Dual fuel diesel engine operation using LPG

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Abstract. Diesel engine fuelling with LPG represents a good solution to reduce the pollutant emissions and to improve its energetic performances. The high autoignition endurance of LPG requires specialized fuelling methods. From all possible LPG fuelling methods the authors chose the diesel-gas method because of the following reasons: is easy to be implemented even at already in use engines; the engine does not need important modifications; the LPG-air mixture has a high homogeneity with favorable influences over the combustion efficiency and over the level of the pollutant emissions, especially on the nitrogen oxides emissions.

This paper presents results of the theoretical and experimental investigations on operation of a LPG fuelled heavy duty diesel engine at two operating regimens, 40% and 55%. For 55% engine load is also presented the exhaust gas recirculation influence on the pollutant emission level. Was determined the influence of the diesel fuel with LPG substitution ratio on the combustion parameters (rate of heat released, combustion duration, maximum pressure, maximum pressure rise rate), on the energetic parameters (indicate mean effective pressure, effective efficiency, energetic specific fuel consumption) and on the pollutant emissions level.

Therefore with increasing substitute ratio of the diesel fuel with LPG are obtained the following results: the increase of the engine efficiency, the decrease of the specific energetic consumption, the increase of the maximum pressure and of the maximum pressure rise rate (considered as criteria to establish the optimum substitute ratio), the accentuated reduction of the nitrogen oxides emissions level.

1. Introduction

Dual-mode fuelling a compression ignition engine main goals are to reduce pollutant emissions and increase energetic performances of the engine. In this paper a compression ignition engine was fueled with diesel fuel and in dual fuel mode with diesel fuel and liquefied petroleum gas. LPG is a very good choice to fuel compression ignition engines due to its good burning properties, the relatively low cost (compared to diesel) and because there is already existent infrastructure for storage, transportation and supply (infrastructure for fuelling spark ignition engines).

1.1. LPG properties presented comparatively with diesel fuel properties.
LPG is generally a fuel derived from petroleum and coal processing and consists mainly of a mixture of two hydrocarbons, propane and butane, in different proportions depending on season and production company. Liquefied petroleum gas main properties are shown in table 1.
    In the table 1 it can be observed that:

Table 1. *LPG properties presented comparatively with diesel fuel properties* [1].

	diesel fuel	propane	butane
Density [kg/m³]	800-840	503	-
Vaporization heat [kJ/kg]	465	420	-
Self ignition temperature [ºC]	355	481	544
A/F ratio [kg/kg]	15	15.71	15.49
Flame temperature [ºC]	2054	1990	-
Lower heating value [MJ/kg]	42.5	46.34	45.55
Cetane number CC	40-55	-2	-

- LPG density is lower than that of diesel fuel, which means the same mass stored in the same tank volume will be lower.
- The heat of vaporization of LPG is lower than that of diesel, 420 kJ / kg compared to 465 kJ / kg, bringing beneficial effects of the mixture formation, especially by direct injection process, because to vaporize LPG consumes less heat.
- LPG flame temperature is lower than diesel fuel flame temperature, 1990 compared to 2054, so the nitrogen oxides emission level of the compression ignition engine fueled with LPG will be lower. An emission level of nitrogen oxides reduced when the diesel engine was fuelled in dual system [2], using the diesel fuel and liquefied petroleum gas.
- The lower heating value of liquefied petroleum gas is higher than diesel fuel lower heating value, allowing the release of a higher quantity of heat burning the same amount of fuel and increasing the indicated efficiency of the engine. In the paper [3] the authors obtained an increase with 4% in the efficiency of a diesel engine with 4 cylinders in line , fueling the engine with diesel fuel and LPG. An increase with 4 percent for engine efficiency was achieved at maximum load and at partial load the efficiency of the engine increased with increasing substitute ratio of diesel with LPG [3]. In the paper [3] the nitrogen oxides emission level has increased by 38% at full engine load and decreased with 40-60% at partial engine loads. Increases in indicate efficiency and reductions in nitrogen oxides emission level were obtained also in [4], [5], by dual fuelling a compression ignition engine with diesel fuel and LPG.
- Autoignition temperature of the liquefied petroleum gas is higher than diesel fuel autoignition temperature, and this combined with a very low cetane number gives this fuel very poor autoignition properties, therefore to fuel a compression ignition engine with LPG must use specific fuelling methodes.

