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Effect of EGR on Performance and Emission Characteristics of Natural Gas Fueled Diesel Engine

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Abstract

In diesel engines, it is difficult to reduce both smoke and NOx simultaneously. An experimental study was conducted to determine the performance and exhaust emission characteristics of a commercial single cylinder, natural aspirated, air cooled DI diesel engine. The system was modified to work on either dual fuel or diesel alone. The objective of this work is to investigate the possibility of decreasing the exhaust emissions and to determine the performance parameters. At part loads, the dual fuelled operation suffers from higher CO and unburnt hydrocarbon emissions. This is mainly due to overall lean mixture and incomplete combustion because of small quantity of pilot fuel. To resolve these problems, the effects of cooled EGR were investigated. The experimental results show that the application of EGR reduces substantially NOx, CO and smoke. Results indicate that performance parameters are comparable with baseline diesel operation.

Keywords: NO_X ; CNG; Dual Fuelled; EGR; Flame Speed.

Abbreviations

CNG	Compressed Natural Gas
BMEP	Brake Mean Effective Pressure
LPM	Litre per minute
EGR	Exhaust Gas Recirculation
U.B.H.C.	Unburned Hydrocarbon
CO	Carbon Monoxide
NOx	Oxides of Nitogen
BTDC	Before Top Dead Centre
DI	Direct Injection
CO2	Carbon Dioxide
O2	Oxygen
MINTAKE	Mass of intake Charge
MEGR	Mass of EGR

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1. Introduction

The concept of using alternative gaseous fuel in diesel engines has gained worldwide attention. Increasing petroleum fuel prices and their deterioration to environment led to the search for alternative fuels from past several years. CNG is one such fuel available in large quantities in many parts of world at attractive prices. It is a clean burning fuel as compared to the conventional liquid fuels like diesel or gasoline.

The use of CNG in diesel engine has both economic and environmental advantages [1]. Further CNG give higher resistance to knock which makes it possible to utilize in engine having higher compression ratio. Its self ignition temperature is 730^0C and it requires intense source of energy to enable combustion i.e. glow plug, spark plug or pilot liquid fuel. It mixes rapidly with air to form homogenous air fuel mixture for efficient combustion inside engine cylinder and substantial reduction in harmful emissions [2]. In dual fuel engines gaseous fuel is mixed with intake air outside the engine cylinder and pilot liquid fuel is injected at the end of compression stroke to initiate combustion.

Then, flame propagation occurs through the premixed gas-air mixture. Thus, dual fuel operation with gaseous fuel can yield higher thermal efficiency, almost comparable to diesel engines at higher loads. However, a dual fuel engines suffers poor efficiency and increased emissions at light loads. This is mainly due to the resulting very lean mixtures at low loads. The lean mixtures are hard to ignite and difficult to burn [3]. The use of exhaust gas recirculation is suggested method to improve part load performance and emissions characteristics. When considering a gaseous fuel for use in existing diesel engines, a number of issues which include, the effects of engine operating and design parameters, and type of gaseous fuel, on the performance of the dual-fuel engines, are important [4]. At lower loads the use of hot EGR promotes improvement in combustion due to increase in intake temperature. This also brings down smoke levels because of unburned in the exhaust are reburned with this method. Hence, it has been concluded that the use of EGR can effectively brings down the emission levels in the exhaust. The use of cooled EGR decreases the emission of NO_X with little sacrifice in performance and other exhaust emissions. In the present study, the main focus is to investigate the effects of cooled EGR on performance and emission characteristics of CNG-dual fuel engine.

2. 2. Description of The Experimental Procedure

The engine typically used for this study was a single cylinder DI commercial diesel engine. It is an air cooled, naturally aspirated constant speed compression ignition engine as per the IS: 10000 [P: 5]:1980 whose major specifications are shown in Table 1. The engine was coupled to a 5 kVA electric generator through which load was applied by increasing the field voltage shown in Annexure 1. The engine was tested at 20, 40, 60, 80 and 100 percent brake load conditions. The engine has capability to run either on pure diesel or dual fuel mode. The engine is modified to run on CNG by introducing it in the intake manifold pipe at a pressure of 1 kg/cm^2 and flow rate was determined by a calibrated rotameter. The CNG flow rate was kept fixed at 15 LPM for a given speed and loads, and a variable pilot injection is controlled by a governor. The entire test was performed at constant speed of 1500 r.p.m. (rated speed).

