INSTRUMENTATION OF CETANE NUMBER RESEARCH ENGINE

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Abstract. Cetane number research engine IDT-69 was instrumented preserving original functionality. The authors describe the instrumentation process and selected hardware, which allows acquisition of in-cylinder pressure, injector needle timing, inlet air and exhaust gas temperature data. The testing methodology and the results of the engine combustion conditions stabilization time are presented.

Keywords: single cylinder engine, cetane number research, diesel fuel, CFR engine, instrumentation, various compression ratio.

Introduction

Corporate Fuel Research F5 (CFR) engine type was introduced in 1938 and is used for determination of the fuel ignition quality parameter, known as cetane number according to the standards ASTM D613 and EN ISO 5165 [1]. Such research engine can be modified by adding different sensors and control devices and then it can be used for studies other than determination of a cetane number. Flowers et al. modified the CFR engine to be used in homogenous charge compression ignition (HCCI) mode. They fitted the engine with the in-cylinder pressure transducer with full-scale range 200 bar and the crankshaft position encoder with resolution of 0.1 °. Data were acquired with National Instruments data acquisition board PCI-6110E. Flowers et al. reported significant noise in the acquired cylinder pressure data. They used eight-order Butterworth digital low-pass filter at cut-off frequency 3 kHz to reduce the noise [2]. Karagoz et al. studied engine performance and emissions while enriching diesel fuel by hydrogen. Ferryman CFR engine was used for this purpose. Additionally to the classic CFR engine setup and cylinder pressure measurement instruments, load cell was used to measure the engine brake power [3]. One limitation of CFR engine for research purposes is its divided combustion chamber design. Kort et al. described interpretation and heat release analysis in divided combustion chamber design CI engine [4]. For more accurate in-cylinder pressure measurement such engine should be equipped with two pressure transducers, one in the main combustion chamber, and the other in the pre-chamber [4]. CFR engine nowadays is a rare and expensive tool, therefore, it is reasonable to modify it for research purposes in non-intrusive manner, so that the engine is still usable for its original purpose – determination of the cetane number. Installation of the pressure transducer in the main combustion chamber requires removal and modification of the cylinder head, so it may make the CFR engine invalid for determination of the cetane number. On contrary, access to the pre-chamber is a part of the typical CFR engine original design.

Materials and methods

Cetane number research engines, with technical properties close to the original Waukesha CFR F5 engine, were produced in other parts of the world. For instance, the research engine IDT-69 was made in the Soviet Union by company SPO Progress. The authors instrumented the cetane number research engine IDT-69 retaining the original functionality and adding new possibilities.

IDT-69 is a single cylinder 4 stroke compression ignition liquid cooled engine. The engine setup is shown in Fig. 1. It has a 2-valve cylinder head with variable volume cylindrical pre-chamber. By moving the plug in the pre-chamber, the engine compression ratio can be continuously changed from 7 : 1 to 23 : 1 without removing the cylinder head. Fuel delivery system consists of three switchable fuel reservoirs, equipped with fuel delivery rate indicators. In-line high pressure pump has controls for injection timing and fuel delivery rate. Hydraulically operated injector is equipped with a needle position switch. Fuel delivery to the injector can be interrupted by the manually operated by-pass valve, allowing easy switching between motored and fired modes. The engine crankshaft is connected to an electric motor using V-belt drive. Asynchronous electric motor is used for starting, motoring and maintaining of constant rotational speed. The engine is equipped with an electric inlet air heater and temperature controller. The exhaust system is equipped with a surge tank to reduce resonant pulsations during the engine operation. Cooling system is of thermal syphon type with a condenser for maintaining stable coolant temperature.

