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Implementation of EGR strategies to reduce NOx by controlling combustion temperature for BS6 norms in Heavy Duty Natural Gas Engine

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Abstract: The emission standards are tightened; more advanced methods are used like modification in engine design and equipment, changing engine parameters and use of exhaust after treatment devices. Reduction of toxic substances from internal combustion engines can be achieved by primary (inside engine cylinder) methods and secondary (outside engine cylinder) methods. To fulfil the specified demand, the utilization of alternative fuels in gasoline and diesel engines has become the topic of interest today. For this reason, natural gas is used as an alternative fuel. In this paper, the effect of application of exhaust gas recirculation (EGR) on the performance and emissions of the engine is analyzed, which is port injected, turbocharged inline four-cylinder 4 stroke natural gas-powered heavy-duty engine. Engine performance and emissions have been evaluated for different load conditions and EGR values. The results are compared with the engine operating with its original configuration (without EGR). A reduction of around 53% of NOx emissions is achieved using 15% EGR rate. With 5% EGR rate, the maximum reduction of NOx is 21%.

Keywords — CNG, EGR, NO_X, SCR, WHTC

I. INTRODUCTION

Nowadays, the world is facing serious problem of the air pollution with the increase in population and its increasing demand of the energy. To meet the required demand, the alternative fuels used in gasoline and diesel engines are becoming the subjects of interest today. Most of the concerns are driven by two factors first is various new laws pertaining to clean air and second is energy independence from petroleum-based fuel. Natural gas, observed as green fuel, has emerged as an answer to depleting fossil fuel resources further as deteriorating urban air quality drawback. There are 3 types of gas: liquefied gas (LNG) liquefied petroleum gas (LPG) and compressed natural gas (CNG). Each LNG and CNG are supported alkane series [3].

Exhaust gases coming back from burning engine contains oxides of carbon (COx), oxides of gas (NOx), unburnt organic compound, oxides of sulphur (SOx), carbon particles, etc. that are terribly venturous and produces dangerous impact on atmosphere. With current technology it's inconceivable to develop such an engine that creates terribly less amount of emission. To cut back these harmful gases, they need to be reduced among the cylinder or treated after exhaust. EGR is often used to scale back quantity of NOx in S.I. engines in addition to C.I. engines.

Production of nitrogen oxide is function of combustion temperature, highest close to stoichiometric condition wherever temperature is at peak value. Most NOx emission happens at slightly close to lean condition, wherever the combustion temperature is high and excess chemical element is accessible to react with nitrogen. Therefore, easiest way to cut back NOx emission is to lower the temperature of combustion chamber. For this, EGR is used. "Heavy duty CNG engines and vehicles, like buses, were normally mass produced in the mid-2000s. Until EURO-V emission regulation, lean burn fossil fuel engines were wide used as a result of those area unit favourable for fuel economy and thermal sturdiness. Until now, the lean burn natural gas engine has been able to cope with EURO-V emission rules while not requiring pricy after-treatment systems.

However, in keeping with the most recent technology trend, once the EURO-VI emission laws were issued, the combustion methodology for large gas engines is step by step changing from lean combustion to a stoichiometric air fuel ratio. In the case of gas engines, lean burning alone cannot satisfy N oxides (NOx) laws for EURO-VI laws and emission standards from the U.S.A. Environmental Protection Agency, thus a pricy after treatment system, like absorption De-NOx catalyst or selective chemical action reduction, ought to be put in. Therefore, most gas engines

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are expected to use a mixture of stoichiometric combustion, three-way catalyst, and cooled exhaust gas recirculation (EGR)" [1].

II. MATERIALS AND METHODS

A. Exhaust Gas Recirculation

"EGR is a useful method for reducing NOx formation. Exhaust consists of CO2, N2 and water vapour mainly. When a part of this exhaust gas is recirculated to the combustion cylinder, it acts as diluents. This additionally reduces the O2 concentration within the combustion chamber. The particular heat of the EGR is way above fresh air thus EGR will increase the heat capability of the intake charge, so decreasing the temperature rise for identical heat release." [2]

"With the employment of EGR, there's a trade-off between reduction in NOx and increase in soot, CO and unburned Hydrocarbons. A large variety of studies has been conducted during this area. It's been indicated that for quite 50 % EGR, particulate emissions exaggerated considerably, and so use of Particulate trap was suggested. The modification in gas concentration causes the change within the structure of the flame and thus changes the length of combustion. It had been advised that the flame temperature suppression is the most vital issue influencing the NO formation" [3].

i) Classification Based on Temperature

"Hot EGR: Exhaust gas is recirculated while not being cooled, resulting in the improved charge temperature.

