EXPERIMENTAL STUDY OF EXHAUST GAS PARAMETERS ON A DIESEL ENGINE IN STATIONARY OPERATING MODE

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ПАРАМЕТРОВ ВЫХЛОПНЫХ ГАЗОВ НА ДИЗЕЛЬНЫЙ ДВИГАТЕЛЬ В СТАЦИОНАРНОМ РЕЖИМЕ

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Abstract: *In this paper an experimental study of exhaust gas parameters of a modern diesel engine is presented. The engine under study is developed for passenger car. It was used a flexible engine management system based on National Instruments real-time controller and LabVIEW code. However, basic settings of the engine calibration values were used over the test. The engine was tested at seventeen operating points which correspond to real operating mode in NEDC of the vehicle. In order to define the engine speed and load a vehicle driving model was used. Finally, exhaust mass flow and temperature were studied as well as exhaust enthalpy was estimated. The results revealed that waste heat recovery system can be applied in order to reduce fuel consumption in NEDC.*

***KEYWORDS**: DIESEL ENGINE, EXHAUST GASES, EXPERIMENTAL TEST, WASTE HEAT RECOVERY*

1. Introduction

Reduction of CO_2 emissions from passenger cars in European Union (EU) is the main challenge for the automotive industry. A new level of 95g/km [1] measured by New European Driving Cycle (NEDC) is the target for 2020. It means a reduction by 26% in comparison with the level in 2015. In order to meet the future restriction of CO_2 emissions for passenger cars, it is necessary to reduce significantly the engine fuel consumption developing more advanced technologies.

A number of research [2-4] revealed that, overall efficiency of automobile engines still remains below 40%. Therefore, more than 60% of fuel energy is lost as a form of heat in the exhaust and cooling system. Due to that fact, waste heat recovery (WHR) applied to automotive engines, seems to be a prospective way to increase the engine efficiency.

A numerical study conducted on a diesel engine [2] revealed that the enthalpy rejected by exhaust gases and that lost in the cooling system is approximately the same. However, an exergetic analysis revealed much higher potential of WHR by exhaust gases than cooling system. It can be explain with higher temperature of the exhaust gases.

Rankine cycle (RC) and Organic Rankine cycle (ORC) can be successfully applied as WHR to engine exhaust system. Punov et al. [5], revealed higher potential of RC than ORC at engine operating point typical for tractors during plowing. In this case RC efficiency was observed to be 15.8%. Daccord et al. [1], reported RC efficiency of 10.3% and ORC efficiency of 6.3%. Glavatskaya et al. [6], studied RC with piston expander machine applied to automotive engine. In that study WHR efficiency was estimated to be within the range from 12% to 14%.

In order to study WHR potential from exhaust gases the heat source parameters need to be determined. For that reason, the aim of this article is to study the exhaust gases parameters on an automotive diesel engine for passenger car in stationary operating mode.

2. Engine data

The engine under study is 2.0liter four cylinders direct injection diesel engine developed by PSA. The maximum output power is 101kW at 4000rpm as the maximum torque is 320Nm at 2000rpm. The engine is equipped with variable geometry turbocharger. Boost pressure is limited to 1.3 bar. Common rail system of the engine is produced by Delphi. The high pressure pump is DFP 3.1 with integrated transfer pump and inlet metering valve. Solenoid controlled 6-holes injectors of generation DFI 1.3 are used into the system. The injection characteristics were studied in [7]. Maximum injection pressure is 1600 bar. The engine is also equipped with water cooled EGR system and post treatment system including catalytic converter. The valves distribution system with four valves per cylinder is developed. The engine is compliant with EURO 4 emission demands. The main engine data are listed in Table 1.

Table 1

Type of engine	HDI
Number of cylinders	4
Total volume	2liter
Cylinder bore	85 mm
Cylinder stroke	88 mm
Compression ratio	17,6
Valves per cylinder	4

3. Experimental setup

The experimental study was conducted at Department of combustion engines, automobiles and transport of Technical university of Sofia. The test facility includes an engine test bed equipped with hydraulic brake, flexible diesel engine management system and data acquisition system for data analysis. The engine test bed is shown in Figure 1.

