TJES

ISSN: 1813-162X
Tikrit Journal of Engineering Sciences
available online at: http://www.tj-es.com

Effect of Exhaust Gas Recirculation (EGR) on the Performance Characteristics of a Direct Injection Multi Cylinders Diesel Engine

Khalil Ibrahim Abaas
Mechines and Equipments Engineering Department, University of Technology, Baghdad, Iraq

Abstract

Owing to the energy crisis and pollution problems of today investigations have concentrated on decreasing fuel consumption and on lowering the concentration of toxic components in combustion products by using exhaust gas after treatments methods like PM filters and EGR for NOx reduction. In this study, the combustion characteristics of diesel fuel were compared with that produced from adding EGR at several percentages to air manifold. The tests were performed in a four-cylinder direct injection (DI) diesel engine at constant engine speed (1500 rpm) and variable loads (from no load to 86 kN/m2), the tests were repeated with constant load (77 kN/m2) and variable engine speeds (from 1250 to 3000 rpm).

The experimental results showed that adding EGR to diesel engine provided significant reductions in brake power (bp), brake thermal efficiency and exhaust gas temperatures, while high increments in brake specific fuel consumption (bsfc). High EGR percentage (as 30% in this article) caused an 11.7% reduction in brake thermal efficiency, 26.38% reduction in exhaust gas temperatures and 12.28% in volumetric efficiency at full load conditions.

Keywords: EGR, Engine performance, Brake thermal efficiency, Brake power, Volumetric efficiency.

تأثير تدوير الغاز العادم (EGR) على ميزات أداء محرك ديزل متعدد الأسطوانات ذي حقن مباشر

الخلاصة

أهتمت الأبحاث العلمية الحديثة بتقليل استهلاك الوقود وتقليل الملوثات السامة الناتجة من الاحتراق، بسبب الأزمة العالمية الخاصة بالطاقة ومشاكل التلوث، وذلك باستخدام طرق معاملة الغاز العادم مثل مصافي الجزيئيات الهبابية وإعادة تدوير الغاز العادم لتقليل أكاسيد النيتروجين (NOx). تمت في هذه الدراسة مقارنة مواصفات أداء محرك يعمل بوقود ديزل بتلك الناتجة عن إضافة غاز عادم مدور بعدة نسب الى مشعب دخول الهواء. أجريت التجارب باستخدام محرك ديزل رباعي الاسطوانات ذي حقن مباشر وعند سرعة محرك ثابته (1500 rpm) وأحمال متغيرة (من بدون حمل لغاية $86\ kN/m^2$). وأعيدت التجارب عند حمل ثابت ($77\ kN/m^2$) وسرع محرك متغيرة (من 1250 لغاية 3000 rpm).

بينت النتائج العملية أن إضافة غاز عادم مدور الى محرك الديزل يسبب انخفاض واضح في القدرة المكبحية والكفاءة الحرارية المكبحية ودرجات حرارة الغاز العادم، كما يسبب زيادة واضحة في الأستهلاك النوعي المكبحي للوقود. تسببت نسب غاز عادم مدور عالية (مثل نسبة 30% في هذة المقالة) انخفاض بحدود 11.7% في الكفاءة الحرارية المكبحية، 26.38% في درجلات حرارة الغاز العادم و12.29% في الكفاءة الحجمية لظروف حمل كلي.

الكلمات الدالة: EGR، أداء المحرك، الكفاءة الحرارية المكبحية، القدرة المكبحية، الكفاءة الحجمية.

Notations

Bsfc Brake specific fuel consumption (kg/kWh)
Bmep Brake mean effective pressure (kN/m^2)
HC Unburned hydrocarbons
bp Brake power (kW)
NOx Nitrogen oxides
DI Direct injection
PM Particulate matters
EGR Exhaust gas recirculation
CN Cetane number
CR Compression ratio
°BTDC Degree before top dead center
IT Injection timing
LHV Lower heating value (kW/kg)
$m_{a,act}$ Actual air flow rate (kg/sec)
N Engine speed (rpm)
T Engine torque (N m)
V_{sn} Displacement volume
v_f Fuel volume
Q_t Engine total heat

