THE EFFECT OF SPARK TIMING ON RESIDUAL GAS FRACTION

by

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Abstract

Residual gas tests were done on a 2.4 liter commercial engine to find a correlation for the effect on spark timing on residual gas fraction. The tests were done by sampling the charge mass during a non-firing cycle through a small hole into cylinder 4. The residual gas fraction was determined by measuring the CO_2 content of the sample. The experiments were conducted for a variety of different spark timing and valve timing settings.

Since the data was taken over a limited range, a physical basis for a correlation was developed. Following the approach used in a previous modeling effort, the residual gas fraction was modeled as the sum of two contributing factors: backflow from the exhaust port to the cylinder during valve overlap and gas trapped inside the cylinder at the time of intake valve open. Additionally, the phenomenon of choked backflow was introduced in the model. Based on the data, a correlation was developed that estimates the residual gas fraction as a function of: intake to exhaust pressure ratio (p_i/p_e), valve profile, engine speed, compression ratio, and spark timing.

Thesis Supervisor: Prof. Wai K. Cheng
Title: Professor of Mechanical Engineering

Acknowledgments

After 2 years at MIT and seven years total in the United States, I am finally ready to go home to Norway for a while. I am starting work with The Boston Consulting Group in Oslo in August, wanting to do something a little different.

Thanks go to all those who have lent a helping hand in the project, and to me personally during the time when I have been working on it. First and foremost, my gratitude is owed to my supervisor, Professor Wai K. Cheng. His assistance both with the test cell setup, and with the research in this thesis has been invaluable. Second, I want to mention John Baron and Brian Corkum, whose help on the test cell setup was tremendous. Additionally, I owe great thanks to DaimlerChrysler, and especially Chris Thomas, for financial and equipment support, and to Prof. John Heywood and Dr. Victor Wong for their continued support in their roles as Director and Manager of the Sloan Automotive Lab. Thanks also to Susan Lutin for a helping hand when I needed it with office supplies, faxes, reimbursements etc.

Much of what one learns and most of what one takes away after working on a project like this, is from the experiences interacting with other students. I must send out thanks especially to Brian Hallgren and Matt Rublewski for help with equipment, and to Jim Cowart for his insight and help with related programming struggles. Thanks also go to Conor McNally and Cornelius O'Sullivan for their friendship and support, to Bridgette Castaign for help with the data acquisition computers, and to Gary Landsberg, Benoist Thirouard, Ioannis Kitsopanidis, Ertan Yilmaz, Gerald Chamarre, Ferran Ayala, Dr. David Schmidt, Dr. Tian Tian, and Chris O'Brien for help I received on bits and pieces of the setup, tests and analysis. Thanks also to the other students at the Lab that have been through in the time I have spent, and helped make my experience a positive one: Rolf Karlsson, Dr. Brad Van der Wege, Martin Kosto, Kelly Canales, Anuscheh Nawas, Dr. Young Chul Ra, Dr. David Kayes, and Markus Megerle.

I am ready to move on now, but not without some fond memories from my time in the Sloan Automotive Laboratory.

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Chapter 1

Introduction

1.1 Motivation

The presence of burned gas in the cylinder of a spark ignition engine has two primary, related effects on the combustion process:

- Reduction of burn rate
- Reduction of combustion temperature

These effects have both positive and negative consequences for practical engine design. The presence of burned gas in the unburned mixture reduces NO_x formation, but simultaneously the indicated mean effective pressure is reduced, hence reducing the combustion efficiency. Therefore, it is desirable for engine designers to control the burned gas content of the charge in order to keep it at an optimal level.

Burned gas in the cylinder can be present due to residual gas from the previous cycle and recycled exhaust gas (EGR). EGR is more easily controlled, but research efforts have been spent to develop models to predict the behavior of the residual gas fraction, defined as molar or mass ratio of residual gas to total gas trapped in the cylinder. The commonly used model for residual gas fraction was developed by Jonathan Fox et.al. at MIT in '93 (referred to here as the Fox correlation). The model predicts the residual gas fraction based on the following contributing factors:

- **Inlet Pressure**
- **Exhaust Pressure**
- **Valve Overlap**
- **Engine Speed**
- **Relative Air/Fuel Ratio**
- **Compression Ratio**

Of these, speed, inlet pressure, and valve overlap are the most important variables [1][1]. The effect of spark timing has not been considered, because engines normally operate at close to maximum brake torque (MBT) timing. However, spark timing is substantially retarded at idle and during engine warm-up. It also offers an easy method of controlling the internal residual gas.

1.2 Background

1.2.1 Fox Correlation

As mentioned above, the residual gas fraction is defined as a mass or molar ratio of residual gas to total charge in the cylinder prior to combustion. There are two factors that contribute to the burned gas remaining in the cylinder: (1) insufficient scavenging of the burned gas and (2) cross-flow from the exhaust manifold to the intake manifold during the valve overlap period due to pressure difference in the manifolds. The existing model represents the residual gas fraction as a sum of these two features [2].

In the Fox correlation, the valve overlap is included using an Overlap Factor (OF). This factor is calculated using integration of the overlap region of the valve profiles (see sec. 3.3.3).

The overlap factor is used to calculate the contribution of the cross flow during valve overlap. Also included in this term are the intake to exhaust pressure ratio, the pressure difference between the intake and exhaust pressure, and the engine speed. The contribution of the insufficient scavenging is calculated using the intake to exhaust pressure ratio, the relative air/fuel mass ratio (Φ), and the compression ratio.

[1] Items in brackets [ ] denote references at the end of the thesis

Fox correlation:

$$X_r = 1.266 \underbrace{\frac{OF}{N}\left(\frac{P_i}{P_e}\right)^{-0.87}\sqrt{|P_e - P_i|}}_{\text{Valve Overlap}} + 0.632 \underbrace{\frac{\Phi(P_i/P_e)^{-0.74}}{r_c}}_{\text{Scavenging}}$$

The data that was used to calibrate this correlation were taken from a single cylinder, two-valve engine [3]. The residual gas fraction was measured with a fast-response flame ionization hydrocarbon detector.

1.2.2 Ford Measurements

In a study completed at Ford Motor Co. in 1998, the authors collected some data on the variation of residual gas fraction with different spark timings [4]. They obtained this data to compare values to that shown by their General Engine Simulation (GESIM) cycle simulation model. This data shows that there is a small, but noticeable increase in the residual gas fraction as the spark timing is advanced.

1.3 Objective

The purpose of the work described in this paper is twofold: First, to expand the existing model for residual gas fraction to include the contribution of the spark timing, and second, to provide additional experimental data for the contribution of valve timing. The tests on which Fox' model are based only included a few points in this dimension, so additional data is needed to verify the valve timing dependency.

The data will be taken from a Chrysler 2.4 liter production engine. The residual gas fraction will be measured by skip-firing every 10th or 20th cycle and sampling the charge mass during the compression stroke of the non-firing cycle. The sample will be collected in an evacuated sampling cylinder through a small hole in the engine head. The sample will be diluted with nitrogen, and run through a CO_2 analyzer. The residual gas fraction can be calculated directly from the CO_2 mole fraction. The experimental apparatus used is discussed in more detail in Chapter 2. The experiments, the test matrix and the data analysis methods are discussed in Chapter 3. Results and explanations can be found in Chapter 4.

Based on the data collected, a new correlation is developed, which may be used to estimate the residual gas fraction in the valve design process.

Chapter 2

Experimental Apparatus

2.1 Engine and Dynamometer

The engine used for the experiments was a Daimler-Chrysler commercial engine used in their minivan series - Chrysler Town and Country. *Table 2.1* shows a summary of the engine specifications

Commercial Use	Chrysler Town and Country minivan
Type	4-cylinder, 4 valves/cylinder, dual overhead cam, aluminum block and head
Bore / Stroke	87.5 mm / 101 mm
Displacement	2.4 dm^3
Compression Ratio	9.4 : 1
Valve Timing	IVO: 1° BTDC
	IVC: 51° ABDC
	EVO: 52° BBDC
	EVC: 8° ATDC

Table 2.1 Engine Geometry

This is a typical spark-ignition engine with a pent-roof shaped combustion chamber and centrally located spark plug. All cylinders were firing under the control of the production EEC unit. The intake and exhaust manifolds were in normal operating state.

The only major alteration made to the engine is a small hole drilled into the engine head to enable access to Cylinder 4. The hole is a #30 drill size (0.1285" diameter). The distance from the outside of the engine head to the cylinder, or the depth of the hole, is 1.390". Coolant regions in the area dictate the location of the hole, as enough aluminum is needed around the hole to prevent leaks. The hole location inside the cylinder is slightly on the intake side, between the valves. The area around the outside of the hole is finished to provide for a flat contact area with the cylinder/disc assembly discussed in sec. 2.2.1. The entrance of the hole is chamfered to allow room for an O-ring, size 006.

