INFLUENCE OF BURN PROFILE ON THE PRECISION OF 1-D ENGINE CYCLE SIMULATION

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Abstract

Mass fraction burned and 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 throughout the combustion process. Three procedures of burn profile determination are described and their specific assumptions are pointed out. These methods were applied to the cylinder pressure traces and suitable burn profiles were computed. The curves of cumulative heat release (R-W, gross and net) versus crank angle, normalized to unity, were entered to 1D Ricardo WAVE code as the user-defined cumulative burn rate profiles. The simulation results were compared and critically evaluated.

Pressure traces of consecutive engine cycles and their indicate, indicated mean effective pressures are presented. Burn profiles of consecutive engine cycles, burn profiles adopted for simulation, comparison of measured and computed pressure and temperature traces, P-V diagrams of measured and simulated engine cycles exemplify results of research work.

Keywords: *internal combustion engine, heat release rate, mass fraction burned, burn profile, 1-D simulation, Ricardo Wave code*

WPŁYW PROFILU SPALANIA NA PRECYZJĘ 1-WYMIAROWEGO MODELOWANIA OBIEGU SILNIKA SPALINOWEGO

Streszczenie

Krzywe udziału ładunku spalonego lub wydzielania ciepła (brutto i netto) są traktowane jako aproksymacje ciepła doprowadzonego do czynnika roboczego w trakcie procesu spalania i nazywane profilami spalania. W pracy przedstawiono i przedyskutowano trzy sposoby wyznaczania profilu spalania. Zostały one zastosowane do analizy ciśnienia. Trzy znormalizowane profile spalania (obliczone metodą R-W oraz w wyniku analizy ciepła wydzielonego brutto oraz netto) wykorzystano do modelowania obiegu silnika przy pomocy 1-W programu Ricardo Wave. Dokonano porównania wyników i wskazano optymalną procedurę.

Słowa kluczowe: *silnik spalinowy, szybkość wydzielania ciepła, udział ładunku spalonego, profil spalania, modelowanie 1-wymiarowe, program Ricardo Wave.*

1. Introduction

The one-dimensional gas dynamic simulation models (1D CFD) are computer codes that combine 0-D approach for the engine in-cylinder processes with 1-D approach for the flow calculations throughout the inlet and outlet engine systems. The best known commercial 1D codes are GT Power (Gamma Technologies), Boost (AVL) and Wave (Ricardo Software) [10,23,24].

Ricardo WAVE, 1-D engine cycle simulation software, has long been an industry standard tool for the computation of engine performance and intake and exhaust gas dynamics. The heat release characteristic of an engine, necessary to model the combustion process, can be entered in many ways as WAVE contains a number of built-in combustion functions. The simplest and most popular is the Vibe function widely used to describe the rate of mass burned (heat release).

As an alternative to the built-in combustion models, for more precise computations, the user may enter a complete combustion heat release function - a dimensionless burn profile calculated during the heat release rate analysis performed on accurate in-cylinder pressure measurements of the engine under development (if this option is enabled, the combustion follows that curve). Burn profile may be entered as rate profile normalized to integrate to unity or as a cumulative fraction of charge burnt/energy released.

2. Burn profiles

Burn profile (being the measure of combustion advancement) may be elaborated from test bench experiments data as a result of the combustion analysis performed on the in-cylinder pressure data. According to Stone [22] there are essentially two types of combustion analysis:

- burn rate analysis to calculate the mass fraction burned (MFB);
- heat release rate analysis to calculate how much heat would be added to the in-cylinder medium to pro-duce observed pressure variations (HRR).

2.1. Mass fraction burned

The basic procedure for MFB calculations is the Rassweiler-Withrow method ([20], originally presented in 1938) still in use (though its evident approximating character [12]) because of its relative simplicity and computational efficiency. The MFB is the burned mass normalized by the total charge mass and it can be seen as a standardized version of the heat deliverance, describing the process of chemical energy release as a function of crank angle (MFB profile assumes values in the interval 0-1). The relation between the mass fraction burned and the amount of heat released can be justified by noting that the energy released is proportional to the mass of the charge that is consumed.

The Rassweiler and Withrow procedure is based on the assumption that, during combustion, the pressure rise Δp (see Fig.1) consists of two parts: pressure rise due combustion (Δp_c) and pressure change due to volume change (Δp_v):