The EGR circuit consists of a water cooled heat exchanger for cooling of exhaust gas, orifice meter connected to a U-tube water manometer for measurement of flow rate of exhaust gas, surge tank, and valves fitted to control the quantity of exhaust gas being recycled. The pilot liquid fuel is measured by a calibrated glass tube by measuring the time required for the consumption of 50ml of fuel. During the experiments, engine speed, fuel consumption, air consumption rate and exhaust gas temperature were recorded. Exhaust gases were analyzed on line by an AVL DiGas analyzer, Model 4000 in which UBHC, CO, O_2, CO_2, and NO_X were measured and AVL make Smoke Meter, Model 437 was used to measure the smoke opacity of exhaust gas. A piezoelectric pressure transducer, Kistler make, model 701A was used for measuring the cylinder gas pressure and magnetic pickup, Electro make, model 3010 AMa was used to measure crank angle.

2.1. Fuel Properties

The fuel properties of CNG and diesel are given in Table 2.

CNG composition: 96.113% methane, 2.571% ethane, 0.359% propane, 0.05% I-butane, 0.09% N-butane, 0.01% I-pentane, 0.598% nitrogen, 0.149% carbon dioxide, 0.06% hexanes (CNG fractional analysis given by Gas Authority of India Ltd.)

Table 1 Engine specifications

Make	Kirloskar
Model	DAF 8
Rated Brake Power (BHP/KW)	8 / 5.9
Rated Speed (rpm)	1500
Number of Cylinder	One
Bore X Stroke (mm)	95 x 110
Displacement volume (cc)	779.704
Compression Ratio	17.5:1
Fuel Injection Timing (Degree)	26 BTDC
Injector opening pressure (bar)	200

Table 2 Fuel properties of Diesel, CNG

Fuel Properties	Diesel	CNG
Chemical Formula	$C_{10.8}H_{18.7}$	
Carbon	84-87	75
Hydrogen	33-16	25
Oxygen	0	0
Mole weight (g)	200	16-18
Density (Kg/m^3)	823 -844	0.79
Flame Speed (cm/s)	2.0-8.0	34
Flammability limits (%vol.)	0.6-7.5	5.3-15.0
Gross Heat of Combustion (MJ/kg)	42.5 – 46.5	50
Cetane Number	45 - 50	6
Auto Ignition Temperature (^{o}C)	230-280	730
Research Octane Number	--	130
Latent Heat of Vaporization @ 1 bar(kJ/kg)	233-251	509
Stoichiometric A/F Ratio	14.7	17.3

3. Exhaust Gas Recirculation

Generally EGR is an effective method for reducing NO_X formation due to lowering cylinder gas temperature resulting from the increased inert gas in the charge [5]. So, it was expected that dual fueling and use of cooled EGR could considerably reduce both smoke and NO_X especially at higher loads. Additionally the unburnt hydrocarbons are reburned in the mixture resulting in reduced unburned fuel and improve thermal efficiency at lower loads [6]. In this work cooled EGR has been used at all load conditions. By definition, the amount of EGR is the ratio of mass of recirculated gas to the fresh charge inducted in the cylinder.

$\% EGR = M_{EGR}/M_{INTAKE}$

Where $M_{INTAKE} = M_{AIR} + M_{EGR} + M_{CNG}$

4. Results and Discussion

4.1. Combustion Characteristics

Figs. 1 and 2 provide the experimental results of in-cylinder pressure and heat release rate at 100% load under normal diesel and dual fuel operation. For dual fuel operation with EGR result are given for cooled EGR 15% ratio. It is clear from the Fig. 2 and 3 that the maximum cylinder gas pressure decreased with the induction of EGR in the dual fuel operation. This is observed during compression and the initial stages of combustion. The reduction in peak cylinder pressure is due to high specific heat of the charge mixture and its slower burning rate. The combustion of CNG becomes visible deteriorating the heat release rate during the expansion stroke as shown in Fig. 3. It is also observed that the peak heat release can reach very high value when the quantity of CNG inducted is high. The high rate of heat release will also lead to increased NO_X formation and also lead to engine knocking condition [7]. The second peak of heat release diagram observed in Fig. 3 is due to the combustion of CNG, in the expansion stroke.

The ignition delay period and combustion duration is generally prolonged in dual fuel mode than normal diesel operation. Addition of EGR further increased the delay time mainly because of reduction of charge temperature close to point of fuel injection, due to its high overall heat capacity compared to the normal single fuel operation [8]. The retardation in flame speed with EGR addition also increased the duration of combustion.