Control modifications for the engine are described in sections 2.4 and 2.5, specifically concerning variations in spark timing and valve timing. The engine operating point was always at stoichiometric

2.2 Sampling Mechanism

2.2.1 Cylinder to Sampling Valve Assembly

A hollow cylinder is inserted into the hole drilled into the engine head. The cylinder is attached to a disc, which is designed to with an O-ring seal to enable a leak-free connection with the sampling valve. The cylinder/disc design is shown below.

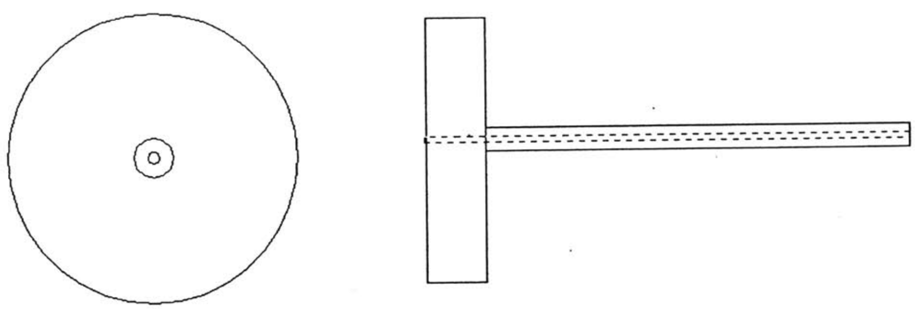

Figure 2.1 Cylinder / disc

Dimensions	
Disc Radius	1.375"
Cylinder Length	1.250"
Cylinder Outside Radius	0.121"
Cylinder Inside Radius	0.040"

Table 2.2 Cylinder / disc dimensions

In order to minimize the dead volume of the cylinder, a thin tube is soldered inside the inner hole of the cylinder. This is necessary to reduce the gas trapped from previous cycles inside this volume.

There are four holes through the disc, not shown in the figure above. Two are through holes, to allow access for screws into two holes that are drilled, tapped and reinforced with 10-32 helicoil in the engine head. The other two are threaded holes. The sampling valve, which is described in sec. 2.2.2, is pressed against the disc using four screws, two screwed into the engine head, and two screwed into the disc. Two o-rings, size 006, provide the seal, one between the disc and the engine head, and the other between the disc and the sampling valve.

2.2.2 Sampling Valve

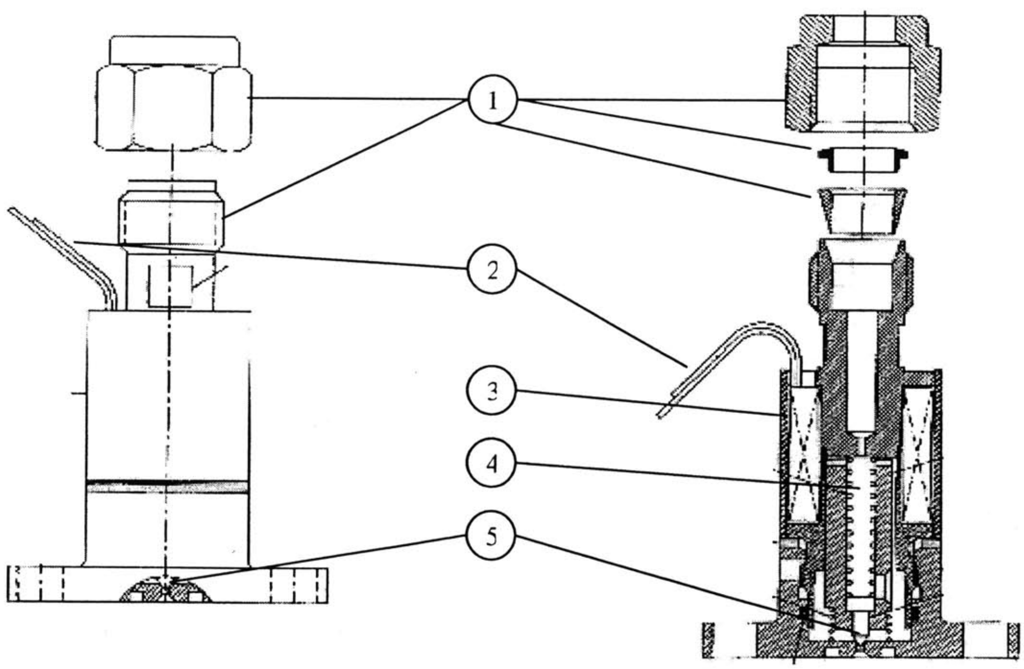

Figure 2.2 Sampling valve

The sampling valve is a pulse valve from the General Valve Division of Parker Hannifin Corporation. *Figure 2.2* shows the valve design, with explanations and design specifications in *table 2.3*.

1	1/4" nut and ferrule assembly for tube fitting
2	Teflon insulated lead wires for pulse control
3	Coil assembly
4	Main spring
5	Poppet

Operating pressures	vacuum - 1250 psi
Operating temperatures	0 - 220°C
Leak rate	<1e-7 cc/sec/atm He
Orifice	0.8 mm Dia
Operating voltage	400 mA @ 28 VDC

Table 2.3 Valve design comments / specifications

The sampling valve connects to the sampling cylinder via a 3 ft long 1/4" diameter nylon tube. A pulse generated by a computer program controls the opening and closing of the valve.

2.2.3 Sampling Valve Control

An Iota One Pulse Driver from General Valve Company (now the General Valve Division of Parker Hannafin Company) outputs a pulse of specified length to the valve. The above mentioned computer program feeds the pulse generator a short pulse, which activates the pulse from the generator to the valve. This simplifies the control of the length of the pulse, as there is a setting, which allows the user to designate the pulse length in units of milliseconds for this purpose.

The computer program, uses input from the engine controller to start the pulse at about 60 CAD ABDC during the compression stroke. Details of the computer program and the c-code can be found in *Appendix B*. Sampling is done every 10^{th} or 20^{th} cycle, depending on the stability of the engine. The computer program also skip-fires the engine each sampling cycle, which can cause a stability issue when spark timing or valve settings deviate substantially from normal operating conditions.

2.2.4 Skip-Fire Control

The same computer program that controls the sampling valve simultaneously controls the skip-fire process. Details of the program are included in *Appendix B*. The computer outputs a pulse that intercepts and neutralizes the spark signal for cylinder 4 on the way from the spark-timing controller to the coil.

2.2.5 Sampling Cylinder

A 1000 cm^3 aluminum gas container is used to collect the samples. Before sampling, a vacuum pump evacuates the cylinder and all the lines up to the sampling valve. The cylinder is connected to two pressure gauges, one with a range of 0-15 psia, and the other with a range of 0-100 psig. A three way valve controls which pressure gauge is exposed to the cylinder. During evacuation and sampling the 0-15 psia gauge is active, and the 0-100 psig gauge is active starting during dilution (discussed in secs. 2.3 and 3.1) until after the CO_2 reading is finished.

2.3 CO_2 Measuring Apparatus

In order to determine the residual gas fraction from the sample, we measure the CO_2 content of the gas. First, the sampled gas is diluted with nitrogen to pressurize it. Then the mixture is driven though a Rosemount Analytical, model 880A, non-disperse infrared (NDIR) analyzer by the pressure difference between the pressurized cylinder and the ambient air. The process is described in more detail in sec. 3.1.

The CO_2 analyzer determines the volume percent of CO_2 on a dry basis. Small volume drying tubes (200 cc) were used to reduce the amount of gas neccessary to purge the measuring instrument. The amount of sampled and diluted gas available was 1 liter volume pressurized to ~2 bar. Slow flow rates (~50 cc/sec) are necessary to ensure sufficient drying through the drier.

2.4 Spark Timing Control

A computer program, the code for which is included with further explanations in *Appendix B*, controls the spark timing. The program outputs two pulses each revolution, one fires cylinders 1-4 and the other cylinders 2-3. Shaft encoder signals are used to control the timing. Since the engine needs the engine controller signal before sampling begins, a switch was installed to accomodate easy transitions between ECU and external computer control.

2.5 Valve Timing Control

The intake and exhaust valve timings were controlled using specially machined cam gears. The standard cam gears for the engine have a slot which lines up with a pin located on the camshaft. These pins, along with grooves on the edge of the gears, align the intake cam with the exhaustcam, and provide markers for the intended valve timing. The gears used for this project have three additional holes on either side of the regular slot in which to align the pin. Each additional hole has a corresponding pair of grooves to align the two cams. The additional holes correspond to 3, 5, and 7 or 2, 4, and 6 crank angle degrees advance or retard. The cam gears used in this project were not equal, the intake had odd and the exhaust cam gear even degree offsets. The gears have 42 teeth each, so by shifting the gear one tooth, it corresponds to a ~17 CAD advance or retard (±3-7 or 2-6 degs with the additional adjustability).