1.2. Liquefied petroleum gas fuelling method.
The fuelling method used in this paper is diesel-gas, method which involves the injection of liquefied petroleum gas in gaseous form in the intake manifold of the engine. The engine is equipped with a liquefied petroleum gas fuelling system, consists of a LPG tank, pipe connectors, vaporizer and a valve to regulate the flow of gaseous fuel that enters in the combustion chamber. The homogeneous air LPG is ignited from the flames appeared in diesel fuel sprays prior injected by the standard injection system of the engine.

The diesel-gas method was successfully applied in [6], the authors fuelled a four cylinders car diesel engine with liquefied petroleum gas. By using the method diesel gas authors were able to reduce engine emissions and improve its energetic performances. The diesel-gas method was also applied in [7], [8], the authors studied the effects of the diesel fuel pilot injection on the dual fuel diesel engine performances.

This paper presents experimental and theoretical investigations of dual fuelling a truck compression ignition engine with diesel fuel and LPG using the diesel-gas method.

2. Experimental investigations

The experimental study was carried out on a test bed equiped with a ROMAN D2156MTN 8 truck compresion ignition engine, with 6 cilinders in line, fuelled with LPG using the diesel-gas method. The main specification of the engine are presented in the table 2. Figure 1 presents the test bed and equipments. The investigations were made at two regimens, 40% engine load and 55% engine load and the investigated engine speed was 1450 rpm. For both regimens, first was determined the reference, fuelling the engine with diesel fuel, then the diesel fuel dose was decreased and the LPG dose was increased maintainig the same engine power as in the case of fuelling with diesel fuel. The investigated energetic substitute ratios of the diesel fuel with LPG were between 18...30% for 55% engine load and between 13.5...25% for 40% engine load. For 55% engine load exhaust gas recirculation was used with a quantity of 2.34% from the total amount of air consumed by the engine.
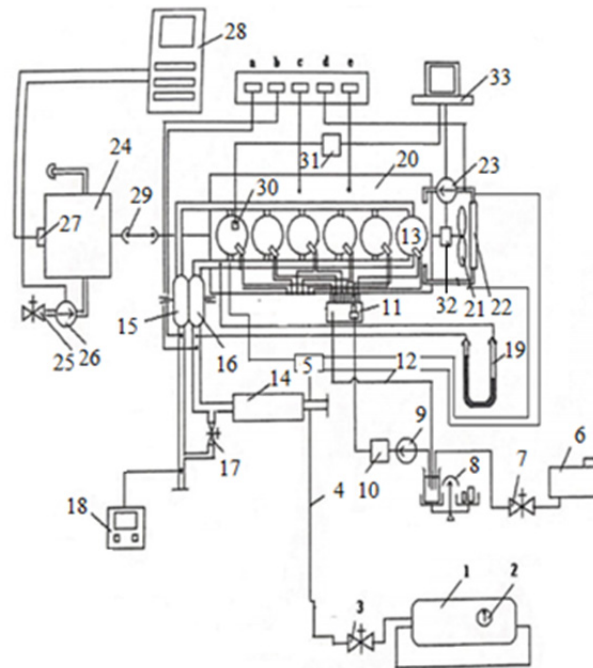

Figure 1. The test bed diagram. 1-LPG tank; 2-LPG tank level indicator; 3-LPG valve for consumption determination; 4-LPG fuel pipe; 5-vaporiser; 6-diesel fuel tank; 7-diesel fuel valve for consumption determination; 8-gravimetric balance; 9-diesel fuel pump; 10-diesel fuel filter; 11-diesel fuel injection pump; 12-diesel fuel return pipe; 13-diesel fuel injector; 14-air flow meter; 15-16-turbocharger; 17-exhaust gas recirculation valve; 18-AVL Dicom gas analyser; 19-differential pressure gauge with mercury for supercharging pressure measuring; 20-engine; 21-cooling fan; 22-engine coolant; 23-cooling system pump ; 24-eddy current dynamometer; 25-dynamometer cooling valve; 26-dynamometer cooling system pump; 27-dynamometer force transducer; 28-dynamometer control panel; 29-coupling; 30-pressure transducer; 31-charge amplifier; 32-angle encoder; 33-aquisition system; a-exhaust gases temperature indicator; b-intake air temperature indicator; c-oil temperature indicator; d-cooling system temperature indicator; e-oil pressure indicator.

Table 2.The main specifications of the engine [9].

