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Development of software used to analyse the combustion and energy release characteristics of diesel fuels

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Development of Software used to Analyse the Combustion and Energy Release Characteristics of Diesel Fuels

Jean-Paul da Costa

A research report submitted to the faculty of Engineering and the Built Environment, of the University of the Witwatersrand, in partial fulfilment of the degree of Master of Science in Engineering.

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DECLARATION

I declare that this research report is my own, unaided work. It is being submitted for the degree of Masters of Science (Mechanical Engineering) at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

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Jean-Paul da Costa Date

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ABSTRACT

Software to analyse the combustion and energy release characteristics of fuels was designed and developed. The software was used to investigate the characteristics of diesel fuels at varying loads by performing thermodynamic analysis techniques and displaying the results.

The software performed the analysis directly according to the objectives as to which it was designed for. It obtained the same energy release curves and other energy modelling characteristics as compared to the original software. The software was also found to increase the power of analysis through its improved analysis components.

The results obtained for the diesel tests appear to be representative of all speeds and loads showing the typical behaviour expected, indicating that the engine and the data analysis techniques performed by the software are consistent and correct. It is apparent that the trends obtained follow the expected patterns and are complementary of each other, demonstrating the absence of any major problems.

The software will be used to further the research into alternative fuels and will make the analysis process more efficient and less time consuming.

1. Introduction

The purpose of internal combustion engines is to produce mechanical power from the chemical energy contained in the fuel. In internal combustion engines, as distinct from external combustion engines, this energy is released by burning or oxidizing the fuel inside the engine. The fuel-air mixture, before combustion, and the burned products, after combustion, are the actual working fluids. The work transfers, which provide the desired power output, occur directly between these working fluids and the mechanical components of the engine.

The fuels have had a major impact on engine development. The earliest engines used for generating mechanical power burned gas. Gasoline and lighter fractions of crude oil, became available in the late 1800s and various types of carburetors were developed to vaporize the fuel and mix it with air. Before 1905 there were few problems with gasoline, though compression ratios were low (4 or less) to avoid knock, the highly volatile fuel made starting easy and gave good cold weather performance. A serious crude oil shortage developed however, and to meet the five fold increase in gasoline demand between 1907 and 1915, the yield from crude had to be raised [1]. In recent times the increase in global growth with emerging markets such as China and India have once again increased the demand for crude oil. This, together with geo-political tensions, have caused the price of crude oil to sky rocket. A third complication of oil resource depletion is also becoming a concern.

Alternative fuel research has always been a formality; however with world events dictating a higher sense of urgency, this research has become imperative. Billions of dollars are being invested by car manufacturers, governments and energy companies to replace current energy fuel resources with an alternative. The focus of this research project is exactly this. More advanced analytical software is required to perform this research. The advancement of computer technology has made this possible.

The author of this research project has developed a software package directly focused on the analytical processes of alternative fuel research. The software has been written

in Java. Java is the latest computer language technology and is platform independent. The package can run on any operating system from linux, to windows, to cell phones.

The software was not only designed to perform the thermodynamic analysis but to represent it in a professional format. Analysis is a very crucial part of the research but the way it is presented is exceptionally important. This is so because one can have all the information and evidence in the world but if it is not properly communicated, it will all be worthless. As a result the software has been developed to have powerful graphic and reporting features.

The software package, named Combustion Analysis software (CAS), was used to analyse the combustion characteristics of diesel. This was an appropriate fuel to test the software on because of the extensive research already done on the fuel. The results using the newly developed software can then be directly compared for accuracy and validity and was found to have fulfilled these requirements.

The software package will allow for improved research with more time being spent on actual research outcomes rather than on optimization of the processes and mechanisms in order to reach these outcomes. The software is intended to develop a solution to the current problem of future oil shortages and environmental concerns. The software will be extremely useful and beneficial for future research and developments.

1.1 Objectives

The primary objectives of this study are defined as follows:

- To develop a software application that analyses the characteristics of a compression ignition engine using alternative fuelling
- To consolidate and compare the results with work carried out previously at the School to further the understanding of the fuel combustion characterisitics.
- To obtain additional analytical and presentable data for future research work.
- To develop software that analyses the combustion and energy release characteristics of alternative fuels.

A secondary objective of the research is:

- To use the newly developed software to perform analysis and obtain data on diesel fuel resulting from the testing of a compression ignition engine.

2. Literature Survey

2.1 Combustion in Compression-Ignition Engines

Combustion engines are divided into two basic categories according to their combustion chamber design,

- Direct Injection (DI) engines, which have a single open combustion chamber into which fuel is injected directly.
- Indirect Injection (IDI) engines, where the chamber is divided into two regions and the fuel is injected into the “pre-chamber” which is connected to the main chamber via a nozzle or one or more orifices. IDI engine designs are only used in the smallest engine sizes.[1]

2.1.1 Direct Injection Systems

In the largest engines, where the mixing rate requirements are least stringent, quiescent direct-injection systems of the type shown in figure 2.1a are used. The momentum and energy of the injected fuel jets are sufficient to achieve adequate fuel distribution and rates of mixing with the air. Additional organised air motion is required. The combustion chamber shape is usually a shallow bowl in the crown of the piston, and a single multihole injector is used. [1]

As engine size decreases, increasing amounts of air swirl are used to achieve faster fuel-air mixing rates. Air swirl is generated by suitable design of the inlet port. The swirl can be increased as the piston approaches top dead centre by forcing the air toward the cylinder axis, into a bowl-in-piston type of combustion chamber. Figure 2.1b and c shows the two types of DI engine with swirl, with a centrally located multihole injector nozzle. Here the design goal is to the amount of liquid fuel which impinges on the piston cup walls to a minimum. Figure 2.1c shows most of the fuel is deposited on the piston bowl walls.[1]

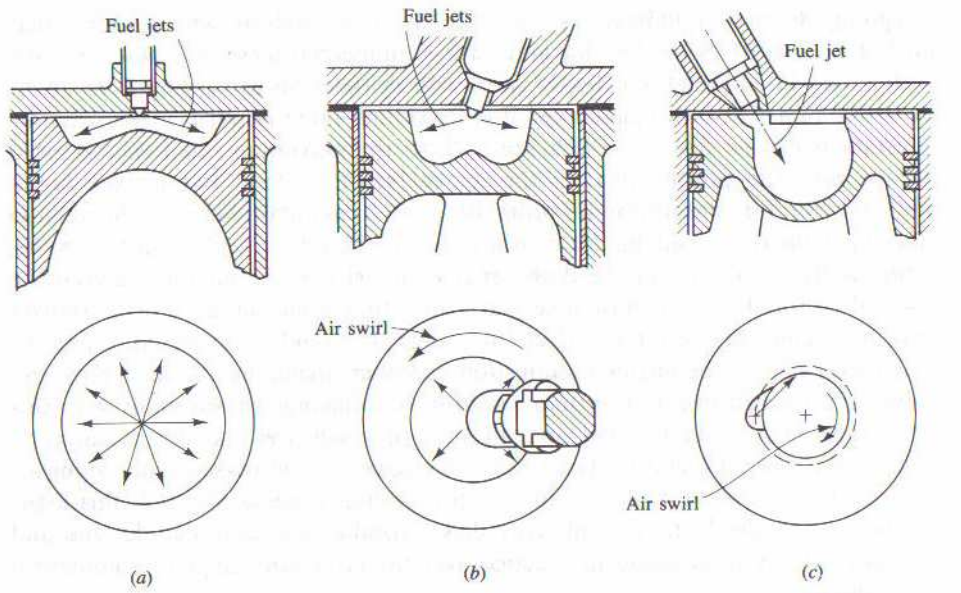


Figure 2.1: Common types of direct-injection compression ignition systems[1]

2.1.2 Indirect-Injection Systems

Inlet generated air swirl, despite amplification in the piston cup, has not provided sufficiently high fuel-air mixing rates for small high-speed diesel engines such as those used in automobiles. Indirect-injection (IDI) or divided chamber engine systems have been used instead, where the vigorous charge motion required during fuel injection is generated during the compression stroke. Two broad classes of IDI systems can be defined: (1) swirl chamber systems and (2) pre-chamber systems, as illustrated in Fig 2.2a and b, respectively. During compression, air is forced from the main chamber above the piston into the auxillary chamber, through the nozzle orifice, or set of orifices. Thus, toward the end of compression, a vigorous flow in the auxillary chamber is set up. In swirl chamber systems the connecting passage and chamber are shaped so that this flow within the auxillary chamber rotates rapidly.[1]

Fuel is usually injected into the auxillary chamber at lower injection-system pressure than is typical of DI systems through a pintle nozzle as a single spray. Combustion starts in the auxillary chamber. The pressure rise associated with the combustion forces fluid back into the main chamber where the jet issuing from the nozzle entrains and mixes with the chamber air. The glow plug shown on the right of the pre-chamber in Figure 2.2 is a cold starting aid. The plug is heated prior to starting the engine to ensure ignition of fuel early in the engine cranking process.[1]

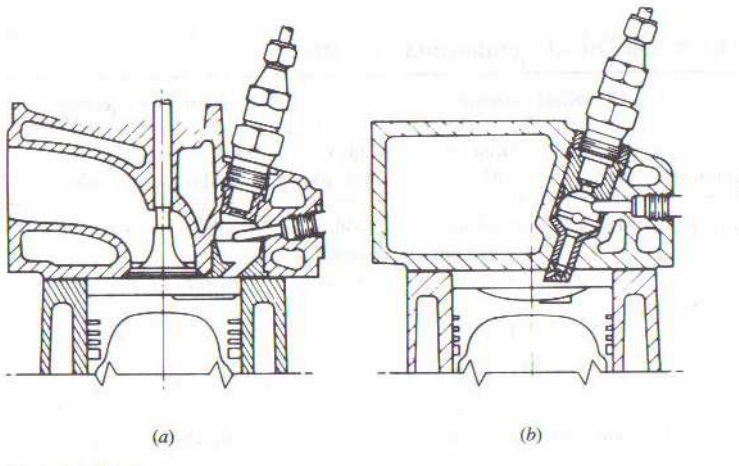


Figure 2.2: Two common types of small indirect injection engine combustion systems (a) swirl chamber (b) turbulent chamber. [1]

2.1.3 Fuel Spray behaviour

Different spray configurations are used in the different compression ignition engines. The simplest configuration involves multiple sprays injected into quiescent air in the largest-size diesels (Figure 2.1 a). Each liquid jet atomises into drops and ligaments at the exit from the nozzle orifice. The spray entrains air, spreads out, and slows down as the mass flow in the spray increases. The droplets on the outer edge of the spray evaporate first, creating a fuel-vapour air mixture sheath around the liquid-containing core. The highest velocities are on the jet axis. The equivalence ratio is highest on the centreline, decreasing to

zero at the spray boundary. Once the sprays have penetrated to the outer regions of the combustion chamber, they interact with the chamber walls. The spray is then forced to flow tangentially along the wall. Eventually the sprays from multi-hole nozzles interact with one another. Figure 2.3 shows diesel fuel sprays interacting with the cylindrical outer wall of disc-shaped combustion chamber in a rapid compression machine, under typical diesel-injection conditions. The cylinder wall causes the spray to split with about half flowing circumferentially in either direction. Adjacent sprays then interact forcing the flow radially inward toward the chamber axis.[22]

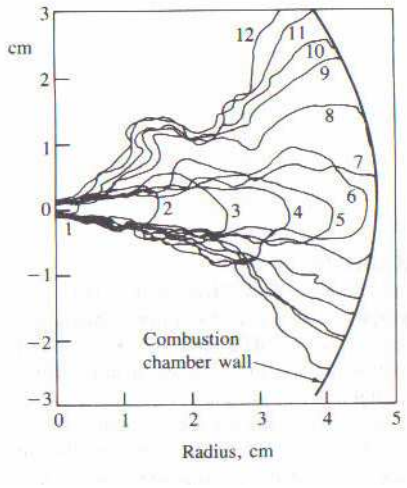


Figure 2.3: The outer vapour boundary of diesel fuel spray with the cylindrical wall of the combustion chamber [22]

A schematic of the spray pattern, which results when a fuel jet is injected radially outward into a swirling flow, is shown in figure 2.4. As a result of there being relative motion in both radial and tangential directions between the initial jet and the air, the structure of the jet is more complex. As the spray entrains air and slows down it becomes increasingly bent toward the swirl direction. Under the same injection conditions it will penetrate less with swirl than without swirl. An important feature of the spray is the large vapour containing region downstream of the liquid containing core.[22]

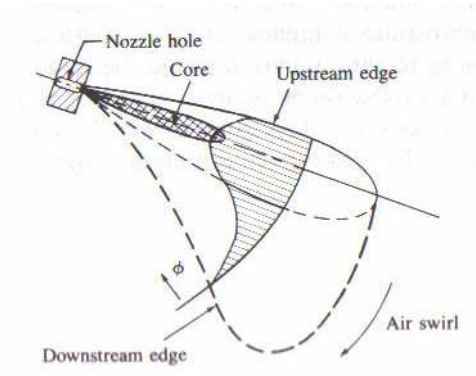


Figure 2.4: Fuel Spray injected radially outward from the chamber axis in swirling air flow. [22]

2.1.4 Atomization

Under diesel injection conditions, the fuel jet usually forms a cone-shaped spray at the nozzle exit. This type of behaviour is classified as the atomization break up regime, and it produces droplets with sizes very much less than the nozzle exit diameter. This behaviour is different from other modes of liquid jet break-up. At low jet velocity, break-up is due to the unstable growth of surface waves caused by surface tension and results in drops larger than the jet diameter. As jet velocity is increased, forces due to the relative lead to drop sizes of the order of the jet diameter. This is called the first wind induced break-up regime. A further increase in jet velocity results in break-up characterized by divergence of the jet spray after an intact or undisturbed length downstream of the nozzle. In this second wind-induced break-up regime, the unstable growth of short-wavelength waves induced by the relative motion between the liquid and surrounding air produces droplets whose average size is much less than the jet diameter. Further increases in jet velocity lead to break-up in the atomization regime, where the break-up of the outer surface of the jet occurs at, or before , the nozzle exit plane and results in droplets whose average diameter is much smaller than the nozzle diameter.

Aerodynamic interactions at the liquid-gas interface appear to be one major component of the atomization mechanism in this regime.[1]

2.1.5 Spray and Flame Structure

The structure of each fuel spray is that of a narrow liquid-containing core surrounded by a much larger gaseous-jet containing fuel vapour. The fuel concentration in the core is extremely high. Local fuel-air equivalence ratios near the nozzle of order 10 have been measured during the ignition period. Fuel concentrations within the spray decrease with increasing radial and axial position at any given time, and with time at a fixed location once injection has ended. The fuel distribution within the spray is controlled largely by turbulent-jet mixing processes. Fuel vapour concentration contours determined from interferometric studies of unsteady vaporizing diesel like sprays, confirm this gaseous turbulent jet like structure of the spray, with its central liquid containing core which evaporates relatively quickly once fuel injection ends. Flame development , along mixture contours close to stoichiometric, occurs rapidly as indicted in figure 2.5. [1]

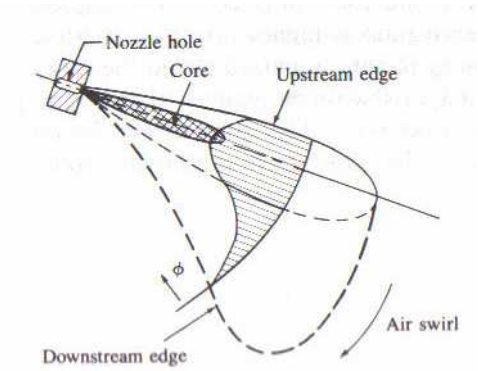


Figure 2.5: Tracings of outer boundary of liquid fuel spray and flame from a rapid compression ignition engine [1]

Initially this is thought to be due to spontaneous ignitions of regions close to the first ignition site due to the temperature rise associated with the strong pressure wave which emanates from each ignition site due to local rapid chemical energy release. Also, spontaneous ignition at additional sites on the same spray, well separated from the original ignition location, can occur.[1]

Gas sampling data indicate that the burned gases within the flame enveloped spray are only partially reacted and may be fuel rich. Figure 2.6 shows CO and CO_2 concentration contours determined from rapid acting sample valve measurements from the combustion chamber of a large quiescent chamber two-stroke cycle diesel engine. The contour maps shown correspond to the centreline of one of the five injected fuel sprays. Injection commenced at 17º BTC and ended about 5º BTC. Ignition occurred at 8º BTC. The contours at 3º BTC show high CO concentrations in the burned gases which now occupy most of the spray region, indicating locally very fuel-rich conditions. Later, at 12 º ATC, fuel injection has ceased, this rich core has moved outward to the piston bowl wall, and combustion within the expanded spray region is much more complete. This oxidation of CO, as air is entrained into the spray region, mixes, burns and releases substantial additional chemical energy.[1]

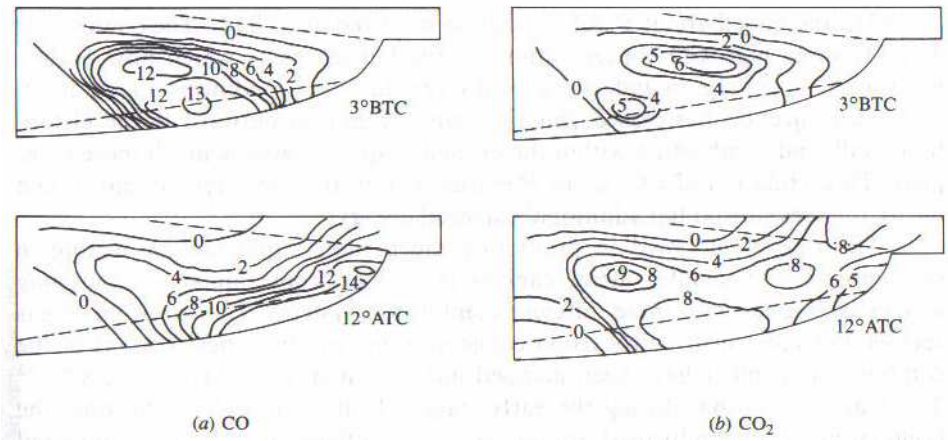


Figure 2.6: Contours of constant CO and CO_2 concentration in a plane [1]

2.2 The fuel properties of alcohol and basic principles of engine conversion

2.2.1 Introduction to alcohols

The alcohols are fuels of the family of the oxygenates. As is known to some, the alcohol molecule has one or more oxygen molecules, which contributes to the combustion. The alcohols are named accordingly to the basic molecules of hydrocarbon which derives from them: Methanol (CH_3 OH); Ethanol (C_2H_5OH); Propanol (C_3H_7OH); Butanol (C_4H_9OH). Theoretically, any of the organic molecules of the alcohol family can be used as a fuel. The list is somehow more extensive, however, only two of the alcohols are technically and economically suitable as fuels for internal combustion engines. These alcohols are those of the simplest molecular structure, i.e., Methanol and Ethanol. [2]

- Methanol is produced by a variety of process, the most common are as follows: Distillation of wood; Distillation of coal; Natural gas and petroleum gas. [4]
- Ethanol is produced mainly from biomass transformation, or bioconversion. It can also be produced by synthesis from petroleum or mineral coal.[3]

Economic reasons dictate, however, the process which can produce the alcohol at the minimum cost. Each country around the world has found the best compromise in the production of an alternative fuel to replace petrol. Of special significance, especially for countries with large areas of land like former USSR, USA, China and Brazil, are the methods of production of ethanol from bio-mass conversion. In this process, it can be said that solar energy is stored in the plants by the photosynthesis process. Ethanol from a bio-conversion is therefore "solar energy in a liquid state". [3]

Ethyl alcohol, or ethanol has been used in Germany and France as early as 1894 by the then incipient industry of internal combustion engines. Brazil has utilized ethanol as a fuel since 1925. By that time, the production of ethanol

was 70 times bigger than the production and consumption of petrol. There have been times when the push for alternatives to petrol were more vigorous, mainly dictated by strategic and economic reasons. It is interesting to note that in Brazil, there was an intense use of ethanol in the year 1930, 1940, 1950, 1958, and 1973. Unfortunately, petroleum has always been considered abundant, almost limitless in availability. It was cheap and versatile, so the industry has always been very keen in the intensive use of this apparently miraculous fuel. All the development effort was toward the use of petrol and so the engines were developed for this fuel. [3]

In those countries with large territorial areas, ethanol has been the alternative fuel choice to replace petrol. The reason is the fact that alcohol is a renewable source of energy. Currently, ethanol is produced from sugar beets and from molasses. A typical yield is 72.5 liters of ethanol per tonne of sugar cane. Modern crops yield 60 tonnes of sugar cane per hector of land. An area of $1km^2$ of sugar cane crop can yield 6000 tonnes per year in a tropical country like Brazil. Other crops can be used for the production of ethanol. In China, for instance, it has been demonstrated that sweet sorghum ("Shennong No.2 sweet sorghum) can yield 267.4 liters of ethanol per Mu. It has also been shown that 1 tonne of corn can produce nearly 300 liters of alcohol. [4]

2.2.2 Conversion of diesel engines

When diesel engines are converted to alcohols, some properties of gasoline, diesel and alcohol should be concerned. Table 1 shows the properties of the fuels .There are several methods for converting a diesel engine to alcohol to be discussed. [2]

Table 1: Some properties of fuels [2]

	Gasoline	**Diesel**	**Methanol**	**Ethanol**
1. Cetane number	-	50	5	8
2. Octane number	96	-	112	107
3. Auto-ignition tempt. ° C	371	315	446	390
4. Latent heat of vaporization (KJ/Kg)	349	220	1177	914
5. Lower heating value (KJ/Kg)	4400	42600	19945	26700

A. Cetane number and cetane improving additive

For a fuel to burn in a diesel engine, it must have a high cetane number or ability to self-ignite at high temperatures and pressures. There exists a significant difference among gasoline, diesel and alcohol in terms of cetane number and auto ignition. A high cetane number leads to a short ignition delay period, whereas a low cetane number results in a long ignition delay period. From table 3.2.1, it can be seen that alcohols have lower cetane numbers than that of diesel, which is not desired when diesel engines are converted to alcohol. Fortunately, some additives, an example of which is nitrate glycol, can increase the cetane number of alcohols. This means that ignition delay period will become short, which will reduce tendency to cause a diesel knock. However, a too short ignition delay period will cause a lower rate of heat release which is not wanted. [9]

B. Alcohol-diesel emulsions

Because alcohols have limited solubility in diesel, stable emulsion must be formed that will allow it to be injected before separation occurs. Hydroshear emulsification unit can be used to produce emulsions of diesel-alcohol. However, the emulsion can only remain stable for 45 seconds. And, 12% alcohol (energy basis) is the maximum percentage. In addition, this kind of method has several problems which are as

follows: 1).Specific fuel consumption at low speed increases; 2).High cost; 3).Instability. Therefore, other methods are developed. [9]

C. Fumigation

Fumigation is a process of introducing alcohol into the diesel engine (up to 50%) by means of a carburettor in the inlet manifold. At the same time, the diesel pump operates at a reduced flow. In this process, diesel fuel is used for generating a pilot flame and alcohol is used as a fumigated fuel. Two points should be noted in using this method. At low loads, quantity of alcohol must be reduced to prevent misfire .On the other hand, at high loads, quantity of alcohol must also be reduced to prevent pre-ignition. [2]

D. Dual injection

In a dual injection system, a small amount of diesel is injected as a pilot fuel for ignition source and a large amount of alcohol is injected as main fuel. It must be noted that the pilot fuel must be injected prior to injection of alcohol. Some ideal results can be achieved when this method is used. Thermal efficiency is better. At the same time, NOx emission is lower. Moreover, CO emissions and HC emissions are the same, however, the system requires two fuel pumps, thus, leading to a high cost. Meanwhile, alcohol needs additives for lubricity. [2]

E. Heated surfaces

Alcohol can ignite with hot surfaces. For this reason, glow-plugs can be utilized as a source of ignition for alcohol. In this system, specific fuel consumption depends on glow-plug positions and temperatures. It must be noted that the temperature of glow-plugs must vary with load. However, the glow-plug becomes inefficient at a high load. In addition, the specific fuel consumption is higher than that of diesel. [2]

F. Spark-ignition

When a spark plug is used, diesel engines can be converted to an Otto cycle engine. In this case, the compression ratio should be reduced, from 16: 1 to 10.5: There are two types of this kind of conversion. They are as follows:

Type 1: The original fuel injection system is maintained. Alcohol needs an additive for lubricity (Nitride glycol). Besides, both distributor and sparkplug need to be installed, thus leading to a high cost of conversion. It is critical to adjust an ideal injection and spark-time for this kind of conversion. [7]

Type 2: Original fuel injection is eliminated. But, a carburettor, a spark-plug and a distributor need to be installed, which increases the cost of conversion. In this conversion, spark timing is critical. [7]

Both the type 1 and type 2 conversions' have a lower thermal efficiency than that of diesel.

G. Neat methanol for diesel cycle

Figure 2.7 shows the basic principle of this conversion in this system, methanol is introduced to the combustion chamber through two separated accesses. One methanol mixture is passed through an inlet manifold over an exhaust-heated aluminum bed (h=70%) heated to 400 ° C. Another methanol mixture ,with 2% castor oil as additive, is injected into the combustion chamber. In the first access, dimethyl ether is produced from methanol. The DME reacts at a normal diesel engine compression temperature and raises the gas temperature above the ignition temperatures of methanol .It acts as a pilot fuel; In the second access, no additive to the methanol is to be converted to DME. A 2% castor oil content, is added in order to improve lubricity. In this system, the thermal efficiency is better than that of diesel. Furthermore, ignition delay period is reduced, which leads to a decrease in the rate of the pressure rising. This means that the engine has no diesel "knock" and has a smoother combustion. At the same time, the peak pressure is 18% higher than that of diesel. Fortunately, this can be

compensated by retarding the injection timing. The problem of this conversion is that DME conversion becomes poor at high speed and at low loads due to the drops of the exhaust gas temperature. Pilot flow (DME) which is critical, depends on load and speed, and less upon temperature. At a high speed, a fuel pump runs out of the design point. [2]

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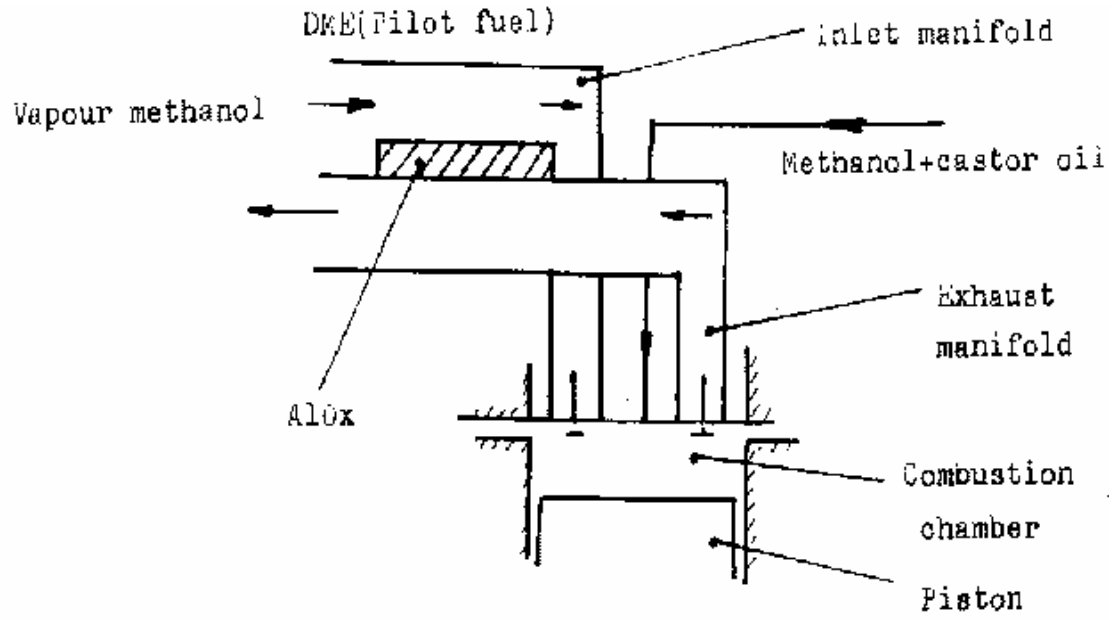


Figure. 2.7: Basic principle of this conversion [2]

2.3 Review of Ethanol in Compression Ignition Engine

Stringent emission legislation all over the world has led to the search for alternative fuels for I.C. Engines. The major pollutants from a diesel engine are oxides of nitrogen (NOx), smoke and particulate matter. Concentration is very much focused on compression ignition engines because they have been recognised as the most ideal power plants in transportation, industrial and agricultural sectors, due to their high fuel efficiency. But their major disadvantage is the production of exhaust particulates which have to face increasingly stringent regulation. [11]

The difficulty in meeting the increasingly stringent limitations on particulate and NOx emissions has stimulated interest in ethanol-fueled compression ignition engines because ethanol diffusion flames produce virtually no soot. Unfortunately ethanol does not have suitable ignition properties under typical diesel conditions because the temperatures and pressures characteristic of the diesel engines causes a longer ignition delay while using ethanol. Therefore, in order to make use of ethanol in a diesel engine, either a system to improve the ignition quality of ethanol or a system of some ignition aids is necessary. The following describes the various systems of using ethanol in diesel engines. [14]

2.3.1 Techniques of Using Ethanol in Diesel Engines

There are various techniques by which ethanol can be used as a fuel in compression ignition engines. The techniques are

- Solution
- Fumigation
- Dual Injection
- Spark Ignition
- Ignition Improvers
- Surface Ignition

The easiest method by which ethanol could be used is in the form of solutions, but ethanol has limited solubility in diesel. As a result ethanol/diesel solutions are restricted to small percentages (typically 20%). This problem of limited solubility has

been overcome by emulsions which have the capability of accommodating larger displacement of diesel up to 40% by volume. But the major drawbacks of emulsions are the cost of emulsifiers and poor low temperature physical properties. [19]

Fumigation is a method by which ethanol is introduced into the engine by carburating or vapourising the ethanol into the intake air stream and about 50% of the fuel energy can be derived from ethanol under road load conditions. This method requires addition of a carburettor or a vapouriser along with a separate fuel tank, lines and controls. Also the distribution of ethanol would be uneven as the diesel intake manifolds are not designed to handle two phase flows. [13]

Dual injection is a method by which nearly 90% displacement of diesel by ethanol is possible. The drawbacks of this method include the complexity and expense of a second injection system and a second fuel tank and system. Fuel injection pumps and injectors to handle neat ethanol have not yet been developed. Also converting to dual injection requires, space in the combustion chamber be available for a second injector at a location where the injector can be effective. [16]

Spark ignition of neat ethanol in diesel engine provides a way of displacing 100% of diesel. A spark plug and the associated ignition system components must be added to the engine. Room must be available for spark plugs in the cylinder head and its location is also important for proper plug cooling. [16]

Another method of using neat ethanol is to increase their cetane numbers sufficiently with ignition-improving additives to ensure that compression ignition will occur. This method saves the expense and complexity of engine component changes, but adds in fuel cost. [16]

Surface ignition is another method of using 100% ethanol in diesel engines. Surface ignition occurs when the temperature of the air-fuel mixture adjacent to a hot surface exceeds its self ignition limit. [16]

2.3.2 Dual Fuel Mode

In the dual fuel mode in a conventional diesel engine the energy release by combustion comes about partly from the combustion of either carburated or manifold injected alternative fuel, while the diesel fuel continues to provide throughout, through timed cylinder injection, the remaining part of the energy release. Ideally, in relation to the alternative supply there is a need for optimum variation in the diesel fuel quantity used any time so as to provide the best performance over the whole load range desired. The main aim is to minimise the use of diesel fuel due to environmental reasons and maximise its replacement by alternative fuel throughout the load and speed ranges. The dual fuel engine is an ideal multifuel engine that can operate effectively on a wide range of fuels with the flexibility of operating it as a conventional diesel engine. [15]

Some of the distinct advantages associated with dual fuel operation are longer engine life, potential cleaner operation and long lasting lubricants with fewer filter changes. However, dual fuel operation also has certain limitations like the requirement of simultaneous availability of two or more fuels which can bring about increased complexity in controls and additional cost. Moreover, a serious problem associated with dual fuel engine is the relatively poor light load and idling performance associated with low efficiency and inferior emission characteristics. The principle of injecting a small quantity of diesel fuel is to auto-ignite the diesel vapour, so that flames produced by diesel-air mixture burns the lean homogeneous charge available in the rest of the combustion chamber. This behaviour of the engine affects the performance of dual fuel engines at light loads adversely. [15]

The introduction of the fuel with the inlet air, even in very small quantities, can also have a significant effect on the cylinder charge during compression, affecting markedly the processes of pre-ignition and subsequent combustion of the pilot and the cylinder charge. This deterioration in performance to a large extent depends on the pilot quantity injected, the fumigated fuel being used, operating conditions and the engine employed. In some cases even idling or light load operation becomes totally impaired, with certain fuels and engines. [15]

In addition to the above problems, the problem of knock is encountered when very high outputs are desired. Thus, a serious practical barrier is set for the maximum load that can be achieved for any engine with any fuel. [15]

The use of alcohol in the dual fuel mode shows the following observations when compared to diesel: [15]

1. Brake thermal efficiency increases at high loads.
2. Carbon monoxide and hydrocarbon formation increases.
3. No significant effect on carbon monoxide and hydrocarbons with water content and type of alcohol used.
4. NOx and particulate matter reduces.
5. NOx emissions decreases with higher water content in alcohol.
6. Ignition delay increases at all operating conditions.
7. Higher water content of alcohol lengthens delay period.
8. Delay period for methanol fuels are longer than those of ethanol fuels.
9. Methanol produce lower NOx and particulates than ethanol.
10. Maximum displacement of diesel is only 80% of the total fuel energy in conventional engines and 85% in the LHR engine.

2.3.3 Ignition Improvers

Ethanol has too low an ignition quality for use in a diesel engine. The step towards " adapting the fuel to the engine " is to increase the ignition quality of ethanol such that it is sufficient for all operating conditions. This is done by adding ignition improvers to ethanol or by the introduction of ignition improvers that have very low self ignition temperatures, into the intake manifold. [12]

Most of the effective ignition improvers that are added to improve the cetane rating are nitrogen based compounds, which can aggravate NOx emissions. Isoamyl nitrate, Ethyl nitrate, Butyl nitrate, Di-Ethylene Glycol Di-Nitrate (DEGDN), Tri-Ethylene Glycol Di-Nitrate (TEGDN) and Kerobrisol are some good ignition improvers. [12]

Other ignition improvers like Di-Methyl ether (DME) and Di-Ethyl ether (DEE) that have very low self ignition temperatures and wider flammability limits are introduced

in a small quantity into the intake manifold, that mixes with the combustion air. This mixture would begin a slow combustion in the compression stroke forming a pool of species and raising the temperature and pressure inside the engine cylinder. This would create an ideal environment for igniting the subsequently injected ethanol. [12]

The summary of observations made on using ignition improved alcohol fuels in diesel engines are as follows: [12]

1. The concentration of DEE required for stable combustion of alcohol varies from 59% by mass at no load to less than 1% at full load.
2. Fuel injection system modified to accommodate extra volume of fuel.Compared to normal diesel operation the following observations are made:
3. Thermal efficiency is higher.
4. Unburn't hydrocarbon emissions are higher.
5. Carbon monoxide emissions remain unchanged.
6. NOx emissions are lower.
7. No soot formation.
8. Ignition delay longer.
9. Aldehyde emissions doubled with ethanol and methanol.
10. Ethanol exhibits lower aldehydes than methanol.

2.3.4 Surface Ignition

The hot surface assisted ignition concept is commonly applied to overcome the low temperature starting problem in diesel engines. Introducing extremely low cetane fuels like ethanol, require an extended application of the hot surface as continuous ignition assistance. The function of the hot surface is to provide favourable local ignition condition, followed by flame propagating through the fuel air mixture to establish a stable diffusion flame. [23]

Surface ignition occurs when the temperature of the air-fuel mixture adjacent to the hot surface exceeds its self ignition limit. The minimum surface temperature needed for this kind of ignition depends on both physical and chemical properties of the fuel to be ignited and the operating conditions prevailing inside the combustion chamber

as well. Material and exposure of the hot surface have also gained some importance. [23]

The hot surface may be provided by concentrating/accumulating the heat of combustion at a position on the piston top or by supplying external energy to the heating elements inside the combustion chamber. Hot surface ignition making use of glow plugs is not a new concept as it is being used in IDI diesel engines to overcome cold starting problems. [23]

Following are the observations made on using alcohol in hot surface ignition engine:

1. Ignition characteristics of ethanol affected by fuel amount, injection timing, position and length of glow plug, glow plug temperature and water content in ethanol.
2. Engine speed, fuel injection timing and position of the glow plugs have a strong effect on the ignition characteristics.
3. Combustion difficulties appear as the load decreases, making idling impossible.
4. Glow plug surface temperature for proper ignition is around 850^{o}C.
5. Brake thermal efficiency is comparable to that of diesel.
6. Higher carbon monoxide and hydrocarbon emissions.
7. Larger reduction in NOx emissions.
8. Soot free combustion.
9. Quieter operation.
10. Longer ignition delay.

2.3.5 Spark Ignition

To accomplish the smooth operation of an engine, combustion must spread smoothly throughout the combustion chamber. This is accomplished in a gasoline engine by having a homogeneous mixture in the cylinder ignited by means of a spark. On the other hand, the heterogeneous mixture in a diesel engine, when using high cetane fuels, combustion depends upon simultaneous auto ignition at different locations rather than a flame propagation. However, when using low cetane fuels like alcohol in a diesel engine with spark ignition, the flame propagate from the flame nucleus fast enough to achieve smooth combustion and rapidly induce auto ignition in the rest of the mixture. Thus, for spark assisted diesel, smooth operation depends upon the formation of air vapour mixture through which the flame can propagate. [7]

The combustion processes in a spark assisted alcohol engine takes place as follows:

a. Ignition and initial flame kernel development away from spark gap along the peripheral, near stoichiometric region of the fuel plume closest to the spark gap,

b. Initial flame propagation along adjacent fuel spray plumes, and

c. Continued flame propagation along fuel spray plumes followed by compression ignition occurring in the peripheral regions of the fuel spray plumes not yet in contact with the flame which results in multipoint ignition and rapid heat release.

The literature survey made on spark plug assisted alcohol operation shows the following points as made compared to diesel operation: [7]

1. Proper timing of both injection and ignition is vital for ignition of alcohol fuel.
2. Injection timing to be advanced.
3. Higher efficiency at full load.
4. More unburnt hydrocarbons.
5. Reduced NOx and noise.
6. Shorter ignition delay.
7. Lower maximum pressure, temperature and rate of pressure rise.

2.3.6 Catalytic Combustion

The possibility of using a combustion catalyst on the surface of the glow plug could also be of great significance to the use of ethanol in diesel engines. Catalysts coating not only increases the rate at which chemical reactions take place but at the same time decrease the minimum temperatures needed for the reactions to take place. Therefore if the glow plug surface can be used as a catalyst for ignition, lower temperatures would be required thereby reducing the energy requirements for proper operation and also increase the lifetime of the glow plugs. Also the presence of a catalyst in the combustion chamber could affect emissions as well. [11]

Normally, catalytic ignition occurs at temperatures several hundred degrees celsius lower than the gas phase ignition temperature for the same combustible mixture. At low temperatures as in region 1, the reaction rate is controlled by surface kinetics with the reaction rate increasing exponentially with catalyst temperature. As temperature increases, the reaction rate becomes so high that the reaction is limited by the mass transfer between the gas and the surface. This regime shown in region 2, is called the mass diffusion controlled region and the heterogeneous kinetics play a secondary role in determining the reaction rate. Finally further increase in temperature results in gas phase reactions as shown in region 3. In this region, catalytic reactions occur simultaneously with heterogeneous reactions. [11]

To obtain maximum performance from a catalytic combustion system, the materials should ideally have the following properties :

1. The catalyst coating should be capable of igniting fuel/air mixtures at the lowest possible temperature i.e., low "light off " temperatures.

2. The catalyst coating should be able to operate at temperatures in excess of 1750 K without thermal degradation or complexing of the materials.

2.3.7 Selection of Catalyst Materials

There are two classes of catalyst coating materials available, one is metal oxides and the other one is noble metals. Metal oxide catalysts are made from the oxides of the transition metals. Among the metal oxides, only those with refractory properties have potential combustion applications. Noble metal catalysts appear to be more promising for combustion applications because, metal oxides have lower activities, higher light off temperatures and are more prone to thermal sintering and sulphur poisoning. But the disadvantages of noble metals for actual engine applications are their exclusively high cost and limited high temperature durability. [8]

However, since the catalysts activity is not necessarily a limiting factor under the expected mass transport limited conditions the effectiveness of metal oxide catalysts could be as great as that of noble metals. The summary of observations made on the utilisation of alcohol in diesel engines with catalyst coated glow plug are given below: [8]

1. Platinum and palladium are used as coating materials on glow plugs.
2. Reduction in glow plug temperature of 1000 K using platinum and 150 K using palladium.
3. Palladium has better combustion characteristics than platinum.
4. NOx emissions are slightly higher for platinum and slightly lower for palladium compared to diesel.
5. Lesser aldehyde emissions in the case of platinum and palladium compared to diesel.
6. Platinum and palladium catalyst coating on exhaust valves reduces glow plug temperatures by approximately 400 K.
7. Palladium catalyst produce more carbon monoxide, lower hydrocarbons and less NOx than platinum.

2.3.8 Low Heat Rejection Engine

Adiabatic engine implies a no heat loss engine, as adiabatic process is defined as a no-heat loss process since the combustion chamber walls have no thermal capacity or inertia. But, under such imaginary cases, there would be no heat flow relative to the cylinder walls. The ways and means of realisation of such a combustion chamber are not realistic in practice. On the other hand, the insulated combustion chamber either partially or wholly can be assumed to have a large thermal capacity or inertia in such a way that the surfaces of the combustion chamber remain at a constant temperature throughout the operation. Such an engine is called a Low Heat Rejection (LHR) engine. In the development of LHR engine, the reduction of heat loss to the coolant system has always been of considerable interest to engine designers since, this would reduce the cost, weight, power requirement and size of the cooling system. In LHR engine the combustion chamber is insulated with high temperature materials which makes the engine operate at hotter environment with less heat transfer. The components that are normally insulated include piston, cylinder head, valves, cylinder liner, and exhaust ports. It is expected that additional power and improved efficiency is possible with engine insulated because thermal energy that is normally lost to the cooling water and exhaust gas is converted to useful power through the use of turbo machinery and high temperature materials The air from the atmosphere, enters into the compressor first and then enters the insulated combustion chamber where combustion takes place and useful energy is extracted. The high temperature and high pressure exhaust gas is then expanded through two turbine wheels to extract as much as possible the remaining energy. Of the two turbine wheels, one is used to drive the compressor and the other one is connected by gears to the engine crankshaft thereby increasing the useful power output of the engine. [8]

2.3.9 Conclusion

Ethanol can be used as a fuel for compression ignition engine however with major modifications to the engine depending on the technique employed.