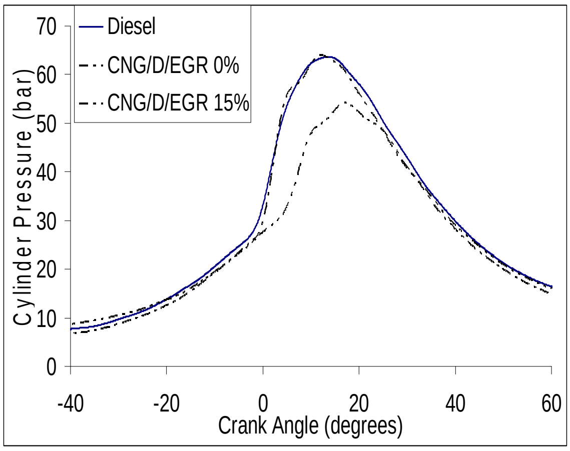

Figure 1. Cylinder pressure versus crank angle diagram at full load condition

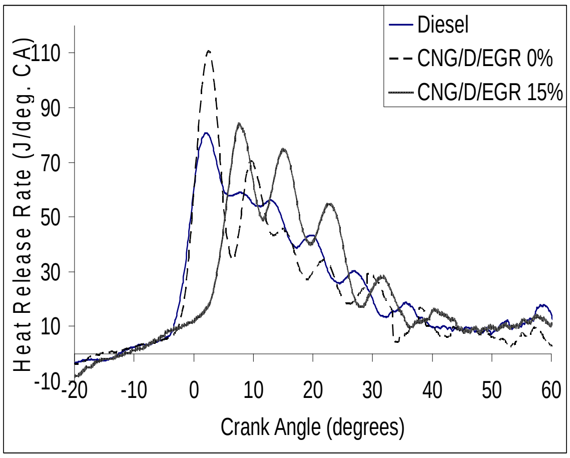

Figure 2. Heat release rate at full load condition

4.2. Engine Performance

In a dual operation with EGR, it is cannot possible to go for higher substitution of CNG or EGR as both displace inlet air required for combustion. So, CNG flow rate was adjusted for smooth engine operation without the onset of knock while EGR was varied from 0-15% on volumetric basis.

Figure 3 represents brake thermal efficiency versus brake mean effective pressure for diesel and CNG-diesel dual fuel operation with different EGR ratio. It shows a great improvement with EGR 5% ratio, than normal diesel and dual fuel operation. The effect of using EGR in a diesel engine has three effects, dilution effect, chemical effect and thermal effect [9].

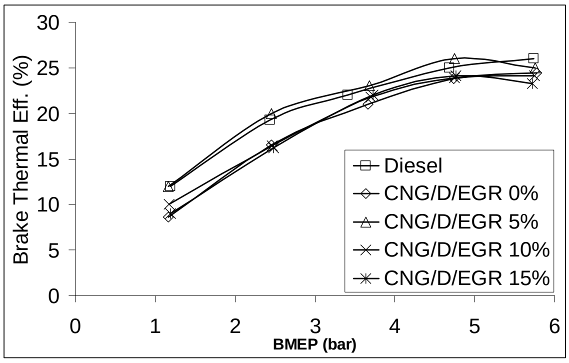

Figure 3. Brake thermal efficiency variations with BMEP

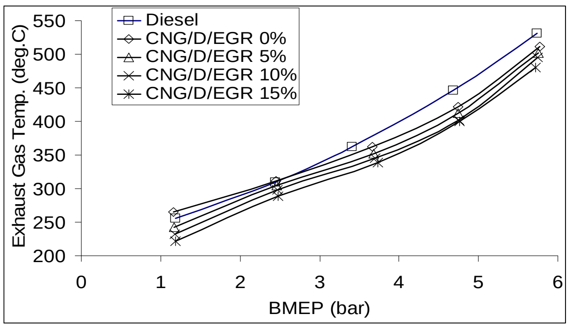

Figure 4. Exhaust gas temperature variations with BMEP

The chemical effect is associated with the participation of active free radicals present in exhaust gas to enhance combustion by taking part in pre-ignition reactions. However, this effect causes an increase in thermal efficiency. With more EGR substitution the thermal efficiency falls. This is due to the dilution effect of the EGR used, as it depleted the oxygen present in the combustion chamber [7].

