JOURNAL OF MECHANICAL AND TRANSPORT ENGINEERING
Vol. 70, No. 3 2018
DOI 10.21008/j.2449-920X.2018.70.3.05

Krzysztof KWIATKOWSKI*
Ireneusz PIELECHA*

(Received 20 Mar 2018, Received in revised form 7 Jan 2019, Accepted 11 Mar 2019)

MODELING AND SIMULATION OF THE THERMODYNAMIC OPERATING CONDITIONS OF THE CI ENGINE

The article presents comparative results of a diesel combustion engine (AVL 5804) along with their simulation analysis. The simulation was performed using the AVL Fire 2017 software. The article focused on the indicated pressure changes in the compression and expansion strokes and on the fuel combustion process. Based on the recorded pressure characteristics in the engine cylinder and its basic construction data, a simulation was performed in which specific initial conditions and models of injection, evaporation and fuel combustion were included. A close resemblance between the test results and the simulation results was observed. The largest discrepancies in the analyzed quantities concerned the pre-flame processes, which means that these issues should inform about the quality of the pressure characteristic and the heat release rate modeling in the cylinder of the internal combustion engine.

Keywords: simulation, modelling, dynamic processes

1. INTRODUCTION

Research on the development of piston engines, the combustion process and the improvement of the drive cycle of the drive units are currently experiencing a rise in popularity and interest. The main reason behind this situation is the strict increase in the requirements imposed by the legal toxic emission limits. With the progress that has brought new technologies and constructions used in internal combustion engines, the demand for modern equipment and research software is increasing.

One of the tools that allows theoretical research and the analysis of the engine work cycle is mathematical modeling. The AVL Fire software [AVL Fire 2017] is

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* Poznan University of Technology.

a tool that can meet the requirements of not only flow models but also three-dimensional models. This program was used to analyze the thermodynamic operating conditions of the AVL 5804 engine.

Modeling engine operation is becoming an increasingly important tool of research. Selected works focused on the analysis of the fuel combustion process are presented below. Tutak and Jamrozik [2010] analyzed the combustion process of the SI engine using AVL Fire and KIVA-3V software. For their modeling, they used the Eddy Breakup Model (EBM) and Turbulent Flame Speed Closure Model (TFSCM) as combustion models. The analysis focused on the comparisons of the pressure characteristics, the heat emitted and the heat release rate using the two previously mentioned software systems. As a result of modeling using FIRE and KIVA, a number of values characterizing the combustion process in the researched engine were obtained, which would be very difficult to obtain in conventional laboratory research.

Similar research using AVL Fire and KIVA-3 software was conducted by Tutak and Jamrozik [2011] using a CI engine. They presented the combustion process modeling results for various settings of the fuel injection angle. The results of the simulation were compared with the results obtained during the engine's indicated pressure tests. The combustion process modeled in the AVL Fire program was based on the Coherent Flame ECFM-3Z Model (ECFM-3Z) as well as the Dukowicz evaporation model. The results obtained were, to a high degree of accuracy, representative of the actual motor pressure. The difference of the maximum pressure for the engine model, in relation to the value of the pressure obtained from the indicated pressure tests was respectively: for the program KIVA-3V – 11.5%, and for the FIRE program – 1.4%.

2. MODELED ENGINE SPECIFICATION

The engine chosen as the object of the thermodynamic conditions modeling was an AVL 5804 located in the laboratory of the Institute of Combustion Engines and Transport at the PUT. Basic engine technical data is included in Table 1.

Table 1. Tested engine AVL 5804 technical data

No.	Data	Unit	Value
1	Displacement	cm^3	510.7
2	Compression ratio	–	16.2
3	No. of cylinder	–	1
4	Injection system		CR, 8-hole injector
5	Max power at speed	kW/rpm	16/4000
6	Max torque at speed	Nm/rpm	53/2000
7	Specific power	kW/dm^3	31.33

The tests were carried out at the engine speed n = 1500 rpm at partial engine load operating without boost and with an inactive exhaust gas recirculation system. Other test conditions are included in Table 2.