Fully cooled EGR: Exhaust gas is cooled before recirculation in to the combustion chamber by the means that of a water-cooled device. During this case, condensed water enters the cylinder and produces undesirable effects.

Partly cooled EGR: To avoid the water condensation, the temperature of exhaust gas is kept simply higher than its saturation point temperature" [3].

ii) Classification Based on Pressure

"Low Pressure Route System: The passage for EGR was provided from downstream of the turbine to upstream side of the compressor. The advantages are reduced control complexity and fuel economy. But this method has some disadvantages too like durability and reliability problems, since EGR is passed through compressor and intercooler, pressure loss in the intercooler increases due to clogging" [3].

"High Pressure Route System: The EGR is passed from upstream of the rotary engine to the downstream of the mechanical device. The essential benefits of this technique are, since EGR hasn't suffered compressor or intercooler, the issues of sturdiness and reliableness aren't there, the particulate trap is not mandatory. NOx can be reduced as low as 0.5g/BHPhr, better combustion control, good cold start performance, avoids condensation of fuel in intake manifold. But the problems that may arise like system contamination, increased soot in oil, transport losses increase with improved TC efficiency, complicated VTG-EGR control" [3].

"Cooled EGR is employed as a result of if it displaces identical quantity of air, it'll represent an outsized fraction of the charge and can increase NOx reductions. In practice, this suggests that a lower level of EGR are often used for a given level of NOx emissions, with a consequentially reduced increase within the particulate and alternative emissions. This additionally means in turbocharged engine at high loads, the required levels of EGR are often achieved without recourse to devices like inlet throttles. Cooled EGR has its disadvantages most notably an inclination to extend the ignition delay amount and thereby increase the combustion noise" [4].

"When EGR is employed, it's necessary to possess some kind of feedback system. Feedback are often provided by measurement the gas level within the manifold or by measurement the air rate of flow, the manifold temperature and also the absolute pressure. Cooled EGR is renowned for its effectiveness to cut back NOx emissions, suppress knock combustion and improve fuel conversion potency in spark ignition engines" [4].

B. Methods to reduce oxide of nitrogen

"The following represents available NOx reduction strategies and technologies for combustion sources:

1) Fuel switching. Fuel switch is simplest and doubtless the most economical way to reduce NOx emissions. Fuel bound NOx formation is most effectively reduced by the change to a fuel with reduced nitrogen content.
2) Flue gas recirculation (FGR). It involves extraction a number of the flue gas from the stack and recirculating it with the combustion air provided to the burners. This method, by diluting the combustion air with flue gas, reduces the oxygen concentration at the burners and therefore the temperature.
3) Low NOx burners. Installation of burners particularly designed to limit NOx formation will reduce NOx emissions by up to fifty percent. Low NOx burners are designed to reduce the peak temperature by causing recirculation zones, staging combustion zones and reducing oxygen concentration.
4) Derating. Some industrial boilers will be derated to provide a reduced amount of steam or hot water. Derating can decrease the flame temperature inside the unit, reducing formation of thermal NOx. Derating can be accomplished by reducing the firing rate or by putting in a permanent restriction like and orifice plate, within the gas line.
5) Steam or water injection. Injecting a small quantity of water or steam into the immediate neighborhood of the flame can lower the flame temperature and reduce the oxygen combustion.