2.4 Biodiesel Fuel

Biodiesel could be an excellent renewable fuel for diesel engines. It is derived from vegetable oils that are chemically converted into biodiesel. As the name implies, it is similar to diesel fuel except that it is produced from crops commonly grown, including canola, soybean, sunflower and safflower. These crops are all capable of producing several gallons of fuel per acre that can power an unmodified diesel engine. Vegetable oil is converted into biodiesel through a chemical process that produces methyl or ethyl ester. After washing and filtering it is usable as an alternate renewable fuel. [15]

2.4.1 Biodiesel

Biodiesel is composed of long-chain fatty acids with an alcohol attached, often derived from vegetable oils. It is produced through the reaction of a vegetable oil with methyl alcohol or ethyl alcohol in the presence of a catalyst. Animal fats are another potential source. Commonly used catalysts are potassium hydroxide (KOH) or sodium hydroxide (NaOH). The chemical process is called transesterification which produces biodiesel and glycerin. Chemically, biodiesel is called a methyl ester if the alcohol used is methanol. If ethanol is used, it is called an ethyl ester. They are similar and currently, methyl ester is cheaper due to the lower cost for methanol. Biodiesel can be used in the pure form, or blended in any amount with diesel fuel for use in compression ignition engines. Figure 2.8 shows basic transesterification technology. [15]

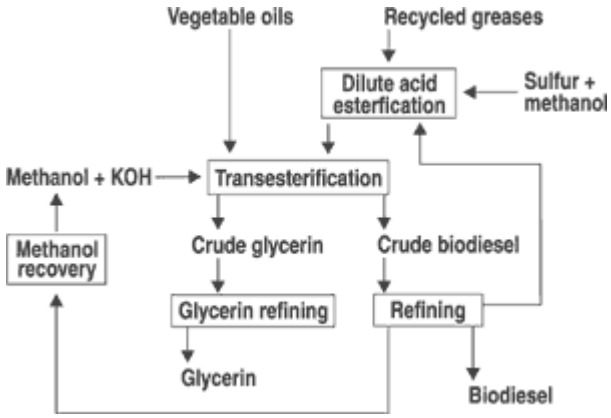


Figure 2.8: Basic Transesterification technology [15]

The transesterification process of converting vegetable oils to biodiesel is shown in figure 2.9. The “R” groups are the fatty acids, which are usually 12 to 22 carbons in length. The large vegetable oil molecule is reduced to about 1/3 its original size, lowering the viscosity making it similar to diesel fuel. The resulting fuel operates similar to diesel fuel in an engine. The reaction produces three molecules of an ester fuel from one molecule of vegetable oil.

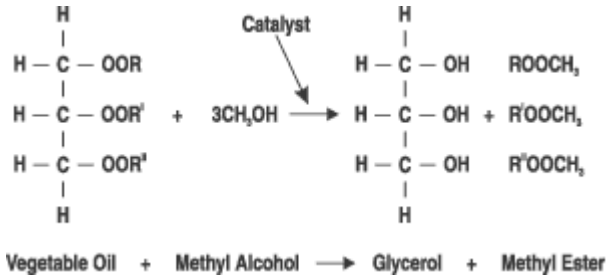


Figure 2.9: Transesterification of vegetable oils. [15]

Some properties of various fuels are shown in Table 2. They include diesel fuel, biodiesel, and vegetable oil. The main differences between diesel fuel, an ester fuel, and vegetable oil are the viscosity, cetane number and heat of combustion. The viscosity of a fuel is important because it affects the atomization of the fuel being injected into the engine combustion chamber. A small fuel drop is desired so complete combustion occurs. A high viscosity fuel, such as raw vegetable oil, will produce a larger drop of fuel in an engine combustion chamber which may not burn as clean as a fuel that produces a smaller drop. Unburned oxidized fuel will build up in the engine around valves, injector tips and on piston sidewalls and rings. Previous NDSU tests using sunflower and other oils mixed with diesel fuel found significant buildup on piston sidewalls, stuck rings and in a few cases, broken rings. Biodiesel has a viscosity much closer to diesel fuel than vegetable oil. This helps produce a much smaller drop, which burns cleaner.

Table 2: Fuel properties [14]

Type	**Fuel Weight**	**Heat of Combustion**	**Cetan Number**	**Viscosity Centistokes**
	Lbs./gal.	**BTU/gal**		
No. 2 diesel 100% Biodiesel (B100)	7.05	140,000.00	48	3
Methyl or ethyl ester	7.3	130,000.00	55	5.7
B20 mix (20/80)	7.1	138,000.00	50	3.3
Raw vegetable oil	7.5	130,000.00	35 to 45	40 to 50

Cetane rating varies considerably among the listed fuels (table 2) and is a measure of the self-ignition quality of the fuel. No. 2 diesel fuel usually has a cetane rating between 45 and 50 while vegetable oil is 35 to 45. Biodiesel is usually 50 to 60. The ignition quality affects engine performance, cold starting, warm up and engine combustion roughness. Cetane rating is related to the volatility of the fuel where more volatile fuels have higher ratings. A high cetane fuel also may lead to incomplete combustion and smoke if the fuel ignites too soon by not allowing enough time for the fuel to mix with air for complete combustion. [14]

The energy content of the fuels also vary. No. 2 diesel fuel typically contains about 140,000 BTU's per gallon while vegetable oil and biodiesel contain about 130,000 BTU/gal. A "BTU" stands for British Thermal Unit which is defined as the energy required to raise the temperature of water one degree fahrenheit. Fuels with a high heat of combustion will usually produce more power per pound of fuel than fuels with lower energy. As a result, an engine using a lower energy fuel will require more fuel to produce the same power as diesel fuel. As a result of the lower energy content, biodiesel will require about 1.1 gallons of fuel to do the same work as a gallon of diesel fuel. [15]

2.4.2 Engine Studies

Several studies show biodiesel can run in a conventional diesel engine for an extended time. Researchers have run diesel engines in pickups, city buses, large trucks and tractors on various mixes of biodiesel/diesel fuel. These mixtures have ranged from 2/98% (B2), 20/80% (B20) up to 100%(B100). The results of these studies look very promising. [20]

Standard diesel engines will operate on 100% biodiesel. In cold weather, biodiesel begins to cloud and thicken at about 30F. Biodiesel thickens at warmer temperatures than No. 2 diesel fuel, but additives are available that will lower the pour point. Pour point is the point at which flow of the fuel ceases. Mixing biodiesel with No.1 diesel as is currently done with No. 2 will lower the pour point. Installing an in-tank or fuel line heater may also be needed to keep the fuel flowing in cold weather. A blend of biodiesel/diesel fuel has a lower pour point than 100% biodiesel, but gelling may still occur unless care as mentioned earlier is taken. [20]

New lower diesel engine emission requirements that dictate a reduction of sulfur in fuel is causing a reduction in the lubricating ability of fuel. This will shorten the operating life of the injection system and engine. Biodiesel blends, even at low rates (2%), indicate improved lubricating ability over diesel which should reduce wear and extend fuel system and engine life. [16]

Studies show that some older engine fuel systems (engines built prior to 1993) may show fuel pump seal deterioration. They may have rubber or nitrile seals in the fuel pump and fuel system that could fail if 100% biodiesel is used. It may be best to replace them with Viton or other non-rubber seals if 100% biodiesel is used. A blend of 20% biodiesel can be used in older engines with no changes, but it is recommended to watch for leaks. Also, biodiesel studies indicate some cleaning action of the fuel system, so a fuel filter may need replacement soon after switching to biodiesel. [18]

2.4.3 Biodiesel and Air Pollution

Research with biodiesel show reductions in several contributors to air pollution. Table 3 is a summary of engine tests completed at the University of Idaho.

These tests were performed with a 100% and a 20% mix of ethyl and methyl ester of rapeseed oil. There were reductions in most emission components except for an increase in nitrous oxide. Biodiesel use could provide reductions in several air pollutants. This could provide significant improvements in cities where air quality is a concern. [10]

Table 3: Engine emission results from the University of Idaho [10]

Emission	**100% Ester Fuel (B100)**	**20/80 Mix (B20)**
Hydrocarbons	- 52.4%	-19.0%
Carbon Monoxide	- 47.6%	-26.1%
Nitrous Oxides	- 10.0%	-3.7%
Carbon Dioxide	+ 0.9%	+.7%
Particulates	+ 9.9%	-2.8%

2.4.4 Mixing and Storage of Biodiesel

Biodiesel mixes well with diesel fuel in any proportion and stays blended even in cold temperatures. A storage study completed over a 24-month period found that biodiesel tends to store about as well as diesel fuel. This study found that engine power decreased about 2% and viscosity, density, peroxide and acid value increased for biodiesel. Usually it is recommended not to store biodiesel longer than 6 months or at the most, a year. This recommendation is similar to diesel fuel storage periods. [17]

2.4.5 Potential Fuel From Oil Crops

In 2001, about 2.1 million acres of soybeans were produced in the state of North Dakota with an average yield of about 33 bushels per acre. Soybeans contain about 18% oil so the average oil production per acre is about 49 gallons. If this oil were converted to an ester fuel, more than 100 million gallons of fuel could be produced. Other oil crops grown in the state could be used to produce additional fuel. Table 4 shows the production potential of biodiesel from the main oil crops grown in North Dakota. [21]

Every gallon of vegetable oil will produce about 1 gallon of biodiesel. The total input/output energy ratio shows a very positive return. For every BTU of energy used to produce the crop and process the oil, about 3.3 BTU's is produced as fuel. [21]

Table 4: Potential fuel from North Dakota oil crops (2001) [21]

Crop	**Acres in State**	**Yield**	**Oil**	**Gallons**
	(**millions)**		**(%)**	**(per Acre)**
Soybean	2.1	33 bu/acre	18	49
Sunflower	1.1	1400 lb/ac	44	84
Canola	1.2	1300 lb/ac	43	76

3 The Combustion Analysis Software Design

3.1 System Overview

The world's fossil fuel resources are depleting and a need to use alternative fuels is becoming very essential for the future. As a result a comprehensive software package is needed to analyse all areas of energy release within internal combustion engines. The software has thus been designed to form the core of this "alternative fuel" research. In order for it to be effective it has been designed to be flexible. The CAS (Combustion Analysis Software) can be configured for differing engine sizes, environment conditions, i.e. ambient temperature, as well as differing fuel properties. The users also have a choice of which form of analysis they want to perform, ranging from the "air standard cycle" to "Weinberg" analysis. The user is able to select multiple forms of analysis from multiple engine tests done by different engines, fuels and engine speeds.

The graphical objects of the software, extend this flexibility further by allowing the user to select which plots one wishes to view. These plots can be viewed independently or superimposed on one another. Any area of the graph can be zoomed in or out and the scales of the axes can be adjusted as seen fit. The look and feel of the graphical data can also be adjusted for reporting purposes.

The CAS software has a reporting module. This module allows the user to generate comprehensive reports extending from engine raw data all the way up to the calculated energy release data. The reports can be presented in PDF Format or simple text format. They also can be exported to csv, html(for ease of posting on the internet) or excel format for further analysis. Due to the confidentiality of the analysis performed, the CAS software package has the following security optionality:

- All export formats can be password protected with a choice of 40 bit or 128 bit encryption.
- The CAS software package has login security, and only users with administrator access can add, delete and edit users from the system.

CAS has been designed with user friendliness and ease of use in mind. In fact all the user is required to do is to configure which engine tests and forms of analysis one requires and at a push of a button, a complete set of analytical and graphical data is automatically created. The user will then have a large variety of reports at his/her disposal with accurate results.

The following “use cases” describe and identify the key parts of the CAS software design.

3.2 Uses Cases

3.2.1 Use Case Summary

The following use cases have been identified:

- Login – this use case authenticates a user with the system so that access to other functions can be provided.
- Load new data- this allows the user to convert and perform energy modelling analysis on a newly performed engine test.
- Load saved data – Allows the user to perform energy modelling analysis on previously converted data.
- View plots – This use case allows users to select which plots to be displayed as well as to modify the plots.
- View Data – This use case allows the user to view and generate a report of all raw and calculated data.

- Memory Manager – This use case allows the user to delete engine tests that have been loaded into the system and to increase or decrease the “engine tests” limit. It allows the user to fully utilise the memory capabilities of the PC on which the software is running. For example if the PC has a large amount of ram, the user can set the “engine test” limit up to the maximum and many different tests can be compared and viewed at once.
- Add user – Adds a new user to the system. (Administrator only)
- Delete User – Deletes a user from the system (Administrator only)
- Edit user - Edits a users profile (Administrator only).

Figure 3.1 illustrates the above use cases.

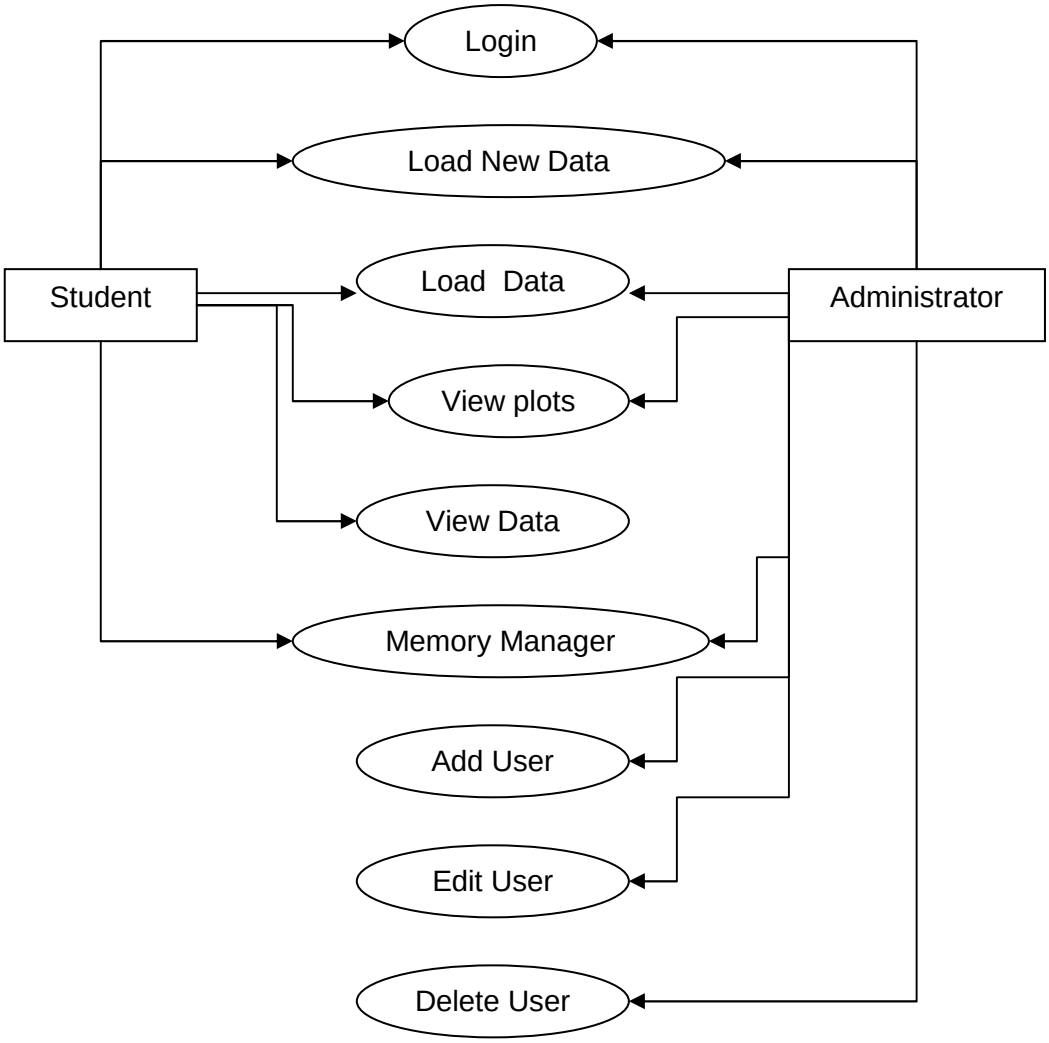


Figure 3.1: Use Case Diagram

The actual use cases that follow, are written according to the UML (unified modelling language) specification. This specification ensures a global standard in which use cases are written.

3.2.2 Login Use Case

- **Actors**
  Student and administrator

- **Primary Goal**

  To authenticate a user with the system so that access to other functions can be provided.

- **Pre-Conditions**

  None.

- **Post Conditions**

  User logged on and access to appropriate functions granted

- **Primary Success Scenario**

  1. The system prompts for a username.
  2. The actor enters a username.
  3. The system prompts for a password.
  4. The actor enters a password.
  5. The system validates the username and password and logs the user on.

- **Alternative Courses**

  5.1 The username is unknown

  5.1.1 The system displays a message indicating "Login details are incorrect" .

  5.1.2 Continue from 1.

  5.2 The password is incorrect.

  5.2.1 The system displays a message indicating "Login details are incorrect".

  5.2.2 Continue from 1.

- **Notes**

  1. User names must be unique

3.2.3 Load New Data Use Case

- **Actors**

  Administrator and student

- **Primary Goal**

  To retrieve technical engine data from an external DLL (Dynamic Link Library) and perform thermodynamic analysis on the data.

- **Pre-Conditions**

  Actor must be logged on.

- **Post Conditions**

  None.

- **Primary Success Scenario**

  1. Actor selects the “Load New Data” option.
  2. System executes external DLL and pauses until external DLL completes its task.
  3. DLL prompts user for engine test file.
  4. Actor selects file.
  5. DLL plots an overlaid Pressure trace graph of all the cycles read into the system.
  6. Actor selects the best cycle.
  7. System retrieves technical engine data
  8. System prompts actor for fuel type, engine dimensions and application parameters.

9. Actor enters parameters
10. System prompts actor for the combustion analysis function to be performed.
11. Actor selects a function.
12. System performs the selected function and stores the manipulated data.

- **Alternate Courses**

4.1 Actor selects an incorrect file.

4.1.1 System displays a message indicating “Incorrect file type selected”.

4.1.2 Continue from step 3.

9.1. Actor enters incorrect parameters.

9.1.1. System displays a message indicating “Incorrect parameters entered, please re-enter”

9.1.2. Continue from step 8.

3.2.4 Load Data Use Case

- **Actors**

Administrator and student

- **Primary Goal**

To retrieve technical engine data from a previously converted and saved raw file and perform thermodynamic analysis on the data.

- **Pre-Conditions**

Actor must be logged on. Load new Data use case must have been performed.

- **Post Conditions**

None.

- **Primary Success Scenario**

1. Actor selects the “Load Data” option.
2. System prompts user for the saved engine test cycle.
3. Actor selects the file.
4. System retrieves technical engine data
5. System prompts actor for fuel type, engine dimensions and application parameters.
6. Actor enters parameters
7. System prompts actor for the combustion analysis function to be performed.
8. Actor selects a function.
9. System performs the selected function and stores the manipulated data.

- **Alternate Courses**

3.1 Actor selects an incorrect file.

3.1.1 System displays a message indicating “Incorrect file type selected”.

3.1.2 Continue from step 2.

6.1. Actor enters incorrect parameters.

6.1.1. System displays a message indicating “Incorrect parameters entered, please re-enter”

6.1.2. Continue from step 5.

- **Notes**

The difference between this use case and the “Load new data” use case is that the cycle selection made by the user from the external DLL

is not carried out. This is because there is a file that has been saved previously, containing the already selected cycle. The advantage of this is that the user can continuously load this file and perform different combustion functions on the same cycle. The actor is then able to compare all the analysis formed, on the same cycle, on one graph.

3.2.5 View Plots Use Case

- **Actors**

  Student and Administrator.

- **Primary Goal**

  To display graphical data of saved manipulated data

- **Pre-Conditions**

  Load New Data use case or Load Data Use Case

- **Post Conditions**

  None.

- **Primary Success Scenario**

  1. System prompts user for graph selection.
  2. User selects graphs.
  3. System plots graphs.
  4. User selects area to zoom.
  5. System zooms by required percentage.
  6. User selects axis range.
  7. System prompts user for range.
  8. Actor enters range.
  9. System alters plot.

- **Alternate Courses**

  8.1 Actor enters incorrect range.

8.1.1 System displays a message indicating “Incorrect range entered, please re-enter values”.

8.1.2 Continue from step 7.

3.2.6 View Data Use Case

- **Actors**

  Student and Administrator.

- **Primary Goal**

  To generate reports of raw and manipulated data.

- **Pre-Conditions**

  Load New Data use case or Load Data Use Case

- **Post Conditions**

  None.

- **Primary Success Scenario**

  1. System prompts user for report of choice.
  2. Actor selects a report.
  3. System retrieves and displays data.
  4. Actor selects “generate report”.
  5. System generates report.
  6. Actor selects “Save as PDF”.
  7. System prompts for file name.
  8. Actor enters file name.
  9. System prompts for title.
  10. Actor enters title.
  11. System prompts for author
  12. Actor enters author.
  13. System prompts user for password protection.
  14. Actor selects password protection option.

15. System prompts for 40 bit or 128 bit encryption.
16. Author enters 128 bit.
17. System prompts for password and confirmation of password.
18. Actor enters password twice.
19. Actor selects ok.
20. System saves report in PDF format.

- **Alternate Courses**

8.1 Actor enters incorrect file name.

8.1.1 System displays a message indicating "Incorrect file name entered, please re-enter".

8.1.2 Continue from step 7.

18.1 Actor confirms password incorrectly

18.1.1 System displays a message indicating "The passwords entered do not match, please reenter"

18.1.2 Continue from step 17.

3.2.7 Memory Limit Use Case

- **Actors**

Student and Administrator.

- **Primary Goal**

To manage memory constraints of the program

- **Pre-Conditions**

None

- **Post Conditions**

None.

- **Primary Success Scenario**

1. System displays a real time, RAM (random access memory graph).
2. System displays current default memory limit.
3. System displays the loaded test cycles.
4. Actor increases memory limit.
5. Actor selects “OK”.
6. System saves the new memory limit.

- **Alternate Courses**

  None.

3.2.8 Delete Loaded Cycle Use Case

- **Actors**

  Student and Administrator.

- **Primary Goal**

  To delete a previously loaded cycle.

- **Pre-Conditions**

  Load new Data Use Case or Load Data Use Case

- **Post Conditions**

  None.

- **Primary Success Scenario**

  1. System displays a real time, RAM (random access memory graph).
  2. System displays current default memory limit.
  3. System displays the loaded test cycles.
  4. Actor selects a test cycle to delete.
  5. Actor selects “OK”.
  6. System deletes the selected cycle.

- **Alternate Courses**

  None.

3.2.9 Add New User Use Case

- **Actors**

  Administrator.

- **Primary Goal**

  To add a new user so as access to CAS functionality can be obtained.

- **Pre-Conditions**

  User with administrator rights must be logged in

- **Post Conditions**

  None.

- **Primary Success Scenario**

  1. System displays current users and their details.
  2. Actor selects add.
  3. System prompts for user name.
  4. Actor enters a user name.
  5. System prompts for password.
  6. Actor enters password.
  7. System prompts for confirmation of password.
  8. Actor re-enters password.
  9. System prompts for administrator rights.
  10. Actor does not tick administrator rights.
  11. Actor selects “OK”.
  12. System saves new user to the database.

- **Alternate Courses**

4.1 Actor enters an existing user name.

4.1.1 System displays a message indicating “The user name entered already exists, please choose another user name”.

4.1.2 Continue from step 3.

8.1 Actor confirms password incorrectly

8.1.1 System displays a message indicating “The passwords entered do not match, please reenter”

8.1.2 Continue from step 5.

3.2.10 Edit User Use Case

- **Actors**

  Administrator.

- **Primary Goal**

  To edit an existing user’s details

- **Pre-Conditions**

  User with administrator rights must be logged in

- **Post Conditions**

  None.

- **Primary Success Scenario**

  1. System displays current users and their details.
  2. Actor selects a user to edit.
  3. Actor selects “Edit”.
  4. System displays username, password and admission rights for the selected user.
  5. Actor enters a new password.
  6. System prompts for confirmation of password.
  7. Actor re-enters password.

8. Actor selects “OK”.
9. System saves the altered user details to the database.

- **Alternate Courses**

  7.1 Actor confirms password incorrectly

  7.1.1 System displays a message indicating “The passwords entered do not match, please reenter”

  7.1.2 Continue from step 6.

3.2.11 Edit User Use Case

- **Actors**

  Administrator.

- **Primary Goal**

  To delete an existing user.

- **Pre-Conditions**

  User with administrator rights must be logged in

- **Post Conditions**

  None.

- **Primary Success Scenario**

  1. System displays current users and their details.
  2. Actor selects a user to delete.
  3. Actor selects “Delete”.
  4. System deletes the selected user.

- **Alternate Courses**

  None

3.3 Object Orientated Programming

The CA software was designed for ease of use and ease of function additivity. As more research is carried out in the future using the CA software, more and more functionality will be required. It is impossible to predict what functionality may be required in the future and for this reason the software was designed to be adaptable to adding new features. In order for this adaptability to be simple to do, the software had to be designed in such away that anyone with a bit of programming knowledge could easily interpret the code and hence add on to it. To make this code easy to understand and re-use, it has been written using object orientation.

The concepts of object orientation stems back to the way we perceive life. We see everything as objects, for example a pair of scissors is an object, a piece of paper is also an object. When we cut the piece of paper, it is not us cutting the paper it is the scissors cutting the paper. Therefore if we had to write this above process in object oriented code it would go as follows. The first object would be the human being, with a method called “pick up scissors” ,”pick up paper” and “press scissors”. The second object would be the scissors itself which would have a method in it called “cut paper”. The sequence of events would be as follows.

1. Human “Pick up scissors”
2. Human “Pick up paper”
3. Human “Press Scissors”
4. Scissors “cut Paper”

These sequence of events are not only logical but they make sense, i.e. a pair of scissors would not know how to pick itself up or pick up a piece of paper. The human object could only be able to do that. Likewise a human can not cut a piece of paper, only the scissors object could do that. This is where the power of object orientation comes in. If a programmer is looking at this code for the first time, they would know exactly how to interpret it and add to it as

it has been written in a way that a person would carry out events in every day life.

Object-oriented programming (OOP) is a programming language model organized around "objects" rather than "actions" and data rather than logic. Historically, a program has been viewed as a logical procedure that takes input data, processes it, and produces output data. The programming challenge was seen as how to write the logic, not how to define the data. Object-oriented programming takes the view that what we really care about are the objects we want to manipulate rather than the logic required to manipulate them. Examples of objects range from human beings (described by name, address, and so forth) to buildings and floors (whose properties can be described and managed) down to the little widgets on your computer desktop (such as buttons and scroll bars).

The section that follows (3.3.2) identifies all the objects required for manipulation and how they relate to each other, an exercise often known as data modelling. Then in section (3.3.3) the defined objects are generalized as a class of objects (think of Plato's concept of the "ideal" chair that stands for all chairs) and define the kind of data it contains and any logic sequences that can manipulate it. Each distinct logic sequence is known as a method. A real instance of a class is called again an "object" or, in some environments, an "instance of a class." The object or class instance is what the computer runs. Its methods provide computer instructions and the class object characteristics provide relevant data. One “communicates” with objects - and they communicate with each other - with well-defined interfaces called *messages*.

The concepts and rules used in object-oriented programming provide these important benefits:

- The concept of a data class makes it possible to define subclasses of data objects that share some or all of the main class characteristics. Called inheritance, this property of OOP forces a more thorough data analysis, reduces development time, and ensures more accurate coding.

- Since a class defines only the data it needs to be concerned with, when an instance of that class (an object) is run, the code will not be able to accidentally access other program data. This characteristic of data hiding provides greater system security and avoids unintended data corruption.
- The definition of a class is reuseable not only by the program for which it is initially created but also by other object-oriented programs (and, for this reason, can be more easily distributed for use in networks).
- The concept of data classes allows a programmer to create any new data type that is not already defined in the language itself.

3.3.1 Layers

The software was designed to have three main distinct layers of objects. These layers are:

1. The Front End Gui (Graphical User Interface) Layer. This layer is where all the objects that display data are situated. For example the objects that plot graphs are situated in this layer. These objects have one sole purpose and that is to display information and allows one to navigate to the information one wants to view, and that is all. They perform no data manipulation or data storage at all. Data manipulation is performed by objects situated in the " Business Layer".
2. The Business Layer. The objects situated in the business layer perform the "business" or manipulation required. For example these objects will perform everything from Weinberg analysis up to calculating pressures, volumes and temperatures. They do not store or display the data, only manipulate it. Once the data has been manipulated it is stored in the objects situated in the "data layer".
3. The Data Layer. As the name implies, these are the objects which are responsible for storing the data, once it has been manipulated. Their primary functionality is to receive the manipulated data from the business layer objects and store it until it is required by the Front End Gui layer objects. The Data Layer Objects pass on the data to the Front

End Gui objects for display purposes. Once the user has viewed the data, the Front End Gui objects loose this data, however if the data is required to be viewed again the Data Layer Objects still have it stored in memory.

The layers are designed to maximize the concepts of object orientation. This is because it makes sense to group objects that perform a similar task into one layer. This not only makes the code easier to understand but also easier to read. The following diagrams illustrate the three main layers described above including the external packages of the java language which the objects in each layer would use:

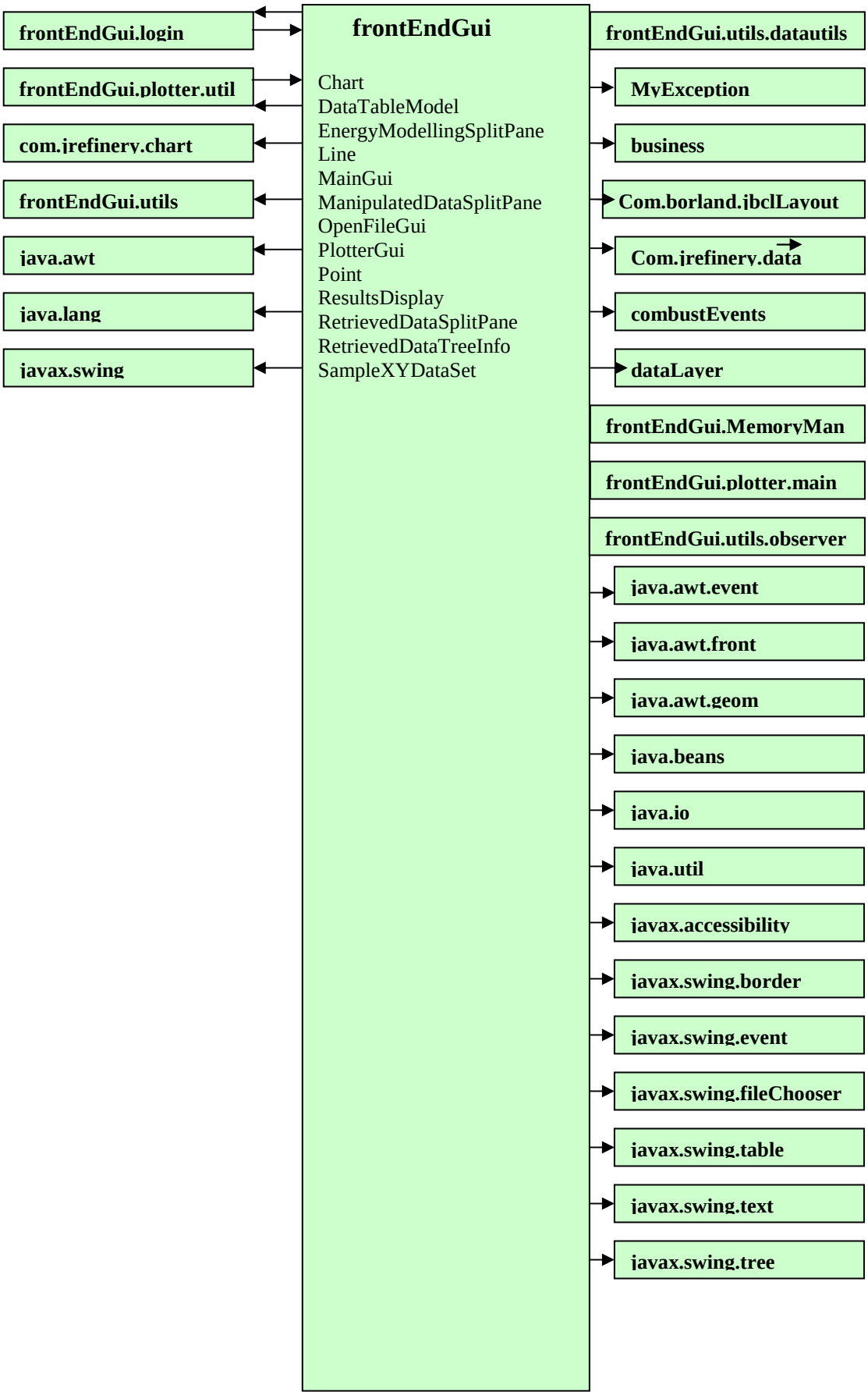


Figure 3.2: Front End Gui Layer

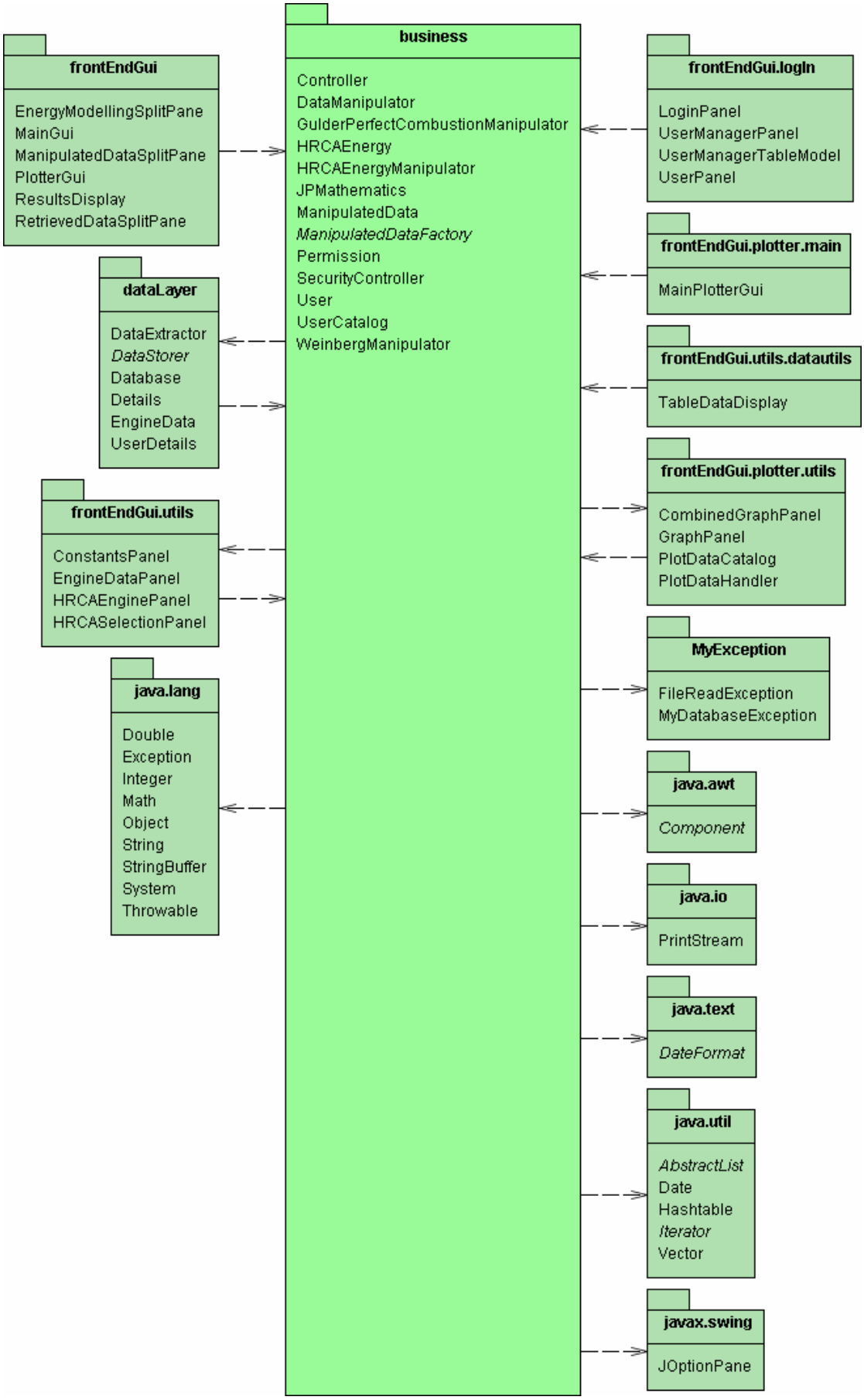


Figure 3.3: The Business Layer

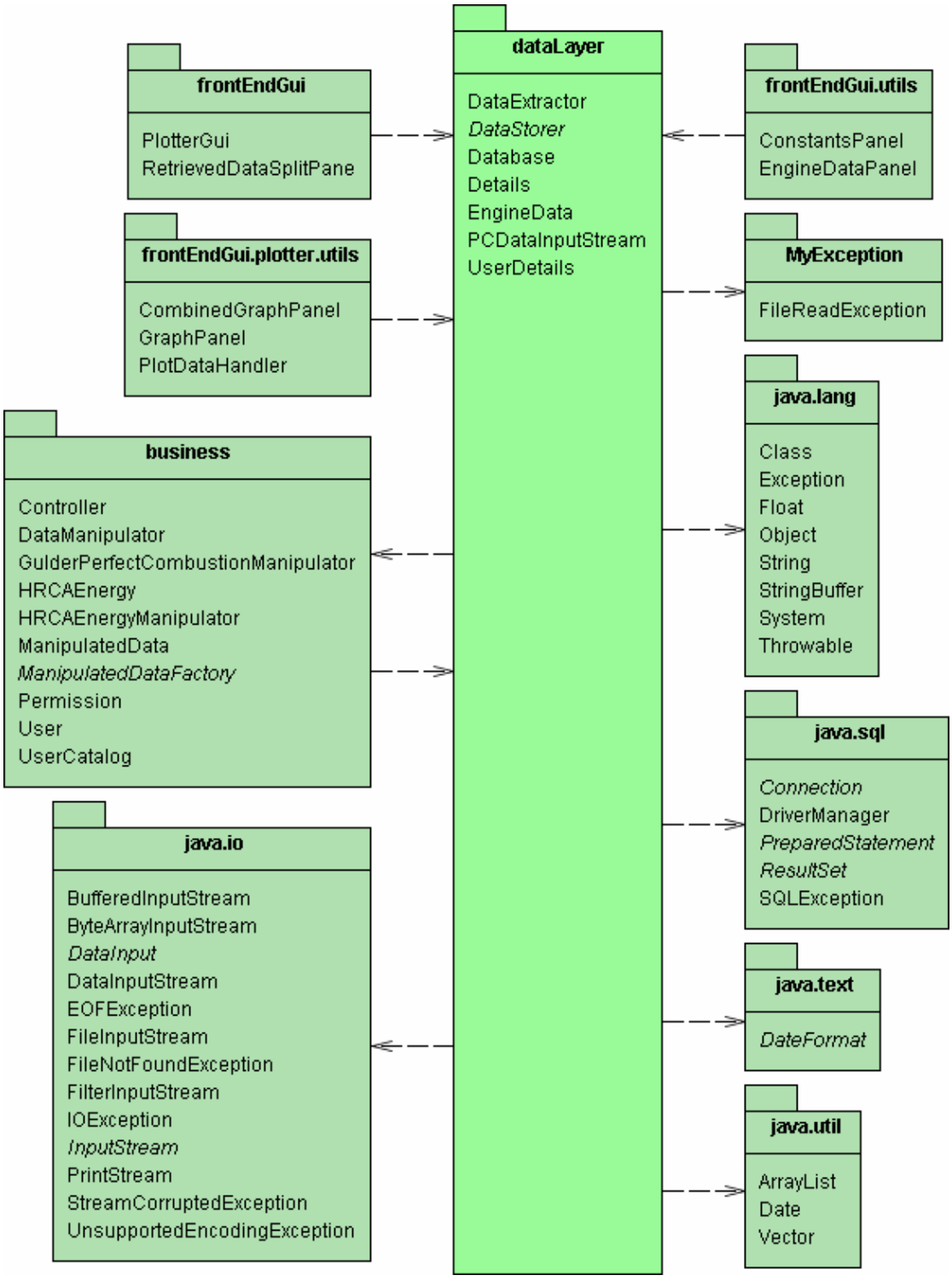


Figure 3.4: The Data Layer

3.3.2 Data Modeling (Sequence Diagrams)

Data Modeling is the process by which the “Objects” that perform the requirements of the use cases are identified and the method flow between the objects are decided upon. The final result is a blue print that together with the class diagrams (in section 3.3.3) are used to write the code. The use cases are the user requirements, the data modeling and class diagrams are the architectural drawings that are used to build the software program. The Sequence Diagrams (data modeling) that follow are the sequence diagrams that were created using the requirements outlined in the use cases in section 3.2.

The actual data Models that follow are written according to the UML (unified modelling language) specification. This specification ensures a global standard in which data models are written.

A. The Login Sequence Diagram

This data model was created using the Login Use case (3.2.2). It describes the objects and method flow that authenticates a user with the system so that access to other functions can be provided. Figure 3.5 illustrates the data model.

