Effect of Compression Ratio and Exhaust Gas Recirculation (EGR) on Combustion, Emission and Performance of DI Diesel Engine with Biodiesel Blends

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Abstract

The present investigation deals with combustion, emission and performance characteristics of a single cylinder DI diesel engine for biodiesel blends (J10, J20, J30, P10, P20, P30) with the optimum use of EGR system by the formulation of matrix analysis. Compression ratios like 17.5:1, 19:1, 20:1 were varied. The piston was modified by cold metal transfer (CMT) welding with the use of aluminium alloy on the piston bowl of the diesel engine. Tests were performed at different loading conditions and results were obtained. The performance study suggests that BTE was found to be increased with J20 CR20 and slight reduction with J20 CR20 E20 blend compared to diesel. Peak pressure was higher for J20 CR20 conforming better combustion characteristics over other biodiesel blends. Ignition delay were shorter for J20 CR20 and P20 CR20 blends with crank angle varying from 23.4 deg to 10.78 deg for J20 CR20 and 23.4 deg to 10.48 deg for P20 CR20 before TDC. NOx emission was increased with the increase in percentage of biodiesel blends. Significant NOx reduction in biodiesel blends were found with the use of EGR in J20 CR20 EGR20 and P20 CR20 EGR20.

Index terms— compression ratio, exhaust gas recirculation, biodiesel blends, combustion, emission.

1 I. Introduction

n alternate fuel resource for IC engines is in great demand owing to various criteria. Usage of fossil fuel inhibits a scarcity of fossils and creates a complication for renewal. In such a case, the use of biodiesel is growing at a rapid rate to replace the diesel fuel. Biodiesel is a term that describes a fuel comprised of mono-alkyl esters of long chain fatty acids derived from vegetable or animal oils. The vegetable oil based biodiesel has found a prominent place as an alternate fuel due to the depletion in the conventional fossil fuels [1], [2], [3]. The esterification of biodiesels from its major crude vegetable oil was used as a well-known biofuel. Early scientists have also conducted experiments on vegetable oils like (Thevetia Peruviana, Neem oil) etc [4], [5]. In India, the large availability of Jatropha and Pongamia makes them a prime raw material for the production of biodiesel. Jatropha, is being spread across India as a vital crop to be cultivated due to the extensive advantages it inhibits [6]. Due to the similar fuel properties of biodiesel with the conventional diesel oil, it can be blended in varying proportions and used as an alternate fuel in Diesel engines [7]. Fuel consumption of biodiesel is slightly higher than conventional diesel due to lesser calorific value [8]. The exhaust gas of a diesel engine consists of particulate matter [9]. All these gases pollute the atmosphere to a great extent that results in serious health hazards to human beings and also in the advent of precarious natural phenomenon like acid rain and greenhouse effect. One of the key method to overcoming this problem in engines is the use of an EGR system. Exhaust gas recirculation system is used as a hot mode by suffusing the varying percentage of burnt gases into the inlet port for reducing NOx emissions [10]. Exhaust gases resulting in lowering the emission of NOx by reduction of combustion temperature and excess oxygen [11]. As the working of this system is in direct concern to the environment, this system may be called an eco-friendly system. The methodology of EGR system is as follows.

2 II. Egr System

EGR is one of the efficacious methods in reducing NO x emissions in diesel engines. EGR has got its own limitations as at higher EGR rates the combustion is affected due to less availability of oxygen and hence increase in smoke emissions results in higher fuel consumption [12]. Hence a by-pass for the exhaust gas is provided along with the manually controlled EGR valve. The exhaust gas comes out of the engine during the exhaust stroke at a high pressure and is pulsating in nature. It is desirable to remove these pulses in order to make the volumetric flow rate measurements of the recirculating gas possible. For this purpose, smaller air box with a diaphragm is installed along the EGR route. A U-tube manometer is mounted across the orifice in order to measure the EGR flow rate. Suitable instrumentation is provided to acquire useful data from various locations. Thermocouples are placed in intake manifold and exhaust manifold at various points along the EGR route. A matrix of test conditions is used to investigate the effect of EGR on exhaust gas temperature and exhaust smoke opacity. The schematic diagram of exhaust gas recirculation (EGR) system attached with the diesel engine is as shown in Fig. 1.

