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USING IN-CYLINDER GAS INTERNAL ENERGY BALANCE TO CALIBRATE CYLINDER PRESSURE DATA AND ESTIMATE RESIDUAL GAS AMOUNT IN GASOLINE HOMOGENEOUS CHARGE COMPRESSION IGNITION COMBUSTION

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NOMENCLATURE

Symbols

P	pressure
V	volume
T	temperature
N	number of moles
R	universal gas constant
Q	heat energy
θ	CAD
b	bore
s	stroke
l	conrod length
V_c	clearance volume
$PinOffset$	piston pin offset
m	mass
c_p	specific heat at constant pressure
c_v	specific heat at constant volume
γ	specific heat ratio
K	polytropic exponent
P_{ivo}	pressure at IVO
P_{ivc}	pressure at IVC
P_{evc}	pressure at EVC
V_{ivo}	volume at IVO
V_{ivc}	volume at IVC
V_{evc}	volume at EVC
T_{ivo}	temperature at IVO
T_{exh}	exhaust gas temperature
T_{mixt}	mixture temperature
T_{trg}	TRG temperature

T_{ch}	charge temperature
N_{mixt}	number of moles of mixture
N_{trg}	number of moles of TRG
N_{ch}	number of moles of charge
m_{trg}	mass of TRG
m_{ch}	mass of charge
$c_{v_{mixt}(T_{mixt})}$	mixture c_v at T_{mixt}
$c_{v_{trg}(T_{trg})}$	TRG c_v at T_{trg}
$c_{v_{ch}(T_{ch})}$	charge c_v at T_{ch}
$IMEP_{gross}$	gross IMEP
$IMEP_{net}$	net IMEP
$IMEP_{meas}$	measured IMEP
$IMEP_{corr}$	corrected IMEP

Abbreviations

AFR	air–fuel ratio
AVT	active valve train
BDC	bottom dead center
BMEP	brake mean effective pressure
CAD	crank angle degrees
CR	compression ratio
EGR	exhaust gas recirculation
EGT	exhaust gas temperature
EVC	exhaust valve closing time
EVO	exhaust valve opening time
FVVT	fully variable valve timing
FMEP	friction mean effective pressure
HCCI	homogeneous charge compression ignition
IMEP	indicated mean effective pressure

ITA	ignition timing advance
IVC	inlet valve closing time
IVO	inlet valve opening time
MAP	manifold air pressure
RPM	revolutions per minute
SI	spark ignition
TDC	top dead center
TRG	trapped residual gas
WOT	wide-open throttle

INTRODUCTION

HCCI engines are likely to become one of the future alternatives to SI engines due to their ability to deliver high efficiency and low NOx emissions. There are, however, problems with the control of the ignition and heat release rate over the entire load and the speed range, which limits the practical application of this technology [1].

In order to investigate the combustion parameters of both SI and HCCI gasoline engines, a widely used and powerful diagnostic tool is the analysis of the in-cylinder pressure time history as derived from in-cylinder pressure transducers [2, 3]. Such information has particular application in HCCI engines for control of TRG levels, valve timing, misfire and knock detection.

Unfortunately, although the use of in-cylinder pressure transducers for that purpose has been an invaluable research tool, it is not without problems. In the case of HCCI combustion, the violent rates of heat release make the signal derived from pressure transducers more prone to thermal shock. In addition, in HCCI research, it is often necessary to establish the TRG amount as accurately as possible. However, TRG presence also complicates pegging techniques. Since the pressure transducer signal can be compromised by these calibration issues, it is prudent to try to address these issues when dealing with pressure signals derived during HCCI operation.

The present article presents an algorithm aiming to account for these calibration issues surrounding the use of pressure transducers in HCCI research. Results for the TRG amount and initial mixture composition and temperature on a cycle-to-cycle basis are also derived.

EXPERIMENTAL SETUP

The engine employed in this research was a single-cylinder, gasoline-port fuel injected, four-stroke research engine based on a GM Family One, 1.8 L series architecture, as shown by the photograph in Figure 1. It has a production piston and stroke with a standard four-cylinder head on top of a water-cooled barrel and a custom-made bottom end. Only the front cylinder of the head is operational. A Lotus Engineering FVVT system named Active Valve Train is fitted to allow a variable valve timing strategy. Variable quantities of TRG can be captured in this way. Use of the AVT gives the capability of trapping the residual gas in the cylinder through early EVC as opposed to recirculating it through the inlet. Because this strategy has been employed throughout this research, the term TRG is being used as opposed to the commonly employed EGR.
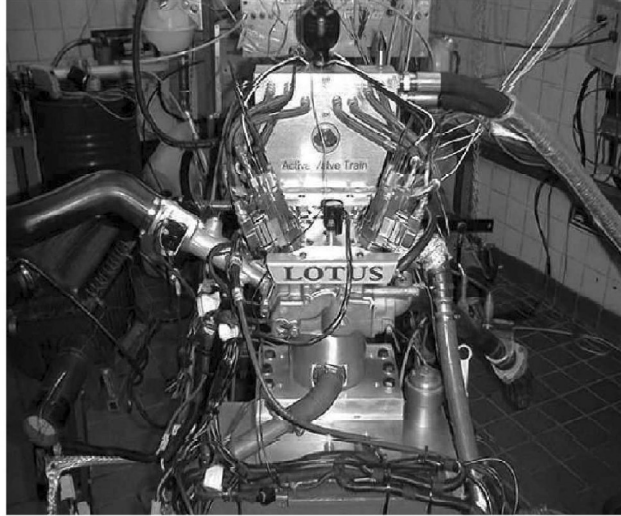
Figure 1. Single-cylinder research engine with AVT system.

For this investigation, the CR was set at 10.5:1.

The engine was connected to a Froude AG30 30-kW eddy-current dynamometer. RedLine ACAP™, from DSP Technology Inc., is a PC-based program for real-time internal combustion engine analysis and general data acquisition. It was used together with a Kistler 6123 piezoelectric pressure transducer and a Horiba MEXA 7100 DEGR emissions analyzer. Port fuel injection was employed, which was managed by a conventional Lotus V8 engine controller.

Note that all signals have been related to CAD through a crank encoder. Hence, volume has been indirectly calculated through the crank slider with pin offset equation:

$$V = V_c + \pi \frac{b^2}{4} \left\{ 1 + \frac{s}{2} - \frac{s}{2} \cos(\theta) - l \cos\left(arc \sin\left(\frac{\frac{s}{2}\sin(\theta) + PinOffset}{l} \right) \right) \right\} \tag{1}$$

where b is the bore, s the stroke, and l the conrod length.

OVERVIEW OF PRESSURE TRANSDUCER CALIBRATION AND TRY ESTIMATION ISSUES

Experimental data gathered through piezolectric pressure transducers needs to be processed before it can be used. The most common form of processing is pegging, which safeguards the signal from drifting into incorrect values over relatively long periods (of the order of whole cycles).

Less common is thermal shock, which affects only part of the signal within short periods (typically after the "hot" part of the pressure trace). In SI operation, the effects of thermal shock, if any, do not interfere too much with measurements since each cycle can be more or less regarded as an individual. In HCCI, however, cycles can be interconnected since each cycle "inherits" TRG from the preceding cycle. In turn, this interconnection creates pegging issues when individual cycles are considered since TRG must be established in order for a cycle to be accurately pegged.

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What must be appreciated here is that TRG must be established in order for a cycle to be pegged but a cycle must be pegged in order for TRG to be established. This apparent deadlock can normally be resolved by starting from reasonable values and applying iterative methods that typically converge very fast. There are, however, complications in this scheme, which arise mainly from thermal shock-related deviations. It is the aim of this article to overcome these hurdles and present a complete numerical recipe for treating such data.