Table 2. The selected conditions of engine tests

No.	Parameter	Unit	Value
1	Engine speed	rpm	1500
2	Fueldose	mg	22.5
3	Ambient pressure	hPa	1008
4	Ambient temperarture	°C	23
5	Oil temperature	°C	80
6	Load	Nm	16
7	EGR share	%	0
8	Fuel consumption	kg/h	1.03

3. MODELING THE INJECTION AND COMBUSTION PROCESS

The AVL ESE Diesel software was used for research, with its settings and parameters limited to a number of base assumptions and construction parameters. In order to predict the turbulent flow in the cylinder the AVL Fire software uses the averaging of the Reynolds equation in the Navier-Stokes equations – RANS as well as the DNS model for phenomena that cannot be described by the RANS model [Paszko and Łygas 2016, Wen-Tao et al. 2015]. The AVL Fire software combines both of the above methods in the Large Eddy Simulation (LES). This model uses a division of the turbulence scale into small and large turbulence [AVL Fire 2017, Eidevåg and Lindström 2013].

Modeling of the thermodynamic process was performed by creating sketches of the combustion chamber (Fig. 1) as well as 2D and 3D parametric grids.

The number of simulation cells was 46820 (of which: for 0-19 degrees on the crankshaft from topology 0 there were 1072 cells, for angles 79-180 degrees on the crankshaft from topology 1 there were 3415 cells), the maximum cell size is 1 mm. A 2-layer wall film with a thickness of 1 mm each was also taken into account. After introducing the initial conditions and the simulation range into the program, the following models were selected:

a) injection – KHRT model (Kelvin Helmholtz Rayleigh Taylor),
b) evaporation – Dukowicz,
c) combustion – ECFM-3Z (Extended Coherent Flame Model – 3 Zones).

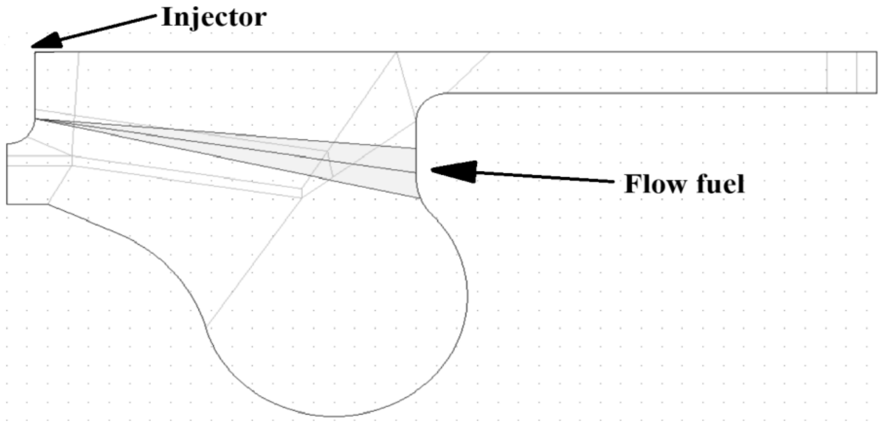

Fig. 1. Sketch of the piston with division into structural blocks

The reference point for the simulation validity was the indicated engine pressure measured on the test bench (Fig. 2). The operating pressure characteristic in the cylinder was measured using a 4 kHz low-pass filter. The appropriate mileage characteristics of this parameter has been obtained, changing only the fuel injection angle in simulation conditions. It took place at 4 degrees on the crankshaft later than it did during actual operation. The other parameters remained in line with the laboratory conditions.