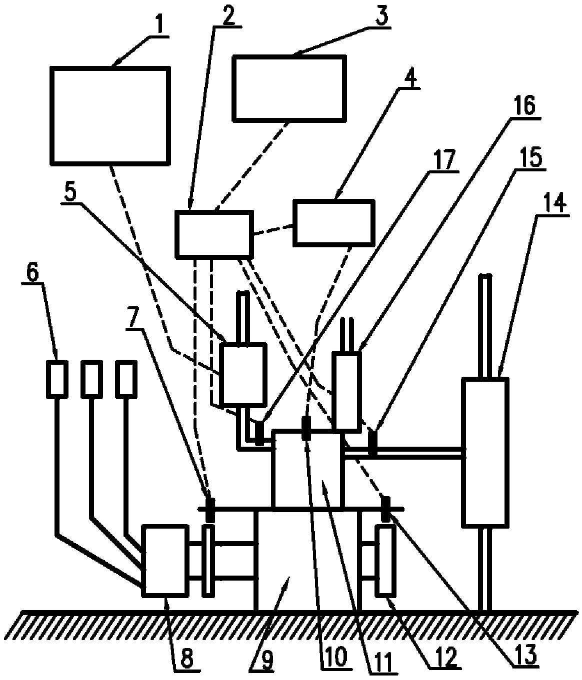

Fig. 1. **IDT-69 engine setup:** 1 – engine control module; 2 – NI 9068 chassis; 3 – host PC; 4 – charge amplifier Kistler 5018A; 5 – inlet air heater; 6 – fuel reservoirs; 7 – camshaft phase HE sensor; 8 – high pressure fuel pump; 9 – cylinder block; 10 – pressure sensor Kistler 6061B; 11 – cylinder head; 12 – flywheel; 13 – flywheel rotation sensor; 14 – exhaust surge tank; 15 – exhaust temperature sensor; 16 – cooling system condenser; 17 – inlet air temperature sensor

The engine lubrication system has an electric heater. The main technical parameters of the IDT-69 engine are given in Table 1.

Table 1

Main technical parameters of IDT-69 cetane number research engine

Parameter	Value
Engine type	4 stroke, single cylinder, pre-chamber, compression ignition
Air supply	Naturally aspirated with electric heater
Cooling system and nominal temperature, ºC	Liquid-cooled, thermal syphon type, 100 ± 2
Bore and stroke, mm	85 × 115
Cylinder volume, cm^3	652
Compression ratio	7 : 1 to 23 : 1
Fuel injector opening pressure, MPa	10.4 ± 0.4
Diameter of cylindrical pre-chamber, mm	42
Inlet valve opens/ closes	10 ± 2 °ATDC / 34 ± 2 ° ABDC
Exhaust valve opens/ closes	40 ± 2 ° BBDC / 15 ± 2 ° ATDC
Valve overlap	5 ° ± 2 °
Speed of fired engine, min^{-1}	900 ± 10
Power of absorbing asynchronous electric motor, kW	5.5

The IDT-69 engine was additionally instrumented by adding sensors for measurement of the inlet air and exhaust gas temperature. The inlet air temperature sensor was placed in the air supply pipe, downstream the electric heater and close to the cylinder head inlet. The exhaust gas temperature sensor was placed in the exhaust manifold, close to the cylinder head outlet. K-type thermocouples were used. They were connected to the Nation Instruments (NI) 9214 thermocouple input module. The module features isothermal terminal block, which contains three internal temperature sensors for cold junction compensation. 24 bit analogue to digital conversion (ADC) enables measurement sensitivity up to 0.02 ºC. Module NI 9214 was connected to the NI 9068 Compact RIO chassis. The authors developed LabVIEW code for the NI 9068 chassis in field programmable gate array (FPGA) module, real time (RT) module and host PC. Temperature data measurements were taken at rate one measurement per second and saved to host the PC's hard disc at the end of the measurement period. Injector needle position switch was connected no NI 9752 and NI 9222, allowing to control and register injector opening and closing timing.

Analysis of the combustion properties of fuel in a reciprocating engine can be performed by using in-cylinder pressure phased with the cylinder volume. Therefore, cylinder pressure acquisition is performed in the crank angle (CA) domain. Rogers suggests selecting the sampling frequency depending on the measurement task [5]. For calculation of the indicated mean effective pressure (IMEP), the polytrophic value and direct analysis of the pressure curve, resolution at one crank angle degree (CAD) is sufficient [5]. Higher resolution is recommended where steep peaks and fast processes may occur, such as combustion noise or heat release analysis in compression ignition engines [6; 7]. To measure the crankshaft rotation and position, a low-cost encoder was developed. The encoder setup is shown in Fig. 2.