Figure 4 represents exhaust gas temperature versus brake mean effective pressure for diesel and CNG-diesel operation for different EGR percentages. With EGR substitutions the exhaust temperature decreased at all loading conditions. In research work, cooled EGR has been used which acts as a thermal sink. The higher specific heat capacity of exhaust gases absorb heat during combustion and lower the exhaust temperature.

Figure 5 shows volumetric efficiency versus brake mean effective pressure for diesel and CNG-diesel with different EGR ratio. It is clear from the Fig. 6 that, with increasing EGR ratio in dual fuel operation, the volumetric efficiency is reduced. This is due to the fresh air is replaced by EGR substitutions.

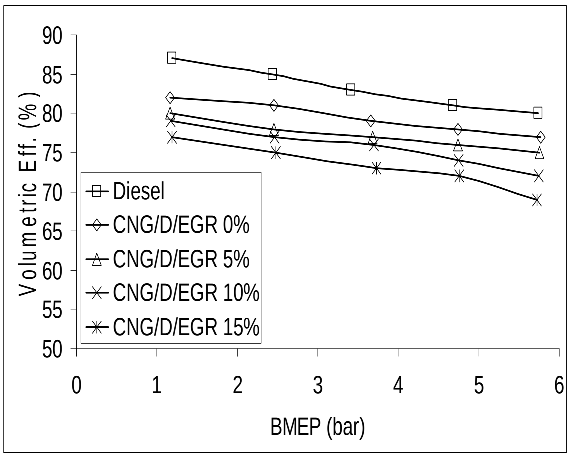

Figure 5. Volumetric efficiency variations with BMEP.

4.3. 4.3 Emission Characteristics

Figure 6 shows the relationship between the smoke opacity versus brake mean effective pressure at different EGR ratio for diesel and CNG-diesel dual fuel operation. It is well known that duel fuel operation remarkably reduced smoke emission. Moreover, combustion of CNG produces no particulates the only smoke associated are mainly due to pilot injection of diesel. With EGR substitution there is trade-off of NO_X and smoke emission. Examining this figure it is clear that dual fuel operation is the potential method to reduce smoke emission. With increasing EGR ratio, smoke opacity is increased. This is because of decrease the amount of oxygen present in the combustion chamber with the substitution of EGR. It also decreases the cylinder temperature by absorbing heat during combustion

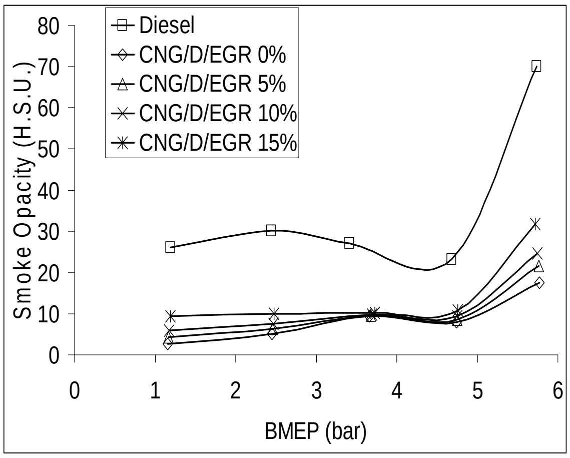

Figure 6. Smoke Opacity variations with BMEP

Both the factor increases the smoke. At light loads less smoke is produced since pilot injection of diesel is small. With increase in load the smoke formation is increased mainly due to increase in pilot fuel. Figure 8 illustrated NO_X emission for diesel and CNG-diesel for different EGR percentages. In duel fuel operation NO_X emission is generally low but with higher substitution of CNG high heat release rates resulting higher emission of NO_X. The figure shows, that with EGR substitutions, NO_X emission is reduced. A possible reason is the reduction of oxygen available for combustion, and reduction of peak combustion temperature due to high specific heat capacity.

