ADDITION OF HYDROGEN TO GASOLINE-FUELLED 4 STROKE SI ENGINE USING 1-DIMENSIONAL ANALYSIS

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SUPERVISOR’S DECLARATION

I hereby declare that I have checked this project and in my opinion, this project is adequate in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

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Position:Lecturer
Date: 24 November 2009

STUDENT’S DECLARATION

I hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurently submitted for award of other degree.

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Dedicate to my beloved dad,lovely mom and my honour siblings

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ABSTRACT

This thesis was about simulation analysis on 4 stroke single cylinder engine by 1-Dimensional software. Objective of this thesis is to investigate the effect of NOx emission when hydrogen addition is added to the engine and relation between hydrogen addition and cylinder temperatures. Through these objectives, result of the project can obtain by using 1-Dimensional analysis software. GT-Power software is 1-Dimensional analysis software used in this project. GT-Power was used to develop a baseline design engine in order to do a simulation for 4 stroke single cylinder engine. Air-fuel ratios for hydrogen-gasoline mixture are calculated to get the stoichiometric for mixture. In this thesis, air-fuel ratio is used as parameters in GT-Power software. Default parameter in the GT-Power software was used as an engine parameter in this thesis. The ratio of hydrogen-gasoline fuel also must be change at SI-inject which is intake valve in GT-Power software. With using default parameter from GT-Power software, a baseline design engine can be developed before run the simulations. After finish the simulation, the results are plotted by using Microsoft Excel. There are many result can be obtained by using GT-Power software but for this simulation, result of NOx emission and temperature are to be consider in this project. These 2 analyses were performed at 3 different engine speeds which are 1000 rpm, 3000 rpm and 5000 rpm, and at 10 until 20 air-fuel ratio. The result shown NOx emissions increased with the increase of hydrogen addition due to the raised cylinder temperature.

ABSTRAK

Tesis ini adalah tentang analisis simulasi pada enjin 4 lejang, satu silinder oleh perisian 1-Dimensi. Objektif dari tesis ini adalah untuk meneliti kesan daripada emisi NOx ketika Selain hidrogen ditambah kepada enjin dan hubungan antara penambahan hidrogen dan suhu silinder. Melalui matlamat ini, hasil daripada projek boleh memperoleh dengan menggunakan analisis perisian 1-Dimensi. GT-Power perisian adalah 1-Dimensional perisian analisis yang digunakan dalam projek ini. GT-Power digunakan untuk membangunkan rekaan asas enjin sebelum simulasi dilakukan terhadap enjin 4 lejang, satu silinder. Nisbah udara-bahan bakar untuk campuran hidrogen-petrol dikira untuk mendapatkan stoikiometrik untuk campuran. Dalam tesis ini, nisbah udara-bahan api digunakan sebagai parameter dalam GT-Power perisian. Default parameter dari perisian GT-Power digunakan sebagai peramter enjin dalam tesis ini. Nisbah bahan bakar hidrogen-petrol juga harus diubah pada SI-Inject iaitu injap intake dalam perisian GT-Power. Dengan menggunakan parameter daripada perisian GT-Power , sebuah dasar enjin dapat dibangunkan sebelum simulasi dijalankan. Setelah selesai simulasi, hasilnya diplot dengan menggunakan Microsoft Excel. Ada banyak keputusan boleh diperolehi dengan menggunakan GT-Power perisian namun untuk simulasi ini, hasil daripada emisi NOx dan suhu harus dipertimbangkan dalam projek ini. 2 analisis ini dilakukan pada 3 kelajuan enjin yang berbeza adalah 1000 rpm, 3000 rpm dan 5000 rpm, dan pada 10 hingga 20 nisbah udara-bahan api. Keputusannya menunjukkan bahawa emisi NOx meningkat dengan pertambahan hydrogen disebabkan meningkatnya suhu didalam silinder.

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LIST OF SYMBOLS

Φ	Equivalent ratio
>	More than
<	Less than

LIST OF NOMENCLATURE

CH_4	Methane
C_3H_8	Propane
C_8H_{18}	Gasoline
CO_2	Carbon dioxide
CO	Carbon oxide

NO_X	Nitrogen Oxides
N_2	Nitrogen

LIST OF ABBREVEATIONS

AFR	Air-Fuel ratio
BMEP	Brake mean effective pressure
CFD	Computational Fluid Dynamics
Deg C	Degree Celcius
DOE	Design of experiment
EGR	Exhaust gas circulation
Env	Environment
Exvalve	Exhaust valve
Exhport	Exhaust port
Exhrunner	Exhaust runner
FProp Gas	Fluid properties gas
FPropLiqIncomp	Fluid properties liquid incompressible
FKM	Fakulti Kejuruteraan Mekanikal
H2	Hydrogen
HC	Hydro Carbon
ICE	Internal Combustion Engine
Intrunner	Intake runner
Ign	Ignore
Intvalve	Intake valve
Intport	Intake port
PPM	Parts per million
SI	Spark ignition

Vap	Vapor

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

1.1.1 Internal Combustion Engine

The Internal Combustion Engine (ICE) is a heat engine that converts chemical energy in a fuel into mechanical energy, usually made available on rotating output shaft. Chemical energy of the fuel is the first converted to thermal energy by mean of combustion or oxidataion with air inside the engine. The thermal energy raises the temperature and pressure of the gas within the engine, and the high pressure gas then expands against the mechanical mechanism of the engine. This expansions is converted by mechanical linkage of the engines to rotating crankshaft, which is the output of the engine. The crankshaft, in turn is connected to transmission and power train to transmit the rotating mechanical energy to the desire final use. For engines this will often be the propulsion of a vehicle (Williard W. Pulkrabek, 2004).

Most Internal Combustion Engine are reciprocating engines having piston and reciprocate back and forth in cylinder internally within the engine. Reciprocating engines can have one cylinder or many, up to 20 or more. The cylinder can be arranged in many different geomatric configurations (Williard W. Pulkrabek, 2004).

The term internal combustion engine usually refers to an engine in which combustion is intermittent, such as the more familiar four-stroke and two-stroke piston engines, along with variants, such as the Wankel rotary engine. A second class of internal combustion engines use continuous combustion: gas turbines, jet engines and most rocket engines, each of which are internal combustion engines on the same principle .

The internal combustion engine (or ICE) is quite different from external combustion engines, such as steam or Stirling engines, in which the energy is delivered to a working fluid not consisting of, mixed with or contaminated by combustion products. Working fluids can be air, hot water, pressurised water or even liquid sodium, heated in some kind of boiler by fossil fuel, wood-burning, nuclear, solar etc .

1.1.2 4 Stroke Engine

The four stroke internal combustion engines has to do 4 things to complete one cycle. The four stroke internal combustion engine which uses petrol as the burning fuel is known as four stroke petrol engine. The fuel actually used in the engine is the mixture of petrol and air (oxygen, used to ignite petrol).Four stroke engine includes the following strokes;

1. Intake or Suction Stroke

The piston starts at TDC, the intake valve opens and the piston moves down to let the engine to take in a cylinder-full of fuel (mixture of air and petrol). This is the intake stroke. Only the tiniest drop of gasoline needs to be mixed into the air for this to work. The piston is connected to crankshaft with the help of connecting rod. This crankshaft is further transforms the mechanical work into desired output.

2. Compression Stroke

Then in the compression stroke the piston moves back up to the extreme top position which compress the fuel (air + petrol mixture). The use or benefit of compression is to make the explosion more powerful. This stroke increases the temperature of fuel which
produces large amount of heat during ignition

3. Power or Combustion Stroke

Then in the Powerstroke, the fuel is then ignited near the end of the compression stroke, with the help of spark plug. The spark plug ignites the spark right before the power stroke which burns the fuel. The resulting pressure of burning fuel pushes the piston back to the extreme end or down position.

4. Exhaust stroke

In the exhaust stroke, once the piston hits the bottom of its stroke, the exhaust valve opens and the exhaust leaves the cylinder to go out through the exhaust pipe which is attached to exhaust valve. Now the engine is ready for the next cycle, so it intakes another charge of fuel and repeats the entire process (Garrett W. Balich, Conrad R. Aschenbach, 2004).

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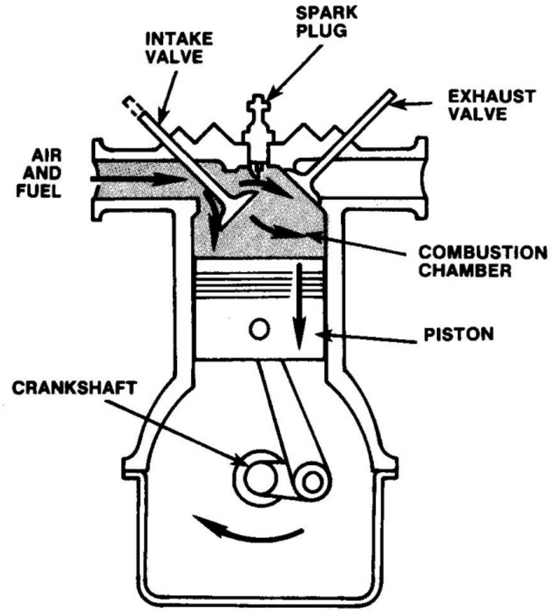


Figure 1.1 Cross-section view 4 stroke engine.

Source: Willard W. Pulkrabek

1.1.3 Spark Ignition(S1)

An SI engine starts the combustion process in each cycle by use of spark plug. The spark plug gives a high-voltage electrical discharge between two electrodes which ignites the air- fuel mixture in the combustion chamber surrounding the plug. In early engine development, before the invention of the electric spark plug, many forms of torch holes were used to initiate combustion from an external flame (John B. Heywood, 1988).

1.1.4 Fuel Injection

Fuel injection systems work by delivering a metered air and fuel mixture to the engine for combustion. The incoming air is controlled through a throttle body, usually controlled with butterfly valves. The incoming air is then metered through a sensing device and an appropriate mass of fuel is added to the air stream through an electrically controlled injector.

Similarly to the carburetor, the most important task of the modern fuel injection system is to deliver a stoichiometric mixture of fuel and air to the engine for combustion, This stoichiometric mixture is achieved by electronically controlling the timing of the injectors from the start to the end of fuel injection, which combat the various needs of the engine operation under varying conditions. To achieve the necessary symmetry in the electronic fuel injection system, the fuel must be delivered to the system continuously and reliably without pulsation at a controlled constant pressure with a fuel pump. The fuel must be closely metered and delivered in an atomized form into the engine manifold through injectors without liquid fuel entering the manifold. And lastly, a multitude of sensors for monitoring the environmental and engine conditions must be able to send accurate information to an engine management computer which must accurately run the whole fuel injection system (Garrett W. Balich, Conrad R. Aschenbach, 2004).

1.2 PROBLEM STATEMENT

Air pollutants cause health problems and smog. As concerns over how emissions from mobile sources affect the environment and human health, and the supply of conventional fuel diminishes, researchers are constantly striving towards developing more efficient combustion while decreasing emissions. Hydrogen has an attractive properties which is clean and renewable. As a result, it has been used as a fuel in internal combustion engines, fuel cells and as an additive to conventional fuels such as gasoline or methane (T. D’Andrea, P.F. Henshaw, D.S.-K. Ting, 2004).

1.3– OBJECTIVE PROJECT

Objectives of this project:

1) To investigate effect of hydrogen addition to gasoline fuel on NOx emission of 4stroke SI engine based on GT-Power simulation.
2) To assess the influence of hydrogen addition to the cylinder temperature.

1.4– PROJECT SCOPE

Scopes of this project:

1) Study about 4 stroke single cylinders Spark Ignition engine.
2) 1-Dimensional analysis for 4 stroke engine based on GT-Power software.
3) Simulation engine using default parameter from tutorial.
4) Investigate on NOx emission when hydrogen are added to gasoline fuel
5) Investigate on NOx concentration and temperature to Air-Fuel Ratio and equivalent ratio
6) Run the simulation at 3 different engine speeds.

1.5 PROJECT PURPOSE

The purpose of this research is to investigate the effect of hydrogen addition on combustion and emissions when added to a gasoline-fuelled SI engine based on GT-Power software.

1.6 PROJECT’S AIM

This thesis should work well and will finish on time. The knowledge from this project supposedly can be applied when practical soon for next semester.

CHAPTER 2

2.1 INTRODUCTION

Combustion of fossil fuels has caused serious problems to the environment and the geopolitical climate of the world. The main negative effects on the environment by Fossil fuel combustion are emissions of NOx, CO, CO2, and unburned hydrocarbons. The main negative effect of burning fossil fuel on the geopolitical climate is the lack in supply of these fuels and the effect pollution has on politics. There are several possible solutions to alleviate the problems of using fossil fuels, but most of them would require years of further development and additional infrastructure. This method involves burning hydrogen gas along with hydrocarbon fuels in engines. The principle of this mode of combustion is to add a percentage of hydrogen gas to the combustion reactions of either compression or spark ignition engines. The addition of hydrogen has been shown to decrease the formation of NOx, CO and unburned hydrocarbons. Studies have shown that added hydrogen in percentages as low as 5-10% percent of the hydrocarbon fuel can reduce that hydrocarbon fuel consumption. The theory behind this concept is that the addition of hydrogen can extend the lean operation limit, improve the lean burn ability, and decrease burn duration. (Jacob Wall, 2008).

2.2 APPLICATION OF HYDROGEN ON CONVENTIONAL ENGINE

As a promising fuel, H2 can be used in traditional internal combustion engine, gas turbine and also the innovative fuel cell. Among these, operation of the most fuel cells requires pure H2. The presence of other components such as CO could deactivate significantly the catalyst of fuel cells and reduce significantly the service life. Such an excessively demanding requirement for high purity H2 makes the operation of hydrogen fuel cells economically uncompetitive though high thermal efficiency could be achieved without formation of pollutant. In comparison to fuel cells, internal combustion engine can burn almost any low purity H2 even with the presence of quiet a large amount of diluents. For example, the reformed gas containing mainly H2 with the presence of CO, CO2, H2O and N2, has been demonstrated as a good fuel showing H2-like desirable combustion properties. The application of H2 or its mixtures with traditional fuels offers also opportunity of optimizing engine performance and reducing exhaust emissions. Considering the significant difference of spark ignition gasoline engine and compression ignition diesel engine, the H2 application in these engines has been reviewed, respectively (Das, L.M, 1990) .

2.2.1 Hydrogen Application in S.I Engines

Most of the past research on H2 as a fuel focused on its application in S.I. engines. It has long been recognized as a fuel having some unique and highly desirable properties, such as low ignition energy, and very fast flame propagation speed, wide operational range. H2 has also been demonstrated being able to supporting a propagating flame at extremely lean mixture, which is a very attractive property of H2 as S.I. engine fuel. The extensive research pure H2 as fuel has led to the development and successful marketing of hydrogen engine. For example, Ford developed P2000 hydrogen engine, which was used to power Ford’s E-450 Shuttle Bus (Li, H.L, Karim, G.A, 2005). BMW developed a 6 liter, V-12 engine using liquid H2 as fuel. With an external mixture formation system, this engine has a power out about 170 kW and an engine torque of 340 N.m. Most of the research associated with H2 application in S.I. engines focused on its substitution to gasoline, which is called H2 enriching process. The extensive researches in this area have demonstrated that H2 enriching help to improve the performance of S.I. engine for the following reasons: (1) Enhancing the flame propagation rate: the propagation rate of H2 flame is about 4 times that of traditional fuels. The addition of hydrogen to traditional fuel was shown to enhance the flame propagation rate; (2) Expended lean operational region: the past experiments have demonstrated the super capability of H2 in supporting flame propagation at very lean mixture. The addition of H2 to traditional fuels has been show to expend the operational region toward the leaner mixture, which is very important to obtain extremely low NOx emissions; (3) Improving combustion stability (less cycle to cycle variation) and enhancing combustion efficiency with reduced emissions of CO and HC. Detailed information can be found in the literature (White C.M., Steeper, R.R., and Lutz, A.E, 2006)

2.3 PROPERTIES OF HYDROGEN

The properties of hydrogen are detailed in Section 1. The properties that contribute to its use as a combustible fuel are its:

- wide range of flammability

- low ignition energy

- small quenching distance

- high autoignition temperature

- high flame speed at stoichiometric ratios

- high diffusivity

- very low density

Wide Range of Flammability

Hydrogen has a wide flammability range in comparison with all other fuels. As a result, hydrogen can be combusted in an internal combustion engine over a wide range of fuel-air mix-tures. A significant advantage of this is that hydrogen can run on a lean mixture. A lean mixture is one in which the amount of fuel is less than the theoretical, stoichiometric or chemically ideal amount needed for combustion with a given amount of air. This is why it is fairly easy to get an engine to start on hydrogen.

Generally, fuel economy is greater and the combustion reac-tion is more complete when a vehicle is run on a lean mix-ture. Additionally, the final combustion temperature is generally lower, reducing the amount of pollutants, such as nitrogen oxides, emitted in the exhaust. There is a limit to how lean the engine can be run, as lean operation can sig-nificantly reduce the power output due to a reduction in the volumetric heating value of the air/fuel mixture.

Low Ignition Energy

Hydrogen has very low ignition energy. The amount of energy needed to ignite hydrogen is about one order of magnitude less than that required for gasoline. This enables hydrogen engines to ignite lean mixtures and ensures prompt ignition.

Unfortunately, the low ignition energy means that hot gases and hot spots on the cylinder can serve as sources of igni-tion, creating problems of premature ignition and flashback. Preventing this is one of the challenges associated with run-ning an engine on hydrogen. The wide flammability range of hydrogen means that almost any mixture can be ignited by a hot spot.

Small Quenching Distance

Hydrogen has a small quenching distance, smaller than gasoline. Consequently, hydrogen flames travel closer to the cylinder wall than other fuels before they extinguish. Thus, it is more difficult to quench a hydrogen flame than a gasoline flame. The smaller quenching distance can also increase the tendency for backfire since the flame from a hydrogen-air mixture more readily passes a nearly closed intake valve, than a hydrocarbon-air flame.

High Autoignition Temperature

Hydrogen has a relatively high autoignition temperature. This has important implications when a hydrogen-air mix-ture is compressed. In fact, the autoignition temperature is an important factor in determining what compression ratio an engine can use, since the temperature rise during com-pression is related to the compression ratio. The temperature rise is shown by the equation:

where:

V_1/V_2 = the compression ratio

T_1 = absolute initial temperature

T_2 = absolute final temperature

γ = ratio of specific heats

The temperature may not exceed hydrogen's autoignition temperature without causing premature ignition. Thus, the absolute final temperature limits the compression ratio. The high autoignition temperature of hydrogen allows larger compression ratios to be used in a hydrogen engine than in a hydrocarbon engine.

