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IDENTIFICATION OF THE ERRORS RELATED TO THE ESTIMATION OF THE ACTUAL COMBUSTION RATE OF THE FUEL FROM THE MEASURED CYLINDER PRESSURE OF DI DIESEL ENGINES

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ABSTRACT

As recognized by various researchers the most important source of information for a reciprocating internal combustion engine is the cylinder pressure diagram. Its validity for direct injection (DI) diesel engines is extremely important since the engineer can estimate and understand the effect of various operating or design parameters on the combustion mechanism. But, since the measured cylinder pressure diagram is the result of various thermo-physical processes taking place inside the combustion chamber it cannot provide direct information concerning the combustion rate of fuel. For this reason techniques have been developed to estimate the rate at which energy is released inside the combustion chamber by processing the cylinder pressure diagram. These techniques are referred to as “Heat Release Rate Analysis” and are used to estimate the combustion rate of fuel inside the combustion chamber. During its estimation various errors may arise due to either the cylinder pressure measurement or inadequate description of the various mechanisms, i.e. heat transfer etc. In the present investigation the heat release rate estimation procedure is analyzed at the fundamental level using a detailed simulation model and available experimental data. A source of error is indicated that is higher compared to any of the conventional ones. From the analysis, it is shown that it is not possible to estimate the actual rate of heat release inside the combustion chamber of DI diesel engines from the measured cylinder pressure trace using existing heat release rate analysis techniques even if all mechanisms are described accurately. From the employment of the simulation technique the actual source of this error is revealed.

INTRODUCTION

The fuel combustion rate is the controlling mechanism for DI diesel engine performance and pollutants formation. For this reason, various techniques are often implemented by engineers for optimizing the rate of fuel combustion and through that, controlling pollutant formation inside the combustion chamber [1-3]. Application of advanced injection timing, variation of injection rate shaping and implementation of split injection techniques (i.e., pilot and post injection) affect directly the rate of combustion released energy inside the combustion chamber and thus, control the evolution of in-cylinder mean gas temperature, soot and NO formation rate [4].

This procedure requires extremely long experimental investigations and a clear understanding of the effect of the various design and operational parameters on fuel combustion rate. A valuable source of experimental information for this purpose is the cylinder pressure diagram [1-3]. It provides valuable information to an experienced engineer concerning the engine cylinder condition, the combustion mechanism or even the condition of the fuel injection system. The cylinder pressure diagram is the result of various thermo-physical processes taking place inside the combustion chamber and not only the result of the combustion rate of fuel injected. For this reason, techniques have been developed in the past aiming at the estimation of the net rate of energy release inside the combustion chamber referred to as the “Net Heat Release Rate” or even the actual rate i.e. the “Gross Heat Release Rate”. A number of researchers have widely investigated the errors that can occur during its estimation and have presented detailed analysis of the various error source terms [5-8].

In the present investigation, a different approach is followed dealing with the fundamentals of the heat release rate analysis methodology. The effect of the conventional error source terms such as, heat exchange, error in trapped mass, pressure measurement error etc are not examined. What is examined is whether the knowledge of the cylinder pressure diagram is adequate. The problem was realized when making an effort to simulate the operation of a DI diesel engine using a detailed multi-zone combustion model [4,9]. As observed during this process, even though the simulation predicts adequately the cylinder pressure trace for various operating conditions, the comparison between the computational actual net heat release rate and the one estimated from the measured cylinder pressure trace reveals a serious difference. No similar problem has been realized when using single-zone models that assume spatial uniformity of temperature and composition inside the combustion chamber. The problem has been realized implicitly by researchers, since in a number of publications it is mentioned that simulation over-predicts the net heat release inside the combustion chamber during the initial stage of combustion [10,11].

In the present investigation, an effort is made to determine the source for this error, to quantify it and to provide an explanation based on thermodynamics that would assist in overcoming this problem. As revealed, the error on a percentage basis, is rather high leading to an underestimation of the actual heat release rate during the initial stages of combustion and an overestimation during the late phases. Considering existing information provided by various researchers this error is higher compared to the one that can result from the improper description of the various terms used in conventional heat release rate analysis methods [5-8, 12]. As revealed, even if all mechanisms are described accurately it is not possible to estimate the actual rate of fuel utilization inside the combustion chamber from the measured cylinder pressure trace using conventional heat release rate analysis techniques. Thus, conclusions derived concerning the amount of fuel consumed during the premixed combustion and diffusive phase are misleading even though the overall effect of various parameters may be qualitatively correct.

