use of vegetable oils as an alternative fuels for internal combustion engines is limited by some unfavorable fuel properties, mainly their high viscosity and density, which cause problems in poor fuel atomization, incomplete combustion and ring carbonization in the combustion chamber. These problems can be overcome by four methods: blending, micro emulsion, trans-esterifaction and pyrolysis [7]. Additional research needs to develop diesel specific additives for better performance, combustion and emissions of diesel engines. DEE has required characteristics and projected to improve low temperature flow properties. Earlier studies have recommended that the weight percent of oxygen content in the fuel is the most important factor for opacity reduction [8-10].

DEE has high cetane number of above 125. The latent heat of vaporization of DEE is higher than diesel. DEE is liquid at room temperature which reduces handling and storage problems. DEE is also has non-corrosive properties compared to alcohols. The flame propagation stages of DEE have been studied by Ohta and Takahashi [11]. DEE has low heat release rates (HRR) during early cool flame generation, but has typical HRR for mid stage blue flame oxidation. The blue flame is followed by a conventional red flame with constant HRR during full combustion. P.Q.E Clothier et al.,[12] reported that adding DEE to diesel fuel will increase the cetane number of the diesel fuel. When used as a cold starting aid, DEE apparently acts as a neat fuel and not in combustion with the diesel fuel. Addition of diethyl ether to biodiesel- diesel blends can increase the oxygen contents, which may further improve the opacity emissions. Investigations have been carried out on different approaches for improving exhaust emission when biodiesel is used. T. K. Kannan et al. [13] experimentally studied on the performance characteristics of a diesel engine when it was fuelled with DEE-diesel blend in the ratios of 5%, 10%, 15% and 20% and carry out their performance. Reduction of 14.63% of opacity and 15% of NOx emissions was observed for 20% DEE blends at full load which was the highest reduction among the blends.

The efficiency levels increase with engine size and range from about 30% for small high speed diesels up to 42-48% for the large bore, low speed engines. According to the literature studies, diesel fuel engines are more efficient than the equivalent ones with gas turbines, since they have a higher thermal performance that the most important parameters [14,15]. Some studies demonstrate that almost 1/3 of the energy of a fossil fuel is destroyed during the combustion process in power generation. An exergy based performance analysis of a system based on second law of thermodynamics that overcomes the limit of an exergy-based analysis [16]. The maximum work output obtainable from a certain heat input in a cyclic heat engine is called the available energy or available part of the energy supplied. The highest available part of energy is also known as exergy. The minimum amount of energy that has been rejected to the sink as per second law of thermodynamics is called the unavailable energy or unavailable part of the energy supplied. This unavailable part of energy is also known as anergy [17]. Availability analysis from the second law application is not a new technique. This kind of analysis has used for many years for evaluating stationary system and automobile engines. The chemical availability is revealed to be significant and essential to obtain an exact estimation of the irreversibility. A different type of studies, the combined energy and exergy analysis can be used to determine a most favorable engine condition [18]. The use of vegetable oils as an alternative fuels for internal combustion engines is limited by some unfavorable fuel properties, mainly their high viscosity and density, which cause problems in poor fuel atomization, incomplete combustion and ring carbonization in the combustion chamber. These problems can be overcome by four methods: blending, micro emulsion, trans-esterifaction and pyrolysis [19-22].

In this study, the first and second laws of thermodynamic are employed to analysis the quality and quantity of energy in a four stroke, single cylinder, 3.5kW capacity direct injection diesel engine using diesel oil and Mahua/mustard biodiesel with DEE blend as fuel. Performance parameters of the engine for each fuel, specifically the brake specific fuel consumption, fuel energy, heat and exhaust losses, exergy loss accompanying heat the exhaust gas and exergy destroyed in the engine [23,24].

Energy analysis

Energy is a fundamental concept of thermodynamics and one of the most significant aspects of engineering analysis. It is crucial to know the maximum possible performance of the blended fuel modes which can provide vital comparison parameters with base engine. In addition, impact of process changes such as, load and bio-fuel etc in the system in terms of system losses is also to be assessed. These findings will help in reducing the available energy loss to improve the overall engine performance.

Towards this, this paper discusses both the energy and exergy balance of the diesel engine fuelled with diesel and blended fuel. Initially, the first law analysis is obtainable for both the diesel and blended fuel modes. This analysis is shown in order to assist the comprehension of the second law analysis to follow.