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6) Staged combustion. Either air or fuel injection can be staged, creating either a fuel rich zone followed by a rich zone or vice versa. Staged combustion can be achieved by installing a low NOx staged combustion burner, or the furnace can be retrofitted for staged combustion. NOx reduction of more than 40% have seen with staged combustion.
7) Fuel reburning. Staged combustion can be achieved through the process of fuel reburning by creating a gas reburning zone above the primary combustion zone. There, extra gas is injected, making a fuel rich region wherever hydrocarbon radicals react with NOx to create molecular nitrogen. Field evaluations of natural gas reburning (NGR) on several full-scale utility boilers have yielded NOx reductions ranging from 40 to 70%.
8) Reduced oxygen concentration. Decreasing the excess air reduces the oxygen available in the combustion zone and lengthens the flame, resulting in a reduced heat release rate per unit flame volume. NOx emissions reduce in an approximately linear rate with decreasing excess air. However, as excess air falls below a threshold value, combustion efficiency will decrease due to incomplete mixing, and CO emissions will increase. The optimum excess air value must be determined experimentally and will depend on the fuel and the combustion system design. A feedback control system can be installed to monitor oxygen or combustibles levels in the flue gas and to adjust the combustion air flow rate until the desired target is reached. Such a system can reduce NOx emissions by up to 50%.
9) Selective catalytic reduction (SCR). It is a post formation NOx control technology that uses a catalyst to improve a chemical reaction between NOx and ammonia to produce Nitrogen and water. An ammonia/air or ammonia/steam mixture is injected into the exhaust gas, which then passes through the catalyst where NOx is reduced. To optimize the reaction, the temperature of the exhaust gas must be in a certain range when it passes through the catalyst bed.
10) Selective non-catalytic reduction (SNCR). It involves injection of a reducing agent or urea into the flue gas. Table 1 shows emission values for vehicle more than 3.5 tones" [5].

Table 1: Emission for vehicles more than 3.5 tones. [7]

Stage	Year	Test	NOx	PM	PN	NH_3
			g/kWh		*No./kWh*	*ppm*
BSIV	2010	ESC	3.5	0.02		
		ETC	3.5	0.03		
BSVI	2020	WHSC (CI)	0.4	0.01	$8.0*10^{11}$	10
		WHTC (CI)	0.46	0.01	$6.0*10^{11}$	10
		WHTC (PI)	0.46	0.01	$6.0*10^{11}$	10

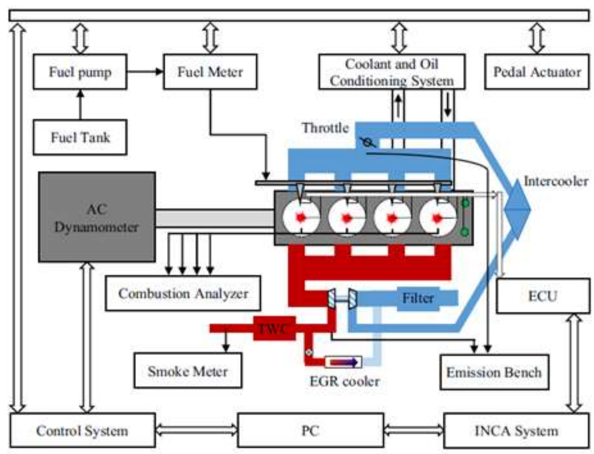
Table 1 shows the emission values of NOx, ammonia and particulate matter. The emission values differ with different test cycles performed. It can be seen that there is drastic reduction in the emission value of NOx (around 88%).

III. EXPERIMENTATION

A. Experimental Setup

The Fig. 1 shows the experimental setup of the turbocharged inline four-cylinder 4 stroke natural gas fueled engine. The engine is fitted with High Pressure Loop, continuous and cooled EGR. The engine is also attached with the various analysers, arranged as shown below and the data is analysed by the software. The engine is coupled with dynamometer and the test is carried out. The ECU manages various parameters. The input parameters are given to dynamometer and the engine is run on predetermined mapped values.

Fig. 1. Schematic diagram of engine coupled with dynamometer



B. Worldwide Harmonized Transient Cycle

"WHTC is specifically developed to be more representative of real-world driving, and includes a much higher percentage of low speed and low load conditions.

The use of the WHTC forces makers to use NOx reductions strategies such as engine calibration, thermal management, SCR catalyst switch, and others that operate across a broader vary of vehicle operational conditions. The WHTC is a transient test of 1800 s duration, with several motoring segments as shown in Fig. 2" [6]

Fig. 2. Harmonized transient cycle

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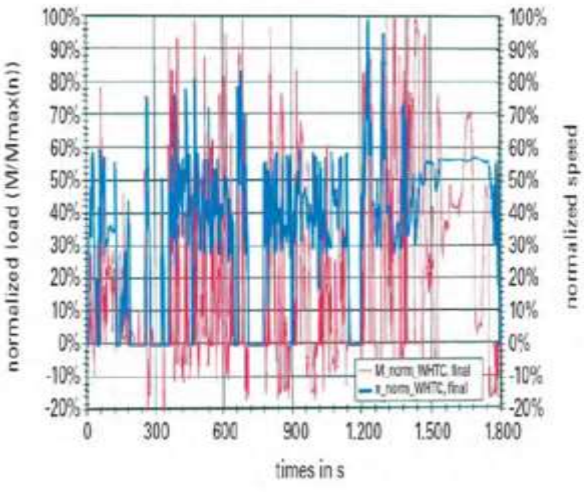