Pegging

Pegging techniques usually fall within two broad categories: using the reading of an extra sensor (e.g., MAP) or fitting a polytropic compression curve [4, 5].

Using an external MAP sensor has the advantage of trustworthy readings in the relatively small range of values it records. Assuming knowledge of the location at which the in-cylinder pressure transducer's trace and the MAP record equal pressure, the signal for a given cycle can be pegged very accurately.

The drawback of the method is that estimating the location of pressure equalization is not trivial. Even assuming a thorough investigation, mapping the engine across the required speed and load range, HCCI combustion can suffer from violent cyclic oscillations [6] which can, in extreme cases, result in a heavy backflow from the cylinder into the inlet. Thus, an assumption of a specific location of pressure equalization between cylinder and inlet for a given speed and load site will often be inaccurate if no further processing is carried out to determine the effects of individual cycles' performance.

On the other hand, trying to fit a polytropic curve of the form $PV^K = C$ has the disadvantage of requiring an accurate value for the choice of polytropic exponent, K, whose value depends upon γ, whose value is in turn dependent upon mixture composition and temperature [7, 8].

The big advantage is that the oscillations of unstable HCCI are less of an issue, and thus, more cycles displaying extreme values can be salvaged.

Both techniques described above need to take TRG into account; the first due to gas dynamics issues, the second since it affects the polytropic exponent. However, the second method lends itself more readily to treating the broad range of conditions that can be expected in HCCI operations. For these reasons, the polytropic pegging method has been chosen for dealing with HCCI data.

To make the results more robust, the procedure described by Tunestal is used [4], where multiple P and V values are used in matrix form:

$$\begin{pmatrix} P_{m1} \\ \vdots \\ P_{mn} \end{pmatrix} = \begin{pmatrix} 1 & V_1^{-K} \\ \vdots & \vdots \\ 1 & V_n^{-K} \end{pmatrix} \begin{pmatrix} \Delta P \\ C \end{pmatrix} \tag{2}$$

and the P_m values represent measured pressure while ΔP is the shift in the data.

TRG Estimation and Thermal Shock

Thermal shock becomes a main issue when considering TRG estimation. The known input quantities for the engine are the measured air and fuel flow and corresponding temperatures. The outputs are known in the form of EGT. The two points where gas exchange events terminate are IVC and EVC. Their attributes are summarized in Figure 2.
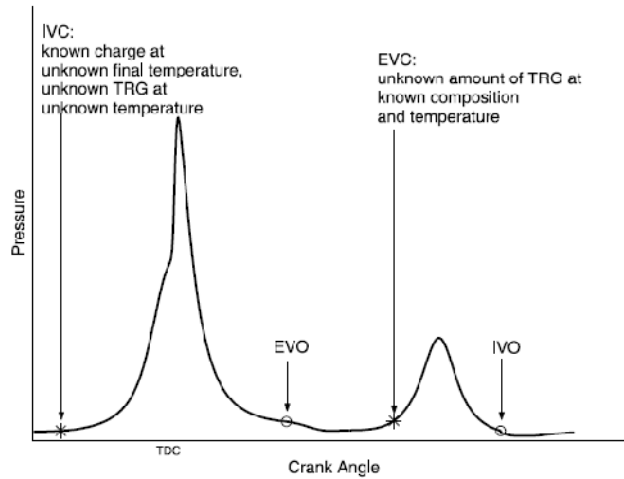

Figure 2. Comparison of IVC and EVC as starting points.

EVC is the best point for calculating TRG because, assuming a non misfiring cycle, the chemical composition is known (burnt charge corresponding to whatever initial AFR and completeness of combustion). At EVC, the gas in the cylinder will have expanded to reach the same pressure as that of the exhaust, while the temperature will have dropped to that recorded next to the exhaust valve [1]. Hence, applying the ideal gas law will yield the molar amount of TRG at EVC as $N_{TRG} = \frac{P_{EVC}V_{EVC}}{RT_{Exhaust}}$, which will be carried unchanged (assuming no significant blowby) to be mixed with a fresh charge at IVO.

The problem of thermal shock becomes apparent when considering the final mixture temperature at IVC as outlined in Figure 3.

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[1] The strength of this assumption is somewhat tenuous at first glance. A much more in depth investigation is presented in the section "EGT Measurement Issues."
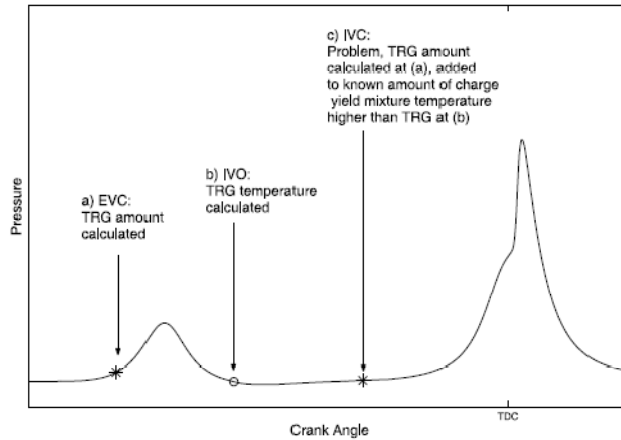
Figure 3. Temperature discrepancy between IVO and IVC.

Because the amount of both TRG and fresh charge are known at IVC, and so are pressure and volume data, it is possible to calculate the final mixture temperature through the ideal gas law as $T_{IVC} = \frac{P_{IVC}V_{IVC}}{RN_{Total}}$.

However, the TRG temperature at IVO can be also be arrived at by simply following the pressure trace from EVC and matching a temperature trace to it via the ideal gas law. Then, the obvious discrepancy shown in Figure 3 is that the TRG temperature at IVO can be lower than that of the total mixture at IVC, where the hot TRG has been mixed with relatively cold fresh charge.

There are two main candidates for such an error—incorrect pegging and thermal shock. However, pegging cannot resolve the problem by itself since shifting the whole curve simply scales the numbers. It is then obvious that the error must lie within the pressure trace itself [2].

DESCRIPTION OF CALIBRATION ALGORITHM FOR AVERAGED DATA

The issues as discussed so far are as follows:

1. pegging: requires knowledge of TRG and charge amount at IVC;
2. TRG estimation: requires accurate pegging; and
3. thermal shock estimation: must be established so that accurate TRG is used.

The cyclic nature of this problem requires some sort of iterative method for treatment since simply altering one parameter so that balance is apparently achieved affects all aspects of the data.

Because the algorithm needs to make use of the charge flow measurements at this stage, the procedure described in this section applies to averaged traces only. This is because, while the measured flows will hold true for such a trace, they will not necessarily do so for a random cycle. Only once the parameters for the averaged trace have been established can the procedure be expanded to treat individual cycles as described in the section "Expansion of Algorithm to Individual Cycles."

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[2] Evidence for thermal shock is elaborated in the section "Thermal Shock-Related Pressure Trace Error."