To eliminate the various error source terms involved in the HRR analysis it is used the simulation model to provide the cylinder pressure trace that serves as the “measured” one. In this way it is known the actual combustion rate of fuel that is used to produce it. In this manner the results obatined from conventional HRR analysis techniques are evaluated. The relative error of the HHR estimation is presented together with an explanation based on thermodynamics obtained using the simulation model.

NOMENCLATURE

c_v	[J/kgK]	Specific heat capacity under constant volume
f	[-]	Function
H_{fuel}	[J/kg]	Fuel heating value
h	[J/kg]	Specific enthalpy
m	[kg]	Mass
p	[N/m^2]	Pressure
Q	[J]	Heat
R	[J/kgK]	Specific gas constant
T	[K]	Absolute temperature
u	[J/kg]	Specific internal energy
U	[J]	Internal energy
V	[m^3]	Volume
x	[-]	Molar fraction
Special characters		
γ	[-]	Ratio of specific heat capacities under constant pressure and constant volume
φ	[deg]	Engine crank angle
Subscripts		
b		Burnt
cal		Calculated
e		Energy
exp		Experimental
f		Fuel
o		Initial value
ref		Reference value
tot		Total
th		Thermodynamic
u		Unburnt
w		Wall
Abbreviations		
CA		Crank angle
DI		Direct injection
AHRR		Apparent heat release rate
HRR		Heat release rate
TDC		Top dead centre

BRIEF DESCRIPTION OF THE HEAT RELEASE RATE ANALYSIS METHODOLOGY

Before dealing with the specific problem, it is given a short description of the heat release rate methodology proposed and followed by most researchers [1-3,5-8,12]. The HRR rate methodology makes use of the first law of thermodynamics to estimate from the measured cylinder pressure traces the experimental Apparent Net Heat Release Rate $Q_{exp,net}$. The net heat-release rate is given by the following equation:

$$\frac{dQ_{exp,net}}{d\varphi}=\frac{dU}{d\varphi}+p\frac{dV}{d\varphi}+\sum_i h_i\frac{dm_i}{d\varphi} \tag{1}$$

where the last term on the right hand side stands for the net enthalpy loss from the cylinder due to blowby or gas leakage from the inlet or/and exhaust valves. The previous equation results in:

$$\frac{dQ_{exp,net}}{d\varphi}=mc_v\frac{dT}{d\varphi}+p\frac{dV}{d\varphi}+\sum_i h_i\frac{dm_i}{d\varphi} \tag{2}$$

As one can see in EQ(2) the derivative of temperature exists, while the only known value is the measured pressure p in the cylinder. To eliminate the temperature term, the ideal gas state equation is also considered:

$$pV=mRT\Rightarrow T=\frac{pV}{mR} \tag{3}$$

Finally resulting to the following expression for the net heat release rate:

$$\frac{dQ_{exp,net}}{d\varphi}=\frac{c_v}{R}\left(P\frac{dV}{d\varphi}+V\frac{dP}{d\varphi}-\frac{PV}{m}\frac{dm}{d\varphi}\right)+p\frac{dV}{d\varphi}+\sum_i h_i\frac{dm_i}{d\varphi} \tag{4}$$

This equation is used to estimate the net energy release inside the combustion chamber, which is due to the combustion rate of fuel and the heat exchange with the cylinder walls. The thermodynamic property values c_v, h and R are calculated using ideal gas relations [2,3] and the mean temperature value from equation (3).

Observing EQ(4) various error source terms are revealed that can alter the result for the net heat release rate. These have been investigated by detail in the past by various researchers [13]:

- Instantaneous charge mass “m”. It affects the mean temperature of the cylinder charge, estimated from EQ(3). Its estimation requires the knowledge of the charge mass at inlet valve closure and its variation during the compression-combustion and expansion stroke if leakages exist [3,14].
- The charge specific heat capacity under constant volume “c_v”. This assuming an ideal gas behaviour for the gas mixture is a function of temperature and composition i.e.

$$c_v=f\left(T,x_i\right) \tag{5}$$

- The measured cylinder pressure itself [15].
- The TDC position which provides the reference for calculating the instantaneous cylinder volume [16,17].