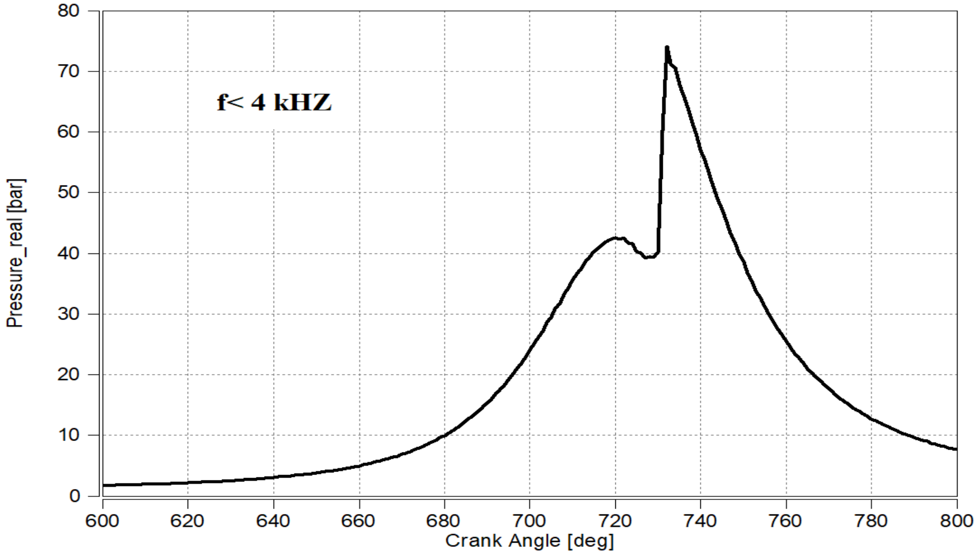

Fig. 2. The operating pressure characteristic as a function of the crankshaft angle of rotation

4. RESEARCH RESULTS

Validation of the obtained simulation results has been divided into the analysis of the cylinder pressure distribution and the analysis of the combustion process. The first one provided information about the simulation validity and the accuracy of the obtained results. The maximum discrepancies were recorded at the level of up to 0.5 bar, except for the fuel injection time – the pressure difference is up to 4 bar (at the end of fuel injection – Fig. 3).

Analysis of the combustion process was performed by comparing the values of the actual results with the simulation results regarding the heat release rate (Fig. 4), temperature (Fig. 5) and the total generated heat (Fig. 6). The actual values of the above-mentioned quantities were converted using the AVL Concerto software. The recorded differences seen in these comparisons are caused by the change of the fuel injection crankshaft angle and faster fuel evaporation in the AVL Fire program while maintaining the same crankshaft angle of the mixture auto-ignition.

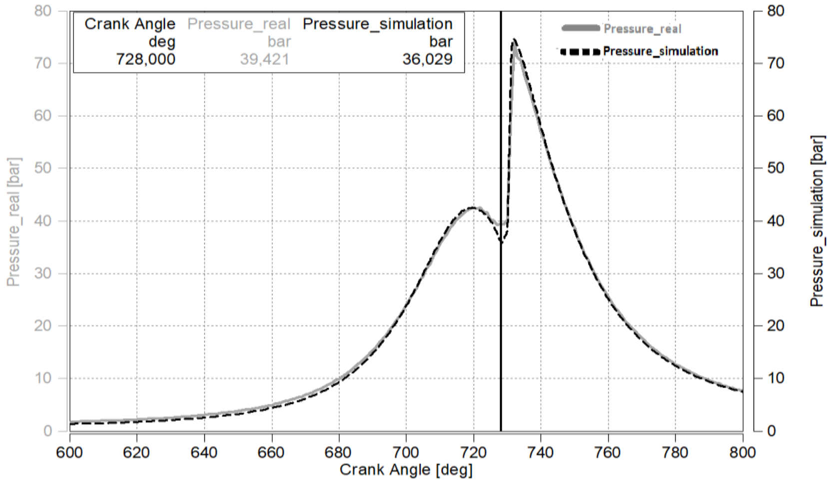

Fig. 3. Comparison of cylinder pressure results for simulation and actual recorded pressure values

The heat release rate analysis indicates similarities in the beginnings of this process, however simulation tests indicate higher release rate values. The maximum dQ/dα value determined through simulations is 39% higher than its actual motor equivalent (however, the angles where the maximum values occur are similar to each other – the difference is around $\Delta\alpha = 0.2$ deg). This may be due to simulation model being incomplete for the engine pre-flame processes. Obtaining such differences leads to the conclusion that it is necessary to more accurately identify these processes and to specify them in the simulation model.