Figure 1. Engine test bed facility

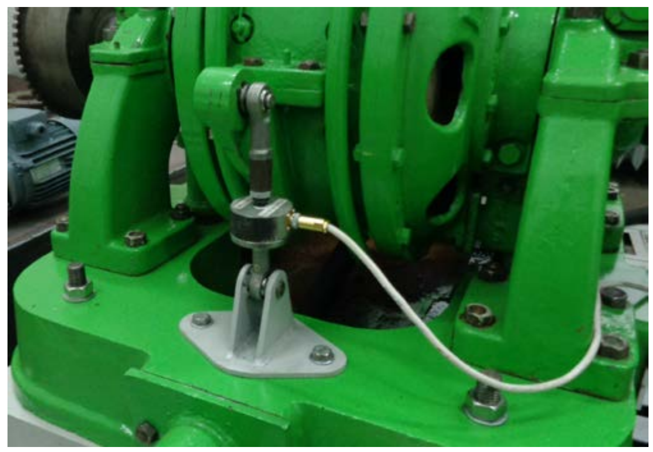

Figure 2. Brake force sensor

The engine is mechanically coupled to hydraulic brake D4. The maximum power absorption from the brake is 257kW at 4500rpm. A strain gauge sensor is used in order to measure the brake force (Figure 2). The sensor was produced at Technical university of Sofia for operating range from 0N to 1500N and accuracy of 0,5% at whole operating range. A strain gauge amplifier Advantech ADAM 3016 is used. Two mechanically controlled valves are used to control the brake.

Figure 3. Intake mass flow meter

The exhaust gases parameters (temperature and mass flow rate) were measured. We estimated the exhaust mass flow by measuring

Figure 4. Fuel consumption measurement

the intake mass flow and fuel consumption. In order to measure the intake mass flow an intake mass flow meter produced by Bosch was used. It is a flow meter based on thermo anemometry principal. The accuracy is 2% over the whole operating range. The flow meter was previously calibrated in respect to a laboratory mass flow meter. The flow meter mounted in the engine intake system is shown in Figure 3.

Fuel consumption was estimated measuring the volumetric flow while the density of the fuel was previously defined to be 0.840g/cm^3. It was used Rotronics RCC101 volumetric fuel flow measurement technic with two flow sensors – one in delivery line and one in return line. The signal from the sensors comes to rack-mounted measurement equipment. Fuel measurement equipment is shown in Figure 4.

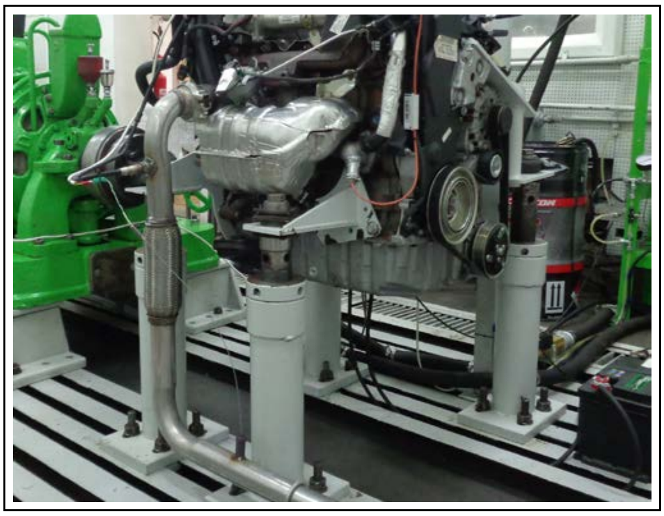

Figure 5. Exhaust temperature sensor position

The exhaust temperature was measured by means of a K-type thermocouple located at exhaust pipe 1.5m downstream the exhaust valves. We considered this location is suitable as inlet section of a Rankine cycle heat exchanger. Measurement range of the thermocouple is up to 1100°C. The probe diameter is 1.5mm. Mounting position of the sensor can be seen in Figure 5.

In our experimental research the engine operation was controlled by means of Real Time controller produced by National Instruments and specialized modules for control and measurement produced by Drivven. It includes: NI Chassis PXI-1031, RT controller NI PXI-8106, FPGA NI PXI-7813R card, two expansion chassis CRIO 9151, two DI driver, AD combo, LS module and O_2 sensor module. The entire system is presented in Figure 6.