Chapter 3

Experimental Methodology

3.1 Procedure

3.1.1 Preparation

Before starting the engine for each experiment, the sampling cylinder and all attached lines were evacuated to a pressure of <0.1 psia. All tests were run steady state, so the engine was allowed to run for a couple of minutes to warm up before testing commenced each time. For each experiment, several parameters were defined by the user. *Table 3.1* below outlines the user inputs for each test, along with typical values for the three main settings.

	World Point	High Load	Idle
RPM	1680	1680	1000
Brake torque (Nm)	46	103	3-20
Intake Pressure (bar)	0.43-0.52	0.67-0.74	0.32
Number of cycles sampled	1000	600	1000
Number of cycles skipped	10	10	20 / 10
Spark timing in CAD BTDC (for valve timing experiments)	30	30	20
Sampling time	12 ms (~120 CAD)	12 ms (~120 CAD)	20 ms (~120 CAD)

Table 3.1 Typical values for user inputs during experiments

The three settings in the table are discussed more closely in sec. 3.2.1-3.

The number of cycles sampled varied with each experiment. The experiments were all conducted until the pressure inside the sampling cylinder reached 6 psia. This pressure was chosen to avoid condensation of the water vapor in the sample. The pressure at which the water vapor will condense depends on the mole fraction of the water vapor in the sample, which is the product of the residual gas fraction and the mole fraction of H_2O in the residual gas. For stoichiometric operation, this mole fraction is 13%. The threshold pressures for condensation in room temperature (295°K) are listed in *table 3.2*.

Residual Gas Fraction	Threshold pressure (psia)
10%	29.4
20%	14.7
30%	9.8
40%	7.4

Table 3.2 Threshold pressures for condensation at 295°K

The residual gas fraction was not expected to exceed 40% for any of the tests, so there should be no condensation with a maximum pressure of 6 psia. Test data, which is included in *Appendix A*, shows that the highest residual gas fraction measured was indeed well within the range (~24%).

As previously mentioned, samples were only taken when cylinder 4 was not firing. The skip-fire causes certain stability issues. This was particularly prevalent during simulated idle operation, when the engine misfired quite frequently when operating outside of the normal spark/valve timing range. Skip-firing less frequently was one solution to this problem. Consequently, for the spark timing sweeps and some of the more severe valve timing variations, we sampled every 20th cycle. For all other tests, every 10th cycle was sampled. Sampling more frequently is of no consequence to the measurements, other than increasing the run-time of the experiments, as the correct thermal state of the engine is maintained when skip-firing every 10th cycle.

For the valve timing experiments at 1680 rpm, the spark timing was kept at 30 CAD BTC, which is the maximum brake torque (MBT) spark timing for this engine speed at the normal valve setting. For idle measurements, the spark timing was kept at 20 CAD BTC. This is not the MBT spark timing, but it is close to the engine's normal operating conditions. The engine control unit (ECU) uses the spark timing as a control factor when the engine is idling, so there is no standard operating point.

3.1.2 Sampling

During sampling, the engine was running steady state. The engine skip-fired as outlined in the previous section. Run time for each experiment varied from about 8 minutes to more than 20 minutes.

For each experiment the following data was recorded during sampling:

- Brake torque
- Intake pressure
- Exhaust pressure
- Exhaust temperature

Each experiment was run until the sampling cylinder was pressurized to 6 psia, as explained in sec. 3.1.1.

3.1.3 CO_2 measurements

After the sample was taken, the sample was diluted with Nitrogen in a 5:1 ratio to a pressure of approximately 2 bar. During the dilution, the pressure gauges needed to be switched over such that the 0-15 psia gauge was not exposed to pressures above its range.

The CO_2 meter had to be calibrated before each measurement. This was done using two different gases: pure nitrogen to establish an origin and a calibration gas consisting of 0.8% CO_2 and 99.2% N_2. This established two points to which a calibration curve had been fitted. The conversion formula from CO_2 reading to actual CO_2 content is included in sec. 3.3.1.

The diluted mixture was sent through a drier on its way into the CO_2 meter. Due to the small volume of the drier, it was necessary to keep the flow rate low. This was done through the use of a valve that was only barely cracked open to restrict the flow. The CO_2 reading on the meter was recorded, and this reading can be converted to give a value for the residual gas fraction, as explained in sec. 3.3.2.

3.2 Test Matrix

The three main settings are referred to as the World Point, High Load, and Idle. The main constant parameters are outlined in *table 3.3*:

	Engine Speed (rpm)	Load Constant
World Point	1680	46 Nm brake torque
High Load	1680	103 Nm brake torque
Idle	1000	0.32 bar intake pressure

Table 3.3 Engine settings

3.2.1 World Point

The speed and brake torque of this setting are close to the DaimlerChrysler World Point at medium speed/light load, hence it is referred to as the world point. The speed had to be adjusted from the 1600 rpm used by DaimlerChrysler because of dynamometer stability issues. The drive shaft hits its resonance frequency around 1500 rpm, and if this happens, the rpm drops uncontrollably, and the experiment must be aborted. Therefore, it was determined that an increased safety margin was necessary, and the speed was increased by 5%. Stability issues were more prevalent at high load, but it was desirable to keep the speed the same for the world point and high load settings. The throttle was adjusted to keep the brake torque the same for all the world point experiments.

3.2.2 High Load

The load chosen was the highest one at which the engine and dynamometer could achieve stable operating conditions for spark/valve timings deviating significantly from normal operating conditions. The engine was misfiring some in the worst cases, but the pressure trace showed that this typically happened in the two or three cycles following the skip-fire, which would not significantly affect the measurements.

3.2.3 Idle

When simulating idle, the intake pressure was kept constant at 0.32 bar rather than at the engine load. This was done to achieve stable operating. Engine speed was set to 1000 rpm for the same reason. Normal idling conditions are ~850 rpm and ~0.3 bar intake pressure. For some of the worse points in the valve timing matrix (sec. 3.2.5), the either the intake pressure could not be brought down to 0.32 bar or the engine would not run with set spark timing (as previously mentioned, the ECU uses the spark timing as a control measure).

3.2.4 Spark Timing

Table 3.4 shows the spark timing points tested:

Spark timing in CAD BTC	15	20	25	30	35	40
Idle	√	√	√	√	√	
World Point	√	√	√	√	√	√
High Load		√	√	√	√	√

Table 3.4 Spark timing testing points

Spark timings beyond this range were too unstable for testing.

3.2.5 Valve Timing

Table 3.5 shows the valve timing points tested

			Intake Cam				
	C-Line		127	120	113	106	99
		Offset	-14	-7	0	7	14
Exhaust Cam	-95	-15	√		√		√*
	-104	-6			√	√**	
	-110	0	√	√	√	√	√
	-116	6			√		
	-125	15	√		√		√

Table 3.5 Valve timing testing points

The cam centerline positions are in crank angle degrees (CAD) from TDC-exhaust. The offsets are in CAD relative to the cam centerlines the engine is designed for.

In the three shaded cells in the table, idle operation was not stable. Therefore, for idle measurements, the tests in the cell marked * were moved to the cell marked **. The other two settings were not tested in that cell.

3.3 Data Analysis

3.3.1 CO_2 Reading Conversions

The CO_2 reading is first converted from a percentage reading on the meter (R) to reflect the dry CO_2 mole fraction of the mixture (y_{CO2}). The following formula is derived from calibration gases: $y_{CO_2} = 8.0(10^{-6})R^2 + 8.6(10^{-3})R + 8.9(10^{-3})$. R is given in percentage of the full range, which is 1% CO_2. The formula gives y_{CO2} as a decimal value.

3.3.2 Residual Gas Fraction from CO_2 Measurement

The residual gas molar fraction can be related to the CO_2 content measurement in the following way. Assuming complete, stoichiometric combustion of gasoline with H / C ratio of 1.87, the burned gas consists of the following gases with mole fractions: nitrogen - $x_{N2} = 0.739$; carbon dioxide - $x_{CO2} = 0.131$; and water vapor - $x_{H2O} = 0.130$. With f as the residual gas fraction and the sample diluted from sample pressure P_s to a total pressure P, the relative molar composition of the sample gas before and after dilution and drying are:

Sample Gas		Dried and Diluted Mixture	
Air	1 - f	Air	1 - f
CO_2	$f * x_{CO2}$	CO_2	$f * x_{CO2}$
H_2O	$f * x_{H2O}$	H_2O	0
N_2	$f * x_{N2}$	N_2	$f * x_{N2} + (P/P_s - 1)$

Table 3.6 Relative molar composition of sample and dried mixture

From the compositions above, the dry mole fraction of CO_2, y_{CO2}, can be obtained. Using this result and solving for the residual gas fraction gives the function for calculating the residual gas fraction given in *Eq. 3.1*.