Greek letters

ρ_f Fuel density (kg/m^3)
ρ_{air} Air density (kg/m^3)
$\eta_{bth.}$ Brake thermal efficiency (%)
$\eta_{vol.}$ Volumetric efficiency (%)

Introduction

The popularity of diesel engine is increasing due to its high efficiency and durability [1]. Diesel engines naturally benefit from high thermal efficiencies as a consequence of lean combustion and rather high compression ratio. Their high compression ratio can provide appropriate conditions required for auto-ignition. High flame temperature is a predominant issue in diesel engines which originates from the non-homogeneous nature of diesel combustion caused by locally stoichiometric air to fuel ratios [2].

To achieve reductions in NOx emissions, exhaust gas recirculation (EGR) can be used in the diesel engines. EGR is an effective technique of reducing NOx emissions from the diesel engine exhaust [3,4]. Controlling the NOx emissions primarily requires reduction of in-cylinder temperatures. However, the application of EGR results in higher fuel consumption and emission penalties, also EGR increases HC, CO, and PM emissions along with slightly higher specific fuel consumption [5,6]. EGR rates are sufficient for high load, also as the load increases; diesel engines tend to generate more smoke because of reduced oxygen. Therefore, EGR, although effective to reduce NOx, further increases the smoke and PM emissions [7,8]. EGR may adversely affect the smoke emission because it lowers the average combustion temperatures and reduces the oxygen intake gases, which in turn keeps soot from oxidizing [9].

Increasing the EGR ratio can change the shape of heat release rate during premixed combustion which can greatly suppress NOx formation [10]. With the increase of EGR rate in diesel engines the following effects on the performance and combustion are observed.

1. Dilution effect

Since EGR application decreases the concentration of oxygen in the cylinder, the fuel spray has to diffuse further to encounter sufficient O_2 to form a stoichiometric mixture suitable for combustion. This extended flammable region contains not only stoichiometric mixture but also additional amount of CO_2, H_2O and N_2. The additional quantity of these components absorbs the released heat from the combustion and combustion temperatures will be lowered [11]. Also the reduced amount of oxygen decreases the oxygen partial pressure and it affects the kinetics of the elementary NOx formation reaction [12].

2. Ignition delay effect

The existence of diluents such as CO_2 and H_2O causes an increase in ignition delay and changes the location of start of combustion. As a consequence, the whole combustion process shifts further toward the expansion stroke. This causes in the products of combustion to be less exposed to high temperature conditions and accordingly less nitrogen oxides formation [13].

3. Chemical effect

The recirculated CO_2 and water vapor from exhaust gases dissociate at the presence of high temperature during combustion period which can modify combustion temperature and NOx formation. Particularly, the endothermic dissociation process of H_2O andCO_2 reduces the flame temperature [14].

4. Thermal effect

According to the higher heat capacity of CO_2 and H_2O contained in EGR in comparison with O_2 and N_2 which are normally apart of inlet air, the overall heat capacity of the in-cylinder mixture will be increased which means less flame temperature [15].

The main objective of the present research is to investigate practically the effect of exhaust gas recirculation with Iraqi conventional diesel fuel on the engine performance, whereas Iraqi diesel fuel characterized by its slightly low Cetane number and its high sulfer content.

Experimental Setup

Experimental apparatus of engine under study is direct injection (DI), water cooled four cylinders, in-line, natural aspirated FIAT diesel engine whose major specifications are shown in Table (1). The engine was coupled to a hydraulic dynamometer (manufactured by Didattica Nel Mondo Company with torque range 0 to 100 Nm) through which load was applied by increasing the torque. The thermocouples used in this study were type K (Ni-Cr/Ni-AL). Air enter to engine through air box that damping pressure fluctuations and cross orifice plate which produces pressure deference which can be measured by using inclined manometer. The dynamometer as well as all other measuring devices like thermocouples, air and fuel flow meters, engine speed tachometer and EGR flow meter was calibrated at Central Organization for Standards and Quality Control, Baghdad. Figure(1) represents photo of the used engine.

Fig.1. A photographic picture of the experimental rig.