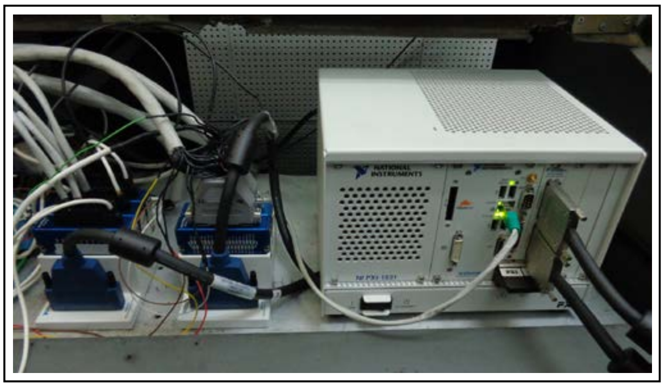

Figure 6. Engine management system

A Lab View project was developed in order to control the engine. The system provides very large functionality for measurement and control such as: injection process control with up to five separate injections per cycle, injection pressure control, boost pressure control, exhaust gas recirculation (EGR) control, closed-loop control of injection by means of wide band oxygen sensor in exhaust gases etc. Moreover, the system can be adapted for diesel engines with up to 6 cylinders in case of solenoid injectors and up to 4 cylinders in case of piezo injectors. The front panel of the project host application and the monitoring system are shown in Figure 7 and 8.

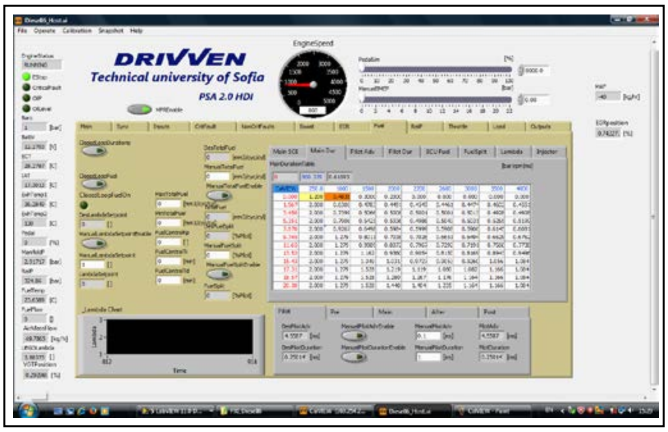

Figure 7. Engine control software

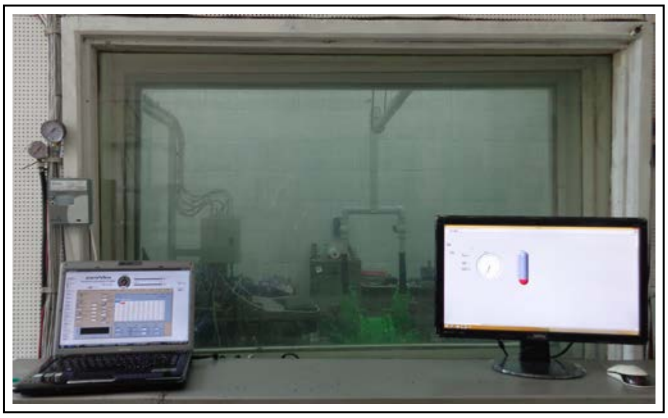

Figure 8. Engine monitoring system

4. Determination of engine test points

The engine performance has been previously studied numerically by means of 1D model in advanced simulation software AVL BOOST [2, 8]. In current study, it was interesting to determine the engine operating points which correspond to engine operating mode in NEDC test of a passenger car. In order to establish the engine operating points a driving model of a vehicle was used. This model is based on the force balance in longitudinal direction of the vehicle. In this case the traction force should be equal to the sum of the aerodynamic force, rolling resistance force and inertial force. The grade resistance force is zero. NEDC begins with cold start, then it follows four repetitions of UDC mode. It finishes with single repetition of EUDC. The NEDC for 6-speed manual transmission is presented in Figure 9.