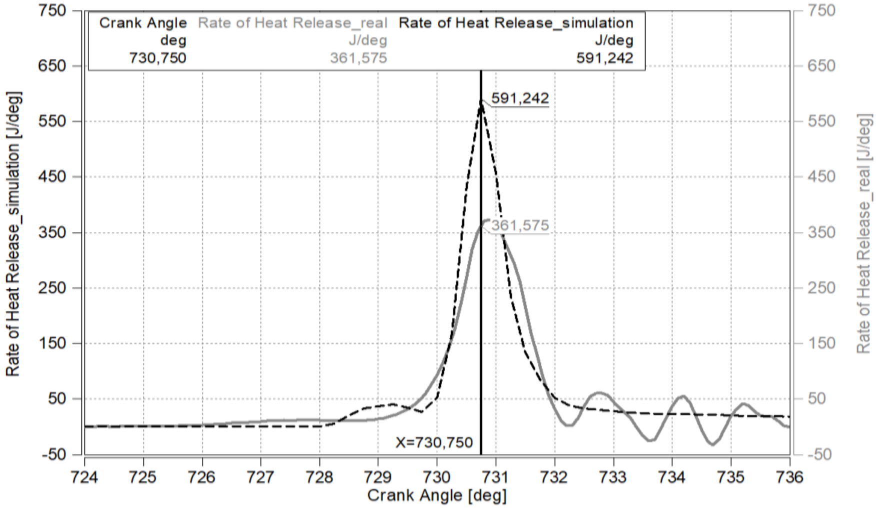

Fig. 4. Analysis of the heat release rate: for motor and simulation tests

Differences resulting from the temperature characteristic during compression indicate the next, incomplete fit of the model to the obtained motor mileage. In the compression stroke, these differences are around ΔK = 150 K (in favor of the simulation), which is quite significant. This may result from improperly defined intake air temperature or pressure. Although the temperature drop in simulation conditions is greater than the drop measured in engine tests, this value does not correlate with the pressure drop in this test range (720–730 deg CA) – Fig. 5.

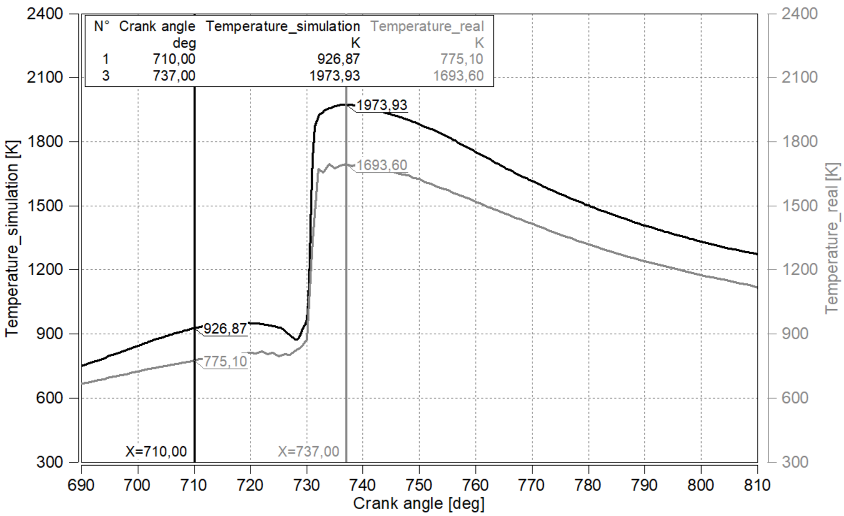

Fig. 5. In-cylinder temperatures comparison for engine tests and simulation

Due to the higher values obtained in simulations, temperature and heat release rate, the amount of heat produced is also greater – Fig. 6. The simulated maximum value of Q is 20% higher than the value of the heat produced obtained in engine tests. A partial explanation of this phenomenon is the limitation (under simulation conditions) of the heat transfer to the medium in the range up to 725 deg CA. However, these values do not compensate for the large final values obtained. The reasons for these differences should be sought in earlier models, both the indicated pressure, temperature and the heat release rate.

