The characteristics of the combustion process occurring under real operating conditions of traction

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Abstract. The authors deal with the issues of the Diesel engine under dynamic conditions. The conditions of the dynamic operation of the engine have most frequently been mapped by the method of free acceleration of the engine caused by the change of the position of the fuel dose lever. The article presents the results of indication of the traction Diesel engine under real operating conditions. This allows for the use of a mobile system to indicate the AVL engine built in the vehicle in research. We analysed a number of thermodynamic parameters of the combustion process in various dynamic states, typical for the process of actual operation of the engine, such as working in start-up conditions and immediately after, working in conditions of acceleration and coasting. Formulated conclusions significantly expand the area of knowledge concerning the functioning of the internal combustion engine in dynamic conditions.

1. Introduction
The topic concerning the specificity of the internal combustion engine work in dynamic conditions has been discussed since the beginning of the previous century [5]. This is done due to the obvious facts which indicate that the work of the internal combustion engine of the traction vehicle proceeds mainly in dynamic conditions [6,11]. Nevertheless, no coherent and explicit methodology of testing the internal combustion engine in dynamic conditions has been developed until the present day due to the lack of normative regulations concerning this type of research. Although an interest in combustion engine work in dynamic conditions has considerably increased recently, it is mainly because of some legal regulations concerning the emission of exhaust toxic constituents. Such regulations enforce the control of emission in dynamic conditions. Therefore, some studies which are concerned with testing the emission of fuel toxic constituents in dynamic conditions [1,2] and modelling engine work in these conditions [3,4] can be found in technical literature. However, there are few papers in which both the specificity of the internal combustion engine work in dynamic conditions and the reasons for the observed differences in the course of work processes in relation to comparable static conditions would be explained in an experimental way. In the present paper, the results of testing the engine with the dispenser fuel injection system have been presented. The engine installed in a vehicle was subjected to indication in different movement conditions. The conditions of vehicle movement were mapped on a chassis test.
bench. The conditions of vehicle movement were selected in such a way that they could consequently create both static and dynamic conditions of engine work. The aim of the research is not the mutual quantitative reference of the obtained parameters of combustion process in the conditions of static and dynamic engine work but the demonstration of the tendencies concerning changes in the course of combustion process parameters for different engine operating conditions resulting from different variants of vehicle movement. As it was mentioned, the chosen characteristic variants of vehicle movement were those which determine engine work in static and dynamic conditions.

2. The specificity of the course of the combustion process in the conditions of diesel engine dynamic work

Determined physical processes can be divided into static and dynamic processes [4,11]. A static process is the process in which:

\[
\frac{dx}{dt} = 0
\]  

(1)

where:

- \(x\) - selected physical parameter describing the physical process,
- \(t\) – the duration of the process.

By analogy, a dynamic process is the process in which:

\[
\frac{dx}{dt} \neq 0
\]  

(2)

The dynamic process of engine work will occur when one of the equations is not satisfied:

\[
\frac{dM_o}{dt} = 0
\]  

(3)

\[
\frac{dn}{dt} = 0
\]  

(4)

\[
\frac{dQ}{dt} = 0
\]  

(5)

where:

- \(M_o\) – usable engine torque,
- \(n\) – engine crankshaft rotational speed,
- \(Q\) – total thermal flux flowing through the engine (the cooling system with all possible ways of exchanging heat with the environment along with the exhaust system).

Analyzing the man-machine-environment arrangement, three groups of reasons that can cause changes in \(M_o\), \(n\) and \(Q\) can be distinguished:

- the change of engine torque loading the engine or the change of the torque of internal losses,
- the change in the amount of fuel delivered,
- the change in air supply.

Periodicity or the lack of periodicity of the changes mentioned above will influence the occurrence of steady-state or transient engine work conditions.

Due to the impact of controllers (rotational speed, load, ignition angle etc.) and man on engine work, a dynamic process of engine work can proceed in three variants:

- \(M_o=\text{const}\) and \(n\neq\text{const}\),
In papers [6, 7, 8, 9, 10, 11] the parameters of engine work were compared: in the conditions of free acceleration of the engine caused by the step change in the position of the lever controlling the fuel dose, and in static conditions which were mapped with the use of external operating characteristics. It has been shown that it is possible to compare the parameters of engine work in such conditions due to the adequacy of engine loading torque, engine crankshaft rotational speed and the dose of injected fuel.