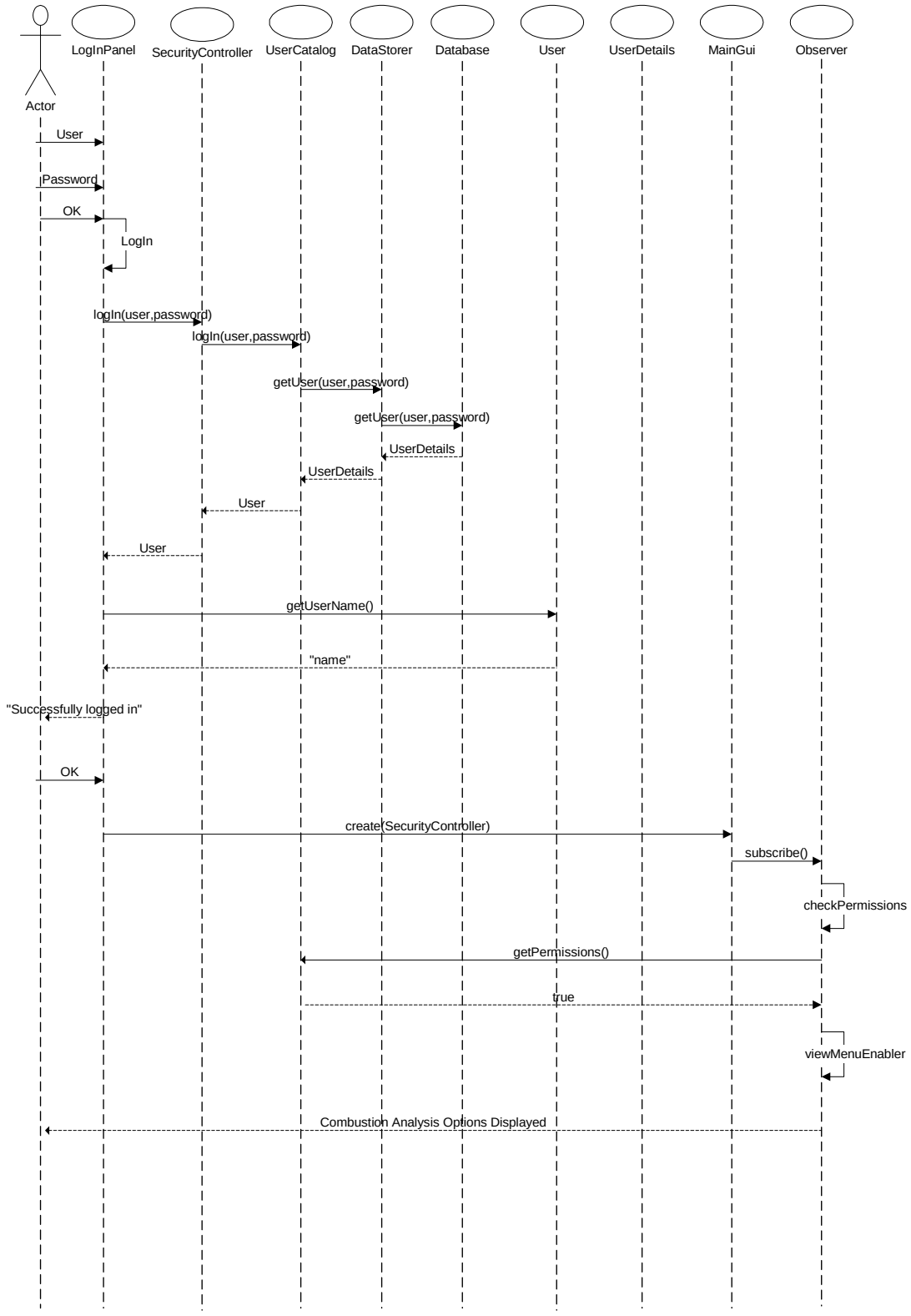


Figure 3.5: Login Sequence diagram

B. The Load Saved Data Sequence Diagram

This data model was created using the Load Data Use case (3.2.4). These objects and method flow allow the user to convert and perform energy modeling analysis on a saved engine test. The following three diagrams describe it.

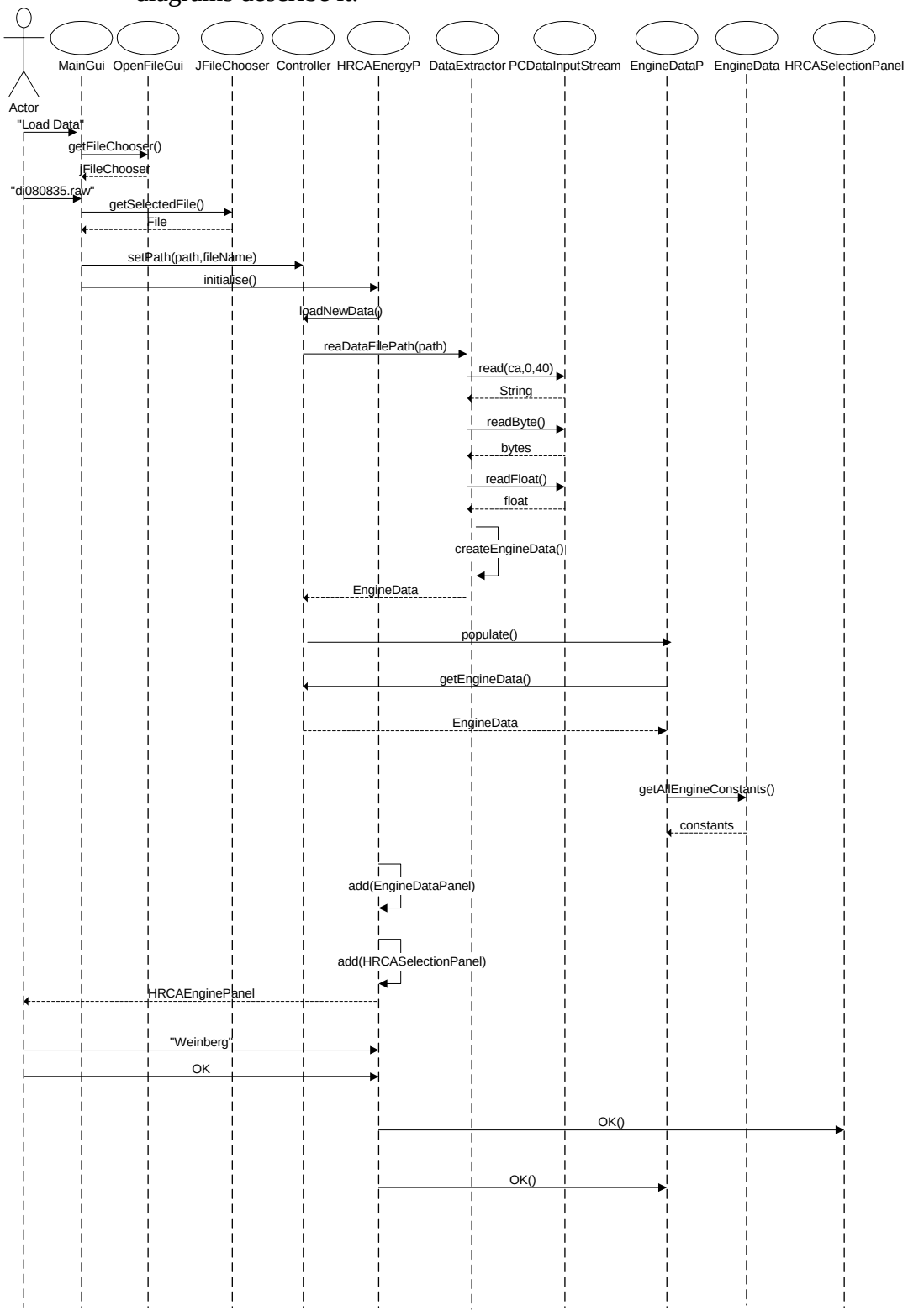


Figure 3.6a: Load Saved Data Sequence Diagram 1

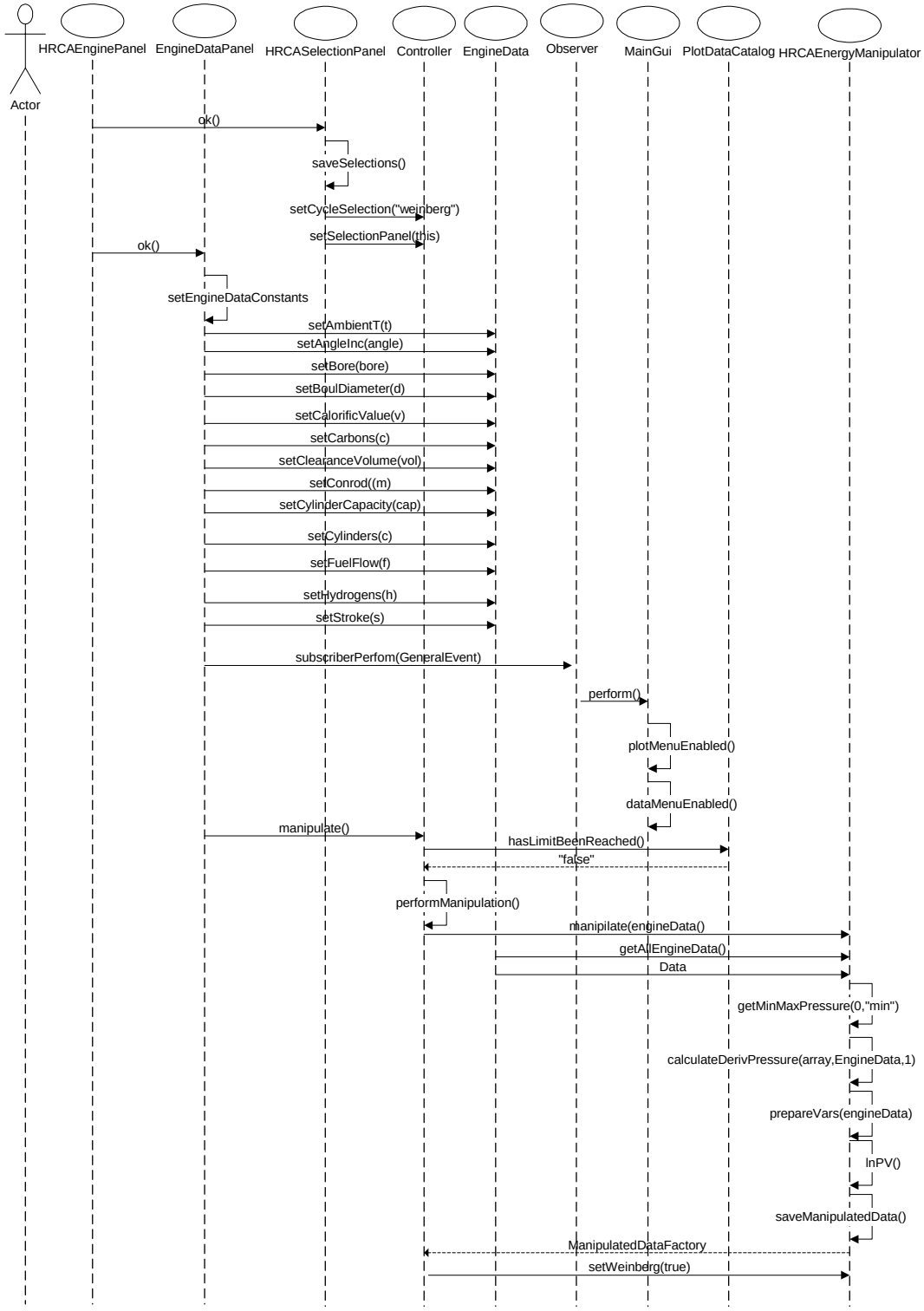


Figure 3.6b: Load Saved Data Sequence Diagram 2

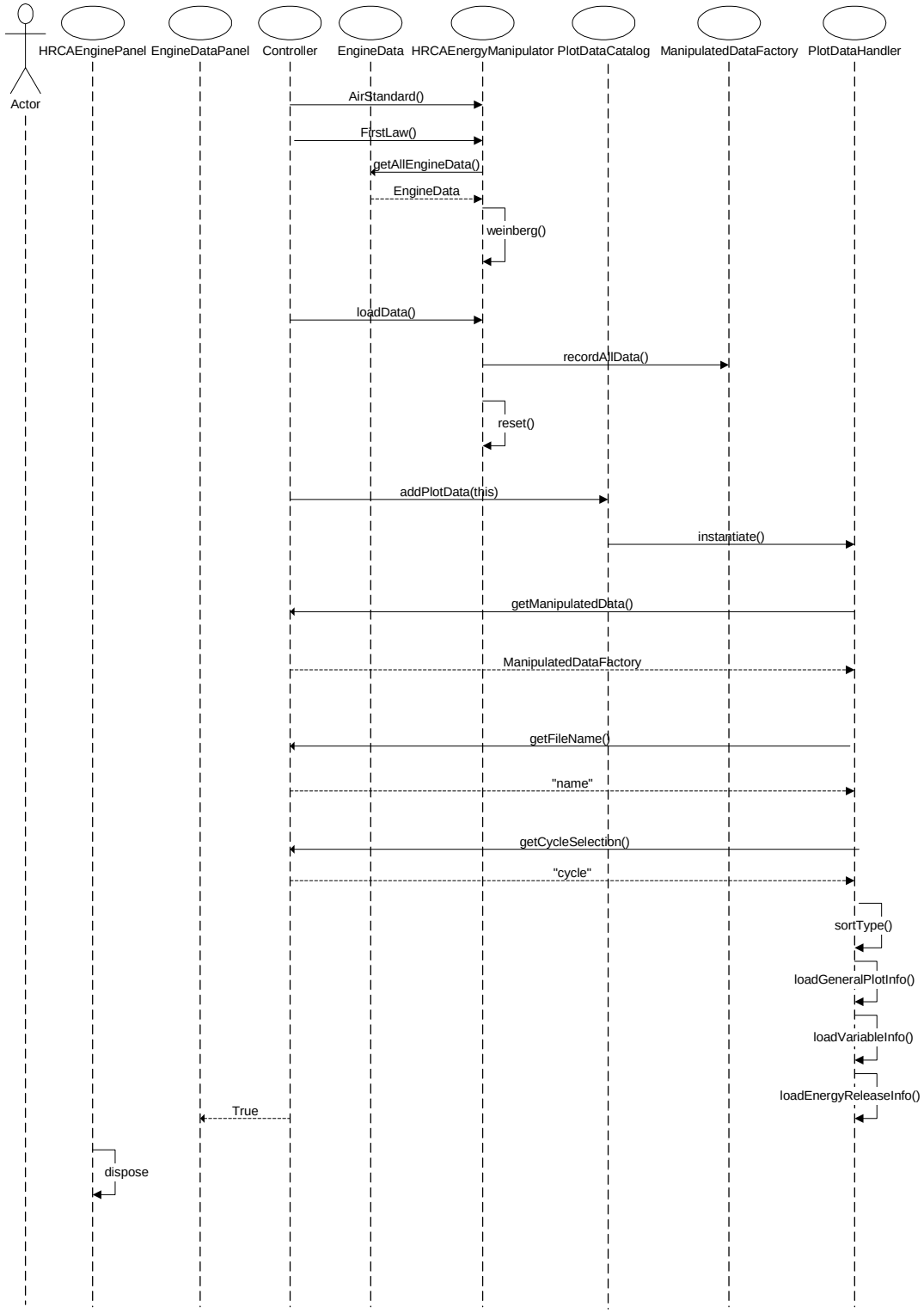


Figure 3.6c: Load Saved Data Sequence Diagram 3

The difference between this data model and the “Load new data” data model (in section C) is that the cycle selection made by the user from the external DLL is not carried out. This is because there is a file that has been saved previously, containing the already selected cycle. The advantage of this is that the user can continuously load this file and perform different combustion functions on the same cycle. The actor is then able to compare all the analysis formed, on the same cycle, on one graph. The difference is in the first sequence diagram,where the method “getRawFile()” makes the call to the external DLL. The methods that follow are identical. Refer to figure 3.7

C. The Load New Data Sequence Diagram

This data model was created using the Load New Data Use case (3.2.3). These objects and method flow allow the user to convert and perform energy modelling analysis on a newly performed engine test. The following three diagrams describe it.

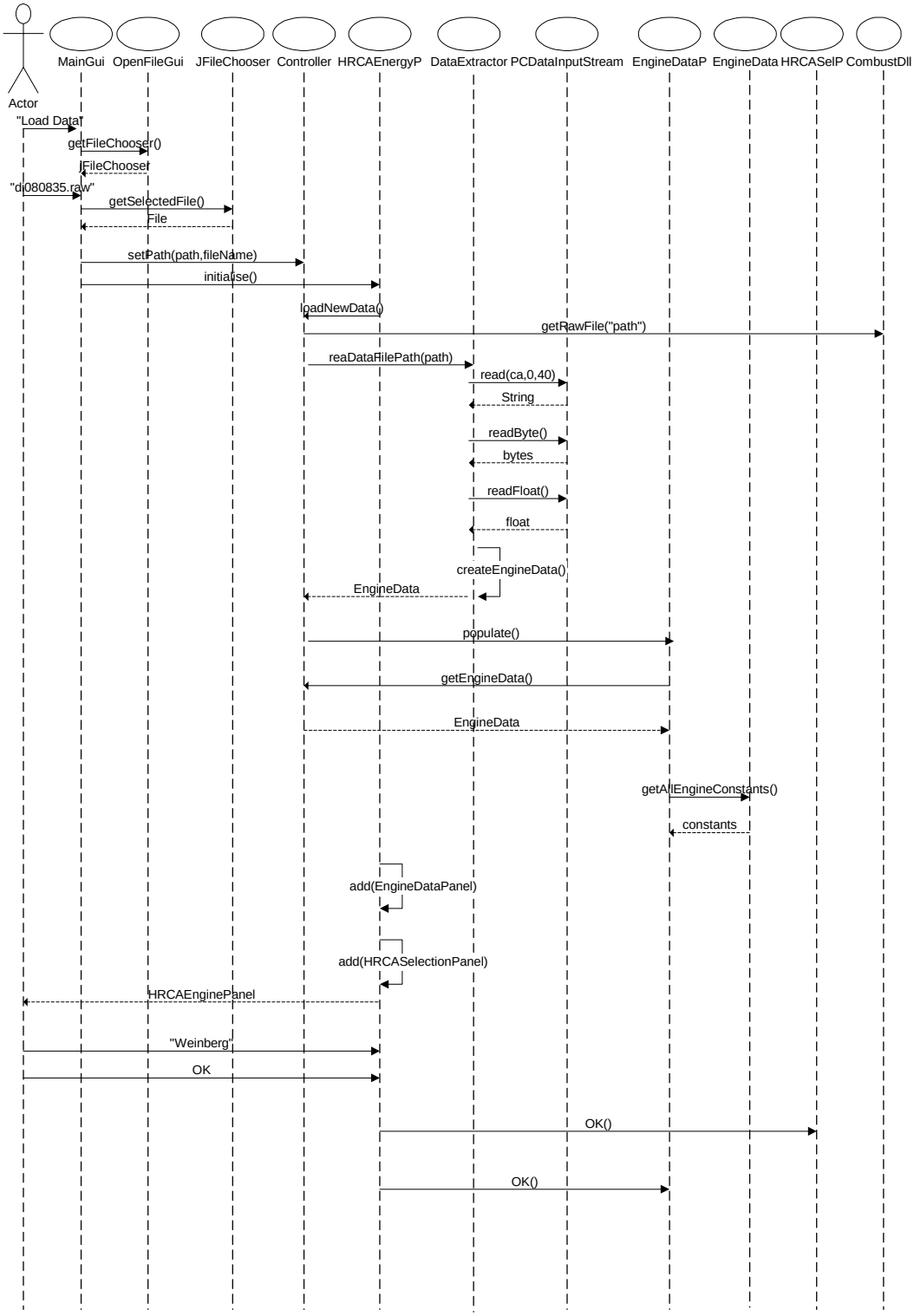


Figure 3.7a: Load New Data Sequence Diagram 1

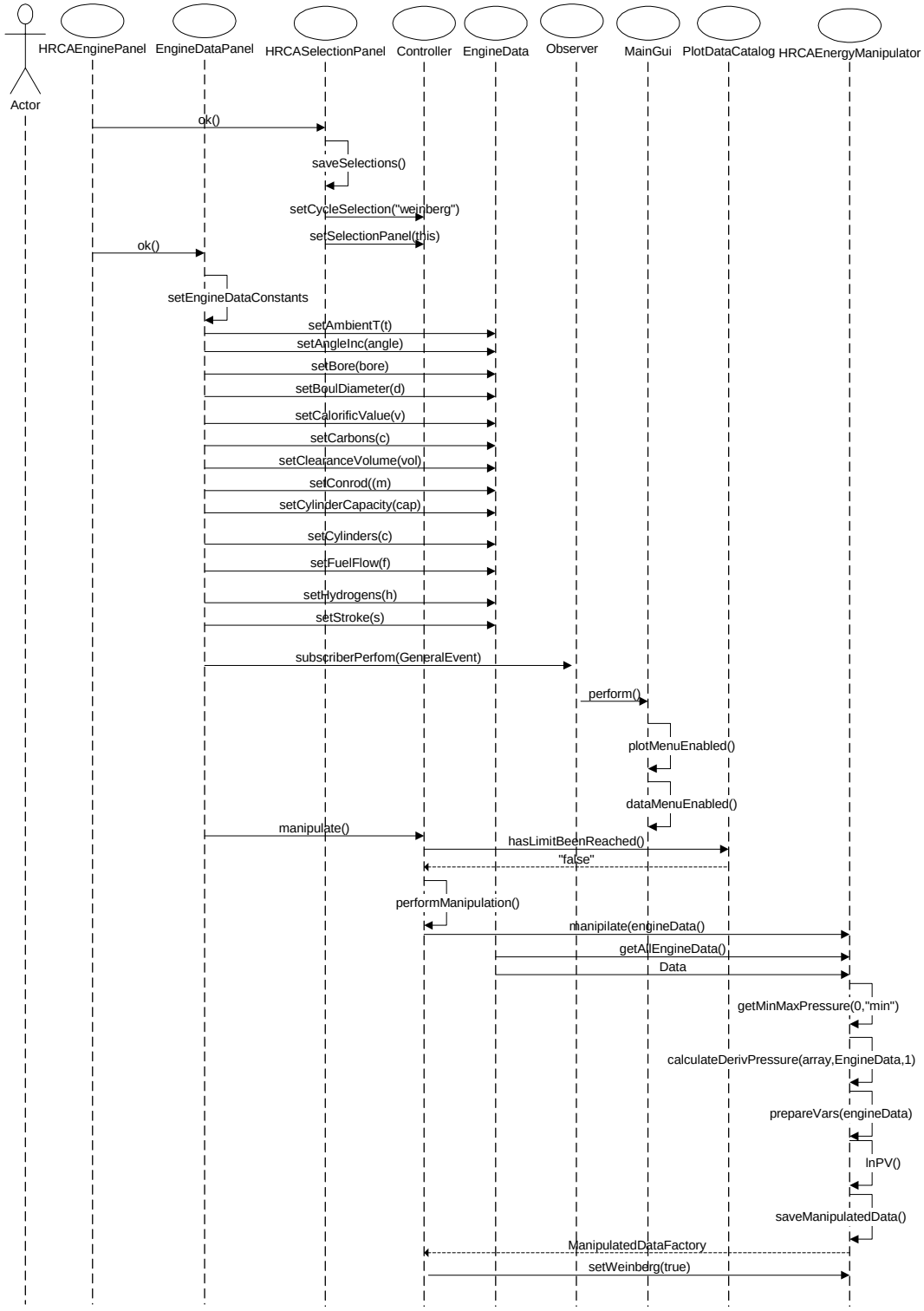


Figure 3.7b: Load New Data Sequence Diagram 2

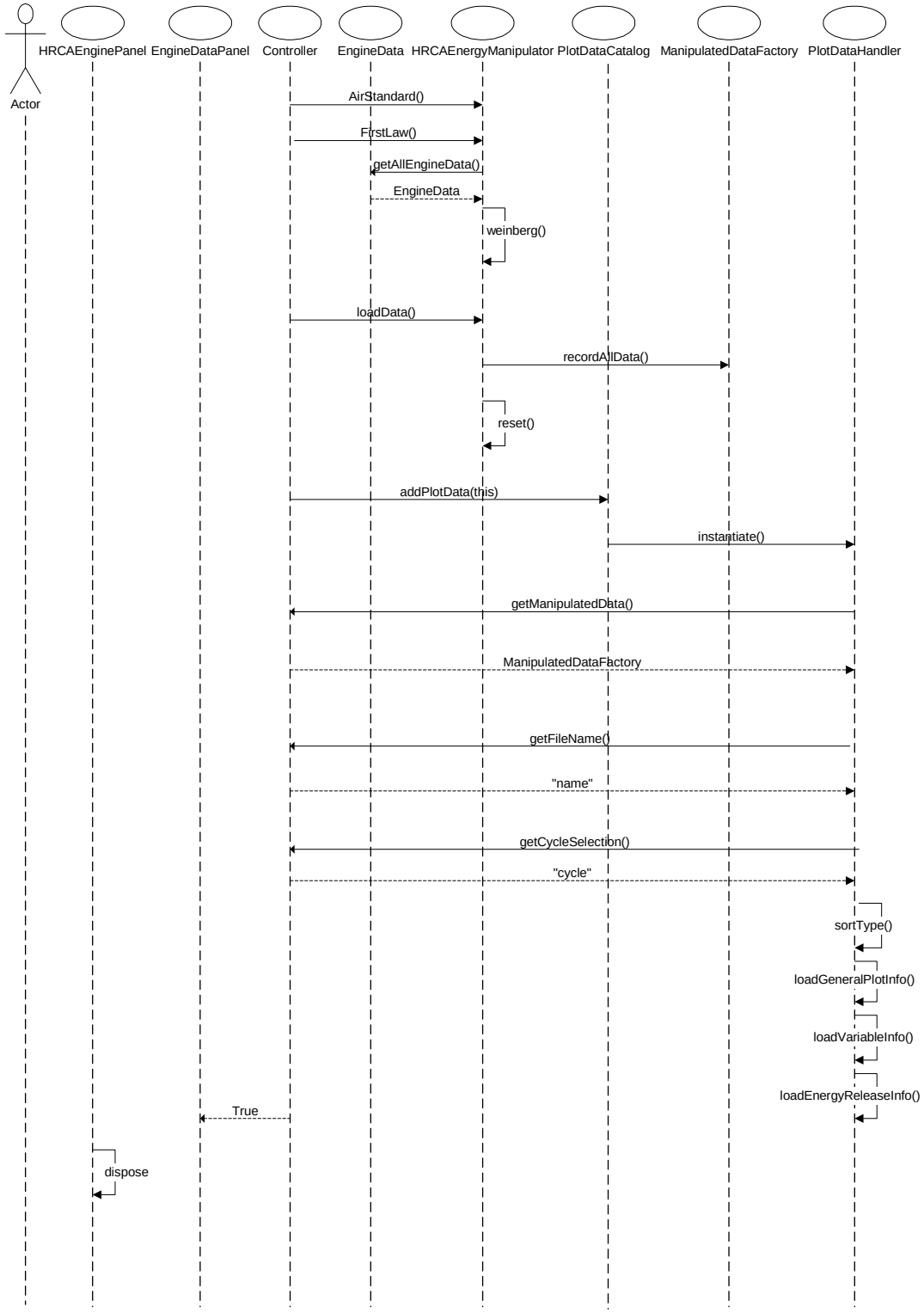


Figure 3.7c: Load New Data Sequence Diagram 3

D. The View Plots Sequence Diagram

This data model was created using the View Plots Use case (3.2.5). These objects and method flow allows users to select which plots to be displayed as well as to modify the plots.

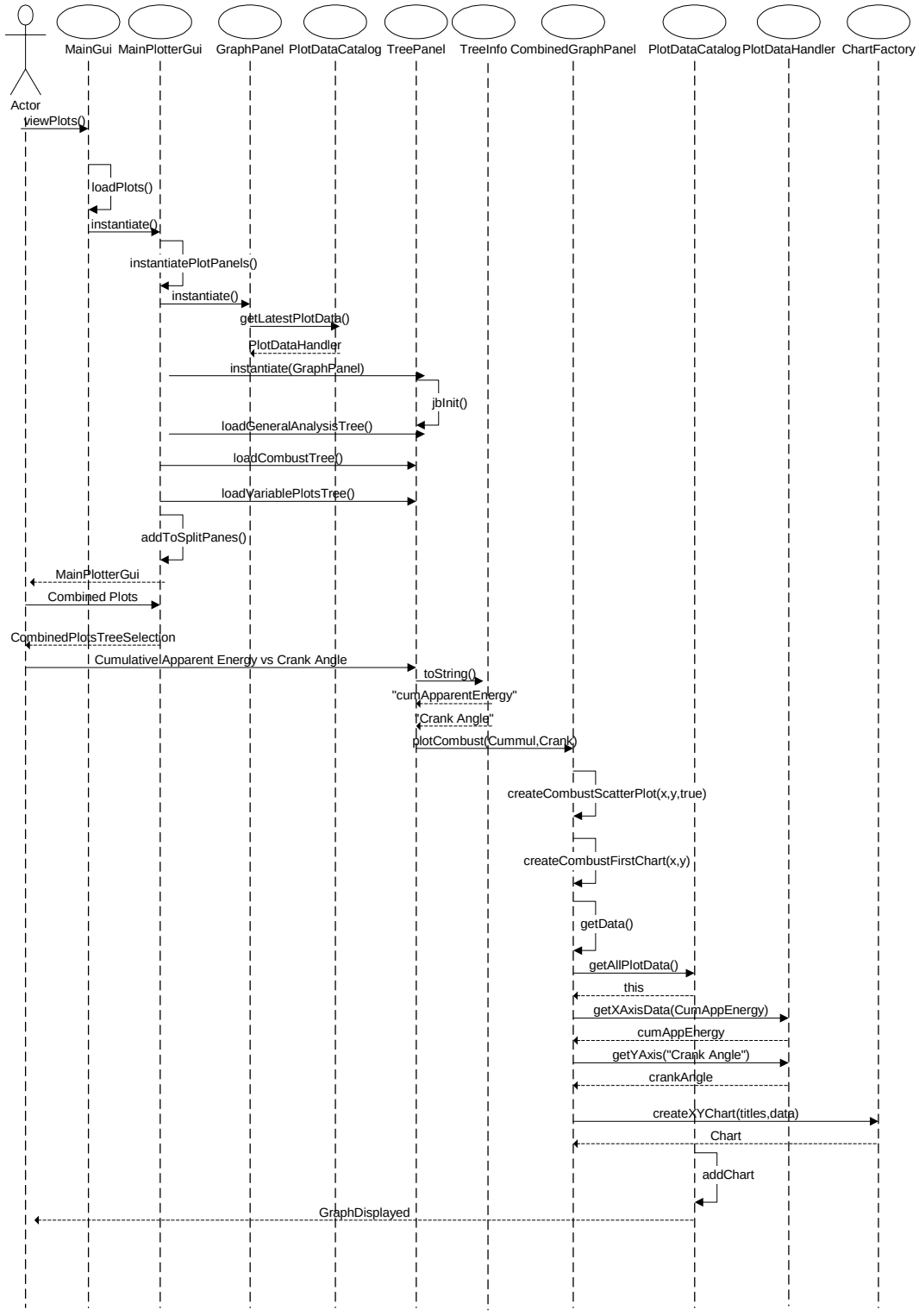


Figure 3.8: View Plots Sequence Diagram

E. The View Data Sequence Diagram

This data model was created using the View Data Use case (3.2.6). These objects and method flow allows the user to view and generate a report of all raw and calculated data.

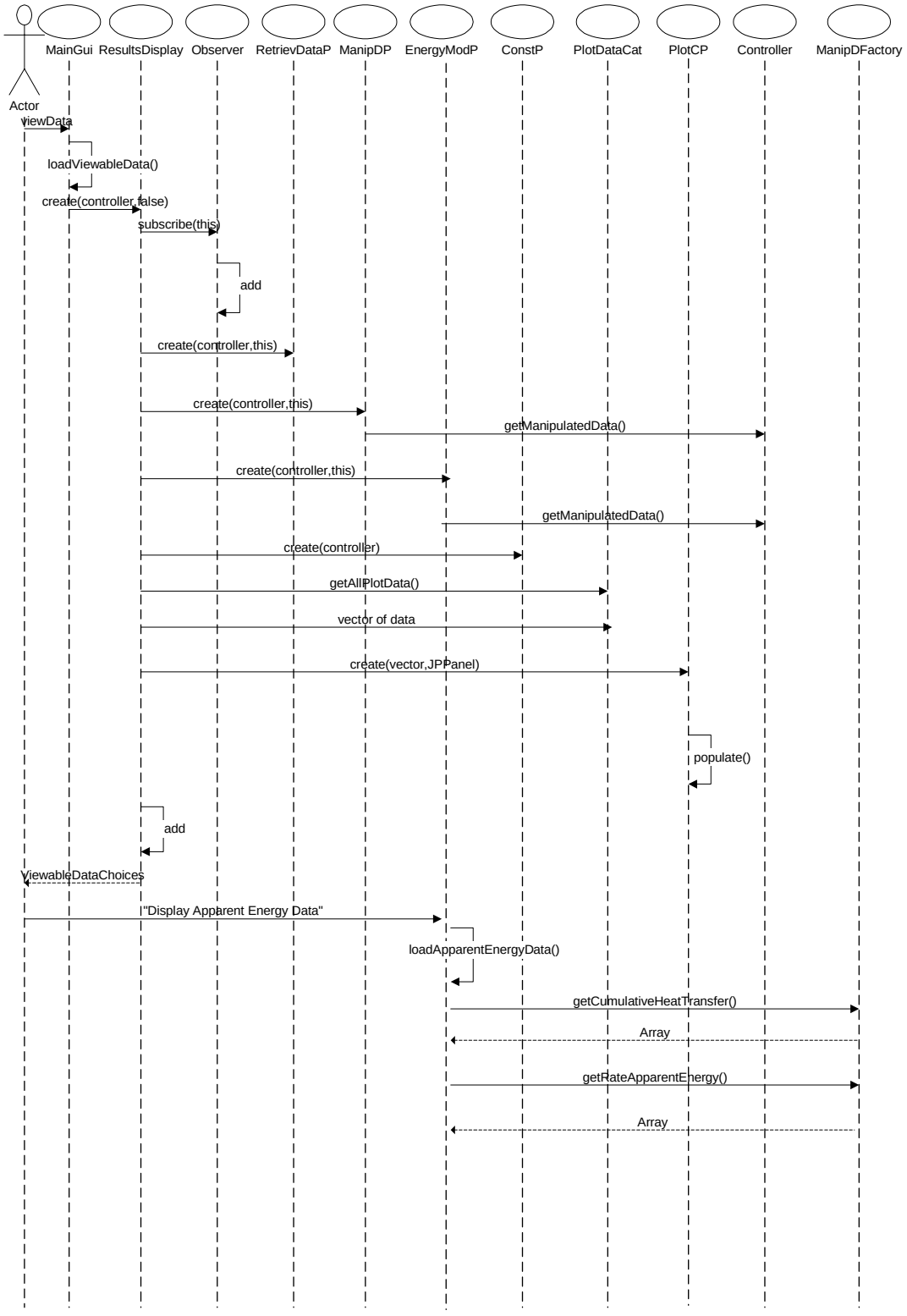


Figure 3.9a: View Data Sequence Diagram

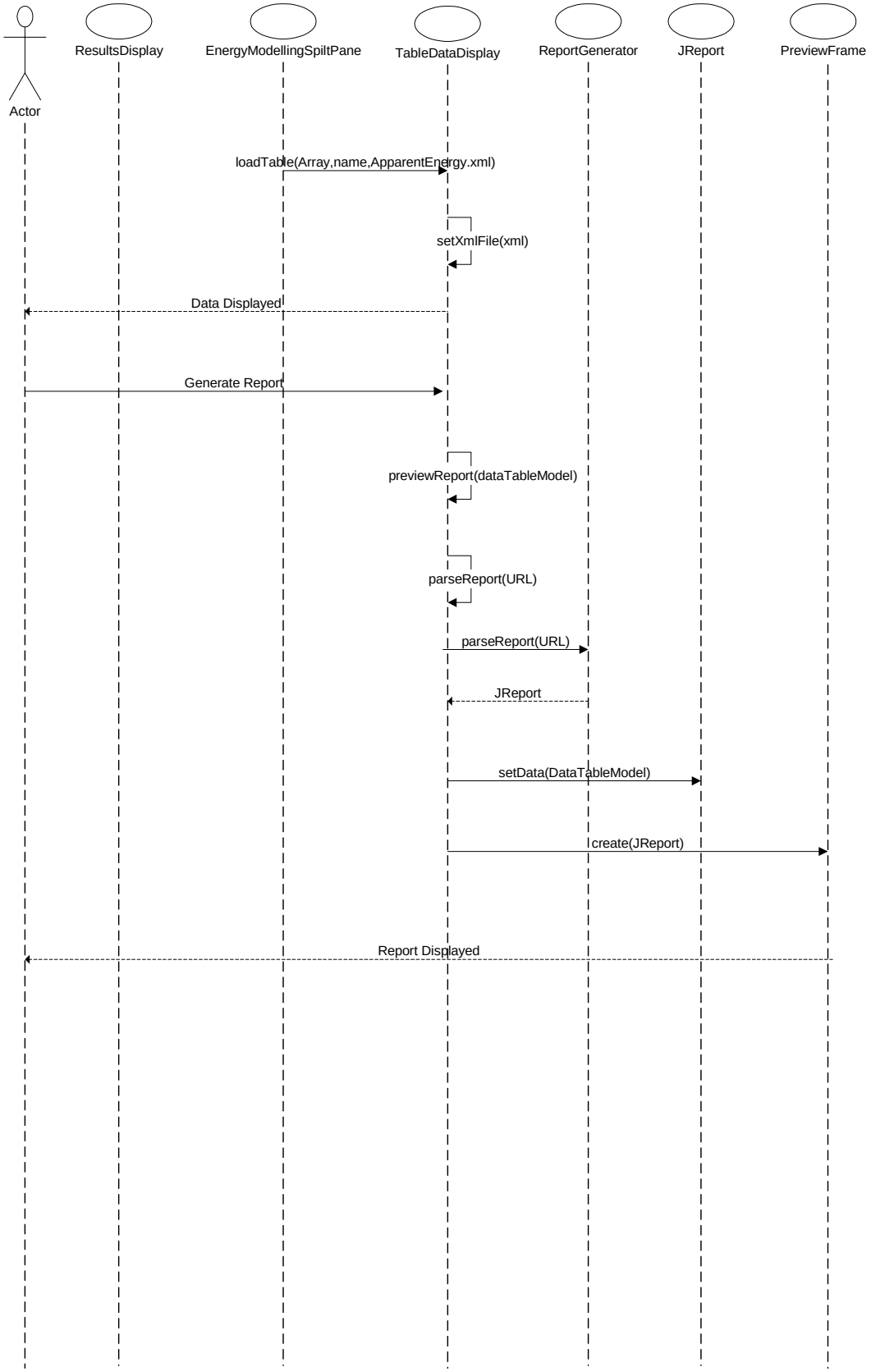


Figure 3.9b: View Data Sequence Diagram 2

F. The Memory Limit Sequence Diagram

This data model was created using the Memory Limit Use case (3.2.7). These objects and method flow allows the user to administrate the PC's memory .

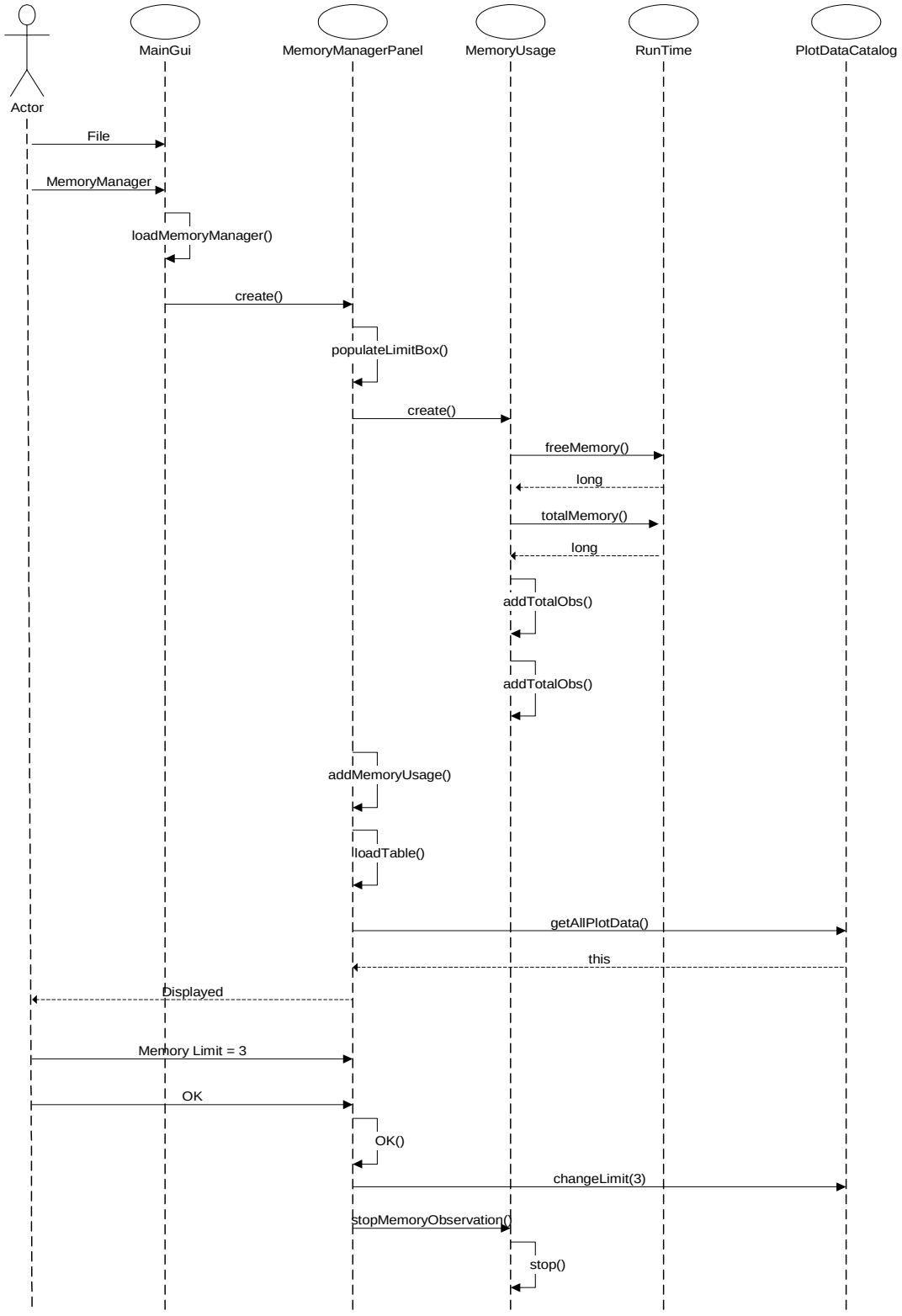


Figure 3.10: Memory Manager Sequence Diagram

G. The Delete Loaded Cycle Sequence Diagram

This data model was created using the Memory Limit Use case (3.2.8). These objects and method flow allows the user to delete previous loaded cycles from the PC's Random Access Memory .