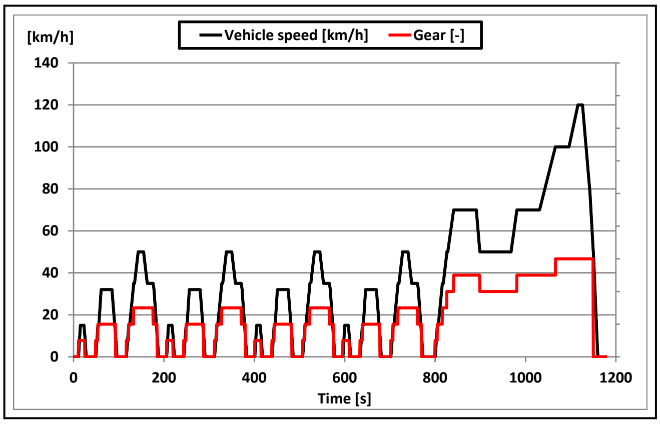

Figure 9. Vehicle speed in NEDC

The main parameters of the vehicle which was used to determine the engine operating points are listed in Table 2.

Table 2

Vehicle type	Medium size
Seats	5
Mass of the vehicle, kg	1486
Tyres	225/60R16
Rolling resistance coefficient	0.008
k	6.10^{-6}
Car frontal area, m^2	2.25
Aerodynamic drag coefficient C_x	0.3
Transmission	6 speed manual

It was observed seventeen typical engine operating points over the cycle simulation. The engine speed and BMEP for each point is listed in Table 3.

Table 3

№	Vehicle speed [km/h]	Gear [-]	Engine speed [rpm]	BMEP [bar]
1	15	2	950	0.35
2	16.1	2	1070	2.88
3	16.7	2	1100	3.82
4	50.8	4	1400	4.93
5	50	3	1420	1.27
6	35	3	1430	0.52
7	35.9	3	1470	4.03
8	70.4	5	1600	4.72
9	15	1	1830	0.13
10	49.1	3	1950	4.72
11	69.2	4	1980	6.25
12	100.5	6	1990	8.56
13	32	3	2020	1.01
14	33.9	2	2150	2.89
15	120	5	2280	5.97
16	119.5	6	2300	9.82
17	100	5	2310	4.02

5. *Results*

The experimental research was conducted at engine steady-state operating mode. Seventeen operating points were observed corresponding to idling, constant vehicle speed and acceleration. These operating points were defined based on vehicle simulation in NEDC in previous section (Table 3). During the test the engine was heated up to normal cooling temperature. The ambient temperature was 18°C while the barometric pressure was 955mbar. Then, the values of intake mass flow, fuel flow and exhaust gases temperature were recorded. Variation of exhaust gases parameters in NEDC is shown in Figure 10, 11 and 12. Exhaust gas enthalpy was calculated as constant value of specific heat capacity was used (c_p=1.15 kJ/kg.K). Exhaust mass flow varies within the range from 53,4kg/h to 188,7kg/h. The highest value was measured at engine operating point corresponds to vehicle speed of 100km/h on 6^{th} gear.