Eq. 3.1
$$x_r = \frac{(P/P_s)}{x_{H_2O} + (x_{CO_2}/y_{CO_2})}$$

The residual mass fraction x_r^* can be related to the residual molar fraction x_r by:

Eq. 3.2
$$x_r^* = \frac{1}{1+\left(\frac{1}{x_r}-1\right)\frac{W_u}{W_b}}$$

For stoichiometric mixture with unburned mixture molecular weight of W_u = 30.38 and burned gas molecular weight W_b = 28.92, the ratio x_r / x_r^* is 0.97. Therefore, the two values are treated as the same, and referred to as residual gas fraction.

3.3.3 Valve Overlap Factor

In order to evaluate different valve configurations, Fox et.al. [2] developed an overlap factor to integrate both the different profiles and nominal overlap factors into the equation. The overlap factor (OF) is defined as follows:

Eq. 3.3
$$OF = \frac{(D_i A_i + D_e A_e)}{V_d} \text{ where } A_i = \int_{IVO}^{IV=EV} L_i d\theta \text{ and } A_e = \int_{IV=EV}^{EVC} L_e d\theta .$$

D and A here denote the inner valve seat diameter and integrated flow area respectively. Subscripts e and i refer to intake and exhaust. For 4 valve cylinders, the areas should be multiplied by a factor of two to account for the extra valves. Graphically, this represents the smallest area underneath the two valve lift curves during valve overlap, as shown in *figure 3.1*.

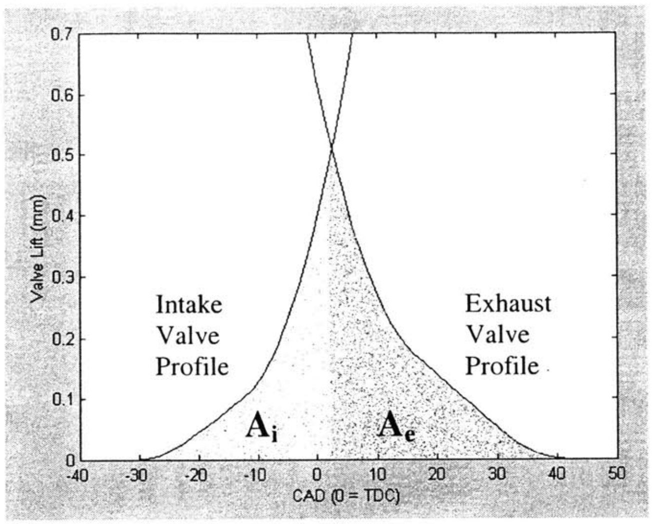

Figure 3.1 Areas used for calculation of overlap factor

The units of the overlap factor are CAD/m (1 CAD/m = 10^3 CAD-mm^2/l). *Table 3.7* shows the valve overlap factors for the valve timings tested in this project. Cam centerlines and offsets are the same as in *table 3.5*.

				Intake Cam			
	C-Line		**127**	**120**	**113**	**106**	**99**
		Offset	**-14**	**-7**	**0**	**7**	**14**
Exhaust Cam	**-95**	**-15**	1.11		2.10		3.73
	-104	**-6**			1.40	1.92	
	-110	**0**	0.52	0.74	1.05	1.46	2.02
	-116	**6**			0.78		
	-125	**15**	0.23		0.49		1.00

Table 3.7 Overlap factor values

Chapter 4

Results and Discussion

4.1 Spark Timing Data

As outlined in sec. 3.2.4, spark sweeps were done at each of the three operating conditions at the original cam configuration. *Figures 4.1, 4.2*, and *4.3* present the residual gas fraction, intake pressure, and exhaust temperatures with increasingly advanced spark timing for the World Point, High Load and Idle settings, respectively.

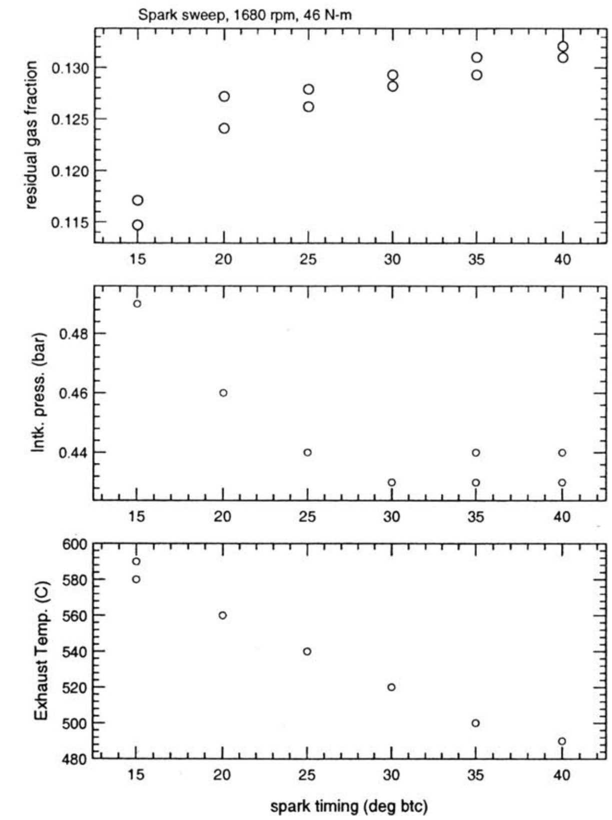

Figure 4.1 Spark sweep, World Point

Chapter 4

Results and Discussion

4.1 Spark Timing Data

As outlined in sec. 3.2.4, spark sweeps were done at each of the three operating conditions at the original cam configuration. *Figures 4.1, 4.2*, and *4.3* present the residual gas fraction, intake pressure, and exhaust temperatures with increasingly advanced spark timing for the World Point, High Load and Idle settings, respectively.