$$\Delta p = \Delta p_c + \Delta p_v$$

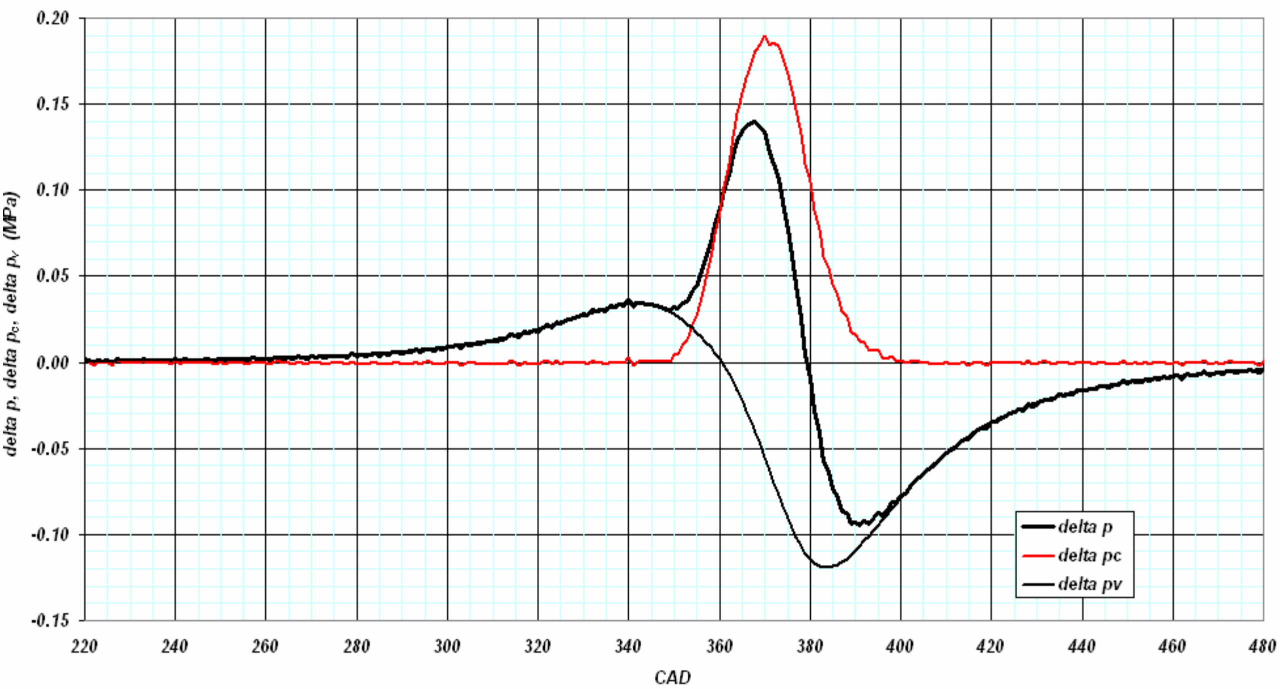


Fig. 1. Components of cylinder pressure rise

Assuming that the pressure rise Δp_c is proportional to the heat added to the in-cylinder medium during the crank angle interval, the mass fraction burned at the end of the considered i-th interval may be calculated as [20,12,14,15]:

$$MFB = \frac{m_b(i)}{m_b(total)} = \frac{\sum_0^i \Delta p_c}{\sum_0^N \Delta p_c},$$

where 0 denotes the start of combustion, N – end of combustion (N is the total number of crank intervals).

For the MFB calculations, knowledge of Δp_c is necessary. It is accepted that the cylinder pressure and volume in the absence of combustion are related by the polytropic equation: $pV^n = idem$ and a pressure change due to volume variation is given by:

$$\Delta p_v = p_{i+1} - p_i = p_i \left[\left(\frac{V_{i+1}}{V_i} \right)^n - 1 \right].$$

Methods based on fitting the recorded pressure trace to a polytropic process have the benefit that no additional data (beside cylinder pressure and CAD) need to be recorded.

2.2. Heat release rate

Cylinder pressure built by combustion process is affected by the changes in the volume of combustion chamber (due to piston travel), chemical composition (and hence thermodynamic properties), heat transfer and gas flows. To examine the combustion process, it is necessary to relate each term to measured in-cylinder pressure and then combine them to quantify the combustion effects. A family of single-zone heat release models [1-7,12,16,17,22] have been derived from the first law of thermodynamics. A single zone model defines the state of the cylinder contents in terms of average properties and does not distinguish between burned and unburned gas.

Heat release analysis can be performed on the cylinder pressure trace, which can either be the ensemble-average of a large number of cycles (in this work typically 40-120) or an individual cycle trace. Heat release depends on the thermodynamic state parameters (pressure, volume) and each HRR equation requires the knowledge of instantaneous thermodynamic properties of the working fluid. The ratio of specific heats for combustion gases is critical for the analysis, strongly influencing the value of heat release rate. In general, $\kappa = cp/cv$ is a function of charge temperature and composition and the dependence of the properties on temperature is much stronger than the dependence on charge composition [17].

From the thermodynamic analysis of IC engine pressure data, different models of heat release with various level of complexity may be derived. Cumulative (gross and net [7,12]) heat 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.