This higher compression ratio is important because it is re-lated to the thermal efficiency of the system. On the other hand, hydrogen is difficult to ignite in a compression ignition or diesel configuration, because the temperatures needed for those types of ignition are rela-tively high.

High Flame Speed

Hydrogen has high flame speed at stoichiometric ratios. Un-der these conditions, the hydrogen flame speed is nearly an order of magnitude higher (faster) than that of gasoline. This means that hydrogen engines can more closely approach the thermodynamically ideal engine cycle. At leaner mixtures, however, the flame velocity decreases significantly.

High Diffusivity

Hydrogen has very high diffusivity. This ability to disperse in air is considerably greater than gasoline and is advanta-geous for two main reasons. Firstly, it facilitates the forma-tion of a uniform mixture of fuel and air. Secondly, if a hydrogen leak develops, the hydrogen disperses rapidly. Thus, unsafe conditions can either be avoided or minimized.

Low Density

Hydrogen has very low density. This results in two problems when used in an internal combustion engine. Firstly, a very large volume is necessary to store enough hydrogen to give a vehicle an adequate driving range. Secondly, the energy density of a hydrogen-air mixture, and hence the power output, is reduced.

2.4 HYDROGEN AS DEDICATED FUEL

Hydrogen's unique properties as a fuel in ICE give it a significant advantage over other fuels including gasoline, diesel, methane or ethanol. An overview of the characteristics of hydrogen as a fuel for SI engines was presented by (Karim, G.A, 2003). Hydrogen possesses some features that make it really attractive: enabling fast, close to constant volume combustion, high combustion efficiency and low emissions. These advantages include the possibility of reaching a near zero emissions of the regulated emissions of CO and HC while simultaneously eliminating CO2 emissions, and greatly improved cold start capability.

$$2H2 + O2 \longrightarrow 2H2O$$

Hydrogen's combustion properties enable the development of an engine that would meet all current and future emissions standards at a price comparable to current engines with cheaper after treatment devices. The flame speed of hydrogen is higher and hydrogen allows operation with significantly higher excess air ratios than conventional hydrocarbon fuels. This enables extended lean burn operation of the engine, potentially leading to a drastic reduction of NOx emissions because of the lower combustion temperatures. High diffusivity and low quenching distance avoids poor vaporization problems. Emissions of CO and HC are practically eliminated with hydrogen fuelled ICE, as the only source of carbon will be the lubricating oil. When hydrogen burns, the main chemical reaction that takes place is shown in Eq. (1), showing the lack of carbon bearing compounds. For the same reason the engine does not emit CO2. The only non-trivial exhaust gas emissions will be the NOx, which result from the oxidation of atmospheric nitrogen under high temperatures. It will be shown below that with hydrogen fuelled ICE operation and a very lean mixture this pollutant can be reduced to near-zero levels. The ignition energy for hydrogen is low, however the temperature required for auto ignition is significantly higher than that of conventional hydrocarbon fuels. Therefore, SI engines using hydrogen fuel require a less energetic plug that permits a shorter plug gap without auto ignition of the fuel/air mixtures before the spark occurs. A comprehensive review of hydrogen fuelled ICEs was presented (White C.M., Steeper, R.R, and Lutz, A.E, 2006)

2.5 ADVANTAGE OF USING HYDROGEN AS FUEL

There are many advantages of using hydrogen as fuel that we should know, below some of this advantages:

- Hydrogen is a very clean fuel that produces minimal emissions when combusted directly or in combination with hydrocarbon fuels.
- Hydrogen can be produced anywhere in the world
- If Hydrogen is used in place of fuel, hydrogen fuel cells will cost a lot less than filling up a tank of gasoline.
- Whey hydrogen is used in a fuel cell, the only byproducts are heat and water.
- Typical gasoline powered cars only use about 20% of the fuel to power the car. With hydrogen fuel cell cars, around 40-60% of the fuel is used to power the electric motor.
- Reduced dependency on foreign oil. The hydrogen used for powering hydrogen fuel cell cars can be made from a variety of sources including water. This means that there will be less dependence on foreign oil for gasoline.
- Use of hydrogen energy will cut down on atmospheric pollution
- Hydrogen is safer than gasoline, diesel, or natural gas.
- High energy content per volume when stored as a liquid. This would give a large vehicle range for a given fuel tank capacity.

2.5.1 Disadvantage Of Using Hydrogen As Fuel

Beside of that, there is also disadvantage of using hydrogen as fuel.

- Hydrogen is most commonly separated by a reforming process that uses natural gas and other fossil fuels. Supplies of natural gas are becoming harder to obtain, and coal is a source of major pollution.
- The technology to produce, store, and transport hydrogen power at an efficient cost is not yet available and will not likely be for a long while.

- It takes more energy to make Hydrogen than you get from it.
- A hydrogen fuel cell car will not be able to travel as far on a tank of fuel as a traditional gasoline powered car. The fuel cell cars are not equipped to store the amount of hydrogen needed for long distances, so you would need to fill up more often.
- If you live in an area where the temperature gets down to freezing, you might have a problem with your hydrogen fuel cell car. Since these cars have water in the fuel cell system constantly, there is a risk it could freeze. Also, the hydrogen fuel cell car has to be at a certain temperature to perform well.
- Requirement of heavy, bulky fuel storage in vehicle and at the service station. Hydrogen can be stored either as a cryogenic liquids or as a compressed gas. If stored as liquid, it would have to be kept under pressure at very low temperature. This would require a thermally super-insulted fuel tank. Storing in gas phase would require a high pressure vessel with limited capacity.
- Poor engine volumetric efficiency. Any time a gaseous fuel is used in an engine, the fuel will displace some of the inlet air and poorer volumetric efficiency will result.
- Fuel cost would be high at present-day technology and availability.
- High NOx emissions because of high flame temperature (V Ganesan, 2003).

2.6 PREVIOUS RESEARCH

2.6.1 Past research involving hydrogen addition to gasoline engine

Work concentrating on the reduction in fuel consumption with the addition of hydrogen has been previously conducted. Lucas and Richards (Lucas GG, Richards WL, 1982) ran an engine on what they called “dual fuel”. The engine was fuelled by hydrogen only while idling and then was run with a constant hydrogen flow rate to which gasoline was added as the load increased. The dual fuelling reduced fuel consumption by up to 30% . The higher thermal efficiency found was a result of the engine being able to run at wide open throttle throughout the load range, minimizing heat losses to coolant and pumping losses. Combustion was maintained throughout the load range due to the wide flammability limit and high flame speed of hydrogen. As a result of lean operation, CO emissions were reduced due to an increase in completeness of combustion and NOx decreased due to a reduction in the peak in-cylinder temperatures. Similarly, May and Gwinner (May H, Gwinner D, 1983) used hydrogen with excess air for starting and idling an SI engine. At part load both hydrogen and gasoline were supplied to the engine and at full load gasoline alone fuelled the engine to avoid a power loss. A 25% improvement in efficiency was found at part load due to the ability to operate at full throttle and emissions were reduced due to the lower fuel/air equivalence ratios.

Stebar and Parks (Stebar RF, Parks FB, 1974) used hydrogen-supplemented fuel as a means of extending the lean limit of operation in a gasoline engine in order to control NOx . A single-cylinder engine was tested while adding 10% hydrogen by mass of fuel. The lean limit was extended from (Φ=0:89) to 0.55 reducing NOx emissions to near minimal levels. However, as a consequence of running on lean mixtures, the HC emissions increased. The effect of hydrogen addition on the combustion processes was also examined by Apostolescu and Chiriac (Apostolescu N, Chiriac R, 1996), who studied the effect of adding hydrogen to a gasoline fuelled single cylinder passenger car engine at mid- and light-load operation. They were able to shorten combustion duration with the addition of hydrogen and thus reduced cycle-to-cycle variability and extended the lean limit of operation. Interestingly, when adding 1.5% and 3% H2 by mass to a gasoline fuelled SI engine, they saw close to the same decrease in the crank angle duration required to burn the 6rst 10% of the charge. There was, however, a noticeable difference in the decrease of the 10–90% burn duration for varying hydrogen additions (1.5% versus 3%), with a greater decrease as the hydrogen addition increased. Unburned hydrocarbon emissions were reduced while operating with excess air; however, the NOx emissions tended to increase at those same conditions. Only at very low fuel/air equivalence ratios ($\Phi \approx$ 0:7) did the NOx emissions decrease at which point the HC emissions increased. Rauckis and McLean (Rauckis MJ, McLean WJ, 1979) investigated the effect of supplementing indolene (automotive test fuel) with hydrogen on the burn duration in an SI engine while varying the equivalence ratio and hydrogen energy fraction from5% to 28%. The added hydrogen led to improved efficiency and reduced cycle-to-cycle variation. They found that the main e8ects of the hydrogen addition were a substantial decrease in the 0–2% burn duration, a smaller reduction in the 2–10% burn duration, and an even smaller change in the 10–90% burn duration. Reductions in burn duration increased with increasing fractions of hydrogen throughout the combustion phases, with the effects being more significant in leaner mixtures (T. D'Andrea, P.F. Henshaw , D.S.-K. Ting, 2004).

Jacob Wall from Department of Biological and Agricultural Engineering University of Idaho have been research about Effect of Hydrogen Enriched Hydrocarbon Combustion on Emissions and Performance by using experimental analysis. He conclude that the usage of hydrogen as additive to gasoline fuel will increase thermal efficiency and decrease fuel consumption, decrease carbon monoxide and unburned hydrocarbon emissions and increase NOx emissions unless proper timing and mixture adjustments are used (Jacob Wall, 2008).

Changwei Ji and Shuofeng Wang College of Environmental and Energy Engineering, Beijing University of Technology already done a research involving hydrogen addition on combustion and emissions performance of a spark ignition gasoline engine at lean conditions by using experimental method . In their paper, they conclude when the excess air ratio is around stoichiometric conditions, Bmep decreases with the increase of hydrogen addition fraction. But when the engine runs under lean conditions, the addition of hydrogen helps in improving Bmep. The engine brake thermal efficiency and the relevant excess air ratio for the maximum brake thermal efficiency increases with the addition of hydrogen. The peak brake thermal efficiency increases from 26.37% for the original gasoline engine to 31.56% for the hydrogen-enriched gasoline engine at 6% hydrogen addition fraction. The maximum cylinder temperature and the peak cylinder pressure increase, while the flame development and propagation durations reduce with the increase of hydrogen addition. The cyclic variation is also effectively eased by hydrogen addition, especially at lean conditions.
HC and CO2 emissions are obviously reduced with the increase of hydrogen blending level. CO emission increases with hydrogen addition when the excess air ratio is around stoichiometric, but decreases with the addition of hydrogen under lean conditions. Due to the increased cylinder temperature, NOx emissions are obviously increased with the Increase of hydrogen fraction at the same excess air ratios (Jingding L, Linsong G, Tianshen, 1998).

2.6.2 Addition of hydrogen on gasoline fuelled SI engine

Using hydrogen as an additive offers the possibility of enhancing the mixture by taking advantage of properties from both fuels. The properties of hydrogen along with those of methane, propane and gasoline are listed for comparison in Table 1. Hydrogen has a flame speed more than five times greater than the hydrocarbon fuels listed here. Also, it has a lean limit (mixture at which flame will not propagate due to excess air) of Φ= 0:1, much lower than the theoretical limit of gasoline (Φ = 0:6). Theoretically, it is possible to extend the lean limit of the mixture, by adding a small amount of hydrogen to a liquid or gaseous hydrocarbon fuel. Operating with abundant excess air ensures more complete combustion, improves efficiency and results in a decrease in peak temperatures, which aids in lowering NOx , while eliminating problems commonly associated with operating on lean mixtures (Stebar RF, Parks FB and Apostolescu N, Chiriac R, 1974 and 1996). Secondly, the higher flame speed increases the rate of combustion of the mixture and lowers cycle-to-cycle variations (Varde KS and Bell SR, Gupta M, 1981 and 1997). Hydrogen has a higher diffusivity compared to hydrocarbon fuels, which improves mixing, enhances turbulence and increases homogeneity in the charge. The lower ignition energy requirement for hydrogen ensures prompt ignition and eases cold starts. The quenching gap refers to the largest passage that will extinguish a flame. The smaller quenching gap exhibited by hydrogen in comparison to gasoline means that the flame could travel closer to the cylinder wall and farther into crevices resulting in more complete combustion. Hydrogen does, however, have a lower heating value per mole than the hydrocarbon fuels, and therefore a power decrease would occur as the hydrogen is substituted for a hydrocarbon fuel.

Table 2.1: Listing of hydrogen properties along with methane, propane and gasoline for comparison.

Properties	Hydrogen	Methane	Propane	Gasoline
Chemical formula	H2	CH4	C3H8	(C8H18)
Minimum ignition energy (mJ)	0.02	0.29	0.26	0.24
a. Flame speed (cm/s)	237	42	46	41.5

b. Diffusion coefficient (cm2=s)	0.61	0.16	0.12	0.05
Quenching gap (cm)	0.06	0.2	0.2	0.2
Higher heating value (MJ/kg)	142	55	50.4	(47.3)
Lower heating value (MJ/kg)	120	50.4	46.4	(44)
Molecular weight	2.02	16.04	44.1	≈ 107 (114)
Lower heating value (kJ/mol)	286	802	2043	(5100)

a = at 20 deg C

b = at stoichiometric conditions

2.7 NOx EMISSION

Exhaust gases of an engine can have up to 2000 ppm of oxides nitrogen. Most of this will be nitrogen oxide (NO), with a small amount of nitrogen dioxide (NO2), and traces of other nitrogen-oxygen combinations. These all grouped together as NOx emission. NOx is undesirable emission, and regulations that strict the allowable amount continue to become more stringent. Release NOx reacts in the atmosphere to form ozone and is one of major causes of photochemical smog.

NOx is created mostly from nitrogen in the air. Nitrogen can also be found in fuels blends, which any contain trace amounts of NH3, NC and HCN, but this would contribute only to a minor degree. There are a number of possible reactions that form NO, all of which are probably occurring during the combustion process and immediately after. These include but are not limited to,

$$\mathrm{O + N2 \rightarrow NO + N} \tag{1}$$

$$\mathrm{N + O2 \rightarrow NO + O} \tag{2}$$

$$\mathrm{N + OH \rightarrow NO + H} \tag{3}$$

NO, in turn, can then further react to form NO2 by various means, including the following:

$$\mathrm{NO + H2O \rightarrow NO2 + H2} \tag{4}$$

$$NO + O2 \rightarrow NO2 + O \tag{5}$$

Atmospheric nitrogen exists as stable diatomic molecule at low temperatures, and only very small trace amounts of oxides of nitrogen are found. However, at the very high temperatures that occur in the combustion chamber of an engine, some diatomic nitrogen (N2) breaks downs to monatomic nitrogen (N), which is reactive:

$$N2 \rightarrow 2N \tag{6}$$

The chemical equilibrium for eq(6) is highly dependent on temperature, with a much more significant amount of N generated in the 2500-3000 K temperature range that can exist in an engine. Other gases that stable at low temperatures, but become reactive and contribute to the formation of NOx at high temperatures, include oxygen and water vapor, which break down as follows:

$$O2 \rightarrow 2O \tag{7}$$

$$H2O \rightarrow OH + 1/2H2 \tag{8}$$

Eqs. (6-8) all reacts much further to the right as high combustion chamber temperatures are reached. The higher the combustion reaction temperatures, the more diatomic nitrogen, N2, will dissociate to monatomic nitrogen, N, and the more NOx will be formed. At low temperatures very little NOx is created (Williard W. Pulkrabek, 2004). Below there is full chemical reaction on how NOx form when gasoline blend with hydrogen react with present of air:

$$\overbrace{[FUEL] + [HYDROGEN]}^{mix} + [AIR] \rightarrow HC + CO + CO_2 + H_2O + NO_x$$

2.8 COMBUSTION COMPARISON BETWEEN THE GASOLINE AND HYDROGEN

2.8.1 Introduction

Idealize gasoline to be octane: $C8H18$. When octane combusts $O2$ is taken from the air and the following
reactions hold:
$2C_8H_{18} + 25O_2 \rightarrow 16CO_2 + 18H_2O$
and
$2C_8H_{18} + 17O_2 \rightarrow 16CO + 18H_2O$.
(Neglect the latter CO production reaction, since it occurs rarely.)

When a hydrogen fuel cell produces energy$O2$ is taken from the air and the following reaction holds:
$2H_2 + O2 \rightarrow 2H_2O$.

2.8.2 Chemical Bonding Energies

Table 2.2: Following energies of carbon bonds

Type of bond	Bond Energy (kiloJoule/mole)
single	314
double	611
triple	837

Table 2.3: Other bond energies

Type of bond	Bond Energy (kiloJoule/mole)
C-H	413
H-H	436
O-O	146
O=O	498
C-O	358
C=O(CO_2)	803
C=O(other)	741-749
H-O	464

2.8.3 Comparison of Energies Released by Gasoline Combustion and by Hydrogen Fuel Cells

Note that H_2O has two single H-O bonds and CO_2 has two double $C = O$ bonds. Using the bond energies given in the tables above one can calculate the difference in bond energies for the gasoline-combustion reaction. (There are 7 *C-C* bonds and 18 *C-H* bonds in octane.) (David Roper, 2006):

Table 2.4 : Gasoline combustion and bond energy

Gasoline Combustion	**Bond Energy (kiloJoules/mole)**
$2C_8H_{18} + 25O_2$	2 x 7 x 347 + 2 x 18 x 413 + 25 x 498 = 32176
$16CO_2 + 18H_2O$	16 x 2 x 803 + 18 x 2 x 464 = 42400
Difference	42400 – 32176 = 10224
Energy released per H atom	$\frac{10224}{2 \text{ x } 18}$=284
Energy released per fuel mass	$\frac{10224}{2(8x12+18)}$=44.8

Using the bond energies given in the tables above one can calculate the difference in bond energies for the hydrogen-fuel-cell reaction:

Table 2.5: Bond energy table

Hydrogen Fuel Cell	**Bond Energy (kiloJoules/mole)**
$2H_2 + O_2$	2 x 436 + 498 = 1370
$2H_2O$	4 x 464 = 1856
Difference	1856 – 1370 =486
Energy released per H atom	$\frac{486}{4}$=121
Energy released per fuel mass	$\frac{486}{4}$=121

Thus, gasoline combustion releases $\frac{284}{121}$=**2.35**times as much energy per hydrogen atom and $\frac{44.8}{121}$=**0.370** $\frac{G.Energy}{H.Energy}$ times as much energy per fuel mass as a hydrogen fuel cell does. Both reactions produce water; gasoline also produces carbon dioxide (David Roper, 2006).

