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BURN RATE PROFILES FOR COMPRESSION IGNITION ENGINE MODEL

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Abstract

This study was done in order to show general trends as user-defined burn profiles are changed for Wave model of naturally aspirated compression ignition engine. The recent advances would have been impossible without the help from the computer-aided engineering (CAE) methods. For the processes governing engine performance and emissions, two basic types of models have been developed. The presented measurements of cylinder pressure and computation of its predicted equivalent have shown that user-defined burn profile should be established using gross (chemical) heat release rate. Such approach offers better accuracy then the net heat release profile which is by definition a simplified measure of combustion process.

1. Introduction

Ever since the first engines were built, designers have wanted to simulate their engines prior to building them. The recent advances would have been impossible without the help from the computer-aided engineering (CAE) methods. Terminology as “virtual prototyping” and “virtual testing” is now being used to describe numerical simulation for the design and development of new engines and their systems. This new trend is driven by the high cost of time-consuming laboratory or field tests.

The virtual testing methods do not entirely eliminate the need for experimental development but they allow exploring numerous options (more abundant than in hardware experiments) in an early stage of engine design at much lower cost.

2. Engine models

For the processes governing engine performance and emissions, two basic types of models have been developed. The models, varying in degrees of complexity, are categorized as thermodynamic or fluid dynamic in nature, depending on whether the equations (which give the model its predominant structure) are based on energy conservation or on full analysis of the fluid motion. Engine simulations that follow the thermodynamic approach are known as zero dimensional (0-D), phenomenological or filling and emptying models [1, 2, 4, 9].

Many efforts have been devoted to the development of engine simulation methods applying fluid dynamic (CFD). The 3D CFD simulation tools compute the spatial resolved flow field offering more realistic image of the engine processes.

Various CFD tools are accessible to simulate IC engine operation. The most popular (mainly due to availability of the source code) is the Kiva family of codes developed by the Los Alamos National Laboratory [13]. The commercial software such as Vectis (Ricardo Software) [18], Fire (AVL) [14], Fluent (Fluent Inc.) [11] and Star CD (Computation

Dynamics) [16] are characterised by superior meshing generation, pre- and post-processing as well as the availability of specialised user support.

It is worth noting that due to the complexity and contradictory character of engine processes (and our limited understanding), most engine models are incomplete and empirical relations and approximations are still needed. That is why the models should be balanced in complexity and detail. While the flows and processes within the engine cylinder are inherently unsteady and three-dimensional, the overall characteristics of an IC engine can usefully be studied with one-dimensional computer codes.

The one-dimensional gas dynamic simulation models (1D CFD) are computer codes that combine 0-D approach for the engine in-cylinder processes with 1D approach for the flow calculations throughout the inlet and outlet engine systems. The combustion is computed as heat release process and the heat transfer (in combustion chamber and flow systems) is taken into consideration in the form of the empirical correlations. Experiment-based equations are also used to evaluate mechanical losses and thus the brake parameters of the engine under development.

In general, the 1D approach can be treated as a further refinement of the filling and emptying method but the pressure variations can be studied with more detail and precision (the acoustic phenomena are also analysed). 1D codes enable the emissions evaluation both with the completeness of the combustion process. The best known commercial 1D codes are GT Power (Gamma Technologies) [12], Boost (AVL) [14] and Wave (Ricardo Software) [15,18].

3. Ricardo Wave

WAVE is CAE code developed by Ricardo Software [18] to analyse 1D gas dynamics in ducts, plenums and channels of various flow systems and machines. It can be used to model the complete IC engine [15]. The basic engine model is a time-dependent simulation of in-cylinder processes, based on the solution of equations for mass and energy. The software offers integrated treatment of time-dependent (crank angle) fluid dynamics by means of a one-dimensional finite-difference formulation incorporating a general thermodynamic treatment of engine charge.