Figure 8 shows the unburned hydrocarbon emission for diesel and CNG-diesel at different EGR ratio. Normally dual fuel operation exhibits higher emission of unburned hydrocarbon at light loads. At light loads the pilot quantity being small so flame cannot propagates fast and far enough to ignite the entire mixture. As the result it causes higher HC emissions but with increase in load the hydrocarbon emission decreases. As load progresses the pilot

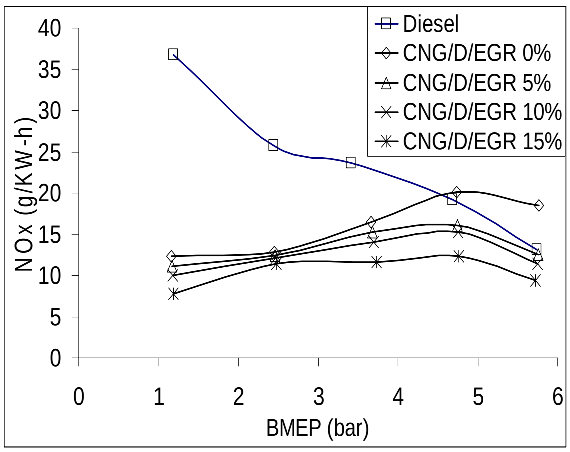

Figure 7. NO_X emissions variations with BMEP

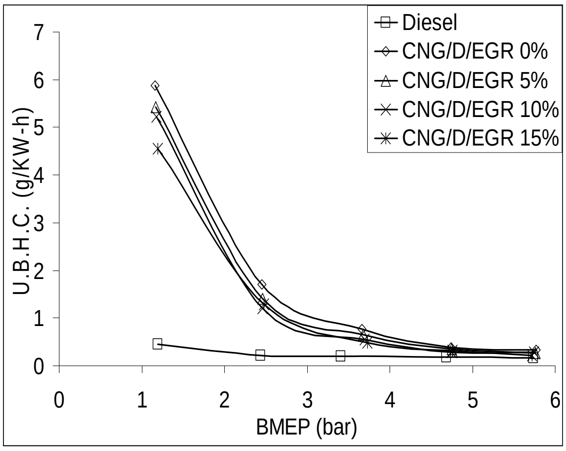

Figure 8 HC emissions variations with BMEP.

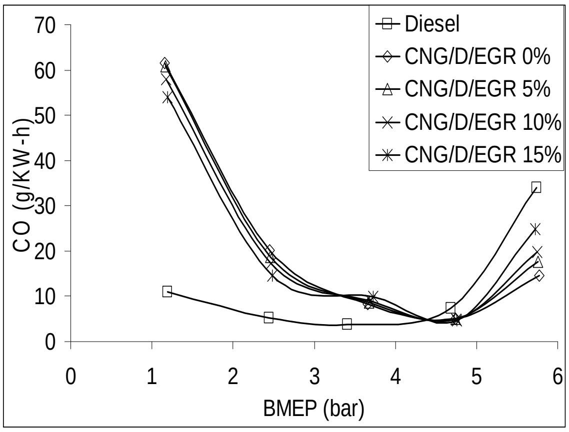

Figure 9. CO emissions variations with BMEP

quantity increases and burns the surrounding fuel-air mixture sufficiently.

From the Fig. 8 it can be seen that the unburnt hydrocarbon emissions decrease as the EGR ratio increases. This is so because a portion of the unburned gases in the exhaust from the previous cycle is recirculated and burned in the succeeding cycle. Also the presence of radicals can help to initiate combustion process especially with the increase of intake temperature due to mixing with exhaust gases [9]. Thus, the unburned hydrocarbon decreases with increasing EGR ratio. Figure 9 shows CO emissions for diesel and CNG-diesel dual fuel operation for different EGR ratio. As shown in Fig 9 the dual fuel operation yield higher CO emissions at light load conditions. At low loads, most of the fuel left unburnt as explained earlier leads to poor combustion and ignition results in higher CO emissions. At higher loads the CO emission is lower than normal diesel operation because of better utilization of fuel. This is mainly due to high gas temperature and faster combustion rates. With EGR substitutions the CO formation is higher at full load condition as shown in Fig. 10 than the dual fuel operation without EGR. At full load condition the availability of oxygen required for complete combustion decreases with increase in EGR ratio. Hence, the CO emission is higher with EGR addition in dual fuel operation at higher load than at the light load condition.