Table 1. Tested engine specifications

Parameter	Value
Engine type	4cyl., 4-stroke
Engine model	TD 313 Diesel engine rig
Combustion type	DI, water cooled, natural aspirated
Displacement	3.666 L
Valve per cylinder	two
Bore	100 mm
Stroke	110 mm
Compression ratio	17
Fuel injection pump	Unit pump 26 mm diameter plunger
Fuel injection nozzle	Hole nozzle 10 nozzle holes Nozzle hole dia. (0.48mm) Spray angle= 160º Nozzle opening pressure =40 Mpa

EGR was achieved by using Prodit EGR assembly illustrates in Figure (2). This assembly contains a two pipes heat exchanger with thermocouples fixed on these pipes to measure working fluids temperatures. Inside this heat exchanger fluid flow can be controlled whether parallel or counter flow by arranging fluid cocks. The inside pipe was used to recirculate exhaust gas while the outer pipe can be used for water used to cool recirculated exhaust gas. EGR (%) is defined as the mass percentage of the recirculated exhaust (mEGR) in total intake mixture (ma)[7].

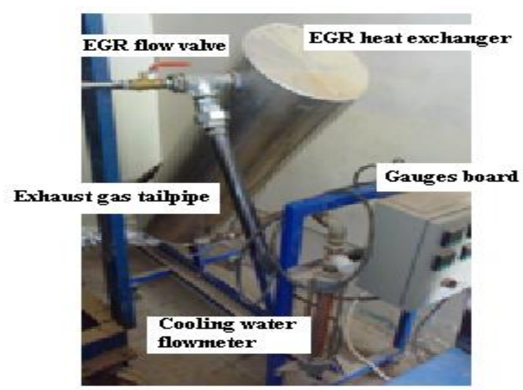

Fig. 2. EGR assembly used in the present study

$$\%EGR = \frac{m_a - m_{a+EGR}}{m_a} \quad \text{......................(1)}$$

Where:

m_a: Mass of air admitted without EGR.

m_{a+EGR}: Mass of air admitted with EGR.

Engine tests were carried out using diesel at 1500 rpm and different EGR rates in order to study the effect of EGR on the engine performance.

The following equations were used in calculating engine performance parameters[16]:

Brake power

$$bp = \frac{2\pi * N * T}{60 * 1000} \quad \text{......................(2)}$$

Brake mean effective pressure (bmep)

$$bmep = bp \times \frac{2 * 60}{V_{sn} * N} \quad \text{......................(3)}$$

Fuel mass flow rate

$$\dot{m}_f = \frac{v_f \times 10^{-6}}{1000} \times \frac{\rho_f}{time} \quad \text{......................(4)}$$

Air mass flow rate

$$\dot{m}_{a,act.} = \frac{12\sqrt{h_o * 0.85}}{3600} \times \rho_{air} \quad \text{......................(5)}$$

$$\dot{m}_{a_{theo.}} = V_{s.n} \times \frac{N}{60 * 2} \times \rho_{air} \quad \text{......................(6)}$$

Brake specific fuel consumption

$$bsfc = \frac{\dot{m}_f}{bp} \times 3600 \quad \text{......................(7)}$$

Total fuel heat

$$Q_t = \dot{m}_f \times LHV \quad \text{......................(8)}$$

Brake thermal efficiency

$$\eta_{bth.} = \frac{bp}{Q_t} \times 100 \quad \% \quad \text{......................(9)}$$

Volumetric efficiency

$$\eta_{vol.} = \frac{\dot{m}_{a,act.}}{\dot{m}_{a_{theo.}}} \times 100 \quad \% \quad \text{................ (10)}$$

The tests were conducted with Iraqi conventional diesel fuel (CN=46.8). CN value was evaluated by Al-Doura refinery laboratory. In the first set of experiments, the engine was run by diesel fuel only. Then EGR was added to air manifold with for proportions (5, 10, 20 & 30%). Engine performance characteristics were measured and analyzed at constant engine speed (1500 rpm) and variable engine loads (from no load to 86 kN/m^2). The tests were repeated but with constant engine load (77 kN/m^2) and variable engine speed (from 1250 to 3000 rpm). The resulted data were compared with those of pure diesel combustion in order to clarify the effect of EGR percentage on engine performance.