2.8.4 Comparison of Water Produced by Gasoline Combustion and by Hydrogen Fuel Cells

Table 2.6: The ratio of water produced to fuel mass for the two cases

Process	**Chemical ratio water to fuel**	**Mass ratio water to fuel**
Gasoline combustion	$\frac{18H2O}{2C8H18}$	$\frac{18(2+16)}{2(8X12+18)}$=1.42
Hydrogen fuel cell	$\frac{2H2O}{2H2}$	$\frac{2(2+16)}{2X2}$=9

That is, $\frac{9}{1.42}$=6.34=$\frac{H.Water}{G.Water}$ times as much water per fuel mass is released by hydrogen fuel cells as is released by gasoline combustion. The difference between the two reactions is because of the $CO2$ produced in gasoline combustion, which carries off the difference in water masses (David Roper, 2006).

The ratio of water released to energy-released per fuel mass is $\frac{H_Water}{G_Water}$x$\frac{G_Energy}{H_Energy}$=$\frac{H_{Water}/H_Energy}{G_{Water}/G_Energy}$= 6.34 x 0370 =2.35 for hydrogen to gasoline.

That is, **over two times as much water per unit of energy is released by a hydrogen fuel cell as is released in gasoline combustion for a given fuel mass.** One could argue that fuel cells are more efficient at producing useable energy than is gasoline combustion. They would have to be several times more efficient to overcome this large water ratio (David Roper, 2006).

2.8.5 The Significance of the Large Water Ratio for Hydrogen Fuel Cells Compared to Gasoline Combustion

The exhaust of gasoline combustion is at a temperature of a few hundred degrees Celsius. So the water comes out as vapor, along with the carbon dioxide, both of which are potent greenhouse gases. The operating temperature of a hydrogen alkaline fuel cell is 50-250 degrees Celsius. So the water comes out as a hot liquid or as low temperature steam, to be deposited on or above the roadway. So over two times as much low-temperature water per energy released is emitted by a hydrogen fuel cell compared to the high-temperature water vapor emitted by gasoline combustion. This would cause dangerous driving conditions on roads, especially during cold weather. However, it could have positive effects for railroad and water transportation (David Roper, 2006).

2.1 1-DIMENSIONAL ANALYSIS

2.9.1 Design of Experiments

There are many types of engine analysis software, one of them is GT-Power. GT-Power is one of the commonly software to design a 1-Dimensional engine. Previous researchers had successfully combine the 1-dimensional simulation and Design of Experiments (DOE) techniques to design and optimize the performance of four stroke inline 4 cylinders engine. The benefit when using DOE are it may enable an optimization range to be studied using fewer experiments and it also reveals the interactions between different variables (Zabidi Bin Mohamad, 2008).

GT-POWER is specifically designed for steady state and transient simulations, and can be used for analysis of engine/ power train control. It is applicable to all types of I.C. engines, and it provides the user with many components to model any advanced concept. In an application, GT-Power can be used for a wide range activities relating to engine design and turning, valve profile and timing optimization, turbocharger matching, EGR system performance , manifold wall temperature, CFD studies conjunction with Star-CD, thermal analysis of cylinder components, combustion analysis, design of active and passive control system, intake and exhaust noise analysis, design of resonators and silencer for noise control and transient turbocharger response (Semin, Abdul R. Ismail and Rosli A. Bakar,2008).

In this study, the GT-Power 1-Dimensional computation model are dedicated gasoline engine with addition of hydrogen will be developed by using default parameter in GT-Power tutorial. The GT-Power engine computational model is used to simulate NOx emission characteristics of Spark Ignition engine. Simulation will be run on 5 different cases which are percentage of hydrogen added to the engine with 5% increment in each case and the engine will be run on 1000(low engine speed), 3000 rpm(medium engine speed) and 5000 rpm(high engine speed).

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter will further describe the study of gasoline engine with addition of hydrogen fuel based on 1-Dimensional simulation GT-Power software. In order to finish this project, methodology is one of the most important thing to be considered to ensure that the project run smoothly and get expected result which is needed. For this chapter, it will be discussing about the process of the project due to flow chart or more specifically due to Gantt chart. In this methodology, there are several steps must followed to ensure that the objective of the project achieved start from literature review, finding until submit the report. All of the process like measuring the parameter, mapping the engine and simulate the model will be explained clearly in this chapter. Also, software were used for this project will be described. Below are the steps of the the project which briefly into flow chart schematic diagram.

3.2 PROJECT FLOW CHART

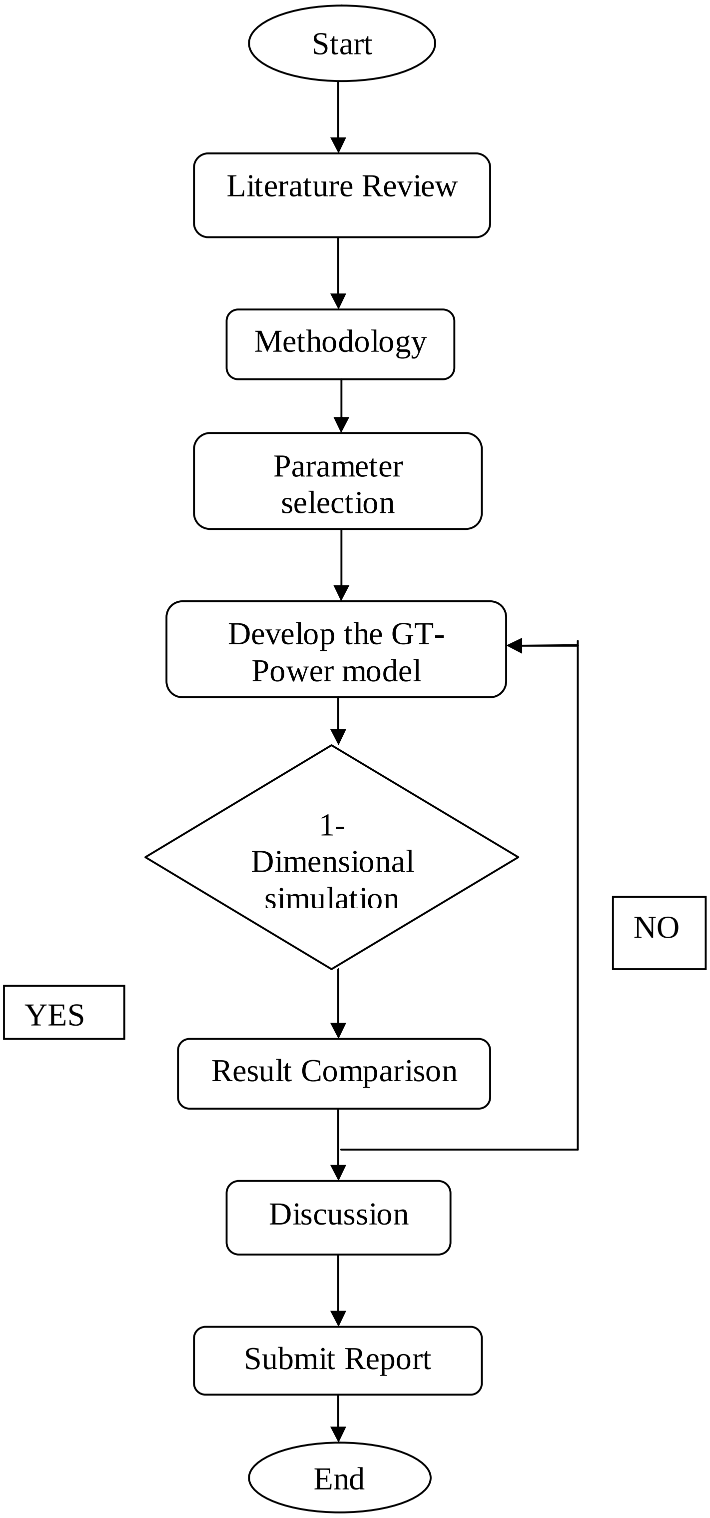


Figure 3.1: Flow Chart of the Project

3.3 NUMERICAL FLOW ANALYSIS

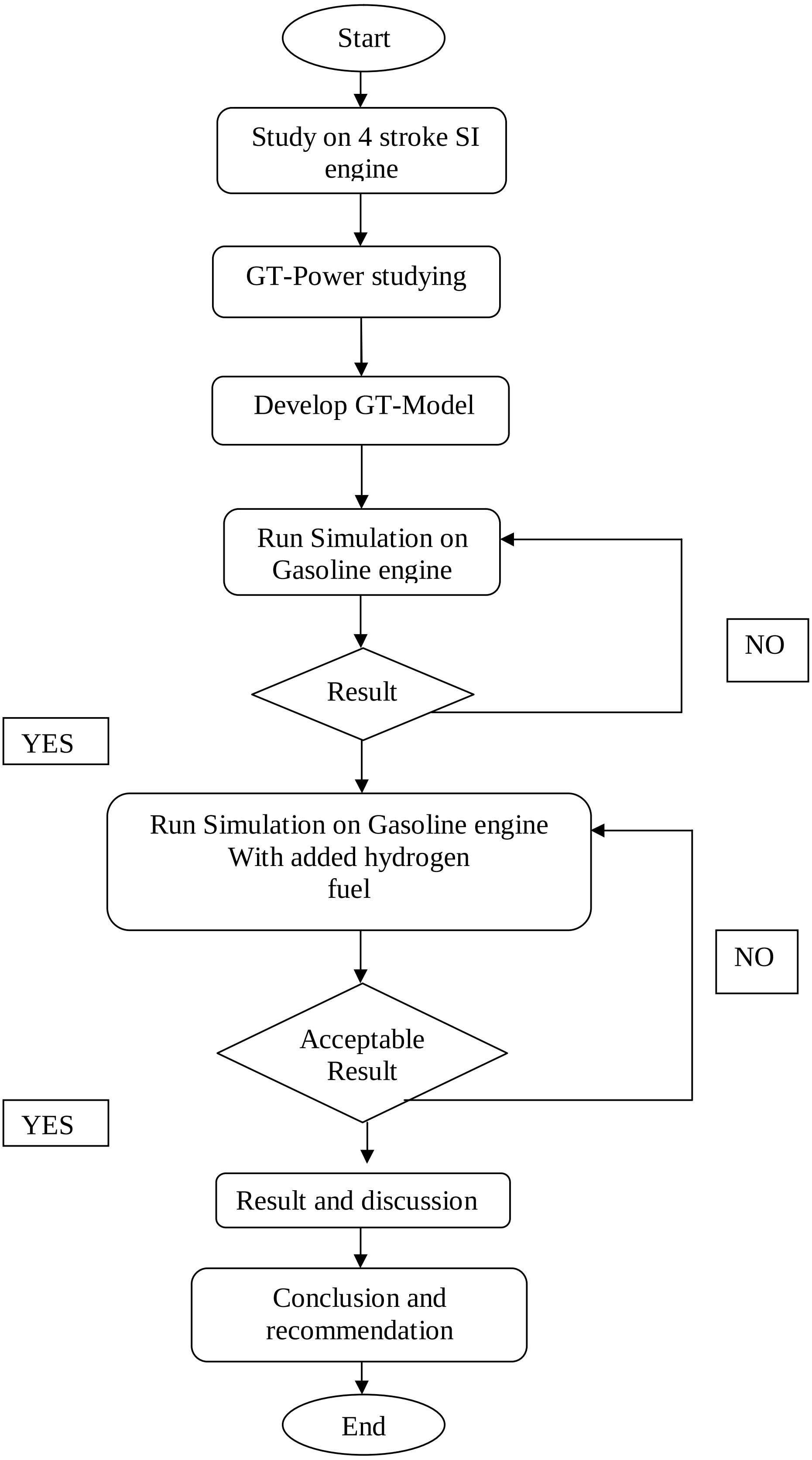


Figure 3.2: Numerical Flow Chart analysis

3.4 MEASURING THE PARAMETER

The parameter of the engine can be measured in two ways. Firstly, the conventional method where a veneer caliper is used to measure the real engine's parameter. All of the parameters required to simulate the engine in 1-Dimensional modeling such as bore, stroke, diameter exhaust, intake, valve, length of connecting rod and etc. All of this component will be measured precisely using the veneer caliper twice to get more accurate value.

Secondly, using the solidworks drawing where all the parameters can be obtained directly from the 3-D drawing. The function of this way is to compare the value obtained from conventional method and by using solidworks drawing. But in this project, parameter for engine were taken from GT-Power tutorial and not measured from those above 2 methods. It is because there is some problem cause measuring the parameter from real engine cannot be perform.

Figure 3.1: cylinder head

Source: FKM Lab

Figure 3.2: Engine block

Source: FKM Lab

3.5 DEVELOP THE GT-POWER MODEL

The basic model for this engine can be build by following step in GT-Power tutorial which is provided with GT-Power software. Below are some basic information in building GT-Power model. Select Window and then Tile With Template Library from the menu. This will place the GT-POWER template library on the left hand side of the screen. The template library contains all of the available templates that can be used in GT-POWER. Some of these templates (those that will be needed in the project) need to be copied into the project before they can be used to create objects and parts. For the purpose of this tutorial, click on the icons listed below and drag them from the template library into the project library. Some of these are templates and some are objects that have already been defined and included in the GT-POWER template library.

Flow Folder:
EndEnvironment
EngCylinder
Pipe
InjAF-RatioConn
InjProfileConn
OrificeConn - def (object)
OrificeConn – bellmouth (object)
ValveCamConn
FPropGas - indolene-vap (object)
FPropGas - diesel-vap (object)
FPropGas - n2-vap (object)
FPropGas - o2-vap (object)
FPropLiqIncomp - indolene-combust (object)
FPropLiqIncomp - diesel2-combust (object)
FPropMixtureCombust - air (object)

Mech Folder:
EngineCrankTrain

The basic idea in GT-ISE is that templates are provided which contain the unfilled attributes needed by the models within the code. The templates are made into objects, and when component and connection objects are placed on the project map, they become parts. These objects and parts may call reference objects. At this point the only reference templates and objects in the project are those that describe the air and fuel properties. During the course of building the model many more of the reference templates will be used; however, these are automatically imported into the project at the time they are first called. All the parameters and value are set at each part like in the tutorial. Below are default parameter use in this software:

Table 3.1: Cylinder Geometric

Parameters	**Value**
Bore	100mm
Stroke	100mm
Connecting Rod Length	220mm
Wrist pin to crank offset	1
Compression ratio	9.5
TDC Clearance height	3

Table 3.2: Port/Runner geometrics

Parameters	**Intake port/mm**	**Intake runner/mm**	**Exhaust runner/mm**	**Exhaust port/mm**
Diameter at inlet end	40	40	30	30
Diameter at outlet end	40	40	50	30
Length	100	80	150	60
Discretazation Length	40	40	55	40

Table 3.3: Int/Exh Valve geometrics

Parameter	**Intake valve**	**Exhaust valve**

Valve reference diameters	45.5	37.5
Valve lash	0.1	0.1
Cam timing angle	239	126

3.6 MAPPING THE ENGINE IN 1-D

3.6.1 Basic 4 stroke single cylinder model(Gasoline Fuel)

After finished to set all the parameter an option GT-Power model, it is now time to place parts on the project map and connect the components together. Click and hold on the ‘End Environment’ object named "env" and drop it on the middle left side of the map. Repeat this with the items listed, in the order listed, from left to right:

intrunner, intport, intvalve, cylinder, exhvalve, exhport, exhrunner, env

Now the components need to be connected together. In the tool bar for GT-ISE, there is a button called Create Links which needs to be pressed. Once this is done the mouse pointer turns into crosshairs. This can also be done by right clicking anywhere on the project map and selecting Create Link Mode. Click on the part created from the “env” object and then on the part created from the “intrunner” object. A default orifice connection was placed between the ‘End Environment’ and the first pipe. Continue the same step until all part are connected together.

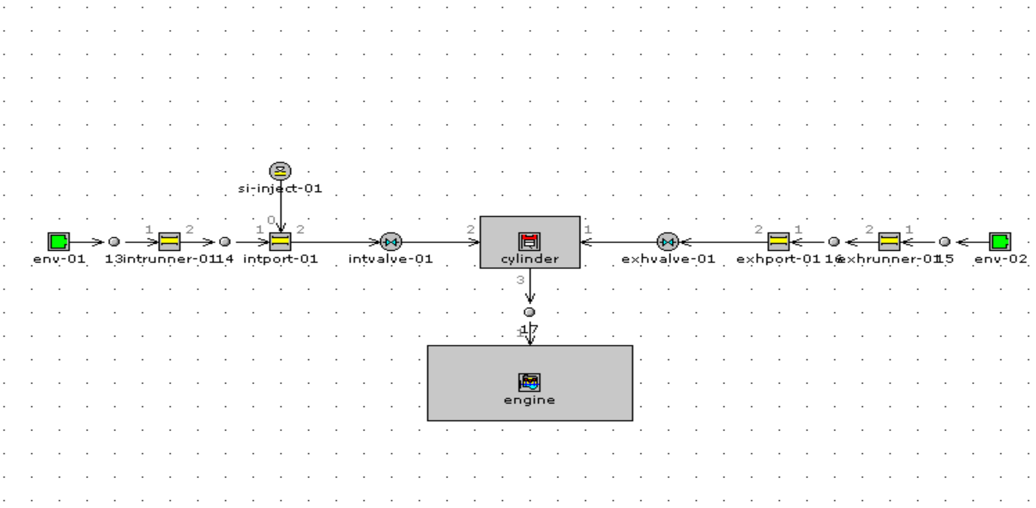


Figure 3.3: **GT-Power mapping for 4 stroke engine**

3.6.1.1 End Environment

This object describes end environment boundary conditions of pressure, temperature and composition. The pressure and the temperature for the end environment must be define in this object. For the pressure flag, the standard(total) had been selected due to the pressure and temperature will be imposed as total conditions at the inlet of the attached flow component. Then, the composition of the end environment is defined as air. **Refer appendix A1**.

3.6.1.2 Pipe

This object is used to specify the properties for round and straight pipes. The properties that need to be defined in this object is diameter at inlet and outlet end, the pipe length, discretization length, surface roughness, wall temperature, heat conduction object and initial state name. There are 4 pipes which are intake port, intake runner, exhaust port and exhaust runner. **Refer appendix A2** (intake runner).

3.6.1.3 Injector Air-Fuel Ratio Connection

This object described an injector that injects fluid at a specified fuel-to-air mixture into a pipe. It uses the local airflow sensor type that means the airflow sensor location will be the same as the point of injection. The injector is connected straight to the throttle body, so the location of the injector is at the inlet of the throttle body. For the air-fuel ratio, the ideal air-fuel ratio needs to be added to give maximum performance of the engine. **Refer appendix A3**.