Number of cylinders	6
Bore [mm]	121
Stroke [mm]	150
Total Displacement [dm^3]	10.34
Compression ratio	17
Rated power [kW]	188
Maximum torque [Nm]	900
Admision type	turbocharged

The test bed equipments consist of: Roman D 2156 MTN 8 diesel engine, Hofman eddy current dyno, Kistler piezoelectric pressure transducer, AVL data aquisition system, AVL Dicom 4000 gas analyser and opacimeter, Optimass masic fuel flow meter, Meriam volumic air flow meter, thermocouples and thermoresistences to measure the temperature, gravimetric system for diesel fuel consumption measuring and gas leaks detector.

3. Theoretical investigations

Theoretical investigations were carried out to determine the rate of heat released and the effective efficiency of the engine. For the rate of heat released the mathematical formula (1) was used [10]:

$$\frac{dQ}{d\alpha} = \frac{1}{m_c - 1} \cdot (m_c \cdot p \cdot dV + V \cdot dp) \tag{1}$$

where:
- p is the in cylinder pressure
- V is the volume
- dV is the volume derivative
- dp is the pressure derivative
- m_c is the politropic coefficient

The indicate mean effective pressure p_i and break mean effective pressure p_e can be calculated using equations (2) and (3):

$$p_i = \frac{L_i}{V_s} \tag{2}$$

$$p_e = \frac{30 \cdot \tau \cdot P_e}{i \cdot V_s \cdot n} \tag{3}$$

where
- L_i is the mechanical work
- V_s is the unitary displacement
- P_e is the engine power
- i is the number of cylinders
- n is the engine speed
- τ is the number of strokes

The mechanical efficiency η_m can be calculated using equation (4) and the effective efficiency η_i with equation (5):

$$\eta_m = \frac{p_e}{p_i} \tag{4}$$

$$\eta_i = \frac{L_i}{H_i} \tag{5}$$

4

where H_i is the lower heating value of the fuel.
    Thus the effective efficiency can now be calculated:

$$\eta_e = \eta_m \cdot \eta_i \qquad (6)$$

4. Experimental and theoretical results
The experimental and theoretical investigations led to the folowing results.

4.1. In cylinder pressure
The in cylinder pressure level increased for all the investigated energetic substitute ratios of diesel fuel with LPG (xc) and for both investigated engine speeds because the burning proces enhance when the homogeneous mixture of air-LPG is present within the combustion chamber. The figures 2 and 3 presents the measured in cylinder pressure for all the investigated cases.

Figure 2. The measured in cylinder pressure for the 55% engine load.

Figure 3. The measured in cylinder pressure for the 40% engine load.
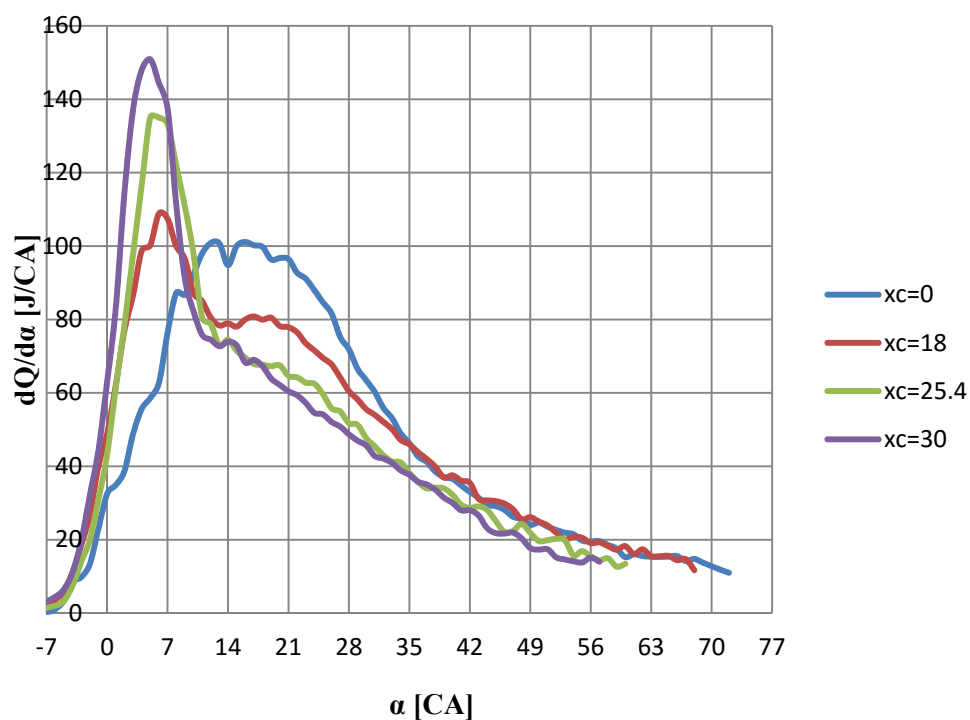
4.2. The rate of heat released diagrams

