

# An Evaluation of Residual Gas Fraction Measurement Techniques in a High Degree of Freedom Spark Ignition Engine

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## ABSTRACT

Stringent fuel economy and emissions regulations have driven development of new mixture preparation technologies and increased spark-ignition engine complexity. Additional degrees of freedom, brought about by devices such as cam phasers and charge motion control valves, enable greater range and flexibility in engine control. This permits significant gains in fuel efficiency and emission control, but creates challenges related to proper engine control and calibration techniques. Accurate experimental characterization of high degree of freedom engines is essential for addressing the controls challenge. In particular, this paper focuses on the evaluation of three experimental residual gas fraction measurement techniques for use in a spark ignition engine equipped with dual-independent variable camshaft phasing (VVT). The flexible VVT system enables control of residual independently of speed and load, thus making quantification of residual gas fraction very important for managing ignition timing, fuel delivery, and engine-out emissions.

## INTRODUCTION

Dual-independent variable valve timing systems are capable of generating high internal residual gas levels over a wide range of operating conditions as compared to fixed cam operation. Knowledge about the actual residual gas fraction (RGF) is important for combustion phasing, efficiency, and emissions control. Taking advantage of recent advances in diagnostic techniques, fast response emission analyzers are used to measure internal residual gas fraction using several different methods. Of primary interest are two techniques that use fast response analyzers to measure in-cylinder pre-combustion gases, one using HC concentration while the second relies on CO<sub>2</sub>. Additionally, a method using a single exhaust port-mounted fast response analyzer to quantify RGF is discussed. These experimental

methods are described and compared using data acquired from a prototype variable valve timing (VVT) engine equipped with a charge motion control valve (CMCV). The relative impact of main operating parameters on residual fraction is also quantified and discussed.

Many researchers have developed residual gas fraction measurement techniques, and these are discussed in the background section. However, comparisons of these methods are not readily available. The availability of a particular instrument is generally a driving factor for choosing a RGF measurement method. In this case, fast response HC and CO<sub>2</sub> analyzers are simultaneously available and were placed in the same cylinder. The presence of these analyzers allows for direct comparison of three commonly used methods to estimate residual fraction.

This paper is organized as follows. First, an overview of previously developed residual gas fraction measurement methods is provided. Following the overview, the experimental setup and fast response emissions instrumentation is described. Then, the method for calculating residual gas fraction from emissions-based experimental data is derived, followed by specific procedures and guidelines for each of the three methods compared in this report. Finally, experimental residual gas fraction results for the three simultaneously recorded methods are compared and conclusions are drawn from the results.

## BACKGROUND

Experimental measurement of residual gas fraction is performed either by indicated cylinder pressure or emissions-based methods. While cylinder pressure based methods are the least expensive they are subject to inaccuracy. Emissions based methods are generally more accurate, but require more complicated experimental setups. The desire for highly accurate

measurements focuses this study exclusively on emissions-based methods; however the basic concepts of cylinder pressure based techniques are also discussed.

Several pressure based residual fraction measurement techniques have been previously developed. Cains [1] calculated RGF by comparing gross indicated mean effective pressures (IMEPg) from cycles with and without residual. A cycle without residual was created by cutting the ignition while continuing fuel injection for 8 to 10 cycles. Residual gases are slowly purged and filled with air and fuel mixture during the misfire period. When the spark is reinstated the first firing cycle occurs without residual, creating an increased IMEPg. Cains developed a routine to correct for relative spark location with and without residual to generate a residual fraction measurement. The primary deterrent from this method is ensuring proper mixture preparation and air-to-fuel ratio after successive misfires. Mladek and Onder [2] also developed a RGF estimate routine based upon cylinder pressure for engine control. Their method used measured temperatures and cylinder pressure along with empirical equations to estimate RGF. Results of the estimate model showed good agreement with engine simulations.