Initial TRG Estimation

So, assuming a pegged trace [3], consider that during the induction, hot TRG arrives at IVO and cold charge is introduced into it. Assuming negligible heat losses, the process is described by

$$(m_{trg} + m_{ch})c_{mixt(T_{mixt})}T_{mixt} = m_{trg}c_{v_{trg}(T_{trg})}T_{trg} + m_{ch}c_{v_{ch}(T_{ch})}T_{ch} \tag{3}$$

which is a conservation of internal energy equation between charge, TRG, and their mixture. m_{trg} and m_{ch} are the masses of TRG and charge, respectively. T_{mixt}, T_{trg}, and T_{ch} are the temperatures of mixture, TRG, and charge respectively. Finally, $c_{v_{mixt}(T_{mixt})}$, $c_{v_{trg}(T_{trg})}$, and $c_{v_{ch}(T_{ch})}$ are the specific heats of mixture, TRG, and charge at their respective temperatures.

In addition to the above, the ideal gas law for the case of the total mixture at IVC becomes

$$P_{ivc}V_{ivc} = (N_{trg} + N_{ch})RT_{mixt} \tag{4}$$

In both Eqs. (3) and (4), there are two unknowns—the amount of TRG (mentioned as mass in Eq. (3) and moles in Eq. (4)) and the final temperature of the total mixture.

Also, "unknown" is the specific heat of the total mixture (since it is at an unknown temperature). However, specific heat changes only slightly with temperature and it can initially be taken as a constant until iterative methods yield a precise value.

As far as TRG temperature is concerned, if we know the initial and final point (in this case EVC and IVO) volume and pressure values, the TRG molar amount is not necessary, and so for TRG at IVO

$$T_{ivo} = T_{exh} \times \frac{P_{ivo}V_{ivo}}{P_{evc}V_{evc}} \tag{5}$$

Solving these equations yields values for both the amount of TRG and the total mixture temperature. Specific heats for TRG and for charge can be calculated since their composition and temperature are known. As for the total mixture, an initial guess can be made by averaging the value of the other two. Then, once a value is calculated for TRG (thus allowing calculation of total mixture composition) and total mixture temperature, the specific heat of the total mixture can be calculated, the whole trace repegged, and the process repeated until a satisfactory level of convergence is reached.

What has been described above is, in effect, a statement that reads: calculate the amount of TRG at known temperature that, when mixed with a known amount of charge at a known temperature, will yield a mixture at an unknown temperature, occupying volume V_{ivc} at a pressure P_{ivc}.

Pressure Shift Estimation and Pegging

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[3] The pegging procedure is also finalized through iteration as will become apparent. Initially, assume a signal pegged at some "reasonable" value.

Now consider the initial TRG estimation method of applying the ideal gas law at EVC. This generally gives a different result than the process described above. Now, assuming this difference is due to the pressure at EVC having been altered by thermal shock, the necessary pressure shift can be established, which would correct the EVC pressure reading and, hence, the calculated TRG amount [4]. This pressure shift will have an effect on the TRG temperature at IVO (Eq. (5)) and, in turn, on the TRG amount and total mixture temperature as calculated based on Eqs. (3), (4), and (5).

Because of this dependency, once the pressure shift has been established, the whole procedure can be started again until satisfactory convergence is reached.

What has been described so far is, in essence, two iterations establishing pegging, TRG amount, and total mixture composition and temperature at IVC. The whole procedure is visually described in Figure 4. What is labeled as "inner iteration" is the process described in the section entitled "Initial TRG Estimation," while "outer iteration" is the process described in section "Pressure Shift Estimation and Pegging."

Starting from the top, it reads as follows (initially assume a trace pegged at some "reasonable" value, e.g., pressure equal to atmospheric at IVC):

- Pressure values at EVC, IVO, and EGT yield TRG temperature at IVO (Eq. (5)).
- TRG temperature at IVO coupled with charge amount and temperature yield TRG amount and total mixture temperature (Eqs. (3) and (4)).
- TRG amount and total mixture temperature yield more precise specific heats and pegging; inner loop continues until satisfactory convergence.
- TRG amount from inner loop is compared to that predicted by ideal gas law at EVC; pressure shift is established for region between combustion and IVO.
- Pressure shift applied changes pressure data; return to top and continue until satisfactory convergence.

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[4] In this research, the pressure shift has been assumed to affect the part of the curve starting after combustion and ending at IVO.
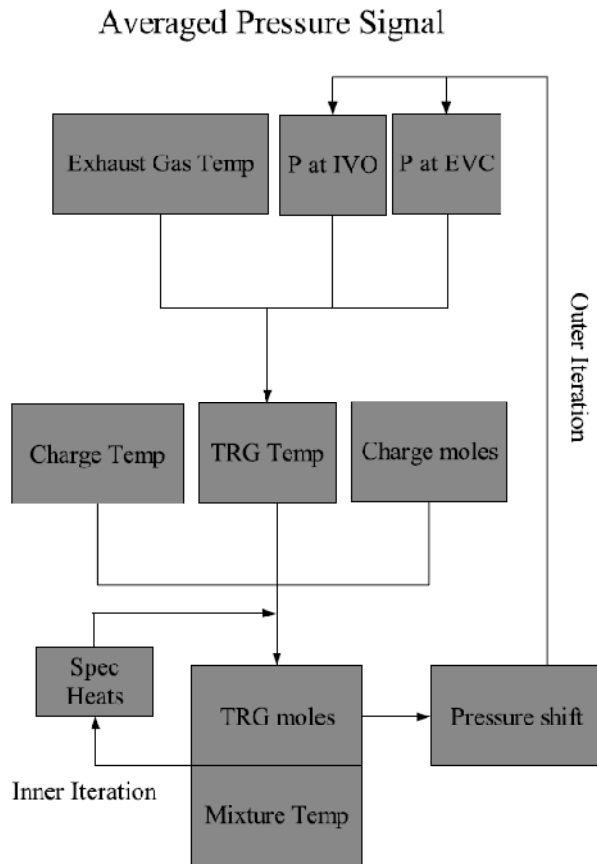
Figure 4. TRG, mixture temperature, and pressure shift calculation process.

EXPANSION OF ALGORITHM TO INDIVIDUAL CYCLES

Once the combustion analysis for the averaged trace has been carried out, cycle-tocycle analysis can be performed. This is because the calculated variables of the average trace will be close, but not necessarily identical, to the variables of the individual cycles within a log taken at a single operating condition. In the case of unstable combustion, where misfires and other extreme phenomena are common, these can vary greatly.

The analysis in this case has to take into account the small variations between successive cycles. In the averaged trace case, the beginning and the end of the cycle could be assumed to touch. In this case, successive cycles pass information from one to the other through the TRG and temperature variables. This means that each cycle's variables, e.g.,

- the pegging,
- the initial mixture composition,
- the thermal shock-related pressure shift,
- the TRG, and
- the exhaust temperature

need to be established individually. Also, due to the nature of this process, small errors can easily accumulate and damage the final result. This needs to be averted as explained in the section entitled "Safeguards Against Erroneous Data in Individual Cycle Procedure."