Increasing the exhaust pipe line length (15 metres) and placing the EGR system far away from the diesel engine reduces the exhaust gas temperature through natural convection. Manually controlled EGR valve was attached to pass the required amount of exhaust gas into the engine cylinder to combine with the intake air and is thus controlled accurately. Percentage of EGR was calculated using the following equation

3 III. Transesterification Process

Transesterification is a suitable method for utilizing vegetable oils in DI diesel engine for long term applications without any major modifications and durability problems. Transesterification of vegetable oil enhances the quality of biofuel by reducing its viscosity. Transesterification is influenced by the reaction temperature, catalyst and stirring speed [13]. A two-step acid base process was used to prepare the biodiesel. In the first step acid pre-treatment was used to extract the biodiesel from crude Jatropha and Pongamia oil followed by base transesterification using Methanol as a regeant; H 2 SO 4 and KOH used as a catalyst. The physical and chemical properties of JME-Diesel; PME-Diesel was evaluated as per the IS 15607-2005 standards. The conversion of methyl esters from triglycerides with the presence of catalyst as represented in the following equation [14]. a) Fuel Properties Jatropha Methyl Ester (JME) and Pongamia Methyl Ester (PME) were mixed separately with diesel in varying proportions (10%, 20% and 30% by volume) and test fuels J10, J20, J30, P10, P20 and P30were prepared. The properties of neat diesel and biodiesel blends are presented in Table **??**. Density and viscosity of biodiesel blends increases with increase in percentage volume of biodiesel due the higher molecular weight of fatty acids in biodiesel [15]. Respectively the density of biodiesel blends is higher than neat diesel oil. Density of higher jatropha and Pongamia blends is found to be 874 kg/m 3 and 891 kg/m 3 . Kinematic viscosity of Jatropha and Pongamia blends is higher at J30 and P30 compared with diesel. Flash point of biodiesel blend is higher when compared with diesel. This is due to high vaporization temperature of biodiesel in air for combustion. Higher flash point enables storage of biodiesel blends safer than diesel and within the IS 5607-2005 standard limits [16]. Cetane number of biodiesel blends is higher when compared to diesel. Higher Cetane values of fuel enhance the combustion quality and hence smooth operation of the engine is guaranteed [17]. The experimental investigation were conducted on a single cylinder air cooled DI diesel engine. The maximum power extracted by an engine was 4.4 kW at a rated speed of 1500rpm. The specification of the engine is shown in Table **??**. The experimental setup is as shown in Fig. 1. Cylinder pressure is measured using AVL GH14D Pressure Transducer. The pressure transducer is located in a hole drilled through the cylinder head into the combustion chamber. The sensing element consists of metal diaphragm, which deflects under pressure. AVL 365C angle encoder is used to convert the Analog signal into a digital electrical signal. DAQ card was connected to the encoder to evaluate the electrical signals and determine the crank angular position. AVL 3066A02 Piezo Charge Amplifier is used to convert the electrical charge output of the pressure transducer into voltage. K type thermocouple was attached with diesel engine to measure the exhaust gas temperature. Electrical dynamometer is coupled to the engine by flexible coupling for measuring the brake power of the engine. It consists of a 5KVA AC alternator (220V, 1500rpm) mounted on the bearings and on the rigid frame for the swinging field type loading. The output power is directly obtained by measuring the reaction torque. Reaction force (torque) is measured by using a strain gauge type load cell. Panel board consists of Ammeter, Voltmeter switches and fuse, load cell indicator and temperature indicator. MRU delta 1600L Exhaust Gas Analyser was used to measure NO x , HC, CO and CO 2 emissions. The emissions of CO (carbon monoxides) and HC (hydrocarbons) were measured by means of infrared measurement. AVL 415 Smoke meter is used to measure the percentage of smoke present in the exhaust gas. A fraction of the exhaust gas was sampled by means of a probe in the exhaust line and drawn through a filter paper. The resultant blackening of the filter paper was measured by a reflectometer and hence the opacity in the exhaust gas was determined. The list of instrumentation details is shown in Table **??**. Exhaust gas recirculation (EGR) system externally fixed with diesel engine analysis the engine combustion and emission characteristics.CH