Emissions-based RGF measurement methods are distinguished by the selection of a tracer species and experimental technique. The species/technique combination dictates the versatility and accuracy of RGF data that can be obtained from a particular method. The main selection criteria for tracer species are the level of mixing, relative concentration, required measurement technique, and physical state (liquid/gaseous). A good tracer species must be present in a sufficient concentration to ensure robust measurement and be relatively insensitive to sampling location (well mixed). Techniques used to measure tracer species are weighed against the following criteria: system complexity, engine modification, measurement type (single point or spatial), and cycle-by-cycle or cycle-averaged results. Several common tracer species and experimental configurations for measuring RGF are weighed against their respective selection criteria in Table 4 and Table 5 of the Appendix.

To use a tracer species for monitoring residual gas content, the molecular species must be formed or destroyed during combustion so that pre and post-combustion levels can be differentiated. This is required because residual gas is comprised only of exhaust products, therefore the dilution level of exhaust products with fresh charge can be used to calculate residual fraction. Such a requirement makes it possible to use CO, CO<sub>2</sub>, NO, H<sub>2</sub>O, or HC among others as residual fraction tracer species. However, the availability of measurement devices for individual species limits the choices to CO, CO<sub>2</sub>, NO, and HC for such a technique. Laser-based and other optical measurements [3-7] allow further flexibility in tracer species and potentially provide

information about spatial RGF distribution; however these techniques greatly increase complexity and engine modification and are not discussed in the current work.

Most common RGF measurement methods utilize either NO, HC, or CO<sub>2</sub> as the tracer species. The measurement technique is different for each species. Using NO or CO<sub>2</sub>, RGF is calculated from the dilution level occurring when exhaust is mixed with fresh air and fuel during the intake and compression strokes. Measured HC concentration prior to ignition is compared with the HC level that would be attained if residual were completely purged from the system. The presence of residual gas reduces HC concentration and increases NO and CO<sub>2</sub> concentration in pre-combustion gases. CO<sub>2</sub> and HC exist in relatively higher pre-combustion concentrations than NO. However, it is important to note that despite low in-cylinder concentrations, successful in-cylinder NO measurements are possible [8-9]. Ultimately, the accuracy of the species measurement technique (e.g. NDIR, FID, etc.) determines the minimum acceptable species concentration.

In-cylinder spatial distribution of a particular tracer species during the pre-combustion is an important factor in the selection of both the species and measurement technique. A well mixed species allows a measurement from a single point in the cylinder to be representative of the entire mixture. A poorly mixed species increases measurement variability when taken from a single point and may require multiple sample locations. Spatial variations in CO<sub>2</sub> values have been found to be lower than those of HC [10]. Additionally, fuel condensation concerns generally limit the use of HC as a tracer species to gaseous fuel operation only [11][12].

Sampling of in-cylinder pre-combustion gases is commonly done with either a fast acting sample valve or continuously sampling fast response analyzers. These methods measure from a single point in the cylinder, therefore they rely on the assumption that contents are well mixed. In-cylinder samples removed with high speed valves are analyzed with either a gas chromatograph [13-14], standard analyzer [15-19], or a fast response analyzer [20]. Low sample flow rates from fast acting valves make the use of standard analyzers difficult and cycle-by-cycle residual measurements are not possible unless fast response analyzers are used. Fast response analyzers continuously sample, either directly from the cylinder [8] [11] [12] [21] or behind a fast acting valve [20], and offer cycle-resolved measurement. Large pressure fluctuations and response time issues can induce measurement error when measuring directly from the cylinder; however, proper setup, calibration, and robust data interpretation allow cycle-by-cycle residual fraction calculation.

A residual measurement method using a single fast response NO sensor in the exhaust port has been developed by Ford and Collings [8]. Their method requires the sensor be positioned in the exhaust port

close to the exhaust valve. The engine is run and a steady-state NO reading in the exhaust port is recorded. A single misfire cycle is used and the pre-combustion gases, including residual, are purged during the exhaust stroke. This method avoids several of the complications in-cylinder sampling, however it has drawbacks. When the cylinder is misfired, the in-cylinder contents can be over-expanded prior to EVO under certain operating conditions. Over-expansion creates a backflow from the exhaust manifold to the cylinder when the exhaust valve opens. The backflow of exhaust port gases from the previous firing cycle will mix with the in-cylinder gases and significantly increase the calculated residual fraction. Ford and Collings [8] used a thermodynamic routine to estimate the quantity of backflow and calculate the expected NO concentration from the residual gas only. This method is more accurate at high engine load or when early EVO cam settings are used. Both conditions will minimize over-expansion of in-cylinder contents.