It was stated that in the conditions of dynamic engine work during the combustion process:

- there is a slight increase in the values of mean indicated pressure,
- self-ignition lag angle increases,
- maximum velocity of pressure growth rises.

As far as the processes of pressing and injection are concerned, the acceleration of injection start angle and a slight increase in maximum injection pressures were confirmed. Those phenomena were mainly caused by the increase in residual pressures in the high pressure conduits. The engine with a classic rotational injection pump was subject to tests. However, the process of engine free acceleration does not occur in regular work of the traction engine. The research in those conditions has a lot of advantages, such as the possibility of repetitive realization of dynamic conditions and the mentioned above comparison of the measured parameters to those of the external operating characteristics or in other words to static conditions.

In the present paper, the authors wanted to confirm the hypothesis about a similar (to the one described above) tendency to change parameters describing the combustion process that proceeds in dynamic conditions in relation to static conditions. Engine work conditions were equivalent to the typical cases of vehicle operation. The engine was equipped with dispenser fuel injection system. The analysis focused on the impact of engine work conditions on: mean indicated pressures, the maximum speed of the pressure growth, the amount of produced heat and the course of producing heat was conducted. As far as the injection process is concerned, the strategy of injection realized by the engine controller was illustrated.

3. Empirical research

3.1. The research stand, the research object

The research was conducted in the Laboratory of the Department of Car Vehicles at the University of Technology in Lublin. The object of tests was Fiat Qubo with a self-ignition engine fulfilling all emission standards specified by Euro 5 and a five speed gearbox. The main technical parameters of the tested car engine are shown in Table 1.

The road conditions were mapped by simulating driving on the chassis test bench for vehicles with biaxial drive of DF4FS-HLS type. The chassis test bench consisted of:

- bench-mounted (first) roller set with an eddy current brake and a hydraulic pump;
- mobile (second) roller set with an eddy current brake, a hydraulic pump and a gear motor for overhauling;
- control panel (dashboard);
- hydraulic system control;
- axial blower for cooling the vehicle;
- PC with the test bench software.
Table 1. The main technical parameters of 1.3 Multijet engine of the tested vehicle - Fiat Qubo.

| Parameter                                      | Value   |
|-----------------------------------------------|---------|
| Number of cylinders                           | 4       |
| Cylinder diameter (mm)                        | 69.6    |
| Piston stroke (mm)                            | 82      |
| Total engine cubic capacity (cm³)             | 1248    |
| Maximum power (kW CEE)                        | 55      |
| Maximum power (KM CEE)                        | 75      |
| Functioning at maximum power (rpm)            | 4000    |
| Maximum torque (Nm)                           | 190     |
| Rotational Speed at maximum torque (rpm)       | 1500    |
| Revolutions at neutral gear (rpm)             | 850 ± 20|
| Compression ratio                             | 16.8 : 1|

The system for indicating the engine Indi Micro 602 made by AVL with a built-in signal amplifier, cooperating with four analogue input channels and two digital inputs was used in tests. The signals recorded by the AVL Indimicro system are the following:

- the course of pressure inside the cylinder – it was recorded by means of a piezoelectric sensor AVL GH13P installed in the glow plug seating of the first cylinder;
- the signal of engine crankshaft position;
- injection parameters were analysed on the basis of the analogue signal of controlling the piezoelectric injector after converting it into the digital signal.

Picture 2 presents the test stand used during the research.

Figure 1. Test stand: 1. Test car Fiat Qubo with the 1.3 Multijet engine 2. Computer with the AVL software 3. AVL Indimicro 602 system for indicating the engine 4. DF4FS-HLS chassis test bench 5. AVL IndiCom V2.7 software.
The engine installed in the vehicle was subject to indication in selected driving conditions which map static and dynamic conditions. Driving conditions were realized on the chassis test bench. The vehicle was loaded with simulated values of rolling resistance force.

The following cases of vehicle work were analysed:
- Case 1 - stop – engine neutral gear, conditions of static engine work;
- Case 2 - driving in the fourth gear at the speed of 50 km/h – conditions of static engine work, constant load from rolling resistance forces;
- Case 3 - starting the vehicle - "cold" engine start, conditions of dynamic engine work;
- Case 4 - starting the vehicle - "hot" engine start, conditions of dynamic engine work;
- Case 5 - acceleration of the vehicle in the first gear - rapid acceleration of the engine, conditions of dynamic engine work.