4 a) Testing Procedure

The single cylinder direct injection diesel engine was initially operated with neat diesel oil to maintain the wall temperature of the engine for proper combustion of biodiesel. Tests were performed for different loading conditions (0%, 25%, 50%, 75% and 100%) using JME and PME blends and for each loading condition the engine was allowed to run for 15minutes. Three sets of readings were taken for each test fuel. Varying compression ratio is attained in a constant compression ratio diesel engine through the modification of the bowl in piston as shown in Fig. 2 using aluminium alloy as an additive material by a low temperature CMT welding process. Compression ratio of 17.5:1, 19:1 and 20:1 were chosen for the present study. Exhaust gas recirculation is used in varying percentage by volume (10%, 20% and 30%). These three parameters were optimized by design of experiments (orthogonal array) and are shown in Fig. 3 and Table **??**. Through this matrix approach the following conditions were selected for the optimized parameters: fuel blends (JME 20% and PME 20%), compression ratio 20:1 and Exhaust gas recirculation 20%.

5 V. Error Analysis

The maximum possible error in various measured parameters namely pressure, temperature, exhaust gas emissions, time, flow and speed estimated from the minimum values of output and accuracy of the instrument is calculated using the method proposed by **??**Moffat 1985). This method is based on careful specification of the uncertainties in the various experimental measurements. Instruments used for measuring various engine parameters as shown in Table **??**.

If an estimated quantity S, depends on independent variables like (x1, x2, x3 ????xn) then the error in the value of S is given by Where,

, are the errors in the independent variables. = square root of ((uncertainty of pressure transducer) The variation of cylinder pressure with respect to crank angle (CA) for diesel, biodiesel blends with different compression ratio and effect of EGR is shown in Fig. **??**. for full load conditions. The peak cylinder pressure for diesel, J20 CR17.5, J20 CR20, J20 CR20 EGR20%, P20 CR17.5, P20 CR20 and P20 CR20 EGR20% was obtained as 75.729bar at 7°CA after TDC, 75.194bar at 7°CA after TDC, 77.987bar at 7°CA after TDC, 76.501bar at 7°CA after TDC, 75.523bar at 7°CA2 1 2 2 2 2 2 1 1 .. .. ? n n x x x x x x S S 1 1 x x ?? ? ?? ?? , 2 2 x x

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after TDC, 75.201bar at 7°CA after TDC and 74.511barat 7°CA after TDC respectively. For all engine loads, cylinder pressure gradually increases for compression stroke. It attains the peak value at 7°CA after top dead centre (TDC). The quantity of fuel burned was increased with increasing the engine load. If a peak pressure occurs very close to TDC that cause severe knock and affects the engine durability [18]. In this experiment, while operating with biodiesel blends the peak pressure takes place after TDC and ensures safe and efficient operation. It is observed from the figure that the peak cylinder pressure with J20 CR20 blend was 2.53 bar higher than that of diesel. The reason for maximum cylinder pressure of J20 CR20 is increase in compression ratio. While engine was operated with EGR system, the peak cylinder pressure was found to decrease due to the increase in intake air temperature [19]. This in turn shortens the ignition delay period and hence results in lower peak pressure.

ii. Heat release rate theoretical consideration Rate of heat release developed inside the cylinder during the combustion stroke was analyzed based on the in-cylinder pressure for various engine loads. The formula used to calculate the rate of heat release is given in Eq (1),

Where, ?-is the ratio of specific heats (C p /C v) (Heywood 1988). The appropriate range of ? (for diesel) heat release analysis is 1.3 to 1.35.

is the heat transfer in kJ/m 3 .degree, P-is the instantaneous cylinder pressure (bar), V-is the instantaneous cylinder volume (m3).

iii. Rate of Heat Release

The change of heat release rate with respect to crank angle (CA) for diesel and biodiesel blends with different compression ratio and the effect of EGR as shown in Fig. **??**. for full load conditions. The peak heat release rate for diesel, J20 CR17.5, J20 CR20, J20 CR20 EGR20%, P20 CR17.5, P20 CR20 and P20 CR20 EGR20% was obtained as 69.854 kJ/m 3 [20]. It is observed from the figure that, heat release rate gets reduced as the percentage of biodiesel blends increases. The reason for reduced heat release rate of biodiesel blends with EGR is due to higher temperature of intake air.

