Transient operation of a direct injection diesel engine

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Abstract. A direct injection diesel engine was studied in transient operation. Experimentally is determined the injected fuel per cycle at varying initial and end load conditions, simulating operation at urban traffic. Phases have been identified in the change of parameters of fuel delivery and components in the exhaust gases, limited by emission standards. There is a potential for reducing the carbon emissions of the engine and the amount of emitted toxic components by influencing the duration of the transient processes.

1. Introduction

Automotive internal combustion engines operate under different conditions in terms of load and rotational speed. Studies show that most of the passenger mobility is carried out by private vehicles, with the average range of cars being driven in relatively short distances or in urban conditions [1]. The impact of cars in such conditions is characterized by predominant acceleration movements that are heavily dependent on the particular infrastructure and organization of the urban environment.

Operating modes of the engine in these cases are transient (non-stationary), associated with continuous change of speed and load, the processes being directly related to both road conditions and the need to switch gears. As a result of these changes in operating conditions, engine performance is significantly different from that of stationary operating modes.

Transient modes are characterized by the successive working processes in one engine cylinder under different thermodynamic conditions [2, 3]. As a result, there is an increase in fuel consumption and associated carbon emissions, as well as an increased content of the limited components in the exhaust gases [4]. In this sense, the actual operating conditions of the motor vehicles require constant updating of the tests provided for in the type approval procedures and the environmental standards [5].

The purpose of the present study is to examine the operation of the engine in transient modes and to determine the variation in fuel consumption and emissions of harmful components in exhaust gases. The main task of this report is to investigate the dependencies of changing cyclic quantity of fuel injected and the emissions of harmful components for a direct injection diesel engine.

The object of the study is the Perkins PRIMA 65 diesel engine. The main technical characteristics of the engine are: rated power \( P_e = 46 \, kW \) at crankshaft speed \( n = 4500 \, \text{min}^{-1} \); maximum torque \( Me = 122 \, N.m \) at rotational speed \( n = 2500 \, \text{min}^{-1} \); engine volume \( V_h = 1.993 \, \text{dm}^3 \); cylinder diameter \( D_c = 84.4 \, \text{mm} \); stroke of the piston \( S_h = 88.9 \, \text{mm} \); number of cylinders - 4; compression ratio \( \varepsilon = 18.1 \); direct injection of fuel and water cooling. The engine is equipped with a fuel injection pump CAV-DPAM 3842 F020 and BDLL 150 S 6556 injectors.
2. Methodology
Experimental engine performance studies have been conducted. Engine operating modes are designed to match the most commonly used by cars when driving in urban areas. When driving in urban areas, engines work mostly on small and medium loads as well as a significant part of the time in idling mode. Rotational speeds are low and are usually in the area around and slightly above the maximum torque of the engine. The movement of the car is characterized by frequent stops and start off, as well as intensive gear changes. Increasing and decreasing of rotational speed are also accompanied by a corresponding increase and decrease in engine load. From operational and environmental point of view, the carbon emissions and the environmental performance of the engine in the positive acceleration modes are of interest.

The study was carried out on a specialized stand. Thermodynamic parameters and all variables necessary to determine the cyclic fuel quantity and the content of the harmful components in the exhaust gases are determined. The recording of measured variables is made with digital storage oscilloscope at high sampling rate. The workflow parameters for each of the working modes are determined directly or calculated. The in-cylinder pressure (indicator diagram), injection pressure, needle stroke, exhaust gas content are recorded.

The injected fuel per cycle is calculated. The injection characteristics (differential and integral) are computed by formulas (1) and (2):

\[
\frac{da(\varphi)}{d\varphi} = \mu F(\varphi) \left(\frac{2}{\rho_g} \left(p_g(\varphi) - p_i(\varphi)\right) \cdot 10^6\right)^{1/2}
\]

\[
q(\varphi) = \frac{p_g}{6n} \int_{\varphi_0}^{\varphi} \frac{da(\varphi)}{d\varphi} d\varphi
\]

as from the inlet fuel pressure and the injector needle lift is calculated the approximate fuel pressure under the needle \(p_g(\varphi)\) (phasing of the injection pressure and the reflected wave at the start of the needle lifting) and the current quantity of the fuel injected \(q(\varphi)\) at a previously experimentally determined effective section of the injector nozzle \(\mu F(\varphi)\). In Formula (1) the additional quantities are as follows: \(\rho_g\) - fuel density; \(\varphi\) – crankshaft rotation angle; \(p_i(\varphi)\) - current in-cylinder pressure; \(n\) - the crankshaft speed.

Prior to calculation, the input data was prepared according to the method described in [6], where the diagrams are represented in step of 0.1° CA (crankshaft rotation angle) and cubic spline transformation, ensuring continuity of the first and second derivatives, necessary for consecutive mathematical processing.

3. Experimental results and discussions
Engine operating modes simulating urban driving are explored. Transition processes cover engine speed ranges from 1500 to 3500 \(min^{-1}\), which is a variation of engine speed relatively to the point of maximum torque of about 40%. The load variation ranges from about 10% to 100% of the maximum torque value of the engine, and the individual tests are shown in table 1.

| No | Start condition | End condition |
|----|----------------|--------------|
| 1  | 9.84 %         | 32.79 %      |
| 2  | 13.11 %        | 50.00 %      |
| 3  | 13.11 %        | 69.67 %      |
| 4  | 25.41 %        | 99.18 %      |
The duration of acceleration and time to complete the transition mode is about 6 s. This value corresponds to the average acceleration time of the vehicle in a given gear and partial loads in the presence of a speed limitation in urban environment.