C. Engine Specification

Table 2: Engine specification

Cubic Capacity of Engine	3800cm^3
No. of cylinders	4
Power	83kW@2400 RPM
Torque	376Nm@1500 RPM
Idle rpm	700 to 800
Type	Turbocharged SI engine
Fuel Used	Compressed natural gas

Table 2 shows the engine specification of the engine used for experiment. It is turbocharged inline four-cylinder 4 stroke single point ported injected natural gas fueled spark ignition engine. The engine develops peak torque in low RPM range which is beneficial for use in public transport buses.

D. Methodology

The engine used in this experiment is a four-cylinder four stroke turbocharged single point port injection spark ignition engine.

The engine crankshaft is coupled to an eddy current dynamometer to provide brake torque and it is fitted with suitable instruments for control and measuring the operating parameters.

The engine uses Compressed Natural Gas (CNG) as a fuel during the experiments. The experimental work begins with the start of injection of the CNG fuel into the system while simultaneously recycling the exhaust gas back into the system. The engine is run until it reaches steady state.

The exhaust gas is taken from the orifice located in the exhaust port with the help of connecting pipe. The EGR rate in the inlet mixture is increased by increasing the amount of exhaust gas flow back into the engine intake.

Two thermocouples, placed in the exhaust port and in the air intake manifold, are used to measure various exhaust gas temperatures and air intake temperatures.

The engine exhaust manifold is connected to exhaust gas analyzer to measure the emission characteristics of the engine.

The basic way to define EGR ratio is:

$$\%EGR = \frac{Volume\ of\ EGR}{Total\ charge\ intake\ into\ the\ cylinder} * 100$$

Another way to define the EGR ratio is by the use of CO_2 concentration is:

$$EGR\ ratio = \frac{[CO_2]_{intake} - [CO_2]_{ambient}}{[CO_2]_{exhaust} - [CO_2]_{ambient}}$$

For testing the engine, two methods are used.

i) Constant load and varying speed

In this method, the engine is subjected to constant load and the engine speed is changed having predetermined intervals.

The various parameters like Brake Power, Torque, BSFC, THC, CO, NOx is measured. It is further carried out with other loads and the data is analysed.

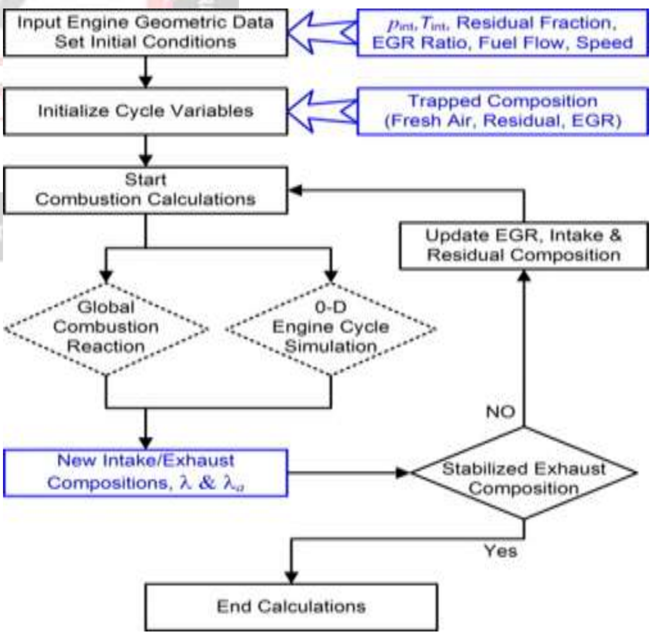
ii) Constant speed and varying load

In this method, the engine is set at constant speed and the load is changed viz. No load, 25%, 50%, 75% and Full load.

The various parameters like Brake Power, Torque, BSFC, THC, CO, NOx is measured. It is further carried out with other engine speeds and the data is analysed.

The flowchart below (Fig. 3) defines the method to optimize the percentage of EGR to be supplied in the engine.