The previous terms can cause an error in the estimation of the AHRR when using the measure cylinder pressure as reported by various researchers [5-8].

At this point a question arises, if all previous conventional error source terms are minimized can the actual combustion rate of fuel be estimated using the cylinder pressure trace and conventional heat release rate analysis techniques? Considering the previous brief analysis an error can result from the use of EQ(3) to estimate the charge mean gas temperature since we know that a quite broad distribution of temperature and composition exists in the combustion chamber of DI diesel engines. The problem has been mentioned by various researchers [3,5-8], and this is the reason for addressing the estimated value as AHRR, but no detailed analysis of the relevant error has been presented. This problem is analysed by detail in the present work.

ANALYSIS OF THE PROBLEM

The inspiration for conducting the present work is that during an investigation where a multi-zone simulation model [4,9] was used to predict the effect of various parameters on performance and pollutants emissions of a DI single cylinder heavy-duty diesel test engine a problem was observed as far as the cylinder pressure and heat release rates are concerned. In Table 1 are given the main data for the engine used for the analysis while in Table 2 is given the test cases examined.

Table 1. Main engine characteristics

Cylinder bore	130 mm
Piston stroke	150 mm
Connecting rod length	274 mm
Compression Ratio	17.8:1

Table 2. Test cases examined

Case	Speed	Load	Injection Timing	Boost Pressure	Boost Air Temperature
1	1130	50%	-3 deg ATDC	1.49 bara	29°C
2	1130	100%	-3 deg ATDC	2.33 bara	30°C
3	1710	90%	-6 deg ATDC	2.40 bara	30°C

The simulation model is calibrated initially to predict engine performance at 1130 rpm engine speed and 100% load. The calibration is based on the estimation of the cylinder pressure trace and models' constants are maintained the same for all other operating conditions. From the experimental investigation, the following data are available:

- Cylinder Pressure Trace.
- Injection Pressure Trace.
- Actual injection rate of fuel.
- Air mass flow rate.
- Fuel mass flow rate.
- Working gas temperatures etc.

Thus, from the previous experimental data, all information required to simulate the engine and estimate the AHRR from the measured cylinder pressure are known. Before analyzing the problem associated with the estimation of the actual rate of fuel utilization from the measured cylinder pressure providing a short description of the simulation model used is provided [4,9].

Brief Description of the Simulation Model

Using the simulation code described above in brief, predictions are made for engine performance and emissions at the three test points mentioned in Table 2. The calculated cylinder pressure traces produced when compared with the measured ones reveal a very good agreement as shown in Figs. 1a-c. Of course cylinder pressure can be predicted accurately using much simpler models. The reason for using a multi-zone approach in the present work is to have a good representation of the spatial distribution of temperature and composition inside the combustion chamber. The simulation manages to predict adequately the compression and combustion/expansion processes. The first suggests that the heat transfer mechanism is predicted with reasonable accuracy. But, as revealed from the analysis, even if an error exists in its estimation, it cannot explain the error observed between the calculated and experimentally derived Net Heat Release Rates shown in the next paragraph.

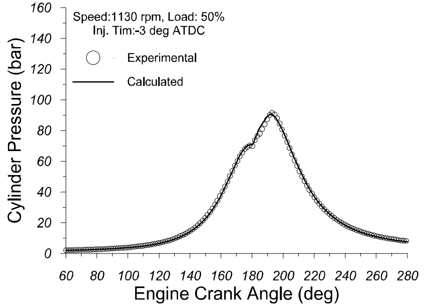

Figure 1a. Comparison between calculated and experimental cylinder pressure traces at 1130 rpm and 50% load

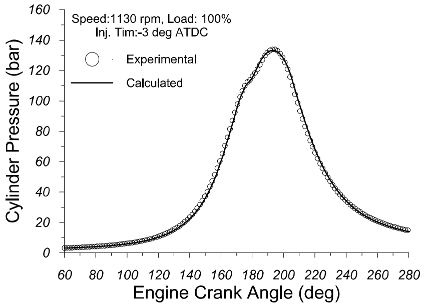

Figure 1b. Comparison between calculated and experimental cylinder pressure traces at 1130 rpm and 100% load