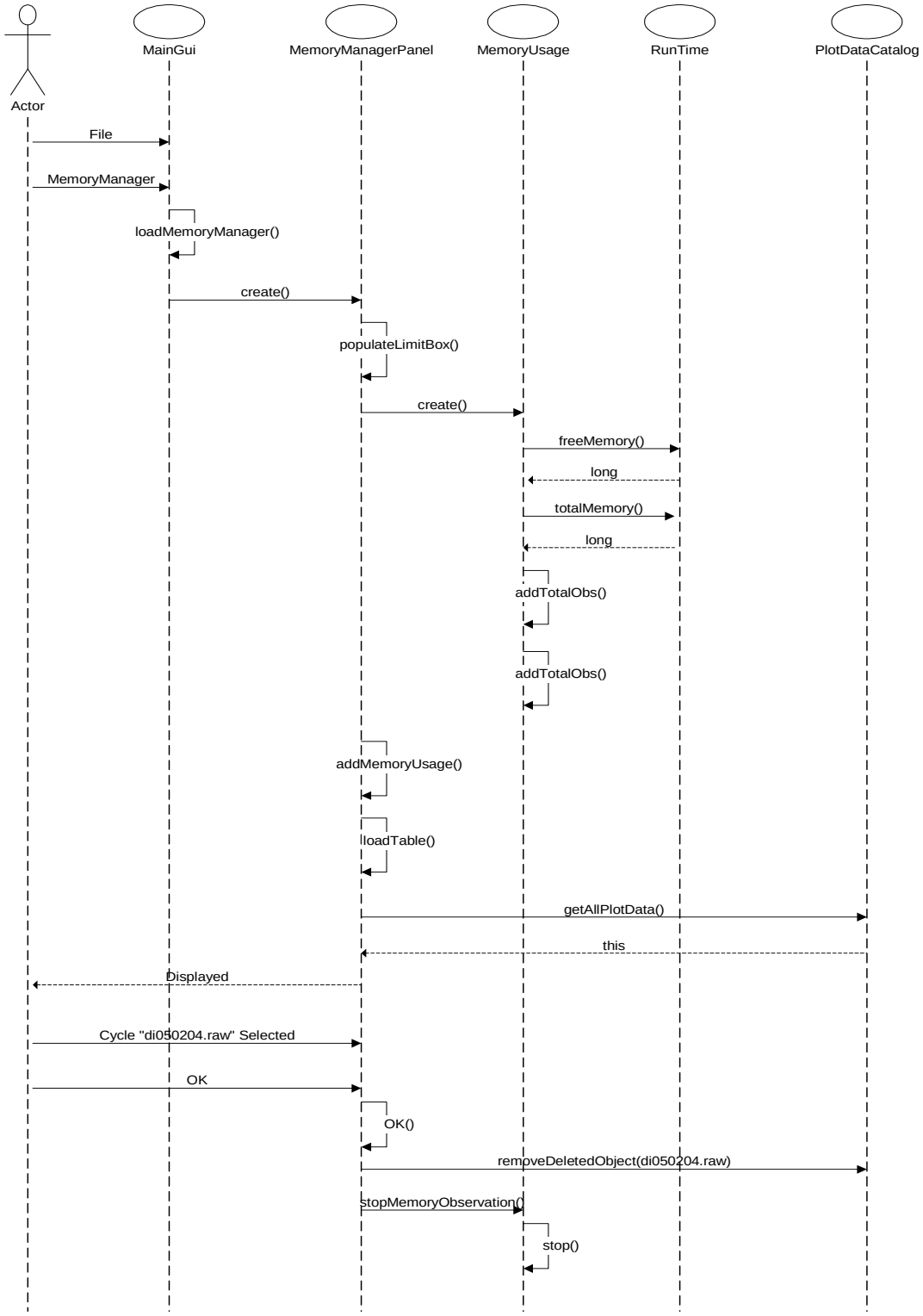


Figure 3.11: Delete Loaded Cycle Sequence Diagram

H. The Add User Sequence Diagram

This data model was created using the Add User Use case (3.2.9). These objects and method flow Adds a new user to the system. (Administrator only)

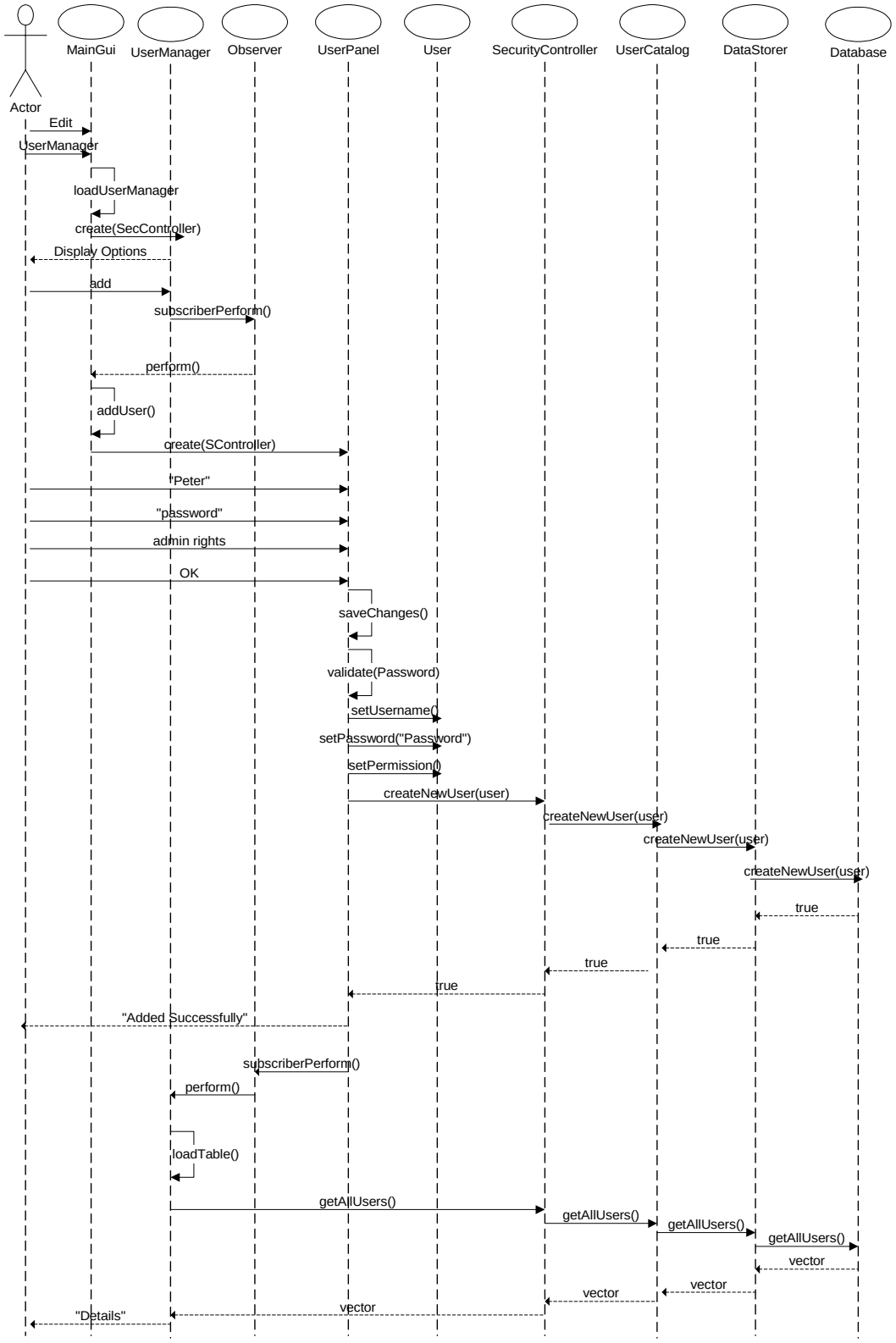


Figure 3.12: Add User Sequence diagram

I. The Delete User Sequence Diagram

This data model was created using the Delete User Use case (3.2.10). These objects and method flow deletes a user from the system. (Administrator only)

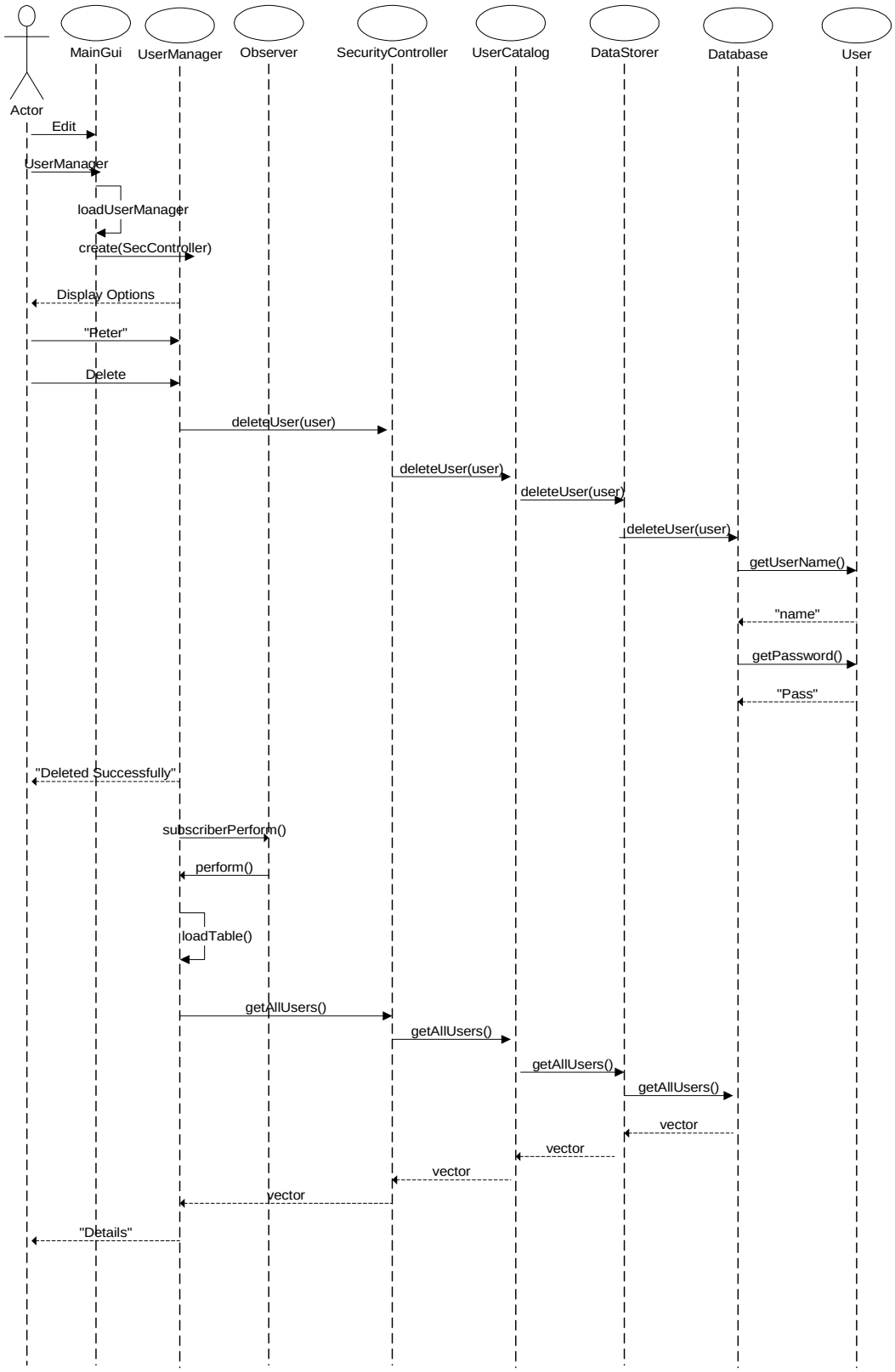


Figure 3.13: Delete User Sequence Diagram

J. The Edit User Sequence Diagram

This data model was created using the Delete User Use case (3.2.11). These objects and method flow allows a users details to be edited. (Administrator only)

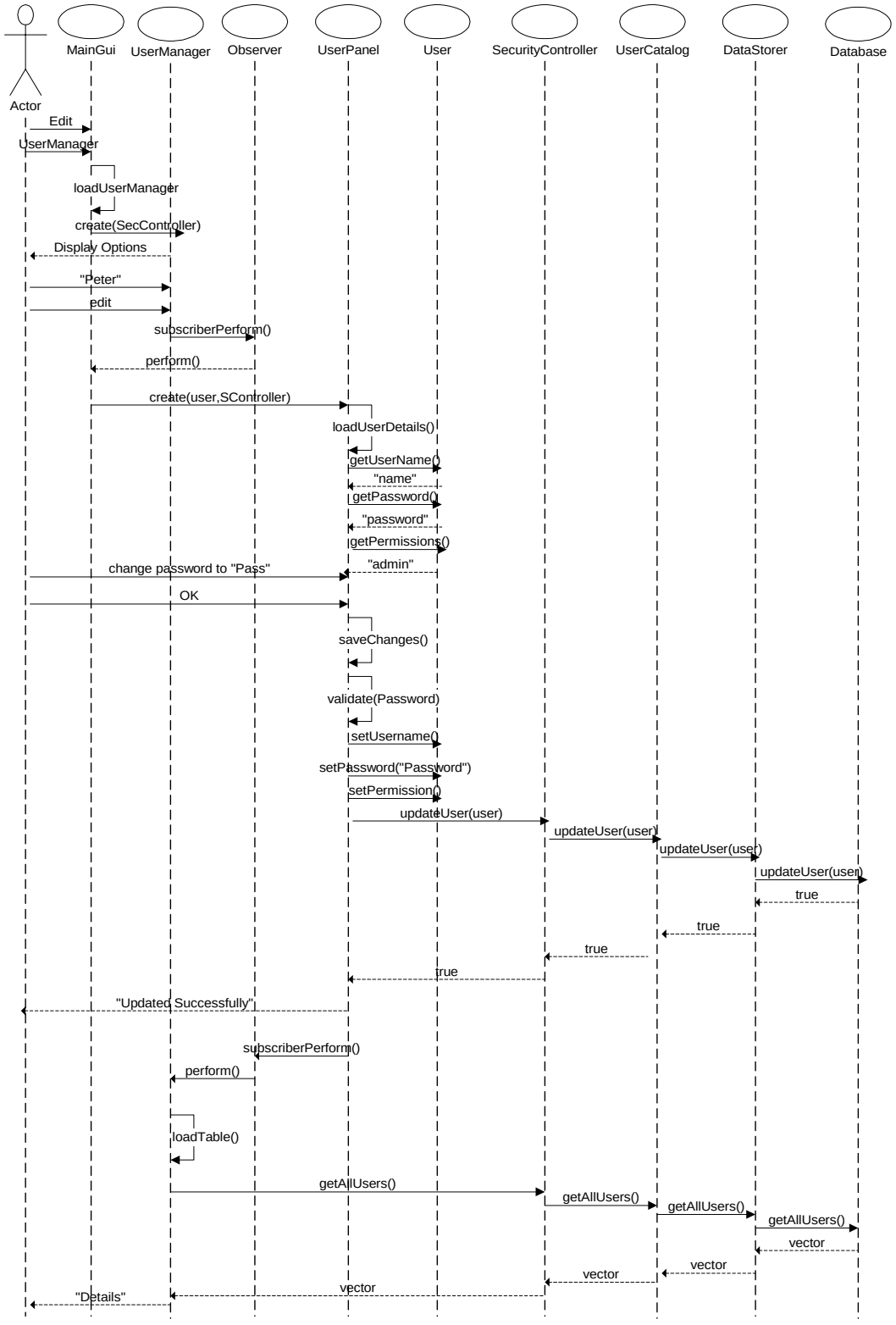


Figure 3.14: Edit User Sequence Diagram

3.3.3 The Class Diagrams (The High Level Architectural Design)

The class diagram is core to object-oriented design. It describes the types of objects in the system and the static relationships between them. The core element of the class diagram is the class. In an object oriented system, classes are used to represent entities within the system; entities that often relate to real world objects. The following section describes the three main Class groups used in the CAS application. It is a high level blue print such that an overall picture of the design is achieved.

The three main class diagram groups discussed are the

- The front end layer, classes
- The business layer, classes
- The data layer, classes

i. The Front End Layer Classes

Figure 3.15 is a representation of the Class diagram structure used in the front end layer of the system. The super class “JPPanel” inherits all the functionality of the Java JPanel object. It contains the reporting and xml objects required to preview reports. It also outlines the graphing methods that will be overridden to generate the graphical display.

The constants panel class inherits all the functionality of the “JPPanel” superclass. The power of this specific object oriented design allows the “ConstantsPanel” class to make use of the reporting functionality without duplication and extend this functionality for its unique specific use. This objects primary function is to display all constant data used in the thermodynamic analysis of CAS and to generate a printable report of this data.

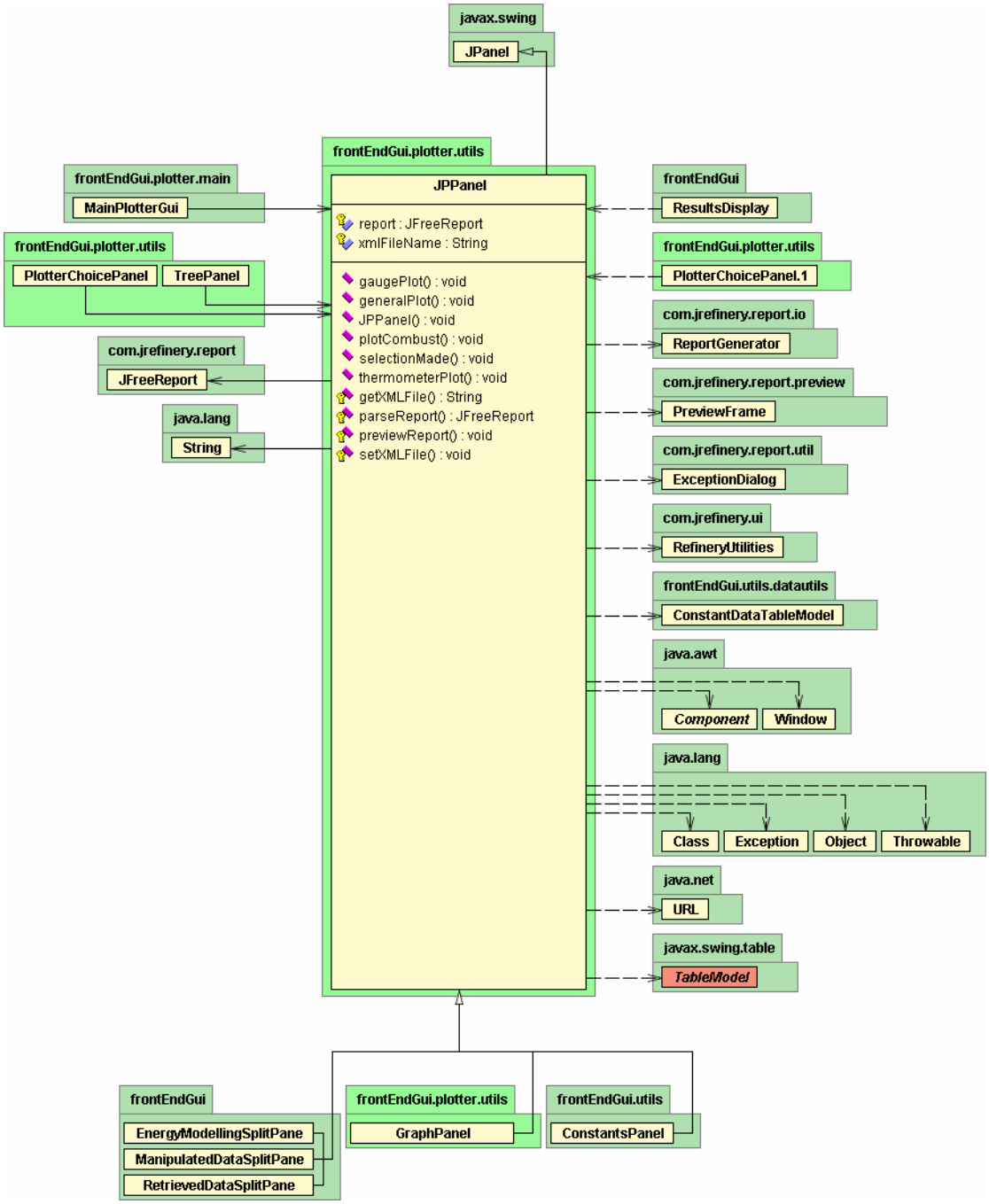


Figure 3.15: Class Diagram of Front End Layer

The “GraphPanel” class also inherits the “JPPanel” functionality, however instead of extending the reporting functionality, it overrides the graphical display methods. It’s primary use is to perform thermometer, gauge, general and combustion graphical plots. Again duplication is avoided and a refinement of the JPPanel graphical methods is performed in this class. This class also makes use of the basic reporting functionality already implemented in JPPanel,

however does not need to refine it in the way required by the ConstantsPanel class. Again duplication of the reporting functionality is avoided and better efficiency is achieved in this way.

The next three classes namely the “EnergyModellingSplitPane”,the “ManipulatedDataSplitPane” and the “RetrievedDataSplitPane” all inherit the JPPanel superclass. Their main focus is to display data grouped into three main regions for display. Firstly the energy modeling data calculated in the business logic, secondly the manipulated data also calculated in the business logic and lastly the retrieved data obtained directly from the sensors surrounding the combustion engine. Again the reporting logic is used and refined in a different way to the “ConstantsPanel” reports.

As can be seen all the Classes mentioned above perform similar tasks but in different ways. The way in which the objects have been designed allow for reuse of code without duplication as well as unique refinement of functionality. This results in improved efficiency and simplicity allowing for benefits in two key areas. Firstly it allows for ease of future development if extra functionality is required and secondly improves system performance.

ii. The Business Layer Classes

These are the classes that perform all the complex thermodynamic algorithms. The classes have been structured into “specialists”. Taking a real life example to describe what is meant by “specialist”, would be a Dermatologist. A dermatologist is only concerned with the skin and as a result knows everything there is to know about the skin. The business layer has specialists of its own, namely the:

(i) JPMathematics class
(ii) DataManipulator class
(iii) WeinbergManipulator class
(iv) GulderPerfectCombustionManipulator class

(v) HRCAEnergyManipulator class

- The JPMathematics class specializes in mathematical routines from interpolation to trigonemtric functions. If the CAS program requires two numbers to be multiplied together, the JPMathematics class will perform it. Its sole purpose is to act as the mathematician.

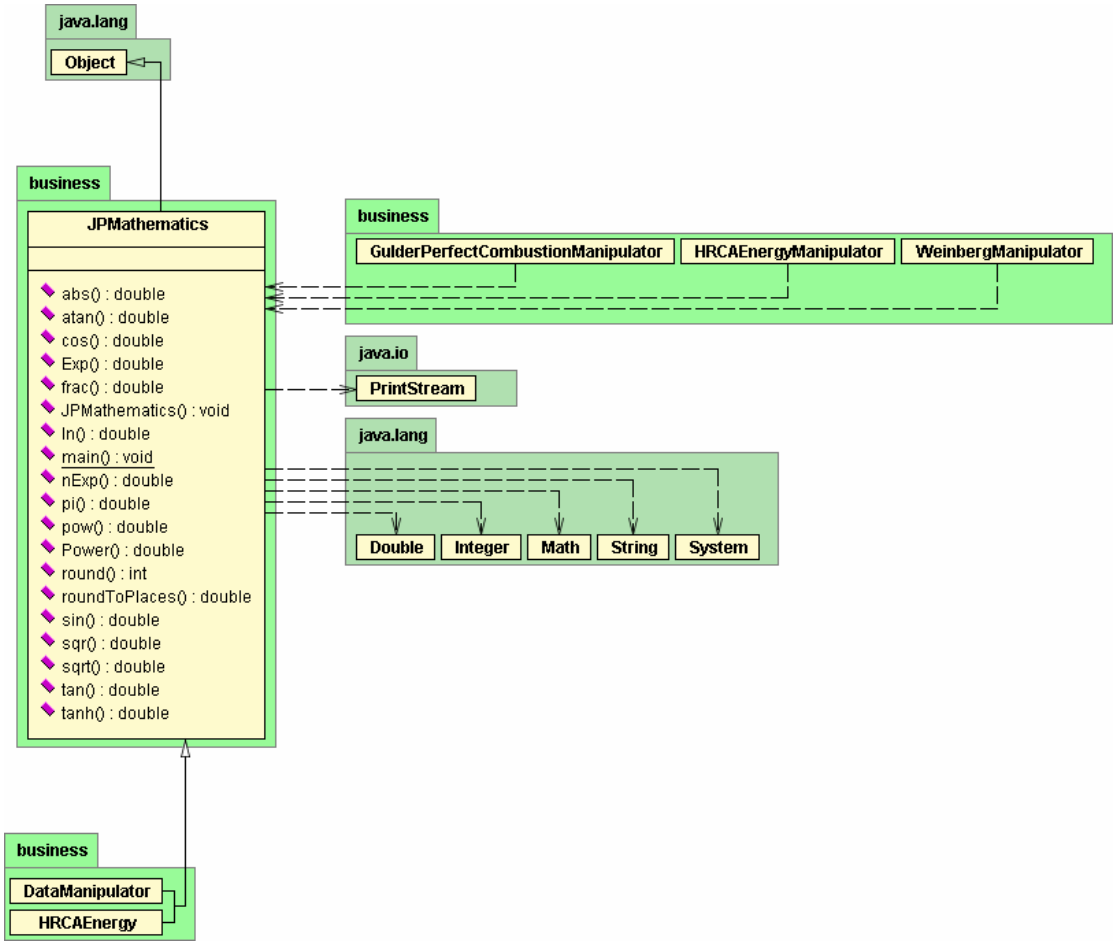


Figure 3.16: The JPMathematics Class Diagram

- The DataManipulator class is the general data specialist. It performs all the pressure and volume calculations, from Cylinder pressure calculations to Injector Lift calculations. If the program needs to perform any kind of analysis using pressure or volumes, it uses this “specialist”.

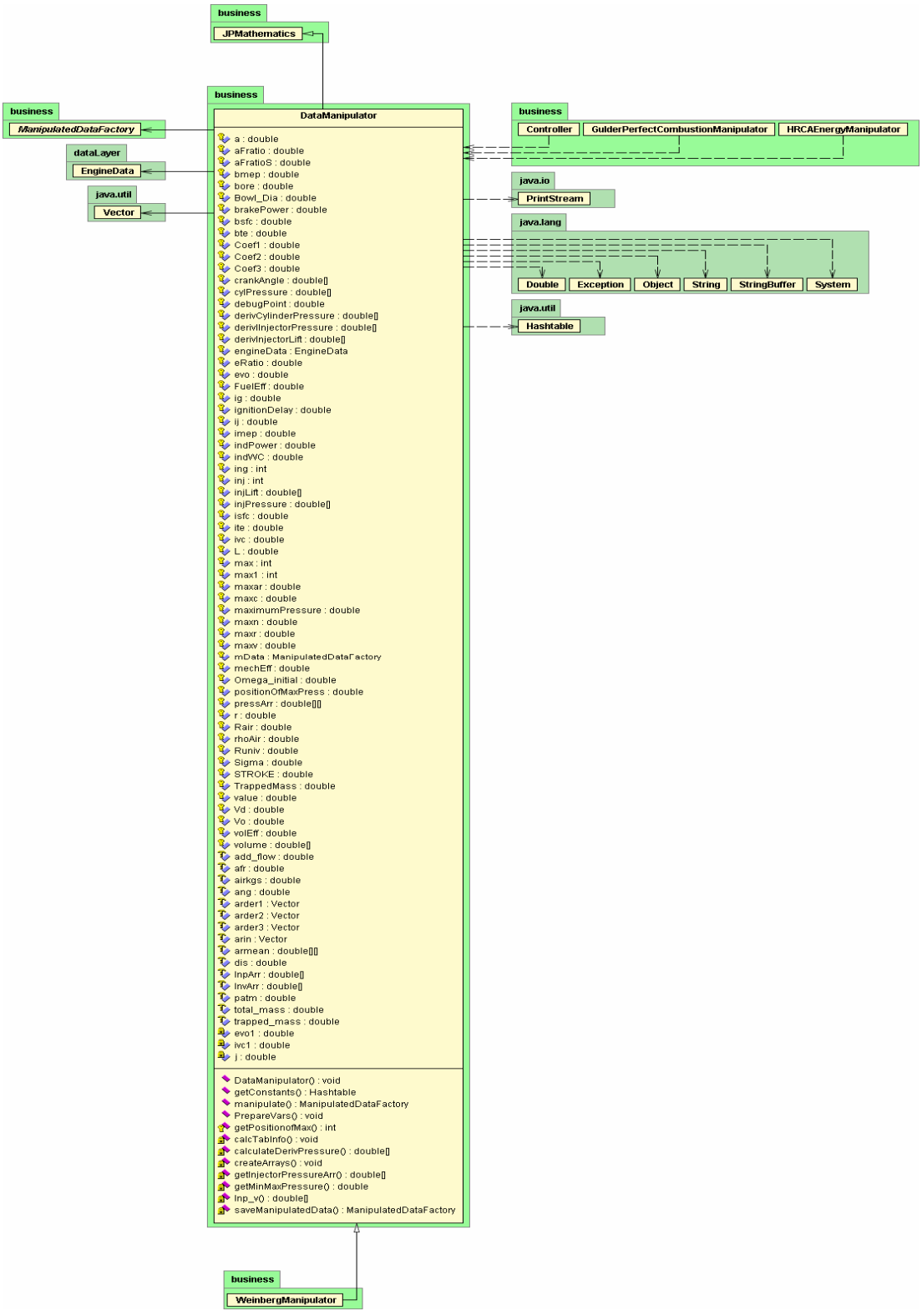


Figure 3.17: The DataManipulator Class Diagram

- The WeinbergManipulator class is the Weinberg Analysis specialist. Is sole purpose is to perform the Weinberg data modeling algorithms.

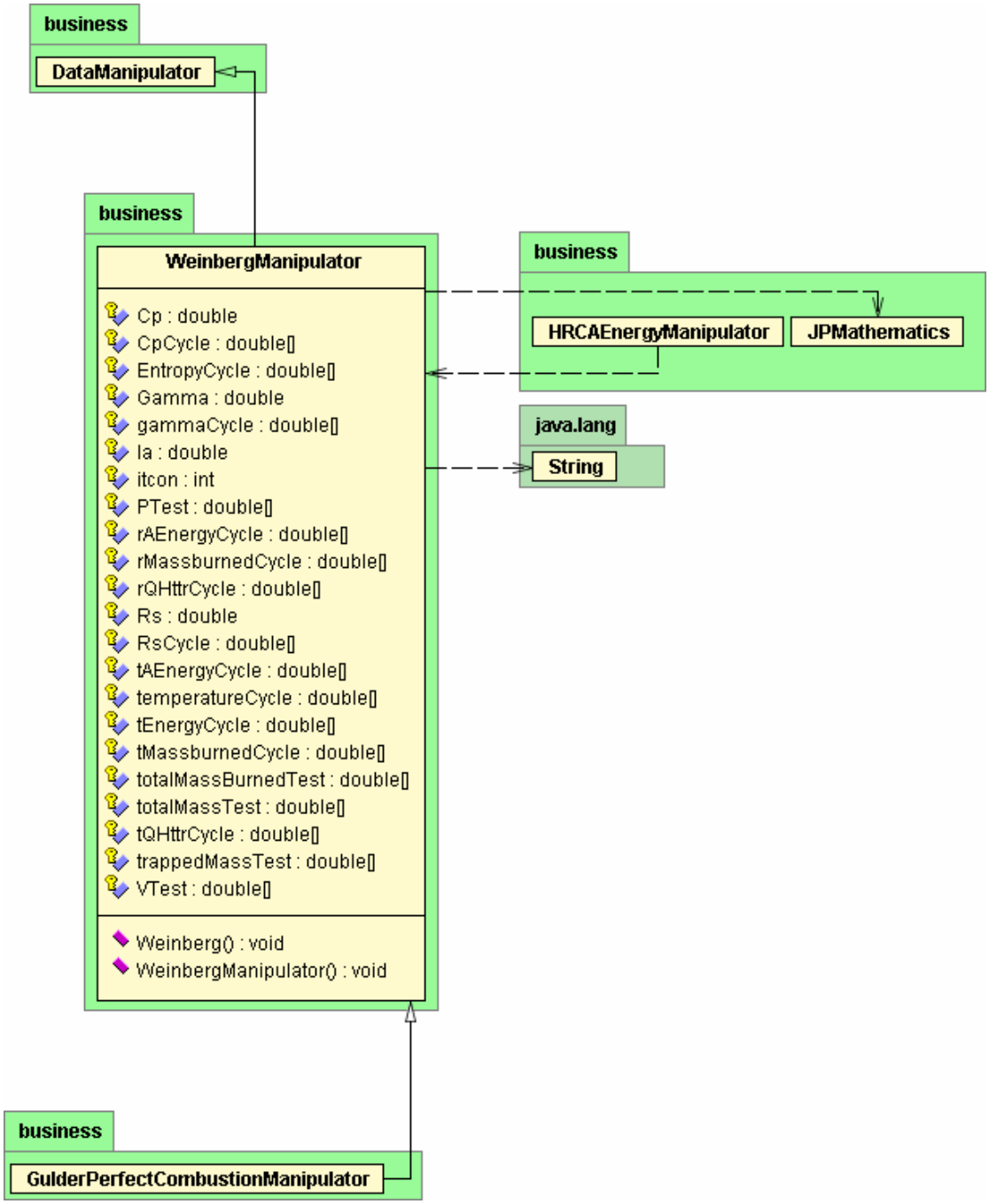


Figure 3.18: The WeinbergManipulator Class Diagram

- The GulderPerfectCombustionManipulator class is as the name implies, it specializes in the Gulder Cycle and perfect combustion algorithms.

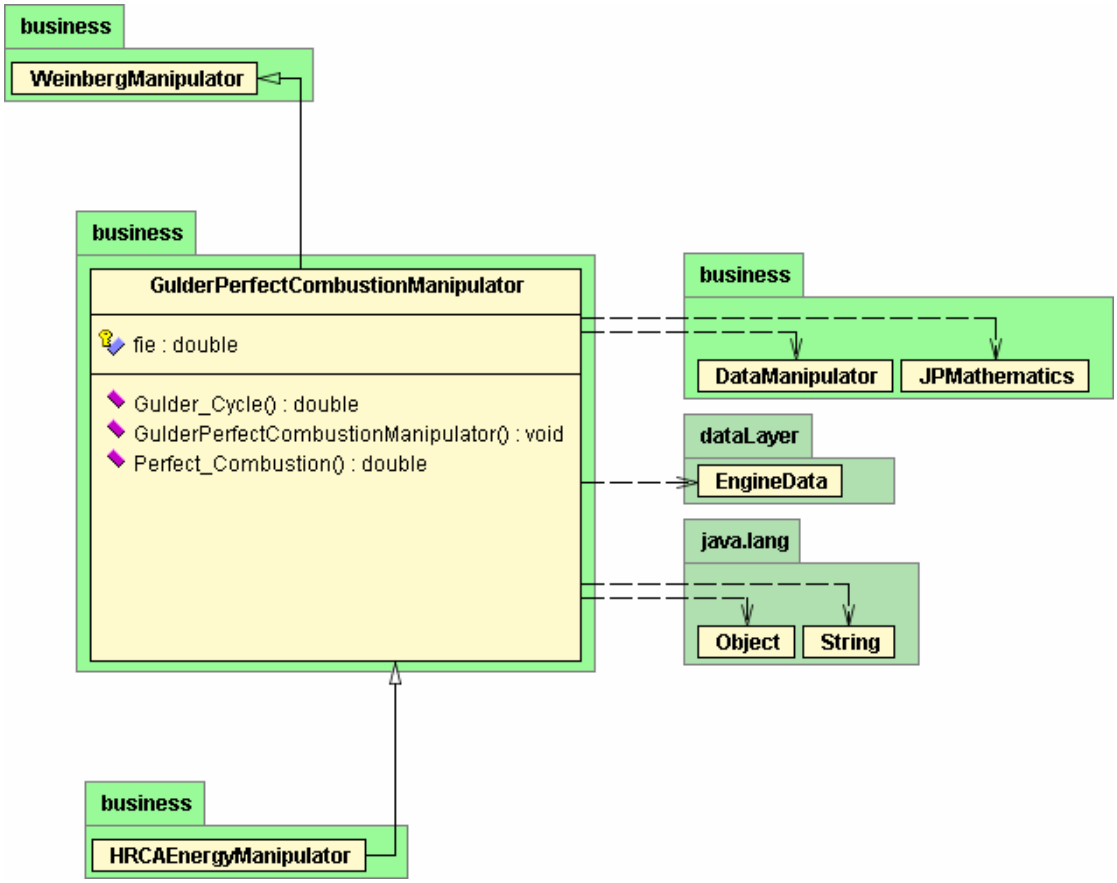


Figure 3.19: The GulderPerfectCombustionManipulator Class Diagram

- The last of the specialists is the HRCAEnergyManipulator. This class performs the First Law and Air standard cycle calculatons.

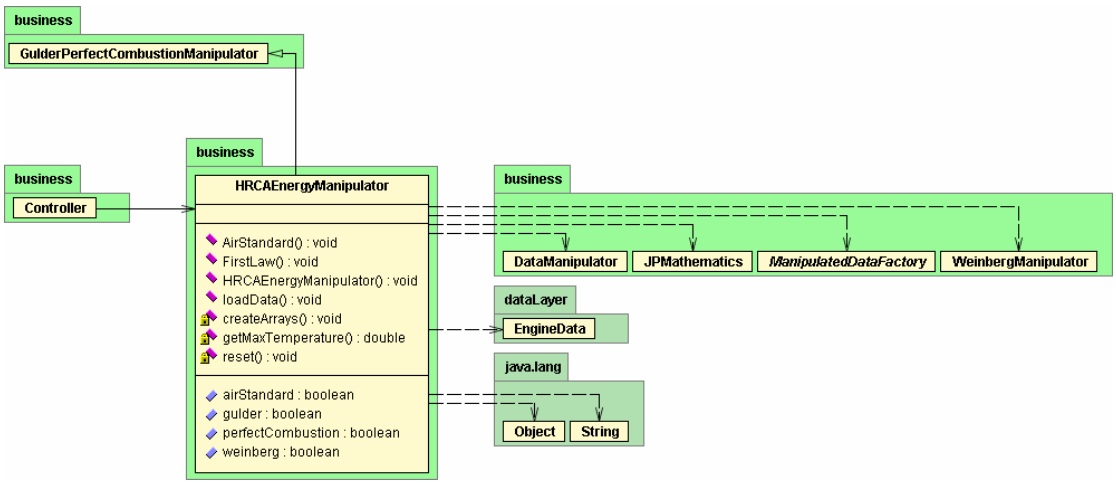


Figure 3.20: The HRCAEnergyManipulator Class Diagram

The power of object oriented programming now comes into play in the way these specialists interact with one another. Imagine a whole family of

academics from the great grandfather being the Mathematician straight down to the great grandson being the HRCA Energy specialist. Wouldn't it be great if the great grandson could inherit all the skills and knowledge of his predecessors. This is exactly the way the CAS software has been written. Figure 3.21 illustrates how this is done.

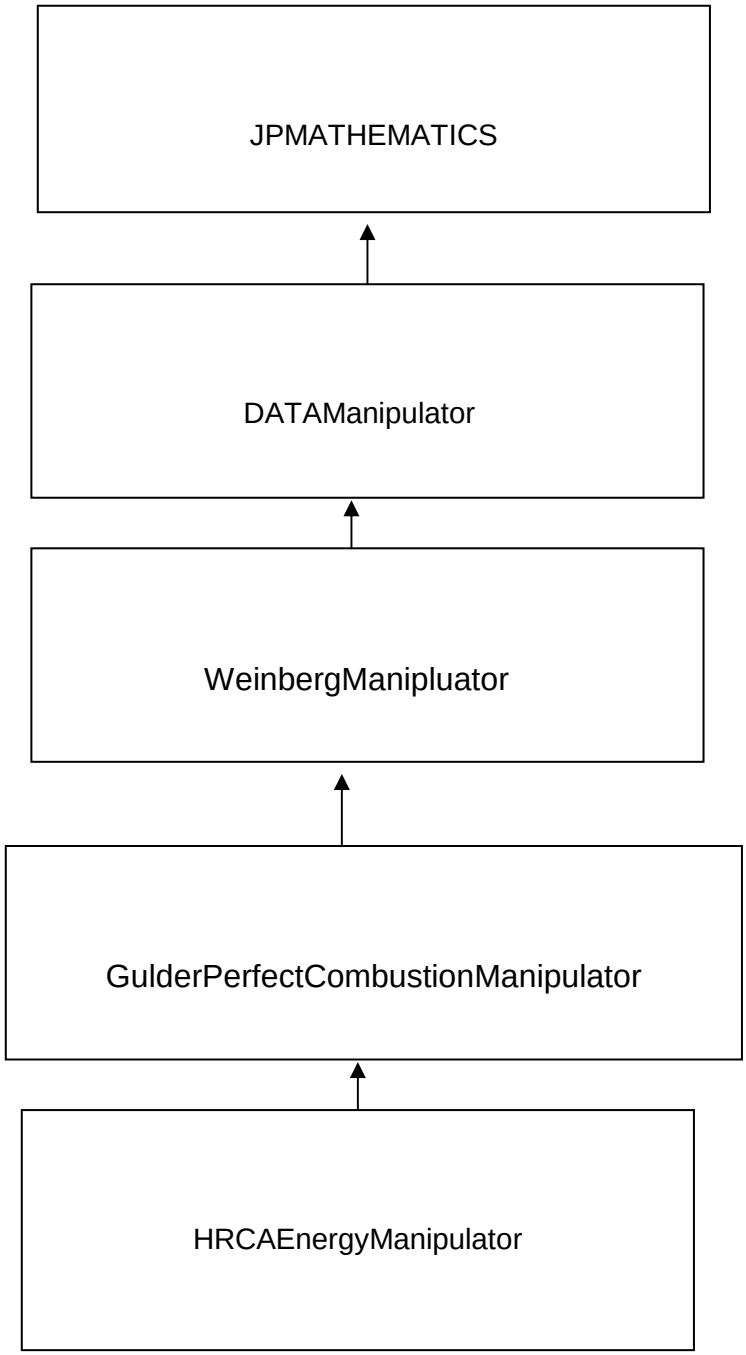


Figure 3.21: Business Layer Classes

The DataManipuator Class inherits all the functionality from the JPMathematics class. The WeinbergManipulator class inherits all the functionality of the DataManipulator class. Hence the WeinbergManipulator can perform all the functionality of the previous two classes as well as its own functionality. The HrcaEnergyManipulator inherits from all the classes above it hence creating the great grandson described earlier. The HrcaEnergyManipulator is the super "specialist". The power of this structure is that you keep all the analytics to their respective specialists however reference it from one point via the HrcaEnergyManipulator.

iii. The Data Layer Classes

The data layer can be split up into two classifications of classes, namely those which transfer data to be stored and those which actually store the data. The two most important data transfer classes in CAS are the DataExtractor and the DataStorer classes.