The first cycle "inherits" the data of the averaged cycle as a starting point. In the following text, we will consider the treatment of a random cycle, graphically represented in Figure 5.
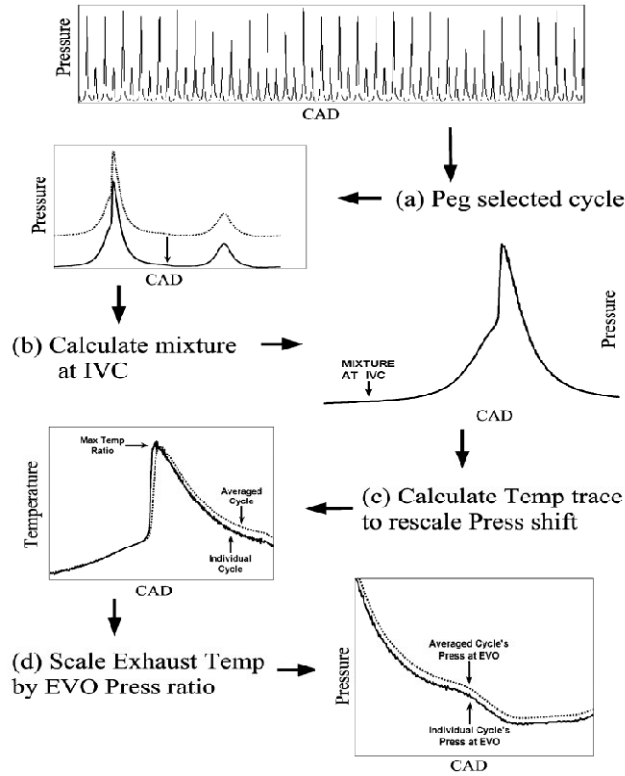

Figure 5. Treatment of individual cycles for cycle-per-cycle calculations.

First, the cycle is pegged using the value of polytropic exponent estimated for the averaged cycle for the given data set (Figure 5a). Once the cycle is pegged, the pressure at IVC is known.

The next step involves calculation of the mixture at IVC (Figure 5b). This time, we cannot assume knowledge of the charge amount as has been the case with the average trace. Hence, we need to reconsider Eqs. (3) and (4). What we have given [5]5 is:

- TRG amount (m_{trg}, N_{trg}),
- TRG temperature (T_{trg}),
- charge composition,
- charge temperature (T_{ch}),

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[5] Note that the first two items, TRG amount and temperature, are "inherited" from the previous cycle and are thus not known for the first cycle of a log. So, in the case of the first cycle, the values for the averaged trace are used.

- pressure at IVC (P_{ivc}), and
- volume at IVC (V_{ivc}).

Composition and temperature for charge and TRG lead to calculation of their specific heats, ($c_{v_{ch(T_{ch})}}$ and $c_{v_{trg(T_{trg})}}$). Knowledge of charge composition leads to calculation of its molecular weight, thus linking the m_{ch} and N_{ch} terms across Eqs. (3) and (4) by $N_{ch} = \frac{m_{ch}}{w_{ch}}$, where w_{ch} refers to the molecular weight of the charge. Finally, the specific heat of the mixture ($c_{v_{mixt(T_{mixt})}}$ cannot be directly calculated yet. However, it can be expected to lie between that of charge and TRG [6].

So, Eqs. (3) and (4) now become a system of two equations with two unknowns – mixture temperature, T_{mixt}, and charge mass, m_{ch}. They can be rewritten as follows:

$$m_{ch}\left(c_{v_{mixt(T_{mixt})}}T_{mixt} - c_{v_{ch(T_{ch})}}T_{ch}\right) = U_{trg} - m_{trg}c_{v_{mixt(T_{mixt})}}T_{mixt} \tag{6}$$

where $U_{trg} = m_{trg}c_{v_{trg(T_{trg})}}T_{trg}$ refers to the TRG internal energy (replaced for brevity), and

$$T_{mixt} = \frac{P_{ivc}V_{ivc}}{R\left(N_{trg} + \frac{m_{ch}}{w_{ch}}\right)} \tag{7}$$

Simultaneously solving these two equations leads to the mixture at IVC (Figure 5b).

The pegged pressure trace is still not treated for the thermal shock-related pressure shift. Since there is no way of estimating how much this shift varies between cycles, a simple technique has been employed. Since the pressure and volume traces are known for the individual and averaged cycles, and number of moles of total mixture has been calculated at IVC; a temperature trace can also be worked out for the individual cycle through the ideal gas law. Assuming that the shift is affected mostly by temperature, the shift of the cycle, ΔP, is calculated by scaling the shift of the averaged signal, ΔP_{ave}, by the ratio of the maximum temperatures of the two traces, $\Delta P = \frac{T_{max}}{T_{max_{ave}}}\Delta P_{ave}$, before being applied to the pressure trace (Figure 5c).

One more variable remains that needs to vary between cycles but whose value can't be directly measured—the EGT. From the ideal gas law, it follows that it is equal to $\frac{PV}{NR}$. Since V at the valve events and R are constant within a data set, the variation in this can be tracked by the $\frac{P}{N}$ fraction since, by this stage, both the corrected pressure and the moles of mixture are known.

This, however, cannot be applied. Using the number of moles of mixture, N_{mixt}, into the exhaust temperature calculation introduces a variable that is inherited directly across cycles: from N_{mixt}, calculated at IVC of the nth cycle, to the N_{mixt}-dependent exhaust temperature that affects the TRG calculation of the nth cycle, which is inherited by the $n + 1$th cycle. In trials, this leads to runaway

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[6] Of course, once the mixture composition and temperature has been calculated based upon this assumption, its specific heat can be calculated as well. Repeating the process using this value yields progressively better results.

results. Thus, the variation in EGT is being scaled by the fraction of pressures only (averaged and individual) at EVC.

TEST OF SUITABILITY OF CALIBRATION ALGORITHM

While the procedure described thus far may sound logical in theory, there are certain issues that need closer inspection in order for the applicability of the whole- to real-life data to be established. These are:

1. the pegging method and its applicability to the problem at hand, specifically focusing on sensitivity to the potential error sources, in this case, composition and temperature;
2. the pressure trace error as to whether it is indeed related to thermal shock;
3. the assumption that bulk TRG temperature is measurable by the EGT thermocouple for plausible deviations of the averaged thermocouple reading to the expected actual value of the gases; and
4. the algorithm for treating individual cycles and its potential proneness to cumulative errors as treating consecutive cycles progresses, and the establishment of its robustness against such errors.
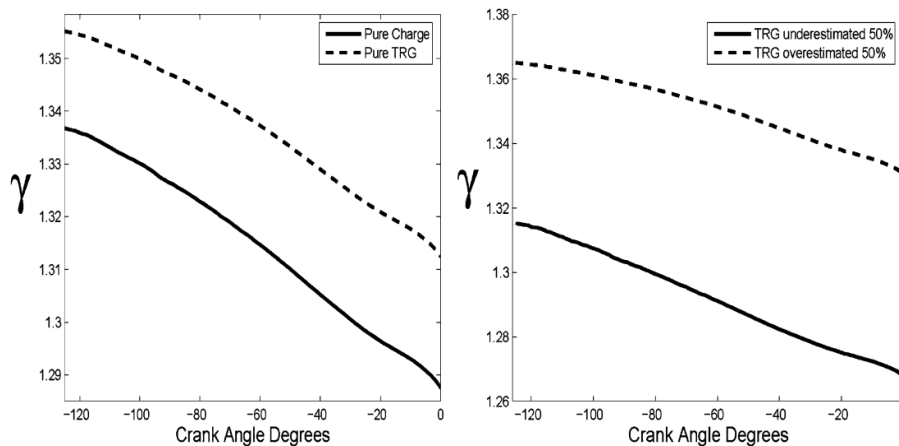

Figure 6. Left: Gamma for the two possible extremes of mixture composition for a typical temperature trace of a compression stroke. Right: Gamma where the temperature traces vary corresponding to varying the estimated TRG (2,000 RPM, 54% volumetric TRG, 2.9-bar IMEP).

Polytropic Exponent and Pegging Issues

The main issue behind using the polytropic exponent pegging method is the choice of the polytropic exponent, K. In an ideal case, $K = \gamma = \frac{c_p}{c_v}$, where c_p and c_v denote specific heat at constant pressure and volume, respectively. In practice, the values of γ and K always deviate somewhat. However, given the composition and temperature of the in-cylinder gases, values for c_p and c_v can be worked out [7, 8]. Hence, if a satisfactory relationship between γ and K can be established, accurate pegging can be carried out for cycles of varying composition.