3.6.1.4 Valve Connection

This object is to dynamically model check valves. The valve is defined such that high pressure at the valve inlet causes the valve to open and high pressure at the valve outlet causes the valve to close. Valve reference diameter is used to calculate the effective flow area from the discharge coefficient arrays. The upstream pressure area is the pressure area on the valve that is acted upon to close the valve. There 2 valves which are intake valve and exhaust valve. **Refer appendix A4**.

3.6.1.5 Engine Crankcase

This object is used to model crankcase chambers. The crankcase must be modeled for 4 stroke engine. The parameters that needed to be defined in engine crankcase are bore, compression ratio stroke, connecting rod length, TDC clearance height and Wrist Pin to Crank Offset. TDC Clearance Height is cylinder clearance height from the top of the piston to the e top of the cylinder wall when the piston is at TDC. This attribute is used to calculate the cylinder wall surface area used for in-cylinder heat transfer calculations .Wrist Pin to Crank Offset is wrist pin offset relative to the crankshaft axis when the wrist-pin bearing position on the piston end is projected toward the crankshaft on a line parallel to the cylinder axis (positive to the thrust side). **Refer appendix A5**.

3.6.1.6 Engine Cylinder

This object is used to specify the attribute of the engine cylinder. The important parameters that need to be defined are the cylinder geometry, wall temperature, heat transfer and combustion objects. Most of the parameters in the engine cylinder need to be defined by another reference such as “geom”,”air-fuel”,”intake”,”cyltwall”,”htr”, ”comb”. **Refer appendix A6.**

3.6.1.7 Engine Crankshaft

This object specifies the attributes of an engine’s crank train. The crank train model the crank slider mechanism and crankshaft which translates the torques generated directly from the pressure acting on each piston in the cylinders into the crankshaft output torque. The important parameters need to be defined are engine type whether 2-stroke or 4 stroke, number of cylinder in the engine, configuration of whether in-line or V, the engine speed, and the start of cycle. **Refer to appendix A7**

3.7 SIMULATION ON GASOLINE ENGINE

After finish mapping the 4 stroke engine, the simulation of the engine will be carried out. To trace the presence of NOx emission some step must be done in order to get graph NOx emission. From GT-Power library at left, there are flow, mechanical, electrical, thermal, analysis. General and control. Choose flow and then find EngCylNOx, see **Figure 3.4**. Next drag this reference to the GT-Power library .Before that, change name to NOx and there are 3 attribute change all that from 'ign' to '1' see **Figure 3.5** . After that, go to mapping choose cylinder, see 3 box at left below of cylinder part. There are 3 which are main, model and plot option. Choose model, then choose comb, see **Figure 3.6.** Next, press comb and it appear 3 box at left below which are main, option and advanced. Choose advance, and at NOx reference object change from 'ign' to 'NOx'. Next, find sensor component from GT-Power library and drag to template and name it as 'NOx_sensor'. After that, drag this sensor to the mapping and placed at above 'exhport'. Linked the sensor with 'exhport' if box appear, choose port number 6 which is NOx mass fraction (burned) see **Figure 3.7**. Clicked sensor at map, then change sensor location from 'ign' to '1' and sensed quantity named as 'prod_no' see **Figure 3.8.**

The engine must be defined to operate for certain RPM, for this thesis there are 3 different RPM which are 1000 rpm(low engine speed), 3000 rpm(medium engine speed) and 5000 rpm(high engine speed).First, run at 1000 rpm(low engine speed) then continue to 3000 rpm(medium engine speed) and 5000 rpm(high engine speed). To run the simulation, a yellow button as shown in **Figure 3.9** will be clicked. When run the simulation, black box with the parameter and the definition of the engine as shown in **Figure 3.10** will appear**.** After the simulation finish, the result and output of the engine can be displayed with the clicking of open GT-Post button as shown in **Figure 3.11.**

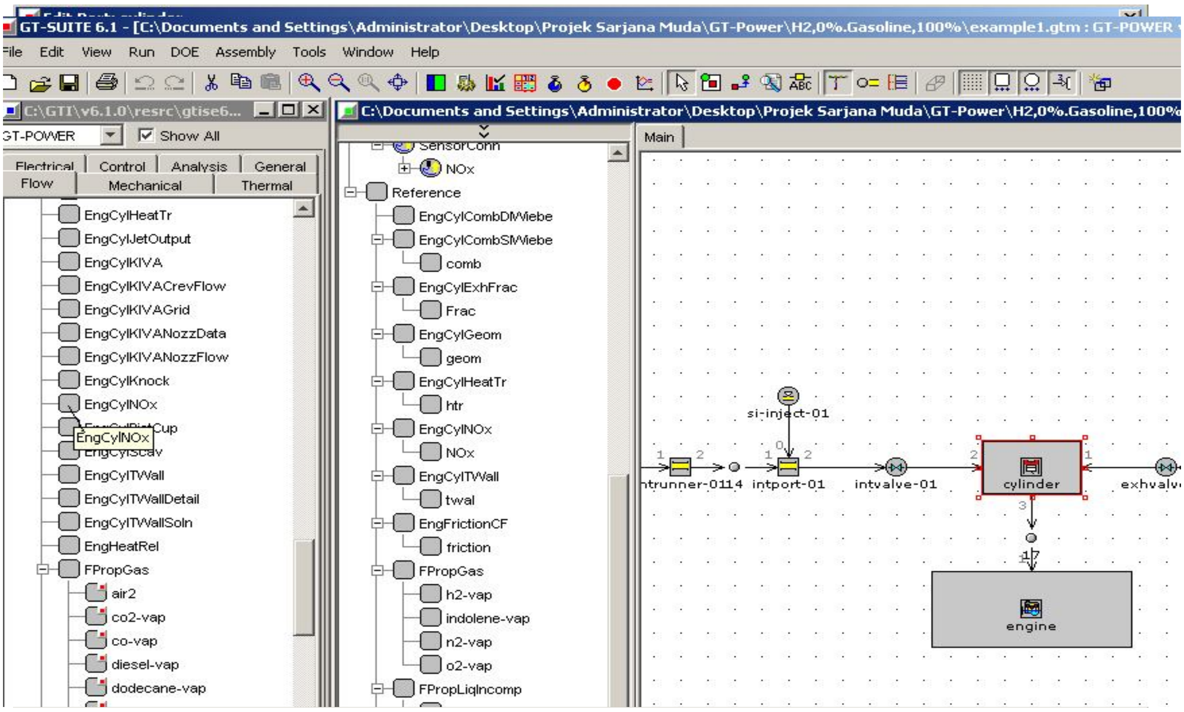
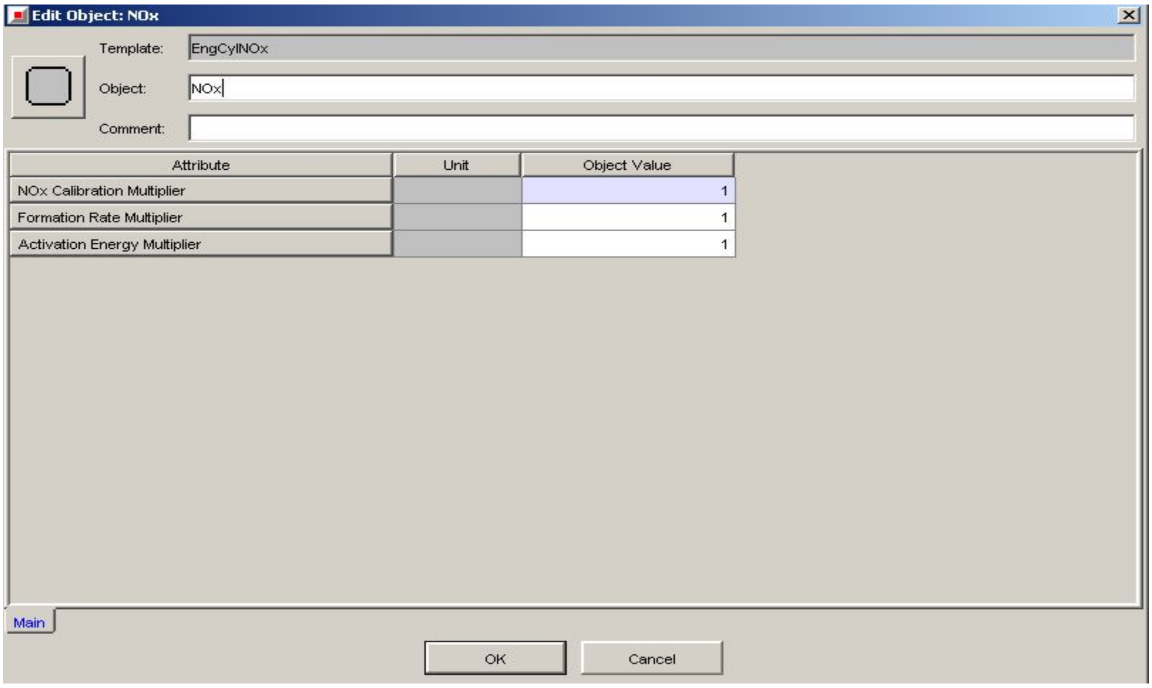


Figure 3.4 : EngCylNOx reference



Template: EngCylNOx

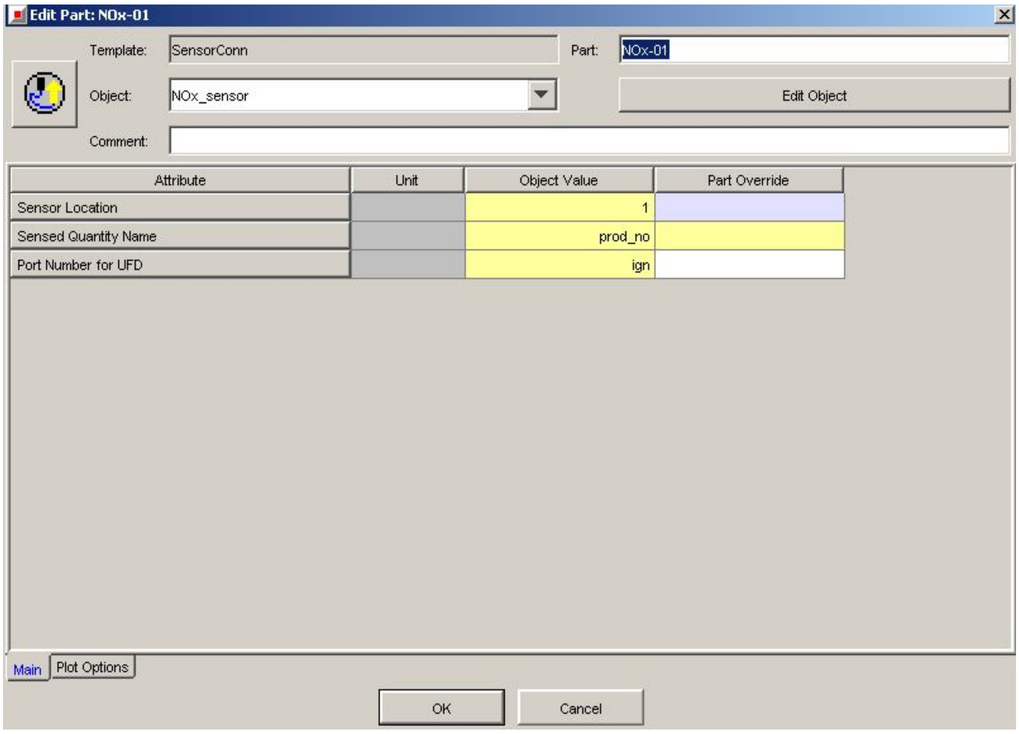
Object: NOx

Comment:

Attribute	Unit	Object Value
NOx Calibration Multiplier		1
Formation Rate Multiplier		1
Activation Energy Multiplier		1

Figure 3.5: NOx reference object

Figure 3.6: Cylinder part comb



Template: SensorConn

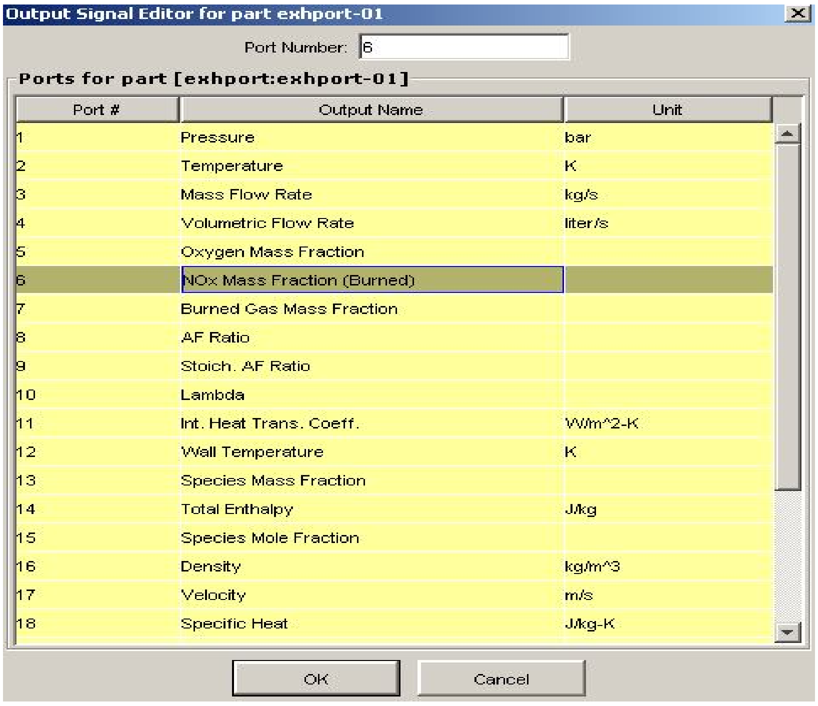
Part: NOx-01

Object: NOx_sensor

Comment:

Attribute	Unit	Object Value	Part Override
Sensor Location		1	
Sensed Quantity Name		prod_no	
Port Number for UFD		ign	

Figure 3.7: NOx mass fraction (burned)



Port Number: 6

Ports for part [exhport:exhport-01]

Port #	Output Name	Unit
1	Pressure	bar
2	Temperature	K
3	Mass Flow Rate	kg/s
4	Volumetric Flow Rate	liter/s
5	Oxygen Mass Fraction	
6	NOx Mass Fraction (Burned)	
7	Burned Gas Mass Fraction	
8	AF Ratio	
9	Stoich. AF Ratio	
10	Lambda	
11	Int. Heat Trans. Coeff.	W/m^2-K
12	Wall Temperature	K
13	Species Mass Fraction	
14	Total Enthalpy	J/kg
15	Species Mole Fraction	
16	Density	kg/m^3
17	Velocity	m/s
18	Specific Heat	J/kg-K

Figure 3.8: Sensor edit

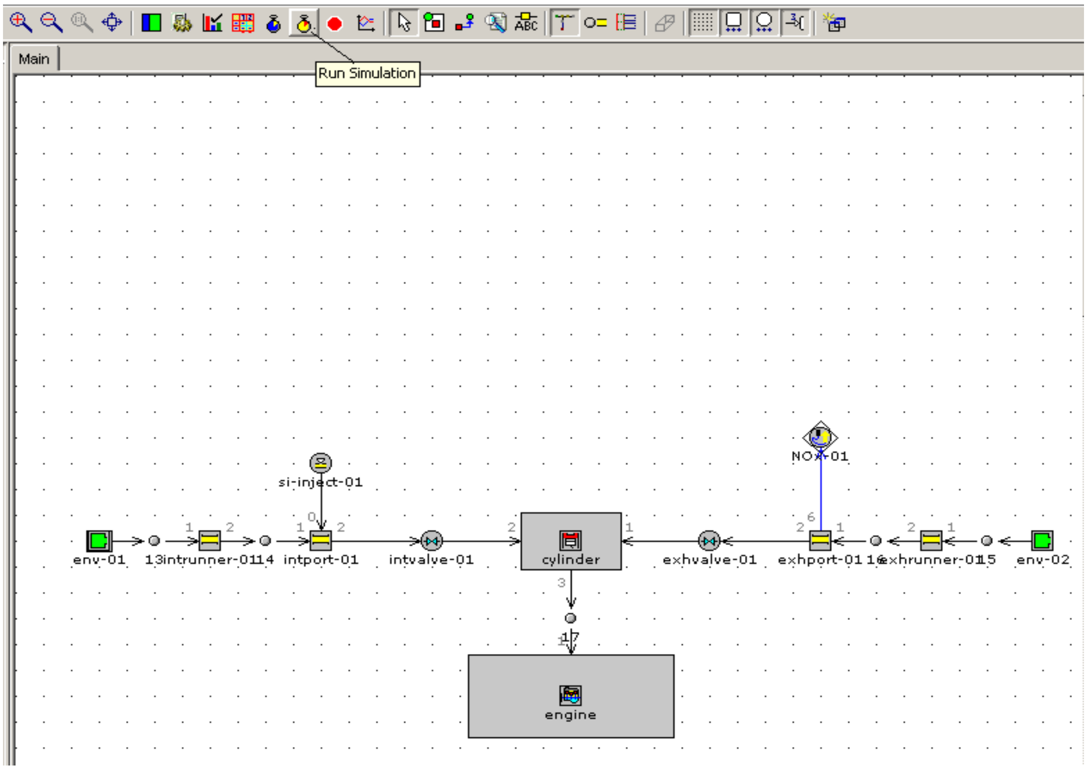
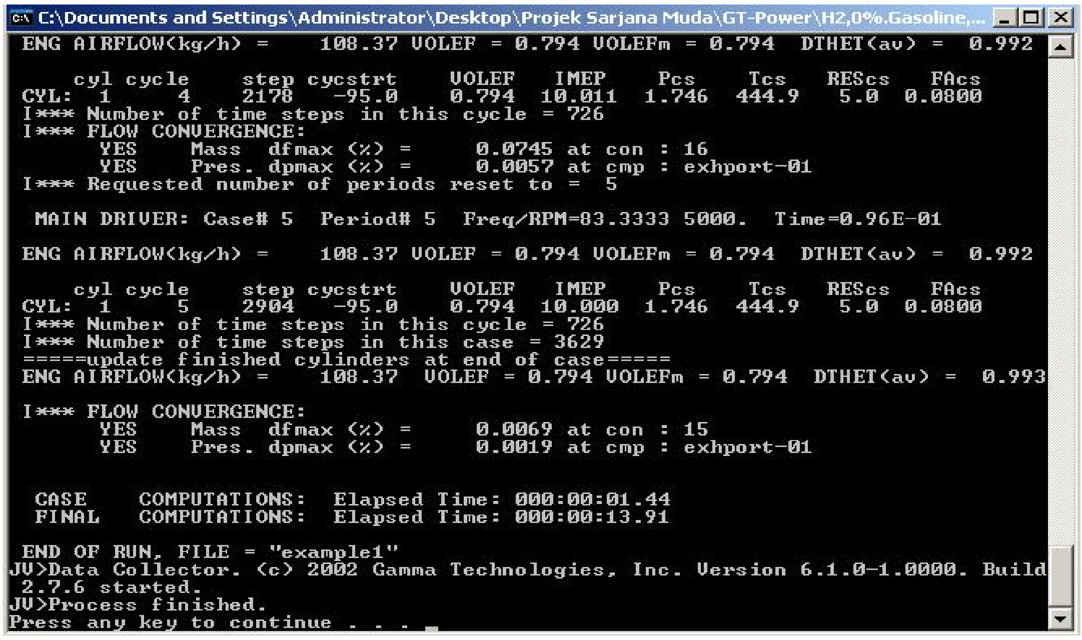