Giansetti [22] used a single Fast FID analyzer in the exhaust port to measure residual level. The residual calculation requires engine misfire, while still injecting fuel, and comparing the HC concentration of the first misfired cycle to the concentration several misfire cycles later. The HC level from the first cycle is lower than that of later cycles because the residual content within the cylinder decays once the spark is stopped. Several cycles after the misfire begins HC concentration stabilizes, at this point it is assumed that all residual is purged from the cylinder. This process, similar to that performed by Ford and Collings [8], is subject to over-expansion backflows and mixing with contents of the previous cycle. Giansetti did not consider the possibility that there may be over-expansion and back-mixing with the contents of the previous cycle. The sample FID signal trace given in the paper suggests that back-flows are indeed occurring and that this phenomenon should be considered. Failure to consider the effects of back-mixing will suggest artificially high residual levels.

The introduction of fast-response CO<sub>2</sub> analyzers enables further improvement of residual measurement techniques. Of the previously mentioned work, the fast FID methods showed good promise, but were only demonstrated with gaseous fuel. The work of Karagiorgis et al. [20] improved RGF measurement by using CO<sub>2</sub> as a tracer species in combination with a fast response analyzer mounted behind a sample valve to provide cycle-by-cycle fidelity while utilizing liquid fuel. The current work employs an experimental configuration with fast response CO<sub>2</sub> and HC analyzers directly measuring in-cylinder gases, allowing accurate cycle-by-cycle measurements under certain conditions while reducing complexity. The HC-based method is modified to account for the use of liquid fuel. Additionally, a low complexity method using a single exhaust port-mounted fast response CO<sub>2</sub> analyzer, in combination with misfire, is utilized. The three methods analyzed are measured

simultaneously from the same engine cylinder to allow for direct comparison.

## ENGINE SETUP AND INSTRUMENTATION

A 2.4L I-4 engine was used to acquire experimental data for this project. The combustion chamber is a pent-roof style containing four valves (2-exhaust, 2-intake) and a centrally located sparkplug. Engine dimensions are given in Table 1. The test engine is equipped with a hydraulically activated dual-independent variable valve phasing mechanism. Valve duration and lift of the camshaft are not altered when the camshaft is moved; only the relative phasing of valve events with respect to piston motion can be changed. Upstream of the fuel injectors, in the intake manifold, is a charge motion control valve (CMCV). The CMCV is designed to generate high levels of charge tumble within the cylinder. When the CMCV valve is active, or blocked, approximately two thirds of the intake manifold flow area is blocked and burn rate nearly doubles at low engine speeds. The CMCV improves charge mixing and is a valuable tool for determining the influence of measuring in-cylinder gases from a single point within the combustion chamber.

Cycle-resolved measurements are recorded once per crank-angle degree using a Kistler Type 2613B crank encoder mounted on the front of the crankshaft. Combustion chambers are instrumented with Kistler Type 6052C piezo-electric passage mounted transducers. Cycle-resolved intake and exhaust pressure measurements were made with Kistler Type 4045A2 piezo-resistive transducers. The piezo-resistive manifold transducers are used for cylinder pressure referencing. All Kistler sensors are transmitted through a Kistler Signal Conditioning Platform (SCP) to a Tektronix 16-Bit VXI data acquisition system. Data is post-processed using a combination of LabVIEW and MATLAB.