First law analysis

The energy input in each IC engine is contained in its fuel.

This amount of input energy is then converted into various forms. In an engine, the input chemical energy of fuel is generally converted to the following forms,

- ➢ Useful work output or shaft energy (P_{shaft})
- ➢ Energy transferred to the cooling water (Q_{cw})
- ➢ Energy transferred to the exhaust gas (Q_{eg})
- ➢ Uncounted loss (Q_{un}) due to friction, radiation, heat transfer to environment, operating auxiliary equipment, etc

The amount of each of these energies stated above evaluated on the basis of the first law of thermodynamics is now described.

The input energy (Qin) to the diesel engine is the amount of fuel energy content in the supplied fuel and is given by,

- $Q_{in} = m_f * LHV$ kW

The energy converted to shaft power (P_{shaft})

- $P_{shaft} = 2 * \pi * N * W * r$ kW

The heat loss from the engine block to the cooling water is given by,

- $Q_{cw} = M_w * C_{pw} * (\Delta T)$ kW

The energy lost in form of exhaust gas losses in evaluated by,

- $Q_{eg} = M_{eg} * C_{pg} * (\Delta t)$ kW

In case of use exhaust gas calorimeter arrangement in exhaust side,

- $Q_{eg} = \frac{m * Cpw * (T4-T3) * (T5-Tatm)}{(T5-T6)}$

Where, T_3= calorimeter water inlet temperature
T_4=calorimeter water outlet temperature
T_5=exhaust gas temperature at calorimeter inlet
T_6=exhaust gas temp. at calorimeter outlet
T_{atm}= atmosphere temperature (32°C)

The amount of the uncounted losses is determined by performing an energy balance and given by,

- $Q_{un} = [Q_{in} - (P_{shaft} + Q_{cw} + Q_{eg})]$ kW

Second law analysis

The understanding of 'how the energy is lost' will help in finding means to reduce the same to improve the performance of the engine in terms of efficiency and power output.

The second law analysis indicates various forms of energy that have different levels of ability to do useful mechanical work. This capacity to perform useful mechanical work is defined as availability. In an IC engine, the availability input (Ain) which contained in its chemical availability of fuel is converted into other exergy forms.

In an engine, the input fuel availability is converted into the various forms:

Chemical availability of fuel or input availability,

- $A_{in} = [1.0338 * m_f * LHV]$ kW

Shaft availability,

- $A_{shaft} = \int (p - p_0) * (dv/d\Theta)$ kW

Availability transferred to cooling water (A_{cw}),

- $A_{cw} = Q_{cw} - [(m_w) * C_{pw} * T_0 * \ln(T_2/T_1)$ kW

Availability transferred to exhaust gases (A_{eg}),

- $A_{eg} = Q_{eg} + [(m_{eg}) * T_0 * (C_{pg} \ln(T_0/T_5) - R_{eg} * \ln(P_0/P_{eg}))]$kW

Destroyed availability,

- $A_{des} = [A_{in} - (A_{shaft} + A_{cw} + A_{eg})]$ kW

Exergetic efficiencies are useful for distinguishing means for utilizing energy resources that are thermodynamically effectiveness from those that are less so. Exergy efficiencies also can be used to evaluate the effectiveness of engineering measures taken to improve the performance of a thermal system. The exergy efficiency or second law efficiency (η_{II}) is the ratio of total availability recovered from the system to the total availability input into the system. The recovered availability includes A_{shaft}, A_{cw} and A_{eg}.

η_{II} = availability recovered/availability input

$\eta_{II} = 1 - (A_{des} / A_{in})$

EXPERIMENTAL SECTION

Test has been conducted on a Kirloskar TV1 Engine, four strokes, single cylinder, water-cooled, direct injection and naturally aspirated diesel engine with a bowl type piston combustion chamber. Properties of diesel, biodiesel and DEE are presented Table 1. Specification of test engine is shown in Table 2. For high pressure fuel injection, a high-pressure fuel pump is used and three hole in injector nozzle. The injector nozzle was located at the center of the combustion chamber and has an operating pressure of 220bar.

Experimental procedure

To estimate the performance parameters i.e operating parameters such as engine speed, power output, and fuel consumption were measured. Significant engine performance parameters such as brake specific fuel consumption and brake thermal efficiency for the test fuels were calculated.