If the First Law of Thermodynamic is applied to a control volume (Fig. 2), the heat released by combustion of fuel is given by the equation:

$$dQ_{ch} = dU + dQ_{ht} + dL + i'dm_{cv} + idm_{bl}$$

dQ_{ch} is the change in chemical energy released from the fuel;

dU denotes the change in internal energy of the mass in control volume (CV);

dQ_{ht} represents heat losses to the cylinder wall

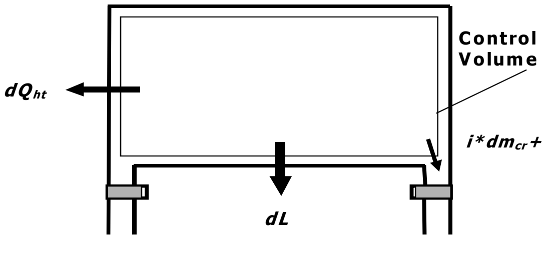


Fig.2. Control volume in engine combustion chamber

across the CV boundary;

dL is elementary work.

The last two terms of HRR equation represent the changes in the enthalpy due to flows of the mass out and into the CV (crevice and blow-by).

After some operations, we arrive at gross heat release rate (gross HRR) equation [7,12,16]:

$$dQ_{ch} = \frac{C_v}{R} Vdp + (\frac{C_v}{R} + 1)pdV + dQ_{ht} - \frac{C_v}{R} mTdR + (C_v T - i' - u)dm_{cr} + (cvT + i - u)dm_{bl}$$

It is the measure of the overall chemical energy of a fuel released throughout the combustion. Applying the concept of net heat release rate dQ_{net} [7,12]:

$$dQ_{net} = dQ_{ch} - (dQ_{ht} + dQ_{cr}),$$

which represents the work and internal energy change only, the chemical energy or gross heat release rate can be expressed as:

$$dQ_{ch} = dQ_{net} + dQ_{ht} + dQ_{cr} + dQ_{bl}$$

Thus, gross (chemical) heat release term dQ_{ch} is net heat release term dQ_{net} combined with heat transfer, crevice and blow-by terms. The gross heat is the measure of chemical energy released by combustion of the fuel. The computation of net heat release (called the apparent heat release by Krieger and Borman) takes neither heat transfer nor flow effects into account. The equation of apparent heat release, describing the incremental net HRR over a given crank angle interval during the period between IVC and EVO, can be expressed as:

$$\frac{dQ_{net}}{d\varphi} = \frac{\kappa}{\kappa - 1} p \frac{dv}{d\varphi} + \frac{1}{\kappa - 1} v \frac{dp}{d\varphi}$$

The net heat release analysis, performed on the measured in-cylinder pressure data, presents rather the heat effectively absorbed by working fluid than the chemical energy of the fuel that is released during combustion.

3. Normalized burn profiles

Heat release analysis, used for combustion diagnostics relies strongly upon robust and accurate in-cylinder pressure measurement [9]. Necessary tests [11] were performed on a single cylinder SI experimental engine (based on S320 engine) instrumented with thermocouples and pressure pick-ups so that any temperature and pressure of interest could be monitored. Kistler piezoelectric pressure transducer was installed in a special insert placed under engine head. Emission analyzer was used to measure CO, equivalence ratio and unburned HC in the engine exhaust gas for the combustion efficiency evaluation. In-cylinder pressure, crank angle and ignition reference data were recorded using the data acquisition system consisting of PC class computer with data acquisition board controlled with LCT program [8]. The system was paced with Kistler shaft encoder.

Mass fraction burned and heat release analysis was performed on the cylinder pressure traces, (120 cycles, Fig. 3) with ThermAn [19] – a program for thermodynamic analysis of the IC engine cycle. With this program, the normalized burn profiles were computed (Fig.5).

Dimensionless heat release profiles, quantifying the conversion of chemical energy of the reactants in the charge, may be obtained by standardization of the analysis results. Three burned profiles were calculated based on Rassweiler-Withrow procedure (R-W), net heat release rate (Net) and gross heat release rate (Gross). The results of the computations provide the crank-angle resolved normalized energy release rate, as well as the normalized cumulative energy release – burn profiles assume values in the interval 0-1. The results of the burn profile computations are illustrated in Fig 4 on the example of R-W procedure.