- The DataExtractor class is used to extract data from the sensors that monitor the engine and store it in the EngineData class.

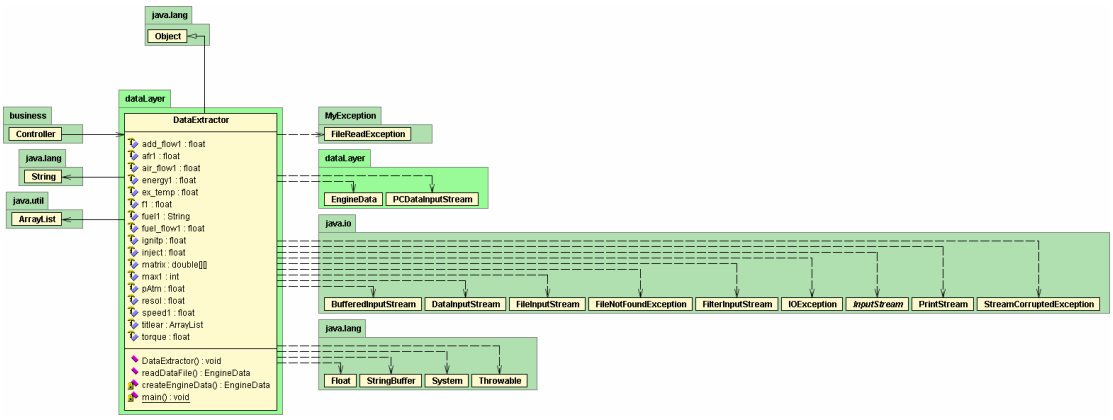


Figure 3.22: The DataExtractor Class Diagram

- The DataStorer class is used to transfer users of the system to and from the database during log in and new user creation. The data storer stores the user information in a Database class which in turn gets transferred to a Microsoft access database.

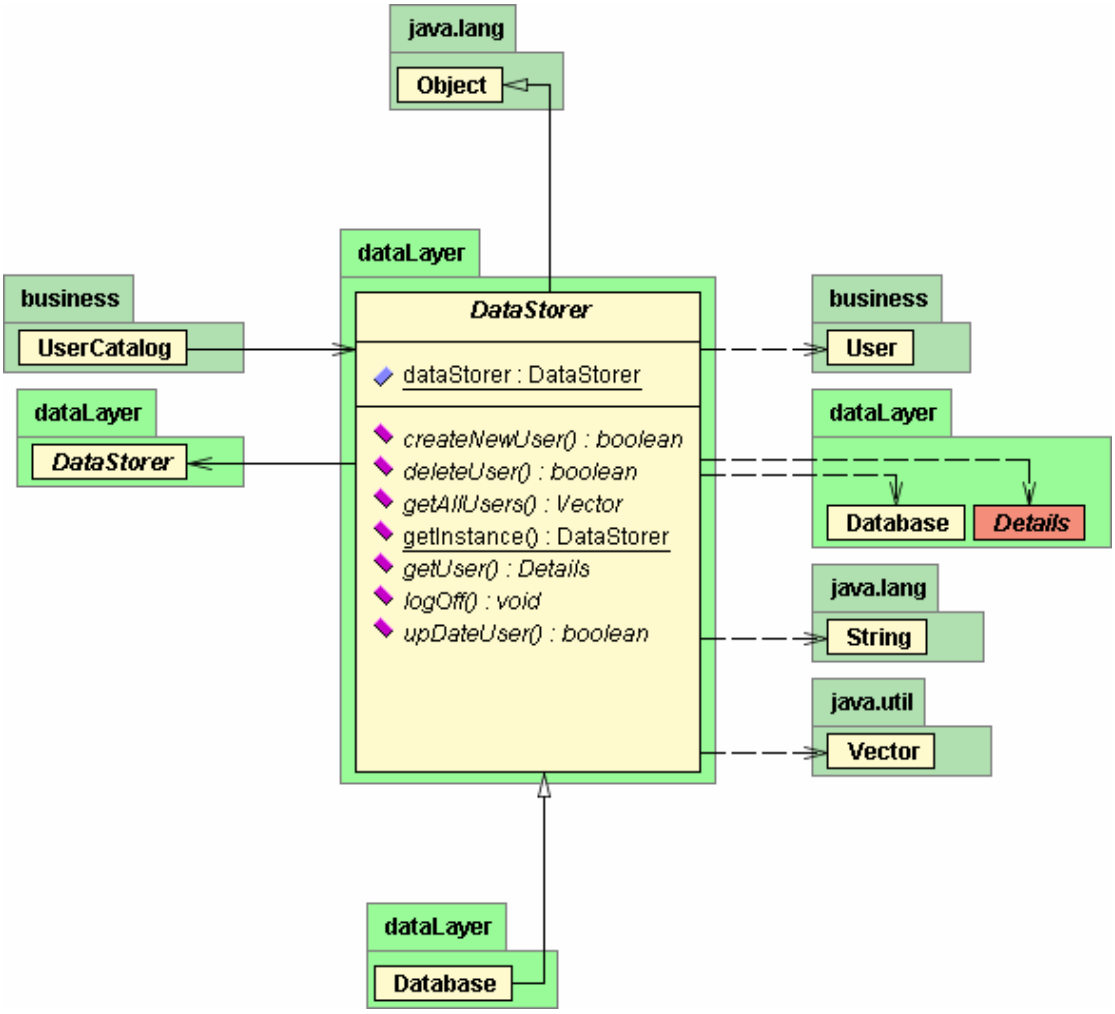


Figure 3.23: The DataStorer Class Diagram

The two most important classes used to store data in CAS are the EngineData and the UserDetails classes. These objects get passed around and used by many objects within the program. Essentially what they are, are a kind of container with information that can be easly accessed from. These classes can be compared to a briefcase carried around and opened when information is required.

- The EngineData class stores all the information obtained from the engine sensors and is transferred around the business logic. The classes in the business logic use it to obtain information to be used in the thermodynamic algorithms.

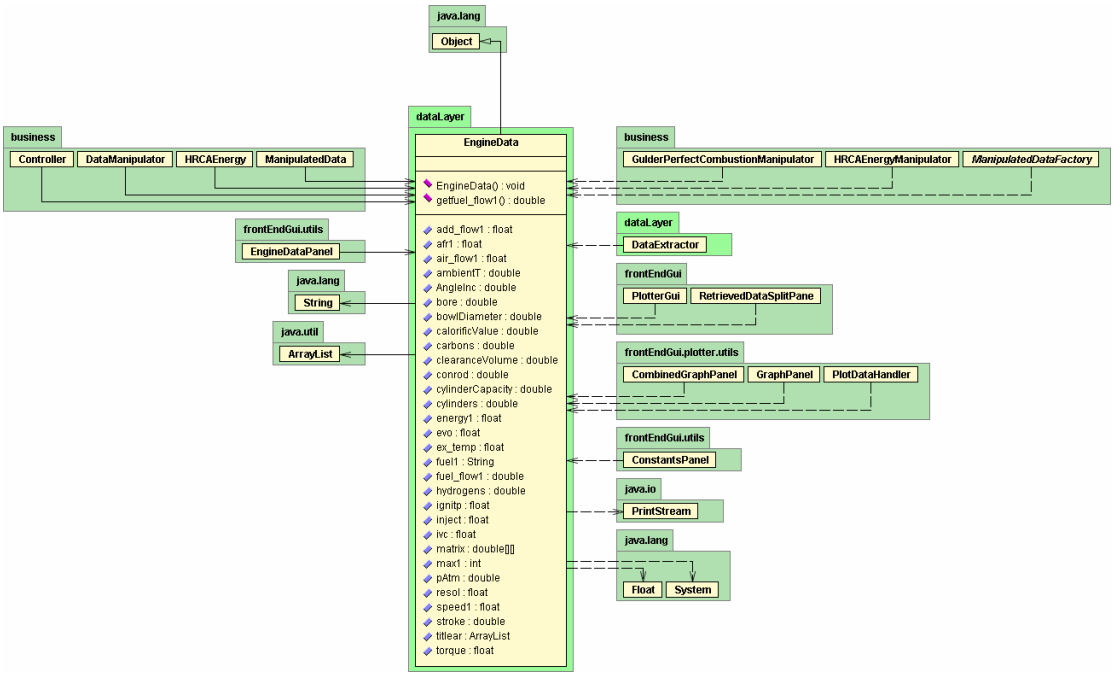


Figure 3.24: The EngineData Class Diagram

- The UserDetails class is used as a container for all the information about the current user logged in as well as all the other users which have been added to the system database. Whenever a user is added or edited this object is transferred around the business layer and altered accordingly. This object is also used by the Database object to obtain the information about the user to be stored to the database.

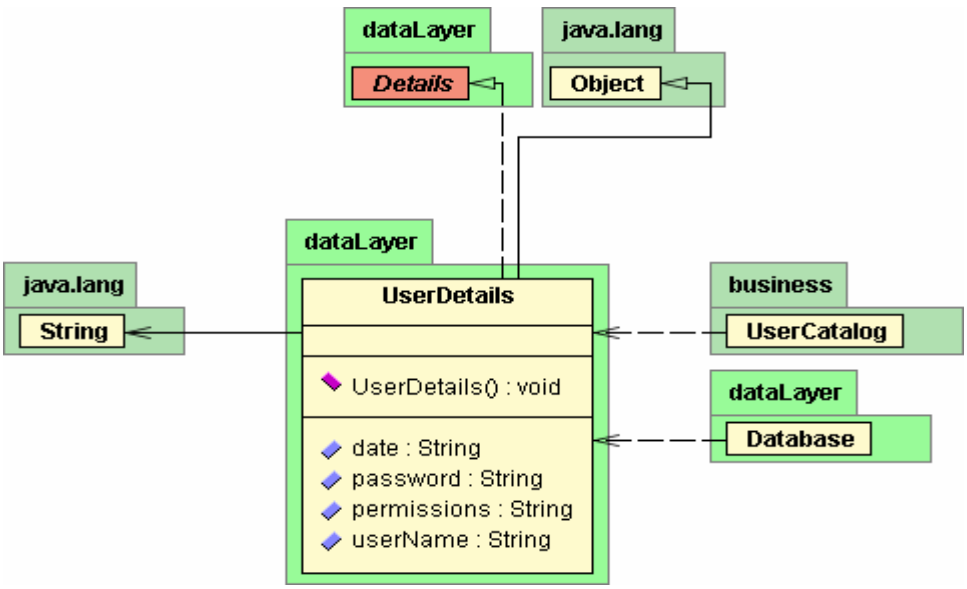


Figure 3.25: The UserDetails Class Diagram

4 EXPERIMENTAL EQUIPMENT

The engine testing facility is located in the Mechanical Engineering Laboratories inside the North-East Engineering building at the University of the Witwatersrand. The diesel engine as well as all additional equipment needed for performance testing is described in this section. The calibration procedure of the instruments as well as the calibration results can be found in Appendix A.

4.1 Test engine

The compression ignition engine used for testing was a water cooled *Lister Petter PH2W* engine. Typically, such an engine would be used in pumping or power generation applications. It is a naturally aspirated, two cylinder, four-stroke, direct injection diesel engine with a power rating of 12,2 kW at 2 000 rpm. Additional specifications are listed in the table below and the engine is shown in Figure 4.1.

Table 4.1: *Petter PH2W* engine specifications

Bore	87,74 mm
Stroke	110,00 mm
Continuous Power Rating at 2 000 rpm	12,2 kW
Displacement	1 330 cm^3
Compression Ratio	16,5 : 1



Figure 4.1: *Petter PH2W test* unit

4.2 Fuel system

The engine is to be run on diesel fuel. Each injector is supplied with its own pump, which runs directly off the engine. Additionally a dual rack connects the

two pumps to ensure uniform fuel supply to both cylinders. The injector and valve specifications are tabulated below.

Table 4.2: Injector and valve specifications

INJECTOR OPENING PRESSURE	
900 to 1 099 rpm	137 - 152 bar
1 100 to 2 000 rpm	197 - 217 bar
INJECTOR TIMING	
Up to 1 650 rpm	24° BTDC
1 651 to 2 000 rpm	28° BTDC
VALVE TIMING	
Inlet valve open	13,5° BTDC
Inlet valve close	38,5° ABDC
Exhaust valve open	38,5° BBDC
Exhaust valve close	13,5° ATDC

A tank was mounted approximately two meters above the pumps. Placing the tank above the pumps allows the fuel to be gravity fed into the injector pumps and removed the necessity of installing a fuel supply pump.

The fuel supply to a cylinder can be cut off instantaneously by means of an inline solenoid valve. Hence, a motoring cycle test can be performed, i.e. the fuel is cut from cylinder one while the other cylinder is left to fire and data is recorded from the starved cylinder. The data captured from two consecutive cycles, one firing and the other motoring could then be overlaid for further analysis. The scope of this research did not include running motoring tests.

The factory installed governor had been removed previously to enable any desired combination of speed and load settings to be tested, in the range between 1 100 to 2 000 rpm. The removal of the governor necessitated the introduction of a safety mechanism. This is provided by means of the above mentioned solenoid valve. As soon as the engine speed exceeds 2 100 rpm the safety trip mechanism cuts the fuel to the engine.

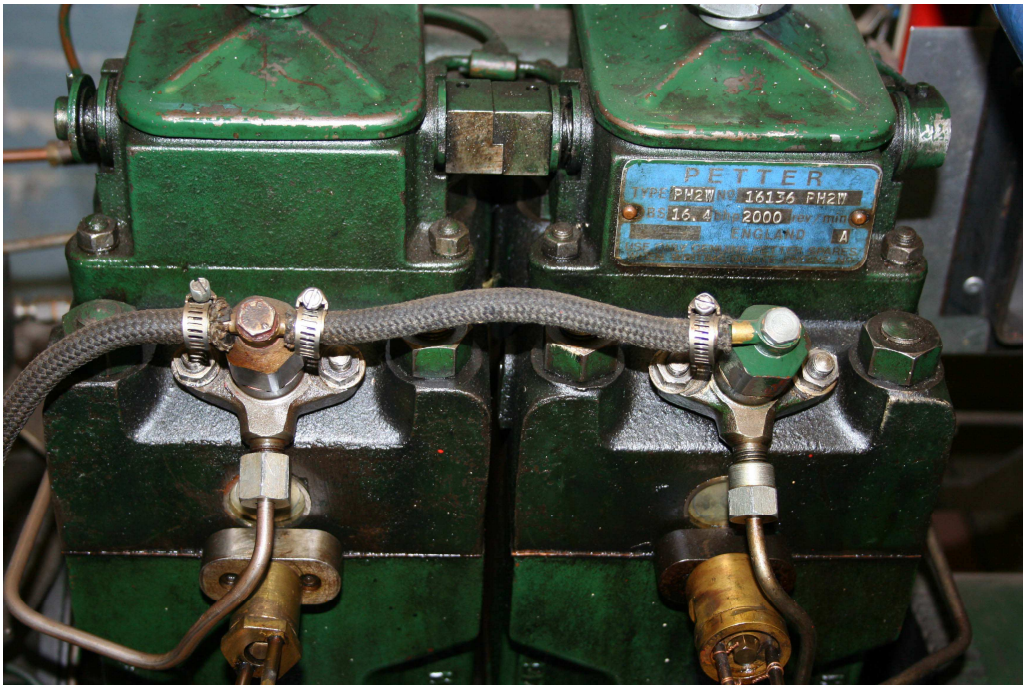


Figure 4.2: Detail of injector and pressure transducer configuration

4.3 Dynamometer

The engine was loaded by means of a water-cooled eddy current dynamometer coupled to the output shaft. The eddy-current dynamometer makes use of a lever system that induces a voltage in a load cell, which makes use of strain gauges mounted in a Wheatstone Bridge configuration.

4.4 Instrumentation

To be able to analyse the engine performance, a number of parameters had to be monitored and subsequently captured. The parameters examined can be divided into steady state and dynamic. A description of the instruments used to capture this data will be given followed by a discussion of the data acquisition system used to store, convert and analyse the raw data.

4.4.1 Steady state parameters

The steady state parameters and their setup are discussed briefly in this section. These parameters do not vary significantly as long as the engine speed and load are kept constant.

Temperatures: Due to the large temperature ranges to be measured K-Type thermocouples were used during testing. The following temperatures were gauged.

> Ambient temperature: A number of subsequent calculations require the exact ambient air temperature.

> Air inlet temperature: This reading corresponds to that of the ambient air temperature, except that the thermocouple was housed in the supply air duct.

> Cooling water temperature: Both cooling water inlet and outlet temperatures were measured.

Torque: A load transfer arm was fixed to the dynamometer housing, which induces a strain in four strain gauges arranged in a Wheatstone Bridge configuration. The voltage signal from the bridge was amplified before it was fed into the data acquisition system.

Fuel flowmeter: The fuel flow was measured by means of an analogue *Pierburg* fuel flowmeter, the output was amplified and then fed to the data acquisition system.

Atmospheric pressure: A barometer measured the ambient pressure. The signal sent by the pressure transducer was amplified before it was input into the data acquisition system.

Airflow: The airflow rate was calculated by monitoring the pressure drop across an orifice plate mounted in the inlet air duct. Pressure tappings downstream measure the pressure, which was read by a digital micromanometer in millimetres of water. This pressure drop was used to calculate the air flowrate using the calibration equation derived for the particular orifice plate being used.

Engine speed: A frequency to voltage converter was attached to the *AVL* crank angle marker, which determined engine speed.

4.4.2 Dynamic variables

A brief discussion of the measured dynamic variables is outlined in this section.

Cylinder pressure: Cylinder one was fitted with a *Kistler 6121A1* high-pressure piezoelectric pressure transducer. To prevent the transducer from overheating, it was housed in a water jacket, which was supplied continuously with cold water. The transducer output was first fed into a charge amplifier and then recorded by the data acquisition system. The captured data from this cylinder allows a cylinder pressure trace to be obtained.

Injector pressure: A pressure transducer was located in the fuel line between the fuel pump and injector one. The transducer output was fed into a *Kistler* charge amplifier and then recorded by the data acquisition system. This data was used to calculate the injection point during testing and plot the graph of Injector Pressure versus Crank Angle.

Degrees Crank Angle (°CA) and Top Dead Centre (TDC): The position of the crank was recorded using an optical crank angle encoder that generates a pulse every 0,2° crank angle. This signal was used to drive the external clock of the data acquisition system. A second pulse is generated at TDC. These two signals were recorded on two separate channels. See figure below.

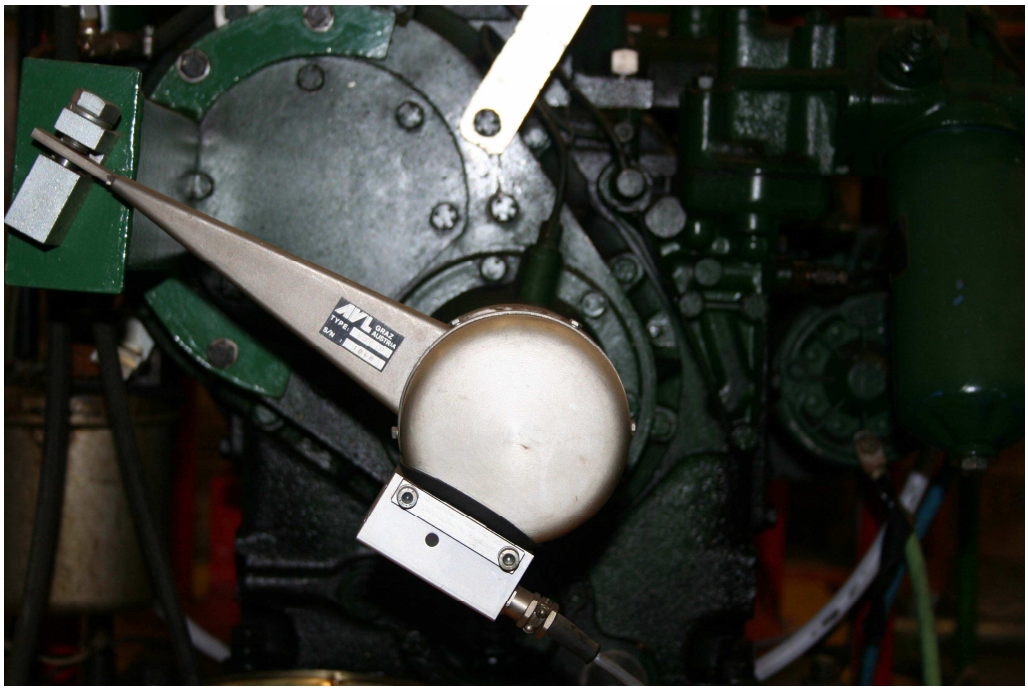


Figure 4.3: A Crank Angle Marker

4.5 Data acquisition system

The data acquisition system is divided into two sections, a hardware and a software part.

The *High Speed Acquisition System* allows one to capture large amounts of data at high speeds. The system provides for six dynamic channel inputs as well as the external clock and trigger. An Analogue-to-Digital card supports each dynamic channel. The six dynamic channels have a sampling rate of up to 1,25 MHz.

This is a higher than required sampling rate, as at a speed of 1 750 rpm and a pulse for every 0,2 degree crank angle a maximum of approximately 105 kHz is attained. The channel allocation is tabulated below.

Table 4.3: Dynamic channel allocation

Channel Number	Description
1	Trigger
2	Fuel Line/Injector Pressure
3	Cylinder Pressure
4	Not used
5	Degrees Crank Angle (°CA)
6	Top Dead Centre (TDC)

A separate analogue input unit is also connected to the rear panel by means of a RS232 cable. A total of sixteen steady state input slots are available on this unit. Channels 1 to 8 are BNC connections, while channel 9 to 16 are thermocouple connections with cold junction compensation. The steady state connections are tabulated below.

Table 4.4: Steady state channel allocation

Channel Number	Description	Units
2	Fuel Flow	g/s
3	Barometric pressure	bar
4	Airflow	mmH_2O
5	Speed	rpm
7	Load	Nm
9	Ambient Temperature	°C
10	Inlet Cat. Temperature	°C
11	Outlet Cat. Temperature	°C
12	Air Temperature	°C
13	Water Inlet Temperature	°C
14	Water Outlet Temperature	°C

A table with the steady state calibration values is listed in Appendix A. A schematic wiring diagram of both the dynamic and steady state channels can be found in Appendix B.

The steady state input voltages were converted by the system software to corresponding values in real time, that were hence displayed on the screen while testing took place. The real time display of the measured variables was used to determine if the engine had settled at the required operating condition.

Data is captured once triggered. This may be done by setting the required engine speed range in the software or by forcing the trigger manually. Channel one was used as the triggering channel. All other channels were ascribed as slaves to this channel and thus were triggered simultaneously.

The data from the dynamic channels could be viewed once the system was triggered. Plots of the dynamic channels versus Degree Crank Angle were displayed on the screen. This allowed for real time diagnostics to be performed. Once the test data had been deemed to be satisfactory it was stored and the next set of data could be captured.

4.6 Emission equipment

The engine emissions measured were NO_X, CO_2, *CO*, *THC* and O_2 as well as smoke concentration. Due to these different exhaust gases being analysed a number of different analysers had to be used. A brief description of the *Signal Gas Analyser*, Oxygen Meter and *Hartridge Smoke Meter* follow.

4.6.1 Signal Gas Analyser

The gas analysis system comprises of several units that are mounted in a common casing. The unit measures CO, CO_2, oxides of nitrogen (NO_X) and levels of unburned hydrocarbons (THC). The system comprises of five different components:

- *Signal Series 200 SM Gas Cooler and Dryer (Model 202):* The Cooler/Dryer unit is designed to remove water vapour from the wet gas stream.

- *Signal 7 000 M GFIR CO Analyser:* The analyser uses an

infrared filter correlation technique using gas-filled optical filters to determine the amount of CO present

. > *Signal 7 000 M GFIR* C0$_2$ *Analyser:* The CO_2 analyser also uses an infrared filter correlation technique using gas-filled optical filters to determine the amount of CO_2 present in the exhaust gases.

> *Signal 4 000 VM Heated Vacuum NO Analyser:* The NO_X analyser uses the principle of chemiluminescence's to detect the presence of both NO and NO_2.

> *Signal 3 000 Heated Total Hydrocarbon (THC) Analyser:* The THC analyser uses flame ionisation to detect volatile substances in the gas stream.

This equipment requires precise start-up, calibration and shutdown procedures to be followed for correct operating results. A computer with customised software was connected to the analyser unit.

The operating procedures for the gas analyser as well as a user manual to capture the emission data can be found in Appendix C.



Figure 4.4: Emission analyser unit

4.7 Oxygen Meter

A *Servomex Oxygen Analyser*, type OA 250, measures levels of oxygen in the exhaust emissions. The emissions are tapped off and are fed through a filter to remove particulates and then passed through copper sulphate crystals to purge the emissions of excess moisture before being fed into the analyser. The unit displays the percentage of oxygen present in the exhaust gas.

4.8 Hartridge Smoke Meter

A Hartridge Smoke Meter MK3 measures the exhaust smoke density. This unit works on a comparative basis by comparing the opacity of the smoke to a clean air sample. The opacity is determined by passing the emissions over a photoelectric cell, which measures the density of the gas in Hartridge Smoke Units (HSU).

4.9 Software

The additional software programs used to analyse the data are discussed briefly below.

4.9.1 Conversion program

The data acquisition system stores the captured data as a *.dat* file. These .dat files are then used by the software developed for this research project for data analysis . The *Borland Pascal* conversion program *(Conver)* converts this information for the data analysis package (CAS – Combustion Analysis Software*)* to perform various routines. *CAS* has dynamic link library (dll) to the *conver* program and is kicked off behind the scenes without the user being aware that they are using two completely separate programs written in two different computer languages. CAS then performs the thermodynamic analysis on the converted data and displays the data numerically as well as graphically. Various versions of *Conver* exist for the different fuels used during testing. All dynamic as well as steady state variables are converted and stored in a new *.raw* file. Some preliminary calculations are also done, such as the calculation of the fuel injection point, equivalence ratio and air/fuel ratio.

4.9.2 Combustion Analysis Package (CAS)

CAS is the software package developed for this research project. General thermodynamic analysis and energy release analysis are performed in *CAS*. The program is split into Five main sections. The five sections are the following:

a. General Analysis. This sections has the following plots.

> Cylinder Pressure
> Injector Pressure
> Ln (p)/p1
> Ln (v)/v1
> Derivative of Injector Pressure
> Derivative of Cylinder Pressure

All these variables and the variables in the next four sections can be plotted against either Crank Angle, Temperature or lnV/V1

b. Property Cycles analysis. This section has the following plots.

> Gamma
> Rs
> Cp
> Temperature
> Total Energy
> Entropy

c. Apparent Energy analysis. This section has the following plots.

> Cumulative Apparent energy
> Rate of Apparent Energy

d. Heat Transfer analysis. This section has the following plots.

- Cumulative Heat Transfer
- Rate of Heat Transfer

e. Mass Burned analysis. This section has the following plots.

- Cumulative Mass Burned
- Rate of Mass Burned

The program automatically displays injection point, ignition point, speed, load, maximum injection pressure and TDC. CAS has very powerful reporting and memory management tools. This is described in the user Manual in Appendix C.

5 EXPERIMENTAL PROCEDURE

All tests performed followed the procedure outlined below to ensure experimental repeatability and compatibility. However, before any testing could commence the measuring systems to be used had to be calibrated and a number of preliminary tests were run in order to ensure proper functioning of the engine, auxiliary equipment and controlling equipment. The equipment that required calibration included the eddy current dynamometer, the fuel meter and orifice plate, oxygen meter, tachometer and the thermocouples used to measure air, water as well as exhaust gas temperatures. The orifice plate and the *AVL* injector pressure transducer had been calibrated previously and thus were not calibrated before these tests.

5.1 Calibration of instrumentation

The instrumentation was calibrated before testing to obtain the relevant calibration equations to be used in the data acquisition system. The detailed calibration procedures and results are given in Appendix A.

A regression analysis was performed on the calibration data points to obtain the correlation of the data to that of a first order polynomial fitted to these points. It was noted that the lowest regression coefficient of determination was determined to be 0,9968, which indicated that the graphs followed a near perfectly linear trend as well as fitting tightly to this line. Thus, the calibration equations obtained could be used with a high degree of certainty.

5.2 Testing procedure

Once calibration of the instruments was completed, a number of preliminary tests were conducted to determine that all instruments and software were functioning as intended.

The research conducted was segmented into a distinct direction namely developing Combustion Analysis Software to analyse the engine performance for diesel fuel. The data obtained was recorded with the purpose of comparing general-purpose performance parameters for diesel fuels.

The testing procedure is based on running the engine at a constant speed and taking tests at varying loads. The load is controlled by an eddy current dynamometer. Load increments of approximately 5 Nm were chosen and the tests were started from 5 Nm and the load was increased to the maximum load condition per speed. Three testing speeds were chosen namely 1 350, 1 550 and 1 750 rpm.

The following procedure was developed by previous researchers at the School and was followed for each set of tests:

> Switch on the emission analyser unit at least three-quarters of an hour before testing is to be commenced, as the analyser unit needs to reach the correct operating temperatures. Once the unit has reached the required temperature, follow the calibration procedure outlined in Appendix C.

> All other instruments need to be switched on well prior to commencement of testing. This was done in order to allow all electronic components to reach steady state operating conditions.

> The computers needed to be switched on and the relevant test software containing the correct calibration constants opened. Follow the set-up procedure given in Appendix C for each program to ensure correct data capture.

> The engine was warmed up on diesel fuel, by allowing it to run for a couple of minutes at a low load. Additionally during warm up all instruments were checked to see if they were measuring correctly.

> Connect the *Oxygen Servomex Analyser* to the copper sulphate crystal filter.

> Once the engine had reached operating temperature it was brought up to the selected testing speed. At the testing speed emissions were observed and once they had stabilised, readings were recorded every second for a 50 second period. A second shorter test of thirty seconds was then captured to verify as a backup and to assure that the good data had been taken.

> The cylinder pressure was monitored continuously. The transducer is prone to clogging and hence all recorded data with an incorrect pressure reading was ignored, as it was meaningless. Once it was noticed that the pressure trace reduced in magnitude the tests were stopped and the transducer cleaned.

> Once the desired speed had been reached, the data analysis system triggered the capture of data. The program gives the user the options of accept or reject the captured test. Hence, after evaluating the worth of the displayed numerical data and graphs the user could save or reject the test. The test data is written to the predefined directory. At every speed, at least four readings were taken for each load setting.

> The data acquisition program records data such as fuel flow, airflow, various temperatures and pressures.

> As a backup, all other instrument readings were recorded manually.

> The same procedure was followed for all tests conducted.

> Once testing was completed, the engine is shut down and the purge and shutdown procedure for the emission equipment commenced. For more detail on these procedures, see Appendix C.

> The copper sulphate crystals were dried and the *Signal Gas Analyser* filters were cleaned.

> The recorded data was subsequently analysed.

6. Discussion

This chapter uses the newly developed software to analyse the characteristics of diesel fuelling.

Diesel tests were performed at increments of 200 rpm starting at 1350 rpm and ending at 1750 rpm. The load was increased by approximately 5 Nm up to full load for all speeds.

The newly developed software captures 9 consecutive engine cycles for a single test. One of these cycles can be selected for analyses or all of them can be combined as a mean value for the test. The software can load 10 of these kinds of tests into memory to be compared against each other. The software can produce reports and graphic data on the performance and energy release of the fuel.

The engine test selected for the discussion was a test done at a load of 55 Nm and a speed of 1550 rpm. Other tests were also used to compare differing loads and speeds. This chapter discusses the results obtained using the new software developed for this research project.

6.1 Cylinder Pressure

Cylinder pressure traces form an effective way to analyse the combustion process in an engine. It indicates important phases in an engine's combustion cycle, namely pressure rise, injection point, vapourisation dips and ignition points.

Pressure rise translates into work produced by an engine. This pressure rise is an indicator of the rate of energy release by the combustion fuel within the combustion chamber. This rate of energy release has a direct influence on the power produced as well as the efficiency of the engine. The peak pressure is influenced by a number of factors including compression ratio, load, volumetric efficiency, fuel heating value and fuel quality. [1]

The graph in figure 6.1 shows the pressure within the cylinder as a function of crank angle (CA) in degrees. The process of one complete combustion process will be described in four stages. The first stage illustrates a rise in cylinder pressure due to the commencement of cylinder compression. This cylinder compression is as a result of the piston "upward" motion resulting in the cylinder contents being compressed.

The second stage illustrated by the letter "J" on the graph, indicates the injection point. At this point, fuel is injected into the cylinder. There is a slight decrease in the slope of the graph as a result of the vaporisation of some of the injected fuel. The period between the injection point and the following ignition point, is known as the ignition delay. During the ignition delay, the fuel has mixed with air.

The third stage, known as the rapid combustion phase, occurs when the fuel is ignited. This point is indicated by the letter "G" on the graph. The slope discontinuity then ends as the fuel is combusted causing a sharp increase in the gradient of the graph as the maximum pressure is reached just after top dead centre (TDC). This sharp pressure rise is caused by the combustion of the fuel. Maximum efficiency occurs when the pressure rise is as close as possible to

TDC. In this test, work was maximised with a minimum amount of negative work. If the steep gradient and maximum pressure occur before TDC, a large amount of negative work is done by the engine. In this graph, the location of the ignition point and the completion of combustion with respect to the CA, indicate near optimal combustion timing.

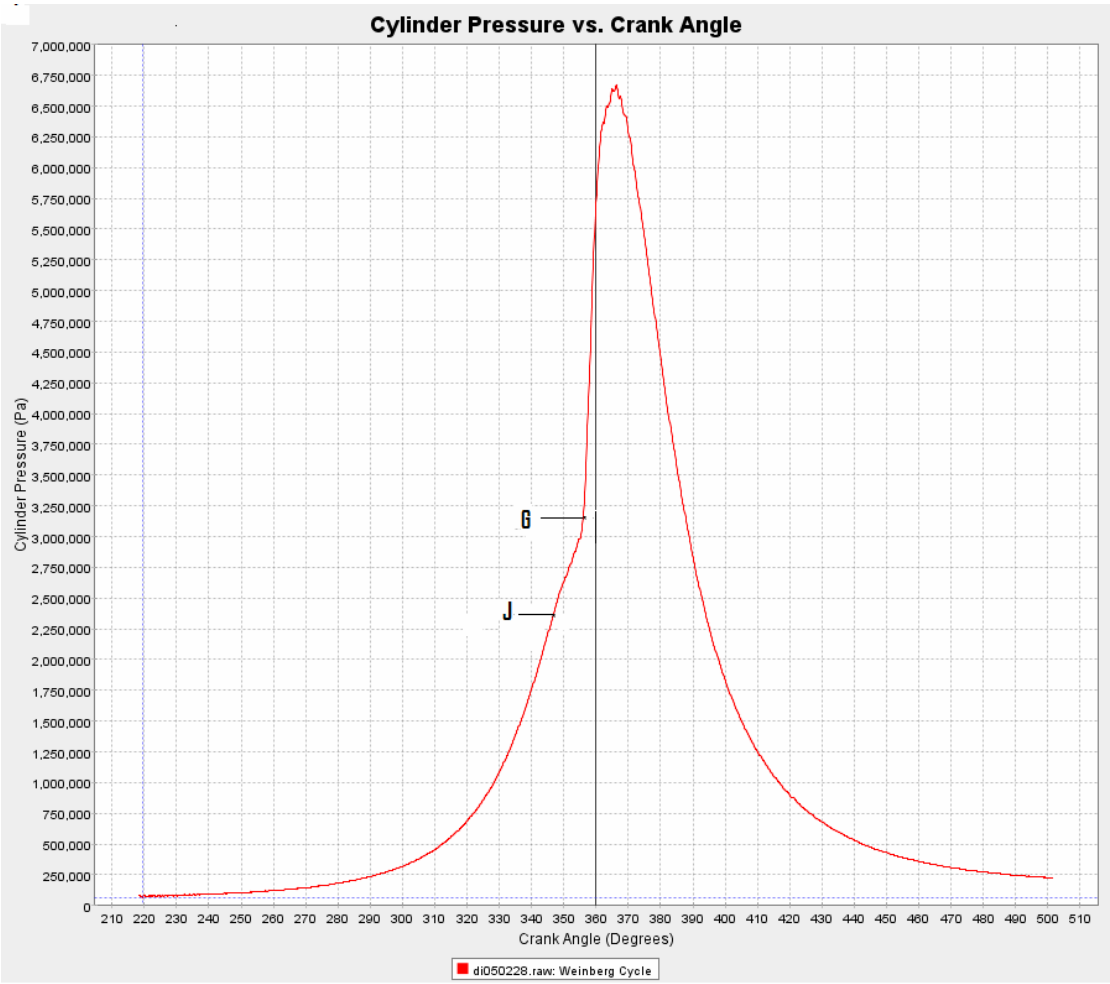


Figure 6.1: Cylinder Pressure vs. Crank Angle for a load of 55 NM.

The transducer is connected to the combustion chamber by means of a narrow passage. This results in resonance in the passage as shown at maximum pressure.

The fourth phase is the expansion phase. The volume within the cylinder increases and the pressure drops gradually to EVO, where the pressure is slightly greater than at the start of the cycle. During this phase, the rate of pressure increase due to combustion is less than the rate of pressure decrease due to the piston returning to bottom dead centre (BDC).

6.1.2 The Effects of Increased Load

The graph below (Figure 6.2) corresponds to two tests. The first (the red line, here on referred to as Line A) is for a load of 7.2 Nm. and the second (the green line, here on referred to as line B) is for a load of 55 Nm. Both tests were performed with engine speeds of 1550 rpm.

As can be seen, an increase in load results in an increase in maximum cylinder pressure. This is to be expected as an increased load requires more power to maintain a constant speed. The ignition point on Line A is at 357.9 °CA and on line B it is at 355.1 °CA, hence the higher the load the shorter the ignition delay. This is due to the fact that at higher loads there are higher temperatures within the cylinder thus resulting in the ignition point being reached sooner.

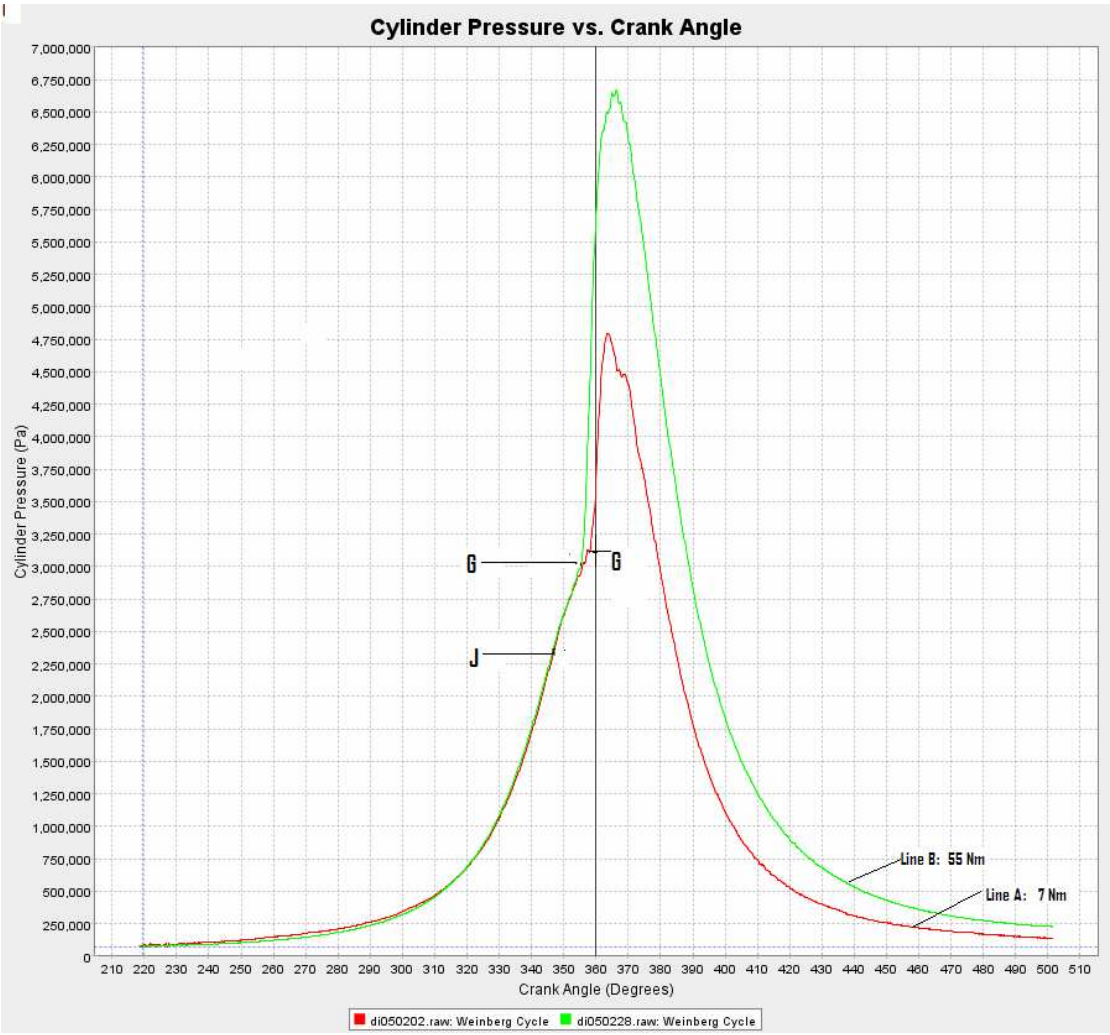


Figure 6.2: Cylinder Pressure vs. Crank Angle for Differing Loads

6.1.3` The Effects of Increased Speed

To analyse the effects of an increase in engine speed, two tests were selected. In figure 6.3, the red line represents an engine speed of 1356 rpm and the green line represents an engine speed of 1554 rpm, both with a load of 23 Nm.

