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Exergy Analysis of Compression Ignition Engine Using Biodiesel Blend : Effect of Compression Ratio and Injection Pressure

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Abstract: - The Considering the many advantages of second law of thermodynamics over first law, this research includes the exergy analysis of single cylinder, 4-stroke, water cooled, variable compression ratio(VCR) engine running with jatropha biodiesel blend(B20). Exergy analysis includes finding of various availability such as input availability, brake power availability, cooling water availability and exhaust gas availability. From exergy analysis component of major exergy destruction can be found out. In this research energy analysis was carried out for B10 to B50 jatropha biodiesel blends. B20 biodiesel blend gave better performance among all blend hence exergy analysis is carried out for this blend to check the effect of compression ratio (CR) and injection pressure (IP) on the exergy efficiency. All possible combination of compression ratio (16,17,18) and injection pressure(180 and 200 bar) were set on the engine. It was found that engine gives higher exergy efficiency at combination CR 16 and IP 180 bar at low and medium load and highest value was found at CR 17 and IP 180 bar at higher load condition which was 34.27%. Also it was noticed that exhaust gas contains higher availability than cooling water. Unaccounted exergy includes exergy destruction due to combustion process, due to friction and due to finite temperature gradient which accounts approximately 60% of exergy input.

Keywords: - *Biodiesel, Compression Ignition Engine, Energy Analysis, Exergy Analysis*

I. INTRODUCTION

Today internal combustion engine plays major role in the society. It finds application in many stationary and transport power generation. Internal combustion engine uses fossil fuel such as diesel and gasoline. These fuels are limited in quantity and will not be available in near future. Hence research in the field of alternative fuel is being done from few past decades. Various alternatives such as methanol, ethanol, biodiesel, biogas, hydrogen etc are found suitable [1]. Emission from the engine is also cause many problems such as air pollution which ultimately leads to health related problem and environmental problem such as global warming. Biodiesel is one the major candidate for future alternative fuel because of its many advantages such as its suitable property for diesel engine and less pollution characteristics except NOx (nitrogen oxides). For power generation machine efficiency is also important. Internal combustion engines have efficiency in the range of 20 to 40% and rest of the energy that is 60% or more is got wasted [2]. So performance of the engine should be optimize to obtain maximum possible efficiency. The performance of IC engine can be increased by newer technologies such as combustion control systems, thermal insulation and exhaust recuperation [1]. Generally engine is analysed with the energy analysis which is based on the first law of thermodynamics. It is known that first law of thermodynamics is inadequate for evaluating some features of energy utilization [3]. Hence energy analysis is enriched with the use of exergy analysis to reveal various unknown facts [3,4]. Concept of exergy analysis is extremely useful in this regard as main advantage of exergy analysis is possibility of finding irreversibility and from that one can identify component of major destruction of exergy in the system [5]. Irreversibility associated in the engine due to processes like combustion, mixing, heat transfer, friction etc which cause destruction or loss of exergy [6,7]. Hence we can say that exergy analysis has its own important and it should be also used for internal combustion engine analysis along with the energy analysis. Mustafa Tat has[1] carried out research on the effect of cetane number on the performance of 4-stroke 4-cylinder diesel engine running with yellow grease methyl ester and soybean methyl ester having different percentage of cetane improver additive. It was concluded that lower cetane number, longer ignition delay period and higher level of premixed combustion may increases the exergy efficiency of the diesel engine. Jibanananda Jena et al.[4] investigated the effect of oxygen on the energy and exergy efficiency of single cylinder diesel engine running with karanja and palm biodiesel, in which it was concluded that palm biodiesel has higher energetic and exergetic efficiency. Mustafa Canaski et al.[8] carried out energy and exergy analysis of the 4 cylinder turbocharged diesel engine fuelled with soybean methyl ester and yellow grease methyl ester and they found that thermal efficiency was higher than petroleum diesel and exergetic performance of all used fuel was similar. A Ghareghani et al.[9] have conducted research work on 4-cylinder gasoline engine in which they checked the effect of gasoline and natural gas on the energetic and exergetic performance of the engine. It was found that energetic and exergetic efficiency of engine running with CNG was 5.4% and 3.14% higher than gasoline respectively and exergy destruction was found 5.8% higher in gasoline than CNG. In literatures, it was also found that most important contributor to the system inefficiency is combustion process [8]. And for typical atmospheric combustion system about $1/3^{rd}$ of the fuel exergy may unavailable due to inherent irreversibilities in combustor and most of the irreversibility is associated with the internal heat transfer within combustor between products and reaction [10]. One cannot measure practically such irreversibility due to combustion but simulation can be possible with appropriate chemical kinetics models. Hongjie Sun et al.[11] analysed the exergy loss occurs due to combustion process by detailed kinetics in gasoline engine fuelled with surrogates of gasoline. Numerical model was developed for analysis which includes non-equilibrium thermodynamics with detailed chemical kinetics. It was concluded that overall exergy loss occurred due to following three process: stage 1- conversion of large fuel molecule into small fuel molecule, stage2- H2O2 loop reaction and stage-3 violent oxidation reaction of CO, H and O.