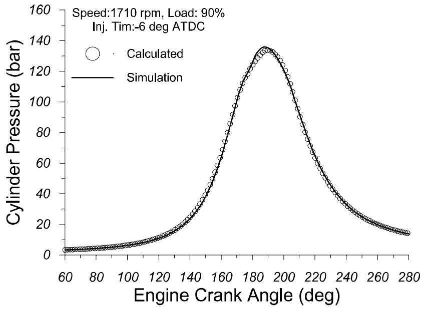

Figure 1c. Comparison between predicted and experimental cylinder pressure values at 1710 rpm and at 90% load.

Prediction of the Net Heat Release Rate

Following this, a comparison is made between theoretical and experimentally derived net heat release traces using the values obtained from EQ(4). The actual net heat release rate used in the model is the one provided by the following equation where dm_f/dt is the calculated combustion rate of fuel:

$$\frac{dQ_{cal,net}}{d\varphi} = \frac{dm_f}{d\varphi} H_{fuel} - \frac{dQ_w}{d\varphi} \qquad (6)$$

H_{fuel} is its heating value and dQ_w the instantaneous heat exchange rate of the working gas with the cylinder walls [18-20]. Comparing values $dQ_{cal,net}$ and $dQ_{exp,net}$ the results shown in Figs 2a-c are obtained for all cases examined. As observed, the calculated actual net heat release rate differs significantly from the experimentally derived apparent one even though a very accurate match is observed when comparing the computed cylinder pressure trace with the measured one. This reveals that either the AHRR estimated form the measured cylinder pressure is not the actual or that an error exists in the solution method used in the simulation. The last is eliminated by checking the first thermodynamic law in each computational time step. The check is performed comparing the above mentioned theoretical net heat release rate $dQ_{cal,net}$ with the following value,

$$\begin{aligned} dQ_{o,net} = & \left[m_u(u_u\text{-}u_{u,ref})\text{-}m_{u,0}(u_{u,0}\text{-}u_{u,ref}) + (\frac{p+p_0}{2})dV_u \right] + \\ & \sum_i \left[m_{bi}(u_{bi}\text{-}u_{bi,ref})\text{-}m_{bi,0}(u_{bi0,}\text{-}u_{bi,ref}) + (\frac{p+p_0}{2})dV_{bi} \right] \end{aligned} \qquad (7)$$

that expresses the energy transferred from the fuel to the working gas. The comparison conducted has shown that the two values are practically the same revealing the accuracy of the method used to solve the thermodynamics in the simulation (i.e. numerical errors).

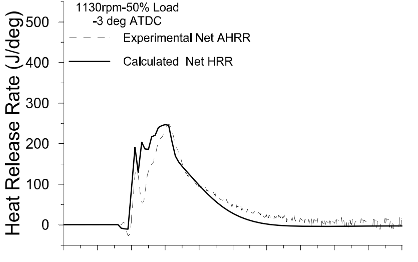

Figure 2a. Comparison between calculated and experimental net heat release rate profiles at 1130 rpm and at 50% load.

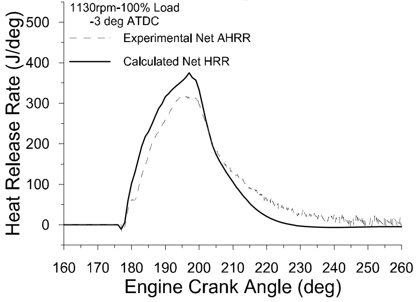

Figure 2b. Comparison between calculated and experimental net heat release rate profiles at 1130 rpm and at 100% load.

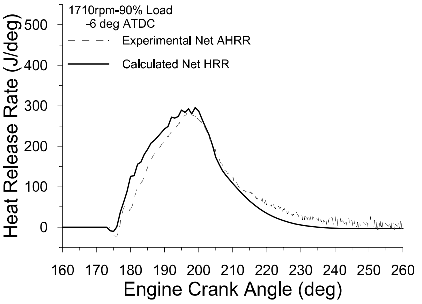

Figure 2c. Comparison between calculated and experimental net heat release rate profiles at 1710 rpm and at 90% load.