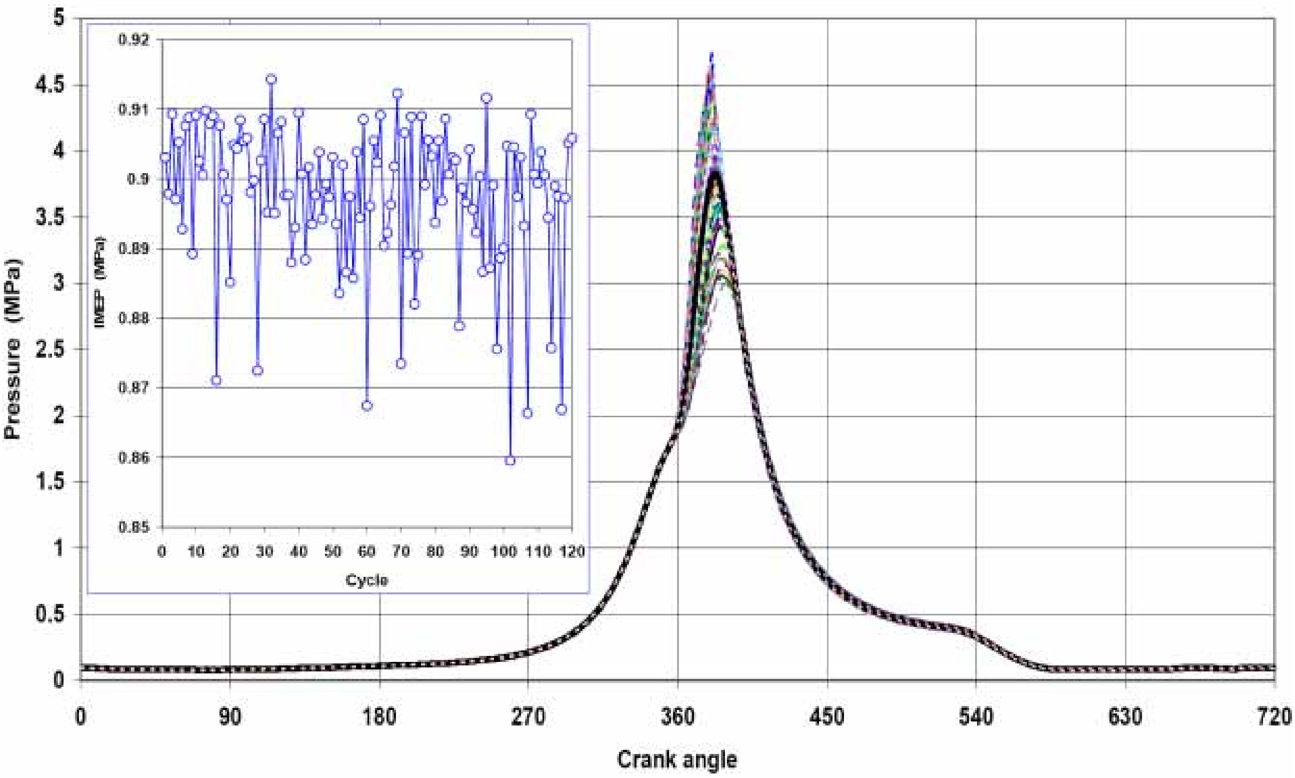


Fig.3. Pressure traces of 120 consecutive engine cycles and their indicated mean effective pressures