Figure 4. The rate of heat released versus crank angle for 55% load.

The intensification of the combustion process with the increasing energetic substitute ratio of the diesel fuel with LPG (xc) is revealed by the rate of heat released diagrams, figures 4 and 5.
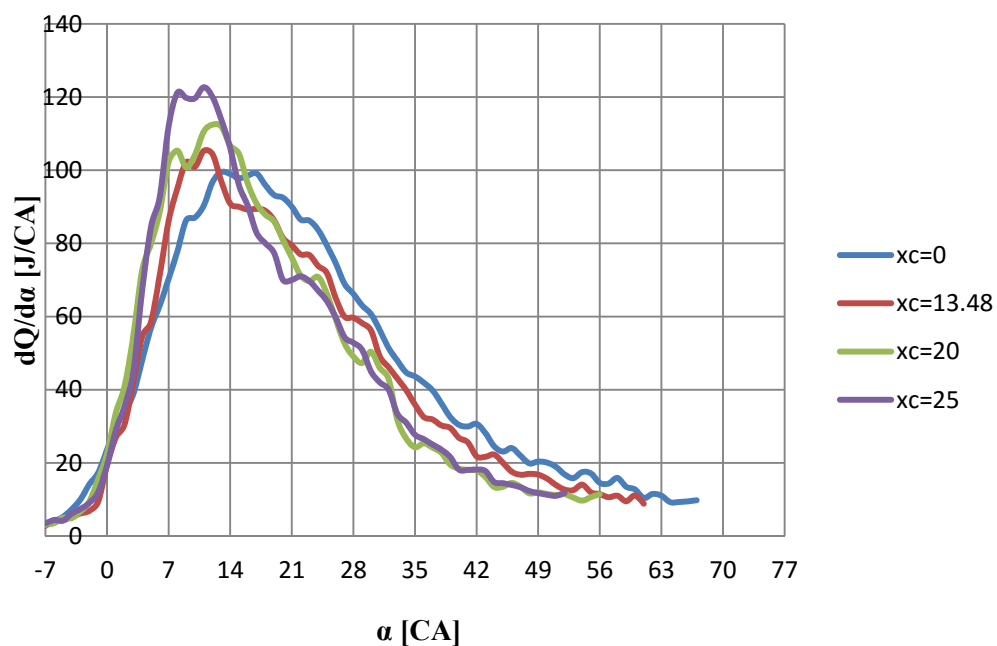

Figure 5. The rate of heat released versus crank angle for 40% load.

4.3. The combustion duration

The combustion duration Cd decreased with the increasing energetic substitute ratio of diesel fuel with LPG (xc). The combustion duration values are presented in the table 3 for all the investigated cases.

Table 3.The combustion duration.

55% engine load		40% engine load	
xc [%]	Cd [CA]	xc [%]	Cd [CA]
0	78	0	72
18	74	13.5	68
25.4	66	20	62
30	63	25	58

4.4. Maximum rate of pressure rise

The maximum rate of pressure rise versus the energetic substitute ratio of the diesel fuel with LPG is presented in the figures 6 and 7. The maximum rate of pressure rise increases for all the investigated cases because the flame appeared in the diesel fuel sprays has a higher speed in the homogeneous mixture of air-LPG.
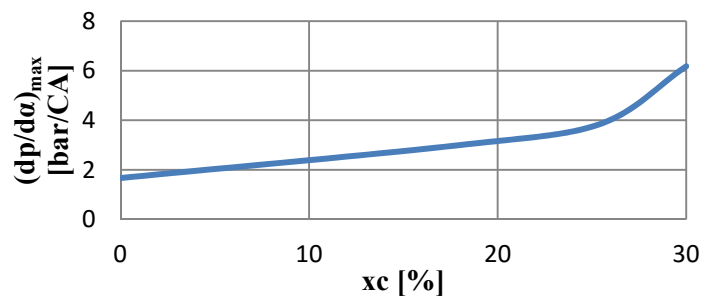