- In the first phase experiments were conducted with neat diesel.
- In the second phase of the work, the engine was operated diesel- biodiesel oil blend ratio of 80: 20, 70:30 and 60:40.
- In the third phase, biodiesel and diesel blend with DEE in the ratio of 15:80:5, 25:70:5 and 35:60:5.

RESULTS AND DISCUSSION

Brake specific fuel consumption (BSFC): The BSFC variation of the test fuels with respect to load [9]. The fuel mass flow rate is calculated from the respective measured volume flow rate value and the fuel density. BSFC of B20 oil blend is 1.5% lower than neat diesel at load 4 kg and B30 blend is approximately same with diesel and 6kg load. BSFC of B15A5 is 1.3% lower than that of neat diesel at 4kg and almost similar to neat diesel in remaining loads. B25A5 fuel has similar BSFC values up to 4-8kg load and slightly higher for higher loads compared to neat diesel. The main reason may be due to the higher volatility of DEE which speeds up the mixing velocity of air/fuel mixture, improves the combustion process and increases the combustion efficiency.

Brake thermal efficiency: The variations of BTE at different loads for various fuel blends has been shown in Fig.6. BTE for diesel is higher than that of all other blended fuels up to 4 kg applied load. BTE for B25A5 blend has 5%, 2% higher than neat diesel at 6kg, 8kg load. This is due the addition of DEE reduces the viscosity which in turn increases the atomization and leads to the enhancement of combustion.

Energy and Exergy values

A detailed analysis of the biodiesel- diesel-DEE fuel performance compared with neat diesel mode. The experimental observation data are retrieved here for the second law analysis purpose. The availability balance for each one of the seven fuel types used during both the diesel and blend fuel operations as a function of engine load. This is a balance between the various terms of the second law analysis described by namely, fuel availability input, work availability, availability exchange through cooling water and exhaust gas, availability destroyed, and exergy efficiency. During the engine operation, as load increases, the richer fuel-air mixture increases combustion temperature. Therefore, increased work availability and reduced heat transfer availability losses are obtained, as percentages of the fuel chemical availability. For this, an increase in the exergy efficiency is resulted at higher loads for all the tested fuels. Specifically, the blended fuel operations are favored thermodynamically at higher loads since their exergy efficiencies improve significantly as compared to low load conditions. Because of the improved combustion characteristics by DEE at higher loads, the exhaust gas availability and cooling availability are increased. In addition, the shaft availability of the fuels is increased for an increased load. Therefore, when load is increased, the added cumulative availabilities increased the exergy efficiency.

Table 1 Properties of diesel, mustard biodiesel and DEE

Property	Diesel	Biodiesel	DEE
Chemical structure	$C_{16}H_{34}$	$C_{17}H_{34}O_2$	$C_2H_5OC_2H_5$
Density (kg/m^3)	830	882	713
Kinematic vis. 35^o C (cS)	2.7	18.1	0.23
Auto ignition point (^{o} C)	200-400	-	160
Cetane number	48	55	>125
Boiling point (^{o} C)	180-330	-	35
Pour point (^{o} C)	-20	-2	-110
Lower heating value ((MJ/kg)	42.8	38.0	33.9
Stoichiometric A/F ratio	14.9	13.5	11.1

Table 2 Properties of fuel blends

Blend	Flash point ^{0}c	Fire point ^{0}c	Density in g/cc at 32^{0}c	Calorific value MJ/kg
Diesel (100%)	68	78	.8878	42.80
Biodiesel (100%)	146	156	.8930	38.00
B20	71	80	.8901	41.84
B30	75	84	.8920	41.36
B40	82	91	.8950	40.88
B15A5	42	52	.8900	41.63
B25A5	45	53	.8910	41.15
B35A5	49	60	.8923	40.67

Table 3 Specification details of kirloskar TV1 engine

Type	Vertical, water cooled
Number of cylinders/ Number of strokes	01/04
Rated power	3.7 kW/ 5 hp @ 1500rpm
Bore (m)/Stroke(m)	0.08/.11
Piston offset (m)	0.00002
Con-rod length (m)	0.235
Piston head ratio	1
Compression ratio	16.7
Speed	1500 Rev/min