As can be seen the higher the engine speed the lower the maximum pressure. It is also noted that the position of maximum pressure occurs slightly further away from TDC with higher engine speeds. Once TDC has been passed, the expansion stroke commences reducing the pressure exerted on the entrapped gas by the piston, although combustion still takes place. On the other hand, the

rate of pressure increase, due to combustion, is less than the rate of pressure decrease due to the piston returning to BDC, thus decreasing the maximum pressure obtained with increasing speed.

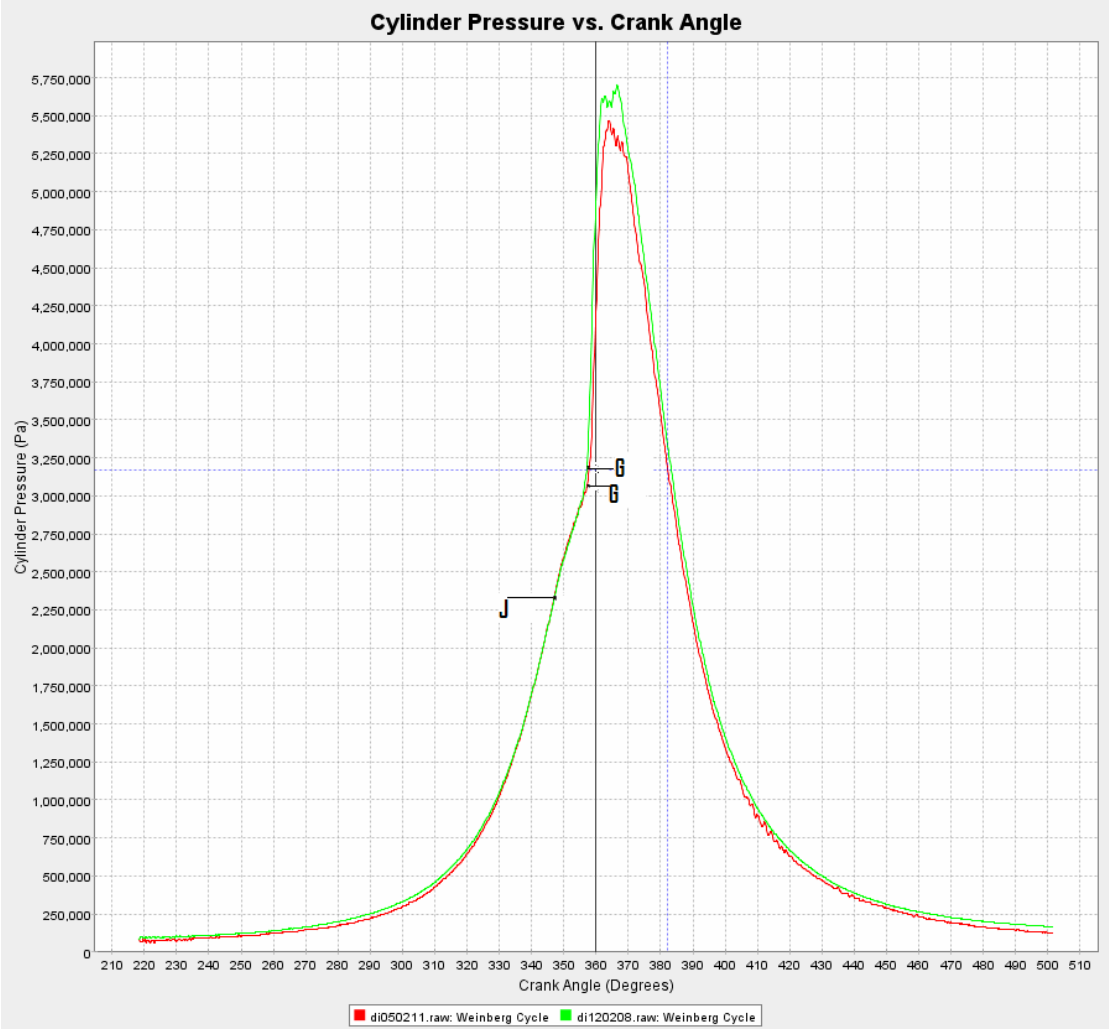


Figure 6.3: Cylinder Pressure vs. Crank Angle for Differing Speeds

6.2 Injector Pressure

The injection pressure trace, shown below, is a typical trace of an injection cycle. At the start of injection, a steep pressure rise can be seen, peaking at a maximum pressure of 280 bar. After the injection point “J”, the residual pressure rapidly dissipates. The pressure dissipates because the fuel has already been injected hence resulting in the pressure subsiding.

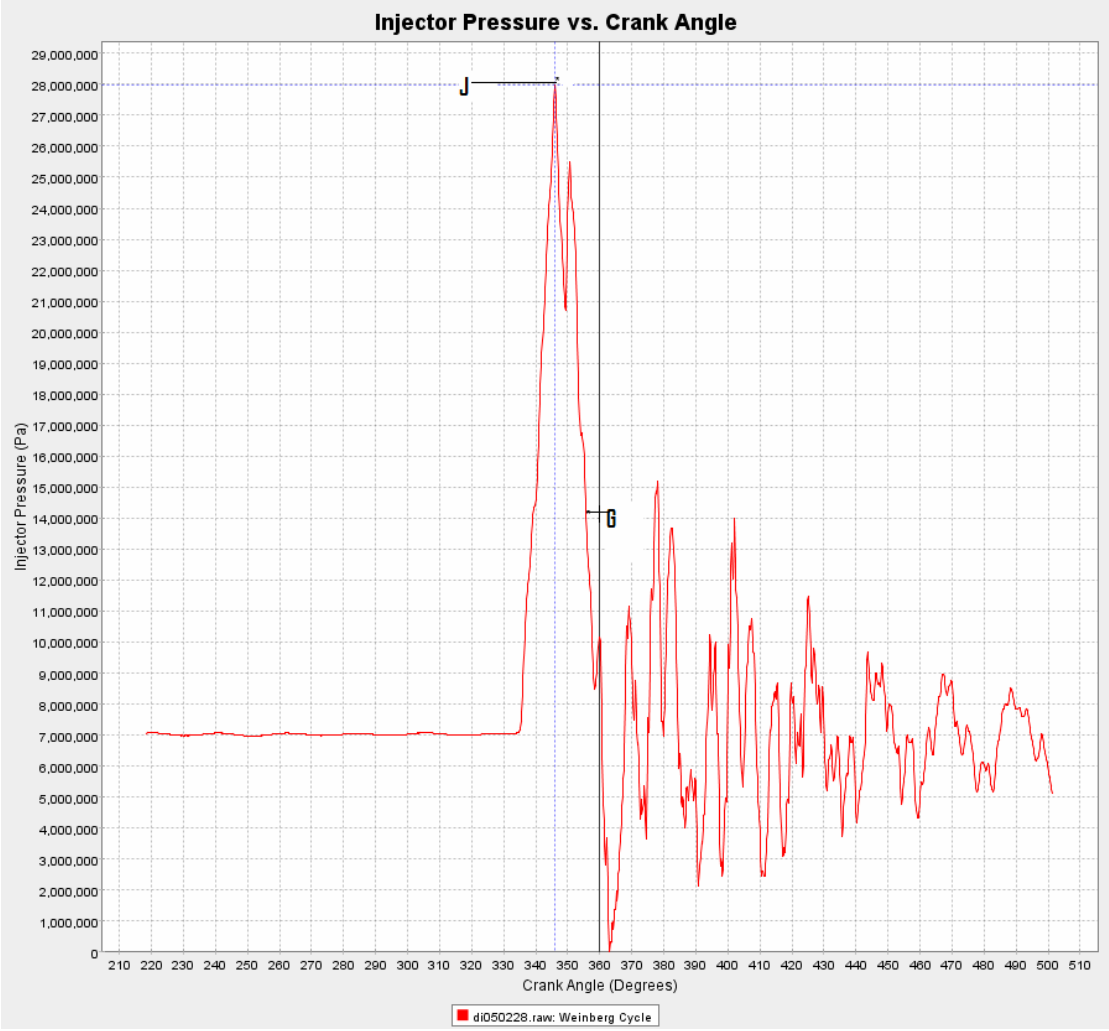


Figure 6.4: Injector Pressure vs. Crank Angle for a load of 55 Nm.

6.2.1 The Effects of Increased Load

The overall pressure within a cylinder with a higher load is greater. As mentioned before, an increased load requires a greater performance to maintain a constant speed. Therefore the initial pressure (shown on the graph below) is higher as a result. This leads to the conclusion that the pressure trace for differing loads is almost identical, the only difference is that a higher load results in a vertical shift as a result of a higher initial pressure.

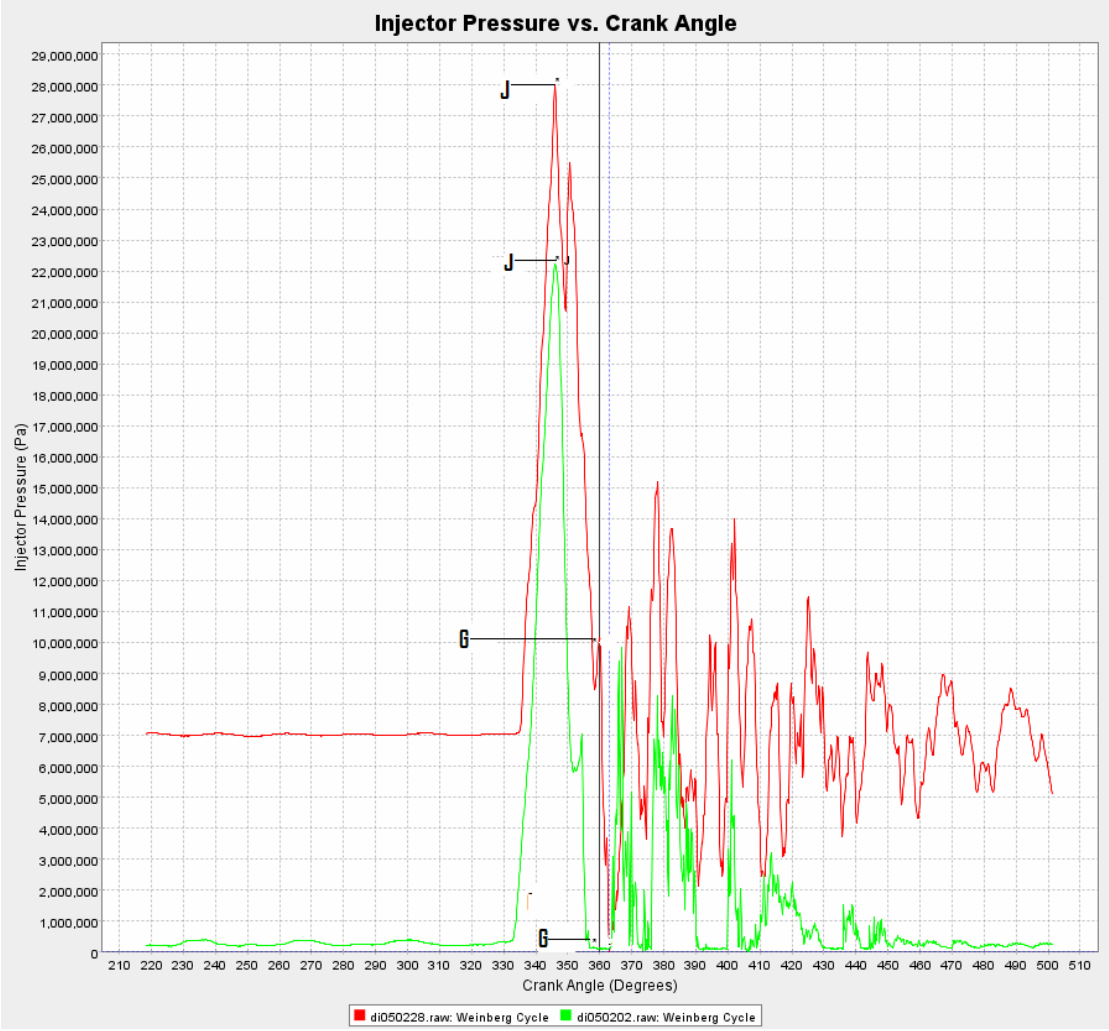


Figure 6.5: Injector Pressure vs. Crank Angle for a load of 55 Nm and 7 Nm at an Engine Speed of 1550 rpm.

6.3 Cylinder Temperature

The temperature versus CA traces form a similar shape to the cylinder pressure traces. This is to be expected as temperature is directly proportional to pressure. [8]

Upon inspection of the graph below, there is a rise in temperature as the compression stroke commences. At injection point there is a discontinuity in the gradient with a flatter slope. This indicates a decrease in the rate of the temperature rise, due to the vaporisation of injected fuel.

The slope gradient steepens considerably after the fuel ignition point, as a result of the combustion of the fuel. The maximum temperature occurs within an average of 5 ºCA degrees after the point of maximum pressure.

The expansion stroke sees a drop in temperature as the pressure decreases.

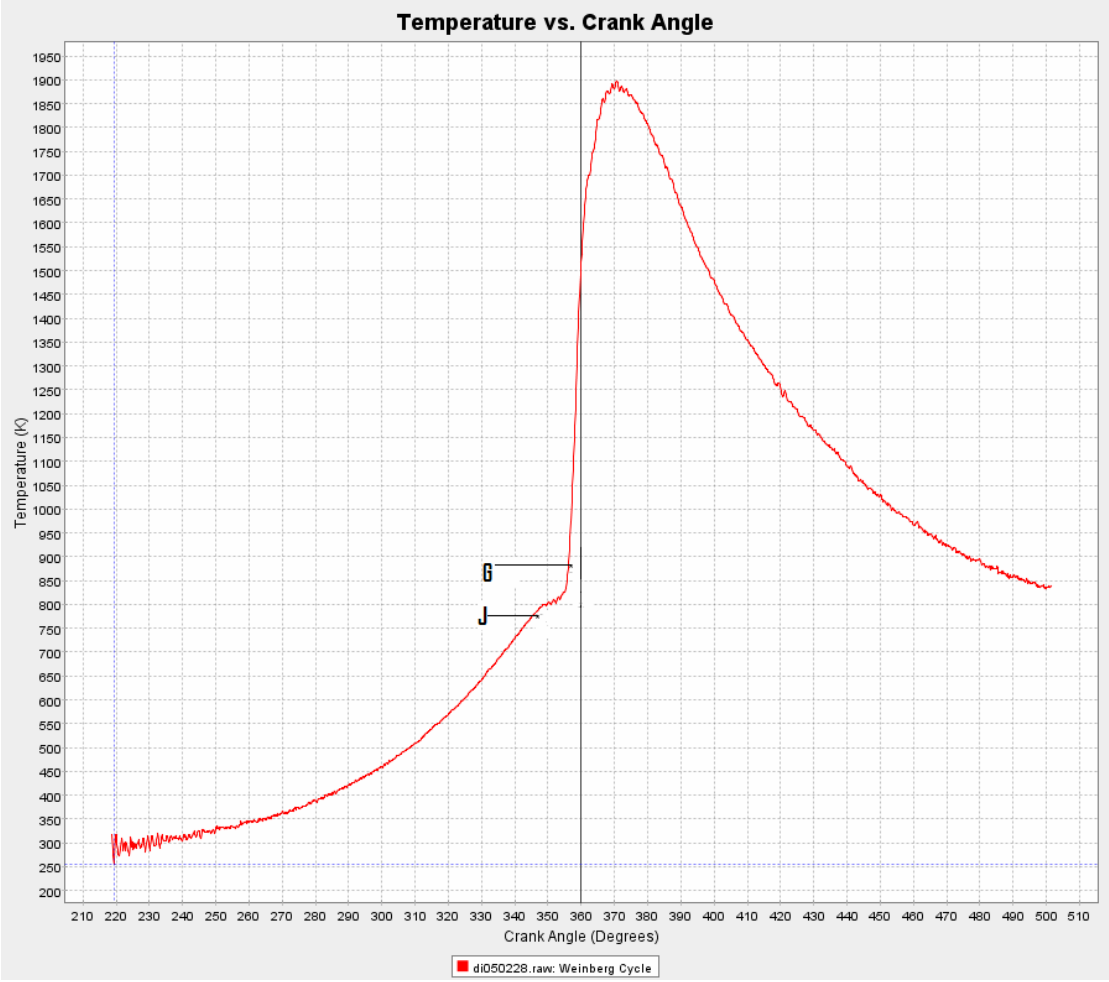


Figure 6.6: Cylinder Temperature vs. Crank Angle for a load of 55 Nm at an Engine Speed of 1550 rpm

6.3.1 The Effects of Increased Load

At higher loads, more energy is released to maintain equivalent speeds. As a result a higher maximum temperature is reached with higher loads.

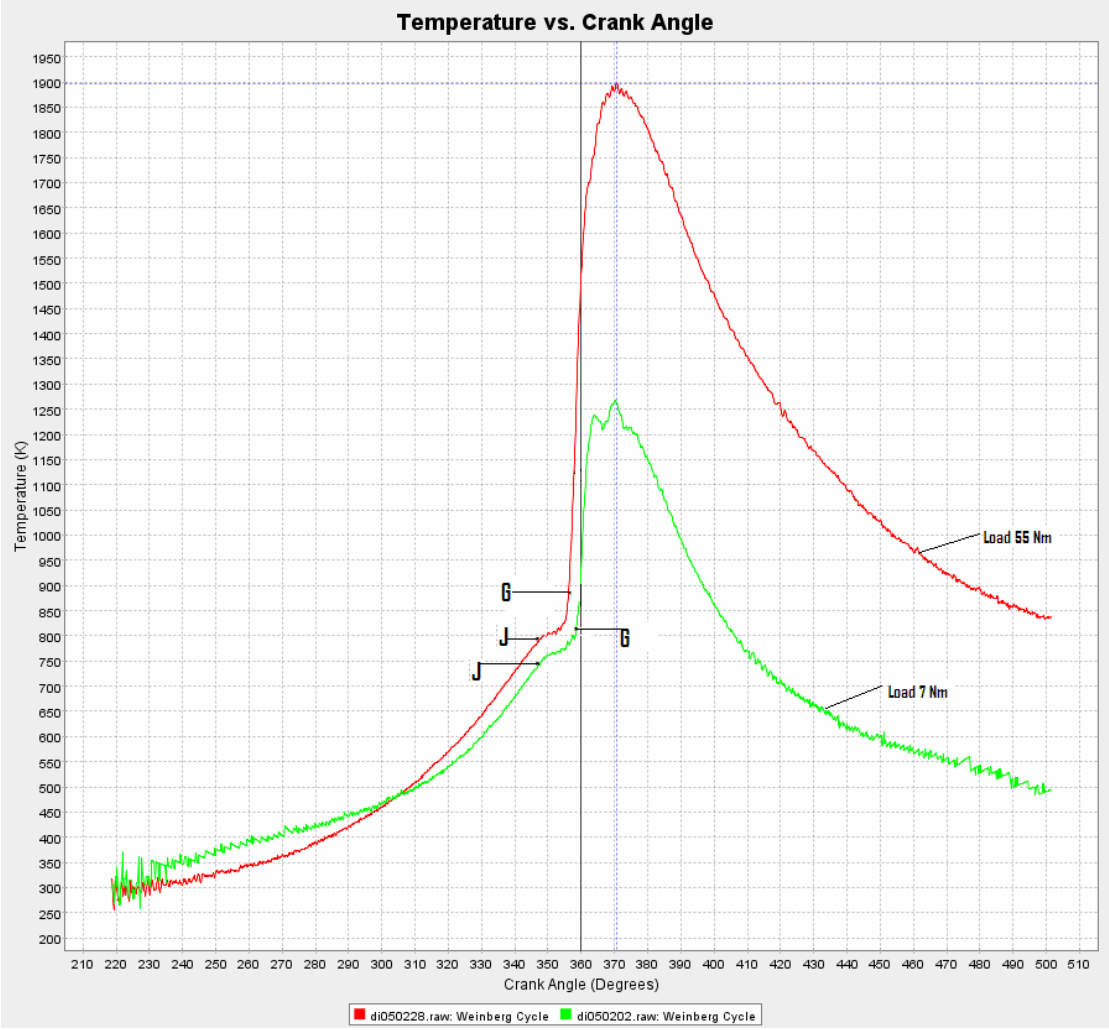


Figure 6.7: Temperature vs. Crank Angle for a load of 55 Nm and 7 Nm and an Engine Speed of 1550 rpm.

6.4 Energy Release

The graph below is a plot of the energy release versus crank angle. The two plots depict the total cumulative energy release and the apparent energy release. The total cumulative energy release contains a heat transfer adjustment.

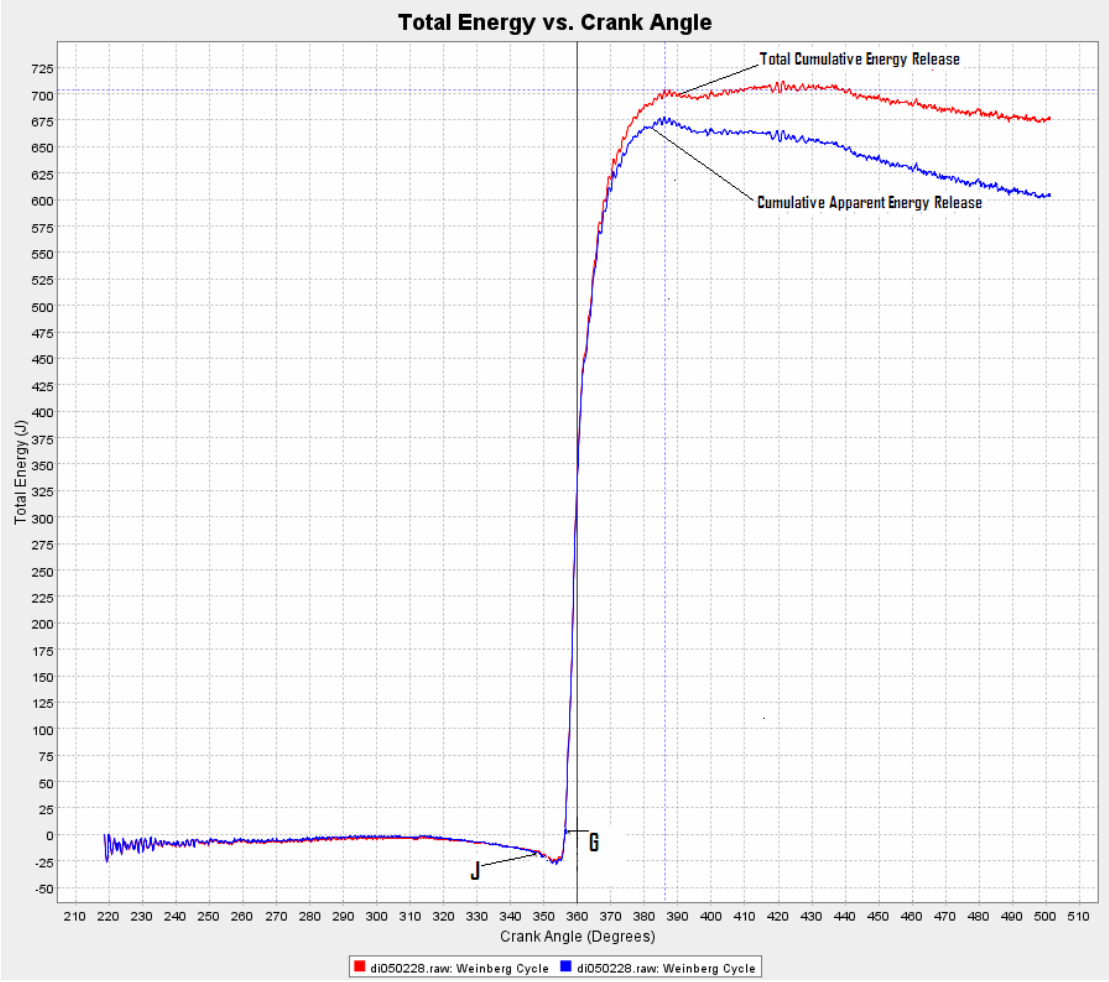


Figure 6.8: Energy Release vs. Crank Angle for a load of 55 Nm.

At the start of the compression cycle it is noticed that the energy release has an almost horizontal line. This indicates that a near adiabatic compression took place. The energy trace then starts to taper downwards. This is due to energy absorption from the system from a endothermic reaction which occurs just before the energy release stage occurs. Again the ignition delay between the injection and ignition point results in a further decline as a result of vaporisation.

Initially combustion is short and lasts for only a few CA degrees. The fastest rate of energy release occurs here as can be seen by the steepness of the slope. Energy is released partly before and partly after TDC indicating correct ignition timing, thus minimising negative work.

As the compression stroke comes to an end, the energy release graph levels off. Here the combustion phase shows a decreasing energy release rate.

As the expansion stroke takes place it is observed that less energy is released. This is because energy is being absorbed and the curves start to diverge at this point due to the heat transfer correction.

Figure 6.9 indicates plots of the apparent energy release for loads of 55 Nm and 7 Nm respectively. As is to be expected, the amount of energy supplied by the fuel increases with load and therefore the energy release also increases with load.

Not all the energy released is converted to brake power. There is energy lost to heat transfer and the formation of exhaust products. At low load the number of incomplete combustion products is relatively small, producing a high combustion efficiency. Increasing the load also increases the amount of incomplete combustion products. This is explained by the level of oxygen in the cylinder. For higher load there is insufficient oxygen to complete the combustion products thus resulting in a lower combustion efficiency. It is observed that the plot of the lower load has smaller energy absorption on the expansion stroke. [1]

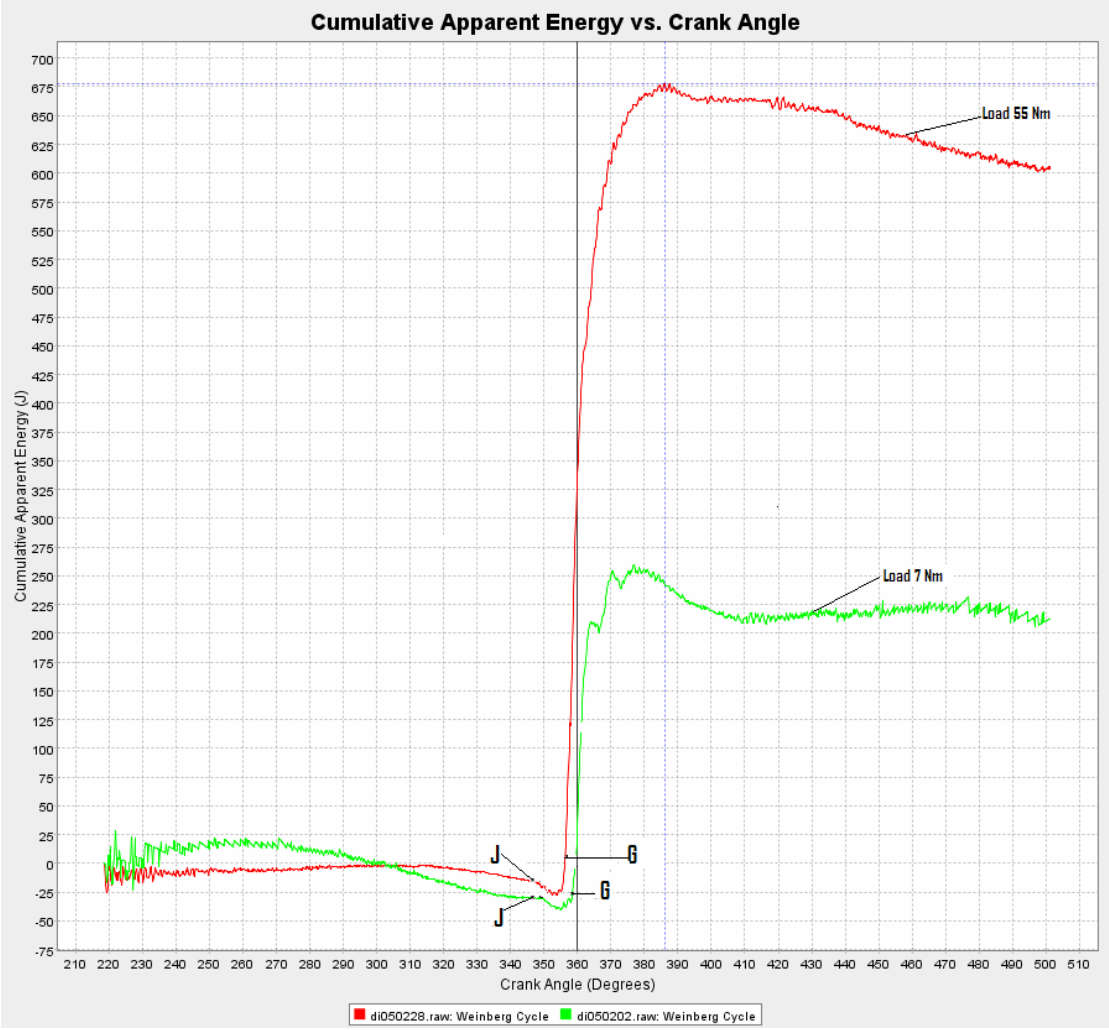


Figure 6.9: Overlaid Plot of Energy Release vs. Crank Angle for a load of 55 Nm and 7 Nm respectively.

6.5 Indicated mean effective pressure and brake power

Indicated mean effective pressure (Imep) is related to the power output of the engine, therefore brake power is discussed with it. Imep is defined as the indicated average constant pressure exerted on the piston during the expansion stroke, which will produce the same amount of work as the actual pressure during the compression and expansion strokes.

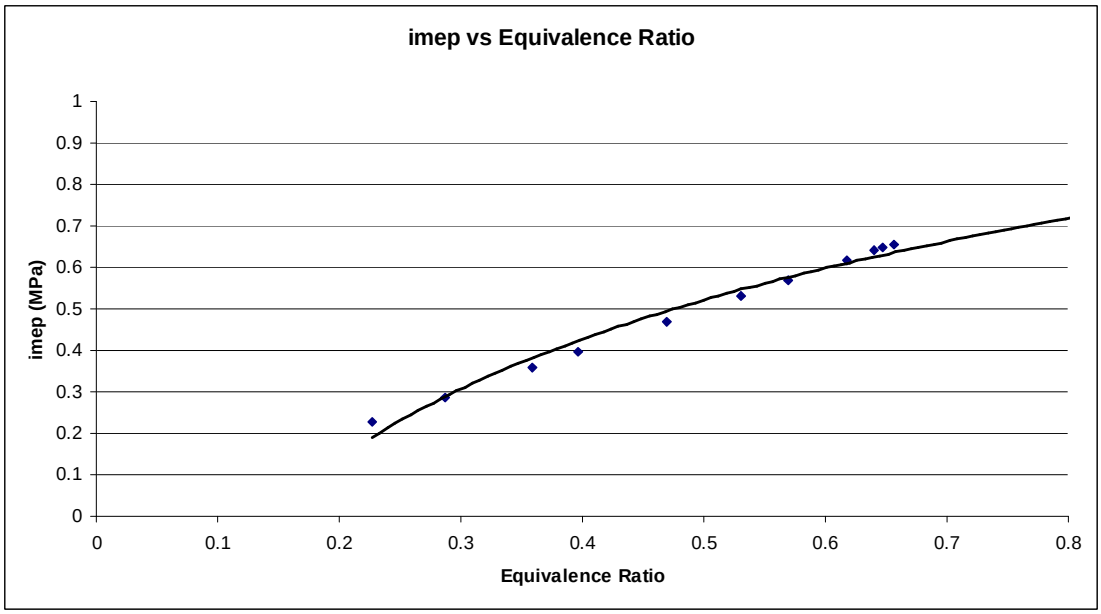


Figure 6.10: Plot of imep vs. Equivalence ratio at a speed of 1550 rpm and a load of 55 Nm.

Figure 6.10 and figure 6.11 follow similar parabolic trends and have a R^2 term of close to unity. It is evident that the imep and brake power increased with the addition of fuel until the reaction between the air and fuel released an optimum amount of energy, indicated by the peak. More fuel could be added at this optimum point, however the maximum pressures will either level off or drop depending on the amount of extra fuel added. Thus air is the limiting factor and is governed by the cylinders' displacement volume. The amount of air inducted into a diesel engine remains the same for a given speed, even when the load is increased. Thus the maximum imep is reached when the fuel/air mixture is most effectively combusted.

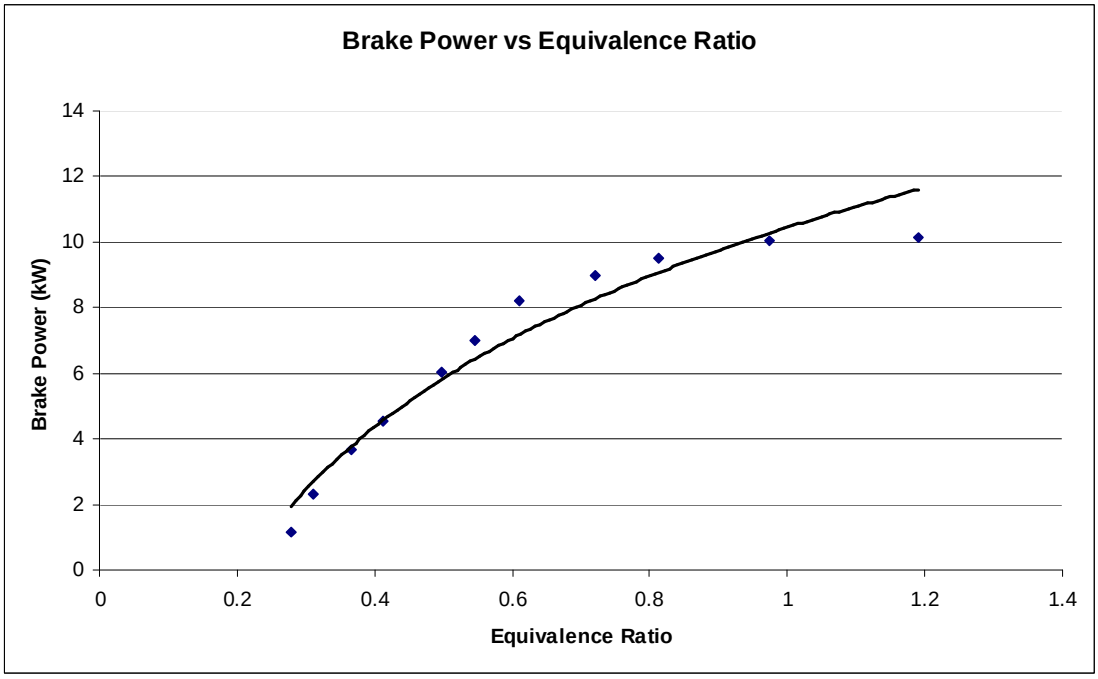


Figure 6.11: Plot of Brake Power vs. Equivalence ratio at a speed of 1550 rpm and a load of 55Nm.

6.6 Indicated specific fuel consumption

The minimum indicated specific fuel consumption (isfc) is reached when all the fuel in the cylinder is most effectively consumed. As can be seen in figure 6.12, the minimum isfc is reached with lean mixtures as opposed to maximum imep being reached with a rich mixture.

Inspection of the graph indicates that load increases until a point where the maximum amount of fuel is burned. If the load increases further, not enough air comes into contact with the fuel and hence the isfc rises again.

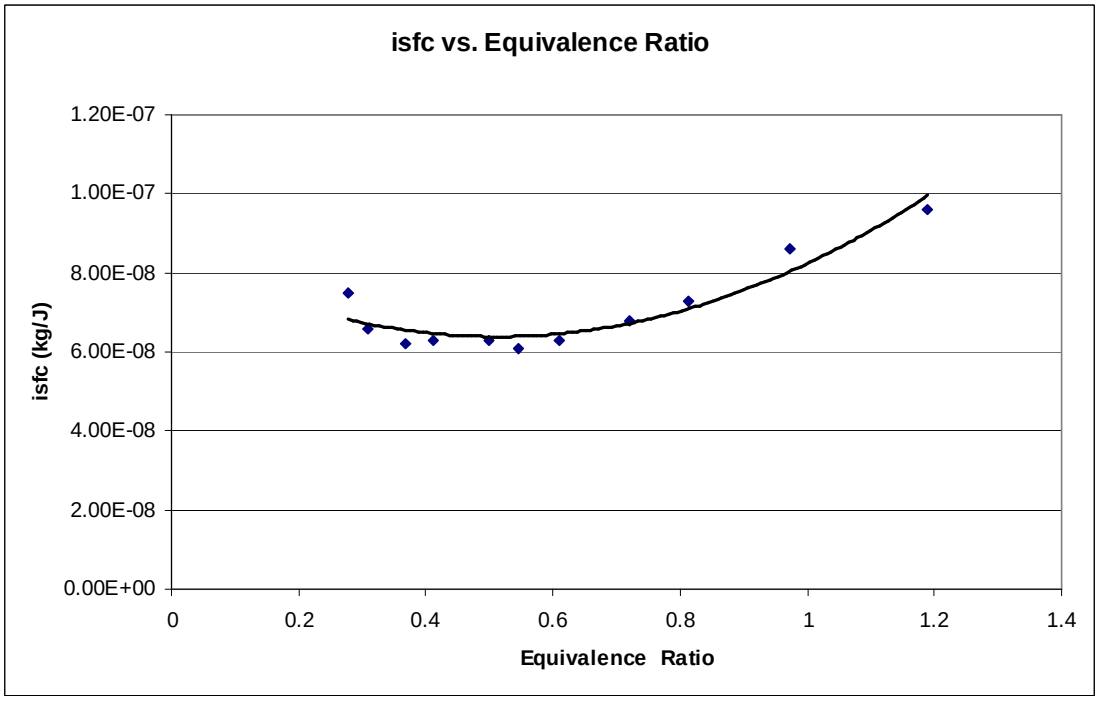


Figure 6.12: Plot of isfc vs. Equivalence ratio at a speed of 1550 rpm and a load of 55Nm.

6.7 Volumetric and fuel conversion efficiency

Upon inspection of figure 6.13, the fuel conversion efficiency increases with increasing load reaching a maximum of 30.4 % before tapering off. It is apparent that the engine has a better fuel conversion efficiency for leaner air/fuel mixtures.

The volumetric efficiency of an engine is defined as the ratio of the actual mass of air inducted by the engine on the intake stroke to the theoretical mass of air that should have been inducted by filling the piston-displacement volume with air at atmospheric temperature and pressure. As noted from figure 6.14, the ratio of actual to theoretical air mass drawn into the cylinder decreases with increasing load. A typical hyperbolic trend is followed.

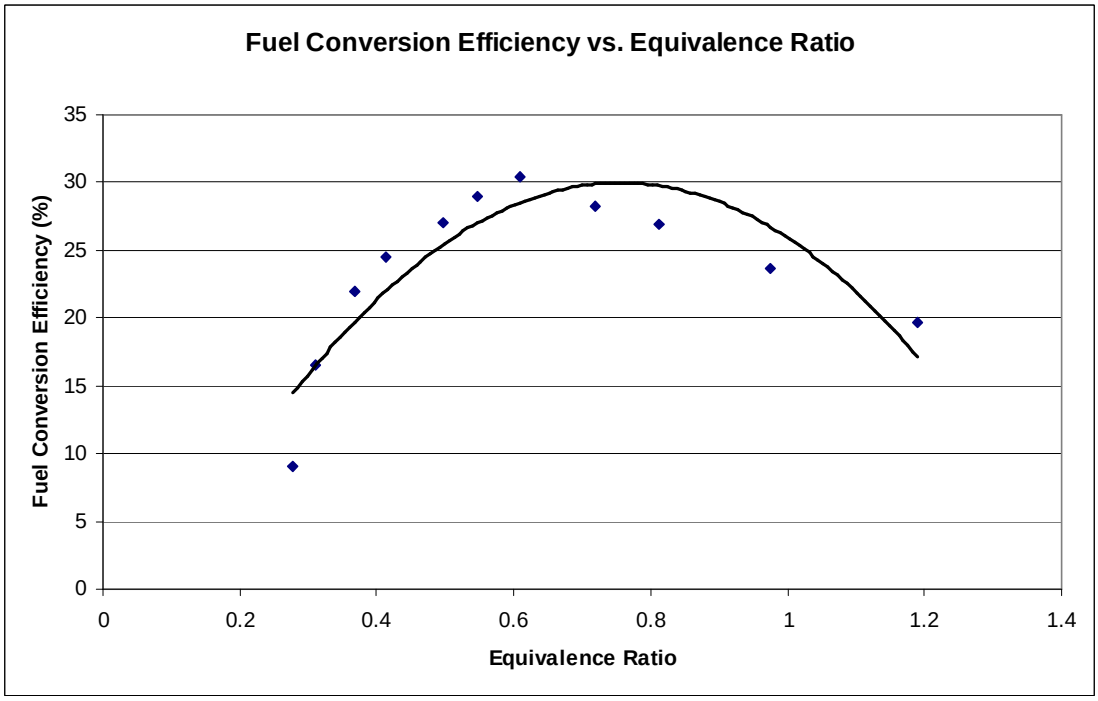


Figure 6.13: Plot of Fuel Conversion efficiency vs. Equivalence ratio at a speed of 1550 rpm and a load of 55Nm.