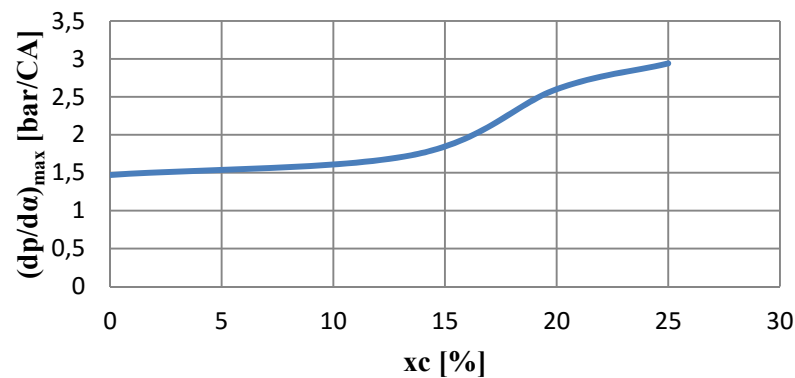**Figure 6.**The maximum rate of pressure rise for 55% engine load.

Figure 7. The maximum rate of pressure rise for 40% engine load.

4.5. The nitrogen oxides emission level

The nitrogen oxides emission level decreased for all the investigated energetic substitute ratios of diesel fuel with LPG because the temperature of combustion decreases when exhaust gas recirculation is used. The exhaust gas recirculation quantity was 2.34% form the total amount of air consumed by the engine. Figure 8 and 9 presents the nitrogen oxides emission level.
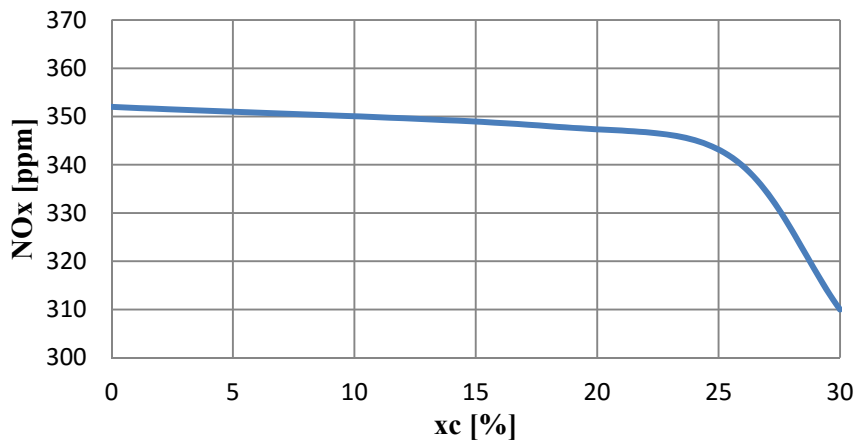
Figure 8. The nitrogen oxides emission level for 55% engine load.
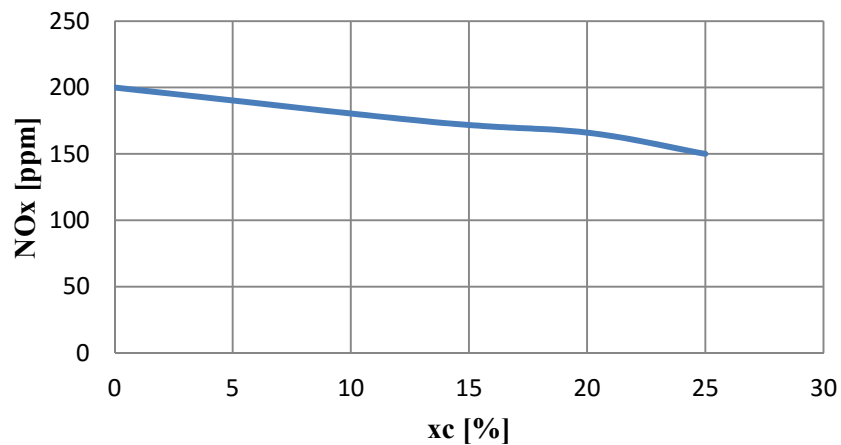
Figure 9. The nitrogen oxides emission level for 40% engine load.