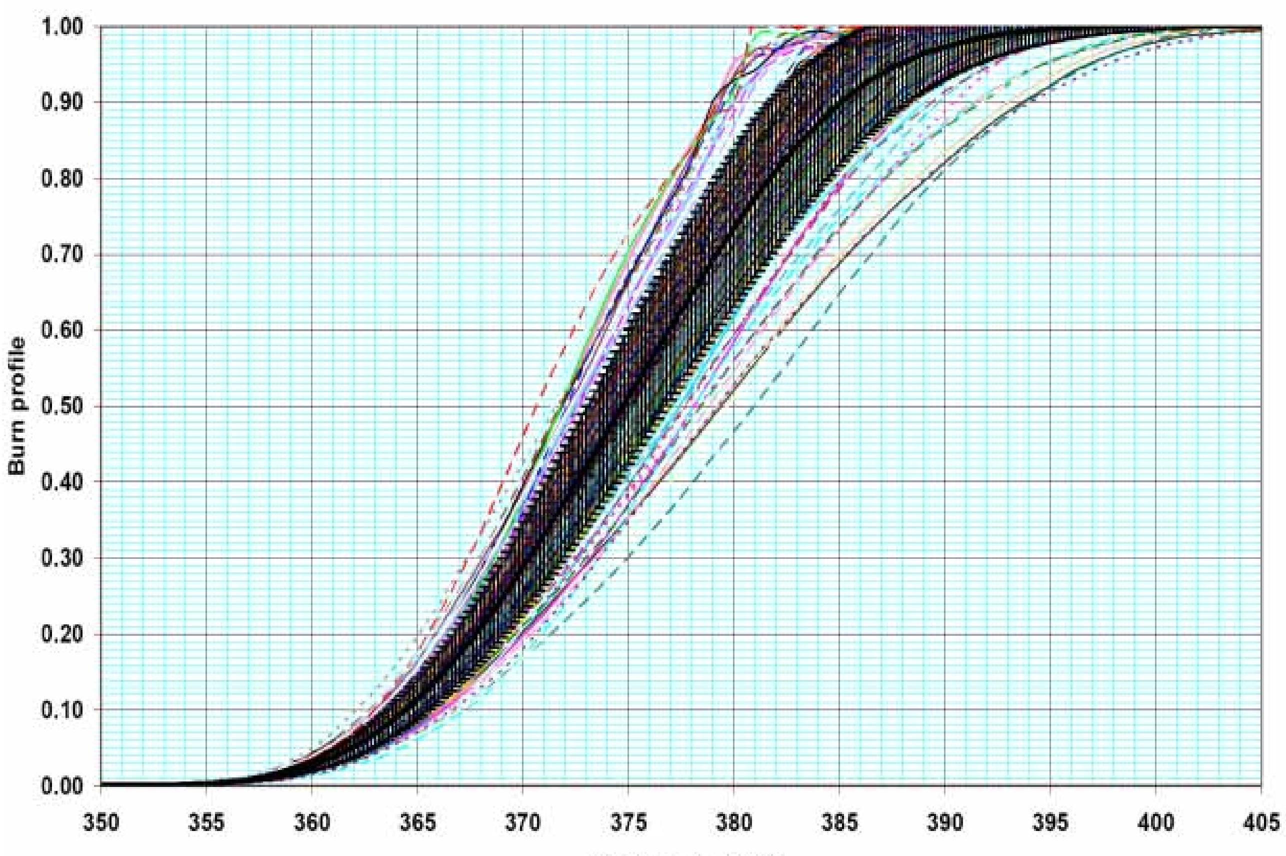


Fig. 4. Burn profiles of 120 consecutive engine cycles (R-W procedure; shaded are the limits of standard deviation)

The averaged results for the three considered models of burn profile computation are presented in Fig.5.