There is a lack of research on the exergy analysis of compression ignition engine using biodiesel and hence this research includes performance of engine with biodiesel blends and the effect of CR and IP on the exergy efficiency of the engine for best suitable blend. Jatropha biodiesel was chosen for the experiment considering its suitability in Indian continent plus it is nonedible oil crop based biodiesel. Also jatropha curcus biodiesel was recognized by the government of India.

II. EXPERIMENTAL SETUP AND METHODOLOGY

2.1 Experiment Setup

The Test engine setup is shown in the Fig.1. It is single cylinder, four stroke, water cooled variable compression ratio (VCR) engine. Full specifications of the engine are shown in Table1

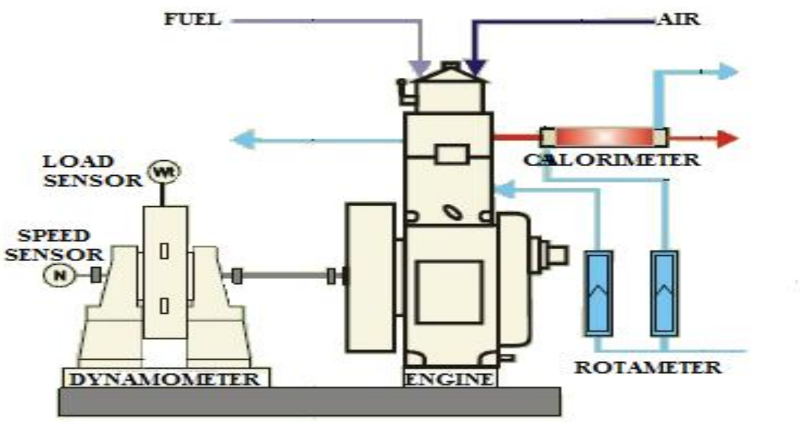

Figure 1 Schematic Diagram of Test Engine

This engine set up consists of many sensors like temperature sensor, load sensor, speed sensor etc. Fuel is supplied from the fuel tank and there is glass burette attached with fuel tank for measurement of fuel consumption. Air is supplied through air box setup having manometer. This setup is required to measure mass of air consumed. Engine output shaft is connected with the eddy current dynamometer. Speed sensor and load sensor is attached with dynamometer. Engine is cooled by water and flow rate of water is controlled by valve. Flow rate value can be measured from rota meter/flow meter. Calorimeter is attached with the exhaust line for some required measurement. For the analysis of exhaust gases separate gas analyzer is also used during experiment. This engine has arrangements to change compression ratio, injection timing, spark timing (in case of petrol engine head is attached), and injection pressure.