4.6. The indicate specific energetic consumption
The indicate specific energetic consumption decreased when the engine was fuelled with LPG by using diesel-gas method. The figures 10 and 11 presents the indicate specific energetic consumption versus the substitute ratio of diesel fuel with LPG.
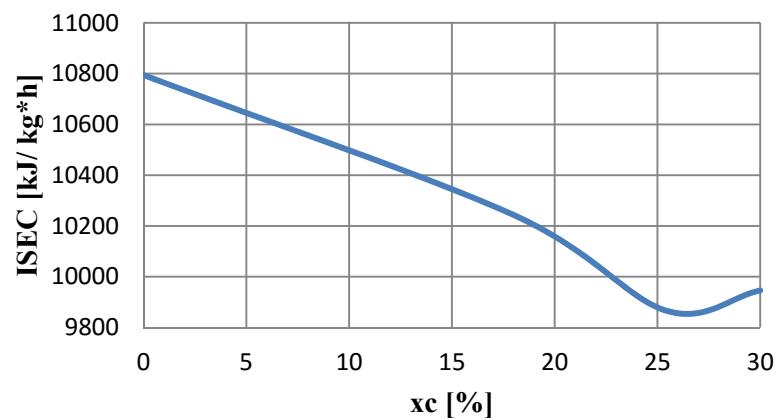
Figure 10. The indicate specific energetic consumption for 55% engine load.
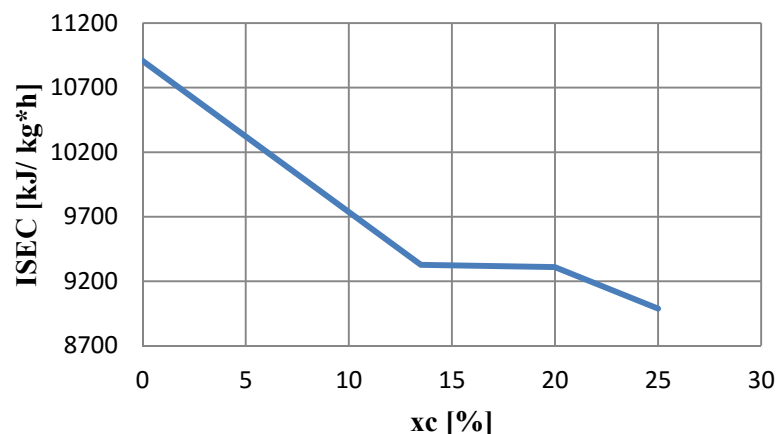
Figure 11. The indicate specific energetic consumption for 40% engine load.

4.7. The effective efficiency of the engine
The effective efficiency of the engine increased with increasing energetic substitute ratio of the diesel fuel with LPG. The effective efficiency is presented in the table 4.

Table 4. The effective efficiency.

55% engine load		40% engine load	
xc [%]	η_e [%]	xc [%]	η_e [%]
0	22	0	17.5
18	24.4	13.5	19.8
25.4	27.3	20	21.5
30	27.6	25	22.2

5. Conclusions

The experimental and theoretical investigations led to the following conclusions: the maximum in cylinder pressure increased with increasing energetic substitute ratio of diesel fuel with LPG, having a maximum value of 73.3 bar for 55% engine load (compared with 58.4 bar when the engine was fuelled only with diesel fuel) and a maximum value of 63.7 bar (compared with 56.73 bar when the engine was fuelled only with diesel fuel); the combustion duration decreased with increasing energetic substitute ratio of diesel fuel with LPG, having a minimum value of 63 CA for 55% engine load and 58 CA for 40% engine load (compared with 78 CA and 72 CA when the engine was fuelled only with diesel fuel); the maximum rate of pressure rise increased for all the investigated cases when the engine was fuelled with LPG by diesel-gas method; the nitrogen oxides emission level decreased for all the investigated energetic substitute ratios of the diesel fuel with LPG for both regimens (55% engine load and 40% engine load), recording a minimum value of 310 ppm for the 55% engine load regimen and a minimum value of 150 ppm for the 40% engine load regimen, compared with 352 ppm and 200 ppm obtained at the reference case; when the engine was fuelled with LPG the indicate specific energetic consumption decreased; the effective engine efficiency increased with 5.6 % at 55% engine load and with 4.7 % at 40% engine load for the maximum energetic substitute ratios of the diesel fuel with LPG.

6. References

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