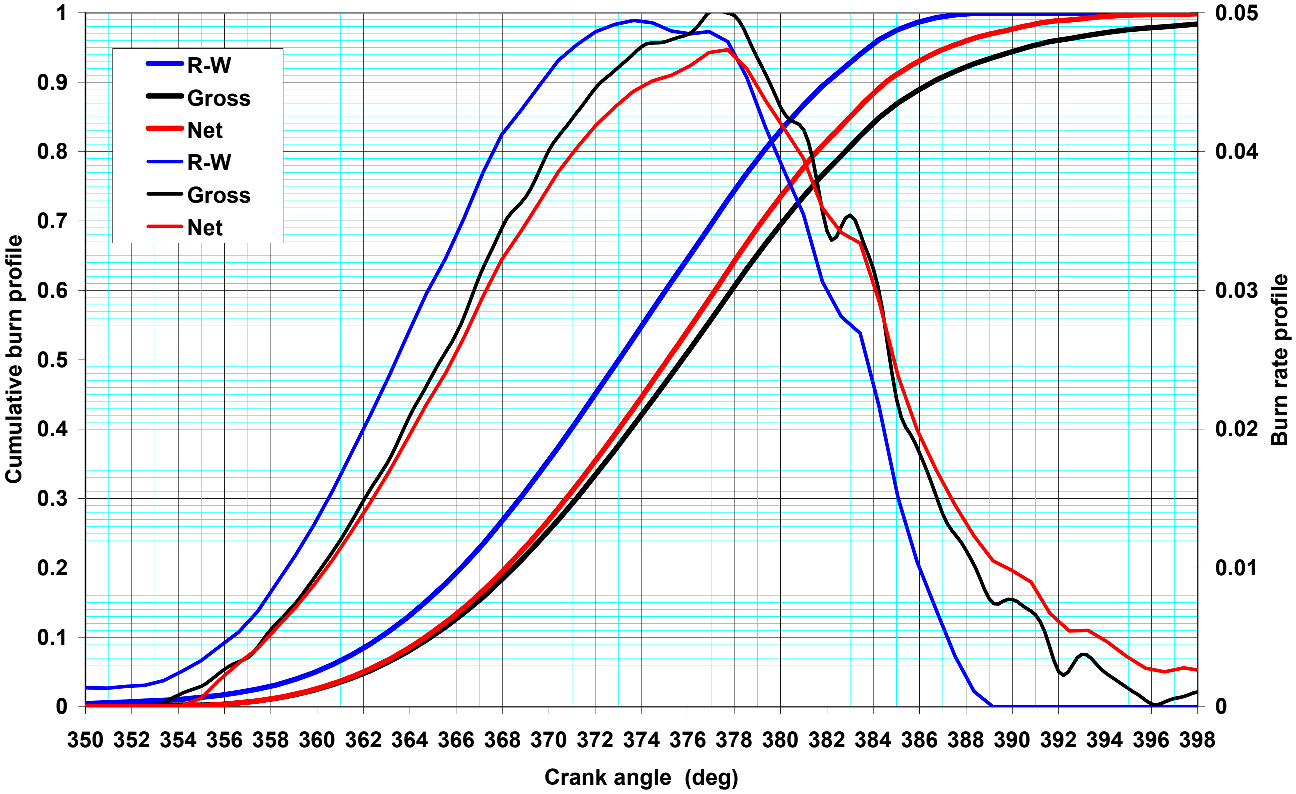


Fig. 5. Burn profiles adopted for simulation

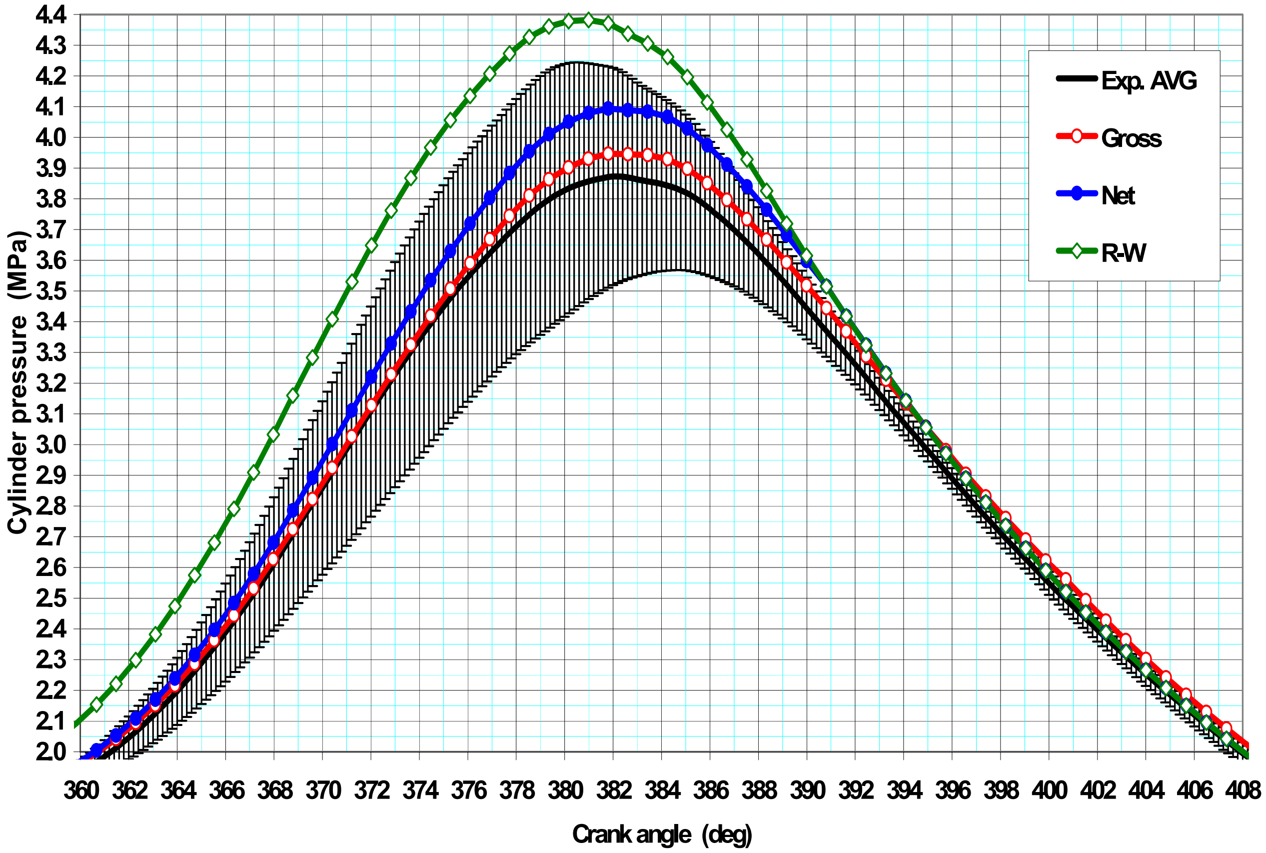
The heat release (both gross and net) profiles are similar to those from the Rassweiler-Withrow method, but they are physically better justified. The Rassweiler-Withrow procedure yields a higher burn rate compared to the heat release rate methods for the same data. This is reflected in the crank angle for 50 % MFB, which is 16 deg ATDC for the gros heat release rate method, 15 deg ATDC for net HRR and 13 deg ATDC for the Rassweiler-Withrow method.

4. Influence of burn profile on the precision of 1-d engine simulation

Cumulative heat (gross and net) release curves, presenting the integrated heat release, and MFB function are thought to be the approximations of the heat added to the working medium during engine cycle through the combustion process. These curves of cumulative heat release (R-W, gross and net, Fig.5) versus crank angle, normalized to unity, may be entered to Ricardo WAVE code as the user-defined cumulative burn rate profiles (Fig.4), as array of crank angle values, measured relative to the start of combustion. Such procedure helps to customize the simulation code, makes it better calibrated to specific computations of the engine under development and offers more realistic results.