Fig. 3. Flowchart of methodology of optimization of EGR %



The initial conditions/parameters of engine like intake manifold pressure, EGR ratio, fuel flow, engine speed etc. are set and the engine is cranked.

After the readings from the various parameters and analyzers are stable, the output parameters like engine power, torque, emissions, lambda, etc. are noted.

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If the output of the engine does not comply with the predefined / suggested output values, the input variables / parameters like fuel flow, EGR ratio etc. are updated / adjusted and the test is performed again; the results are analyzed till the required parameters are achieved.

Formulae used for the calculation:

$$\lambda = \frac{(^{A}/_{F})_{actual}}{(^{A}/_{F})_{stoichiometric}}$$

$$Q = m_1 CV - m_2 C(T_e - T_o)$$

$$\eta = \frac{\text{Indicated power}}{Q};\ \eta = 35\%\ \text{(approx)}$$

$$IMEP = \frac{I.P. \times 60000}{LAN}$$

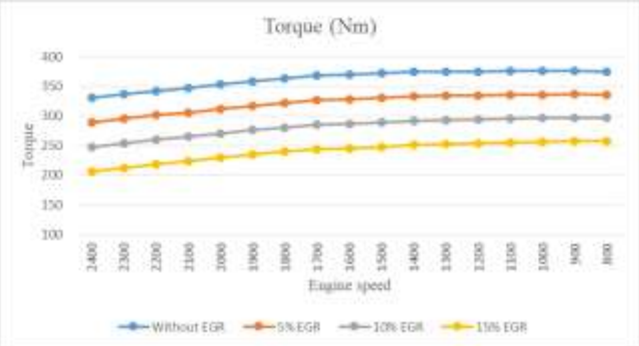
$$\eta_m = \frac{BMEP}{IMEP};\ \eta_m = 85\%\ \text{(approx)}$$

$$BP = \frac{2\pi NT}{60000}$$

$$BSFC = \frac{\text{Mass of fuel}}{\text{Net brake work}}$$

IV. RESULT AND DISCUSSION

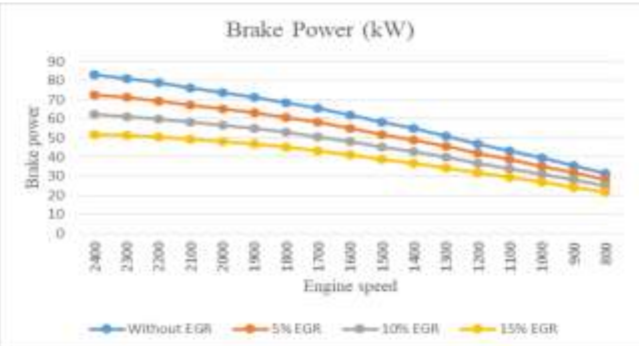
Graph 1: Torque values at various engine speed for different EGR rates



Graph 1 shows effect of EGR on engine torque. The engine torque drops as the EGR is introduced because the charge intake in the engine decreases. It is evident further as the EGR is increased.

The average torque reduction is 11%, 22.5% and 34% for 5%, 10% and 15% of EGR rates respectively.

Graph 2: Brake power values at various engine speed for different EGR rates

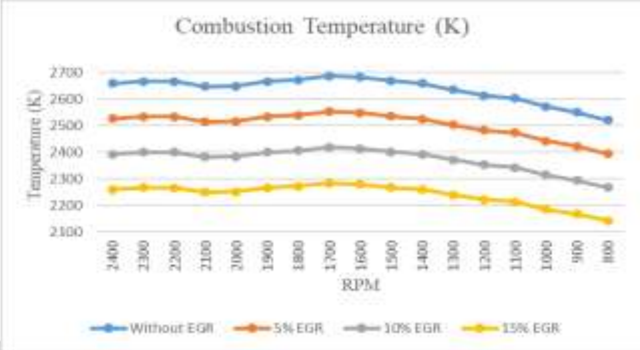


Graph 2 shows effect of EGR on engine brake power. The engine power drops as the EGR is introduced because the charge intake in the engine decreases.

The decreased charge, when burnt, produces less torque which, in turn, results in less power generation. It is evident further as the EGR is increased.

The average brake power reduction is 11%, 22.5% and 34% for 5%, 10% and 15% of EGR rates respectively.