100 successive engine work cycles were recorded. The tests for each case were repeated ten times.

3.2. Analysis of the obtained results
In the pictures from 2 to 7, the obtained results of tests and calculations are shown. The course of producing heat and the amount of produced heat were also analysed for the successive engine work cycles. The courses of engine rotational speed and mean indicated pressure were also analysed for the successive engine work cycles. Mean, minimum and maximum values and standard deviations of mean indicated pressure, engine rotational speed, maximum combustion pressure and maximum speed of pressure growth were calculated from all cycles of engine work. The conducted research refers to static conditions of the engine work (Cases 1 and 2) and dynamic conditions (Cases 3, 4, 5). As for the starting process (Cases 3 and 4), engine work cycles were analysed directly after the occurrence of self-ignition. Consequently, a successful starting process is meant to lead to engine idling. However, in the initial cycles after the occurrence of combustion, the rotation speed is slightly higher than the one for engine idling. After about 20 engine work cycles, the rotation speed starts to stabilize on the level of idling rotational speed. Significant differences concern "cold" and "hot" engine start. In the case of "cold" engine start, in the second engine work cycle, the biggest increase in mean indicated pressure to the value of about 0.418 MPa occurs. At the same time, the period of kinetic combustion is almost unnoticeable. This probably results from the activity of glow plugs. In the case of "hot" engine start, the biggest increase in mean indicated pressure occurs in the first cycle, achieving the value of 0.250 MPa. The periods of kinetic and diffusive combustion are sharply visible here. Maximum speeds of pressure growth are higher in the conditions of engine start in relation to engine idle running. In the first case, they exceed 0.2 MPa°/CA; in the second case they amount to around 0.187 Mpa°/CA. Engine work in static conditions (Case 2) and engine work in the conditions of acceleration (Case 5) were subject to detailed analysis. It was stated that mean values of maximum speed of pressure growth are higher in dynamic conditions in relation to static conditions. Obviously, in the studied conditions of engine work, fuel doses are different. However, in static conditions, the maximum speed of pressure growth was 0.498 MPa°/CA for engine rotational speed of about 1583 rpm. At similar engine rotational speed of 1586.5 rpm in dynamic conditions, the maximum speed of pressure growth was 0.325 MPa°/CA. The observation presented above results from the fact that in static conditions, the maximum rate of heat release during the process of kinetic combustion was 55 kJ/m°.CA and in dynamic conditions 40kJ/m°.CA.
Figure 2. Case 1 – engine idle running, the courses of: heat production (Q1), the amount of produced heat (I1) for the first cycle of engine work and mean indicated pressure (IMEP1) and engine rotational speed (SPEED) for the tested cycles and mean, minimum and maximum values of mean indicated pressure, engine rotational speed, maximum combustion pressure (P MAX1) and maximum speed of pressure growth (RMAX1).

Figure 3. Case 2 – conditions of static engine work, the courses of: heat production (Q1), the amount of produced heat (I1) for the first cycle of engine work and mean indicated pressure (IMEP1) and engine rotational speed (SPEED) for the tested cycles and mean, minimum and maximum values of mean indicated pressure, engine rotational speed, maximum combustion pressure (P MAX1) and maximum speed of pressure growth (RMAX1).
Figure 4. Case 3 – ‘cold’ engine start, the courses of: heat production (Q1), the amount of produced heat (I1) for the second cycle of engine work and mean indicated pressure (IMEP1) and engine rotational speed (SPEED) for the tested cycles and mean, minimum and maximum values of mean indicated pressure, engine rotational speed, maximum combustion pressure (P MAX1) and maximum speed of pressure growth (RMAX1).

Figure 5. Case 4 – ‘hot’ engine start, the courses of: heat production (Q1), the amount of produced heat (I1) for the first cycle of engine work and mean indicated pressure (IMEP1) and engine rotational speed (SPEED) for the tested cycles and mean, minimum and maximum values of mean indicated pressure, engine rotational speed, maximum combustion pressure (P MAX1) and maximum speed of pressure growth (RMAX1)
Figure 6. Case 5 – engine rapid acceleration, the courses of: heat production (Q1), the amount of produced heat (I1) for the eighteenth cycle of engine work and mean indicated pressure (IMEP1) and engine rotational speed (SPEED) for the tested cycles and mean, minimum and maximum values of mean indicated pressure, engine rotational speed, maximum combustion pressure (PMAX1) and maximum speed of pressure growth (RMAX1)