Having correctly built Wave model that shows expected breathing properties [13,18] the simulations were performed with the same tuned-up engine model parameters (tests were run at constant speed, ignition timing and air-fuel ratio; the same as in experiments illustrated in Fig.3) but with various burn profiles (the curves of normalized cumulative burn profiles, were alternatively entered to WAVE as the user-defined functions).

The predicted pressure traces are presented in Fig. 6 together with the average experimental results of in-cylinder pressure measurements (Fig.3) as the function of crank angle.



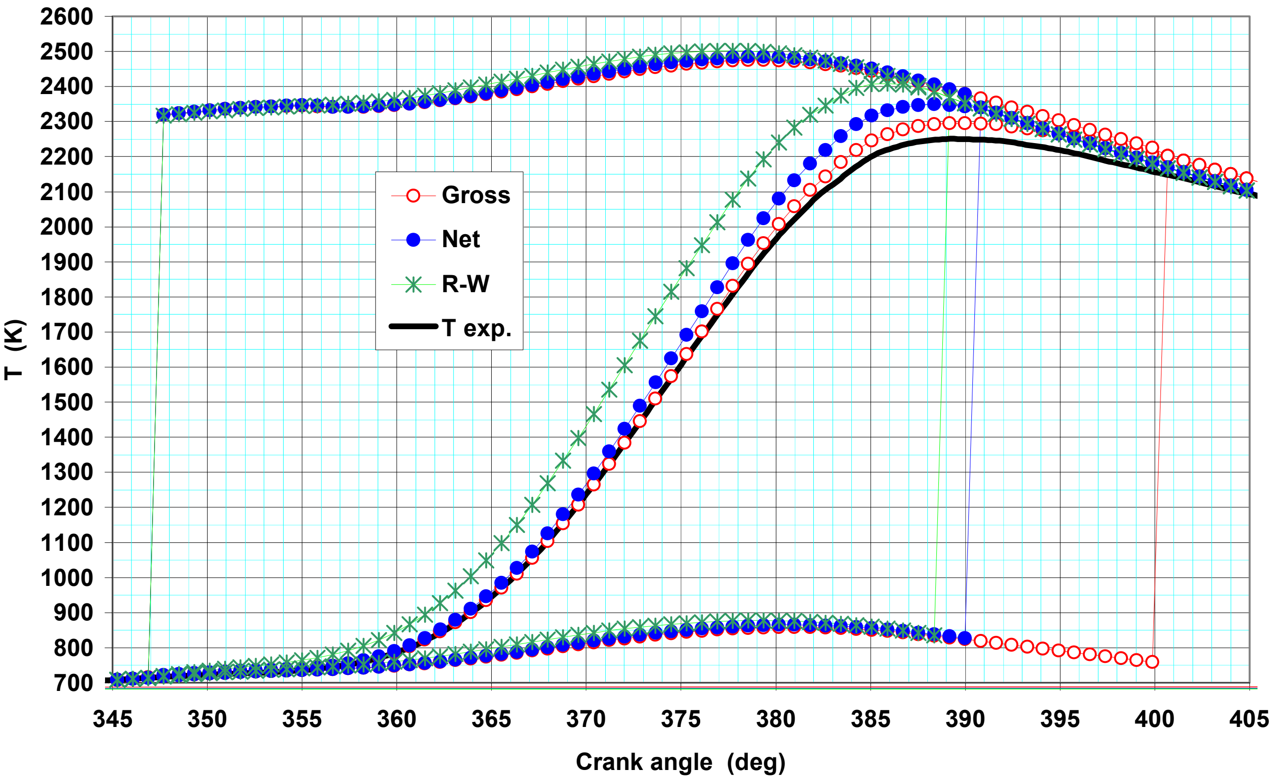


Fig.6. Comparison of measured and computed pressure (upper figure) and temperature (lower figure) traces (figures present combustion part of engine cycle, shaded are the standard deviation limits of pressure measurements)

The comparison of p-V diagrams is presented in Fig.7. Table 1 and 2 contain respectively the measurement uncertainties of the parameters involved and final results of the comparison.