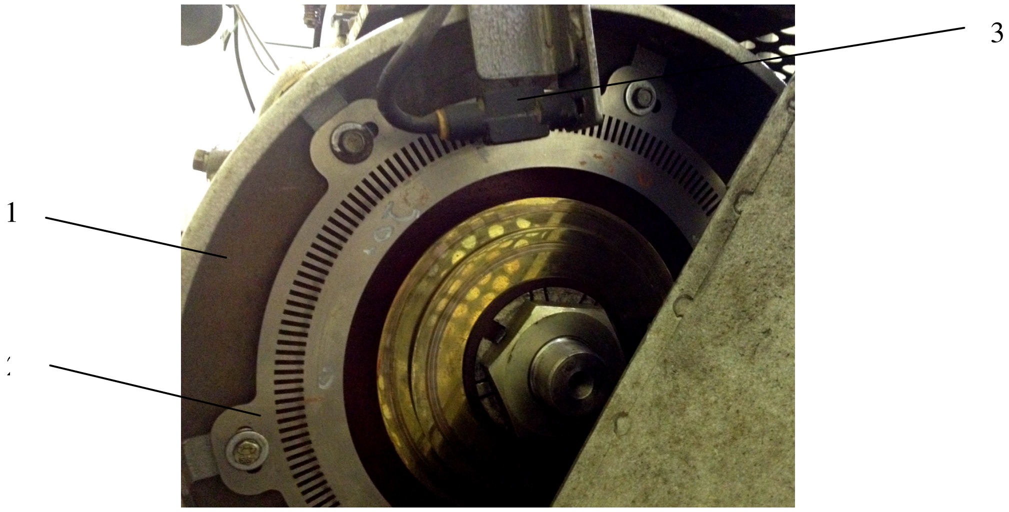

Fig. 2. **Crankshaft encoder:** 1 – flywheel; 2 – encoder target; 3 – VR sensor

Many production engines have a toothed wheel fitted or machined on the flywheel. Resolution of a typical toothed wheel is close to 60 teeth and it is sufficient for the engine control system, but not for analysis of in-cylinder pressure. Typically for engine applications, only the front end of the crankshaft is accessible for placing the research grade crankshaft position encoder. In case of the IDT-69 engine there is free access to the flywheel. To increase accuracy, the encoder target wheel with diameter close to the flywheel diameter was machined from 0.5 mm thin steel sheet. Rectangular openings were cut by the laser cutter having the angular width of 1 º. They were evenly spaced around the target wheel. One opening was omitted to create the reference tooth. The reference tooth was placed 60 CAD before the piston top dead center (TDC). The encoder wheel position was adjusted using shims to compensate the flywheel run-out. The variable reluctance (VR) sensor was fitted to detect the flywheel rotation with a resolution of 2 º. To distinguish between the 4 stroke engine phases, a Hall effect (HE) sensor was fitted to detect the single tooth located on the high pressure fuel pump input shaft. For TDC detection purpose another HE sensor was fitted to read the zero degree mark on the flywheel. All three engine rotation detection sensors were connected to the NI 9752 module. The module provides sensor feed voltage and processing of raw signal. The NI 9752 module has a 12 bit ADC converter and the sample rate is 12 $kS \cdot s^{-1}$. The signals are filtered, processed and converted to Boolean type data, using the FPGA module of the NI 9068 chassis. The authors used a programmable signal divider in the FPGA module to increase CAD resolution to 0.2 º, which was used for triggering of in-cylinder pressure measurement events.

The IDT-69 engine is designed to have access to pre-chamber for detecting start of combustion by electromechanical device. The authors used original access hole to fit the Kistler 6061B piezoelectric quartz water cooled cylinder pressure sensor. To ensure the sensor cooling the electric pump was used for circulation of distilled water. Kistler 5018A charge amplifier was used to convert the pressure transducer charge to voltage. The amplifier features automatic drift compensation. The NI 9068 chassis and the NI 9222 4 differential channel voltage measurement module was used. The NI 9222 module features ± 10 V range with a 16 bit resolution at a sample rate up to 500 $kS \cdot s^{-1}$. In-house code for the NI 9068 FPGA and RT modules was developed for data acquisition purposes. In-cylinder pressure trace is displayed during the measurement and the data are saved to the host PC's hard disc at the end of the measurement. First attempts to obtain in-cylinder pressure data revealed regular pressure oscillations during motored and fired modes. The frequency of oscillations was determinated to be approximately 3 kHz. Use of the charge amplifier internal low-pass (LP) filter, set at 3 kHz, eliminated oscillations in the recorded pressure curve. Use of the LP pass filter can lead to excessive smoothing of the pressure curve and consequential loss of information. The authors modified the connecting passage to the pre-chamber to allow flush mounting of the pressure sensor. This modification eliminated the pressure oscillations.