Table 1: Test Engine Specifications

|                        |                        |
|------------------------|------------------------|
| Total Displacement     | 2429 cm <sup>3</sup>   |
| Firing Order           | 1-3-4-2                |
| Compression Ratio      | 9.4:1                  |
| Bore                   | 87.5 mm                |
| Stroke                 | 101.0 mm               |
| Bore/Stroke            | 0.866 (under-square)   |
| Connecting Rod Length  | 151 mm                 |
| Intake Valve Duration  | 244 CAD (0.15 mm lift) |
| Exhaust Valve Duration | 247 CAD (0.15 mm lift) |
| Fuel                   | Gasoline: Tier II EEE  |

Exhaust port and in-cylinder CO<sub>2</sub> concentrations are acquired using Cambustion NDIR500 fast response analyzers. The sample probes use a non-dispersive infra-red (NDIR) technique to detect CO<sub>2</sub> concentrations.

of both CO and CO<sub>2</sub> concentration with a fast response time. Standard NDIR CO/CO<sub>2</sub> analyzers use a system to filter water from the sample gases prior to measurement (dry basis) to avoid overlap with the IR absorption ranges of CO and CO<sub>2</sub>. The NDIR500 uses a special filter system to measure both CO and CO<sub>2</sub> on a wet basis (the sample contains water). A 10-90% response time on the order of 6 ms [23] is achieved by significantly modifying the standard NDIR detector. Specific details pertaining to the NDIR measurement technique are found in [23-28].

The Cambustion NDIR500 instrument consists of two sample probes. One sample probe is configured for in-cylinder measurement, while the second probe is used for exhaust gas measurement in the exhaust port. The probes are configured to provide high accuracy for the specific conditions at each measurement location. NDIR measurement accuracy is dependent upon the density level within the sample chamber as well as the level of pressure fluctuation. In general, higher sample chamber densities with low pressure fluctuation provide the most accurate species concentration reading [24]. The exhaust port mounted probe is configured with a higher sample chamber pressure than the in-cylinder probe for higher accuracy. Sample chamber pressure for the in-cylinder NDIR sample probe must be maintained lower than manifold absolute pressure (MAP) to ensure that sample flow into the probe does not reverse during the intake stroke. The in-cylinder NDIR chamber volume is expanded by 2.5L to dampen pressure fluctuations which induce measurement error. Specific set points for each of the sample probes are given in Table 2.

**Table 2: CAMBUSTION NDIR500 Configuration**

|                            | Exhaust Probe | In-Cylinder Probe |
|----------------------------|---------------|-------------------|
| Chamber Pressure           | 550 mbar      | 200 mbar          |
| Sample Probe I.D.          | 1.07 mm       | 0.41 mm           |
| Sample Probe Temperature   | 120°C         | 120°C             |
| Sample Chamber Temperature | 150°C         | 150°C             |
| Filter Wheel Speed (RPM)   | 15,000        | 20,000            |

In-cylinder and exhaust port hydrocarbon concentrations are measured on a crank-angle resolved basis using a Cambustion HFR500 fast response flame ionization detector (FID). Each measurement probe has a 10-90% response time on the order of 1.5 ms. A 2.5L expansion volume is added to the in-cylinder measurement probe to dampen pressure fluctuations in the sample chamber. Measurement settings for each measurement location are given in Table 3. In-cylinder samples are measured through the ground body of a specially designed offset sparkplug. Calibration of the in-cylinder probe is done with a span gas containing 40,000 ppm propane (C<sub>3</sub>H<sub>8</sub>) with the balance comprised of N<sub>2</sub>.

A FID measures HC concentration by counting the number of carbon atoms found in a hydrocarbon sample. The actual hydrocarbon composition is not measured therefore the carbon to hydrogen ratio and average number of carbon atoms per hydrocarbon molecule must be determined by a different means. Fuel properties are used for in-cylinder measurement, and a smaller molecular composition is usually assumed for exhaust hydrocarbons.