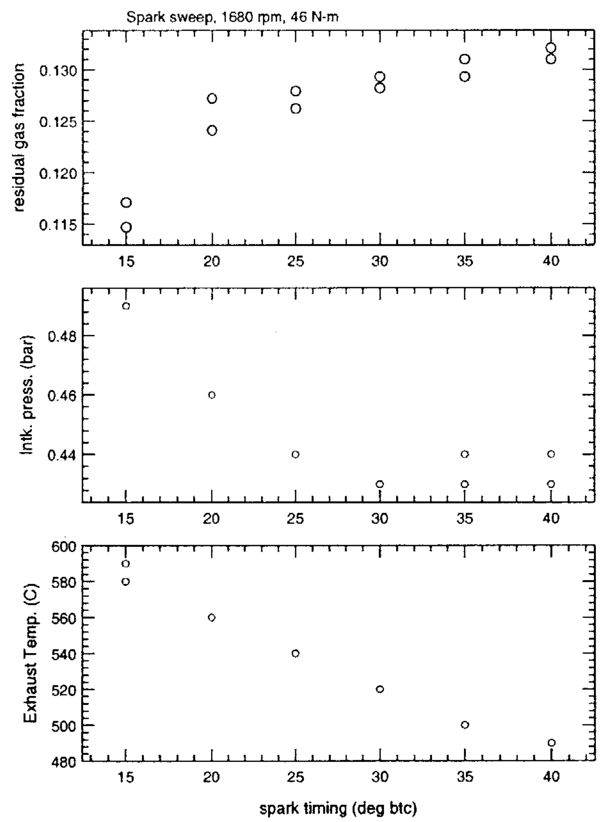

Figure 4.1 Spark sweep, World Point

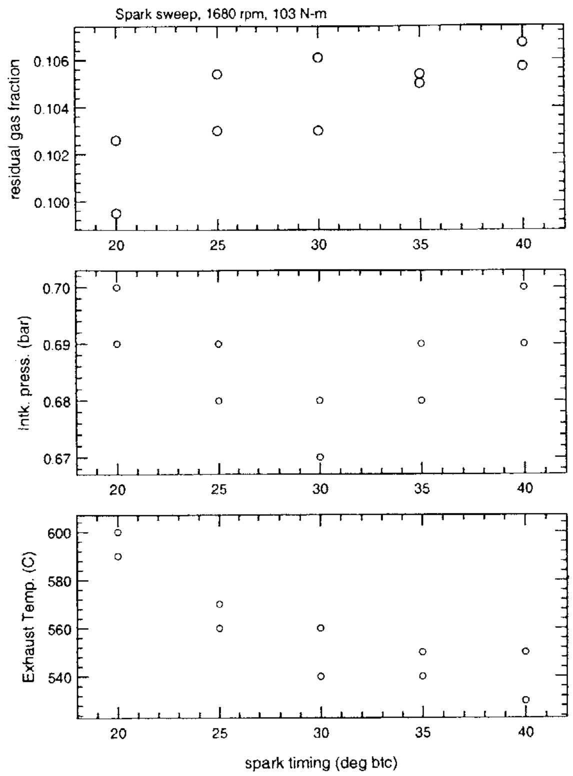

Figure 4.2 Spark sweep, High Load

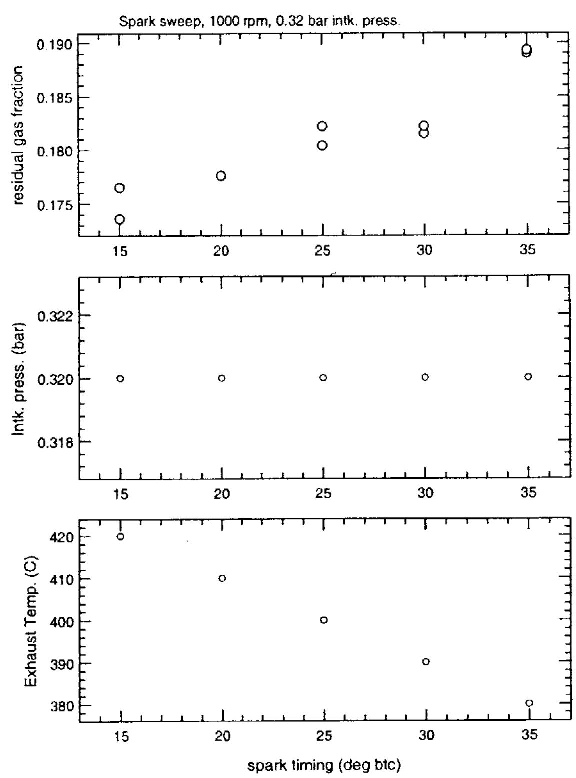

Figure 4.3 Spark sweep, Idle

As the figures show, the residual gas fraction increases as the spark timing is advanced. This is primarily a result of two phenomena. First, the advanced spark timing causes an earlier peak pressure, resulting in lower cylinder pressures and temperatures during the exhaust stroke, and lower exhaust gas density. Second, the advanced spark timing leads to more efficient combustion, and other factors that influence the residual gas fraction, either directly or indirectly, are affected. The intake pressure and exhaust temperature are examples of this. As *figs. 4.1-3* show, the exhaust temperature steadily declines with advanced spark timing, and intake pressures required to maintain a constant load drops significantly close to MBT spark timing. For idling runs, the intake pressures are constant by design, but the break torque is significantly higher for advanced spark timing, adversely affecting the scavenging process.

4.2 Valve Timing Data

Figure 4.4 shows how the residual gas fraction increases with overlap factor.

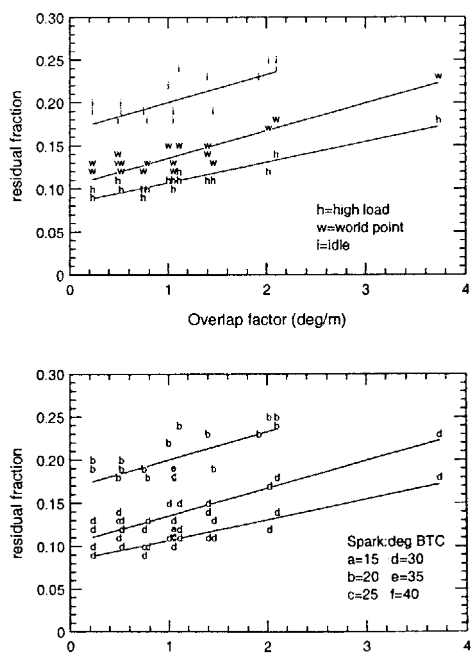

Figure 4.4 Valve overlap variation

As the graphs show, the slope of the three fit lines are similar. The overlap factor is included as a parameter in the residual gas correlation explained below.

4.3 Residual Gas Correlation

The data taken covers only a limited range of operations. Therefore, a physically based correlation is required for it to be applied to a wide range of running conditions. The approach used here follows that of Fox et.al.'s correlation, outlined in sec. 1.2.1, but with important modifications - primarily the addition of the phenomenon of choked backflow.

As mentioned in Chapter 1, the residual gas is a result of two effects: First, backflow from the exhaust port to the intake port during valve overlap, and second, the trapped gas in the cylinder before the valve overlap. All the exhaust gas that flows into the intake port during the overlap flow is assumed to flow back into the cylinder during the intake process. Hence, the residual gas fraction is given by *Eq. 4.1*:

Eq. 4.1

$$x_r = \frac{m_r}{m_c} = \frac{\int_{IVO}^{EVC} \dot{m}_e dt}{m_c} + \frac{m_{IVO}}{m_c}$$

Most terms in this section follow normal nomenclature, with subscripts i = intake, e = exhaust, IVO = intake valve open, EVC = exhaust valve close, c = charge (m_c) or compression (r_c). *Appendix C* explains the nomenclature used in this paper.

The last term of the above equation, the trapped gas term, is to a good approximation equal to:

Eq. 4.2

$$\frac{m_{IVO}}{m_c} = \left(\frac{\rho_e}{\rho_i}\right)\frac{1}{r_c}$$

The backflow term is more complicated. When the backflow is not choked, the flow rate is governed by the resistance of the exhaust and intake valve opening in series. The combined resistance is dominated by the limiting opening. The overlap factor, which by definition recognizes the limiting flow area, is therefore a good metric for the extent of the backflow. For the choked flow, the cylinder pressure dictates whether the intake or exhaust valve opening is choked. The cylinder pressure is dynamically determined by the flow process. This complication is not modeled, for simplicity, and the choking is assumed to take place at the smaller of the intake or exhaust flow area. With this assumption, the overlap factor is still an appropriate parameter for determining the overlap flow. With the assumptions above, the exhaust gas backflow is given in *Eq. 4.3* [5].

Eq. 4.3

$$\dot{m}_e = \dot{m}_{choked} \frac{\xi^{1/\gamma}\sqrt{\frac{2\gamma}{\gamma-1}\left(1-\xi^{\frac{\gamma-1}{\gamma}}\right)}}{\sqrt{\gamma}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}} \quad \text{for } 1>\xi>\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

$$\dot{m}_e = \dot{m}_{choked} \quad \text{for } 0<\xi<\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

ξ is the ratio of the intake pressure to the exhaust pressure (p_i/p_e). The choked flow rate is given by *Eq. 4.4*.

Eq. 4.4

$$\dot{m}_{choked} = A\rho_e\sqrt{\gamma R T_e}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

A in this equation is an effective area. For $\gamma = 1.33$, choking occurs at pressure ratio $\xi = 0.54$. To a good approximation, *Eq. 4.3* may be fit by:

Eq. 4.5

$$\frac{\dot{m}_e}{\dot{m}_{choked}} = f(\xi);$$

$$f(\xi) = 1-\exp\left(-4.78\beta^{0.7} - 153.8\beta^{4.5}\right); \beta = 1-\xi = 1-\frac{p_i}{p_e}$$

Eq. 4.5 is a single formula applicable to both the choked and unchoked regimes. Then, using *Eq. 4.4* and *Eq. 4.5*, the backflow term of *Eq. 4.1* can be expressed by:

Eq. 4.6 $$\frac{\int_{IVO}^{EVC} \dot{m}_e dt}{m_c} = \left(\frac{\bar{A}\Delta t}{V_D}\right)\left(\frac{r_c - 1}{r_c}\right)\frac{\rho_e}{\rho_i}\sqrt{\frac{T_e}{T_i}}\sqrt{\gamma R T_i}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} f(\xi)$$

Ā in this equation is the average limiting flow area during the overlap period Δt. Using the definition of the overlap factor from *Eq. 3.3*, the first factor of the right hand side of *Eq. 4.6* simplifies to:

Eq. 4.7 $$\left(\frac{\bar{A}\Delta t}{V_D}\right) \propto \frac{OF}{N}$$

For standard values of compression ratios in spark ignition engines, the factor $(r_c - 1)/r_c$ changes by less than ±2%, and may be considered constant.

In an ideal cycle, the exhaust to intake temperature ratio T_e/T_i is:

Eq. 4.8 $$\frac{T_e}{T_i} = 1 + \left(\frac{1}{r_c^{\gamma-1}}\right)\frac{LHV}{c_p T_i (1 + A/F)}$$

The above expression remains reasonably constant (within ±3%) over the nominal range of r_c and A/F values. Therefore, the term may be treated as a constant.

Spark timing has an effect on T_e, which affects the right hand side of *Eq. 4.6* through the density term ρ_e and the speed of sound term $(\gamma R T_e)^{1/2}$. The relationship is further complicated by the fact that to maintain constant torque, the airflow has to be adjusted when the spark timing is changed. In our correlation, the spark timing is assumed to be mainly affecting the exhaust gas density, neglecting the effect on the speed of sound.

With the above assumptions, the backflow term as expressed in *Eq. 4.6* may be simplified to:

Eq. 4.9 $$\frac{\int_{IVO}^{EVC} \dot{m}_e dt}{m_c} \propto \frac{\rho_e}{\rho_i}\frac{OF}{N} f(\xi)$$

Combining *Eqs. 4.1, 4.2* and *4.9*, the residual gas fraction is:

Eq. 4.10 $$x_r = \alpha_1 \frac{OF}{N} f(\xi) \frac{\rho_e}{\rho_i} + \frac{1}{r_c} \frac{\rho_e}{\rho_i}$$

α_i is a proportional constant, where i = 1, 2 and 3 for *Eqs. 4.10, 12* and *14*.