True TDC detection is important for analysis of cylinder pressure data. Incorrect alignment of cylinder pressure data with cylinder volume data can lead to large errors in further calculations. According to Rogers and other authors, pressure – volume phasing must be within 0.1 crankshaft degree [5, 7]. Well recognized method is direct detection of the piston TDC position using a specific capacitive probe. This method requires access to the piston top while the engine is motored, which is not possible for the IDT-69 engine without a modification of its cylinder head. IDT-69 engine has TDC marking on the flywheel and corresponding marking on the cylinder block. The authors used the HE sensor to detect when these two markings were aligned. As the HE effect sensor works in non-dynamic mode, it is possible to adjust its position while turning the crankshaft by small increments. Data from the HE sensor were used to programmatically adjust the TDC position, deducted from the reference tooth of the flywheel encoder wheel. Thermodynamic analysis of motored cylinder pressure data in this case is complicated due to uncertainties rising from unknown pressure gradient in the main chamber. Additional TDC position adjustment was performed after analysis of the log-log pressure – volume diagram of motored in-cylinder pressure data, as suggested by Callahan et al [8].

IDT-69 is a research engine that can be operated in continuous firing mode. Switching to motored mode or changing of the compression ratio requires certain waiting time for temperature and combustion conditions to stabilize. The authors performed series of tests to determine the minimal waiting time between changes of the operating mode. Commercial EN590 diesel fuel was used. Compression ratio was set at 12.77 : 1. The engine was warmed up in motoring mode, using electrical oil and inlet air heaters. When the oil temperature has reached 50 ºC and the inlet air temperature has reached the target at 65 ºC, the engine was switched to fired mode. When the cylinder head temperature has reached 38 ºC and the exhaust temperature stabilized, the injection timing was set to 13 º BTDC and fuel supply adjusted to 13 $ml \cdot min^{-1}$. The engine was operated in motored mode for 30 cycles and fired again. In-cylinder pressure data and the exhaust temperature data were recorded for 180 s. In-cylinder pressure data were divided in parts, containing 50 cycles. Mean pressure from 50 cycles for each crank degree step was calculated. Further analysis included calculation of net indicated mean effective pressure (IMEP), assessment of IMEP variation, calculation of apparent heat release rate (AHRR) and finding ignition delay (ID). The calculations were performed basing on the methodology presented by Heywood [9]. Heat losses at cylinder walls were not included in AHRR calculation.

Results and discussion

Instrumented IDT-69 engine has better control on injection timing and allows recording of the crankshaft position, cylinder pressure, inlet air temperature and exhaust temperature. As the engine and fuel delivery parts were not mechanically modified, the original function of determination of the cetane number was retained. Research on combustion properties of different fuels, surrogates and additives can be performed using well known engine design. Stabilization time of combustion mode of the IDT-69 engine was sought by analyzing several parameters. Switching from firing to motoring mode decreased the temperature of the pre-chamber, main chamber walls and exhaust system parts. Decrease of the exhaust gas temperature was observed. After re-enabling of fired mode, the exhaust gas temperature has raised and stabilized.