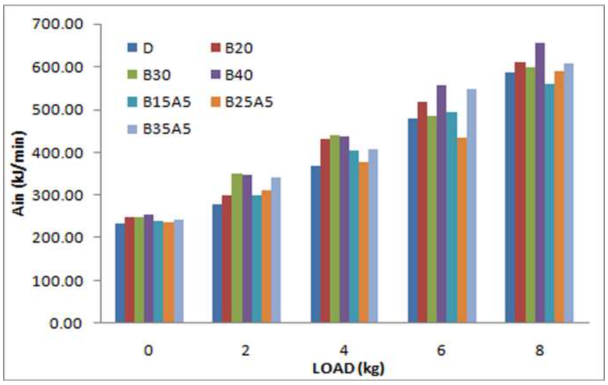

Fig. 1 Availability in fuel input Vs. Load

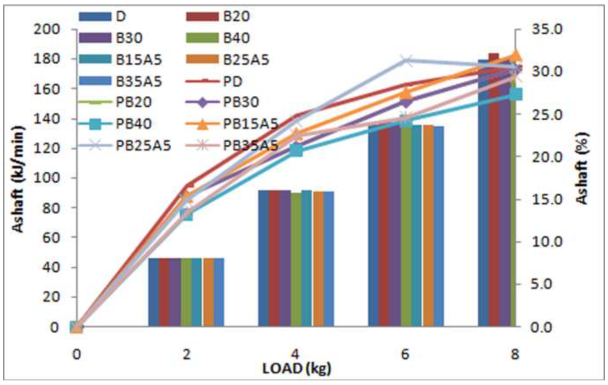

Fig. 2 Availability in shaft Vs. Load

Fig.1 depicts the availability distribution on the basis of kJ/min of available energy input to the diesel and blended fuel operations. When load is raised to maintain a higher power output at higher loads, the supply of fuel chemical energy into the engine cylinder is increased. In the process, at elevated engine loads, the shaft availability is calculated against the amount fuel exergy input. The quantity of fuel exergy input for the engine operation at a given load mostly depends on the energy content of the fuel type and effective combustion of the fuel-air mixture. Although some tested fuels seem to have higher energy content than diesel fuel, however, at lower loads of 20-40%, all the tested blended fuel operations required higher fuel exergy input as compared to diesel mode. This is because of their lower energy content and combustion characteristics due to the low temperature environment. As the load increased, the differences in fuel exergy input reduced under blend fuel modes as opposed to diesel mode for their improved combustion.