The density ratio is

Eq. 4.11 $$\frac{\rho_e}{\rho_i} = \frac{p_e}{p_i} \frac{T_i}{T_e} = \xi^{-1} \frac{T_i}{T_e}$$

As discussed above, for ideal cycle, the dependence of the temperature ratio term on compression and air/fuel ratios is small. The effect of the spark timing on this ratio was modeled by fitting the data. To allow for better fit to the data, the dependence on ξ in *Eq. 4.11* was fit to a power law instead of to a power of minus one. Thus, *Eq. 4.11* becomes:

Eq. 4.12 $$\frac{\rho_e}{\rho_i} = \frac{p_e}{p_i} \frac{T_i}{T_e} = \alpha_2 \xi^{\alpha_3} g(\theta_{spark})$$

To obtain the function g's dependence on spark timing, the spark sweep data was normalized at each of the three operating conditions by the highest values, averaged over repeated runs. The fit gives the following dependence:

Eq. 4.13 $$g(\theta_{spark}) = 1 - \left(\frac{\theta_{spark} - 40}{81.3} \right)^2$$

θ_{spark} is in crank-angle degrees BTC.

Combining *Eqs. 4.10, 4.12* and *4.13* and grouping the model constants together, the final overall fit to the residual gas data is:

Eq. 4.14 $$x_r = \left(\alpha_1 \alpha_2 \frac{OF}{N} f(\xi) + \alpha_2 \frac{1}{r_c} \right) \xi^{\alpha_3} \left[1 - \left(\frac{\theta_{spark} - 40}{81.3} \right)^2 \right]$$

The model constants α_1, α_2, and α_3 were obtained by using a non-linear regression program to regress x_r against OF/N and the pressure ratio ξ. The result is the correlation given in *Eq. 4.15*.

Eq. 4.15 $$x_r = \left(0.401 \frac{OF}{N} f(\xi) + 0.546 \frac{1}{r_c} \right) \xi^{-0.84} \left[1 - \left(\frac{\theta_{spark} - 40}{81.3} \right)^2 \right]$$

The correlation is shown in *Figure 4.5*.

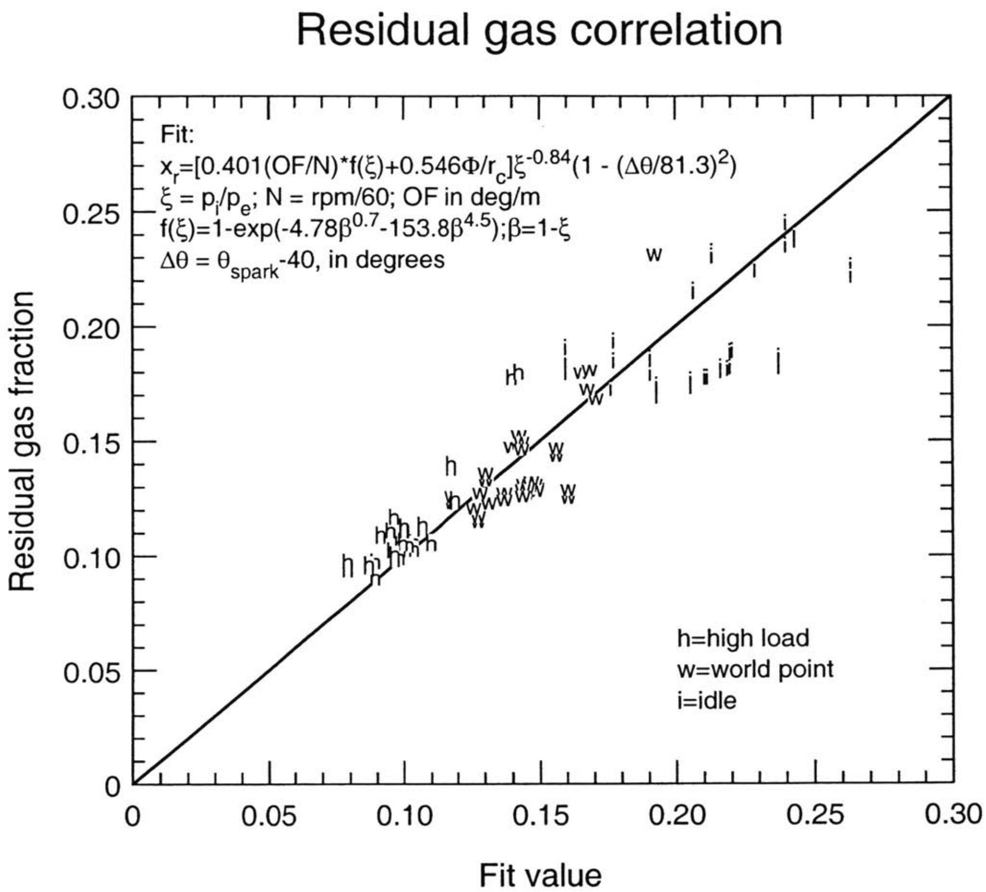

Figure 4.5 Residual Gas Correlation

Chapter 5

Conclusions

Based on experimental data, a correlation for predicting the residual gas fraction has been developed. The correlation is intended for use in valve design, and requires the following input parameters:

- Engine speed
- Valve profile, represented by a valve overlap factor
- Intake/Exhaust pressure ratio
- Compression ratio
- Spark timing

Though it was found that the dependence on spark timing was relatively small (~5% variation for 10 CAD advance/retard from MBT), the correlation is the first to incorporate this effect. Additionally, the effect of the valve overlap period is modeled more rigorously than what has previously been done.

References

1. John B. Heywood. *Internal Combustion Engine Fundementals*, McGraw-Hill Inc. 1988.
2. Jonathan W. Fox, Wai K. Cheng and John B. Heywood. "A Model for Predicting Residual Gas Fraction in Spark-Ignition Engines," SAE Technical Paper Series #931025
3. Francois Galliot, Wai K. Cheng, John B. Heywood et al. "In-Cylinder Measurements of Residual Gas Concentration in a Spark Ignition Engine," SAE Technical Paper Series #900485
4. R. Miller, S. Russ, C. Weaver et al. "Comparison of Analytically and Experimentally Obtained Residual Fractions and NO_x emissions in Spark-Ignited Engines," SAE Technical Paper Series #982562
5. J. Fay. *Introduction to Fluid Mechanics*, MIT Press, Cambridge, MA, 1994.

Appendix A

Summary of data from residual gas sampling experiment

The data columns are

C1	rpm
C2	Torque(Nm)
C3	Spark timing (deg BTC)
C4	Intk Cam offset; + is earlier intk valve opening; 0 is cam CL at 113 deg ATDC
C5	Exht cam offset; - is later exht valve closing; 0 is cam CL at -110 deg ATDC
C6	Intake pressure (bar)
C7	Exhahast pressrue (kpa)
C8	Exhaust T (C)
C9	Residual gas fraction (%)
C10	Valve overlap factor (deg/m); multiply by 1000 for mm^2-deg/Liter
C11	test code (w=world pt; h=high load; i=idle)
C12	spark code (deg btc: a=15,b=20,c=25,d=30,e=35,f=40)