Ricardo has developed the engine simulation package WAVE to analyze the dynamics of pressure waves, mass flows, and energy losses in ducts, plenums, and manifolds of various systems and machines. This program provides fully integrated time-dependent fluid dynamic and thermodynamic calculations using a one-dimensional formulation. WAVE uses a general treatment of working fluids including air, air-hydrocarbon mixtures, combustion products, and liquid fuels. The thermodynamic properties of the working fluid are provided by the pre-processor PROPTY.

A simulation of in-cylinder processes versus crank angle, on the basis of mass and energy equations, is the principal engine model in WAVE. The energy equation is based on the first law of thermodynamics and calculates the change of internal energy of in-cylinder gases and the sum of enthalpy fluxes in and out of the chamber, heat transfer and piston work. The mass equation calculates the changes of in-cylinder mass due to flow through valves and due to fuel injection. Fluxes of air, vaporized fuel, liquid fuel and products of combustion are calculated separately (it is assumed that the liquid fuel has mass but occupies only a very small volume). Fuel injection, which is applicable for liquid and gaseous fuels, has the form of manifold or direct injection. The heat transfer is calculated using the Woschni equation [10]. The implementation of heat transfer model includes additional scaling multiplier, adjusted by the user. WAVE is capable of giving many different results, and is not limited to just calculating torque curves. It can also give emission data, as well as fuel consumption results.

Once a model is run, the results should be correlated with dynamometer data. This assures that future changes made on the model will be very accurate, and do not necessarily need to be checked with the dynamometer - general trends shown by the simulations should be correct. This study concentrated on the cylinder pressure results ensuring proper heat release.

The combustion of fuel in an engine is a chemical process influenced by many parameters. The most important is the ratio between fuel and air which is one of the input data (fuel library is incorporated). The total heat supplied during the engine cycle can be computed from the F/A ratio and LHV of the fuel which is also an input data. The heat release characteristic of an engine, which is necessary to model the combustion process, can be entered in many ways as WAVE contains a number of built-in combustion models.
The simplest and most popular approach is to use the Vibe function to approximate the actual heat release. As an alternative to the built-in combustion model, for more precise computations, the user may enter a complete combustion heat release profile - a dimensionless burn profile (being the measure of combustion advancement) elaborated from test bench experiments data as a result of the thermodynamic analysis performed on the in-cylinder pressure data of the engine under development. If this option is enabled, the combustion follows a user-defined curve, which may be entered as rate profile or as a cumulative fraction of fuel burnt (MFB).

4. WAVE model of CI engine

The engine model consists of three basic sub-models linked together. The first one is the model of a complete intake system with intake channels, injector, elements used for measurement of air flow and engine throttle, which is one of the intake components that has to be modelled. The second block is the thermodynamic model of an engine. The last one is the model of complete exhaust system, which includes all elements of exhaust gases ventilation structure situated in the laboratory of combustion engines.