Table (2) shows the experimental accuracies.

Table 2. Experimental Accuracies

Measurements	Accuracies in this study
Thermocouples	± 1 %
Engine speed tachometer	± 2 %
Fuel flow meter	± 0.2 %
Air flow meter	± 1.3 %
EGR flow meter	± 0.9%
dynamometer	± 1.8%

Results and Discussions

Figure (3) represents the effect of EGR on brake specific fuel consumption (bsfc) for the tested conditions. Increasing EGR percentage in entering charge increases engine bsfc.

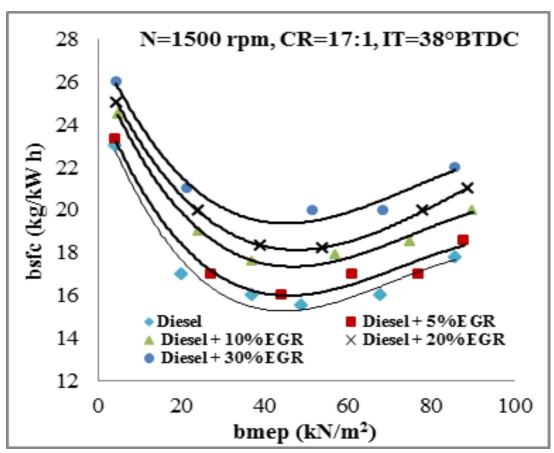

Fig. 3. EGR percentage effect on engine bsfc for variable load

At low loads bsfc for all cases is very high compared to medium loads. Temperature levels inside combustion chamber might be the reason. Reducing temperature due to EGR addition increases fuel delay period and reduces engine peak pressure causing lower output. This case requests consuming more fuel to reach the required engine speed, resulting in higher bsfc.

Brake thermal efficiency reduces by increasing EGR percentage, as Figure (4) represents. EGR reduces the availability of oxygen for fuel combustion, which results in relatively incomplete combustion and increased formation of particulate matters (PM) and reducing NOx emissions emitted from diesel engine. Also, increasing load at constant speed needs higher fuel consumption. This effect appears clear when engine runs with high dilution (30% EGR) and full load. The recorded reductions in brake thermal efficiencies for the whole working range were 2.56, 5.09, 9.2 & 11.7% for 5, 10, 20 & 30% EGR respectively compared to conventional diesel fuel case.

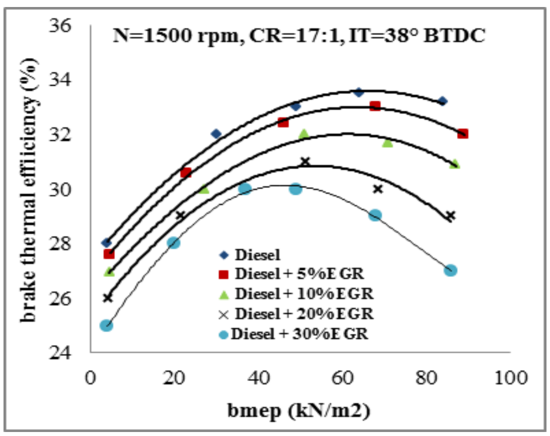

Fig. 4. EGR percentage effect on engine brake thermal efficiency for variable load

Diesel engine operates with lean mixture that gives it high volumetric efficiency especially at very low loads, as Figure (5) indicates. Increasing load makes the engine consumes more fuel to approach the required speed. Also, EGR replaces part of fresh air entering combustion chamber during suction stroke, causing a reduction in available oxygen for combustion. EGR affects engine volumetric efficiency especially at medium and high loads. EGR reduced volumetric efficiency for the whole working range by about 1.64, 6.29, 9.14 & 12.28% for 5, 10, 20 & 30% EGR respectively compared with diesel fuel.

Exhaust gas temperatures increased by increasing load. Increasing EGR percentage reduces these temperatures, as Figure (6) shows.

Increasing load needs more fuel to be burned which rise exhaust gas temperatures. On the other hand, increasing dilution increases the existence of CO_2 and H_2O which causes an increase in ignition delay and changes the location of start of combustion[13]. The whole combustion process shifts further toward the expansion stroke. The combustion reactants will be exposed less to high temperature conditions.