ANALYSIS OF THE ERROR IN THE ESTIMATION OF THE ACTUAL NET HEAT RELEASE RATE

Based on the previous it appears that possibly the estimated AHRR estimated from the measured cylinder pressure trace is not the actual one i.e. the one resulting form the combustion rate of fuel. An answer to the problem would be to have the measured cylinder pressure diagram and at the same time the actual rate of fuel utilization inside the combustion chamber, but the last is extremely difficult if not impossible. To overcome the problem it is decided in the present to use the simulation as a source for this information. Using the simulation, we estimate the cylinder pressure trace and treat it as if it were the experimental one. Then we apply the HRR analysis method used for the experimental cylinder pressure trace. Using this procedure, we have the following advantages:

- The actual combustion rate of fuel is known (the one used by the simulation to produce the cylinder pressure trace).
- The initial trapped mass is known and equal to the one used by the simulation.
- The variation of cylinder mass is known.
- The overall composition at each time instant is known.
- Errors concerning the TDC position and the cylinder pressure value are eliminated since the values used are the calculated ones.

If the conventional methodology followed for the estimation of the heat release rate where correct one would expect the estimated net heat release rate to compare with the one used in the simulation, EQ (6). The results from this comparison are given in Figs 3a-c while in each figure it is also given the corresponding relative error between the two heat release rates. As revealed the heat release rate obtained from the HRR analysis does not compare with the one actually used to produce the corresponding cylinder pressure diagram. The error is high during the initial and final stages of combustion. Furthermore, the error increases with decreasing load and engine speed. The reason for this error is provided from the simulation.

For the HRR analysis procedure, the instantaneous working gas temperature is estimated from the perfect gas state equation. This value is a mean one and is not thermodynamically correct since inside the combustion chamber of a DI diesel engine there is a relatively wide distribution of temperature and composition during the combustion-expansion process. This is supported by Figs 3a-c where it is observed that the error is higher at part load and low engine speed where the heterogeneity in temperature and composition inside the combustion chamber is higher. For this reason if one wishes to estimate a mean temperature that is thermodynamically correct, the following relation should be satisfied:

$$\sum_i m_i u_i(T_i) = m_{tot} u(\overline{T}_{th}) \tag{8}$$

this temperature does not compare with the one estimated from the perfect gas state equation using the measured cylinder pressure, i.e.:

$$\overline{T}_{th} \neq \overline{T} = \frac{pV}{mR} \tag{9}$$

This difference is shown in Fig. 4, where it is given the comparison for one test case examined between the two temperature values. The error is relatively high and affects the accuracy of the heat release rate analysis procedure. If one had used the mean thermodynamic temperature $\overline{T}_{th}$ instead of the spatial mean one, the error would be practically zero. This is verified by Fig. 5, where it is given the comparison between the net AHRR estimated from the HRR analysis methodology using the mean thermodynamic temperature, instead of the mean arithmetic one, with the actual net heat release (theoretical) EQ(6). Thus it is verified that the error observed is due to the non-uniform distribution of temperature and composition inside the combustion chamber and is relatively high.

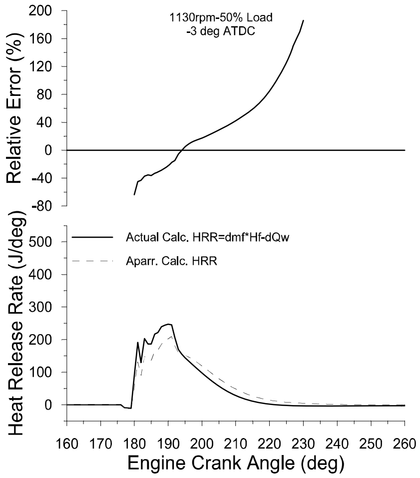

Figure 3a. Apparent and actual net heat release rates at 1130 rpm and at 50% load obtained from the simulation.