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A first step is to look at γ and the factors affecting it – namely composition and temperature.

Figure 6 (left) demonstrates the γ variation of two drastically different mixtures – one made up completely of a fresh (stoichiometric) charge of the type used in this research [7] and the other made up entirely of burnt gas. The calculation has been based upon a typical temperature trace from a high TRG, HCCI data log. As can be seen in the figure, the value of γ remains largely unperturbed by the change in composition. The difference between the two traces is of the order of 1.6%.

Having examined the effect of composition upon γ, the temperature effect also needs to be investigated. Temperature cannot be directly measured and has to be derived from the pressure trace through use of the ideal gas law. Hence, the amount of TRG plays a role, not only as a variable affecting the value of the mixture composition, but also as a variable affecting the temperature trace. This double effect is examined by varying the estimated TRG amount by $\pm50\%$ and the results are demonstrated in Figure 6 (right). The data log used in this figure has the maximum amount of TRG of a series of experiments. Thus, the varying of the TRG amount has maximum impact within experimentally reasonable numbers.

The effect shown here is calculated by taking a pegged pressure trace, changing the TRG amount, and then calculating the new temperature trace and, hence, the new γ trace. Thus, the changing TRG has a twofold impact on the final result. Note that by looking at Figure 6 (left), an increased amount of TRG in the mixture composition increases the value of γ. Also, since temperature increases from left to right as the compression stroke progresses towards TDC, it follows that increasing temperature decreases γ. Now, because the temperature trace is affected by the TRG amount according to the ideal gas law, it follows that an increased amount of TRG decreases the temperature, thus increasing γ. However, γ is further increased through the effect of increased TRG in the mixture composition. Still, despite the fact that the two effects add up, the overall effect on γ is of the order of 4%.

Having established the strength of the effect of mixture composition and temperature on γ, it follows that the next variable to be examined is the pegged pressure trace. In this case, K has been varied by ±0.05, roughly the same magnitude as the variation presented in the extremes of Figure 6 (right). The result is demonstrated in Figure 7. The pegging has been done following the matrix algebra technique of Eq. (2) with a fixed value for K as quoted in the legend. The effect of the (approx 4%) K variation on BDC pressure is around 6%.

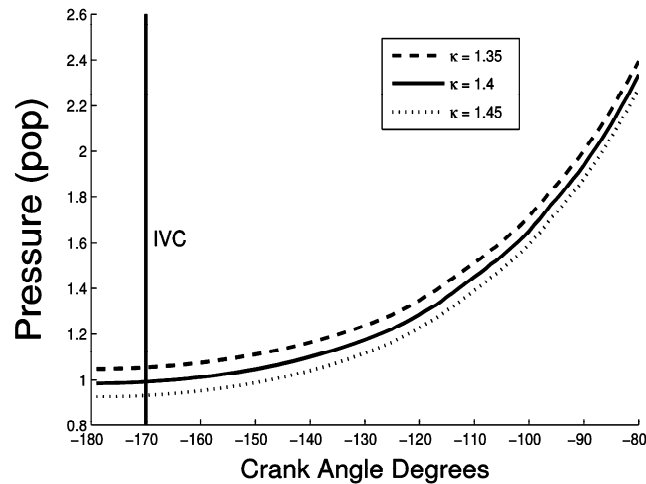[7] Commercial gasoline with H/C ratio of 1.78.

Figure 7. Effect of varying polytropic exponent on pressure pegging.

In order for the fixed K assumption to yield accurate results, a suitable region has to be chosen to provide pressure/volume value pairs. The idea is to find a region that will yield some non trivial pressure/volume variation while keeping the value of γ, and hence K, largely constant. The chosen region for the data throughout this research has been between -125 and -80 CAD.

As can be seen from Figure 6, changes in γ are minuscule within this CAD region, hence making the constant K assumption reasonable. It is also worth noting here that, because this region is early in the compression, temperature and pressure have not been increased significantly; hence, any heat transfer between the gases and the walls are more insignificant than in the latter part of the compression.

Multiple data log method for estimation of the polytropic exponent. It is immediately obvious from Figure 7 that high values of K result in pegging the pressure trace lower. In the figure, the trace to the left of IVC is extrapolated using $PV^K = C$, while the trace to the right is the recorded experimental data. By extrapolating to the left of IVC, the value of mixture pressure at BDC can be established. This is, of course, an ideal value, assuming that the mixture has been constant, i.e., discounting the effects of the valve flows. However, this value is important because there is an upper limit to it; that is, *it cannot exceed the value of MAP. Hence, this poses a lower limit on the value of K.*

This result proves to be of great help when trying to establish the relationship between γ and K. This is established by examining multiple data logs from different speed and load sites. The idea here is that the extrapolated pressure value at BDC will vary according to these two settings. The simple assumption $K = \gamma$ does not yield satisfactory results because certain data logs return pressure values at BDC above 1 bar. This is clearly an error, attributed to the fact that the K deviation from γ cannot be considered negligible.

To account for this, a linear relation $K = \alpha \times \gamma$ is assumed. Because the pressure traces need to be pegged lower, α will have to be greater than 1.

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Figure 8 demonstrates the resulting pressure values at BDC for data logs from multiple speed and load (TRG-controlled) sites. For this research, setting the value of α to 1.05 yields the graph in Figure 8, which is clearly satisfactory. Thus, a very modest departure from the value of γ corrects for $K - \gamma$ deviation.
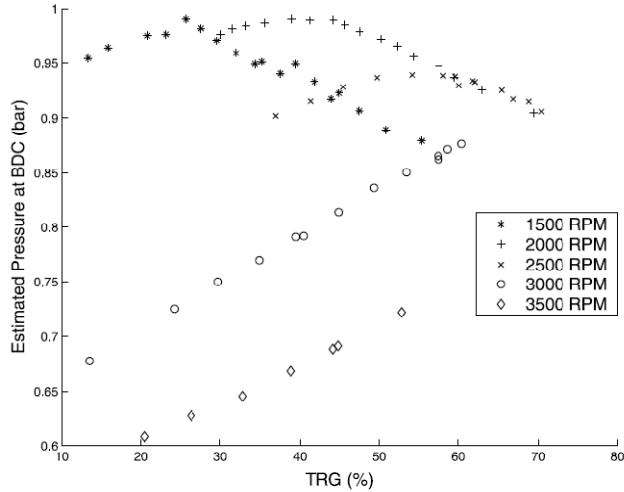

Figure 8. Estimated BDC pressure of averaged traces.

Thermal Shock-Related Pressure Trace Error

The problem of the pressure trace errors affecting TRG calculation as seen in the section "Pressure Shift Estimation and Pegging" most likely lies with the response of the pressure transducer to thermal shock. The specifications of the non water-cooled transducer used in this research allow for a possible 10% error in IMEP estimation on an SI engine. In this case, a water-cooled transducer could not have been used due to limited space on the experimental engine cylinder head. Furthermore, HCCI combustion places a greater strain on the transducer due to the increased rate of pressure rise (typically, maximum rate of rise of HCCI is 2.3 times greater than its SI equivalent).

This becomes apparent when investigating the characteristics of the HCCI cycle through P-V diagrams. A data set has been considered, consisting of data where TRG was varied across its possible range (0% to 50% volumetric in that instance), while $IMEP_{gross}$ was kept constant by throttling the inlet. By subtracting the losses of the gas exchange cycle, $IMEP_{net}$ can be worked out. Finally, through knowledge of BMEP, the value of FMEP can be derived.