Table 1 Test Engine Specification

Particular	Specification
Engine Type	Single Cylinder, 4-Stroke, Water Cooled
Bore and Stroke	87.5 mm * 110 mm
Rated Power	3.5 kW at 1500 rpm

CR range	12:1 to 18:1
Injection Variation	0-25 degree BTDC
Dynamometer	Eddy Current type, Water Cooled with Load Unit
Calorimeter	Pipe in Pipe type
Temperature Sensor	RTD type PT100 and Thermocouple, type K
Load Sensor	Load Cell, type Strain Gauge, Range 0-50 kg
Rotameter	Engine Cooling 40-400 LPH, Calorimeter 25-250 LPH

2.2 Experiment Methodology

Firstly engine was made to run at manufacturers set value of compression ratio 17.5 and readings for energy analysis were taken for different blends (B10 to B50). Engine was made to run on three different loading conditions as low, medium and high for same blends. The measurements were taken after the steady state condition was reached. Though this engine setup has facility to automatic reading measurements at some fixed interval of time with data acquisition system, due to some technical problems readings were measured and noted manually. Load was varied with the help of voltage knob and reading directly indicates values in terms of load in kilogram. Fuel consumption was measured manually by measuring time for fixed amount of fuel consumption (10cc in this case) for all fuels at different loading conditions. From the air box manometer difference was noted every time which is used to calculate mass of air consumption. Mass flow rate of water for engine cooling and for calorimeter was set by valves and values of flow rates were indicated by rota meter. Temperature readings were taken from the digital indicator connected with sensor which shows various temperature readings such as engine cooling water inlet and outlet, calorimeter water inlet and outlet and exhaust gas inlet and outlet. During this initial experiment all readings were taken at compression ratio of 17.5 and injection pressure of 180 bar. Best suitable blend was chosen whose performance was found similar to diesel fuel from initial analysis. Then after experiment was done at various combination of different compression ratio 16, 17 and 18 and injection pressure of 180 and 200 bar for that suitable blend. This second experiment was done to check the effect of change in engine parameter(CR and IP) on exergy efficiency of the engine. Readings for this second experiment were taken similar way as taken during first experiment, only difference is that operating parameters were changed and fuel blend remains same throughout this second experiment. Fuel used during experiment was purchased from the biodiesel manufacturer in Nagpur, India. Required fuel property was tested in chemical laboratory. Properties for pure jatropha biodiesel (B100) are listed in Table2. Further Element Analysis Report for B20 blend is also shown in Table3 which is useful in exergy analysis.

Table 2 Properties of Pure Jatropha Biodiesel

Calorific Value	38074.4 kJ/kg
Specific Gravity	0.85
Fire Point Temperature	208 ^{0}C

Table 3 Element Test Report for B20 blend

Element	% by weight
Carbon (C)	85.02
Hydrogen (H)	11.08
Oxygen (O)	1.82
Sulphur (S)	0.025
Nitrogen (N)	0.04

III. EXERGY ANALYSIS

The Exergy is defined as maximum theoretical work that can be obtained from a system as it comes to equilibrium with reference environment [8]. Exergy analysis is carried out to find various availabilities or potential of energy which are lost or destroyed during operation of system and it also allows us to comment on process irreversibility. Steps involving exergy analysis are as follow: [1,4,8,12]
Input availability is the actual energy supplied to the engine by the fuel and it contains two parts which are known as thermo mechanical and thermo chemical exergy.

$$A_{in} = A^{tm} + A^{tc} \qquad (1)$$

$$A^{tm} = (h - h_0) - T_0(s - s_0) \qquad (2)$$

$$A^{ch} = \dot{m}_f \times \left[1.0401 + 0.1728\frac{h}{c} + 0.0432\frac{o}{c} + 0.2169\frac{s}{c}\left(1 - 2.0628\frac{h}{c}\right)\right] \times \text{LCV} \quad (3)$$

Where A_{in}, A^{tm}, A^{ch} are fuel availability, thermo-mechanical exergy and thermo chemical exergy respectively. In equation (3) h , c , o , s are mass fractions of hydrogen, carbon, oxygen and sulphur in fuel respectively. But thermochemical exergy is consider as zero assuming it is initially at dead state hence only thermo-chemical exergy is considered as input.