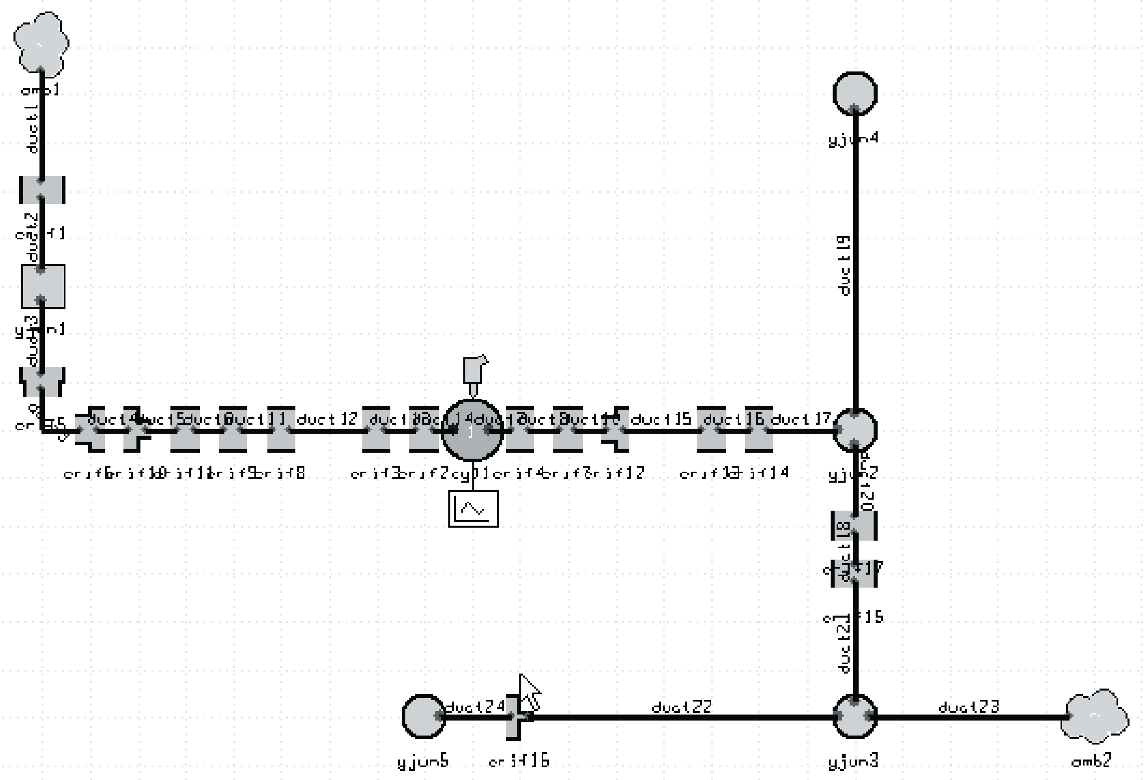

Fig. 1. Ricardo WAVE model of the experimental engine

The object of modelling was the 1-cylinder experimental engine (naturally aspirated compression ignition) in the laboratory of the Institute of IC Engines and Control Engineering, Częstochowa University of Technology. It is a modified S320 engine which main specification is given in Table 1.

Table 1. Experimental CI NA engine specification

Bore	120 mm
Stroke	160 mm
Compression ratio	15
Speed	750 rpm

The engine models in WAVE are built using the dimensions of each runner that the air goes through from the air intake to the tip of the exhaust. Every volume is assumed to be either a cut-off cone or a sphere. Bends are entered separately, and the model takes the energy losses into account.

Figure 1 shows the model used for the experimental engine. Each block on the model represents a junction between ducts, while the lines are the ducts. The model starts at the top-right corner, on an ambient junction. The fuel injectors can be seen on cylinder. The intake ports connect to the cylinder, with similar exhaust ports on the right side of the cylinders.

5. Heat Release Analysis

The heat release analysis of carefully measured cylinder pressure time-history has been used as a diagnostic tool of the combustion process. An extensive review of the thermodynamic analysis of engine pressure data is made in [5, 6]. From that analysis, different models of heat release with various level of complexity may be derived [2,4,5,9]. First, a model for computing apparent (or net) heat release. Second, a model of gross heat release including heat transfer, crevice and blow-by effects [7].

Net heat release rate is the measure of the rate at which the work is done plus the change of internal energy - it represents the energy effectively (apparently) absorbed by working fluid. The gross heat is the measure of chemical energy released by combustion of the fuel. The approach derived by Rassweiler and Withrow to calculate the mass fraction burnt (MFB) is mainly applied to SI engines [9].

Tests were performed on a single cylinder CI engine (Tab.1) coupled to the asynchronous brake. Experimental engine was instrumented with in-cylinder transducer, thermocouples and pressure pick-ups so that any temperature and pressure of interest could be monitored. Emission analyzer was used to measure CO, NO_x, equivalence ratio and unburned HC in the engine exhaust gas for the combustion efficiency evaluation. The engine was run at both part and full load. Engine performance characteristic parameters were monitored and recorded. In-cylinder pressure, crank angle and ignition reference data were recorded using the Institute's data acquisition system consisting of PC class computer with data acquisition board controlled with LCT programme [3]. The system was paced with Kistler shaft encoder (CAM) at 360 points per engine resolution. The cut off frequency was fixed at 3 kHz. No sophisticated filtering techniques were applied on the cylinder pressure signal data. All other data, necessary for the final evaluation, including ignition secondary signal, air and fuel flows, pressures and temperatures were also recorded.