The aforementioned higher mean values of the maximum speed of pressure growth in dynamic conditions are caused by the fact that for high engine rotational speeds, the maximum speed of pressure growth in the conditions of acceleration increases rapidly up to 2,56 MPa/°CA. The period of kinetic combustion prevails while the course of heat release in the period of diffusion combustion is subject to substantial fluctuations - see Figure 8. In comparison, in the conditions of acceleration, at the speed of approximately 1586.5 rpm, 5% of heat is produced at angle -5,25°CA, 10% at angle-2,45°CA and 90% at angle 24,65°CA. At the rotational speed of around 4785,3 rpm, 5% of heat is produced at angle -2,8°CA, 10% at angle 2,15°CA and 90% at angle 42,15°CA. The strategy of realizing the injection process has a major impact on the observed phenomena - Figure 9.

Figure 8. Case 5 – the course of heat production and the amount of produced heat in the conditions of acceleration at the speed of about 4785,3 rpm.
In the conditions of acceleration, the initial injection is realized closer to the TDC (top dead centre) than in static conditions. This makes it possible to shorten the period of self-ignition delay and to reduce the maximum speed of pressure growth. At high values of engine rotational speed, one injection before the TDC is realized. It is caused by insufficient amount of time for preparing the fuel for self-ignition - there are no physical conditions for realizing the initial injection.

4. Conclusions
The purpose of the experiment was to show significant differences in specific cases of engine work in static and dynamic conditions. The current state of knowledge concerning the specificity of engine work in dynamic conditions was confirmed. In the conditions of dynamic engine work, higher maximum speeds of pressure growth occur [6]. This is noticeable particularly for the process of acceleration and high values of engine rotational speed. It is possible to observe here significant speeds of heat production during the kinetic combustion and fluctuations in the course of heat production during the diffusion combustion. Large values of maximum speed of pressure growth contribute to the increase in the mechanical load of engine structural nodes. They also influence on the toxic constituents of exhaust emission. However, this issue has not been discussed in this paper. In some areas of engine work, it is possible to influence in an effective way the observed negative phenomena occurring in dynamic states by adopting the right injection strategy, mainly in the form of one or two initial injections. And yet, such steps have some limitations which result from insufficient amount of time to prepare the fuel for self-ignition at high values of engine rotational speed.

5. References
[1] Armas O., Ballesteros R. 2008 Diesel emissions from an emulsified fuel during engine transient operation, SAE Paper No. 2008-01-2430
[2] Chłopek Z 1999 Modelowanie procesów emisji spalin w warunkach eksploatacji trakcyjnej silników spalinowych, Oficyna Wydawnicza Politechniki Warszawskiej
[3] Giakoumis E 2007 Cylinder wall insulation effects on the first- and second law balances of a turbocharged diesel engine operating under transient load conditions, Energy Conversion and Management 48 Science Direct
[4] Giakoumis E and Rakopoulos C 2004 Parametric study of transient turbocharged diesel engine operation from the second-law perspective, SAE Paper No. 2004-01-1679
[5] Jante A 1933 Spezifische Schnellaufzahlen ATZ 24
[6] Longwic R 2011 Charakterystyka działania silniki o zapłonie samoczynnym w warunkach swobodnego rozpędzania Monografia Politechnika Lubelska
[7] Longwic R, Litak G, Asok Sen and Górska K 2008 Analisys of cycle-to-cycle pressure oscillation in a diesel engine. Mechanical Systems and Signal Processing
[8] Longwic R, Litak G, Asok K and Sen 2009 Recurrence plots for diesel engine variability tests. Zeitschrift Naturforsch. Sectio A-A Journal of Physical Sciences, 64 a, 96-102
[9] Litak G and Longwic R 2009 Analisys of repeatability of Diesel engine acceleration. Applied Thermal Engineering 29, 3574-3578
[10] Longwic R, Sen A, K, Górska K, Lotko W and Litak G 2011 Cycle-to-Cycle Variation of the Combustion Process in a Diesel Engine Powered by Different Fuels. Journal of Vibroengineering VOLUME 13 ISSUE 1
[11] Longwic R 2007 Dynamic Aspects of Work of the Diesel Engine SAE Paper No. 2007-01-4210