Figure 3.9: Run Simulation button



```
 ENG AIRFLOW(kg/h) =    108.37 VOLEF = 0.794 VOLEFm = 0.794  DHTET(av) =  0.992

    cyl cycle    step cycstrt    VOLEF   IMEP    Pcs     Tcs    REScs    FAcs
 CYL:  1     4    2178   -95.0    0.794  10.011  1.746   444.9   5.0  0.0800
 I*** Number of time steps in this cycle = 726
 I*** FLOW CONVERGENCE:
        YES    Mass  dfmax (%) =     0.0745 at con : 16
        YES    Pres. dpmax (%) =     0.0057 at cmp : exhport-01
 I*** Requested number of periods reset to =  5

  MAIN DRIVER: Case# 5  Period# 5  Freq/RPM=83.3333 5000.  Time=0.96E-01

 ENG AIRFLOW(kg/h) =    108.37 VOLEF = 0.794 VOLEFm = 0.794  DTHET(av) =  0.992

    cyl cycle    step cycstrt    VOLEF   IMEP    Pcs     Tcs    REScs    FAcs
 CYL:  1     5    2904   -95.0    0.794  10.000  1.746   444.9   5.0  0.0800
 I*** Number of time steps in this cycle = 726
 I*** Number of time steps in this case = 3629
 =====update finished cylinders at end of case=====
 ENG AIRFLOW(kg/h) =    108.37  VOLEF = 0.794 VOLEFm = 0.794  DTHET(av) =  0.993

 I*** FLOW CONVERGENCE:
        YES    Mass  dfmax (%) =     0.0069 at con : 15
        YES    Pres. dpmax (%) =     0.0019 at cmp : exhport-01


  CASE    COMPUTATIONS:  Elapsed Time: 000:00:01.44
  FINAL   COMPUTATIONS:  Elapsed Time: 000:00:13.91

 END OF RUN, FILE = "example1"
JV>Data Collector. (c) 2002 Gamma Technologies, Inc. Version 6.1.0-1.0000. Build
 2.7.6 started.
JV>Process finished.
Press any key to continue . . .
```

Figure 3.10: Running of the 1-D Simulation

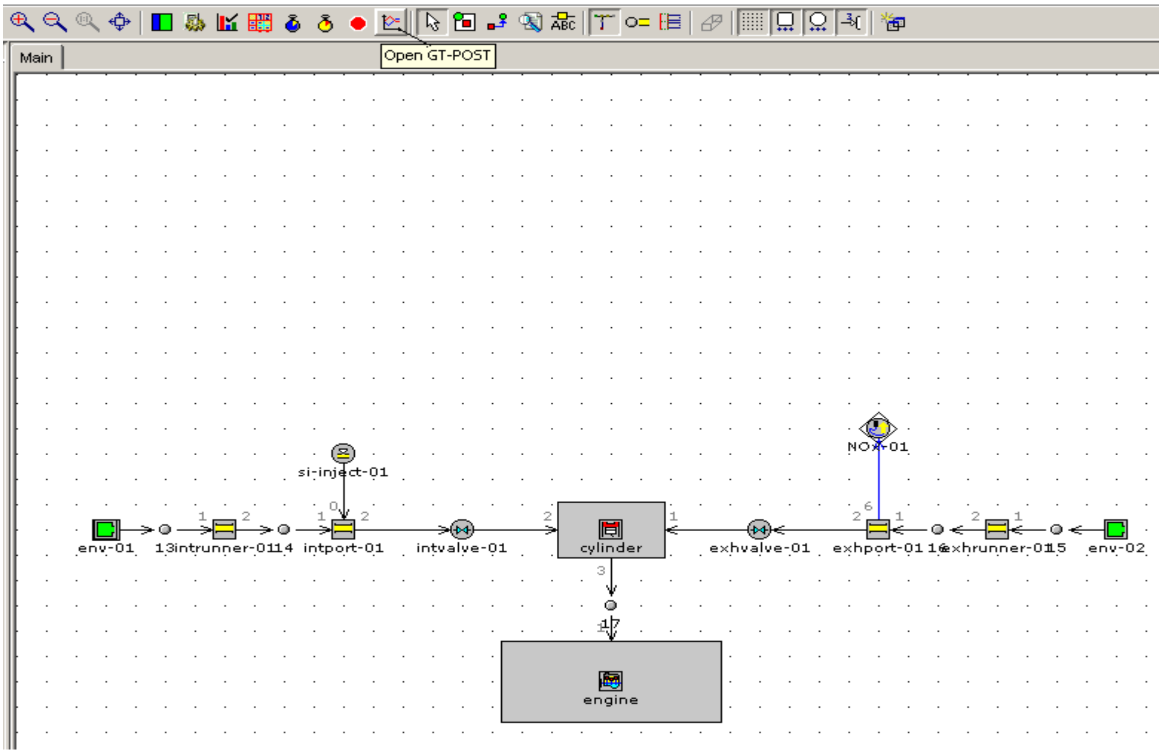


Figure 3.11: Open GT-Post button

3.8 SIMULATION ON GASOLINE ENGINE WITH ADDITION OF HYDROGEN FUEL

To fulfill this thesis objectives which is to investigate the effect of addition hydrogen fuel on 4 stroke Gasoline SI engine must added 5% increment of hydrogen on each case until 20% hydrogen. First, set Air-Fuel Ratio as a parameter but, before this there are some calculation must perform in order to know stoichiometric Air-Fuel ratio for mixture gasoline and hydrogen. See **Figure 3.12** and **3.13** how to set.But before that, h_2 vapor must drag from GT-Power library to template .Next, clicked at si-Inject →indolene combust→indolene vapor, then change the value at indolene combust properties with the value h_2+gasoline(indolene)=100% refer **Figure 3.14** and **3.15**. Below there is calculation on how to get stoichiometric Air-Fuel ratio for gasoline-hydrogen mixture:

$$\overbrace{\qquad\qquad\qquad}^{\text{Fuel}}\quad\overbrace{\qquad\quad}^{\text{Air}}$$

$C_8H_{18} + H_2 + 13O_2 \rightarrow 8CO_2 + 10H_2O$

Left side	**Right side**
C=8	C=8
H=20	H=20
O=26	O=26

(Molar mass number C=12, O=16, H=1)

Gasoline(C_8H_{18})	**Hydrogen (H_2)**	**Oxygen ($13O_2$)**
(12x18) + (18x1)	2x1	13(16x2)
114	2	416

For mixture(Fuel):	**For Oxygen(Air):**
$C_8H_{18} + H_2 = 114 + 2 = 116$	$13O_2 = 416$

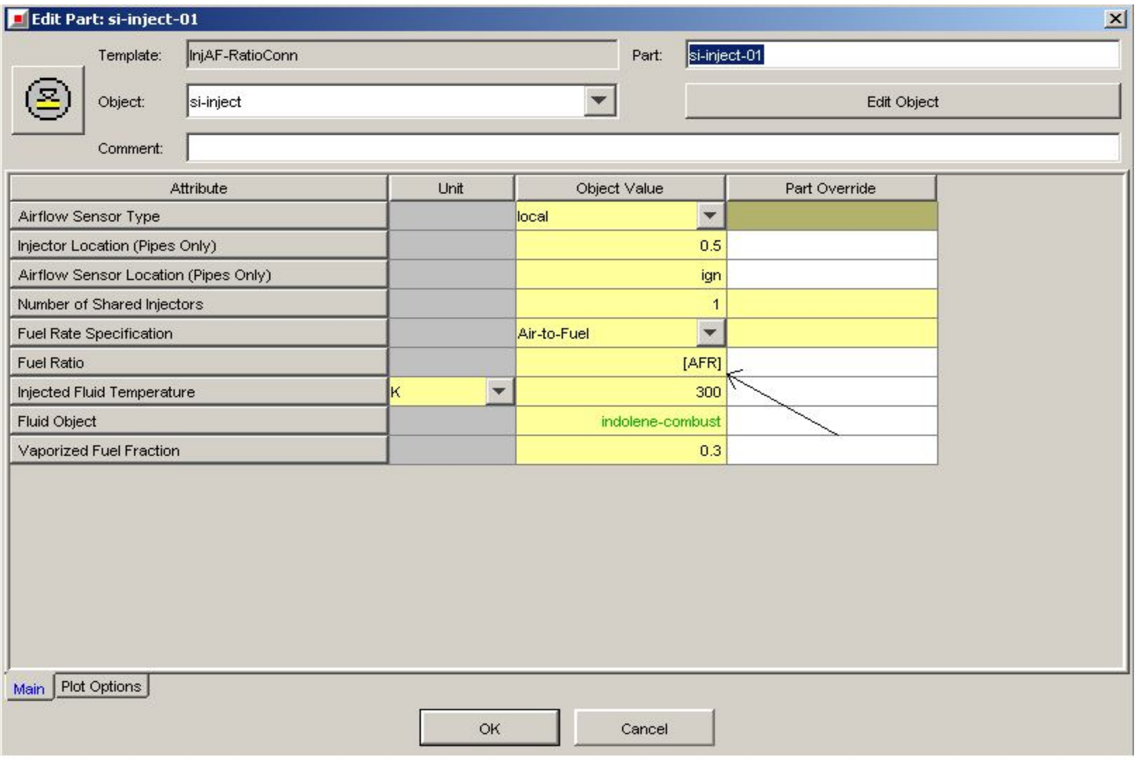
Oxygen-Fuel mass ratio:

$\frac{416}{116}$=3.59kg

So, we need 3.59 kg of oxygen for every 1 kg of fuel. Since, 23.2 mass percent of air is actually oxygen, we need:

$$\frac{3.59}{100/23.2} = 15.47$$

So, 15.47 for every 1kg of mixture(gasoline-hydrogen). So the stoichiometric air-fuel ratio of fuel(gasoline-hydrogen) is **15.47**. For the parameters, AFR are set to 10 until 20.



Template: InjAF-RatioConn

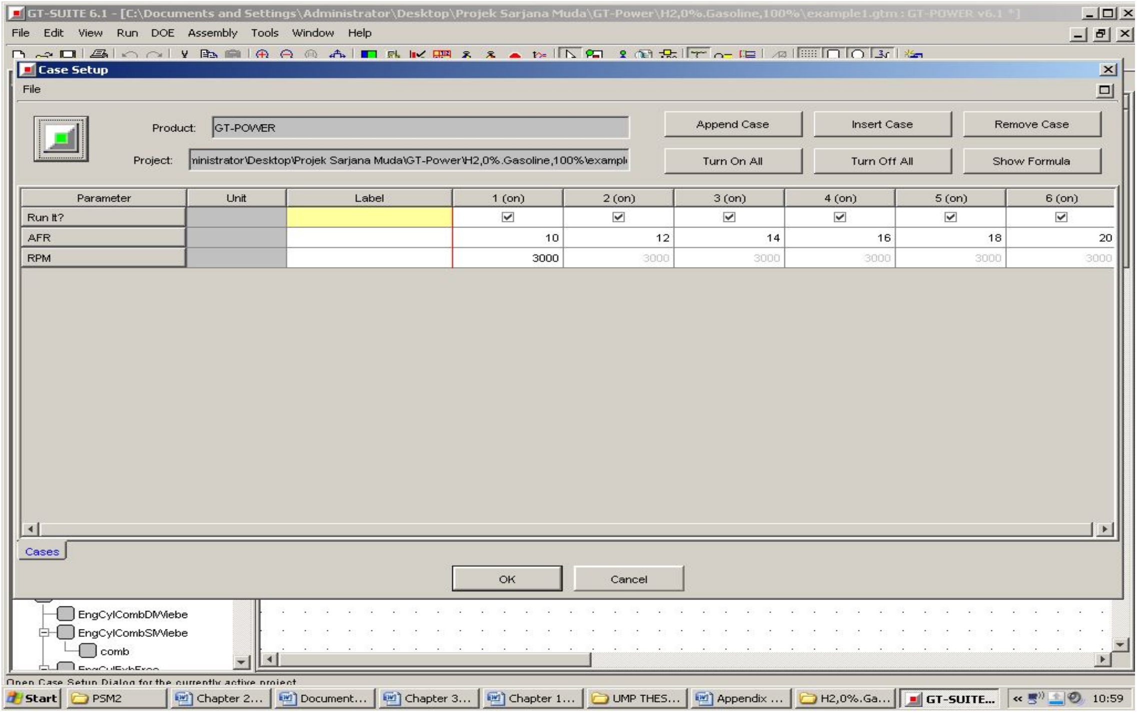
Part: si-inject-01

Object: si-inject

Comment:

Attribute	Unit	Object Value	Part Override
Airflow Sensor Type		local	
Injector Location (Pipes Only)		0.5	
Airflow Sensor Location (Pipes Only)		ign	
Number of Shared Injectors		1	
Fuel Rate Specification		Air-to-Fuel	
Fuel Ratio		[AFR]	
Injected Fluid Temperature	K	300	
Fluid Object		indolene-combust	
Vaporized Fuel Fraction		0.3	

Figure 3.12: Air-Fuel Ratio



Product: GT-POWER

Project: ninistrator\Desktop\Projek Sarjana Muda\GT-Power\H2,0%.Gasoline,100%\exampl

Parameter	Unit	Label	1 (on)	2 (on)	3 (on)	4 (on)	5 (on)	6 (on)
Run It?			☑	☑	☑	☑	☑	☑
AFR			10	12	14	16	18	20
RPM			3000	3000	3000	3000	3000	3000

Figure 3.13: AFR as a parameter

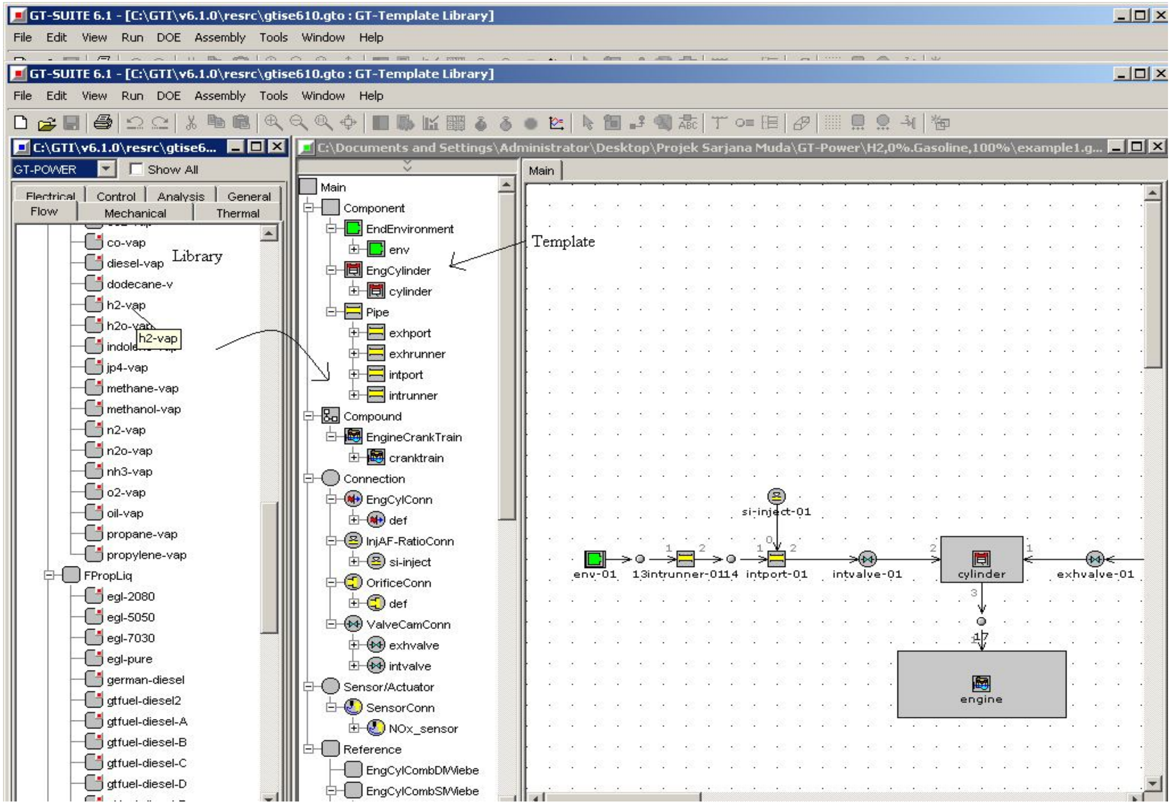
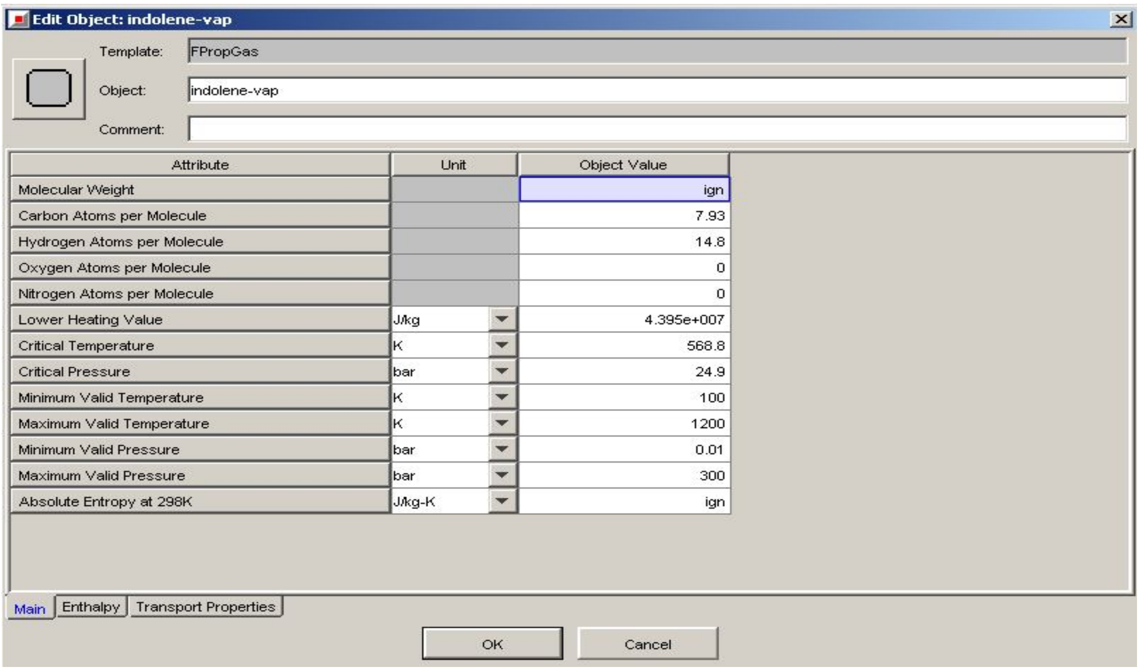


Figure 3.14: H2-Vapor



Template: FPropGas

Object: indolene-vap

Comment:

Attribute	Unit	Object Value
Molecular Weight		ign
Carbon Atoms per Molecule		7.93
Hydrogen Atoms per Molecule		14.8
Oxygen Atoms per Molecule		0
Nitrogen Atoms per Molecule		0
Lower Heating Value	J/kg	4.395e+007
Critical Temperature	K	568.8
Critical Pressure	bar	24.9
Minimum Valid Temperature	K	100
Maximum Valid Temperature	K	1200
Minimum Valid Pressure	bar	0.01
Maximum Valid Pressure	bar	300
Absolute Entropy at 298K	J/kg-K	ign

Figure 3.15: Indolene(gasoline) vapor properties

After change the value properties of gasoline (indolene) vapor, start the simulation same with step before. The table for calculation all 4 cases are in shown in appendix 8.