7 iv. Cumulative Heat Release Rate

The change of cumulative heat release rate with respect to crank angle (CA) for diesel and biodiesel blends with different compression ratio and the effect of EGR as shown in Fig. **??**. The CHRR values were evaluated from the end of compression stroke to the beginning of expansion stroke. It is observed from the figure that JME blends shows higher cumulative heat release rate compared to diesel because of the presence of oxygen molecules in the biodiesel fuel. Meanwhile, CHRR gets lowered for biodiesel fuels with EGR operation because of the reduction in combustion temperature.

8 v. Ignition Delay

Ignition delay is the delay period between the start of injection and the start of combustion. The ignition delay period of DI diesel engine was calculated by Eq (2).

(2) ? id -Ignition delay, E A -apparent activation energy, -universal gas constant, A, nconstants (depend on fuel injection and air-flow characteristics). The ignition delay for Jatropha, Pongamia methyl ester blends and diesel at full load condition is shown in Table **??**. The ignition delay period in a diesel engine has an influence on both the engine design and its performance [21]. Ignition delay of Diesel, J20 CR17.5, J20 CR20, J20 CR20 EGR20%, P20 CR17.5, P20 CR20 and P20 CR20 EGR20% is 14.18°, 13.62°, 12.62°, 11.24°, 13.1°, 13.92° and 11.59° (CA) respectively. The ignition delay for biodiesel blends decreases with the increase in percentage of biodiesel due to the higher Cetane number of biodiesel compared with diesel.

9 b) Emission

The emission and performance characteristic of the IC engine is shown in Table **??**.

10 i. NO x formation mechanism

Thermal NOx is produced by the reaction of atmospheric oxygen and nitrogen at elevated temperatures and is reported to contribute about 20% of the total NOx. Nitric oxide is the predominant oxide of nitrogen produced inside the engine cylinder. Nitric oxide (NO) and Nitrogen oxide (NO 2) are grouped together as a NOx emission [22]. Mechanism of NO x formation is proposed by Zeldovich was given by,O + N 2 = NO + N (3) N + O 2 = NO + O (4) N + OH = NO + H**(5)**

ii. NO x emission

The change of NO x emission for Diesel, J20 CR17.5, J20 CR20, J20 CR20 EGR20%, and P20 CR17.5, P20 CR20 and P20 CR20 EGR20% with brake power was shown in Fig. **??**. At lower temperatures, nitrogen exists as a stable diatomic molecule but at higher temperature it becomes reactive. Hence higher temperature and availability of excess oxygen are two main factors which facilitate the formation of NO x [23]. to be 668 and 721ppm for J20 and 678 and 741ppm for P20 as optimum blend for 17.5 and 20 CR. This is due to higher Cetane number and availability of excess oxygen in the biodiesel inducing proper combustion [24]. NO x level decreases with the use of EGR system due to the higher specific heat of recirculated exhaust gas and reducing the excess oxygen in the intake charge. The NO x level of Jatropha and Pongamia with EGR system was found to be 534ppm and 612ppm.

iii. HC Emission

The variation of hydrocarbon (HC) for diesel and blends J20 CR17.5, J20 CR20, J20 CR20 EGR20%, P20 CR17.5, P20 CR20 and P20 CR20 EGR20% with brake power is shown in Fig. 8. Hydrocarbon emission from diesel engine acts as irritants and odorants while some are toxic carcinogenic. HC emission is due to the insufficiency of oxygen level to consume all the fuel during combustion. This is because of non-homogeneity of fuel-air mixture [25]. The HC emission varies from 13 ppm at part load to 30 ppm at rated load for diesel, while for J20 CR17.5 it varies from 4 ppm at part load to 24.59 ppm at rated load. For J20 CR20 it varies from 5.89 ppm at part load to 21.77 ppm at rated load, for J20 CR20 EGR20%, it varies from 5.32 ppm at part load to 32.34 ppm rated load, for P20 CR17.5 it varies from 12ppm at part load to 28.17 ppm at rated load, for P20 CR20 it varies from10.9 ppm at part load to 25.2 ppm at rated load and forP20 CR20 E20% it varies from 14.16 ppm at part load to 36.7 ppm at rated load. It is also observed from the figure that J20 CR20 has the lowest HC emission compared to other test fuel blends. Further it is perceived from the figure that, Increase in percentage of biodiesel blends and compression ratio decreases the HC emission due to complete combustion and availability of O 2 in the biodiesel blends. Meanwhile inverse trends were detected with EGR system i.e. the HC emission increased with increase in percentage of EGR.