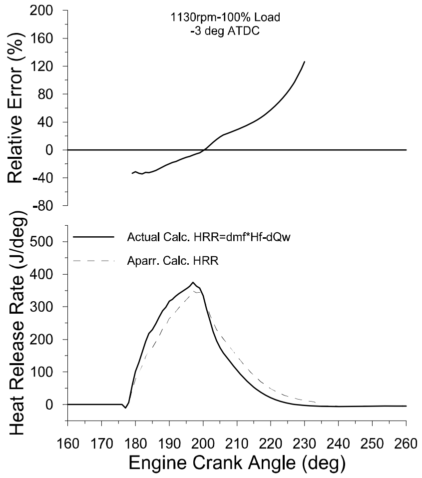

Figure 3b. Apparent and actual net heat release rates at 1130 rpm and at 100% load obtained from the simulation.

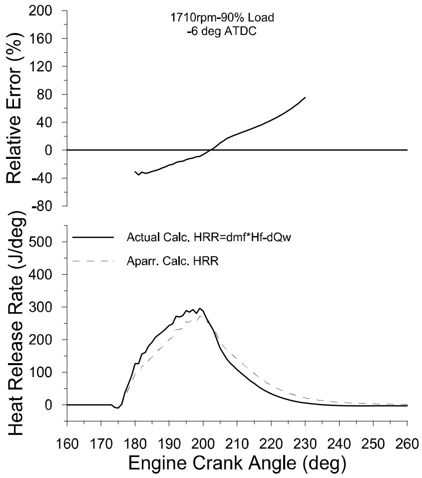

Figure 3c. Apparent and actual net heat release rates at 1710 rpm and at 90% load obtained from the simulation

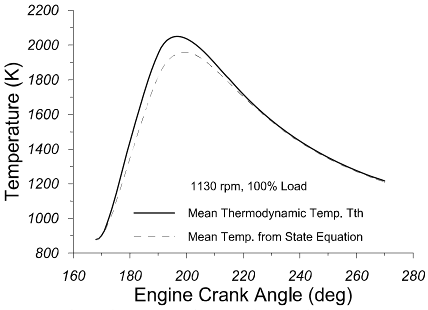

Figure 4. Comparison between thermodynamic mean gas temperature and mean gas temperature calculated from state equation at 1130 rpm and at 100% load.

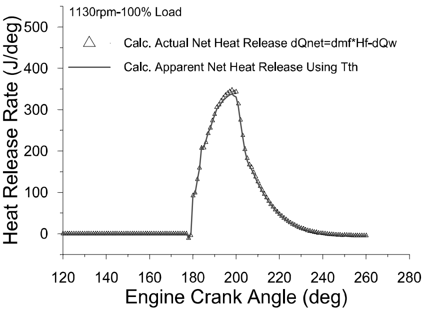

Figure 5. Calculated actual and apparent net heat release rates using the thermodynamic mean gas temperature at 1130 rpm and at 100% load.

CONCLUSIONS

The present investigation deals with the errors involved in the estimation of the actula net heat release rate of fuel obtained from the processing of measured cylinder pressure data using conventional heat release rate techniques.

From an investigation conducted on a single cylinder DI diesel engine it is realised that an error exists when estimating the net heat release rate using conventional HRR analysis techniques. The error is observed at all operating cases examined and its relative value is high especially during the initial and final stages of the combustion mechanism. The combustion rate of fuel obtained from the HRR analysis is underestimated during the initial phases of combustion and overestimated during expansion (diffusion combustion). The source of error is revealed using a simulation model as a “virtual” engine to produce the cylinder pressure traces used by the HRR analysis. Using this methodology, the actual combustion rate of fuel required to produce the specific pressure trace is known accurately. As revealed that the error in HRR estimation arises from the fact that distribution of temperature and composition during DI diesel engine combustion is extremely heterogeneous. As a result, the temperature estimated from the perfect gas state equation and the measured cylinder pressure is only an indicative mean value and does not provide the thermodynamic state of the working gas. This is the main source of the error observed.

Thus, it is not possible to estimate the actual combustion rate of fuel from the measured cylinder pressure using conventional techniques. This is in line with comments made in the past by various researchers. In the present work a more thorough investigation has been conducted, that has allowed us to quantify the relevant error. To estimate the actual rate of fuel utilization inside the combustion chamber using the measured cylinder pressure trace,a different analysis is required, involving possibly the use of at least a two-zone model to provide an acceptable representation of the spatial distribution of temperature and composition inside the combustion chamber.

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