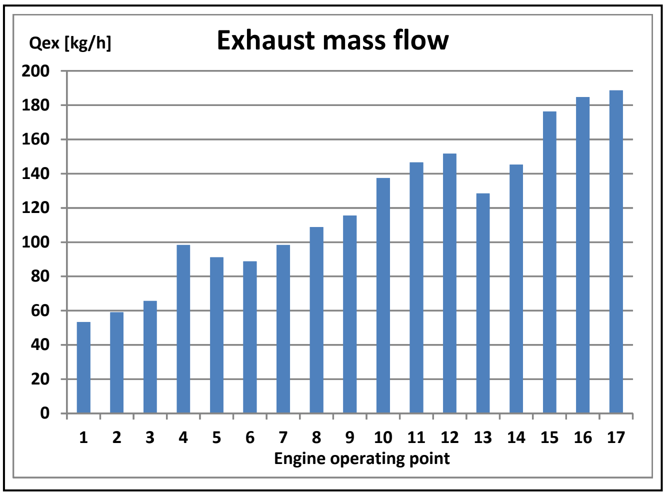

Figure 10. Variation of exhaust mass flow

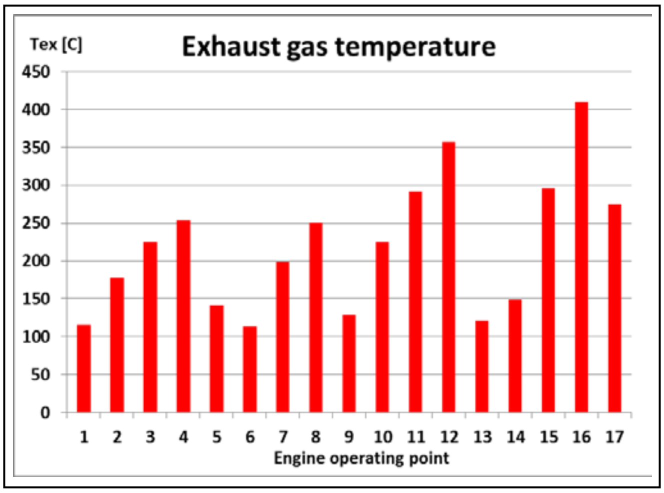

Figure 11. Variation of exhaust gas temperature

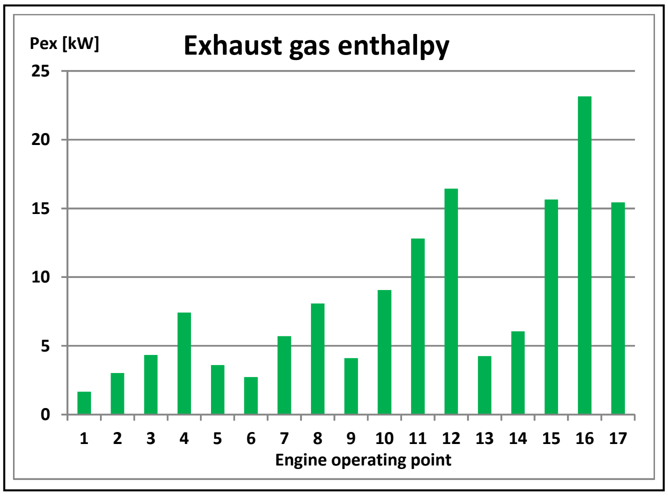

Figure 12. Variation of exhaust gas enthalpy

Exhaust gas temperature (Fig. 11) depends on engine load. At those operating points where output power is high the temperature is much higher than other points. The maximum value was measured at the 16th operating points which corresponds to vehicle speed of 119.5km/h and BMEP of 9.82bar. In this transient operating mode of the vehicle, exhaust gas temperature accounts to 410.3°C. At the same operating point was observed the highest exhaust power. The exhaust enthalpy, calculated per time is 23.1kW.

6. Conclusions

An experimental study of modern diesel engine in stationary operating mode was conducted. Over the test, exhaust gas parameters (mass flow and temperature) were measured. The temperature was measure at the location situated 1.5m downstream the exhaust valve. That place has been considered as suitable for the heat exchanger of waste heat recovery system based on Rankine cycle.

The engine was equipped with flexible management system based on National Instruments real time controller and modules developed by Drivven. In order to control the engine a real time project was developed in LabVIEW. It provides opportunities for precise control of injection process (according the manufacturer settings), fuel pressure, boost pressure, EGR system, cooling system and etc.

NEDC is still used in homologation of new passenger cars in Europe. For that reason the engine was tested at operating points which are defined by vehicle model in NEDC. It was observed that the homologation cycle can be represented by seventeen operating points. The engine speed ranged from 950min^{-1} to 2310min^{-1} while the BMEP ranged from 0.13bar to 9.82bar. Therefore, the output power ranged from zero to 37,7kW.

In order to assess the potential of exhaust gases for waste heat recovery in NEDC their thermodynamic parameters were experimentally studied. Experimental results revealed that all parameters vary at wide range. Exhaust mass flow ranged from 53,4kg/h to 188,7kg/h while the temperature changes within the range from 115°C to 410.3°C. Enthalpy of exhaust gases was calculated per time, i.e. as power. The values ranged from 1.66kW to 23.15kW.

Obviously, NEDC is not very dynamic cycle. Moreover UDC is repeated four times. It means that exhaust gas energy will be not too high over the first part of the cycle. For that reason, in future researches will be better to study Rankine cycle working with organic working fluid rather than steam Rankine cycle.

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