11 iv. CO Emission

The variation of carbon monoxide (CO) for diesel, J20 CR17.5, J20 CR20, J20 CR20 EGR20%, P20 CR17.5, P20 CR20 and P20 CR20 EGR20% with brake power was shown in Fig. 9. CO emission varies from 0.06% at part load to 0.154% of full load for diesel, while for biodiesel blends it varies from 0.07% at part load to 0.139% at full load condition for J20 CR17.5, for J20 CR20 it varies from 0.08% at part load to 0.121% at full load, for J20 CR20 EGR20 it varies from 0.085% at part load to 0.163% at full load, for P20 CR17.5 it varies from 0.05% at part load to 0.1% at full load, for P20 CR20 it varies from 0.066% at part load to 0.147% at full load, for P20 CR20 E20% it varies from 0.05% at part load to 0.124% at rated load. It is noted from the figure that, biodiesel blends produces lower CO emission when compared to diesel. It is concluded that increase in biodiesel blends and compression ratio results in reduction in CO emission. However, CO emission increases with increase in the percentage of EGR. This is due to the overall reduction of excess oxygen resulting from EGR [26].

12 v. CO 2 Emission

The variation of carbon dioxide (CO 2) for diesel, J20 CR17.5, J20 CR20, J20 CR20 EGR20%, P20 CR17.5, P20 CR20 and P20 CR20 EGR20% with brake power is shown in Fig. 10. CO 2 emission varies from 4% at part load to 8.7% at rated load for diesel, as for biodiesel blends 3.6% at part load to 8.1% at full load for J20 CR17.5, 3.8% at part load to 8.7% at rated load for J20 CR20, 4.2% at part load to 9% at full load for J20 CR20 EGR20%, 3.8% at part load to 8.6% at rated load for P20 CR17.5, 3.7% at part load to 8.8% at rated load for P20 CR20, 4.1% at part load to 9.2% at full load for P20 CR20 E20%. The increasing of CO 2 emission with load is might be due to the higher fuel consumption of biodiesel blended and due to the excess presence of oxygen in biodiesel molecular structure [27].

13 vi. Smoke Opacity

The variation of smoke opacity for diesel, J20 CR17.5, J20 CR20, J20 CR20 EGR20%, P20 CR17.5, P20 CR20 and P20 CR20 EGR20% with brake power is shown in Fig. 11. The smoke opacity varies from 0.35FSN at part load to 3.61FSN at rated load for diesel, 0.25FSN at part load to 2.24FSN at rated load for J20 CR17.5 and 0.39FSN at part load to 3.31FSN at rated load J20 CR20, 0.4FSN at part load to 3.49FSN at rated load for J20 CR20 EGR20%, 0.26FSN at part load to 2.8FSN at rated load for P20 CR17.5, 0.33FSN at part load to 2.62FSn at rated load for P20 CR20, 0.32FSN at part load to 4.24FSN at rated load for P20 CR20 E20%. It is observed from the figure that, smoke opacity decreases with increase of biodiesel in blends and compression ratio due to availability of O 2 in fuel during diffusion combustion phase [29]. Meanwhile smoke opacity increases with increase in percentage of EGR this is due to present of carbon content. c) Performance i. Brake Thermal Efficiency Brake thermal efficiency is the efficiency of the diesel engine in which chemical energy of the fuel is extracted in the form of heat and utilized for mechanical work. The variation of brake thermal efficiency for J20 CR17.5, J20 CR20, J20 CR20 EGR20%, P20 CR17.5, P20 CR20, P20 CR20 EGR20% and diesel with brake power is shown in Fig. 12. It can be seen that the brake thermal efficiency increased with increase in engine loads for all test fuels. It is observed from figure that the thermal efficiency of diesel is 28.81% at rated power and for J20CR17.5; P20CR17.5 is 27.9%, 27% respectively. It shows that efficiency of J20, P20 blends is slightly less compare with diesel this is due to lower calorific value. Brake thermal efficiency for J20 CR20, P20 CR20 is Year 2014 ume XIV Issue