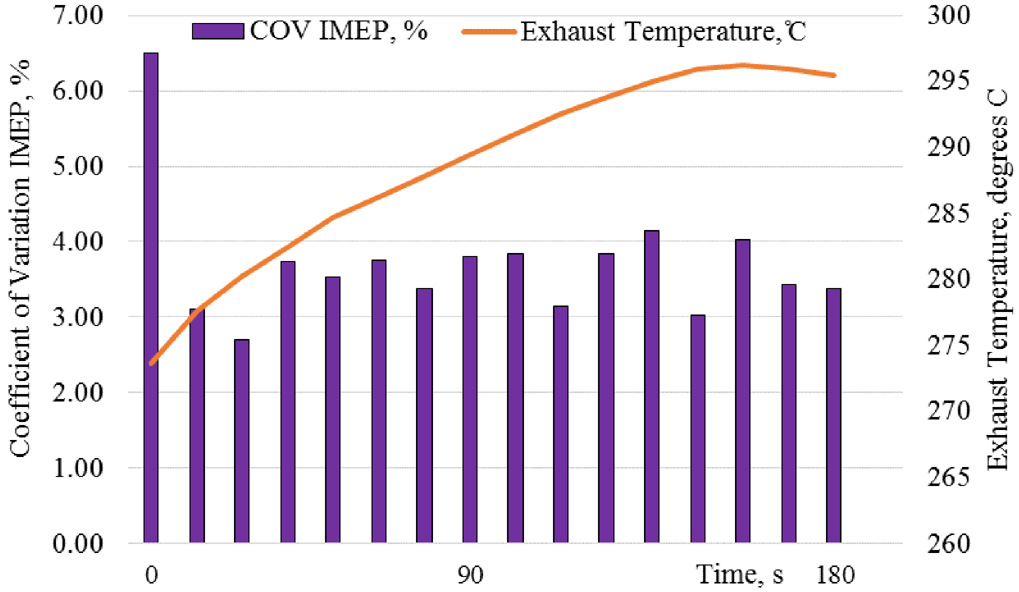

Fig. 3. **Assessment of variation of indicated mean pressure**

Coefficient of variation (COV) of IMEP can be used as characterization of combustion cycle-by-cycle stability. Fig. 3 shows that after initial instability following the first fired cycles, the value of COV IMEP is within 3 … 4 % in the tested conditions, regardless of the time passed since enabling of fired mode and stabilisation of the exhaust gas temperature.

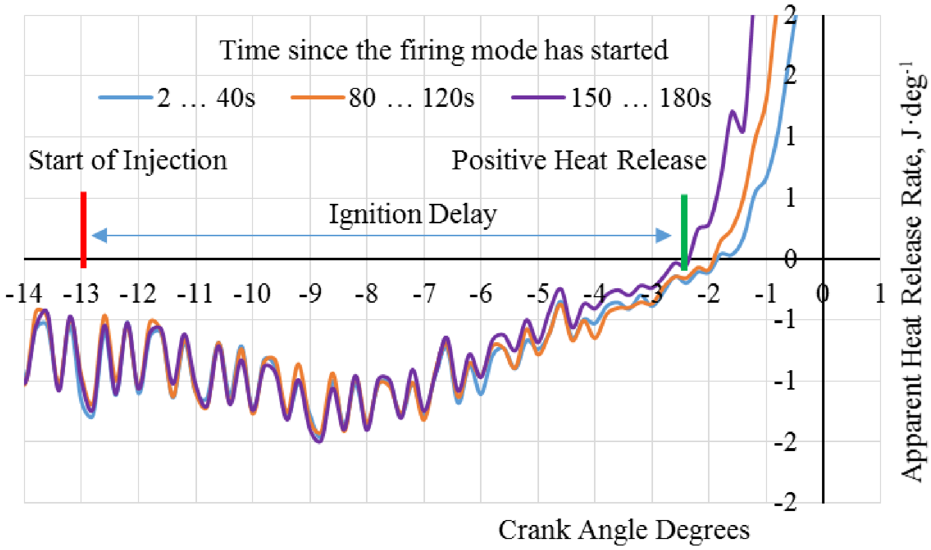

Fig. 4. **Assessment of apparent heat release rate**

AHRR diagram is presented in Fig. 4. Only part of the diagram showing the start of injection (SOI) and apparent heat release zero line crossing is displayed. Time between SOI and the point, where heat release rate crosses the zero line, can be considered as ignition delay. AHRR was calculated from the mean data from the engine cycles within three time periods since firing mode was enabled. Oscilations of the apparent heat release line migh be resulted from irregularities of in-house made encoder gaps and non-optimal configuraiton of the programmable signal divider. Ignition delay is strongly affected by temperature and pressure conditions in the combustion chamber. Ignition delay reached the value 1.87 … 1.89 ms and no further shortening or major variations were observed when the engine was operating in fired mode for longer period then 180 s. Exhaust gas temperature was stabilised at approximately 296 ºC at the same time, as shown in Fig. 3. Stabilisation time for different fuels, inlet air temperature and compression ratio may differ and should be tested separately.

Conclusions

1. Cetane number research engine IDT-69 was instrumented, allowing acquisition of in-cylinder pressure, injector needle timing, inlet air and exhaust gas temperature data.
2. Modification of the engine preserved original function.
3. The instrumented engine can be used for wider application, such as research of combustion properties of different fuels, fuel surrogates and fuel additives.
4. Stabilization time in fired mode following motoring was approximately 180 s.
5. Exhaust gas temperature steadiness can be used as an indicator of stabilization of combustion conditions.

Further development of cetane number research engine IDT-69 is planned. Critical flow nozzle will be installed for inlet air flow control. The original inlet air heater temperature regulator will be replaced by an electronic controller.

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