Figure 1 shows the variation of the injected fuel per cycle $q_c$ in a transient engine mode with an increase of the rotational speed $rpm$ from 1500 to 3800 $min^{-1}$ and a load increase of 12 to 40 $N$, where $F_{dyn}$ is the load of the engine dynamometer. The transient mode has a duration of about 6.2 s.

![Figure 1](image.png)

**Figure 1.** Injected fuel per cycle (a) and carbon emissions CO$_2$ (b) in transient engine mode with load up to 40 $N$.

At the beginning of this mode the engine runs at low load and fuel consumption is 5.8 $mg/cycle$. In the first phase of the transition regime, there is a sharp increase in fuel consumption and after about 2 s it reaches a local maximum of 18.38 $mg/cycle$ at a rotational speed of 2360 $min^{-1}$. Afterwards there is a decrease in consumption to reach the set speed of 13.3 $mg/cycle$. Once the load and speed regime has been established, the injected fuel per cycle is stabilized at 10.3 $mg/cycle$. Similar tendency is observed with the carbon emission results shown in figure 1. Minor differences in graphs are due to the damping effect of the total exhaust gases in the engine exhaust manifold when carbon dioxide data is recorded.

The amounts of hydrocarbons HC and nitrogen oxides NOx measured before the catalyst are shown in Figure 2.

![Figure 2](image.png)

**Figure 2.** HC (a) and NOx (b) emission values for transient engine operation with load up to 40 $N$.

The HC values are not significantly affected by the parameters of the transition process. The behaviour of nitrogen oxides follows the increase in engine load and the fuelling behaviour of the engine. It can be seen from figure 2b) that in the acceleration mode, their values also increase beyond
those of the established mode after reaching the set load. The maximum values are recorded at the moment when the maximum load and the rotation speed are reached, and thereafter they are reduced to those with established modes. The amount of nitrogen oxides emissions in the transition process compared to the stationary mode is about 130.9 %.

Figure 3 shows the results for transient operating modes of the engine with a 50 % increase in load to 60 N - figure 3a), and a 70 % increase in load to 85 N, figure 3b, relative to the initial load.

![Figure 3](image)

**Figure 3.** Injected fuel per cycle in transient engine operation with load up to 60 N (a); and up to 85 N (b).

The tendency to increase fuel delivery per cycle in the first phase of the transitional regime with a subsequent decrease in the established one is maintained. At higher final load values, the difference between the recorded maximum of the cyclic fuel portion in the transition and the established regime decreases. With a continuous increase in the final load mode, the local maximum disappears and the fuel delivery aims to reach that of the established mode.

Emissions of nitrogen oxides follow the increase in engine load. There is some lag, probably due to the lower thermodynamic conditions of the environment in which the working process develops in the first phase of the transition regime, figure 4.

![Figure 4](image)

**Figure 4.** NOx emission values in transient engine operation with load up to 60N (a); and up to 85N (b).

Immediately after the start of the transition process, heat exchange with the walls of the combustion space is significant. This prevents the development of high temperatures in the combustion chamber and the generation of higher emissions of nitrogen oxides in the first phase. The regime with increasing load leads to a gradual increase of temperature of the combustion chamber and to higher
maximum temperatures of the working cycle, with consequent impact on the emissions of nitrogen oxides. The results for NOx emissions at discussed loads of the engine dynamometer plus a full load curve are summarized in figure 5.

![Figure 5. NOx emission values in transient engine operation with varying load.](image)

4. Conclusion

Driving in urban areas is dominated by transient modes of operation. In such environment automotive engines operate with varying loads, frequent gear shifts and depending on the duration of the transition process, can be approximated with engine speed characteristics with partially open throttle.

The direct injection engine tests have shown the presence of phases of the transient modes in terms of fuel consumption and the content of harmful components in the exhaust gases. These phases are more pronounced in transient processes at engine operating modes in the low and medium load range. During the first phase at low speeds there is a rapid increase in the injected fuel per cycle as the engine tries to increase the kinetic energy of the vehicle and the rotating parts of the transmission. Together with increased fuel consumption, carbon dioxide and nitrogen oxide emissions are also increased. Next there is a drop in fuel delivery, which results from the reduced rate of rise of the rotation speed and gradually reaching the set load of the dynamometer. The third phase is related to the settlement of engine parameters to steady mode. By changing the mode in the area of high loads, the transient mode is characterized by the operation of the engine with wide-open-throttle speed characteristics.

In the first phase of the transient process, nitrogen oxides have a local maximum only at low loads. In such mode, after reaching the established parameters, as a result of reduced fuel delivery, the amount of nitrogen oxides also decrease. In all other modes, their amount is continuously increased as a result of improved thermodynamic combustion conditions in the engine cylinder.

By increasing the duration of the transition mode and creating conditions for the engine to work with part-open-throttle speed characteristics, there is a potential for reducing fuel consumption when driving in urban areas and reducing emissions of toxic components in exhaust gases.

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