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Effect of Compression Ratio and Exhaust Gas Recirculation (EGR) on Combustion, Emission and Performance of DI Diesel Engine with Biodiesel Blends 31.7%, 30% due to the effect of increase in compression ratio. For J20 CR20 EGR20%, P20 CR20 EGR20%, the BTE is 30.89%, 29.37% which is reduced with the use of EGR. This is because of reduced amount fresh oxygen content present in the combustion chamber [29].

ii. Exhaust Gas Temperature

The variation of exhaust gas temperature for J20 CR17.5, J20 CR20, J20 CR20 EGR20%, P20 CR17.5, P20 CR20 and P20 CR20 EGR20% and diesel with brake power is shown in Fig. 13. The EGT varies from 263°C at part load to 456°C at rated load condition for diesel. 263°C at part load to 456°C at rated load condition for J20 CR17.5, 270°C at part load to 464°C at rated load condition and for J20 CR20, 244°C at part load to 430°C at rated load condition. For J20 CR20 E20, 271°C at part load to 470°C at rated load condition and for P20 CR17.5, 283°C at part load to 477°C at rated load condition for P20 CR20 and 243°C at part load to 435°C at rated load condition for P20 CR20 E20 respectively. Exhaust gas temperature gets decreased continuously as the percentage of exhaust gas recirculated into the engine is increased. It can be observed from the figure that exhaust gas temperature gets reduced considerably with EGR; resulting in lower combustion temperature and NO x emission.

15 VII.

16 Conclusion

It is concluded from the results that, ? The effect of increase in compression ratio increase the brake thermal efficiency, exhaust gas temperature, NO x emission and reduces the smoke opacity, CO emission and Unburned hydrocarbon emission. ? NO x emission was higher for biodiesel and its blends due to higher in-cylinder temperature and availability of free oxygen in the fuel.

? Smoke emission decrease due to availability of O 2 in fuel during diffusion combustion phase.

? Both HC and CO Emission decreases due to complete combustion and availability of excess oxygen in biodiesel blends.

? Effect of EGR, Decreases NO x , EGT, thermal efficiency and increases Smoke, UBHC and CO.

? NO x , Brake thermal efficiency, EGT gets reduced considerably by adopting EGR; meanwhile it slightly increases the Smoke, HC and CO emissions Thus the usage of EGR to the optimum biodiesel blends reduces NO x emission and improves combustion characteristics providing an energy based fuel economy in diesel engines.

17 VIII.

Abbreviation J10, J20, J30 -Jatropha 10%, Jatropha 20%, Jatropha 30% P10, P20, P30 -Pongamia 10%, Pongamia 20%, Pongamia 30%, J20 CR17.5 -Diesel 80%-Jatropha 20% and compression ratio 17.5:1 J20 CR20 -Diesel 80%-Jatropha 20% and compression ratio 20:1 J20 CR20 EGR 20% -Diesel 80%-Jatropha 20% and compression ratio 20:1, Exhaust gas recirculation 20% P20 CR17.5 -Diesel 80%-Pongamia 20% and compression ratio 17 Oxides of nitrogen (ppm) Brake power (KW) Diesel J20 CR17.5 J20 CR20 J20 CR20 EGR20% P20 CR 17.5 P20 CR20 P20 CR20 EGR20% Carbon dioxide emission (%) Brake power (KW) Diesel J20 CR17.5 J20 CR20 J20 CR20 EGR20% P20 CR 17.5 P20 CR20 P20 CR20 EGR20%

Figure 12 : Brake power vs. brake thermal efficiency 28 Exhasut gas temperature (°C) Brake power (KW) Diesel J20 CR17.5 J20 CR20 J20 CR20 EGR20% P20 CR 17.5 P20 CR20 P20 CR20 EGR20% [1]

Figure 1: d?