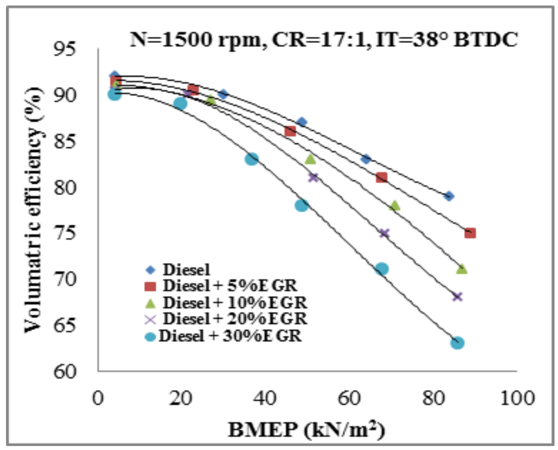

Fig. 5. EGR percentage effect on volumetric efficiency for variable load

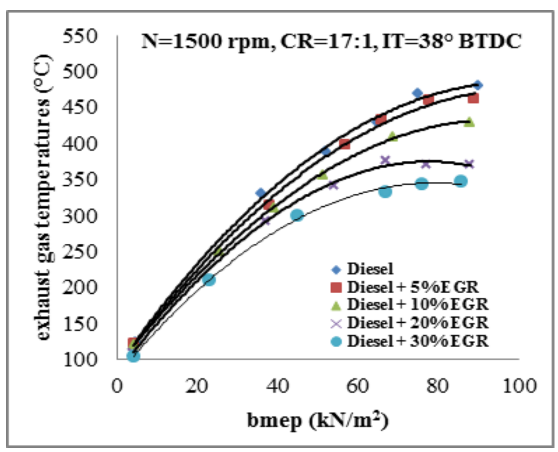

Fig. 6. EGR percentage effect on engine exhaust gas temperatures for variable load

Increasing EGR rate reduces exhaust temperatures by 1.41, 15.64, 16.08 and 26.38% for EGR addition of 5, 10, 20 and 30 respectively compared to diesel for the entire operation range.

Brake power (bp) increased with increasing engine speed, as shown in Figure (7). Increasing EGR percentage reduced bp. Brake power reduced by 1.12, 3.26, 5.42 and 16.79% for EGR 5, 10, 20 and 30% respectively compared to diesel fuel. These results indicate the hazards of using high dilution.

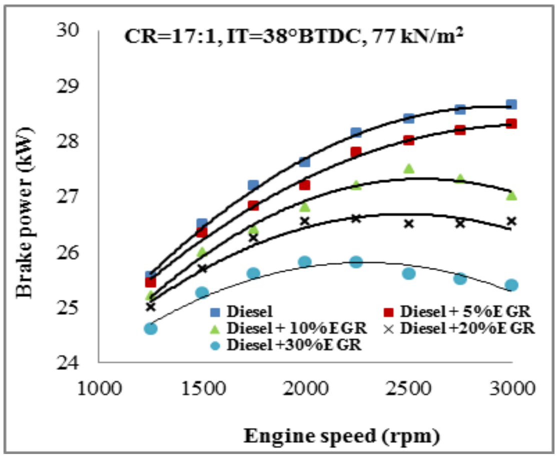

Fig. 7. EGR percentage effect on engine brake power for variable engine speed

EGR addition increases bsfc for all engine speed range, as Figure (8) represents. Increasing EGR increases burned fuel needed to achieve the required engine speed. BSFC increments were 6.14, 11.99, 15.72 and 21.37% for 5, 10, 20 & 30% EGR for all operation range.

Raising EGR percentage reduces exhaust gas temperatures for all engine speed range, as Figure (9) indicates. It can be observed that with increase in engine speed, exhaust gas temperature also increases. The exhaust gas temperature was found to be lower for EGR-operated engine compared with diesel due to lower availability of oxygen for combustion and higher specific heat of intake exhaust gas air mixture. The reductions for whole working range were 2.44, 5.84, 9.52 and 13.53% for EGR 5, 10, 20 and 30 respectively.