**Table 3: CAMBUSTION HFR500 FID Configuration**

|                          | Exhaust Probe | In-Cylinder Probe |
|--------------------------|---------------|-------------------|
| Sample Probe I.D.        | 1.07 mm       | 0.33 mm           |
| FID Chamber Pressure     | 500 mbar      | 440 mbar          |
| CP Chamber Pressure      | 590 mbar      | 530 mbar          |
| Sample Probe Temperature | 235°C         | 235°C             |
| Sample Head Temperature  | 150°C         | 150°C             |

### EMISSIONS-BASED RESIDUAL FRACTION CALCULATION

Methods of calculating internal residual content from emissions are best described by first analyzing the in-cylinder chemical equations involved. Equation (1) describes the generic make-up of the in-cylinder mixture prior to combustion. The compositions of exhaust gas, internal residual, and EGR are given in Equations (2), (3), and (4) respectively. Although these three parts originate from exhaust gas, it is important to separate them because they can have significantly different species compositions, especially during transient operation.

The left hand side of Equation (1) represents the gases measured in-cylinder prior to combustion. Exhaust gases measured by an exhaust port-mounted probe are represented by the right hand side of Equation (1). Note that wet mole fractions represented in Equations (2), (3), and (4) are the fractions within each component. For example, the sum of all mole fractions in Equation (2) is equal to one. The same condition holds for Equations (2), (3), and (4) individually. The wet mole fractions found in these equations will be used in the same form to simplify future calculations.

Although re-circulated exhaust gases (EGR) and internal residual (RGF) originate from exhaust gases they may have different compositions due to transient engine conditions and engine design. Internal residual is assumed to be comprised of exhaust gases from the previous cycle, whereas EGR may originate from several cycles previous depending on transit time through the EGR system. For example, if operation switches from rich to lean the internal residual could be comprised of lean exhaust species and the EGR comprised of rich exhaust species. Additionally, the

fresh air and fuel inducted into the cylinder could also be at yet another AFR than the EGR and internal residual were created, making the final exhaust products a mixture of the three parts. In this case, calculating internal residual content or AFR from the measured exhaust composition may be invalid. This issue is generally neglected when dealing with spark-ignition engines because the AFR does not alter greatly. However, compression ignition engines operate over a wide AFR range and may be significantly affected by such errors.

$$M_{FUEL} C_X H_Y + M_{AIR} (O_2 + 3.77 N_2) \dots \\ \dots + M_{EGR} [EGR] + M_{RGF} [RGF] \longrightarrow [Exhaust] \quad (1)$$

Where:

$$[Exhaust] = \chi_{H_2O}^{EXH} H_2O + \chi_{CO_2}^{EXH} CO_2 \dots \\ \dots + \chi_{CO}^{EXH} CO + \chi_{O_2}^{EXH} O_2 + \chi_{N_2}^{EXH} N_2 \dots \\ \dots + \chi_{H_2}^{EXH} H_2 + \chi_{NO}^{EXH} NO + \chi_{HC}^{EXH} C_A H_B \quad (2)$$

$$[EGR] = \chi_{H_2O}^{EGR} H_2O + \chi_{CO_2}^{EGR} CO_2 \dots \\ \dots + \chi_{CO}^{EGR} CO + \chi_{O_2}^{EGR} O_2 + \chi_{N_2}^{EGR} N_2 \dots \\ \dots + \chi_{H_2}^{EGR} H_2 + \chi_{NO}^{EGR} NO + \chi_{HC}^{EGR} C_A H_B \quad (3)$$

$$[RGF] = \chi_{H_2O}^{RGF} H_2O + \chi_{CO_2}^{RGF} CO_2 \dots \\ \dots + \chi_{CO}^{RGF} CO + \chi_{O_2}^{RGF} O_2 + \chi_{N_2}^{RGF} N_2 \dots \\ \dots + \chi_{H_2}^{RGF} H_2 + \chi_{NO}^{RGF} NO + \chi_{HC}^{RGF} C_A H_B \quad (4)$$

Molar residual gas fraction is defined in Equation (5) using the number of moles of each in-cylinder constituent. Equation (5) only represents the fraction of internal residual in-cylinder. If the number of EGR moles is included in the numerator, the total burned gas fraction would be represented. Molar residual fractions can be converted to a mass basis if the molecular weight of each constituent is known or approximated.