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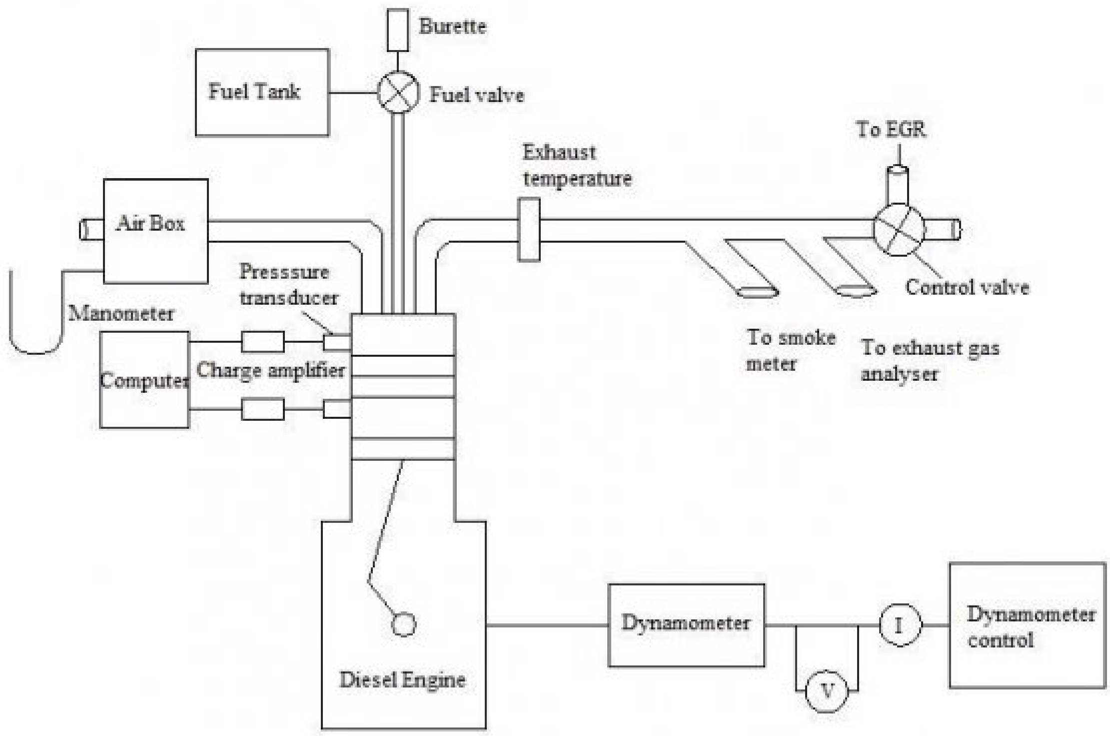

Figure 2: .5: 1 P20

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Figure 3: Figure 2 :

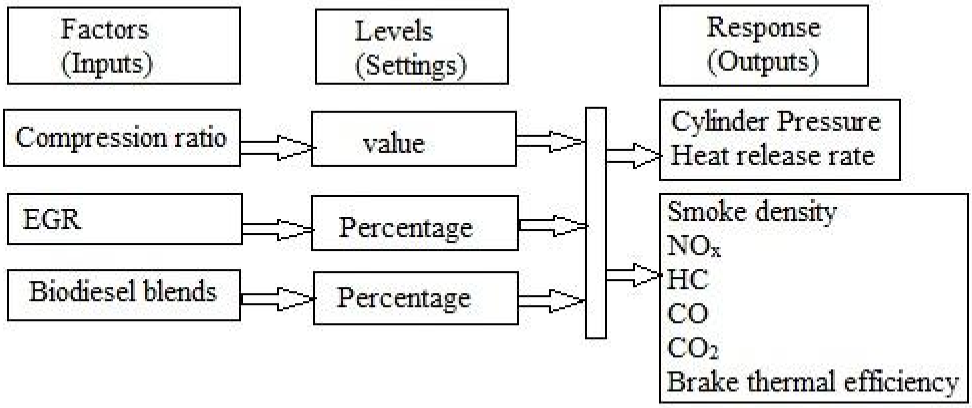

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Figure 4: Figure 3 :

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Percentage of EGR =	volume of air without EGR ? volume of air with EGR volume of air without EGR	× 100

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Figure 5:

Figure 6:

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