Table 2. Measurement relative uncertainties

Measured quantity	Relative uncertainty
Air Flow	3.0 %
Fuel Flow	1.5 %
Pressure	2.0 %
IMEP	4.0 %
Indicated efficiency	5.0 %

Measurement relative uncertainty, associated with the test results, defines the range of the values that could reasonably be attributed to the measured quantity. Values of measurement relative uncertainties of basic engine characteristic parameters are presented in Tab. 2.

The example of cylinder pressure and injection signal (presented in Fig. 2) is based on the data acquired during 40 consecutive engine working cycles and analysed with ThermAn [7] – a program for thermodynamic analysis of the engine cycle. With this program, the normalized burn profiles were computed (Fig. 3).

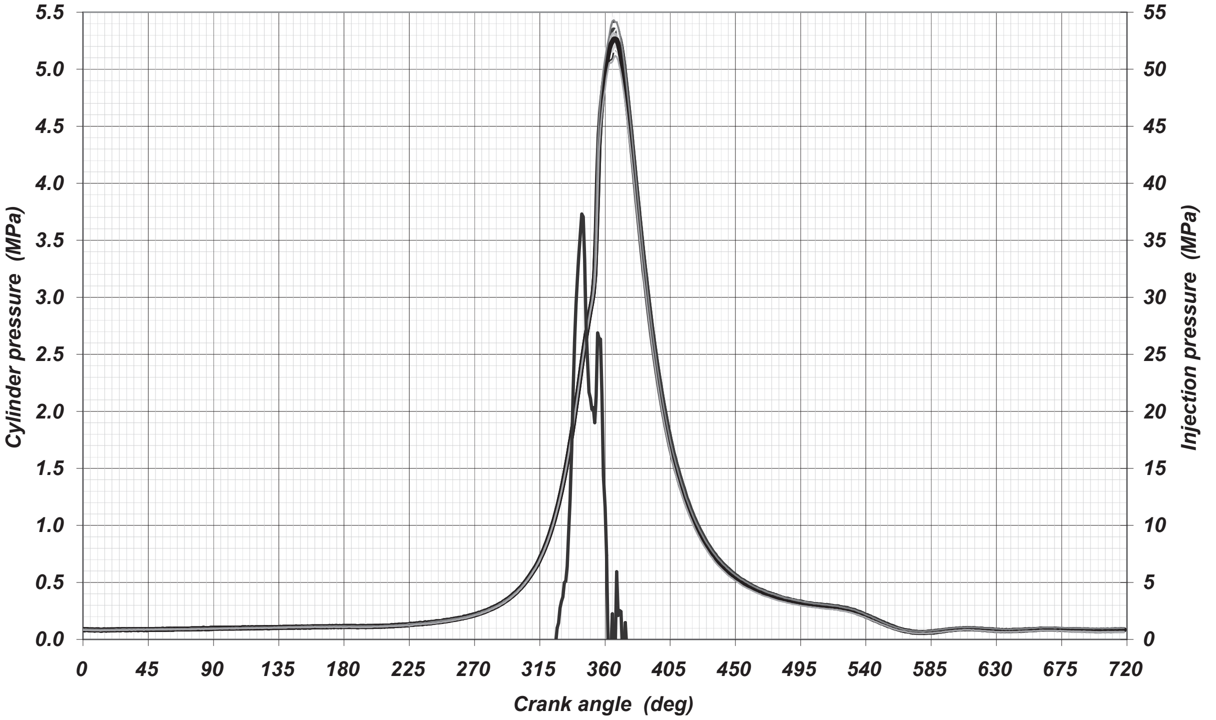

Fig. 2. Cylinder pressure and injection pressure

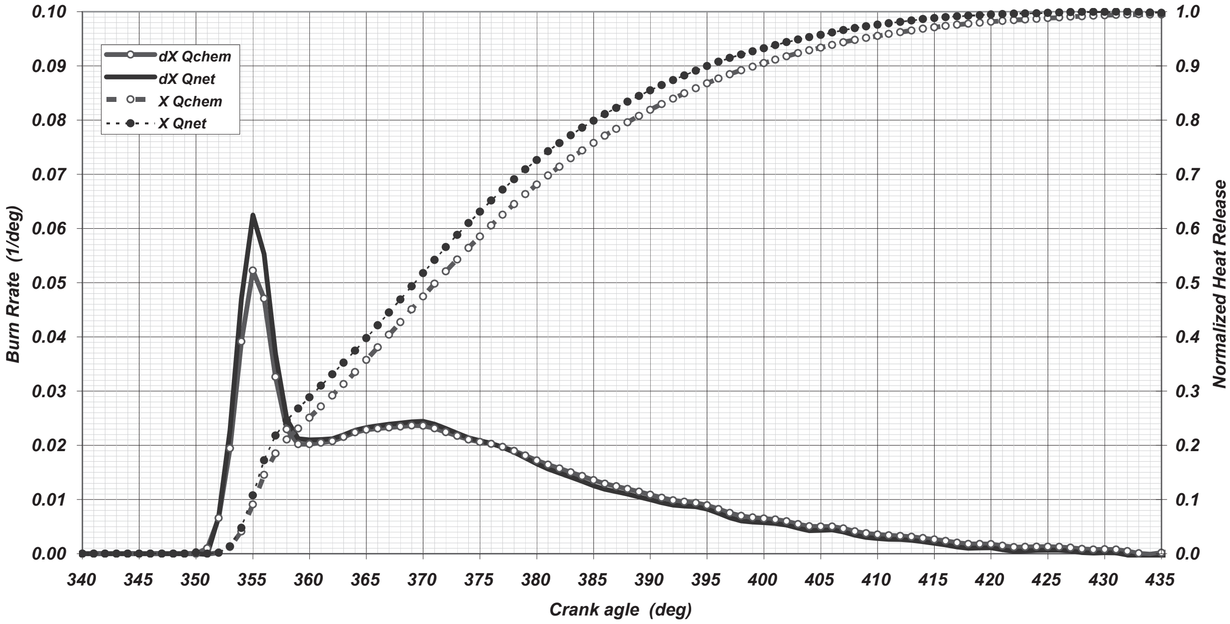

Fig. 3. Normalized burn profiles

Cumulative heat (gross and net) release curves, presenting the integrated heat release, are thought to be the approximations of the heat added to the working medium during engine cycle through the combustion process. With the ThermAn program, the normalized burn profiles were computed from experimental results illustrated above (thermodynamic loss angle was determined as in [20]).

These curves of cumulative heat release (gross and net) versus crank angle, normalized to unity, were alternatively entered to WAVE as the user-defined cumulative burn profiles (array of crankangle values, measured relative to Start of Combustion for the heat release profile).

6. Engine Modelling

Having correctly built Wave model that shows expected breathing properties [19], the recommended Ricardo's best practice tips were applied to firing engine. According to these suggestions, at first the fuel issues were corrected. Respecting the measured combustion efficiency, the fraction of charge to burn was set to 0.96 (educational license server does not support the IRIS feature and the crevice model is not available for CI engine model). The main calibration operations were executed for the normalized burn profile (cumulative fraction burned) computed with ThermAn as gross (chemical) heat release rate.

The simulations were repeated with the same tuned-up engine model parameters but with different burn profile. The results, presented in Fig. 4, indicate that burn profile evaluated on the base of net heat release analysis is less precise measure of combustion process course.