Shaft power availability is given as below equation which is the same as the brake power because mechanical power is high grade energy and is completely available:

$$A_{BP} = (2\pi \times N \times T)/60{,}000 \quad (4)$$

Engine cooling water availability is calculated by considering this as a heat transfer process only and it is calculated as follow:

$$A_{cw} = Q_{cw}\left(1 - \frac{T_0}{T_{cw}}\right) \quad (5)$$

Exhaust gas availability also contains two parts : thermo mechanical and thermochemical exergy. Thermo-mechanical exergy is as given below:

$$A_{Ex}^{th} = \left[\sum_{i=1}^{n} a_i \left\{\bar{h}_i(T) - \bar{h}_i(T_0) - T_0\left(\bar{s}^0(T) - \bar{s}^0(T_0) - \bar{R}\ln\frac{p}{p_0}\right)\right\}\right] \quad (6)$$

Where h and s values are enthalpy and entropy of component for particular temperature and value of a_i represents moles of particular gas.

Thermochemical exergy is given as:

$$A_{Ex}^{ch} = \bar{R}T_0 \sum_{i=1}^{n} a_i \ln\frac{y_i}{y_i^e} \quad (7)$$

Where $\bar{R}$ is universal gas constant and yi and ye are molar ratio of i th component in exhaust and environment respectively. Reference environment condition is taken as N_2(75.67%) , O_2(20.35%), CO_2(0.0345%), CO(0.0007%) . All value represent mole fraction of each component in atmosphere [5]. Hence total exhaust gas availability would be summation of the thermo-mechanical and thermo chemical exergy.
Exergy destroyed in the system is given as below which includes exergy destructed due to friction, combustion and heat loss due to finite temperature gradient.

$$A_d = A_{in} - (A_{Ex} + A_{cw} + A_{bp}) \quad (8)$$

Second law efficiency or exergy efficiency is given as follow:

$$\eta_{II} = \left(1 - \frac{A_d}{A_{in}}\right) \times 100\ \% \quad (9)$$

IV. RESULT AND DISCUSSION

From the energy analysis of the biodiesel blends it was found that at low and medium load diesel has highest efficiency and at high load all blends have higher efficiency than diesel. Biodiesel blend B20 gave higher performance among all blend at all loading condition. Comparison of brake thermal efficiency is shown in Figure 2. From this energy analysis B20 performance was comparatively higher and hence exergy analysis of B20 blend was carried out by changing compression ratio (16,17 and18) and injection pressure (180 and 200 bar).

Result obtained from the exergy analysis is discussed below. From the Figure3 we can say that while operating at 180 bar injection pressure and if we change compression ratio it can be observed from both of these figure that at low and medium loading condition compression ratio 16 gives highest second law efficiency while at high load compression ratio 17 gives highest second law efficiency. Higher first law efficiency is direct result of higher second law efficiency because higher second law efficiency results into less destruction of energy or less irreversibility and hence results into higher first law efficiency or energy efficiency. Similarly if we compare results at injection pressure of 200 bar from Figure4 at all loading condition compression ratio of 16 has highest performance at all loading condition. Also if we compare Fig.3 and Fig.4 we come to know the effect of injection pressure on the performance of the engine. From figures we can see that at two injection pressures 180 and 200 bar and same compression ratio performance is different and engine has higher performance at injection pressure of 180 bar for particular compression ratio So from this observation from the results we can find that highest performance of the engine was at compression ratio 16 during low and medium loading and at 17 during high loading condition. Exergy efficiency were 23.41% , 30.34% and 34.27% during above stated setting of parameter and obviously energy efficiency will be higher at this setting of parameter.