C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
1680	46	15	0	0	0.49	102.5	580	11.47	1.05	'w'	'a'
1680	45	20	0	0	0.46	102	560	12.72	1.05	'w'	'b'
1680	45	25	0	0	0.44	102.5	540	12.79	1.05	'w'	'c'
1680	45	30	0	0	0.43	102.5	520	12.93	1.05	'w'	'd'
1680	46	35	0	0	0.43	102	500	13.1	1.05	'w'	'e'
1680	45	40	0	0	0.43	102	490	13.21	1.05	'w'	'f'
1680	47	15	0	0	0.49	102.5	590	11.71	1.05	w'	'a'
1680	45	20	0	0	0.46	102	560	12.41	1.05	'w'	'b'
1680	45	25	0	0	0.44	102.5	540	12.62	1.05	'w'	'c'
1680	45	30	0	0	0.43	102.5	520	12.82	1.05	'w'	'd'
1680	46	35	0	0	0.44	102	500	12.93	1.05	'w'	'e'
1680	46	40	0	0	0.44	102	490	13.1	1.05	'w'	'f'
1680	45	30	7	0	0.44	104.5	530	12.51	1.46	'w'	'd'
1680	45	30	7	0	0.44	104.5	530	12.86	1.46	'w'	'd'
1680	45	30	-7	0	0.46	102	530	12.3	0.74	'w'	'd'
1680	45	30	-7	0	0.46	102	530	12.27	0.74	'w'	'd'
1680	44	30	14	0	0.45	102.5	520	16.8	2.02	'w'	'd'
1680	46	30	14	0	0.46	102.5	520	17.22	2.02	'w'	'd'
1680	45	30	-14	0	0.45	102.5	520	12.72	0.52	'w'	'd'
1680	47	30	-14	0	0.46	102.5	520	12.06	0.52	'w'	'd'
1680	46	30	-14	-15	0.47	102.5	520	14.71	1.11	'w'	'd'
1680	44	30	-14	-15	0.46	102.5	520	15.21	1.11	'w'	'd'
1680	45	30	-14	15	0.46	102.5	510	12.3	0.23	'w'	'd'
1680	46	30	-14	15	0.46	102.5	510	12.58	0.23	'w'	'd'
1680	45	30	14	15	0.44	101.5	510	14.93	1	'w'	'd'
1680	46	30	14	15	0.44	101.5	510	14.61	1	'w'	'd'
1680	45	30	14	-15	0.52	101.5	530	23.12	3.73	'w'	'd'
1680	45	30	14	-15	0.52	101.5	530	23.05	3.73	'w'	'd'
1680	45	30	0	-15	0.47	101.5	530	17.93	2.1	'w'	'd'
1680	44	30	0	-15	0.46	101.5	530	18.04	2.1	'w'	'd'
1680	46	30	0	-6	0.44	102.5	520	14.33	1.4	'w'	'd'
1680	45	30	0	-6	0.44	102.5	520	14.68	1.4	'w'	'd'
1680	46	30	0	6	0.42	102.5	510	12.86	0.78	'w'	'd'
1680	45	30	0	6	0.42	102.5	510	12.58	0.78	'w'	'd'
1680	47	30	0	15	0.44	103	510	13.28	0.49	'w'	'd'
1680	46	30	0	15	0.44	103	510	13.59	0.49	'w'	'd'
1680	102	20	0	0	0.69	101	590	10.26	1.05	'h'	'b'
1680	103	25	0	0	0.68	101	560	10.54	1.05	'h'	'c'
1680	103	30	0	0	0.67	104.5	540	10.61	1.05	'h'	'd'
1680	104	35	0	0	0.68	104	540	10.54	1.05	'h'	'e'
1680	102	40	0	0	0.69	104	530	10.67	1.05	'h'	'f'
1680	104	20	0	0	0.7	105.5	600	9.95	1.05	'h'	'b'
1680	104	25	0	0	0.69	106	570	10.3	1.05	'h'	'c'
1680	104	30	0	0	0.68	106	560	10.3	1.05	'h'	'd'
1680	104	35	0	0	0.69	105.5	550	10.5	1.05	'h'	'e'
1680	103	40	0	0	0.7	105.5	550	10.57	1.05	'h'	'f'
1680	104	30	7	0	0.69	105.5	560	10.61	1.46	'h'	'd'
1680	103	30	7	0	0.69	105.5	560	10.57	1.46	'h'	'd'

Appendix A: Data Points

C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
1680	102	30	-7	0	0.73	103.5	560	9.75	0.74	'h'	'd'
1680	103	30	-7	0	0.73	103.5	560	9.06	0.74	'h'	'd'
1680	103	30	-7	0	0.73	103.5	560	9.06	0.74	'h'	'd'
1680	103	30	14	0	0.69	104	540	12.37	2.02	'h'	'd'
1680	104	30	14	0	0.69	104	540	12.48	2.02	'h'	'd'
1680	103	30	-14	0	0.72	104	540	9.54	0.52	'h'	'd'
1680	103	30	-14	0	0.72	104	540	9.64	0.52	'h'	'd'
1680	103	30	-14	-15	0.74	104	540	11.12	1.11	'h'	'd'
1680	103	30	-14	-15	0.73	104	540	11.71	1.11	'h'	'd'
1680	103	30	-14	15	0.74	103	540	9.4	0.23	'h'	'd'
1680	104	30	-14	15	0.74	103	540	9.75	0.23	'h'	'd'
1680	104	30	14	15	0.68	103	540	11.12	1	'h'	'd'
1680	105	30	14	15	0.68	103	540	11.3	1	'h'	'd'
1680	103	30	14	-15	0.73	102.5	540	17.76	3.73	'h'	'd'
1680	104	30	14	-15	0.72	102.5	540	18.01	3.73	'h'	'd'
1680	103	30	0	-15	0.7	103	540	13.84	2.1	'h'	'd'
1680	103	30	0	-15	0.7	103	540	14.01	2.1	'h'	'd'
1680	104	30	0	-6	0.69	103.5	540	11.19	1.4	'h'	'd'
1680	103	30	0	-6	0.69	103.5	540	11.37	1.4	'h'	'd'
1680	104	30	0	6	0.68	104	540	9.85	0.78	'h'	'd'
1680	103	30	0	6	0.68	104	540	10.09	0.78	'h'	'd'
1680	102	30	0	15	0.68	104.5	540	10.88	0.49	'h'	'd'
1680	104	30	0	15	0.68	104.5	540	10.95	0.49	'h'	'd'
1000	14	20	0	0	0.32	102.5	410	17.76	1.05	'i'	'b'
1000	10	15	0	0	0.32	103	420	17.36	1.05	'i'	'a'
1000	15	25	0	0	0.32	103.5	400	18.04	1.05	'i'	'c'
1000	18	30	0	0	0.32	103.5	390	18.15	1.05	'i'	'd'
1000	18	35	0	0	0.32	103.5	380	18.9	1.05	'i'	'e'
1000	8	15	0	0	0.32	103	420	17.65	1.05	'i'	'a'
1000	12	20	0	0	0.32	103	410	17.76	1.05	'i'	'b'
1000	14	25	0	0	0.32	103.5	400	18.22	1.05	'i'	'c'
1000	18	30	0	0	0.32	104	390	18.22	1.05	'i'	'd'
1000	18	35	0	0	0.32	104	380	18.93	1.05	'i'	'e'
1000	10	20	7	0	0.32	103.5	420	18.22	1.46	'i'	'b'
1000	10	20	7	0	0.32	103.5	420	18.68	1.46	'i'	'b'
1000	10	20	-7	0	0.32	102	400	17.93	0.74	'i'	'b'
1000	10	20	-7	0	0.32	102	400	18.61	0.74	'i'	'b'
1000	10	20	14	0	0.36	102	450	23.74	2.02	'i'	'b'
1000	10	20	14	0	0.36	102	450	24	2.02	'i'	'b'
1000	16	20	-14	0	0.32	102	390	18.5	0.52	'i'	'b'
1000	15	20	-14	0	0.32	102	390	19.36	0.52	'i'	'b'
1000	2	20	-14	-15	0.32	102	430	23.23	1.11	'i'	'b'
1000	4	20	-14	-15	0.32	102	430	23.05	1.11	'i'	'b'
1000	14	20	-14	15	0.32	102	360	19.08	0.23	'i'	'b'
1000	13	20	-14	15	0.32	102	360	17.97	0.23	'i'	'b'
1000	14	20	-14	15	0.32	102	360	18.47	0.23	'i'	'b'
1000	10	20	14	15	0.32	102	380	21.49	1	'i'	'b'
1000	12	20	14	15	0.32	102	390	21.56	1	'i'	'b'
1000	6	20	0	-15	0.37	101	440	23.52	2.1	'i'	'b'
1000	7	20	0	-15	0.37	101	440	24.51	2.1	'i'	'b'
1000	9	20	0	-6	0.32	101	420	22.43	1.4	'i'	'b'
1000	8	20	0	-6	0.32	101	420	22.54	1.4	'i'	'b'
1000	18	20	0	6	0.32	102	390	16.94	0.78	'i'	'b'
1000	19	20	0	6	0.32	102	390	17.44	0.78	'i'	'b'
1000	20	20	0	15	0.32	102.5	370	17.29	0.49	'i'	'b'
1000	21	20	0	15	0.32	102.5	370	17.29	0.49	'i'	'b'
1000	5	20	7	-6	0.32	102.5	430	22.61	1.92	'i'	'b'
1000	4	20	7	-6	0.32	102.5	430	22.21	1.92	'i'	'b'

Appendix B

Computer Code

B.1 Sampling Valve / Skip-Fire Control

The code is included, with numerical points referring to explanations below. The program uses the cam signal as its reference point. The input signal consists of two high pulses of different lengths over the 720 cad cycle. The program uses the rising edge of the longer of the two pulses to initialize the sampling valve pulse, and the falling edge of the preceding short pulse to raise the skip-fire puls. The skip-fire output goes low when the longer pulse goes low. The sampling valve output pulse is a short (10ms) signal that triggers a pulse output from an external source (as discussed in sec. 2.2.3).

B.1.1 Main Program

1. Variable and address definitions
2. User input # of cycles sampled and direct input of # of cycles skipped
3. Timer initialization
4. Engine calibration - read cam signal
    a. wait for signal to go low
    b. read length of both pulses to determine which is longer
    c. initialize value for main loop
5. Main loop
    a. skip short pulse
    b. raise the skip-fire output
    c. wait for signal to go high
    d. output sampling valve pulse
    e. wait for signal to go low
    f. lower the skip-fire output
    g. skip the next n cycles, as defined in 2.