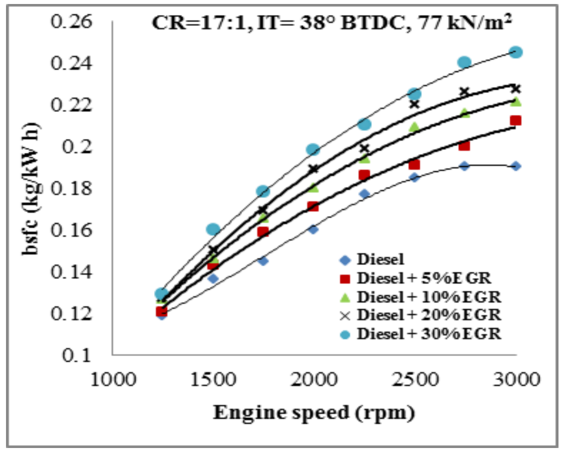

Fig. 8. EGR percentage effect on engine bsfc for variable engine speed

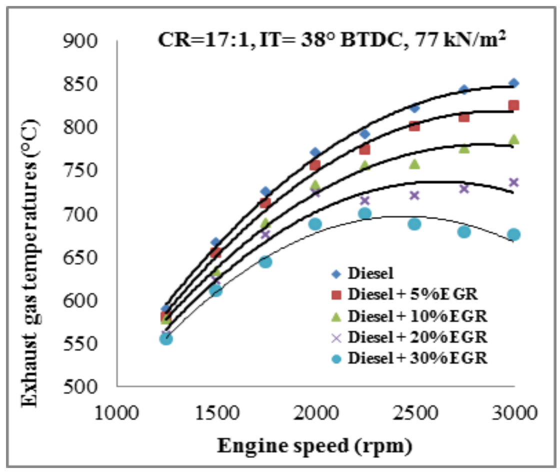

Fig. 9. EGR percentage effect on engine bsfc for variable engine speed

Comparison with other Studies

Many valuable studies were conducted in this field. Comparing recent study results with other researches clarifies the study validation, except it is very difficult issue. Each study used different engine and testing procedures, still one can used increment and reduction percentages as an indicator of validation. Table (3) collects some of these results and it can be compared with present study.

The table indicates that resent study results are comparable with other studies except for (Agrawal et al, 2004) that used slightly cooled EGR and PM trap. Jacobs et al, 2003, used turbocharging with EGR addition; this procedure increased oxygen inside combustion chamber and reduced the EGR reduction effect on brake thermal efficiency, and improved indicated mean effective pressure. Walke et al, 2008, used single cylinder with cooled EGR.

Table 3. Comparison between some studies results

Name	Cylinders numbers	Max. EGR added	Brake thermal efficiency	Bsfc	IMEP
Walke et al, 2008	single	0 to 23%	-21.5	+16.69	-
Selim, 2003	single	0 to 15%	-16.68%	-	-11.76%
Jacobs et al, 2003	6-cylinders with turbocharging	0-20%	-8.64%	-	- 2%
Agrawal et al, 2004	2-cylinders	0-21%	-1%	-	-
Present study	4-cylinders	0-30	-11.7%	+21.39	-16.79

Conclusions

The effects of EGR on the performance characteristics of a four cylinders, direct injection compression ignition engine fueled with diesel fuel has been investigated, and compared to the baseline diesel fuel. The main results can be obtained as follows:

1. The bsfc increased compared to the baseline diesel, and the thermal efficiency deteriorates remarkably with increasing EGR percentages.
2. Engine exhaust gas temperatures reduced remarkably with increasing EGR percentage.
3. The impacts of EGR vary with engine operating conditions. At high load conditions, it has stronger effects on bsfc, brake thermal efficiency and exhaust gas temperatures. While at low loads, it has slight effects on these parameters.
4. At high engine speeds the effect of EGR appears clear for bsfc, bp and exhaust gas temperatures, while at low speeds this effect reduce.