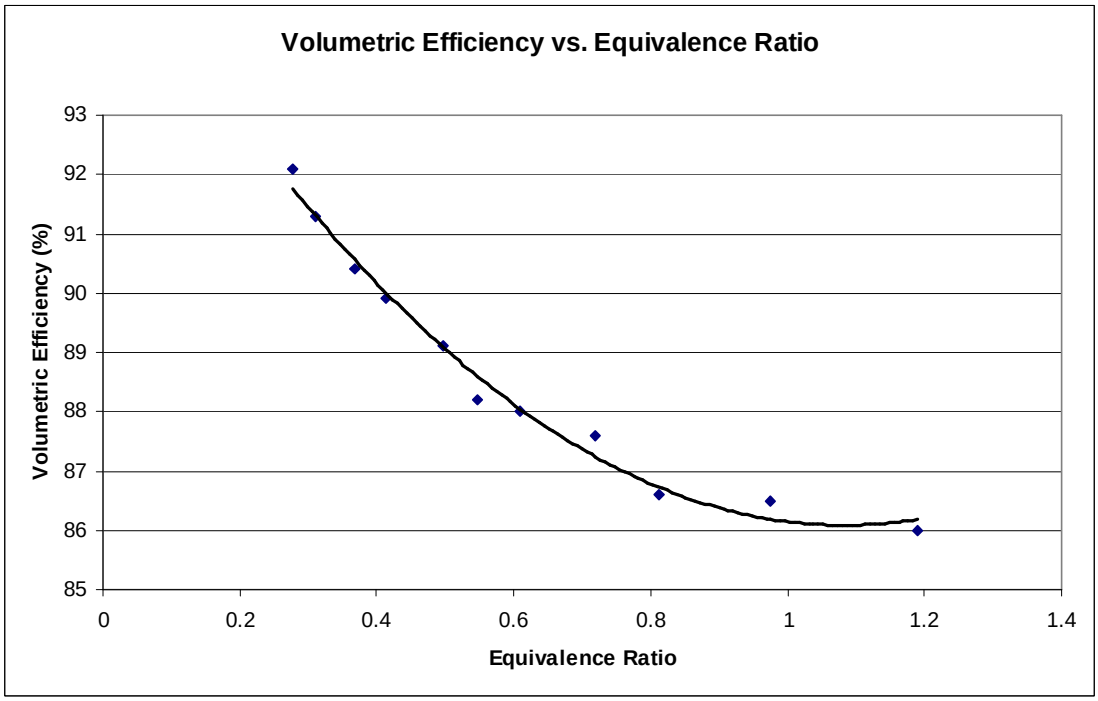


Figure 6.14: Plot of Volumetric Conversion efficiency vs. Equivalence ratio at a speed of 1550 rpm and a load of 55 Nm.

The lowest volumetric efficiency is reached at maximum load, this can be ascribed to the fact that the wall temperatures are higher, making the air less dense and thus allowing a smaller volume of air into the cylinder.

7. Conclusion

The combustion analysis software (CAS) performed the analysis directly according to the objectives for which it was designed. The results obtained for the diesel tests appear to be representative of all speeds and loads showing the typical behaviour expected, indicating that the engine and the data analysis techniques performed by the software CAS are consistent and correct. It is apparent that the trends obtained follow the expected patterns and are complementary of each other, demonstrating the absence of any major problems. The picture created using the newly designed software is summarised as follows:

- CAS was written in the latest computer language java and can run on any platform namely windows, linux, unix etc. It can also be adapted to run on PDA's.

- The plots of cylinder pressure indicated the stages of combustion as expected. It was noted that the maximum cylinder pressures increased with increasing load. It was also noted that the ignition delays became shorter as the load was increased. It was concluded that the maximum pressures occurred just after TDC indicating maximum efficiency with minimal negative work done. The maximum pressures were found to be less with a higher engine speed and this was explained by the fact that these maximum pressures occurred closer to the expansion stroke.

- The injector fuel line pressure graphs for differing loads were comparable. It was concluded that the injector fuel line pressure traces for differing loads were almost identical, the only difference being that a higher load results in an upward parallel shift due to a higher initial pressure.

- The cylinder temperature had similar trends. Again they followed the expected stages of the combustion process. The maximum cylinder temperatures increased as load increased. The main reason for this increase in temperature comes about as a result of the increased amount of fuel being injected into the combustion chamber as the load is increased.

- The energy release graphs showed that near adiabatic compression took place initially. Energy was released partly before and partly after TDC hence leading to the fact that the engine had correct ignition timing. It was noted that the energy curves started to divert at the start of the expansion stroke due to the heat transfer adjustment. Again it is realised that the engine releases more energy with higher loads to maintain the same speed, however there are more incomplete combustion products due to oxygen shortages and higher loads.

- The oxygen constraint was again highlighted when analysing the brake power and indicated mean effective pressure (imep). Adding more fuel at higher loads, increased the brake power and imep until a point when more oxygen was needed. It was found that air is the limiting factor and is governed by the cylinders' displacement volume. Thus the maximum imep is reached when the fuel/air mixture is most effectively combusted.

- Indicated specific fuel consumption (isfc) was found to be optimal for lean fuel mixtures as opposed to imep being optimal with rich fuel mixtures. It was found that as the load increased, a point was reached where all the fuel would not be burnt. If the load was increased further, not enough air came into contact with the fuel and the isfc would begin to rise.

- As with isfc it was found that maximum fuel conversion efficiency was reached with lean fuel/air mixtures. The lowest volumetric efficiency was found to occur at maximum load, and this was concluded to be the case because of the fact that the wall temperatures are higher, making the air less dense and thus allowing a smaller volume of air into the cylinder.

The CAS software can be used to further the research into alternative fuels and makes the analysis process more efficient and less time consuming. CAS also increases the power of analysis through its improved analysis components.

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Appendix A

Fuel Flow Meter Calibration Procedure

- Using an electronic scale and a clean container, the fuel is to be bled from the fuel line leading to the engine.
- The time taken to collect a certain amount of fuel in the container on the scale is recorded using a stopwatch. Usually the time interval is set at about 2 minutes.
- The mass of the fuel collected is then also recorded.
- The input voltage to the data acquisition system is measured by means of a voltmeter and this is also noted.
- The fuel flow is increased for each consecutive reading. The scale of the flow meter has a maximum of 12 1/hr and therefore the readings are randomly selected at approximately 11/hr intervals. These readings are also recorded.
- All the above mentioned recordings are listed in table A1.
- After plotting the fuel mass flow rate (g/s) vs. the voltage output of the flow meter, a linear curve fit is fitted to the data points from which the calibration equation constants may be obtained.
- The results of the calibration are shown in figure A1.

Table A1: Fuel Flow Meter Calibration

	Flow Meter Output					
Reading	Up(V)	Average (V)	Fuel Mass (g)	Time (s)	Fuel Mass Flow (g/s)	Fuel Flow (l/hr)
1	0.029	0.029	0.0	0.0		0.0
2	0.459	0.459	50.0	184.0	0.271	0.8
3	0.864	0.864	80.0	151.0	0.529	1.8
4	1.540	1.540	125.2	130.0	0.963	3.2
5	2.114	2.114	175.4	134.0	1.308	4.4
6	2.388	2.388	190.6	127.0	1.500	5.0
7	2.881	2.881	255.7	140.4	1.821	6.2
8	3.225	3.225	270.0	133.0	2.030	7.0
9	3.618	3.618	300.5	131.5	2.285	7.8
10	4.058	4.058	315.1	123.6	2.549	8.8
11	4.585	4.585	361.1	125.0	2.888	10.0
12	4.808	4.808	380.7	126.0	3.021	10.6
13	5.308	5.308	426.3	128.0	3.330	11.8

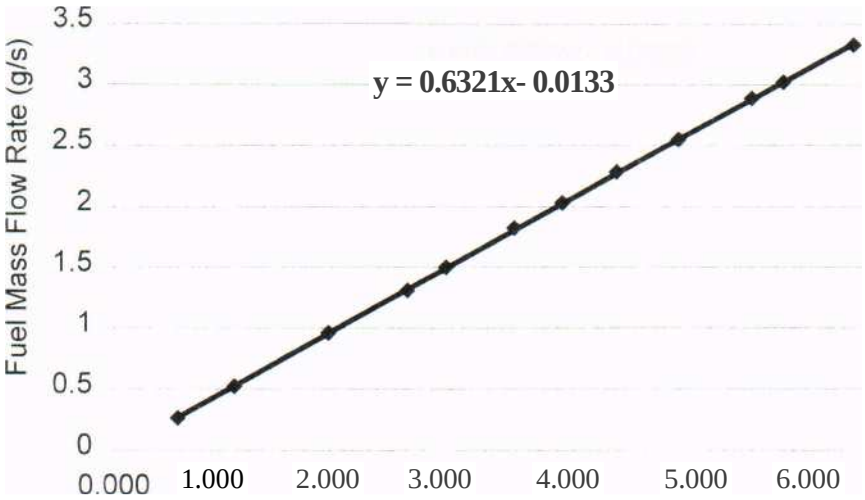


Figure Al: Fuel Flow Meter Calibration Results

Load Cell Calibration Procedure

- Mass pieces are suspended from the static torque arm of the dynamometer in random intervals. These masses are recorded for calibration purposes.
- The input voltage to the data acquisition system from the load cell is measured using a voltmeter. These measurements are then also noted.
- The process is done for increasing and decreasing loads on the torque arm. After which the increasing and decreasing voltage readings are then averaged.
- The calculated torque is then plotted against the average output voltage of the load cell and a linear curve is then fitted to the plotted data points.
- The above measurements are recorded in table A2 and plotted in figure A2.

Table A2: Load Cell Calibration

Load Cell Calibration:						
Amplifier voltage: SVolts				Torque Arm Length = 0.4003m		
		Load Cell Output				
Reading	Mass (kg)	Up(V)	Down (V)	Average (V)	Torque (Nm) (g = 9.78549)	Torque (Nm) (g = 9.8)
1	0.000	3.760	3.755	3.758	0.000	0.000
2	0.616	3.862	3.970	3.916	2.413	2.417
3	1.616	4.199	4.312	4.256	6.330	6.339
4	3.887	4.990	5.098	5.044	15.226	15.248
5	4.884	5.352	5.435	5.394	19.131	19.160
6	8.212	6.509	6.641	6.575	32.167	32.215
7	9.209	6.870	6.963	6.917	36.073	36.126
8	10.484	7.339	7.412	7.376	41.067	41.128
9	11.481	7.671	7.729	7.700	44.973	45.039
10	12.756	8.110	8.193	8.152	49.967	50.041
11	13.753	8.457	8.511	8.484	53.872	53.952
12	15.022	8.833	8.862	8.848	58.843	58.930
13	16.019	9.048	9.072	9.060	62.749	62.842
14	17.156	9.092	9.087	9.090	67.202	67.302
15	18.153	9.000	9.000	9.000	71.108	71.213

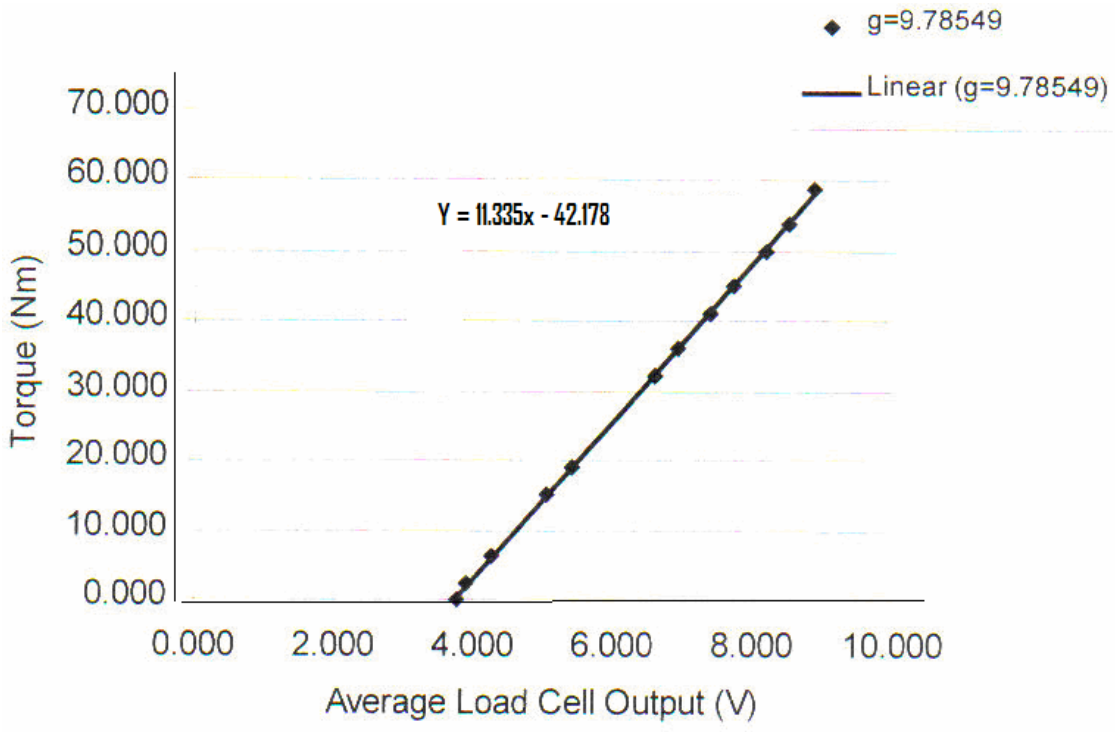


Figure A2: Load Cell Calibration Results

Calibration of Cylinder pressure transducer:

The cylinder pressure was measured by means of *Kistler* piezo-electric transducer. The output from the pressure transducer was to be amplified, using a charge amplifier. The amplifier has settings for mechanical units per volt and for sensitivity.

The pressure transducer/amplifier output was calibrated using a *Budenberg* pressure tester. The tester uses oil subjected to a known pressure, this pressure is then applied to the transducer and the output is calibrated against the known pressure.

The calibration procedure was as follows:

> The pressure transducer and its housing were fitted to the *Budenberg* tester.

> The 10 mechanical units per volt were selected on the charge amplifier.

> To measure the output a digital voltmeter was connected to the output of the charge amplifier.

> The charge amplifier was zeroed.

> The calibration was done by first increasing the pressure and then decreasing the applied pressure.

> For each increment, the output was recorded. The recorded data can be viewed below.

Table A3: Calibration table of cylinder pressure transducer

Reading	Applied pressure	Applied pressure	Output up	Output down	Average output
	(Psi)	(Bar)	(Volts)	(Volts)	(Volts)
1	0	0	0.080	0.120	0.100
2	100	6.895	0.6119	0.623	0.621
3	200	13.790	1.326	1.280	1.303
4	300	20.684	2.010	1.996	2.003
5	400	27.579	2.876	2.680	2.778
6	500	34.474	3.430	3.380	3.405
7	600	41.369	4.110	4.080	4.095
8	700	48.263	4.830	4.800	4.815
9	800	55.158	5.510	5.510	5.510
10	900	62.053	6.270	6.240	6.255
11	1000	68.948	6.960	6.960	6.960
12	1100	75.842	7.700	7.700	7.700

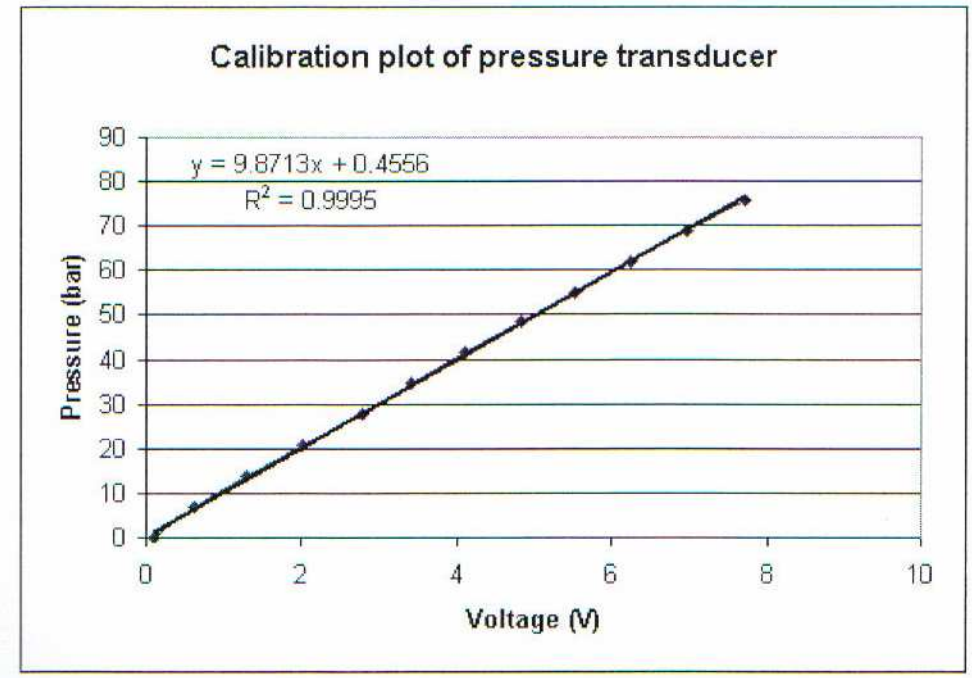


Figure A3: Calibration plot of cylinder pressure transducer

Speed calibration;

Unlike the other instruments, the engine speed could be calibrated using a two-point calibration technique.

> An offset of 2.5 mechanical units had been established, which represents the y-intercept of the assumed linear curve.

> Two further speed settings were chosen and their voltage output recorded. This could be done due to the residual error present in the analog revolution meter.

Table A4: Calibration table of revolution meter

RPM	Voltage
0	0.009
546	1.842

Using 2.5 as the offset and the values from the m can be calculated:

M = (546+2.5)/1.842 = 297.77

Airflow calibration:

The pressure difference across the orifice plate, situated in the inlet duct, was used to obtain the airflow. The pressure drop was measured by a micromanometer, whose output voltage was fed into the data acquisition system. A linear curve was fitted to the data points.

> With the engine running and having let it stabilise at a random speed setting, take pressure readings across the orifice plate. These values will be displayed in millimetres of water.

> Voltage readings are to be taken from the data acquisition system.

> The results are tabulated and then plotted. A linear curve is fitted to the data to determine the calibration constants.

Table A5: Calibration table of airflow meter

Pressure ($mm\ H_2O$)	Voltage (V)
25.7	1.349
44.6	2.231
54.9	2.752
58.9	2.99
65.6	3.289
74.7	3.745
78.9	3.963
85.9	4.308

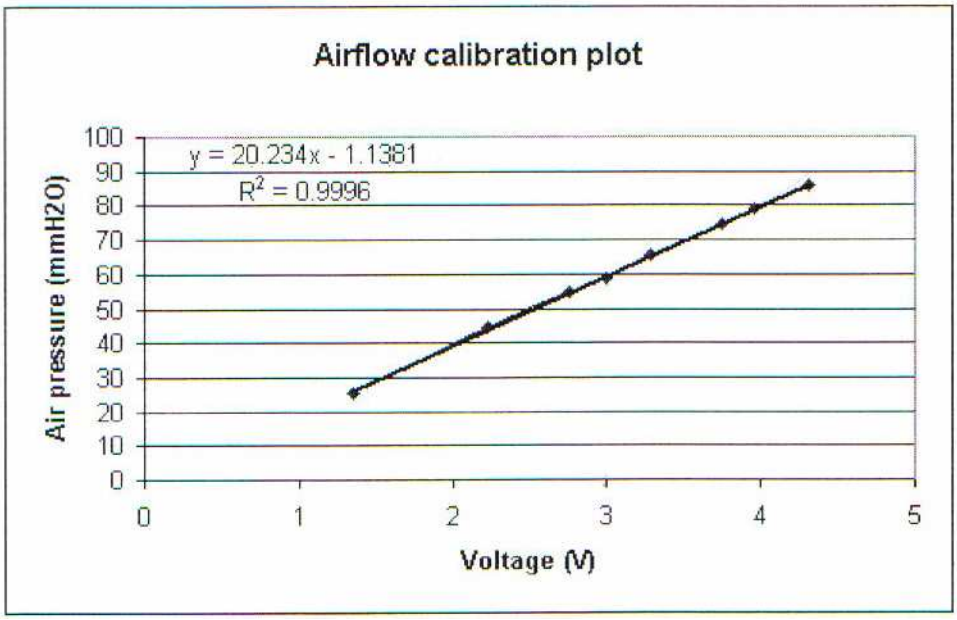


Figure A4: Calibration Plot of airflow meter

Table A7: Calibration equation table

Channel Number	Name	Conversion	Calibration
2	Fuel Flow (g/s)	0.637	-0.02
°	Barometric Pressure (bar)	1	0
4	Air Flow (mm/H20)	20.234	1.138
5	Speed (rpm)	297.77	2.5
7	Lad (Nm)	12.611	41.444
9	Ambient Temp. (°C)	99.6	2.273
10	Inlet Cat.Temp. (°C)	99.611	0.119
11	Outlet Cat.Temp. (°C)	98.884	3.614
12	Air Temp. (°C)	98.995	5.881
13	Inlet Water Temp. (°C)	102.29	5.869
14	Outlet Water Temp. (°C)	102.41	2.751

From y = mx+c Conversion = m Calibration = -c

Appendix B

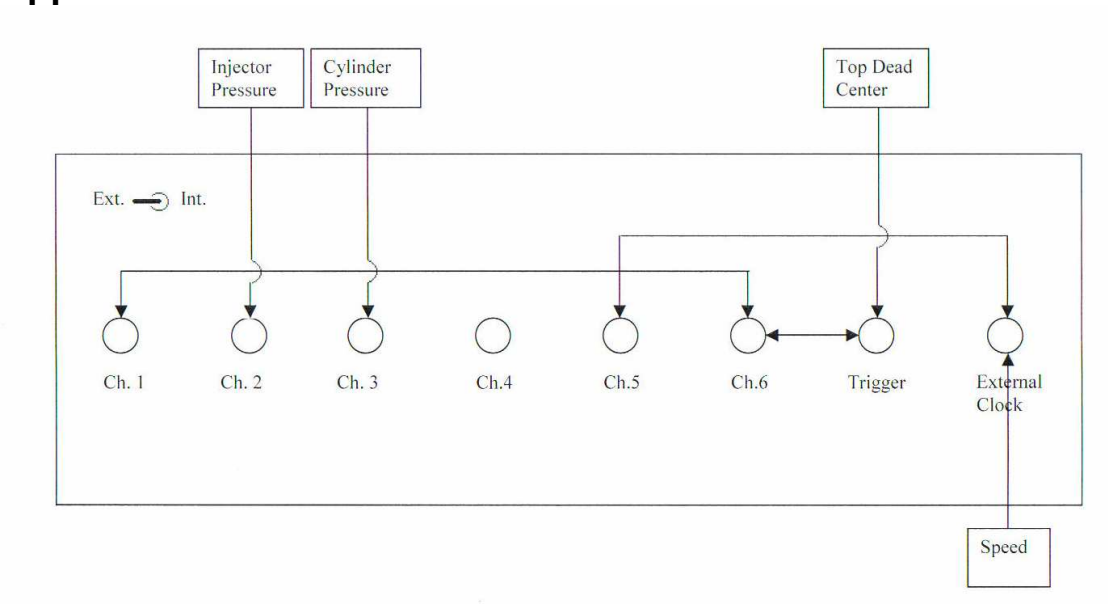


Figure B1: Wiring Diagram of dynamic channel data acquisition system

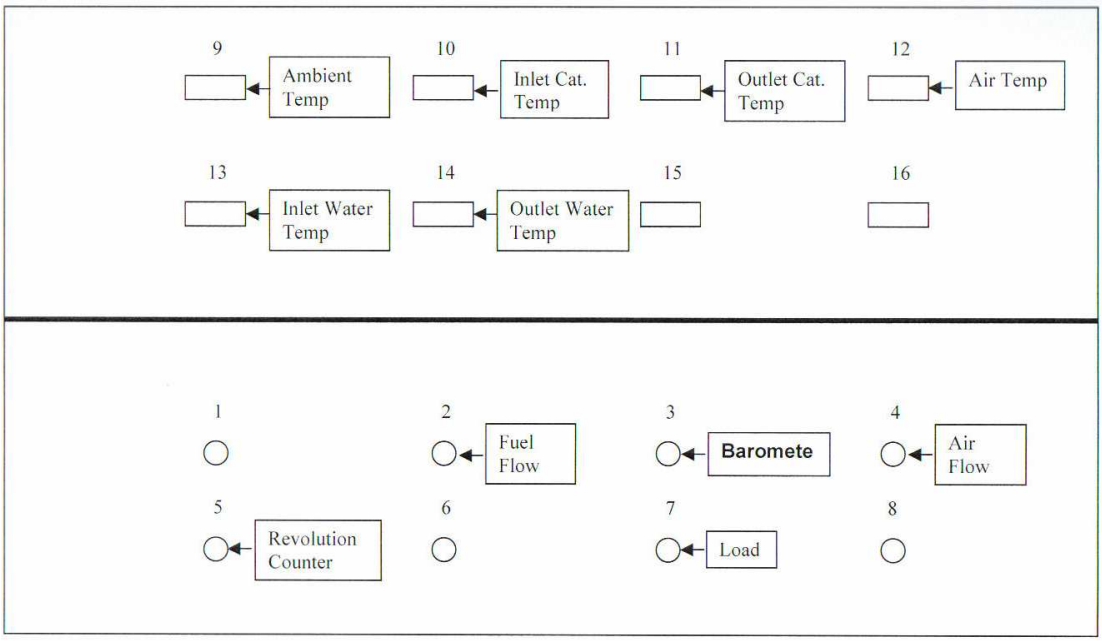


Figure B2: Steady state channel data acquisition system

Appendix C

Combustion Analysis Software

The following is a user manual for the Combustion Analysis Software (CAS) developed for this research project by the author. The software has powerful security and analysis tools which will be described below.

1. CAS Security

CAS has been developed with user security in mind. There are two levels of security, namely *administrator access* and *normal access*. *Administrator access* allows the user to add, edit and delete users from the system. *Normal user access* allows the user to use all the features offered by CAS, except the user administrator features offered by the software.

Once the CAS software is initialised a Login prompt screen is displayed (refer to figure C1). Here the user is prompted for their user name and password.



Figure C1: Login Screen

Upon incorrect log in, the user is required to re-enter their log in details. Once Logged in, the main CAS graphical user interface (GUI) is displayed (see Figure C2). As can be seen, the main GUI has menu options at the top and shortcuts to these menu options in the form of action buttons in the centre of the gui. On the right hand side is a route tracker which indicates the progress made while using the software.

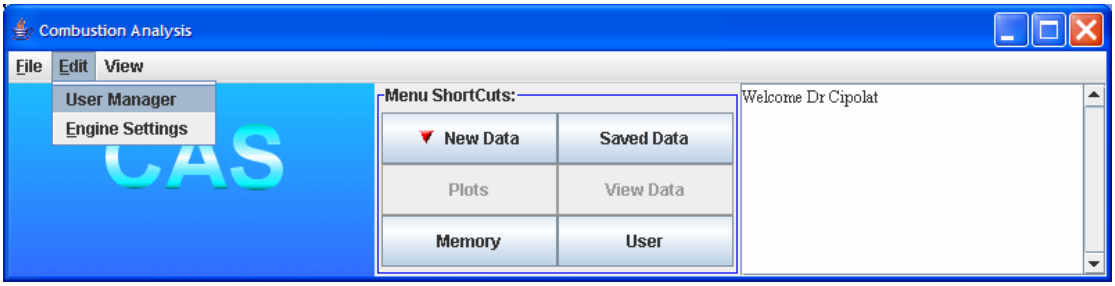


Figure C2: CAS Main GUI

If the user, currently logged on, has administrator rights, the User shortcut button, and the User Manager menu option will be active as shown above. If the user then requires to add, delete or edit a user, they can either select the option from the shortcut bar or from the menu option.

This then brings up the User Manager GUI as shown in Figure C 3. As illustrated below, the administrator can view the user name, password and permissions of the users loaded onto the system. The user “jp” below, has normal permissions as opposed to admin rights and will hence not be able to access the user manager GUI.

To **add** a new user, press the “Add” action button. This brings up the “Add User” Gui. On this GUI, a username and password is required. There is also another security measure where the user is prompted to re- type the password. If the passwords don’t match, the new user will not be entered into the system.

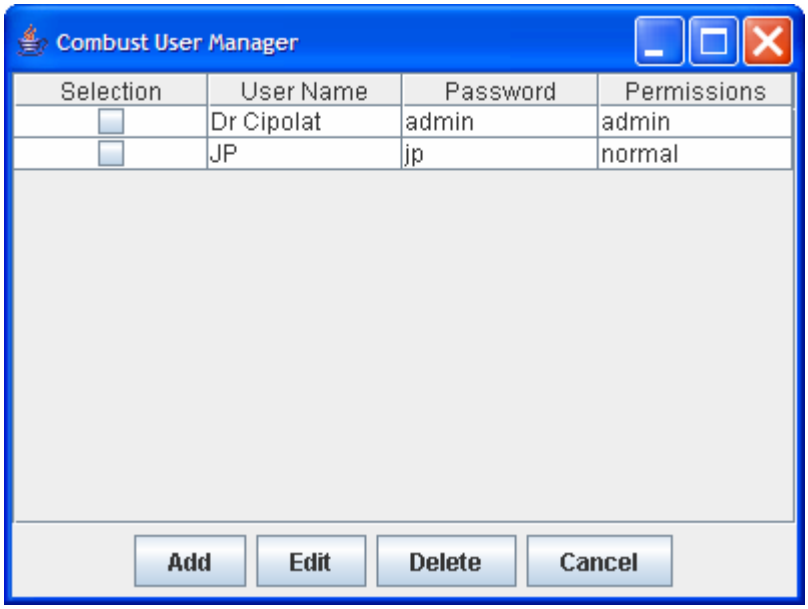


Figure C3: The Combust User Manager GUI



Figure C4: The Add New User GUI

If the “Admin Rights” check box is ticked, the new user will have administrator rights. Once the new user details have been entered press the “OK” button and the new user will be entered into the system. If the “Cancel” button is pressed, the system returns to the User Manager Panel.

To **edit** a user, tick next to the user which requires editing and press the “edit” button. This brings up the “Edit User Gui”. Only the users password and admin rights can be edited, not their user name. Once editing is completed, select the “OK” button and the details will be saved.

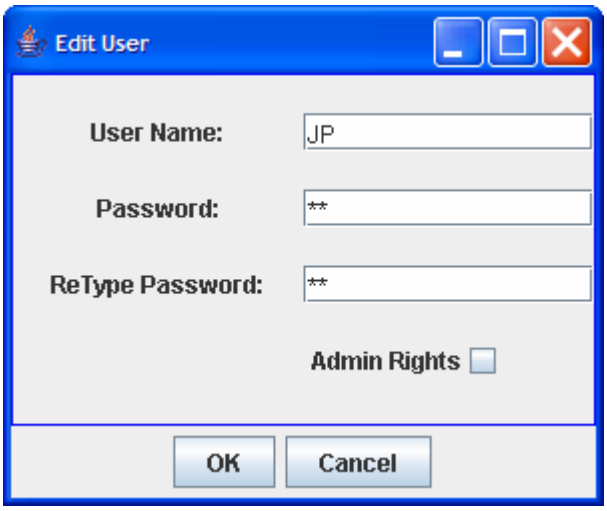


Figure C5: The Edit User GUI

To **delete** a user, select the user to be deleted on the User Manager GUI and press “delete”. The user will then be deleted from the system.

2. Configuring Engine Settings

CAS is configured for three engine types namely, PH2, PH2W and Petrol. To change any of these engine settings go to edit on the main menu and then select “Engine Settings”. The Engine Settings Manager GUI is then shown (see Figure C6). On this gui, the three engine settings can be seen. These can be edited. Once edited click the “Save” action button and the new settings will be applied.

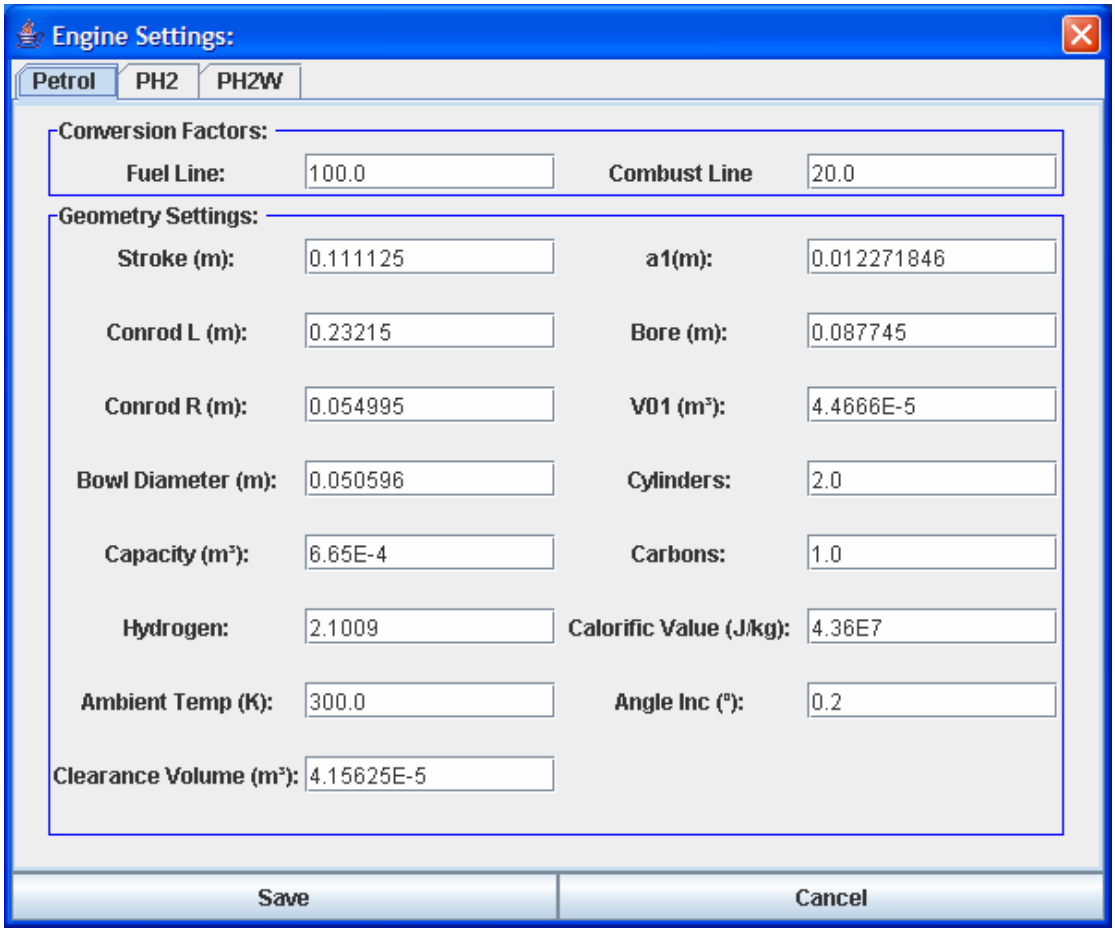


Figure C5i: The Engine Settings GUI

3. Loading New Data

To Load new Data press either the “New Data” shortcut button, or choose the “Load New Data” option from the File menu. Once selected, a four step wizard is displayed. In **step 1** the wizard asks which engine type the analysis is to be performed on. Select the engine type and then press the “Select Test” action button.

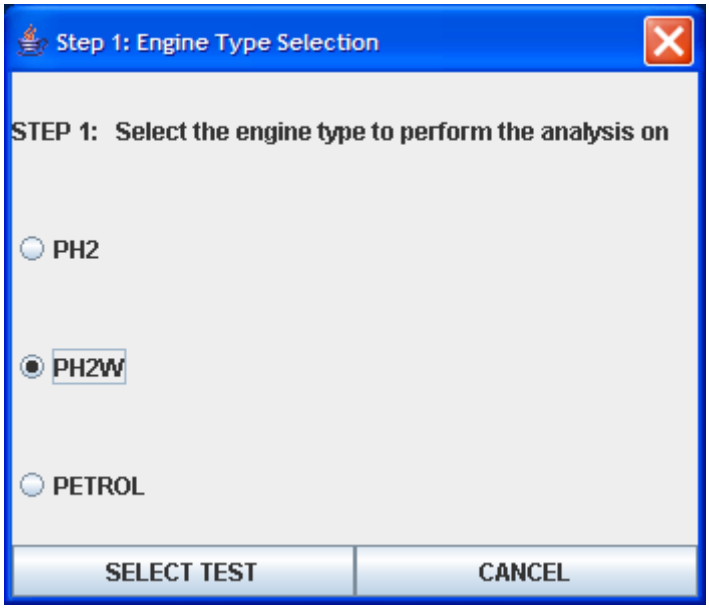


Figure C6: Step 1 Engine Type Selection GUI

Step 2 then allows the .dat file, produced by the Data Acquisition Software, to be selected. Upon selection, the dynamic link library within the system automatically executes the *Conver* program. Here the user is prompted to select if the test performed was either *motoring* or *firing,* as well as to indicate which engine setting was used. Then press the "Process File" action button. The software reads the .dat file and plots an overlaid plot of Cylinder Pressure vs. Crank Angle from all the channels used. The user can either select a pressure trace from one channel or average a group of Channels. Once decided, press the "Convert Data" button. This the converts the .dat file into a .raw file to be used by CAS. The *Conver* program is then terminated and Step 3 is illustrated.

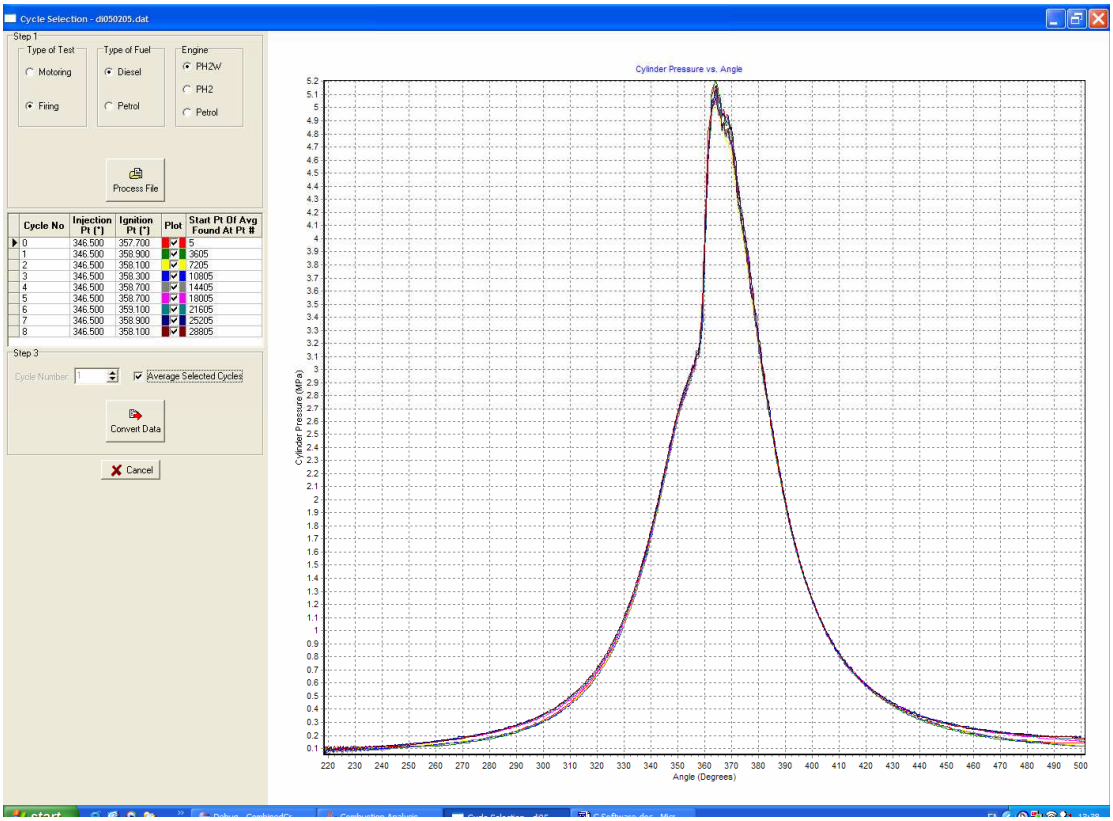


Figure C7: Step 2 The Conver Program GUI

In Step 3 the user is prompted to select the Heat release Analysis to be performed, by CAS, on the Converted data. Once selected, press the "OK" action button and the analysis is automatically performed and saved.

Step 4 is a continuity selection. Here the user has a choice of viewing Plots or Reports (discussed later) or Loading another cycle (discussed next) or Loading a New File. If the user selects the *Load New File* option, the same four steps are repeated on a different test. The user can select up to ten different tests to be compared against one another.

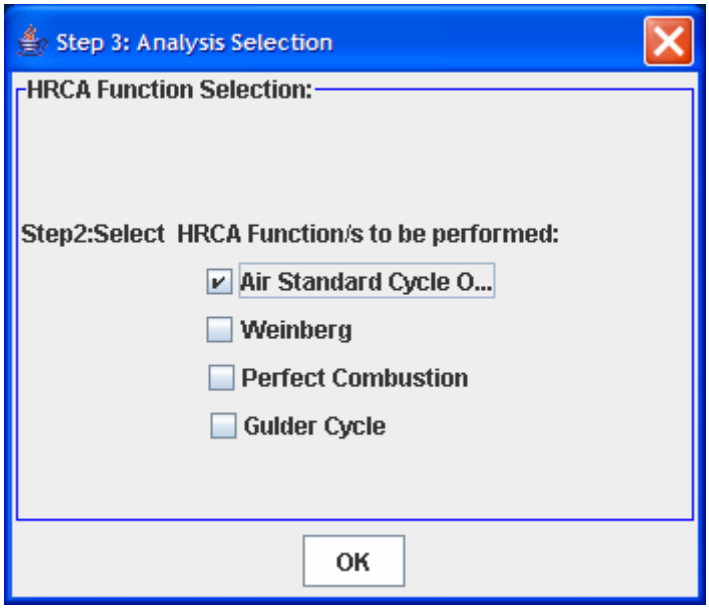


Figure C8: Step 3 The Heat Release analysis Selection Gui

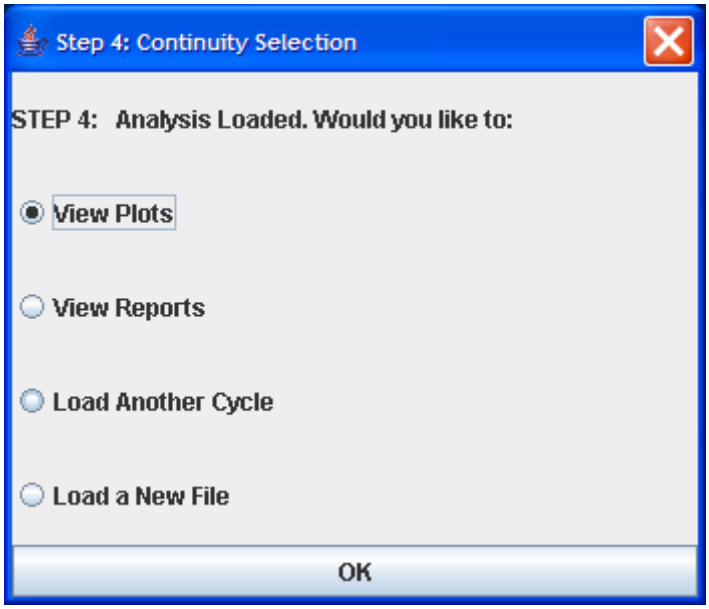


Figure C9: Step 4 The Continuity Selection GUI

4. Loading Saved Data

This option is exactly the same as the “Load New Data” option previously described, however there is one difference. This option skips step 2. In other words it allows you to perform a different Heat release analysis on a file which has already been converted to a .raw file. In order to select this option you can either press the “Saved Data” short cut action button or select the “Load Saved Data” option from the File Menu. This option can be repeated when you select the “Load Another Cycle” radio button in step 4, as shown in Figure C9.