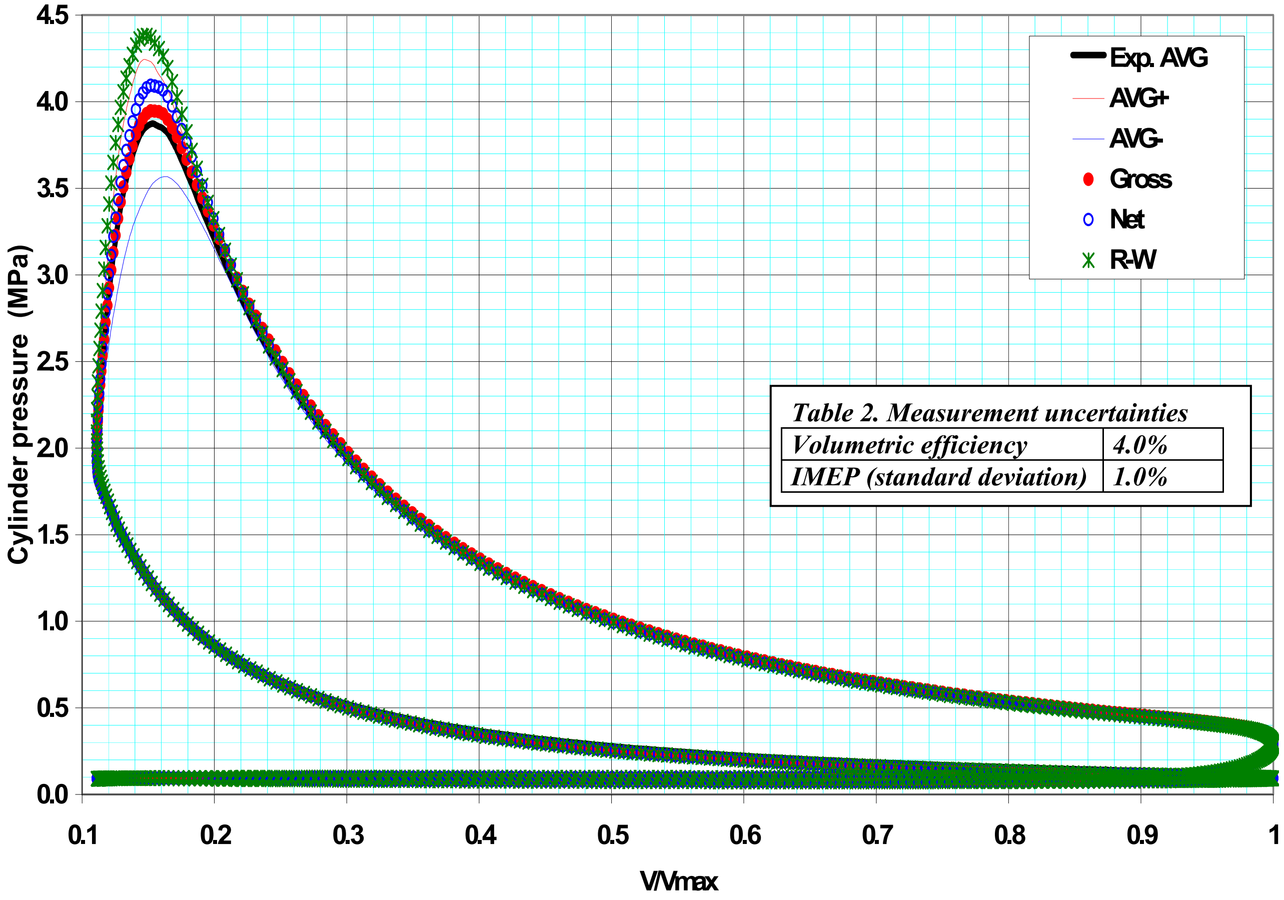


Table 2. Measurement uncertainties

Volumetric efficiency	*4.0%*
IMEP (standard deviation)	*1.0%*

Fig.7. P-V diagrams of measured and simulated engine cycles

Table 2. Comparison of the final results

Quantity		***Model***					
	Experiment	***R-W***		***Net HRR***		***Gross HRR***	
		Result	***Rel. diff.***	***Result***	***Rel. diff.***	***Result***	***Rel. diff.***
Vol. efficiency	0.85	0.863	1.53%	0.863	1.53%	0.863	1.53%
IMEP [MPa]	0.91	0.9385	3.13%	0.9217	1.29%	0.92	1.10%

From the figures 6 and 7 and the results contained in the Table 2, one can see that:

- 1-D engine cycle simulation using burn profile elaborated throughout thermodynamically based heat release rate analysis (both gross and net HRR) offers more precise results than the user defined burn profiles from the Rassweiler-Withrow procedure;
- the differences implied by different approach to the heat release rate analysis (gross or net) are rather not significant (from the point of view of measurement uncertainty, see table 2 for the uncertainties);
- the most significant differences apply to the maximum cycle parameters (pressure, temperature).

Taking these results into consideration, 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 and precise internal combustion engine simulation.

5. Summary

Three procedures for the determination of burn profile for 1D engine cycle simulation software have been described and their specific features are pointed out. The curves of cumulative heat release (R-W, gross and net) versus crank angle, elaborated from in-cylinder pressure data, were entered to 1-D Ricardo WAVE code as the user-defined cumulative burn rate profiles. The simulation results were compared and critically evaluated.

Comparison of the pressure and temperature predicted throughout the course of computer simulation of the cycle of SI internal combustion engine with experimentally determined data has shown that the gross heat release burn profile evaluated during the thermodynamic analysis of cylinder pressure data offers the best agreement with experimental results thus ensuring the most precise simulation of IC engine cycle.

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