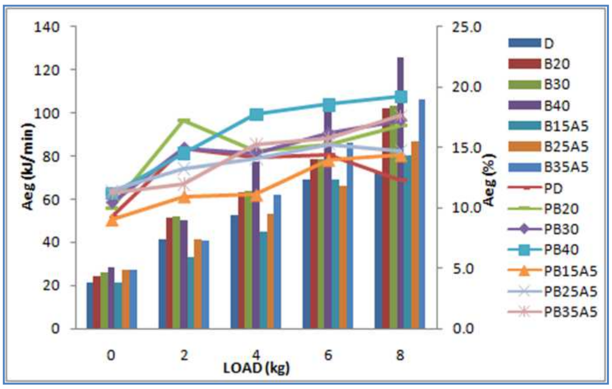

Fig. 3 Availability in exhaust gas Vs. Load

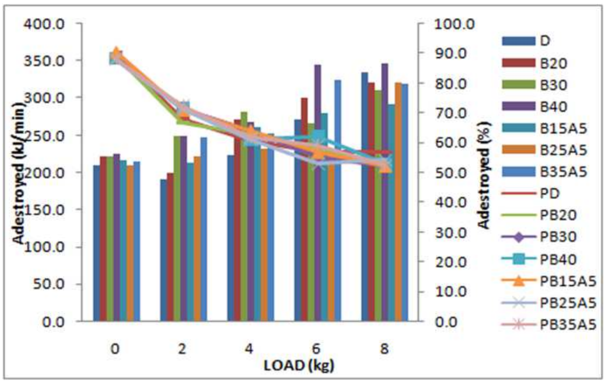

Fig. 4 Availability destroyed Vs. Load

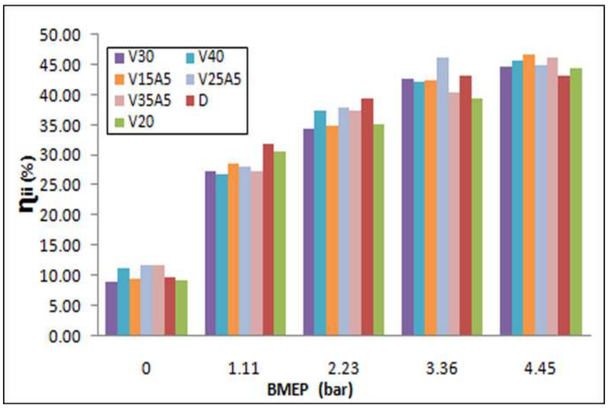

Fig. 5 Exergy efficiency Vs. Load

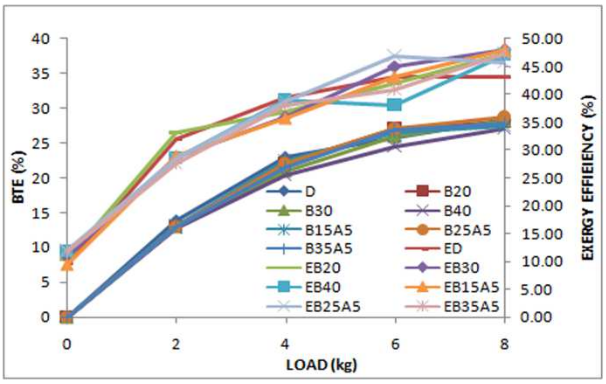

Fig.6 BTE, Exergy Efficiency Vs. Load

Fig.2 shows the shaft availability (kJ/min) as a function of load. The availability results showed that, as the load increases the blended fuel operations generated the more increased cumulative exhaust gas and cooling water availabilities. This favorable factor improves the availability accessible for conversion to work availability. The increase in the gross work output availability increased the corresponding exergy efficiency.

Fig.3 presents the diesel and blend fuel mode comparison for exhaust gas and percentage of exhaust loss with load with respect to their respective fuel chemical availability. As discussed previously, the shaft work produced at different loads of both diesel and blended fuel modes are almost same. However, the maximum exhaust gas lost is observed as 18.3% at 100% load. This is due to the incomplete combustion of fuel at higher temperature zone. Due to these huge availability losses through exhaust gas, the efficiencies of blend fuel operations are lower than that of diesel mode. Therefore, it can be concluded that the exhaust gas available energy loss must be reduced to improve blend fuel engine performance.

Fig.4 shows that, the amount of destroyed availability (as a percentage of fuel input) is decreased with increasing load. At low loads of 20% and 40%, poor combustion of biodiesel blend fuels causes less cooling water and exhaust gas availabilities i.e., higher destroyed availability. The destroyed availability was found minimum at the maximum efficiency condition of 80% engine load.

Fig.5 despite that, 8kg load, the second law efficiency is observed highest in case of diesel mode and recorded a maximum of 43.4%, while at same loading condition, when the B25A5 blend in 45%. As shown in Fig.6 describes BTE with load and exergy efficiency. This demonstrates that blended fuel engine operations cannot be ignored on the basis of their lower efficiency in a diesel engine which was actually designed for the standard diesel fuel.

CONCLUSION

The diesel-biodiesel-DEE fuel mode produced lower energy conversion efficiency; which was offset by large replacement of neat diesel. In this study, test engine was operated at steady state without any modifications in existing diesel engine. Using data gathered from the experimental study, energy and exergy balances to the engine were performed for the all experimental fuels. Then, energetic and exergetic performance parameters of the engine computed and compared with each other. From the experimental work, exergy analysis was measured the quality of engine performane. The net calorific value of diesel is greater than that of the biodiesel blends. The most important factor of the system inefficiency is the destruction of exergy by irreversible processes. This detailed analysis provides a powerful and systematic tool for identifying all cost sources and for optimizing the design of diesel engine powered systems.

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Nomenclature

BTE	*Brake Thermal Efficiency*
B20	*80% diesel + 20% SVO*
B30	*70% diesel + 30% SVO*
B40	*60% diesel + 40% SVO*
B15A5	*80% diesel + 15% SVO +5 DEE*
B25A5	*70% diesel + 25% SVO +5DEE*
B35A5	*60% diesel + 35% SVO +5DEE*
PB20	*Percentage V20*
PB30	*Percentage V30*
PB40	*Percentage V40*
PB15A5	*Percentage V15A5*
PB25A5	*Percentage V25A5*
PB35A5	*Percentage V35A5*
EB20	*Exergy efficiency V20*
EB30	*Exergy efficiency V30*
EB40	*Exergy efficiency V40*
EB15A5	*Exergy efficiency V15A5*
EB25A5	*Exergy efficiency V25A5*
EB35A5	*Exergy efficiency V35A5*