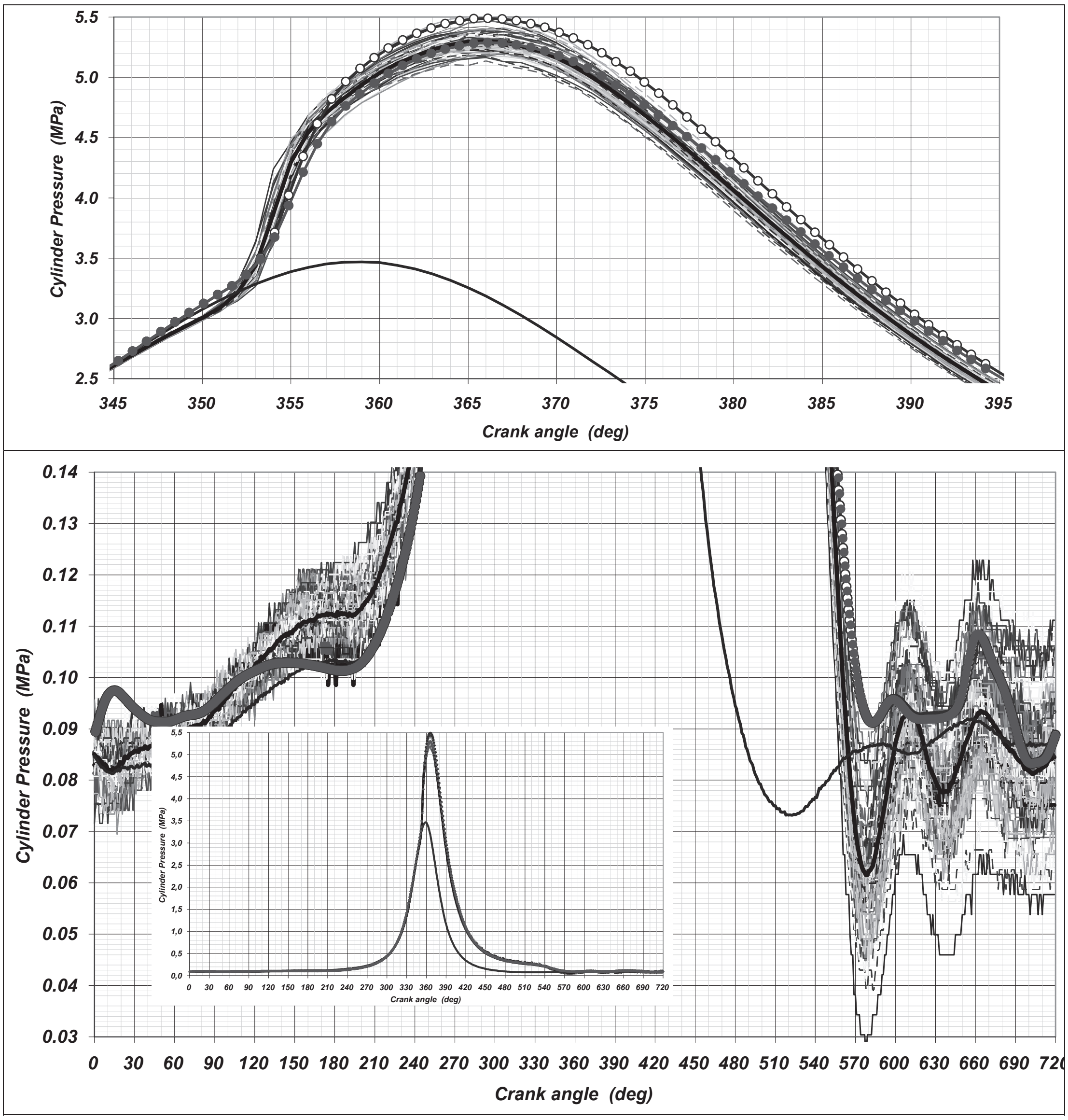

Fig. 4. Cylinder pressure – comparison of measured and computed results (for gross and net heat release user-defined profile)

The final results of the simulations made for both cumulative burn profiles are summarized in Table 3.