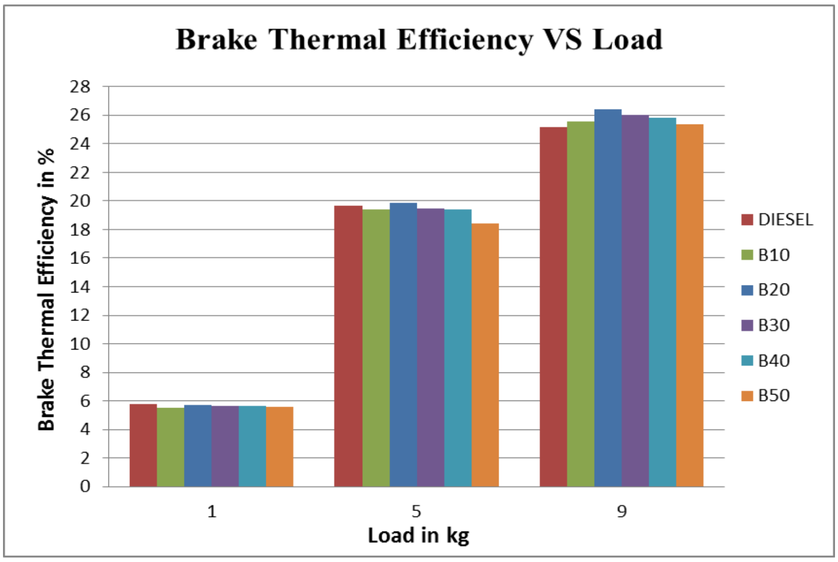

Figure 2 Comparison of Brake Thermal Efficiency of Various Fuels

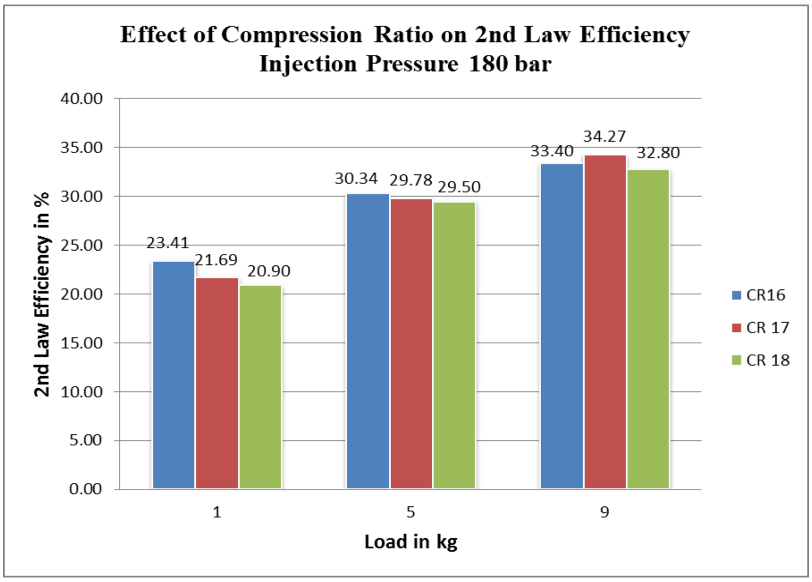

Figure 3 Comparison of Exergy Efficiency at Injection Pressure 180 bar

From the exergy analysis we can conclude that compression ratio 16 has higher performance at both set value of injection pressure 180 and 200 bar. But injection pressure 180 bar has comparatively higher performance than 200 bar. Highest exergy efficiency was found at compression ratio 17 and injection pressure 200 bar which is 34.27%. Hence full exergy analysis diagram indicating fraction value is shown in Figure5 for CR17 and IP180 bar. From the Figure5 we can conclude that exhaust gas contains highest availability which can be recovered. It contains 11.60% of the input availability. Engine cooling water has not much availability with it, it accounts only 0.67% of input availability. Shaft power availability is 22.00% which is fully available. Exergy destruction of the energy is more than 60% due to various irreversibilities. These irreversibilities include combustion process, friction and heat loss due to finite temperature gradients. There is scope of recover the exhaust gas availability by using suitable heat recovery method. Combustion process is affected by operating parameters and hence for higher exergy efficiency operating parameters must be optimized.