References

1- Obodeh O. & Ajuwa C.I., “Evaluation of Artificial Neural Network Performance in Predicting Diesel Engine NOx Emissions”, Research Journal of Applied Sciences, Engineering and Technology, Vol. 1, No. 3, pp: 125-131, 2009.

2- Ghazikhani M., Feyz V., Joharchi A., “Experimental Investigation of the Exhaust Gas Recirculation Effects on Irreversibility and Brake Specific Fuel Consumption of Indirect Injection Diesel Engines”, Applied Thermal Engineering, Vol. 30, pp: 1711-1718, 2010.

3- Mohamed S.Y.E., “Effect of Exhaust Gas Recirculation on some Combustion Characteristics of Duel Fuel Engine”, Energy Conversion & Management, Vol. 44, pp: 707-721, 2003.

4- Zheng M., Reader G. T., Hawley J. G., “Diesel Engine Exhaust Gas Recirculation a Review on Advanced and Novel Concepts”, Energy Conversion & Management, Vol. 45, pp: 883-900, 2004.

5- Hountalas D.T., Mavropoulos G. C., Binder K. B., “Effect of Exhaust Gas Recirculation (EGR) Temperature for Various EGR Rates on Heavy Duty DI Diesel Engine Performance and Emissions”, Energy, Vol. 33, pp: 272 – 283, 2008.

6- Tatur M., Laermann M., Koehler E., Tomazic D., Holland T., Robinson D., Dowell J. & Price K., “Development of an Emissions Control Concept for an IDI Heavy-Duty Diesel Engine Meeting 2007 Phase-in Emission Standards”, SAE Technical Paper No. 2007-01-0235, 2007.

7- Rajan K., Senthilkumar K. R., “Effect of Exhaust Gas Recirculation (EGR) on the Performance and Emission Characteristics of Diesel Engine with Sunflower Oil Methyl Ester”, Jordan Journal of Mechanical and Industrial Engineering, vol. 3, No. 4, pp: 306 – 311, 2009.

8- Santoh K., Zhang L., Hatanaka H., Takatsuki T. & Yokoto K., “Relationship Between NOx and PM Emissions from DI

Diesel Engine with EGR", Society of Automotive engineers of Japan, Vol. 18, pp: 369-375, 1997.

9- Nabi N., Akhter S. & Shahadat Z., "Improvement of Engine Emissions with Conventional Diesel Fuel and Diesel–Biodiesel Blends", Bio Resource Technology, Vol. 97, pp: 372-378, 2006.

10- Abd-Alla G. H., Soliman H. A., Badr O. A., "Rabbo M F, Effects of Diluents and Intake Air Temperature in Exhaust Gas Recirculation of an Indirect Injection Dual Fuel Engine", Energy Conversion & Management, Vol. 42, pp: 1033-1045, 2001.

11- Tsolakis A., Megaritis A., Theinnoi M. L., "Engine Performance and Emissions of a Diesel Engine Operating on Diesel-RME (rapeseed methyl ester) Blends with EGR (exhaust gas recirculation)", Energy, Vol. 32, pp: 2072-2080, 2007.

12- Maiboom A., Tauzia X. and Hetet J., "Experimental Study of Various Effects of Exhaust Gas Recirculation (EGR) on Combustion and Emissions of an Automotive Direct Injection Diesel Engine", Energy, Vol. 33, pp: 22-34, 2008.

13- Avolio G., Beatrice C., Del Giacomo N., Guido C. and Migliaccio M., "Effects of Highly Cooled EGR on Modern Diesel Engine Performance at Low Temperature Combustion Condition", Society of Automotive Engineers paper No. 2007-24-0014, 2007.

14- Haber B. S., "A Robust Control Approach on Diesel Engines with Dual-Loop Exhaust Gas Recirculation Systems", MSc thesis, Ohio State University, 2010.

15- Som S. K. and Datta A., "Thermodynamic Irreversibilities and Energy Balance in Combustion Processes", Progress in Energy and Combustion Science, Vol. 34, pp: 351-376, 2008.

16- Keating E. L., "Applied Combustion", 2nd Edition, Taylor & Francis Group, LLC, 2007.

17- ASHREA GIUDE LINE. Guide Engineering Analysis of Experimental Data, Guideline 2-1986.