5. Viewing Plots

Once a new cycle has been loaded or a saved raw file has been loaded, the *View Plots* feature is enabled. To view plots one can either press the “Plots” action button or select the “Plots” from the View Menu at the top of the main GUI. The plots can also be viewed in step 4 of the wizard.

The Plot Viewer Gui, displays the plots and has two tabs. The second tab (The *Combined Combust Plots* tab) allows the user to view all the tests selected on one overlaid plot. The Y axis shown in figure C10 allows the user to view plots in the categories of General analysis, Property Cycles analysis, Apparent energy, Heat Transfer and Mass burned. The X axis shown below, allows the user to plot any of the Y axis categories against Crank Angle, Temperature and ln V/V1. The user just selects the Y axis plot and X axis plot desired and CAS automatically generates the plot.

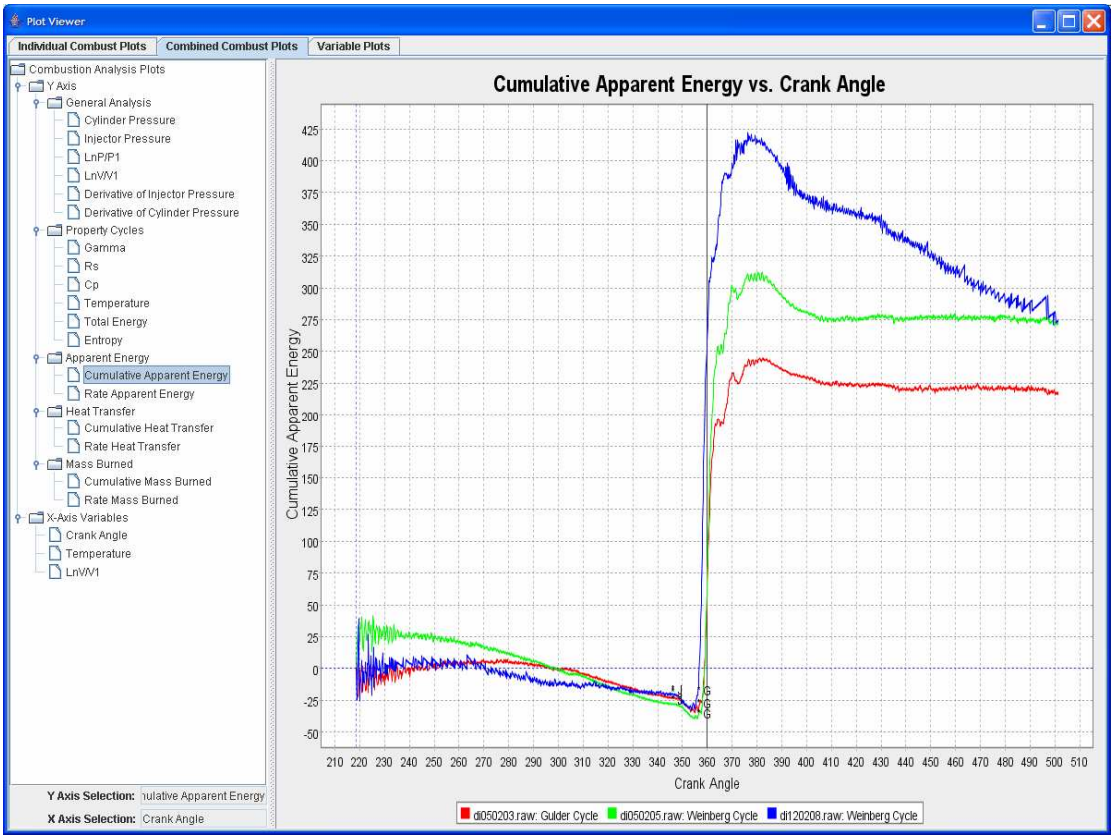


Figure C10: The plot Viewer Gui

The first tab (The Individual Combust Plots Tab) allows the user to view the plots exactly the same way as in the second tab, except it plots the different loaded tests individually and not overlaid. As can be seen in Figure C11, the user can flip between tests by selecting the desired engine test or cycle from the drop down box. The corresponding plot is then automatically displayed.

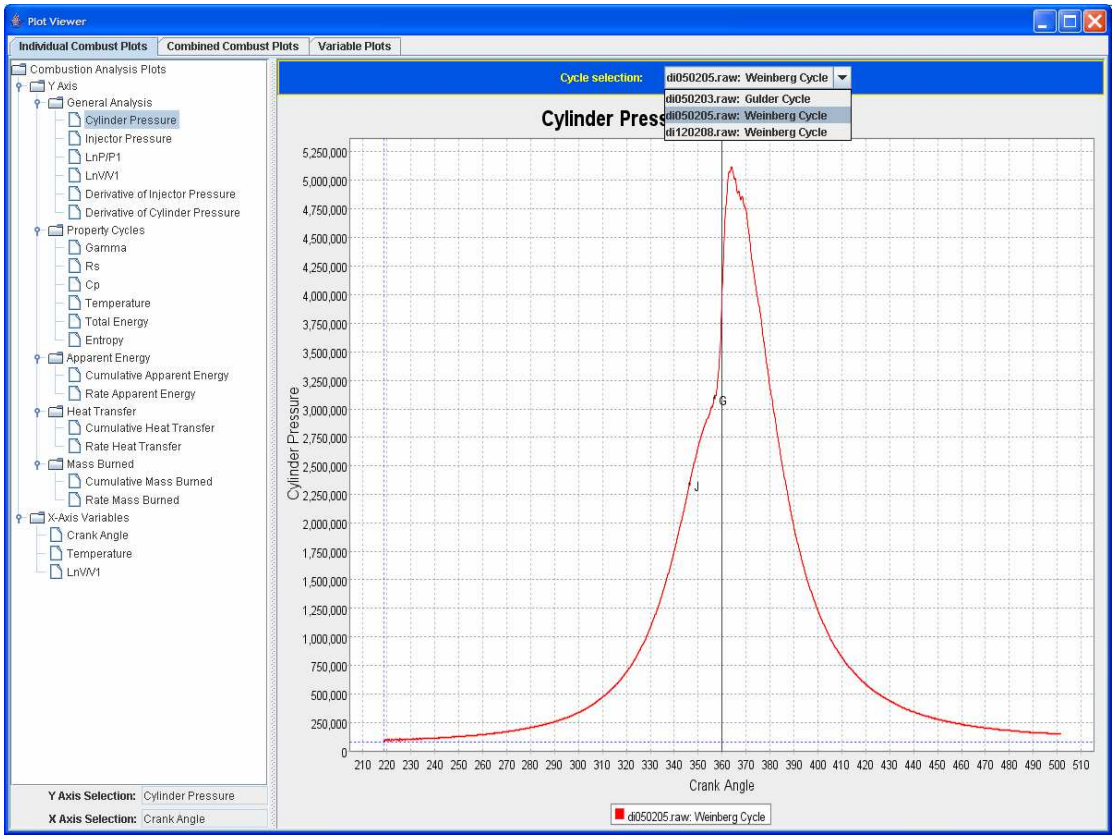


Figure C11: The Plot Viewer Gui Displaying the Individual Combust Plot's Tab

Each graph is fully customisable. In order to customise the plots, right click on the graph and follow the menu options. The following options are available:

- Chart Properties. This allows the user to alter three main chart properties namely the *Chart Legend*, the *Plot* and an *Other Category.* In *the Chart Legend* the user can alter the Outline, the series font, the background and the legend colours. Under the *Plot properties* the user can alter the domain axis, range axis and the appearance. Under the *Other* properties, the user can alter the general background colour of the graph as well as the series stroke and colours.

- The *Save AS* option. This option as the name implies allows the selected plot to be saved to the hard drive.

- The *Print* option. Allows the user to select a printer to print the graph to.

- The *Zoom in* , *Zoom out* and *Auto Range* functions can be applied to either the x-Axis or y-Axis individually or to both simultaneously. Figure C12 illustrates this.

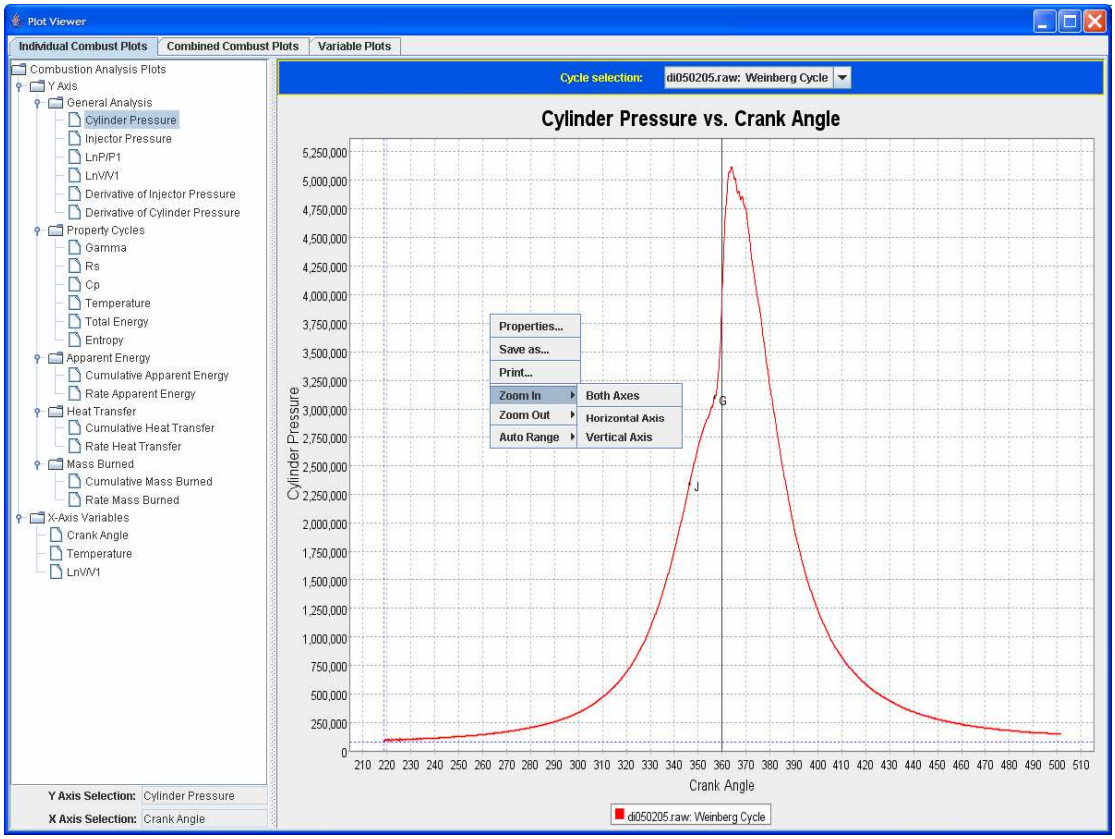


Figure C12: The Plot Viewer Gui illustrating the Zoom In feature

6. Viewing Data

Once a new cycle has been loaded or a saved raw file has been loaded, the *View Data* feature is enabled. To view the data reports, one can either press the “View Data” action button or select the “View Data” option from the View Menu at the top of the main GUI. The data can also be viewed in step 4 of the wizard.

The Data viewer Gui displays the following Tabs, and each tab has a drop down box allowing the user to select which cycle or engine test’s data, they wish to view (Shown in Figure C13)

- The constant Data tab. The information displayed here, ranges from the fuel type to the calculated mechanical efficiency data. Shown in figure C13.

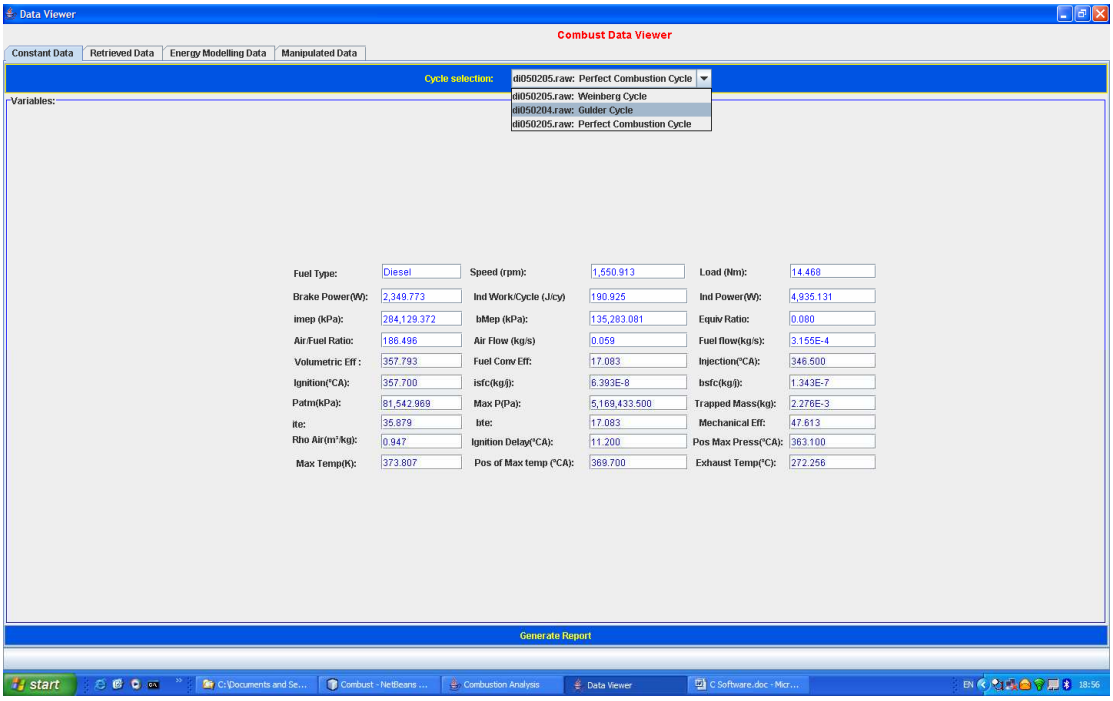


Figure C13: The Data Viewer GUI illustrating the Constant Data Tab and Drop down Engine Test Selection box

- The Retrieved Data Tab. This tab displays all the unprocessed data retrieved from the *Conver* program.

- The Energy Modelling Tab. This tab displays the manipulated data under the categories Property Cycles, Apparent energy, Heat Transferred and Mass Burned.

- The Manipulated Data Tab. This tab displays the Cylinder Pressures and Volumes, Injector Pressure and LnP, LnV and Crank Angle Data.

CAS has a report generating tool which can automatically format all the data in each of these tabs for professional report display purposes. To generate a report, click on the “Generate Report” action button. This automatically generates the report illustrated in figure C14.

The report generated has a selection of features. If the File Menu is selected the report can be saved as a text file, PDF Format, exported to excel for editing purposes, exported to html format for web uploading as well as exported to csv format. The report can also simply be printed with the option to change the page setup.

If the report is saved under any of the following formats, a few features can be selected when saving (see Figure C15). The user can select a title and author for the report. The user also has the option to add security to the report. For a lower level of security, the report can be password protected with 40 bit encryption, or if a higher level of security is required, it can be saved with 128 bit encryption. Additional security can be added to specific features of the report, such as allowing printing, copying, usage of screen readers, modification of contents etc.

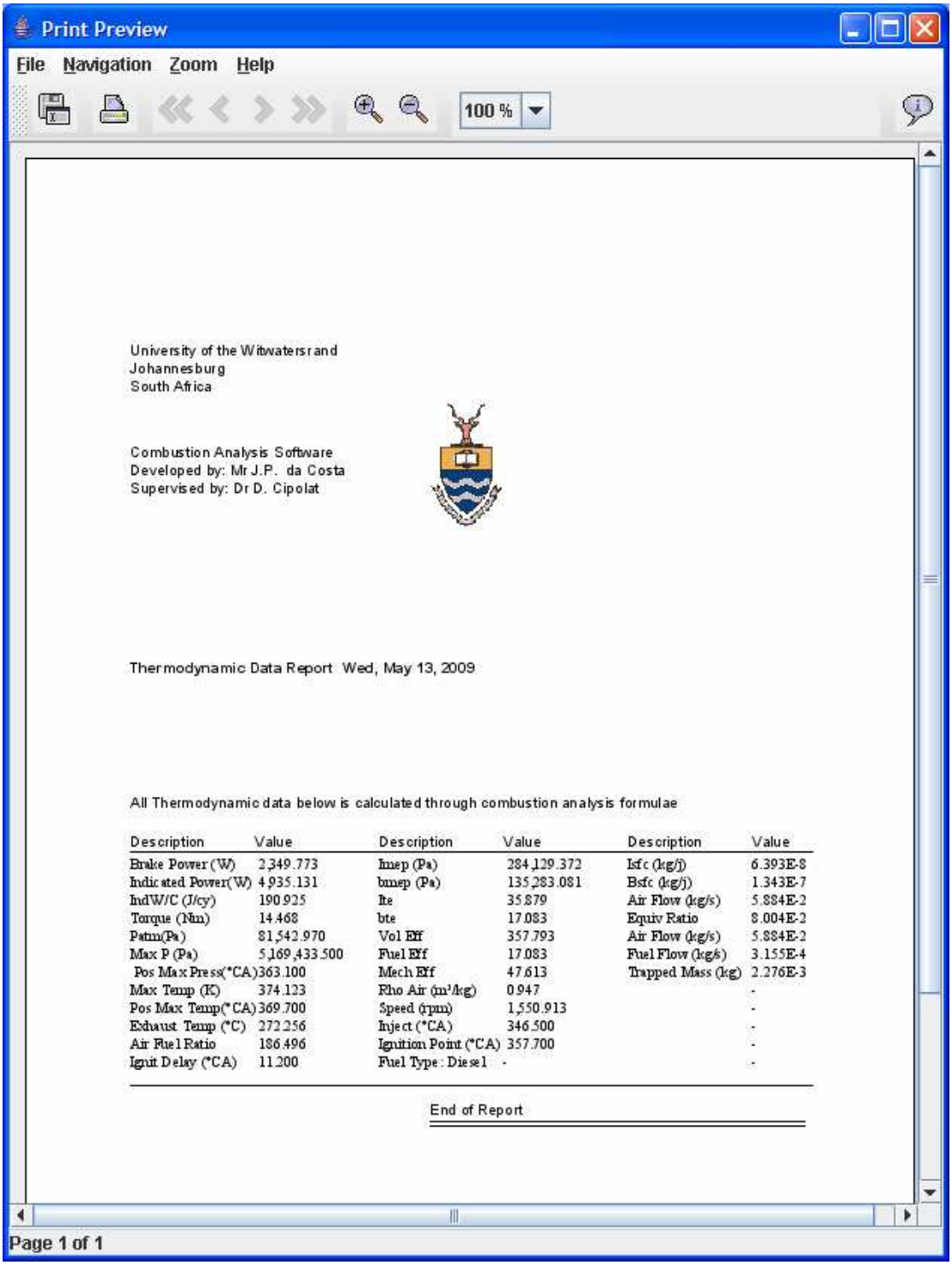


Figure C14: Generated Report of the Constant Data Tab

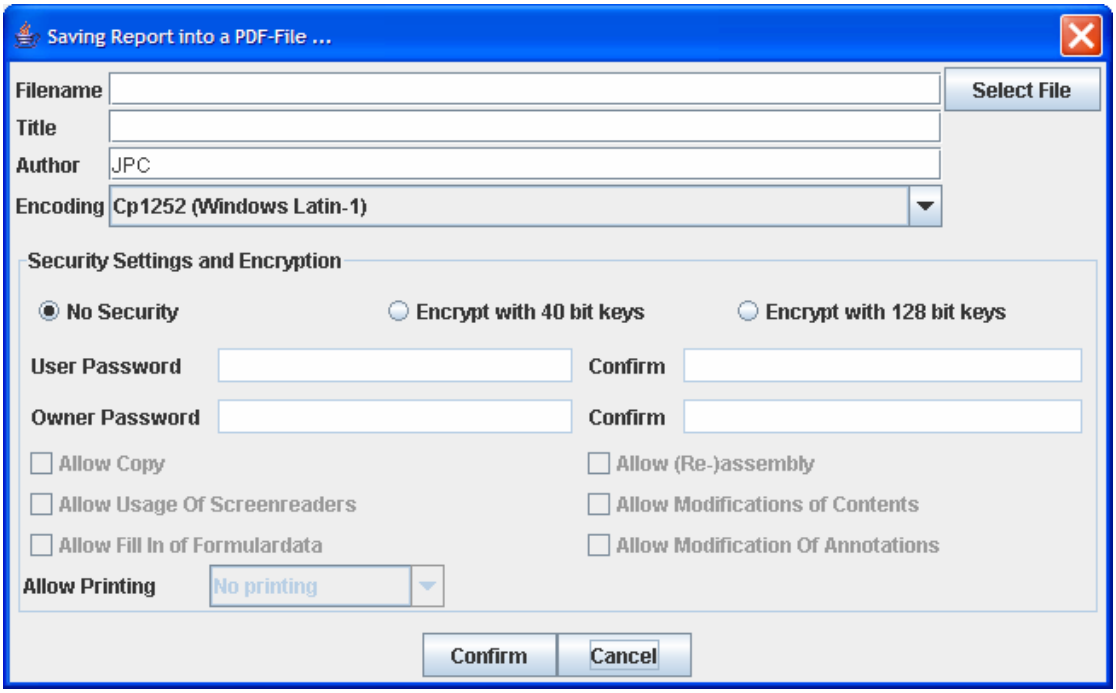


Figure C15: Security Features when saving the Generated Report.

The navigation menu on the *Print Preview Gui* of the report (See Figure C14), allows the navigation between the various pages of the report. The report also has zooming functionality allowing the user to adjust the percentage zoom applied to the report.

7. The Memory Manager

The memory manager can be selected by pressing the “Memory” action button on the main gui (see figure C2) or selecting the Memory Manager option under the File menu.

The memory manager allows the user to delete loaded tests and increase or decrease the maximum amount of tests that can be loaded by the system. This is important because each test utilises the computer’s random access memory (RAM). Therefore being able to control the amount of tests loaded in the CAS system allows better utilisation of the PC’s RAM.

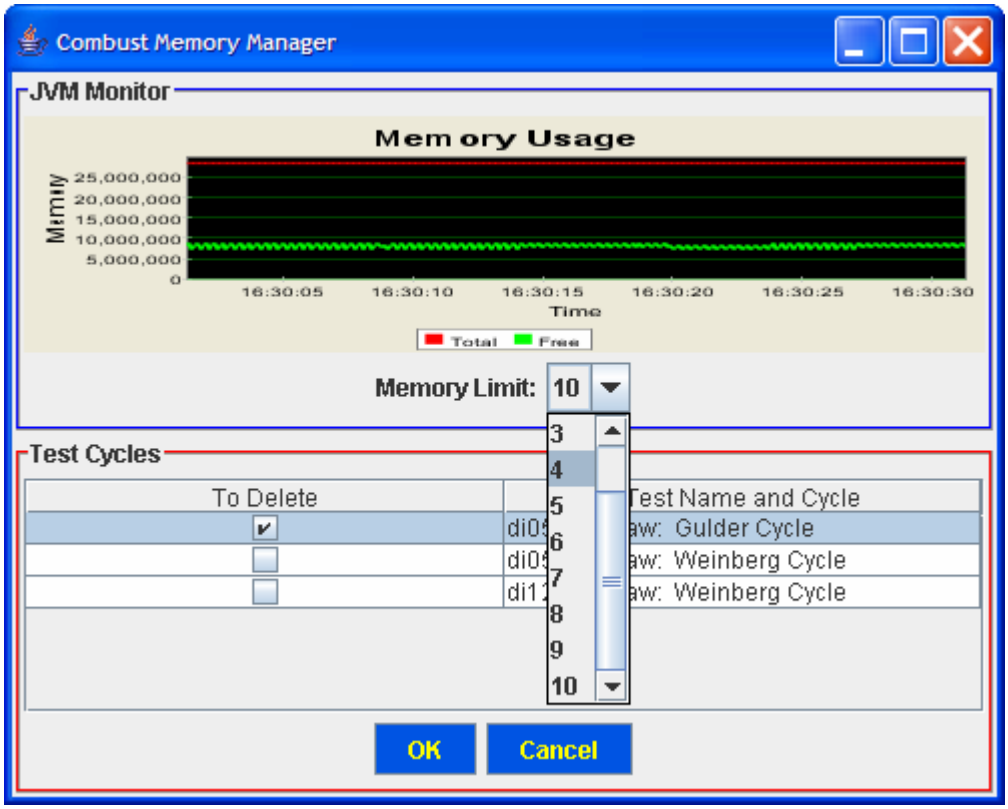


Figure C16: Combust Memory manager GUI

The engine test limit, in CAS, can be changed by selecting the limit from the Memory Limit drop down box shown in figure C16. As can be seen CAS displays a real time memory usage graph. This gives a live update on the PC's memory usage.

In order to delete a test, select the test in the Memory Manager GUI and press the "OK" Action button. This erases the manipulated data, of the test, from memory.

Data Acquisition Software

Once the computers and all the instruments have been switched on, then the preparation for saving test data may begin. Be sure to start the PC without the network cable plugged in. This is to ensure that the DOS conversion programmes run smoothly without any interference. The following procedure outlines the steps involved when setting up the directories to which the test data should be stored in the Windows software package such that the DOS conversion programmes may locate the data files for conversion.

- Once Windows has started up, double click on the icon that reads **"Shortcut to Engine Test."** This will open up the operating window of the Engine testing programme.
- In this window on the menu bar, click the **File** button and scroll down to **"Test Data Directory"** and click on this button.
- Now select the directory path as **D:\PH2W\{Folder}** and then click the OK button. The entry **{Folder}** is to be replaced with whichever folder the data is to be stored in. This is usually a month for example **aug06** (i.e. August 2006 as used for this project).
- Then click on the **Settings** button on the menu bar and scroll down to **"Test Settings"** (or just click on the icon with the screw driver, spanner and hammer). This will open the **"Speedwave Channel Settings"** window.
- Next, click on the **Test Settings** label. This will enable the operator to select the test settings for the specific test rig in operation.
- In the space for **Test Engineer,** select the desired test setting. For this project, click on the far left icon on the menu bar to open the desired test rig setting. The location of the test setting for this project may be found in **C:\Program Files\Tlc\Engine TestXdata.** Once in this directory, select the **Petter PH2W** file and then click the OK button.
- Make sure that the **Storage Option** settings are for **Multi-Event** and that the **Saving Method** is in **DOS Compatible Format.**
- The steady state channel trigger settings are to be set to the desired speed and tolerance band.

- The **Test Filename** is to be set as **{fuel type} {date} {month} {test number}** for example, **ed230834** The codes for the fuel type can be found in table Cl.

Table Cl: Test Filename Codes

Fuel Type	Code
Diesel	di
Dimethyl Ether (DME)	dme
Methanol / DME	md
Ethanol / DME	ed
Motoring	mo

- Now check to see that the steady state channel settings are correct according to all calibration factors and instrumentation settings. To do this click on the **Steady State Channels** label
- Once this has been done, click on the icon with the lightning bolt to open the**ArmSystem_I** window.
- Here two sets of graph axes are shown. The graphs show the traces of the top dead centre (TDC) (graph 6), injector pressure (graph 2), cylinder pressure (graph3), trigger (graph 1) and injector lift (graph 4). To view each of the graphs separately, click the **Strip Graphs** icon on the menu bar. To refresh the graphs click the **Redraw Graph** icon on the menu bar. To activate a graph just click the number of the respective channels above each graph axis window.
- Once the trigger has been activated, the operator is given the choice as to **Accept Test, Ignore Test** or **Cancel Test.**

Once testing is complete then the PC is restarted in the **Command Prompt** mode. This is done to be able to print graph traces from within the DOS conversion programmes.

Appendix D

Table D1: Table of 1350 rpm diesel performance results

TLC Test Name	Speed (rpm)	Load (Nm)	Brake Power (kW)	Indicated Work/Cycled (J)	Indicated Power	imep (MPa)	bmep (MPa)	Equivalenc Ratio	Air/Fuel Ratio	Air Flow (g/s)	Fuel Flow (g/s)	Fuel Conv Eff(%)	isfc (kg/J)	bsfcf (kg/J)	Inj Point (°CA)	Ign Point (°CA)	Ign Delay (°CA)
di 20200	1353.2	5.0	0.715	146.1	3.296	0.220	0.048	0.259	57.79	14.277	0.25	6.6	7.50E	3.50E-07	340.0	356.9	16.9
di 20204	1353.2	14.0	1.989	184.2	4.153	0.277	0.133	0.322	46.63	13.985	0.30	15.2	7.20E	1.50E-07	340.0	355.3	15.3
di 20210	1 356.0	23.4	3.322	233.7	5.282	0.351	0.221	0.389	38.74	14.03	0.36	21.0	6.90E	1.10E-07	340.0	355.9	15.9
di 20213	1356.0	29.1	4.136	267.4	6.044	0.402	0.275	0.43	34.74	13.985	0.40	23.6	6.70E	9.70E-08	340.0	355.5	15.5
di 20219	1356.0	36.9	5.237	296.2	6.693	0.445	0.349	0.494	30.28	13.792	0.46	26.4	6.80E	8.70E-08	340.0	355.1	15.1
di 20223	1353.2	42.5	6.134	327.7	7.390	0.493	0.401	0.562	26.66	13.717	0.51	26.8	7.00E	8.50E-08	340.0	354.1	14.1
di 20226	1353.2	50.6	7.172	367.0	8.276	0.552	0.478	0.629	23.96	13.596	0.57	29.0	6.90E	7.90E-08	340.0	353.7	13.7
di 20229	1356.0	55.7	7.904	388.7	8.784	0.585	0.526	0.702	21.31	13.551	0.64	28.5	7.20E	8.00E-08	340.0	354.1	14.1
di 20235	1356.0	57.9	8.280	389.4	8.801	0.586	0.548	0.783	19.09	13.444	0.70	26.8	8.00E	8.60E-08	340.0	353.3	13.3
di 20238	1356.0	61.4	8.717	416.6	9.415	0.626	0.580	0.911	16.39	13.274	0.81	24.7	8.60E	9.30E-08	340.0	354.5	14.5
di 20242	1358.8	62.6	8.902	438.7	9.935	0.660	0.591	1.008	14.81	1 3.336	0.90	22.7	9.10E	1 .OOE-07	340.0	354.3	14.3

TLC Test Name	Pressure Atm. (kPa)	Before Cat. Temp. (^{C}C)	After Cat. Temp. (°C)	Max Pressure (MPa)	Position of Pmax (°CA)	Max Temp. (K)	Position of Tmax (°CA)	Mechanical Efficiency (%)	ITE (%)	BTE (%)	Vol Eff(%)	Ambient Temp. (°C)	Manifold Air Temp. (°C)	Injector Pressure (MPa)
di 120200	82.5	160.7	195.2	4.83	361.4	1232.8	367.0	21.7	30.6	6.6	94.6	26.4	27.1	112.4
di 120204	82.5	190.6	240.3	5.19	361.2	1 340.4	366.6	47.9	31.8	15.2	93.5	27.4	29.9	106.7
di!20210	82.5	227.3	285.8	5.71	365.6	1473.3	366.2	62.9	33.5	21.0	93.4	28.3	30.0	102.3
di 120213	82.5	256.7	317.9	6.00	365.2	1 544.0	370.2	68.4	34.4	23.6	93.1	28.8	30.4	98.5
di 1 20219	82.5	305.7	353.6	6.16	364.6	1618.4	368.2	78.2	33.7	26.4	91.8	29.2	31.9	100.0
di 120223	82.5	341.0	388.9	6.49	365.0	1697.6	369.2	82.2	32.9	26.8	91.5	29.9	32.4	95.7
di 120226	82.5	395.9	437.7	6.63	364.2	1769.9	369.0	86.7	33.5	29.0	90.7	30.3	33.3	99.9
di 120229	82.5	438.0	492.3	6.75	364.8	1817.6	370.2	90.0	31.7	28.5	90.2	30.7	33.8	97.6
di!20235	82.5	476.8	546.3	6.74	364.0	1826.0	371.8	93.5	28.7	26.8	89.5	31.6	35.3	97.6
di!20238	82.5	504.7	660.9	6.79	365.2	1889.1	372.6	92.6	26.7	24.7	88.3	32.3	36.7	92.3
di 1 20242	82.5	508.1	771.1	6.94	366.6	1 93 1 .4	374.4	89.6	25.3	22.7	88.1	33.3	37.2	92.3

Table D2: Table of 1550 rpm diesel performance results

TLC Test	Speed	Load	Brake Power	Indicated	Indicated	imep	bmep	Equivalence	Air/Fuel	Air	Fuel	Fuel Conv	isfc	bsfcf	Inj Point	Ign Point	Ign Delay
Name	**(rpm)**	**(Nm)**	**(kW)**	**Work/Cvcle (J)**	**Power (kW)**	**(MPa)**	**(MPa)**	**Ratio**	**Ratio**	**(g/s)**	**(g/s)**	**Eff(%)**	**(kg/J)**	**(kg/J)**	**(°CA)**	**(°CA)**	**(°CA)**
di050202	1550.9	7.2	1.170	150.8	3.898	0.227	0.068	0.278	53.88	15.824	0.29	9.1	7.50E-08	2.50E-07	340.0	357.7	17.7
di050207	1550.9	14.3	2.330	190.7	4.929	0.287	0.136	0.31	48.32	15.693	0.32	16.5	6.60E-08	1.40E-07	340.0	357.5	17.5
di050208	1553.7	22.5	3.656	238.7	6.180	0.359	0.212	0.367	40.90	15.575	0.38	22.0	6.20E-08	1.00E-07	340.0	357.1	17.1
di050215	1553.7	28.0	4.558	264.1	6.838	0.397	0.265	0.413	36.22	15.482	0.43	24.5	6.30E-08	9.40E-08	340.5	357.3	16.8
di050218	1553.7	37.0	6.021	311.7	8.073	0.469	0.350	0.498	30.01	15.348	0.51	27.0	6.30E-08	8.50E-08	341.0	356.60	15.6
di050220	1556.5	43.0	7.005	352.5	9.144	0.530	0.406	0.546	27.41	15.213	0.55	29.0	6.10E-08	7.90E-08	341.0	355.70	14.7
di050224	1556.5	50.4	8.220	378.2	9.811	0.569	0.477	0.61	24.48	15.186	0.62	30.4	6.30E-08	7.50E-08	341.0	355.70	14.7
di050230	1556.5	55.0	8.962	410.8	10.656	0.618	0.520	0.72	20.73	15.118	0.73	28.2	6.80E-08	8.10E-08	342.0	355.90	13.9
di050233	1559.3	58.4	9.531	430.2	11.179	0.647	0.552	0.813	18.41	14.968	0.81	26.9	7.30E-08	8.50E-08	342.5	355.30	12.8
di050239	1559.3	61.6	10.054	436.5	11.343	0.656	0.582	0.974	15.34	14.955	0.97	23.7	8.60E-08	9.70E-08	342.5	354.70	12.2
di050240	1559.3	62.1	10.145	425.7	1 1.062	0.640	0.587	1.19	12.56	14.858	1.18	19.7	1.10E-07	1.20E-07	343.0	354.90	11.9

TLC Test	Pressure	Before Cat.	After Cat.	Max Pressure	Position of	Max	Position of	Mechanical	ITE	BTE	Vol	Ambient	Manifold Air	Injector
Name	Atm. (kPa)	Temp. (°C)	Temp. (°C)	(MPa)	Pmax (°CA)	Temp. (K)	Tmax (°CA)	Efficiency (%)	(%)	(%)	Eff(%)	Temp. (°C)	Temp. (°C)	Pressure (MPa)
di050202	82.0	178.8	214.0	4.79	363.4	1257.4	370.2	30.0	30.4	9.1	92.1	26.4	29.0	91.6
di050207	81.5	210.2	264.0	5.06	364.0	1336.4	370.2	47.3	34.8	16.5	91.3	27.4	31.4	86.7
di050208	81.1	246.9	311.0	5.51	363.8	1494.2	369.4	59.2	37.2	22.0	90.4	28.3	32.4	80.9
di050215	81.1	285.2	337.0	5.68	363.0	1536.5	368.8	66.7	36.7	24.5	89.9	28.8	33.3	76.6
di050218	81.1	338.1	381.0	6.02	366.8	166.3.5	368.0	74.6	36.2	27.0	89.1	29.2	33.8	75.7
di050220	81.1	385.6	424.0	6.26	366.4	1769.9	369.2	76.6	37.8	29.0	88.2	29.9	34.8	71.4
di050224	81.1	431.2	472.0	6.47	365.8	1791.9	368.6	83.8	36.3	30.4	88	30.3	35.3	71.4
di050230	81.1	492.4	540.0	6.67	366.4	1879.6	370.8	84.1	33.5	28.2	87.6	30.7	37.2	66.8
di050233	81.1	532.6	605.0	6.77	365.8	1931.1	370.2	85.3	31.5	26.9	86.6	31.6	37.7	69.0
di050239	83.5	560.1	785.0	6.86	365.8	1961.6	371.8	88.6	26.7	23.7	86.5	32.3	38.6	71.4
di050240	83.5	548.3	779.0	6.77	366.0	1966.5	370.4	91.7	21.4	19.7	86	33.3	39.6	64.3

Table D3: Table of 1750 rpm diesel performance results

TLC Test Name	Speed (rpm)	Load (Nm)	Brake Power (kW)	Indicated Work/Cycle (J)	Indicated Power (kW)	imep (MPa)	bmep (MPa)	Equivalenc Ratio	Air/Fuel Ratio	Air Flow (g/s)	Fuel Flow (g/s)	Fuel Eff(%)	isfc (kg/J)	bsfcf (kg/J)	Inj Point (°CA)	Ign Point (°CA)	Ign Delay (°CA)
di060201	1748.6	6.7	1.229	169.2	4.932	0.255	0.063	0.245	61.12	17.761	0.29	9.7	5.90E-08	2.401 --07	341.0	358.5	17.5
di060207	1751.4	13.5	2.473	198.2	5.786	0.298	0.127	0.3	49.79	17.876	0.36	15.8	6.20E-08	1.50E-07	341.0	358.7	17.7
di060208	1751.4	22.3	4.099	256.4	7.485	0.386	0.211	0.365	40.98	17.772	0.43	21.7	5.80E	1.10E-07	342.0	358.1	16.1
di060214	1751.4	27.3	5.003	274.3	8.008	0.413	0.258	0.418	35.70	17.61	0.49	23.3	6.20E-08	9.90E-08	342.0	357.9	15.9
di060220	1751.4	37.4	6.866	321.0	9.371	0.483	0.354	0.543	27.50	17.398	0.63	24.9	6.80E-08	9.20E-08	342.00	357.30	1 5.3
di060224	1754.2	43.1	7.918	380.2	11.116	0.572	0.407	0.641	23.33	17.16	0.74	24.7	6.60E-08	9.30E-08	342.50	356.70	14.2
di060227	1754.2	50.5	9.275	433.8	12.683	0.652	0.477	0.783	19.11	17.148	0.90	23.7	7.10E-08	9.70E-08	342.50	355.90	13.4
di060234	1757.0	52.8	9.720	438.0	12.826	0.659	0.499	0.954	15.68	16.943	1.08	20.6	8.40E-08	1.10E-07	343.00	355.30	12.3

TLC Test Name	Pressure Atm. (kPa)	Before Cat. Temp. (°C)	After Cat. Temp. (°C)	Max Pressure (MPa)	Position of Pmax (°CA)	Max Temp. (K)	Position of Tmax (°CA)	Mechanical Efficiency (%)	ITE (%)	BTE (%)	Vol Eff (%)	Ambient Temp. (°C)	Manifold Temp. (°C)	Injector Pressure (MPa)
di060201	84.0	191.6	241.0	4.92	364.4	1288.1	371.0	24.9	38.9	9.7	91.6	28.4	30.4	48.9
di060207	84.0	213.1	267.8	5.18	365.2	1362.4	371.6	42.7	37	15.8	92.1	28.8	30.9	78.5
di060208	84.0	251.8	312.9	5.43	365.2	1461.0	371.6	54.8	39.6	21.7	91.6	29.3	31.4	74.3
di060214	84.0	285.6	340.4	5.62	365.2	1563.8	372.0	62.5	37.3	23.3	90.7	29.7	32.4	73.8
di060220	83.5	369.0	416.7	6.08	365.2	1696.1	370.2	73.3	34.0	24.9	89.6	28.4	30.9	71.4
di060224	83.5	457.2	501.0	6.34	367.0	1823.9	375.2	71.2	34.7	24.7	88.3	29.3	32.9	72.8
di060227	83.5	527.2	587.6	6.91	366.6	1964.4	373.0	73.1	32.4	23.7	88.2	30.5	32.9	76.6
di060234	83.5	582.1	800.8	6.82	367.2	1981.0	372.2	75.8	27.2	20.6	87.0	33.6	34.3	71.7