The observed trend was for measured BMEP to rise by approximately 0.5 bar across the TRG range, as seen in Figure 9, leading the calculated FMEP to a drop of the same magnitude since $FMEP = IMEP_{net} - BMEP$, and the gas exchange work that is the difference between $IMEP_{gross}$ and $IMEP_{net}$ did not vary enough to affect the relation.
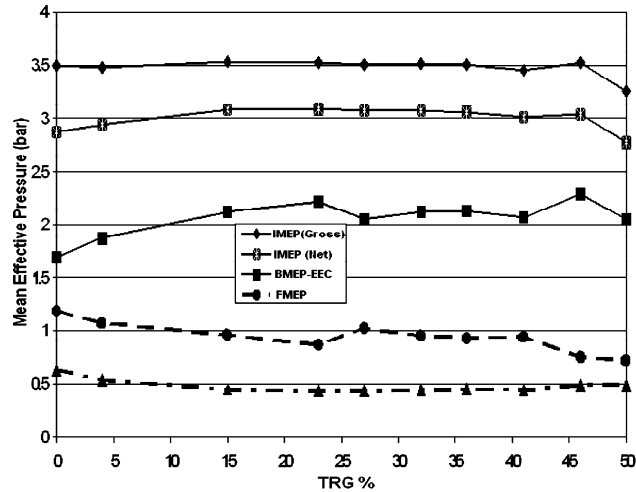
Figure 9. Suspicious IMEP, BMEP, and FMEP trends.

Rai et al. [9] mentioned that cyclic exposure of a piezoelectric pressure transducer to combustion results in the expansion and contraction of its diaphragm due to large temperature variations throughout the cycle. This causes the force on the quartz to be different to that applied by the cylinder pressure alone. Thermal shock affects all parameters derived from pressure data, but the greatest is IMEP, which can be affected more than -10%. Thermal shock was found to be more significant at advanced ignition timings. Rai et al. [9] derived an equation to compensate for thermal shock of a Kistler 6125A transducer used on a Ford Zetec engine. This equation is

$$IMEP_{corr} = IMEP_{meas} + (F \times Pmax) + Offset \tag{8}$$

where F and $Offset$ are functions of RPM only. Although this equation cannot be used here directly, what is more important is that the compensation factor derived is only a factor of RPM and maximum pressure, increasing as they increase. It follows that HCCI combustion, with its greater peak in-cylinder pressures, has a greater effect on the IMEP measured by the sensor. That is why, although the $IMEP_{gross}$ appears to be constant, BMEP keeps increasing since BMEP has no errors introduced with increasing TRG. But as the peak in-cylinder pressures increase with increasing TRG and shift towards HCCI combustion, their difference increases.

Further evidence in support of this scenario surfaces when investigating unstable combustion. In this case, a misfiring cycle will produce exhaust gases partly made up of its unburned charge. When these are recompressed during the TRG compression phase, they can sometimes ignite [6]. This ignition leads to an underestimation of the descending side of the curve. It is easier to appreciate this in the IVO region because the pressure values are expected to be in the region of 1 bar, as is demonstrated in Figure 10.
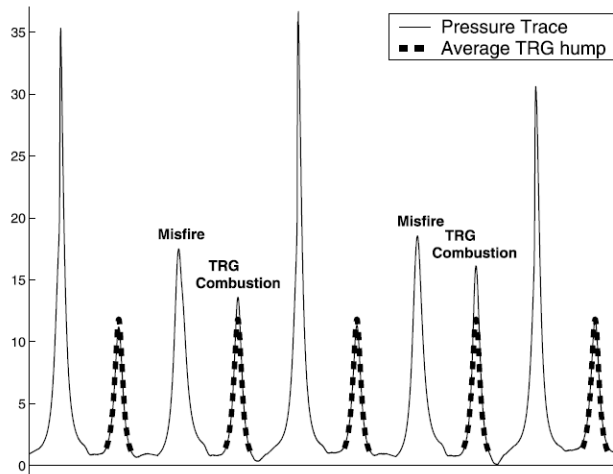
Figure 10. Thermal shock evidence following TRG combustion.

In this figure, the second and fourth cycles misfire. Their respective TRG compression humps are noticeably larger than the average (shown as a thick, dashed line). It is clearly visible that the lowest points of their IVO regions are unrealistically lower than their neighbors' and, in the case of the fourth cycle, almost reaching a pressure of zero.

EGT Measurement Issues

One major point that needs clarification is the assumption that the averaged thermocouple reading of the EGT is representative of the TRG temperature at EVC. Due to its slow response characteristics, this reading is suspect. However, studies with fast response thermocouples [6] indicate a temperature variation under 80ıK across the whole cycle for SI and HCCI combustion at 2-bar BMEP and 2,000 RPM. This implies that by taking an averaged value, the corresponding error is a maximum underestimation of temperature of the order of 40^oK.

Because the temperature is measured in degrees Kelvin, the temperatures involved are large numbers (generally in the 600 to 900 range). Thus, a value shift of 40, as is the likely underestimation of the EGT, is a relatively small variation, making the resulting overestimation of TRG equally small.

Figure 11 demonstrates the percentage difference between TRG amount calculated by taking the averaged EGT and correcting by adding a 40ıK shift. As can be seen from the figure, the resulting error in TRG is minimal, even in the case of data log with the maximum TRG amount. When considering Figure 6 (right), this TRG error will have a maximum impact of around 0.5% on γ.

The previous analyses of Figures 6, 7, and 11 have dealt with single effects on certain variables at specific steps in the proposed method. However, it is not clear how the *overall* result is affected by errors in the actual value of bulk TRG temperature at EVC.
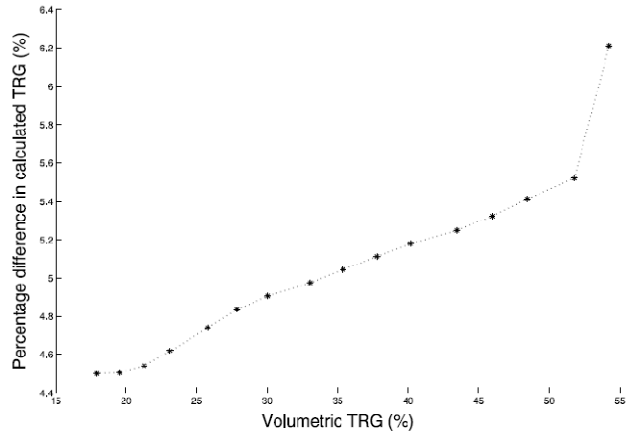
Figure 11. Percentage difference between TRG calculated by taking an averaged measurement and correcting by a temperature shift of 40ıK (2,000 RPM, WOT, TRG sweep).

To test for this, a sensitivity analysis has been performed on a high TRG amount log at 2,000 RPM. The reasoning behind this is twofold: (a) at higher RPM, the temperature variability should drop since it is time dependent through cooling of the exhaust gases in the exhaust pipe; 2,000 RPM, being close to the low end of the experimental data available (data span 1,500 to 3,500 RPM), is a perfect candidate; (b) a high TRG log will exhibit higher sensitivity to variables affecting TRG amount.