$$\chi_{RGF}^{Molar} = \frac{M_{RGF}}{M_{Air} + M_{Fuel} + M_{EGR} + M_{RGF}} \quad (5)$$

## RESIDUAL GAS FRACTION MEASUREMENT USING IN-CYLINDER CO<sub>2</sub> CONCENTRATION

Carbon dioxide (CO<sub>2</sub>) is a commonly used tracer species for the calculation of RGF because it is well-mixed with intake air and fuel and it occurs in relatively high concentration. RGF calculation from CO<sub>2</sub> is done using a combination of pre-combustion and exhaust concentrations. In-cylinder pre-combustion and exhaust port post-combustion CO<sub>2</sub> concentrations are defined by Equations (6) and (7) respectively. Pre-combustion CO<sub>2</sub> concentration depends upon the species composition

and total quantity of both EGR and internal residual. For post-combustion measurement the CO<sub>2</sub> concentration measured is a combination of CO<sub>2</sub> from internal residual, EGR, and the combustion of air and fuel. The CO<sub>2</sub> level produced by the air and fuel will reflect the cylinder air-to-fuel ratio (AFR). Under lean operation, air is recycled back into the cylinder as part of the internal residual and EGR, affecting global AFR.

$$\chi_{CO_2}^{Pre-Comb} = \frac{\chi_{CO_2}^{RGF} M_{RGF} + \chi_{CO_2}^{EGR} M_{EGR}}{M_{Air} + M_{Fuel} + M_{EGR} + M_{RGF}} \quad (6)$$

$$\chi_{CO_2}^{Post-Comb} = \frac{\chi_{CO_2}^{RGF} M_{RGF} + \chi_{CO_2}^{EGR} M_{EGR} + \chi_{CO_2}^{AFR} M_{AFR}^{EXH}}{M_{AFR}^{EXH} + M_{EGR} + M_{RGF}} \quad (7)$$

Where:

$$M_{AFR}^{EXH} = \frac{M_{AIR} MW_{AIR} + M_{FUEL} MW_{FUEL}}{MW_{EXH}} \quad (8)$$

The pre-combustion CO<sub>2</sub> measurement equation is solved to yield an expression for the internal residual gas fraction in Equation (9). This equation does not assume that the CO<sub>2</sub> concentrations of the EGR and internal residual are equal; therefore, it could be used for transient conditions. A problem is encountered since the number of RGF moles is required to solve for the molar RGF and iteration is required. However, if external EGR is not used or the engine is operated at steady-state the molar internal RGF is represented by Equation (10). In this case, the CO<sub>2</sub> concentration within the residual gases is assumed to be equal to that of the previous exhaust cycle.

$$\chi_{RGF}^{Molar} = \frac{1}{\chi_{CO_2}^{RGF}} \left( \chi_{CO_2}^{Pre-Comb} - \frac{\chi_{CO_2}^{EGR} M_{EGR}}{M_{Air} + M_{Fuel} + M_{EGR} + M_{RGF}} \right) \quad (9)$$

$$\chi_{RGF}^{Molar} = \frac{\chi_{CO_2}^{Pre-Comb}}{\chi_{CO_2}^{RGF}} = \frac{\chi_{CO_2}^{Pre-Comb}}{(\chi_{CO_2}^{EXH})_{Previous Cycle}} \quad (10)$$

A typical in-cylinder CO<sub>2</sub> concentration profile measured with an NDIR500 is shown in Figure 1. CO<sub>2</sub> concentration decreases to pre-combustion levels during the compression stroke and is sampled until the flame traverses the measurement location, at which time the concentration rapidly increases to reflect exhaust gas levels. The measurement periods occurring before and after the pre-combustion period do not provide valid data. During combustion, cylinder pressure can rise too high for accurate measurement. The instrument will recover during the remainder of the expansion and exhaust strokes. During the intake stroke the pressure difference between the cylinder and measurement chamber can be low, reducing sample flow rate.