Table 3. Comparison of final results (gross and net heat release)

Quantity	Experiment	Model		Relative difference Model/Experiment		Uncertainty
		Gross	Net	Gross	Net	
Volumetric efficiency	0.942	0.9317	0.9313	-1.09%	-1.14%	3 %
IMEP (MPa)	0.6257	0.6058	0.6068	-3.18%	-3.02%	4%
Indicated efficiency	0.3814	0.3727	0.3735	-2.28%	-2.07%	5 %
Max. pressure (MPa)	5.3	5.28	5.49	-0.38%	3.58%	0.6 % (st.dev.)

From the Figure 4 and the results contained in the Table 3, one can see that the differences implied by different estimation of heat release profile are mostly not significant (from the point of view of measurement uncertainty) and the only significant differences apply to the maximum cycle pressure. Taking into consideration that different maximum pressure implies different maximum temperature which in turn influences engine emission, it is thought that user defined burn profile based on gross heat release curve evaluated during thermodynamic analysis of engine cycle is the optimum choice for reliable engine simulation.

For the Wave model, user-defined burn profile should be established using gross (chemical) heat release rate. Such approach offers better accuracy then the net heat release profile which is by definition a simplified measure of combustion process.

7. Summary

This study was done in order to show general trends as user-defined burn profiles are changed for Wave model of NA CI internal combustion engine.

The presented measurements of cylinder pressure, computations of its predicted equivalent and their comparison have shown that the gross heat release profile evaluated during thermodynamic analysis of cylinder pressure data gives the best agreement with experimental results.

References

[1] C.R. Ferguson, A.T. Kirkpatrick, Internal Combustion Engines Applied Thermosciences. John Wiley & Sons, 2001.

[2] J. A. Gatowski, E. N. Balles, K. M. Chun, F. E. Nelson, J. A. Ekchian, and J. B. Heywood, Heat release analysis of engine pressure data. SAE Technical Paper 841359, 1984.

[3] Gruca M., LCTxr - program do rejestracji i analizy harmonicznej sygnałów. Politechnika Częstochowska 2002.

[4] J. B. Heywood, Internal Combustion Engine Fundamentals. McGraw-Hill series in mechanical engineering. McGraw-Hill, 1988.

[5] K. Z. Mendera:,Thermodynamic Analysis of Spark Ignition Engine Pressure Data. Journal of KONES Internal Combustion Engines Vol.11 nr 3-4, 2004. ISSN 1231-4005. str. 45-52.

[6] K.Z. Mendera, Thermodynamic properties of working fluid of internal combustion engine. Journal of KONES Internal Combustion Engines Vol.11 nr 3-4, 2004. ISSN 1231-4005.

[7] K. Z. Mendera,ThermAn – Program for thermodynamic analysis of internal combustion engine cycle. Częstochowa University of Technology. Częstochowa 2005.

[8] Oberkampf W. L., Trucano T. G., Verification and Validation in Computational Fluid Dynamics. Sandia National Laboratories, P. O. Box 5800, Albuquerque, New Mexico 87185.
[9] R. Stone, Introduction to Internal Combustion Engines. Palgrave, 3rd edition, 1999.
[10] G. Woschni, A universally applicable equation for the instantaneous heat transfer coefficient in the internal combustion engine. SAE Technical Paper 670931, 1967.
[11] http://www.fluent.com/.
[12] GT Power. Gamma Technologies. http://www.gtisoft.com/.
[13] KIVA-2 A computer program for chemically reactive flows with sprays. LA11560MS.
[14] http://www.avl.com/.
[15] WAVE v5 Engine. Reference Manual. Ricardo 2002.
[16] http://www.cd-adapco.com/news/releases/engine.htm.
[17] http://www.engineeringtalk.com/news/rca/rca104.html.
[18] http://www.software.ricardo.com/.
[19] Mendera K. Z., Pasternak M. , Smereka M., Sobiepański M., Sosnowski M., Calibration of spark ignition engine model. Paper submitted for I Congress of PTNSS.
[20] Gruca M., Mendera K.Z.: Wyznaczanie GMP tłoka. Paper submitted for Kones 2005.