The affected variables are both TRG and the whole-pressure trace, whose pegging depends upon the TRG amount through the temperature/composition-dependent polytropic exponent. For varying TRG temperature at EVC, the resulting TRG amount is shown in Figure 12. The thick vertical line marks the EGT as measured through the thermocouple, hence, averaged. The dashed vertical line marks the $+40^o$K point, which is the likely maximum underestimation of the actual value of EGT at EVC due to the averaging effect of the slow response thermocouple. Thus, the marked region contains the likely actual values of EGT and, hence, TRG. It can be seen that the likely TRG error is of the order of 6%.
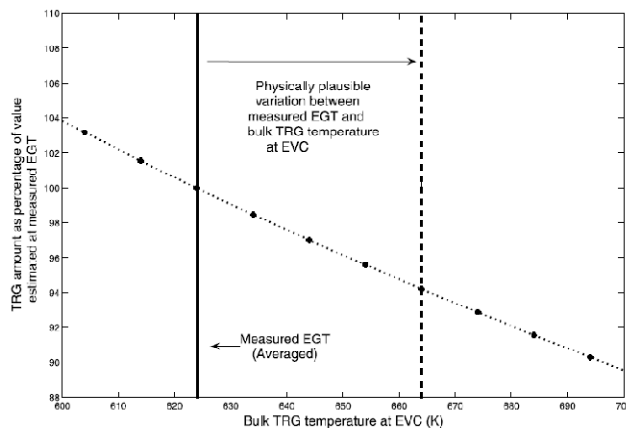

Figure 12. TRG amount dependent upon assumed bulk TRG temperature at EVC (2,000 RPM, WOT, 2.9-bar IMEP).

Similarly, Figure 13 demonstrates the dependence of pegged pressure at IVC on TRG temperature at EVC. In this case, the result is even more insensitive, being under 1% for the whole 100ɪK region presented in the figure, let alone the 40ɪK plausible region.

From the above analysis, it follows that, within the expected inaccuracy due to the slow response nature of the thermocouple, the corresponding errors of pegging and TRG amount estimation are minimal once the whole procedure laid out in Figure 4 has been carried out. Hence, EGT can be reasonably directly used as a measurement of TRG temperature at EVC.
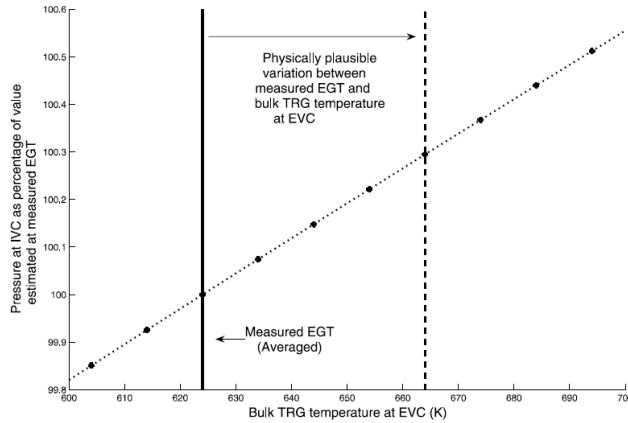

Figure 13. Pressure at IVC dependence upon assumed bulk TRG temperature at EVC (2,000 RPM, WOT, 2.92-bar IMEP).

Safeguards Against Erroneous Data in Individual Cycle Procedure

Once the individual cycle treatment is considered, it is prudent to observe the existence of safeguards that guarantee results will be robust despite the unpredictability of the signal and the great potential for cumulative errors. The main problem of the analysis is that certain cycles will yield wildly incorrect pressure values despite all corrective actions performed on the signal. These cycles, most often occurring after exceptionally violent combustion events, can exhibit unrealistically low pressure values that might persist after the pegging procedure. Since HCCI analysis is dependent on the fact that one cycle's TRG is used in the next cycle's mixture, such cycles will pass on highly inaccurate values.

The best safeguard for one incorrect cycle destroying the results of all subsequent cycles is that the amount of TRG is calculated by each cycle at EVC as a function of the directly measurable pressure trace only. To elaborate, consider that cycle n has a very inaccurate signal. Its TRG is calculated at its EVC and is wrong both as a mass and as a temperature, since the pressure at EVC is wrong and the temperature, scaled from the average signal's EGT via its pressure at EVO, is also wrong. The cycle following it, $n + 1$, inherits a wrong TRG estimation, leading to a wrong calculation of mixture moles at IVC. However, the damage stops here. The $n + 1$ cycle's EGT is correct, assuming its pressure is correct, since it is scaled at its own EVO by pressure trace ratio only (averaged and individual). The TRG calculated for it will also be correct and, hence, the variables that it passes on to cycle $n + 2$.

Of course, all of this can be avoided if wrong cycles can be identified and specially treated. Such a safeguard has been put in place, stating that if a cycle's pressure value at IVC deviates into improbable values [8] even after pegging, it should be forcibly pegged to coincide with the averaged IVC pressure. This will avoid getting values that are too implausible and, to some extent, salvaging the following cycle. However, in some extreme cases, the pressure trace is visibly damaged along the whole length of the cycle, e.g., yielding extremely unrealistic pressure values in the EVO–EVC region, even if it is forcibly pegged at IVC. This is because a violent combustion leading to very high thermal shock underestimating the descending part of the pressure trace will be most apparent in the low pressure EVO–EVC region where very low pressure will be recorded.

Given that such problems exist, having an effective stop at the propagation of any information not dependent on the pressure trace makes for a robust analysis of most cycles.

APPLICATION TO EXPERIMENTAL DATA

Having explained the whole algorithm in depth, real life results should be shown. There are two major components to the algorithm—the treatment of averaged traces as described in the section "Description of Calibration Algorithm for Averaged Data" and its expansion to individual cycles as described in the section "Expansion of Algorithm to Individual Cycles."

As an example of the former, results for TRG representation across the logged data range are presented. For the latter, an example of the interplay of cycles' parameters is discussed.

TRG Representation Example

Often, TRG is quoted as a ratio of volume at EVC to total cylinder volume. This is a good tool for easy classification of data points but fails to take into account the effects of the engine's operating conditions on gas dynamics.

On the contrary, by calculating the amounts of gases present, the ratios of moles or masses can be quoted. In this research, moles rather than masses have been used because, when dealing with gases at the same temperature and pressure, moles directly relate to volumes. Hence, quoting a number for molar TRG of a homogeneous mixture effectively gives the volume ratio of the gases. This is comparable to the classic "volumetric" method mentioned above, with the added bonus that this number reflects a more accurate ratio of gases, implicitly taking the effects of gas dynamics into account. The obvious drawback is that, in order to calculate it, the considerable procedures described in the section entitled "Description of Calibration Algorithm for Averaged Data" have to be carried out.

Figure 14 highlights the relation between the two TRG measuring conventions. It is noticeable that, in general, molar TRG is higher than volumetric. This is because the exhaust gases present at EVC are always at a pressure higher than that of the inlet (due to both exhaust back pressure being higher than inlet pressure and low valve lift of 2.5 mm employed in the logging of these data). Hence, when

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[8] In this research a maximum deviation of ± 0.3 bar has been tolerated.

the remaining volume fills up with fresh charge with the whole cylinder equating with the inlet pressure, the TRG takes up more volume than it did at EVC. The effect gets more noticeable with increasing RPM.
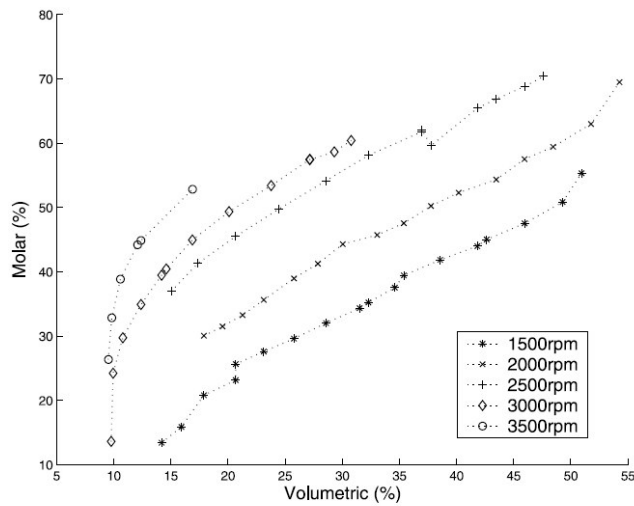

Figure 14. Comparison between TRG measuring methods.