B.1.2 Subroutines

6. p_width: reads the pulse width
    a. starts counter when pulse goes high
    b. latches counter when pulse goes low
    c. reads and returns length of pulse (counter uses 100kHz clock)
7. p_skip: skips the next pulse by waiting for input signal go high and then low
8. ip2_go_high/low: continously reads input signal and waits for transition
9. outpulse: outputs sampling valve pulse
    a. defines and loads a count to a timer
    b. raises pulse output
    c. reads timer as it is counting down
    d. lowers output when count is finished

Appendix B: Computer Code
Sampling Valve and Skip-Fire Control

```
#include <stdio.h>
#include <conio.h>

unsigned short addr, timer0, timer1, timer2, timerctl;
unsigned short dio, cnten;
unsigned short int op_state;
unsigned short int n_sample, n_skip;
unsigned short int p_width();
unsigned short int filter();
void outpulse();void p_skip();
void ip2_go_low(); void ip2_go_high();
                                                            1
void main() {
      unsigned short int i,j,k;
      unsigned short int count1, count2;

      addr = 0x300;
      timer0 = addr + 0xc;
      timer1 = addr + 0xd;
      timer2 = addr + 0xe;
      timerctl = addr + 0xf;
      dio = addr + 0x3;
      cnten = addr + 0xa;

      printf("\n How many cycles do you want to sample?\n");    2
      scanf("%d", &n_sample);
      n_skip=9;

      outp(dio, 0x0);
      outp(cnten, 0x2);                                         3
      outp(timerctl,0x54);
      outp(timer1,0xa);

      if (inp(dio) & 0x4) {ip2_go_low();}
      count1=p_width();
      count2=p_width();                                         4
      if(count2>count1) {p_skip();}
      j=n_sample;

      while(j) {
            p_skip();
            op_state=0x2;
            outp(dio,op_state);
            ip2_go_high();
            outpulse();                                         5
            ip2_go_low();
            op_state=op_state&0xfd;
            outp(dio,op_state);
            for (k=1;k<=n_skip;++k) {p_skip();  p_skip();}
            --j;
      }
}
```

```
unsigned short int p_width(){
      unsigned short int i,j,n;
      void ip2_go_high();
      void ip2_go_low();
      outp(timerctl, 0x30);
      outp(timer0, 0xff);
      outp(timer0, 0xff);
      ip2_go_high();                                   6
      ip2_go_low();
      outp(timerctl, 0x0);
      i = inp(timer0);
      j = inp(timer0);
      n = 65535 - (i + j * 256);
      return(n);
}
void p_skip(){
      void ip2_go_high();
      void ip2_go_low();                               7
      ip2_go_high();
      ip2_go_low();
      return;
}
void ip2_go_low(){
      unsigned short int i=1;
      while (i>0){
            i=inp(dio)&0x4;
      }
      return;
}                                                      8
void ip2_go_high(){
      unsigned short int i; j;
      i=0;
      while(i==0){
            i=inp(dio)&0x4;
            }
return;
}
void outpulse(){
      #define COUNT 10
      unsigned short int i,lsb,msb;
      outp(timerctl, 0xb0);
      outp(timer2, COUNT);
      outp(timer2, 0x0);
      op_state=op_state|0x1;
      outp(dio,op_state);
      i=COUNT;
      while(i<=COUNT){                                 9
            outp(timerctl, 0x80);
            lsb = inp(timer2);
            msb = inp(timer2);
            i = msb * 256 + lsb;
      }
      op_state=op_state&0xfe;
      outp(dio,op_state);
      return;
}
```

B.2 Spark Timing Control

The code is included, with numerical points referring to explanations below. The program uses the shaft encoder as its input. The shaft encoder provides two signals: (1) BDC pulse which is connected to port ip1, and (2) CAD pulse, which is connected to counter0. The BDC pulse calibrates the CAD pulse, which is used for timing the spark pulses. The program prompts the user for rpm and spark timing.

B.2.1 Main Program

1. Variable and address definitions
2. Initialize counter0
3. User prompt
4. Calculate charge time and define timing
5. Main loop
    a. load counter
    b. wait for bdc signal
    c. start charging spark for cyl 1/4
    d. spark discharge cyl 1/4
    e. start charging spark for cyl 2/3
    f. spark discharge cyl 2/3

B.2.2 Subroutines

6. ca_reset: resets crank angle counter
7. crank: reads current crank angle
8. ip1_go_high/low: continously reads input signal and waits for transition

Appendix B: Computer Code
Spark Timing Control

```
#include <stdio.h>
#include <conio.h>
unsigned short int addr, timer0, timer1, timer2, timerctl, dio, cnten;
main(){
      unsigned short int event[5];
      unsigned short int answer,i,j,rpm, spark, charge;
      unsigned short int crank();
      void ca_reset(),ip1_go_high(),ip1_go_low();                   1
      addr = 0x300;
      timer0 = addr + 0xc;
      timer1 = addr + 0xd;
      timer2 = addr + 0xe;
      timerctl = addr + 0xf;
      dio = addr + 0x3;
      cnten = addr + 0xa;
      outp(dio, 0x0);
      outp(cnten, 0x0);                                             2
      outp(timerctl, 0x30);
      answer = 0;
      while (answer == 0){
            printf("\n Please enter the rpm and spark timing (as CA BTC): ");
            scanf("%d %d", &rpm, &spark);
            printf("\n RPM: %4i", rpm);                             3
            printf("\n spark timing (before TDC): %3i", spark);
            printf("\n Are these the correct values (1=yes,0=no)");
            scanf("%d", &answer);
      }
      charge=(24*(rpm/10))/100;
      event[2] = 180-spark;
      event[1] = event[2]-charge;
      event[4] = 360-spark;                                         4
      event[3] = event[4]-charge;
      printf("spk(BTC)|  rpm   | dwell  |1-4chrge|1-4 fire|2-3chrge|2-3
      fire|\n");
      printf("%8i|%8i|%8i|%8i|%8i|%8i|%8i|\n", spark, rpm, charge, event[1],
      event[2], event[3], event[4]);
      i=0;
      while(i<1) {
            if((inp(dio)&0x2)==0) {ip1_go_high();}
            ca_reset();
            ip1_go_low();
            j=0;
            while(j<1000){j++;};
            j=1;
            while (j<event[1]) {j=crank();}                         5
            outp(dio,0x1);
            while (j<event[2]) {j=crank();}
            outp(dio,0x0);
            while (j<event[3]) {j=crank();}
            outp(dio,0x2);
            while (j<event[4]) {j=crank();}
            outp(dio,0x0);

      }
}
```

```
void ca_reset(){
      unsigned short int j1,j2;
      outp(timer0,0xff);                   } 6
      outp(timer0,0xff);
      return;
}

unsigned short int crank(){
      unsigned short int lo, hi;
      outp(timerctl, 0x0);
      lo = inp(timer0);                         } 7
      hi = inp(timer0);
      return (65535 - hi*256 - lo);
}

void ip1_go_high(){
      unsigned short int i;
      i=0;
      while(i==0){i=inp(dio)&0x2;}
return;
}                                               } 8

void ip1_go_low(){
      unsigned short int i;
      i=1;
      while(i!=0){i=inp(dio)&0x2;}
return;
}
```

Appendix C

Nomenclature

Symbol	Explanation	First appears in Eq.:
A/F	Air to fuel ratio	4.8
c_p	Specific heat at constant pressure	4.8
L_e	Exhaust valve lift	3.3
L_i	Intake valve lift	3.3
LHV	Lower heating value	4.8
dm_e/dt	Flow rate of exhaust gas into intake port during valve overlap	4.1
m_{IVO}	Mass of burned gas trapped in cylinder just before IVO	4.1
m_r	Residual gas mass	4.1
m_c	Charge mass	4.1
N	Engine speed in revolutions per second	4.7
OF	Overlap factor	3.3
P	Pressure of sample after dilution	3.1
P_s	Pressure of collected sample	3.1
p_e	Exhaust pressure	4.5
p_i	Intake pressure	4.5
r_c	Compression ratio	4.2
T_e	Exhaust temperature	4.4
T_i	Intake temperature	4.6
V_D	Displacement per cylinder	3.3
W_u	Unburned gas molecular weight	3.1
W_b	Burned gas molecular weight	3.1
$x_{chemical\ symbol}$	Mole fraction of specified gas	3.1
x_r	Residual gas fraction	3.1
$y_{chemical\ symbol}$	Mole fraction of specified gas after mixture is dried	3.1
γ	Specific heat ratio	4.3
θ	Crank angle	4.12
ρ_e	Exhaust gas density	4.2
ρ_i	Intake gas density	4.2
ξ	Pressure ratio (p_i/p_e)	4.3