3.9 INTERPRETING DATA

From the raw result that will be displaced after the simulation, the results will be arranged in order and interpreted. All of the results will be discussed for the reasons and factors that lead to the output. Also, all the results that come out will be discussed in terms of their functions and relations to each other.

CHAPTER 4

4.1 INTRODUCTION

In this chapter, all the raw results will be arranged and the selected findings will be discussed briefly to give the proper explanation about the process and the important point in the results. Below there are the resulted get after running the simulation at 3 different RPM with AFR range from 10 to 20 and after adding hydrogen fuel until 20 percent. The data get from GT-Power software are plotted by using Microsoft Excel so it looks more understanding.

4.2 RESULT

4.2.1 At 1000 RPM(low engine speed)

Result for NOx and temperature at 1000 rpm(low engine speed)

Equivalent ratio, Φ = AFR stoichiometric / AFR actual

***Air-Fuel Ratio at stoichiometric = 15.47**

Table 4.1: Data distribution for 0% hydrogen addition

H2,0%

NOx concentration (ppm)	Air Fuel Ratio(actual)	Equivalent ratio,Φ	Cylinder Temperature (K)
98.28	10	1.547	588.89
979.78	12	1.289	1337.41
1687.9	14	1.105	1955.88
2187.89	16	0.967	2315.32
1787.9	18	0.859	1987.53

1367.88	20	0.774	1616.86

Table 4.2: Data distribution for 5% hydrogen addition

H2,5%

NOx concentration (ppm)	Air Fuel Ratio(actual)	Equivalent ratio,Φ	Cylinder Temperature (K)
401.3	10	1.547	1019.36
1267.32	12	1.289	1643.86
1979.89	14	1.105	2155.72
2479.88	16	0.967	2424.25
2012.17	18	0.859	2149.71
1606.01	20	0.774	1828.22

Table 4.3: Data distribution for 10% hydrogen addition

H2,10%

NOx concentration (ppm)	Air Fuel Ratio(actual)	Equivalent ratio,Φ	Cylinder Temperature (K)
689.23	10	1.547	1307.1
1456.23	12	1.289	1832.28
2199.11	14	1.105	2307.25
2678.89	16	0.967	2514.22
2171.45	18	0.859	2323.69
1791.18	20	0.774	2032.83

Table 4.4: Data distribution for 15% hydrogen addition

H2,15%

NOx concentration (ppm)	Air Fuel Ratio(actual)	Equivalent ratio,Φ	Cylinder Temperature (K)
923.76	10	1.547	1676.15
1672.9	12	1.289	2064.49

2348.9	14	1.105	2468.8
2849.76	16	0.967	2636.74
2401.78	18	0.859	2499.84
2017.78	20	0.774	2330.59

Table 4.5: Data distribution for 20% hydrogen addition

H2,20%

NOx concentration (ppm)	Air Fuel Ratio(actual)	Equivalent ratio,Φ	Cylinder Temperature (K)
1116.8	10	1.547	1925.44
1895.87	12	1.289	2250.2
2574.87	14	1.105	2603.73
3049.78	16	0.967	2712.96
2689.56	18	0.859	2619.13
2339.78	20	0.774	2522.05

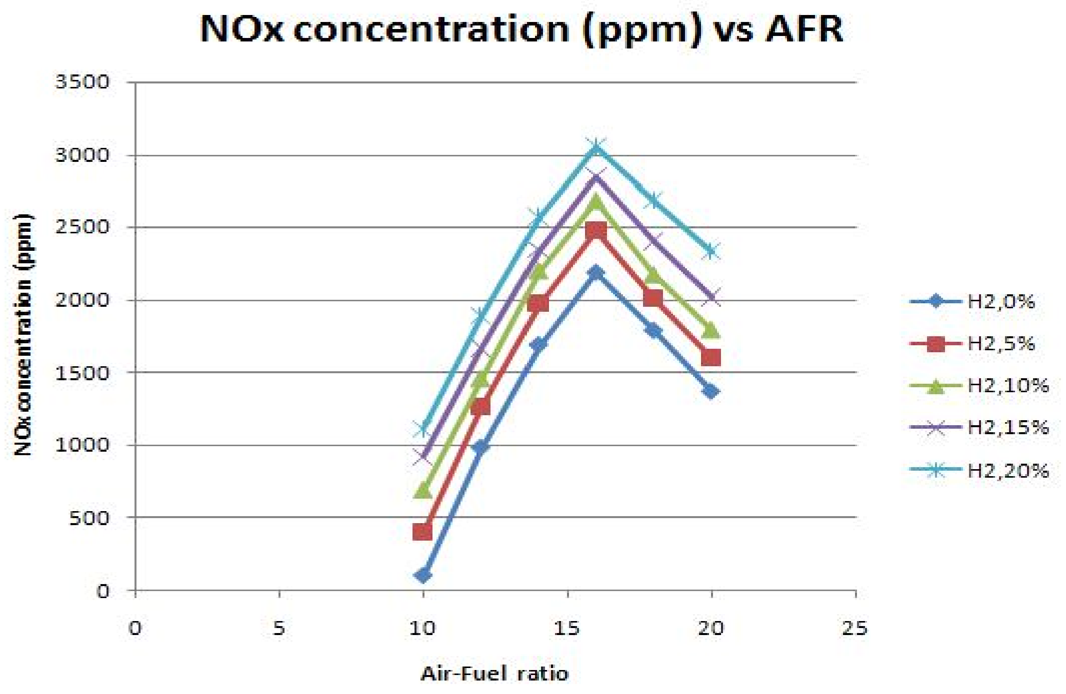


Figure 4.1: NOx concentration vs AFR

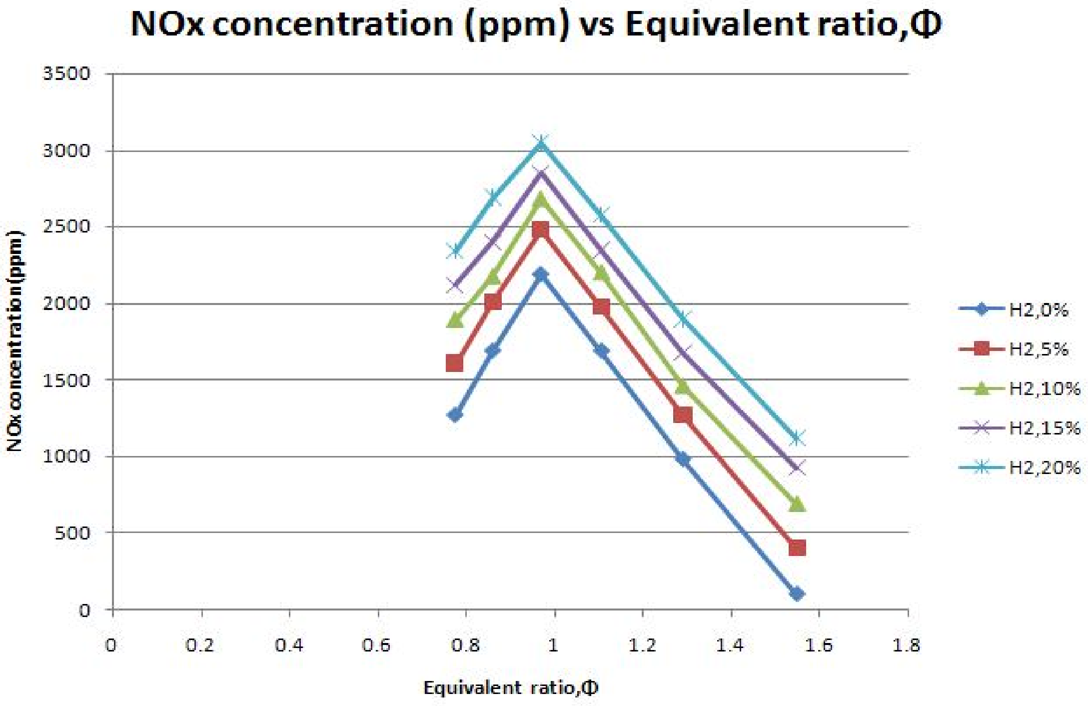


Figure 4.2: NOx concentration vs equivalent ratio

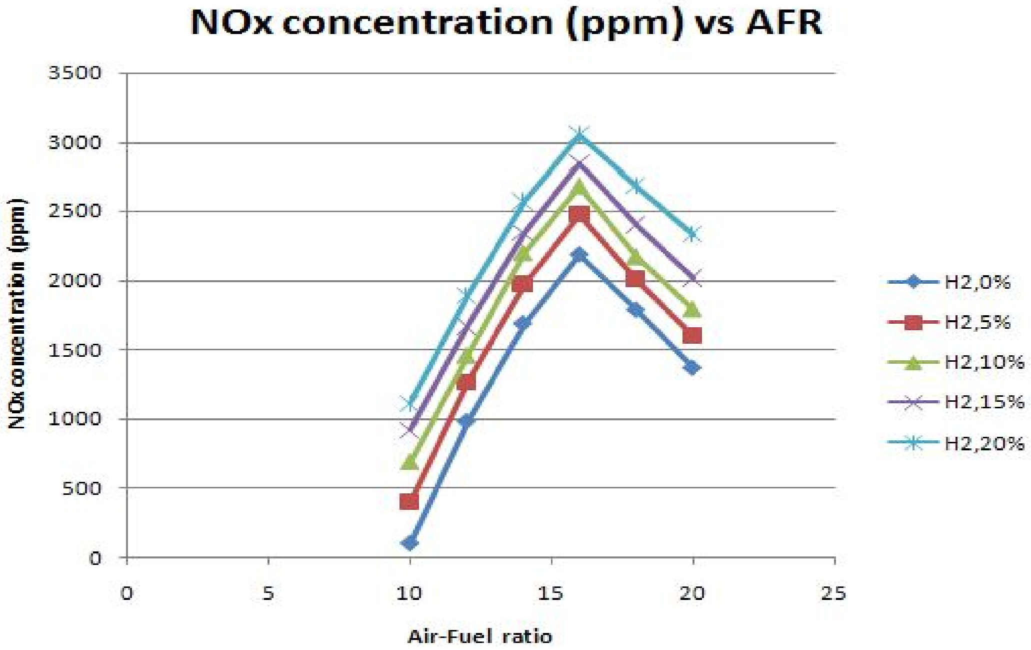


Figure 4.3: Cylinder temperature vs AFR

From figure 4.1, the entire graphs are shown in increasing before decreasing when air-fuel ratio is increase. For the beginning when there is no hydrogen added to the gasoline engine, at AFR 10 NOx concentration is 98.28 ppm and maximum concentration occur at AFR 16 which is 1367.88 ppm. After 5 percent added, there are slightly increasing in NOx concentration and the maximum concentration occur at AFR 16 which is 1606.01 ppm. For 10 and 15 percent hydrogen added the maximum concentration occurred at 16 AFR which are 1791.18 ppm and 2017.78 ppm respectively. Lastly, for 20 percent hydrogen added, maximum concentration occurred at 16 AFR which is 2339.78 ppm.

From figure 4.2, all of the graph is increase with increasing of equivalent ratio but it decrease at certain point of equivalent ratio and the maximum concentration always occurred at 0.967 Φ where for 0 percent hydrogen added, maximum concentration is 2187.89 ppm. For 5 percent hydrogen added, the highest concentration is 2479.88 ppm. For 10 percent hydrogen added, the maximum concentration is 2678.89 ppm. For 15 percent hydrogen added, the highest concentration is 2849.76 ppm. For 20 percent hydrogen added, the maximum concentration is 3049.78 ppm.

From figure 4.3, the entire graph is increasing before it decrease at certain point. For 0 percent hydrogen added, the lowest temperature occurred at 10 AFR which is 588.89 K while the highest occurred at 16 AFR which is 2315.32 K. For 5 percent hydrogen added, minimum temperature occurred at 10 AFR which is 1019.36 K while maximum occurred at 16 AFR which is 2424.25 K. For 10 percent hydrogen added, the lowest temperature occurred at 10 AFR which is 1307.1 K while the highest occurred at 16 AFR which is 2514.22 K. For 15 percent hydrogen added, the lowest temperature occurred at 10 AFR which is 1676.15 K while the highest occurred at 16 AFR which is 2636.74 K. For 20 percent hydrogen added, minimum temperature occurred at 10 AFR which is 1925.44 K while maximum occurred at 16 AFR which is 2712.96 K.

4.2.2 At 3000 RPM(medium engine speed)

Result for NOx and temperature at 3000 rpm(medium engine speed)

Table 4.6: Data distribution for 0% hydrogen addition

H2,0%

NOx concentration (ppm)	**Air Fuel Ratio(actual)**	**Equivalent ratio,Φ**	**Cylinder Temperature (K)**
98.28	10	1.547	588.89
979.78	12	1.289	1337.41
1687.9	14	1.105	1955.88
2187.89	16	0.967	2315.32
1787.9	18	0.859	1987.53
1367.88	20	0.774	1616.86

Table 4.7: Data distribution for 5% hydrogen addition

H2,5%

NOx concentration (ppm)	**Air Fuel Ratio(actual)**	**Equivalent ratio,Φ**	**Cylinder Temperature (K)**
401.3	10	1.547	1019.36
1267.32	12	1.289	1643.86
1979.89	14	1.105	2155.72
2479.88	16	0.967	2424.25
2012.17	18	0.859	2149.71
1606.01	20	0.774	1828.22

Table 4.8: Data distribution for 10% hydrogen addition

H2,10%

NOx concentration (ppm)	**Air Fuel Ratio(actual)**	**Equivalent ratio,Φ**	**Cylinder Temperature (K)**
689.23	10	1.547	1307.1

1456.23	12	1.289	1832.28
2199.11	14	1.105	2307.25
2678.89	16	0.967	2514.22
2171.45	18	0.859	2323.69
1791.18	20	0.774	2032.83

Table 4.9: Data distribution for 15% hydrogen addition

H2,15%

NOx concentration (ppm)	Air Fuel Ratio(actual)	Equivalent ratio,Φ	Cylinder Temperature (K)
923.76	10	1.547	1676.15
1672.9	12	1.289	2064.49
2348.9	14	1.105	2468.8
2849.76	16	0.967	2636.74
2401.78	18	0.859	2499.84
2017.78	20	0.774	2330.59

Table 4.10: Data distribution for 20% hydrogen addition

H2,20%

NOx concentration (ppm)	Air Fuel Ratio(actual)	Equivalent ratio,Φ	Cylinder Temperature (K)
1116.8	10	1.547	1925.44
1895.87	12	1.289	2250.2
2574.87	14	1.105	2603.73
3049.78	16	0.967	2712.96
2689.56	18	0.859	2619.13
2339.78	20	0.774	2522.05