Figure 14. Comparison between TRG measuring methods.

Individual Cycle Investigation Example

The full power of the analysis comes into play when looking at individual cycle results. Figure 15 displays cycles from the same region as Figure 10. The data is logged from an unstable combustion at 1,500 RPM, ITA D 34, WOT, and volumetric TRG is set to 50% that results in an IMEP of 3.47 bar. In order to understand the flow of events, information on the following variables is very useful:

1. moles of charge,
2. moles of TRG,
3. moles of total mixture,
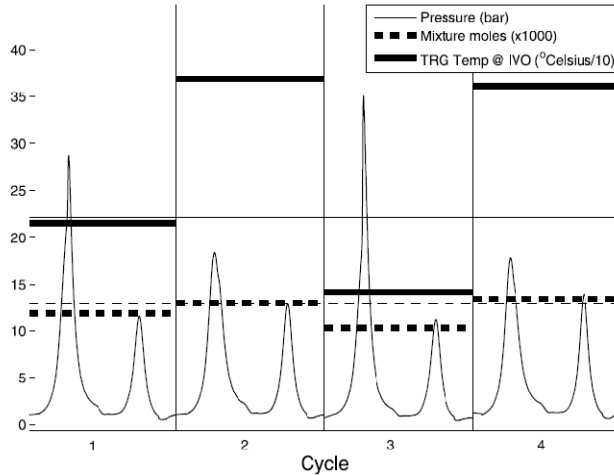4. TRG temperature (at IVO), and
5. EGT (at EVO).

Figure 15. Cycle-to-cycle analysis of unstable combustion.

In order to not overly clutter the figure, only parameters 3 and 4 are displayed. The values of the moles of total mixture and TRG temperature are displayed as thick bars of different styles over the regions of their respective pressure traces. The thinner bars in the same style mark their respective mean values for the whole data set and act as a reference. The addition of standard deviation bars would lead to cluttering problems,

so these have been omitted as well. It should, therefore, be noted that the temperature variation on the Y -axis is larger than that of the moles of total mixture, as can be seen by the scattering of the respective bars in the figure.

The leftmost cycle is slightly less energetic than average, having started with a slightly lower number of mixture moles (thick dashed bar) than average (thin dashed line). It is followed by a normal TRG compression hump, at the end of which TRG has a temperature (thick solid bar) very slightly lower than average (thin solid line).

The slightly low TRG temperature of the first cycle leads to a good intake at the start of the second cycle (as the fresh charge is not heated too much), ending up with total mixture just above average. The cycle then misfires, as can be seen by the low peak pressure of its first hump. The misfire leads to TRG rich in unburned charge being recompressed during the second hump of the cycle. This second compression ignites the TRG, leading to a high peak pressure for the second hump and a TRG temperature far above average.

This very hot TRG now mixes with fresh charge at the start of the third cycle. Due to the high temperature heating up and expanding the incoming charge, the moles of total mixture end up very low. The cycle ignites relatively early, hence, the high peak pressure. Then due to the early ignition leading to increased heat losses and to the low initial charge, bringing in less chemical energy, the final TRG temperature is very low.

This TRG at low temperature mixes with fresh charge in the final cycle, leading to the highest value of total mixture of these four cycles. The cycle then also misfires and ignites during the TRG compression, as can be seen from the high peak pressure and TRG temperature.

This example illustrates both the interplay of consecutive cycles in HCCI combustion and the usefulness of carrying out the described combustion analysis in full in order to be able to investigate the variations of all the representative variables.

CONCLUSION

This article explores techniques of post-processing pressure data in order to gain a deeper understanding of events on both averaged and individual cycle data. The focus has been on HCCI combustion, which poses certain demands not normally associated with SI operation. However, the same techniques in a simplified form (no need for TRG estimation, thermal shock not as important an issue) can be adapted for SI data analysis.

The drive for devising such an analysis has been the nature of HCCI combustion. Because of the interlinking between cycles, a close look at the conditions dominating each individual cycle is a valuable tool in order to obtain an understanding of how and why certain behaviors are observed. This information cannot always be supplied directly by contemporary sensors and, thus, must be calculated indirectly. By carrying out the presented analysis, the following are derived:

1. polytropic of compression,
2. pressure trace pegging,
3. pressure trace correction for thermal shock-related error,
4. TRG amount, and
5. mixture composition.

This information is particularly useful in investigating the behavior of HCCI combustion.

Future work will employ the results of this analysis in order to explain the mechanisms at play during HCCI combustion. The most challenging task at present is the identification of the factors leading to combustion. Use of the tools developed in this research will be helpful in investigating the feasibility of predicting the behavior of a cycle in advance, potentially opening the way to sophisticated control algorithms for real time implementation.

REFERENCES

1. N. Milovanovic, R. Chen, R. Dowden, and J. Turner, An Investigation of Using Various Diesel-Type Fuels in Homogenous Charge Compression Ignition (HCCI) Engines and Their Effects onOperational and Controlling Issues, Int. J. Engine Res., vol. 5, pp. 297–316, 2004.
2. L. E. Eriksson and I. K. Andersson, An Analytical Model for Cylinder Pressure in a Four-Stroke SI Engine, SAE 2002 World Congress & Exhibition, SAE 2002-01-0371, Detroit, pp. 1–10, March 2002.

3. A. E. Catania, D. Misul, A. Mittica, and E. Spessa, A Refined Two-Zone Heat Release Model for Combustion Analysis in SI Engines, Jap. Soc. Mech. Eng. Int. J. Ser. B, vol. 46, pp. 75–85, 2003.

4. P. A. Tunestal, The Use of Cylinder Pressure for Estimation of the In-Cylinder Air/Fuel Ratio of an Internal Combustion Engine, PhD Thesis, Lund University, Sweden, 1993.

5. A. L. Randolph, Methods of Processing Cylinder Pressure Transducer Signals to Maximize Data Accuracy, International Congress & Exposition, SAE 900170, Detroit, pp. 1–12, February 1990.

6. L. Koopmans, I. Denbratt, and O. Backlund, Cycle-to-Cycle Variations: Their Influence on Cycle Resolved Gas Temperature and Unburned Hydrocarbons from a Camless Gasoline Compression Ignition Engine, SAE 2002 World Congress & Exhibition, SAE 2002-01-0110,Detroit, pp. 1–12, March 2002.

7. Thermal Research Laboratory, Dow Chemical Co., JANAF Thermochemical Tables, 2nd ed., U.S. National Bureau of Standards, USA, 1971.

8. J. B. Heywood, Internal Combustion Engine Fundamentals, McGraw-Hill Book Company, New York, 1988.

9. H. S. Rai, M. F. J. Brunt, and C. P. Loader, Quantification and Reduction of IMEP Errors Resulting from Pressure Transducer Thermal Shock in an S.I. Engine, International Congress & Exposition, SAE 1999-01-1329, Detroit, pp. 1–17, March 1999.