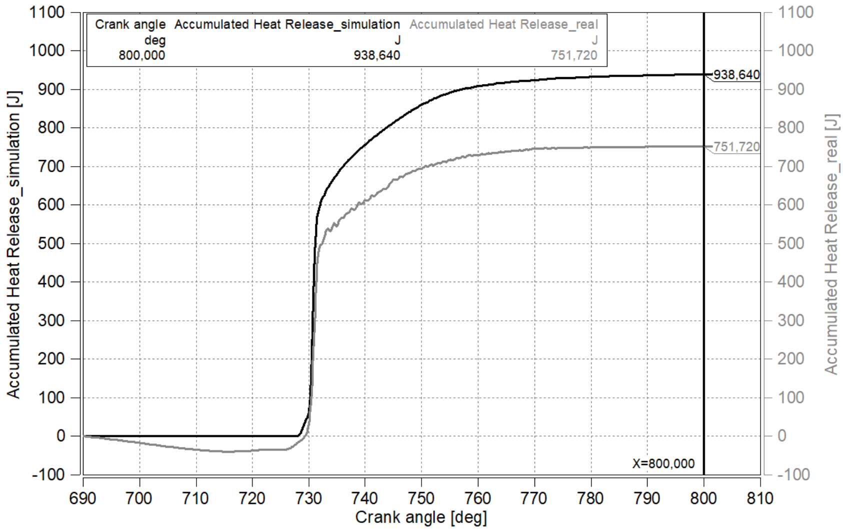

Fig. 6. Heat release rate comparison for engine tests and simulation

5. CONCLUSIONS

Once finished, the simulation of compression and expansion processes of exhaust gases proved that there is a link between the results of non-engine tests (models and simulations) with the results obtained with tests on a real engine. Model tests indicate the desirability of delaying the fuel injection angle while maintaining the proper combustion process registered in real operating conditions. This means that further work is needed in the field of modeling of pre-flame processes. The research performed and its analysis does not exhaust the subject matter. There are still problems that should be addressed in future research work: toxic substances emissions tests, as well as increasing the accuracy of simulations by increasing the number of 2D and 3D parametric mesh cells. The obtained results can be improved by using individual process parameters in areas with large pressure differences in the main simulation settings.

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ACKNOWLEDGEMENTS

The study presented in this article was performed within the statutory research 05/52/DSPB/0246.

MODELOWANIE I SYMULACJA TERMODYNAMICZNYCH WARUNKÓW PRACY SILNIKA ZS

Streszczenie

W artykule przedstawiono porównawcze wyniki pracy silnika spalinowego o zapłonie samoczynnym (AVL 5804) wraz z ich analizą symulacyjną. Symulację zrealizowano za pomocą oprogramowania AVL Fire 2017. W pracy skupiono się na przebiegu ciśnienia indykowanego w zakresie suwów sprężania i rozprężania oraz na procesie spalania paliwa. Na podstawie zarejestrowanych przebiegów ciśnienia w cylindrze silnika oraz jego podstawowych danych konstrukcyjnych prowadzono symulację, w której zawarto określone warunki początkowe oraz modele: wtrysku, odparowania oraz spalania paliwa. Uzyskano dużą zgodność wyników rzeczywistych z wynikami symulacji. Największe rozbieżności analizowanych wielkości dotyczyły procesów przed płomiennych, co powoduje, że zagadnienia te powinny stanowić o jakości modelowania przebiegu ciśnienia oraz szybkości wywiązywania ciepła w cylindrze silnika spalinowego.

Słowa kluczowe: symulacja, modelowanie, procesy szybkozmienne