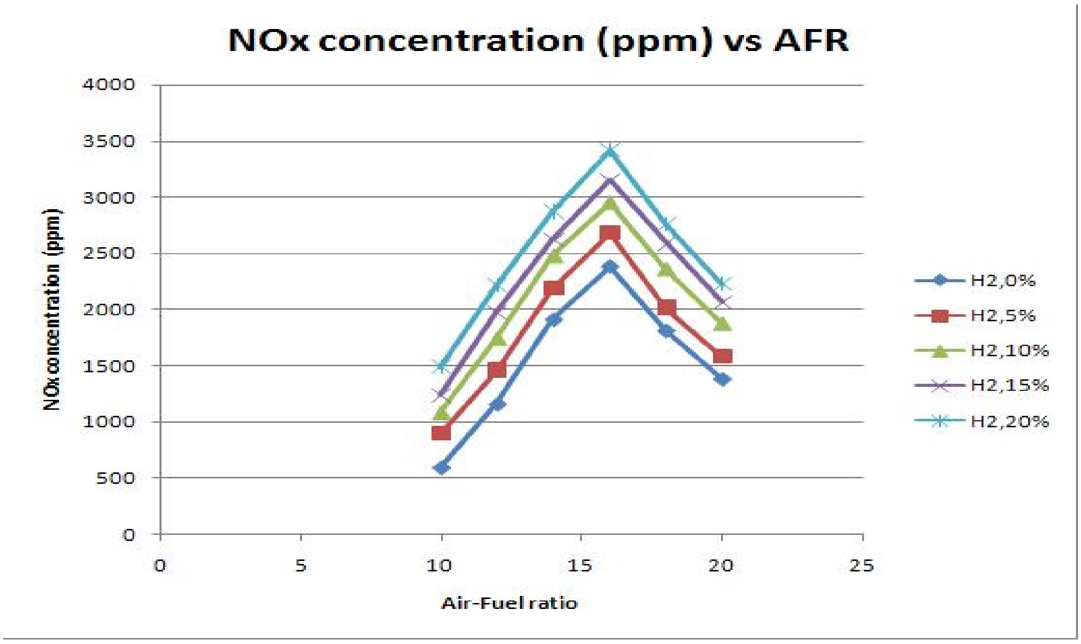


Figure 4.4: NOx concentration vs AFR

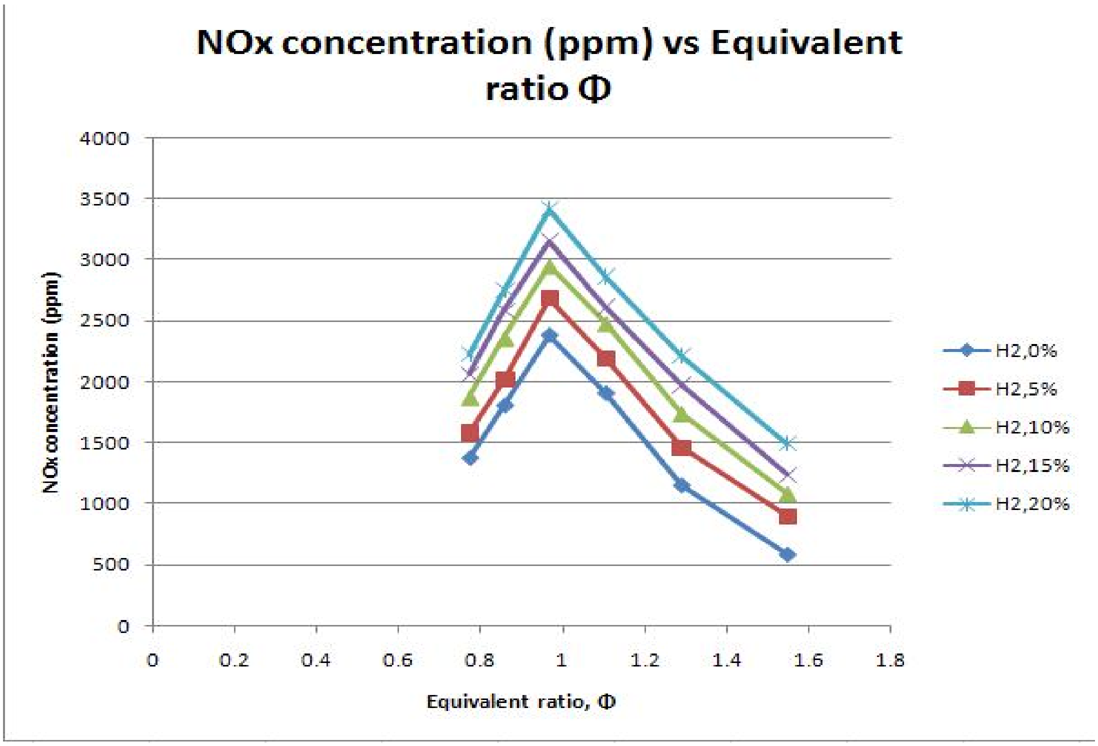


Figure 4.5: NOx concentration vs Equivalent ratio

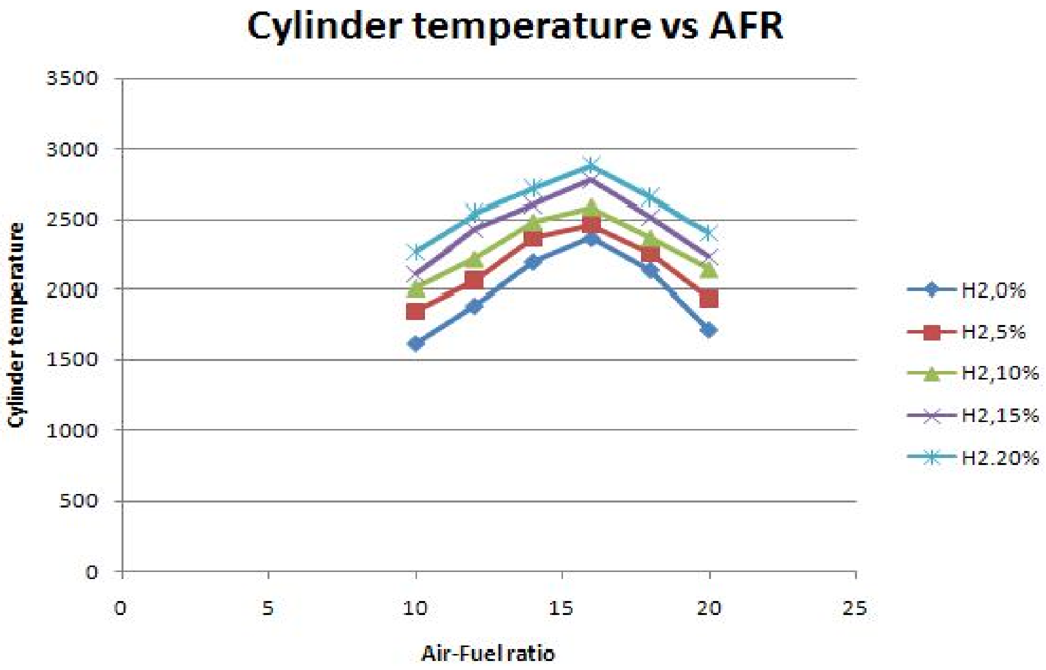


Figure 4.6: Temperature vs AFR

From figure 4.4, the entire graph is shown in increasing before decreasing when air-fuel ratio is increase. For the beginning when there is no hydrogen added to the gasoline engine, maximum concentration occurred at AFR 16 which is 2379.89 ppm. After 5 percent added, there are slightly increasing in NOx concentration and the maximum concentration occurred at AFR 16 which is 2678.81 ppm. For 10 percent hydrogen added the highest concentration occurred at 16 AFR which are 2950.77 ppm. For 15 and 20 percent hydrogen added, maximum concentration occurred at 16 AFR which is 3148.87 ppm and 3414.56 ppm respectively.

From figure 4.5, the entire graph is increase with increasing of equivalent ratio but it decrease at certain point of equivalent ratio. For 0 percent hydrogen added, maximum NOx concentration occurred at 0.964 Φ which is 2379.89 ppm. For 5 percent hydrogen added, the highest NOx concentration occurred at 0.964 Φ which is 2678.81 ppm. For 10 percent hydrogen added, peak NOx concentration occurred at 0.964 Φ which is 2950.77 ppm. For 15 percent hydrogen added, maximum NOx concentration occurred at 0.964 Φ which is 3148.87 ppm. For 20 percent hydrogen added, the highest NOx concentration occurred at 0.964 Φ which is 3414.56 ppm.

From figure 4.6, the entire graph is increasing before it decreases at certain point. For 0 percent hydrogen added, the lowest temperature occurred at 10 AFR which is 1618 K while the highest occurred at 16 AFR which is 2365.32 K. For 5 percent hydrogen added, minimum temperature occurred at 10 AFR which is 1849.45 K while maximum occurred at 16 AFR which is 2459.88 K. For 10 percent hydrogen added, the lowest temperature occurred at 10 AFR which is 2006.94 K while the highest occurred at 16 AFR which is 2581.41 K. For 15 percent hydrogen added, the lowest temperature occurred at 10 AFR which is 2110.2 K while the highest occurred at 16 AFR which is 2776.52 K. For 20 percent hydrogen added, minimum temperature occurred at 10 AFR which is 2271.18 K while maximum occurred at 16 AFR which is 2876.59 K.

4.2.3 At 5000 RPM(high engine speed)

Result for NOx and temperature at 5000 rpm(high engine speed)

Table 4.11: Data distribution for 0% hydrogen addition

H2,0%

NOx concentration (ppm)	**Air Fuel Ratio(actual)**	**Equivalent ratio,Φ**	**Cylinder Temperature (K)**
707.8	10	1.547	1416.86
1456.58	12	1.289	1987.53
2116.38	14	1.105	2455.88
2587.98	16	0.967	2665.32
1994.6	18	0.859	2357.41
1408.87	20	0.774	1918

Table 4.12: Data distribution for 5% hydrogen addition

H2,5%

NOx concentration (ppm)	**Air Fuel Ratio(actual)**	**Equivalent ratio,Φ**	**Cylinder Temperature (K)**
998.81	10	1.547	1665.21
1770.33	12	1.289	2183.42

2450.88	14	1.105	2534.59
2996.91	16	0.967	2734.12
2342.6	18	0.859	2542.3
1804.08	20	0.774	2178.08

Table 4.13: Data distribution for 10% hydrogen addition

H2,10%

NOx concentration (ppm)	Air Fuel Ratio(actual)	Equivalent ratio,Φ	Cylinder Temperature (K)
1201.89	10	1.547	1865.21
2029.68	12	1.289	2422.24
2729.68	14	1.105	2671.85
3293.86	16	0.967	2816.89
2588.1	18	0.859	2609.75
2059.78	20	0.774	2390.81

Table 4.14: Data distribution for 15% hydrogen addition

H2,15%

NOx concentration (ppm)	Air Fuel Ratio(actual)	Equivalent ratio,Φ	Cylinder Temperature (K)
1432.81	10	1.547	2139.41
2309.29	12	1.289	2595.39
2997.01	14	1.105	2760.89
3537.93	16	0.967	2910.65
2865.1	18	0.859	2705.68
2271.2	20	0.774	2495.7

Table 4.15: Data distribution for 20% hydrogen addition

H2,20%

NOx concentration (ppm)	Air Fuel Ratio(actual)	Equivalent ratio,Φ	Cylinder Temperature (K)

1659.89	10	1.547	2489.59
2583.42	12	1.289	2719.68
3290.47	14	1.105	2904.51
3867.63	16	0.967	3073.22
3092.87	18	0.859	2850.02
2470.9	20	0.774	2654.93

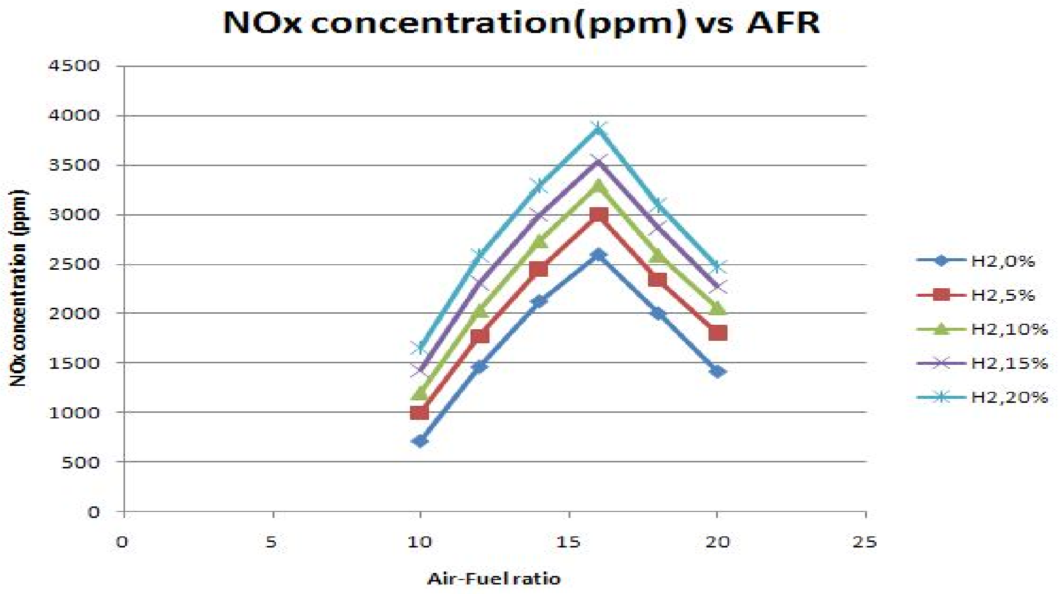


Figure 4.7: NOx concentration vs AFR

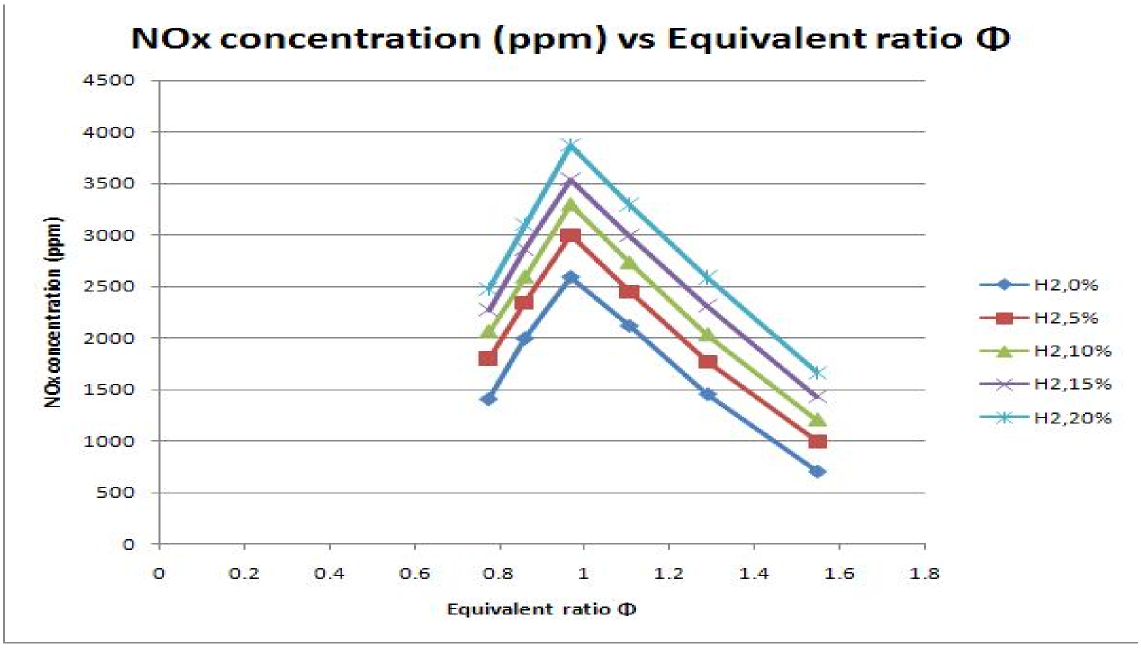


Figure 4.8: NOx concentration vs Equivalent ratio

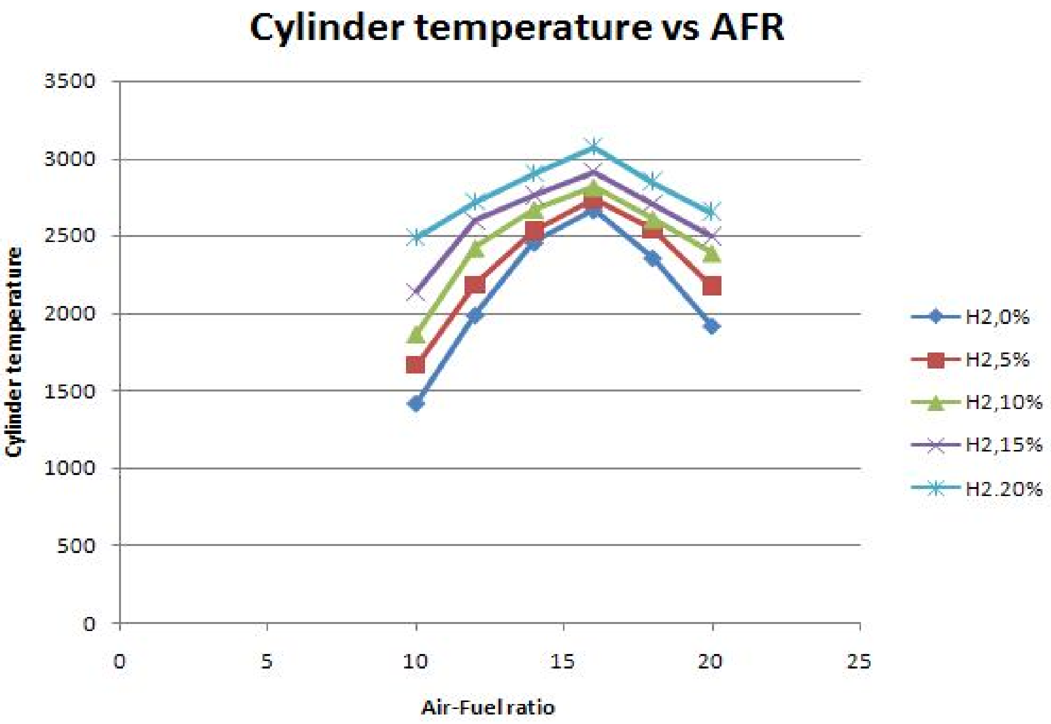


Figure 4.9: Temperature vs AFR

From figure 4.7, the entire graph is shown in increasing before decreasing when air-fuel ratio is increase. Starting with no hydrogen added to the gasoline engine, maximum concentration occurs at AFR 16 which is 2216.38 ppm. After 5 percent added, there are slightly increasing in NOx concentration and the maximum concentration occur at AFR 16 which is 2750.88 ppm. For 10 percent hydrogen added there are slightly difference where maximum concentration occurred at 16 AFR which are 3029.68 ppm. For 15 and 20 percent hydrogen added, maximum concentration occurred at 16 AFR which is 3537.01 ppm and 3990.47 ppm respectively.

From figure 4.8, the entire graph is increase with increasing of equivalent ratio but it decrease at certain point of equivalent ratio. For 0 percent hydrogen added, maximum NOx concentration occurred at 0.964 Φ which is 2587.98 ppm. For 5 percent hydrogen added, the highest NOx concentration occurred at 0.964 Φ which is 2996.91 ppm. For 10 percent hydrogen added the peak NOx concentration occurred at 0.964 Φ which is 3293.86 ppm. For 15 percent hydrogen added, maximum NOx concentration occurred at 0.964 Φ which is 3537.93 ppm. For 20 percent hydrogen added, highest NOx concentration occurred at 0.964 Φ which is 3867.63 ppm.

From figure 4.9, the entire graph is increasing before it decreases at certain point. For 0 percent hydrogen added, the lowest temperature occurred at 10 AFR which is 1416.86 K while the highest occurred at 16 AFR which is 2665.32 K. For 5 percent hydrogen added, minimum temperature occurred at 10 AFR which is 1665.21 K while maximum occurred at 16 AFR which is 2734.12 K. For 10 percent hydrogen added, the lowest temperature occurred at 10 AFR which is 1865.21 K while the highest occurred at 16 AFR which is 2816.89 K. For 15 percent hydrogen added, the lowest temperature occurred at 10 AFR which is 2139.41 K while the highest occurred at 16 AFR which is 2910.65 K. For 20 percent hydrogen added, minimum temperature occurred at 10 AFR which is 2489.59 K while maximum occurred at 16 AFR which is 3073.22 K.