Graph 3: Combustion temperature values at various engine speed for different EGR rates

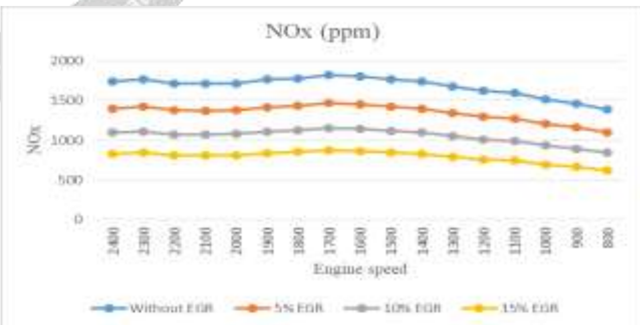


Graph 3 shows effect of EGR on combustion temperature. The combustion temperature decrease as the EGR rate is increased.

It is because, the fresh charge entering the combustion chamber decreases as the EGR rate increases. This reduces the fuel burnt per cycle and the combustion temperature is reduced.

The average combustion temperature reduction is 5%, 10% and 15% for 5%, 10% and 15% of EGR rates respectively.

Graph 4: NOx values at various engine speed for different EGR rates



Graph 4 shows effect of EGR on NOx emission. The NOx values decrease as the EGR rate is increased. It is because, the in-cylinder combustion temperature decreases as the EGR is increased. This, in turn, reduces the NOx formation rates and the NOx emission is reduced.

The average NOx emission reduction is 19.8%, 37.44% and 52.9% for 5%, 10% and 15% of EGR rates respectively.

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Graph 5: BSFC values at various engine speed for different EGR rates

Graph 5 shows effect of EGR on brake specific fuel consumption. The BSFC of the engine increases as the EGR rate is increased. This is because effective power output of the engine reduces as the fresh charge in the cylinder for combustion reduces.

Although higher BSFC is not desirable as the performance of the engine has reduced but it is necessary to maintain low NOx emission levels. So, there is trade-off between BSFC and NOx emission values.

The average increase in BSFC values is 7%, 16% and 29% for 5%, 10% and 15% of EGR rates respectively.

V. CONCLUSION

Following conclusions has been drawn by experimentation:

1) As the EGR rate is increased, the NOx emissions reduce drastically.

Table 3: Reduction of NOx with respect to EGR rate

EGR Rate	NOx Reduction
5%	19.8%
10%	37.44%
15%	52.9%

2) The engine power reduces with increase in EGR rate. So, there is trade-off between engine performance and NOx emission.

Table 4: Reduction of engine performance @ 2400 rpm with respect to EGR rate

EGR Rate	Engine power reduction @ 2400 rpm
5%	12.49%
10%	24.97%
15%	37.46%

3) The maximum torque without EGR is 376.11 Nm. The torque also reduces with the increase in EGR rate.

Table 5: Reduction of torque @ 1500 rpm with respect to EGR rate

EGR Rate	Torque values (Nm) @ 1500 rpm
5%	336.33
10%	296.12
15%	256.77

4) The BSFC value without EGR @ 2400 rpm is 215.51 g/kWh. The BSFC increases with the increase in EGR rate.

Table 6: BSFC values @ 2400 rpm with respect to EGR rate

EGR Rate	BSFC (g/kWh) @ 2400 rpm
5%	233.95
10%	258.51
15%	292.89

5) The average combustion temperature is 2653.44 K. It reduces with increase in EGR rate.

Table 7: Reduction of combustion temperature with respect to EGR rate

EGR Rate	Combustion temperature reduction %
5%	5
10%	10
15%	15

6) In most situations, the use of EGR decreased engine brake power and engine brake torque.

VI. FINDINGS AND SUGGESTION

Based on the results of experimentation, for simultaneous decrease of NOx, engine brake power and engine brake torque, with only small increases on Brake Specific Fuel Consumption (BSFC), it is recommended the use of 10 % EGR at low and moderate loads.

Considering the latest strict emission norms, implementation of EGR has become necessary because it is one of the economical ways of reducing NOx emissions from the exhaust of the engine.

Although there is compromise of engine performance, the cost effectiveness for the public use is justified.

If there is requirement of high performance from the given engine and demand for using its maximum potential, this is not feasible method to be used for this purpose. Then, other after treatment methods has to be used, which are costlier and high in maintenance, if it needs to comply the emission norms, i.e. for public use.

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