5. Conclusions

An experimental study was conducted to determine the performance and emission characteristics on a single cylinder direct injection diesel engine fueled with CNG. The main focus of the work was to reduce the harmful emissions and improving the performance. To achieve these goals the effect of cooled EGR were investigated. The following results were obtained from this study:

- The use of EGR up to 5% is useful in improving the brake thermal efficiency. Increasing the EGR substitution decreases the air required for combustion. However, with increasing EGR ratio decreases the thermal efficiency.
- A higher substitution of EGR was effective in reducing the emissions of NO_X. EGR is one of the potential methods in reducing the NOx emission.
- Smoke opacity increases with increase in EGR substitution rates. This is mainly due to depletion of oxygen inside the combustion chamber.
- Peak cylinder pressure reduced and ignition delay prolonged with 15% EGR substitution. Addition of gaseous fuel makes the prolonged combustion and increases combustion duration.
- CO emission increases at higher loads with increase in EGR ratio mainly due to incomplete combustion.

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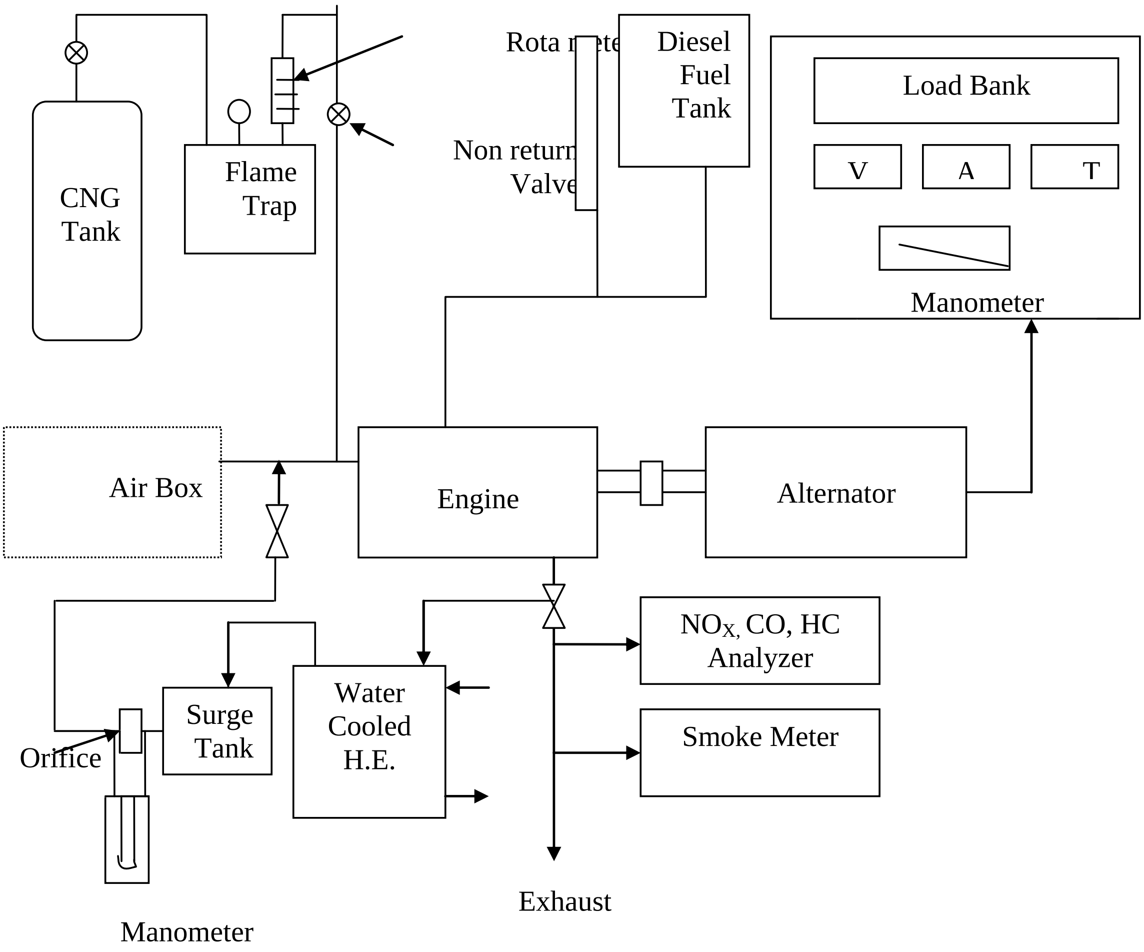
Appendix



Rota meter
Diesel Fuel Tank
Load Bank
V
A
T
Manometer
CNG Tank
Flame Trap
Non return Valve
Air Box
Engine
Alternator
NO_X, CO, HC Analyzer
Smoke Meter
Water Cooled H.E.
Surge Tank
Orifice
Manometer
Exhaust