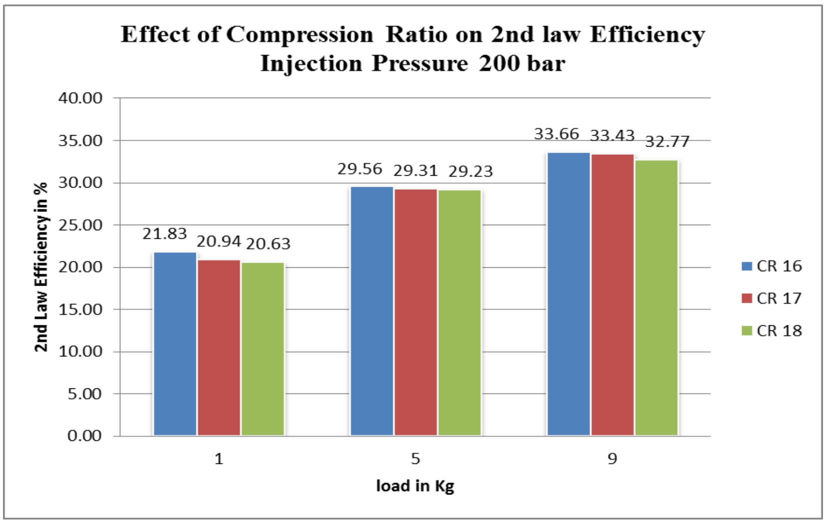

Figure 4 Comparison of Exergy Efficiency at Injection Pressure 200 bar

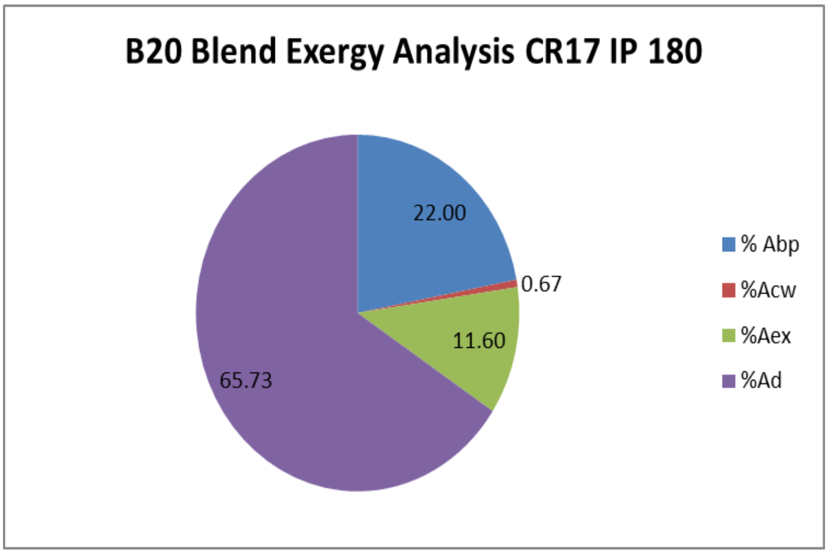

Figure 5 Complete Exergy Analysis of B20 blend at Highest Performed Parameters

V. CONCLUSION

From energy analysis it can be conclude that biodiesel gives similar performance compare to diesel. Lower blend ratio gives higher performance among all blends. Lower blend ratio is preferable because it has less fuel consumption than higher blend ratio. Though biodiesel has less calorific value than the diesel due to oxygen content in it, it promotes better combustion and hence it has similar kind of performance compare to diesel.

From the exergy analysis of the B20 blend at different compression ratio and injection pressure we can conclude that at one particular combination there will be a maximum performance. In this case at low and medium loading compression ratio 16 and injection pressure 180 bar gives maximum performance having exergy efficiency values 23.41% and 30.34% respectively and during high loading condition compression ratio 17 and injection pressure 180 gives maximum exergy efficiency(34.27%). For injection pressure 200 bar efficiency was found lower than the 180 bar injection pressure at all compression ratio and at all loading condition. Also from exergy analysis we are able to calculate the various availabilities. More than 60% of the exergy is destroyed due to irreversible process such as combustion, friction and exergy loss due to finite temperature gradient. Exhaust gases have higher value of availability than engine cooling water availability. Hence by knowing availability we can make decision about amount of energy that can be recovered.

VI. ACKNOWLEDGEMENTS

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