4.3 DISCUSSION

4.3.1 Effect of NOx emission on Air-Fuel Ratio

From those graph it can be seen that while operating close to stoichiometric conditions the addition of hydrogen has little impact on the NOx concentration.The highest NOx concentration mostly found at 16 AFR which is about 0.964 Φ where near to stoichiometric AFR which is 15.47. As described in the theory NOx concentration has a maximum in the fuel-lean zone ($\Phi < 1$). This maximum comes from the amount of excess oxygen existing in the fuel-lean region (Changwei Ji, Shuofeng Wang, 2009). And at for $\Phi > 1$, it seems that NOx cencentration decrease or less than fuel-lean region. It is because a fuel-rich air-fuel ratio does not have enough oxygen to react with all the carbon and hydrogen, and both HC and CO emissions increase. Although the hydrogen-enriched engine ejects more NOx emissions when the excess air ratio is around stoichiometric conditions, NOx emissions for all hydrogen enrichment levels drop to an acceptable value when the engine runs under rich conditions, ($\Phi > 1$).

4.3.2 Effect of NOx emission on Cylinder Temperature

The generation of NOx emission is a function of the combustion temperature (Williard W. Pulkrabek, 2004), being greatest near stoichiometric conditions when temperatures are the highest. Peak emission occurs at slightly lean conditions, where the combustion temperature is high and there is an excess of oxygen react with the nitrogen (John B. Heywood, 1988). Beside that the increment of NOx emission is increasing with increasing of hydrogen addition to the gasoline engine. Because temperatures cylinder is raised after hydrogen addition. So NOx emissions increase with the increase of hydrogen addition level (Changwei Ji, Shuofeng Wang, 2009). With increasing of hydrogen addition level, the relevant excess air ratio for the maximum NOx emissions slightly increase. The possible explanation could be that the higher hydrogen addition fraction is, the more air is needed for hydrogen to be fully burnt to produce higher in-cylinder temperature. Because of the existence of inhomogeneity of gasoline–hydrogen–air mixture in the cylinder, a larger excess air ratio is needed for the hydrogen contained in the gasoline–hydrogen–air mixture a larger hydrogen addition fraction to be fully combusted to produce a maximum cylinder temperature. So the higher hydrogen addition fraction is, the larger excess air ratio is required to accomplish the maximum cylinder temperature and form the maximum NOx emissions. From the result also, NOx emission is slightly increase with increasing the engine speed because the NOx concentration of the three different engine speed are differ from each other. As increase an engine speed the NOx emission also increase.

CHAPTER 5

CONCLUSION

5.1 INTRODUCTION

The 1-D simulation is essential to model or to analyze the engine. From the 1-D simulation, the information and performance of the engine can be obtained. From the analysis of the engine, optimum engine speed for the operating condition of the engine can be determined. Also, any other performances and analysis can be obtained like NOx concentration emission, brake specific fuel consumption, pressure and temperature at combustion chamber also can be determined.

5.2 CONCLUSION

For this thesis, the effect of hydrogen addition to gasoline fuel on NOx emission are investigated. The analysis was performed by using GT-Power simulation software with default parameters. From this analysis, NOx emission is increasing with percentage of hydrogen fuel addition. Also, the temperatures have big influence in NOx formation whereas with the addition of hydrogen causes an increase in peak burned gas temperatures. Consequently, the hydrogen addition level will increase cylinder temperature and increase favours the formation of NO over NO2 and also causes an increase in NO formation rates. NOx formations also depends on pressure, air-fuel ratio, and combustion time within the cylinder and the chemical reactions not being instantaneous.

5. 3 RECOMMENDATION

As a recommendation, at some point, there are some recommendations in order to overcome the constraints during the simulations. This recommendation can be used for the future in order to improve this project so that more successfully and to achieve quality finding.

For this study it is important to get more precise result, the simulation result should be compare with the experimental result so that the result get from the 1 of the method not very far different.

Besides that, the simulation must conduct on real baseline engine design which is used parameter measured from real engine in order to get a better result and easier to do a comparison with the experimental result.

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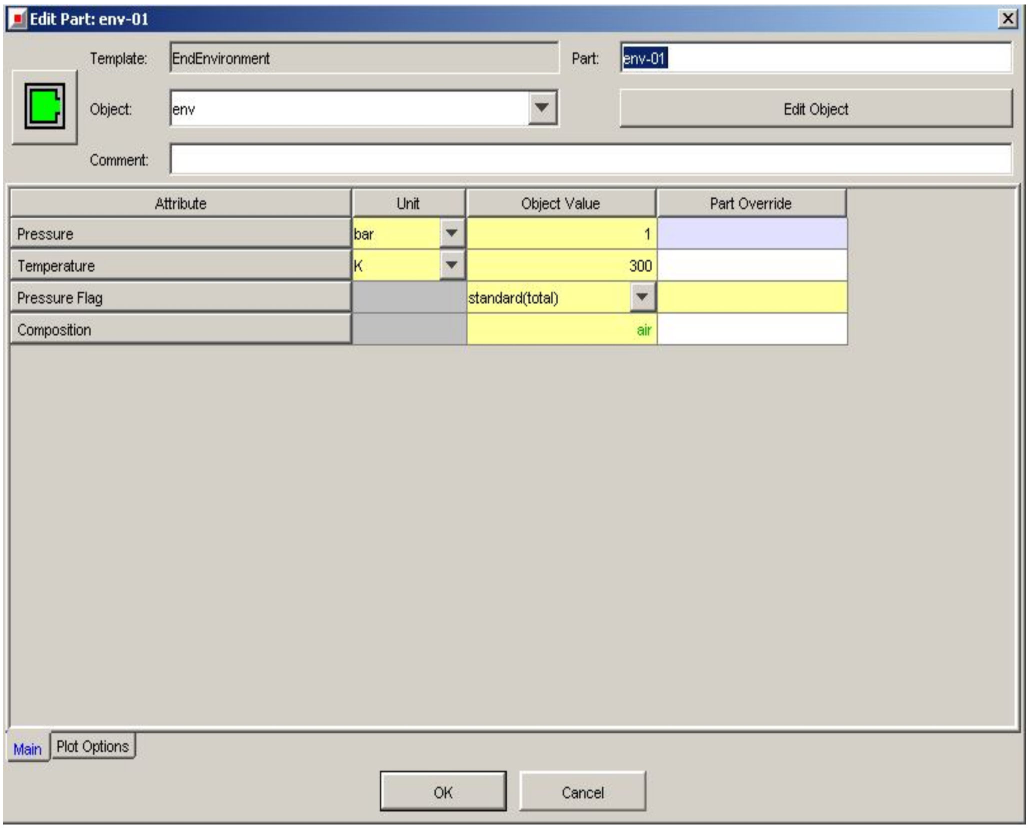
APPENDIX A

1)



Edit Part: env-01

Template: EndEnvironment

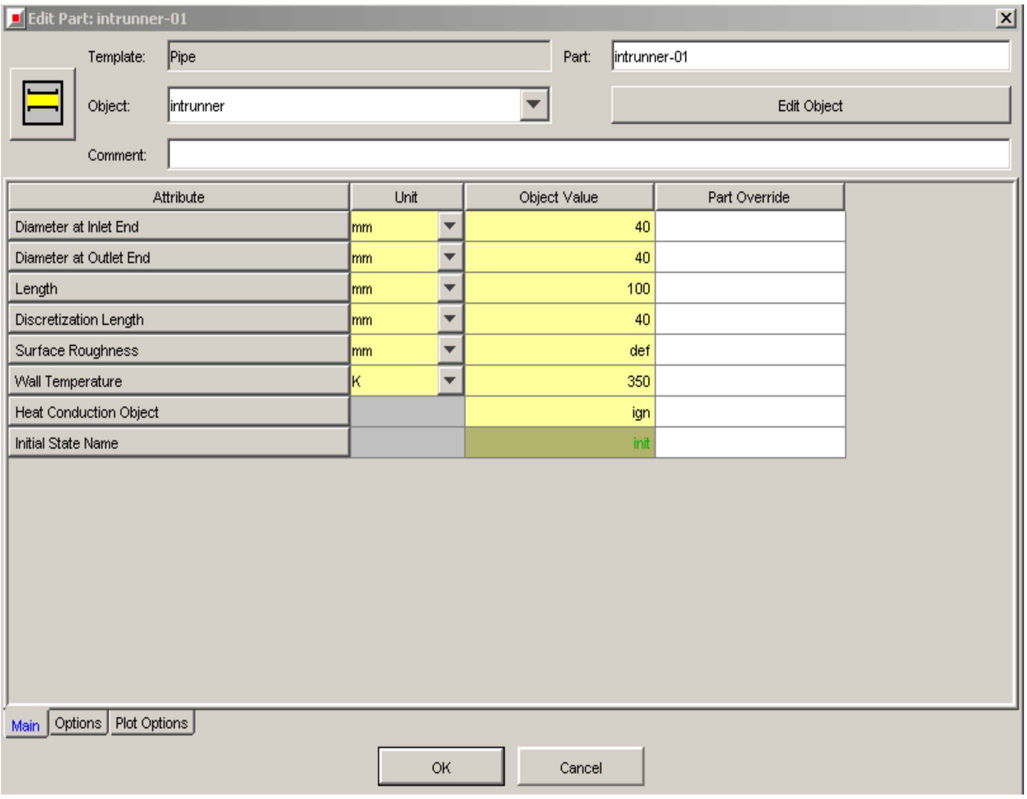
Part: env-01

Object: env

Comment:

Attribute	Unit	Object Value	Part Override
Pressure	bar	1	
Temperature	K	300	
Pressure Flag		standard(total)	
Composition		air	

2)



Edit Part: intrunner-01

Template: Pipe

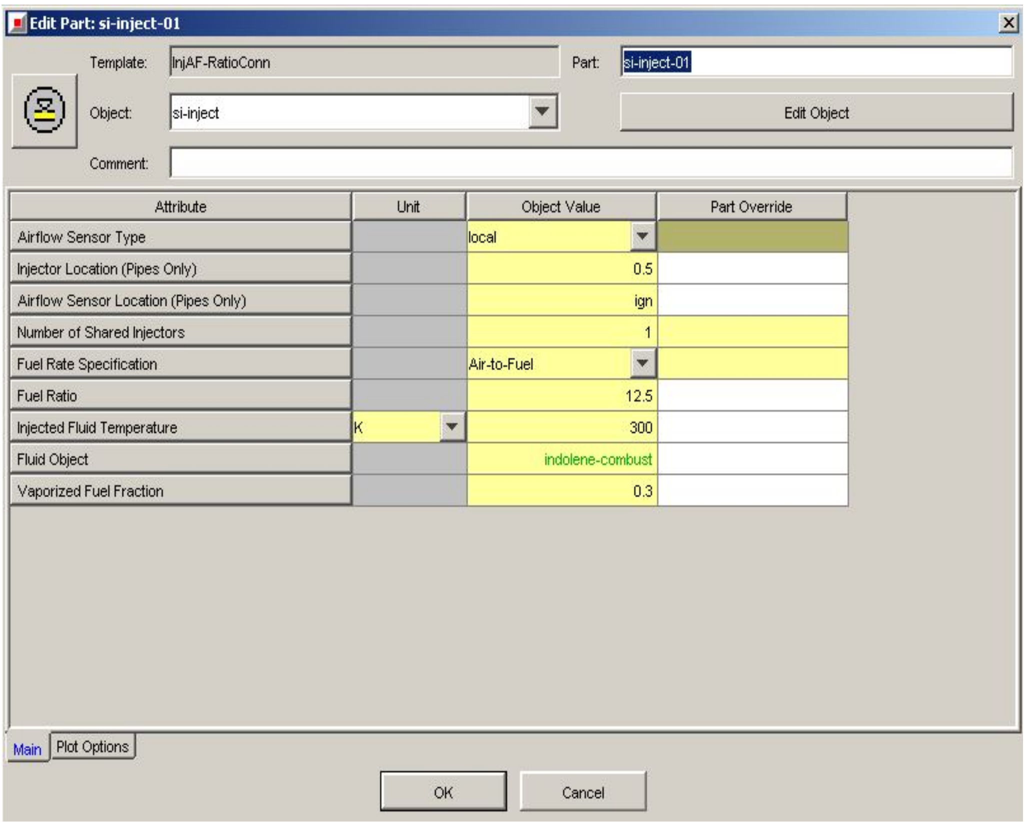
Part: intrunner-01

Object: intrunner

Comment:

Attribute	Unit	Object Value	Part Override
Diameter at Inlet End	mm	40	
Diameter at Outlet End	mm	40	
Length	mm	100	
Discretization Length	mm	40	
Surface Roughness	mm	def	
Wall Temperature	K	350	
Heat Conduction Object		ign	
Initial State Name		init	

3)



Edit Part: si-inject-01

Template: InjAF-RatioConn

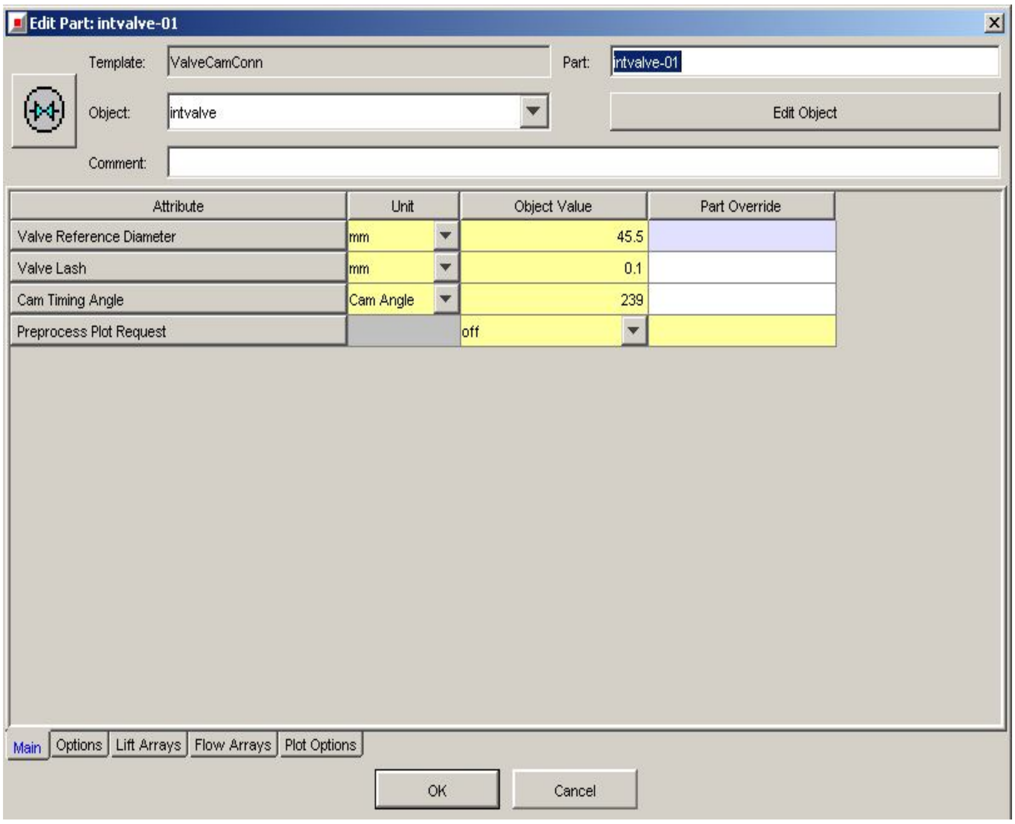
Part: si-inject-01

Object: si-inject

Comment:

Attribute	Unit	Object Value	Part Override
Airflow Sensor Type		local	
Injector Location (Pipes Only)		0.5	
Airflow Sensor Location (Pipes Only)		ign	
Number of Shared Injectors		1	
Fuel Rate Specification		Air-to-Fuel	
Fuel Ratio		12.5	
Injected Fluid Temperature	K	300	
Fluid Object		indolene-combust	
Vaporized Fuel Fraction		0.3	

4)



Edit Part: intvalve-01

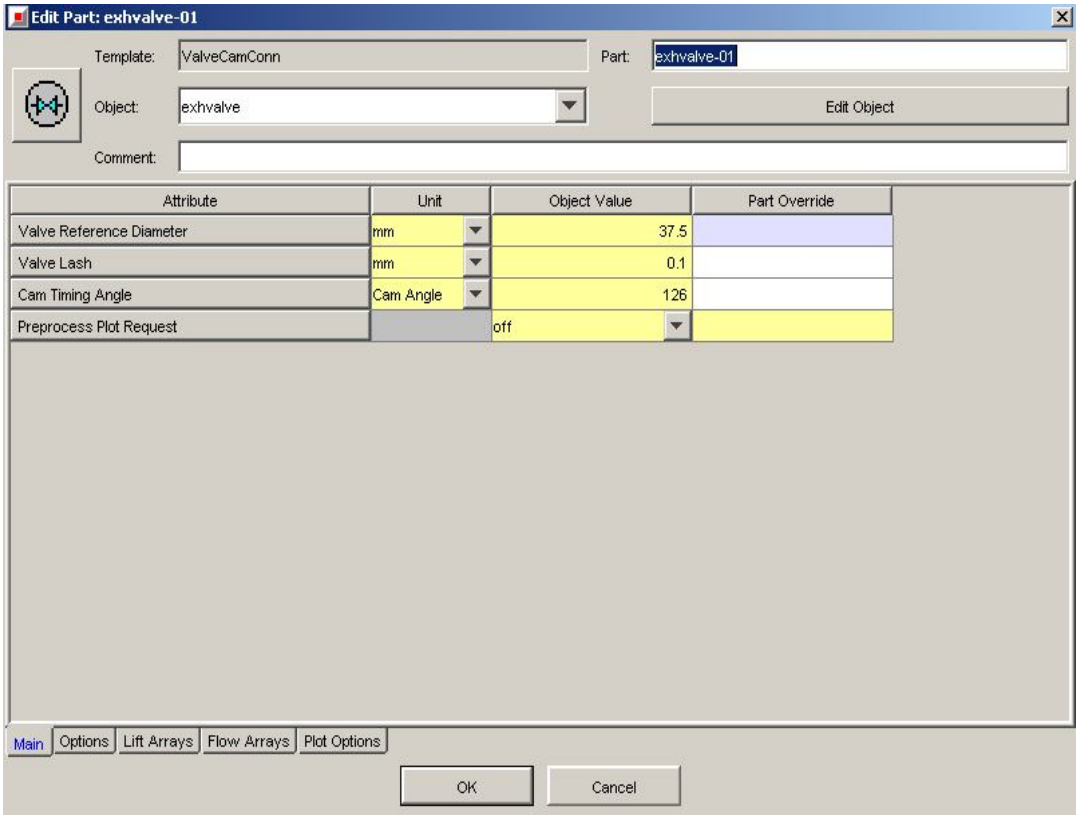
Template: ValveCamConn

Part: intvalve-01

Object: intvalve

Comment:

Attribute	Unit	Object Value	Part Override
Valve Reference Diameter	mm	45.5	
Valve Lash	mm	0.1	
Cam Timing Angle	Cam Angle	239	
Preprocess Plot Request		off	



Template: ValveCamConn

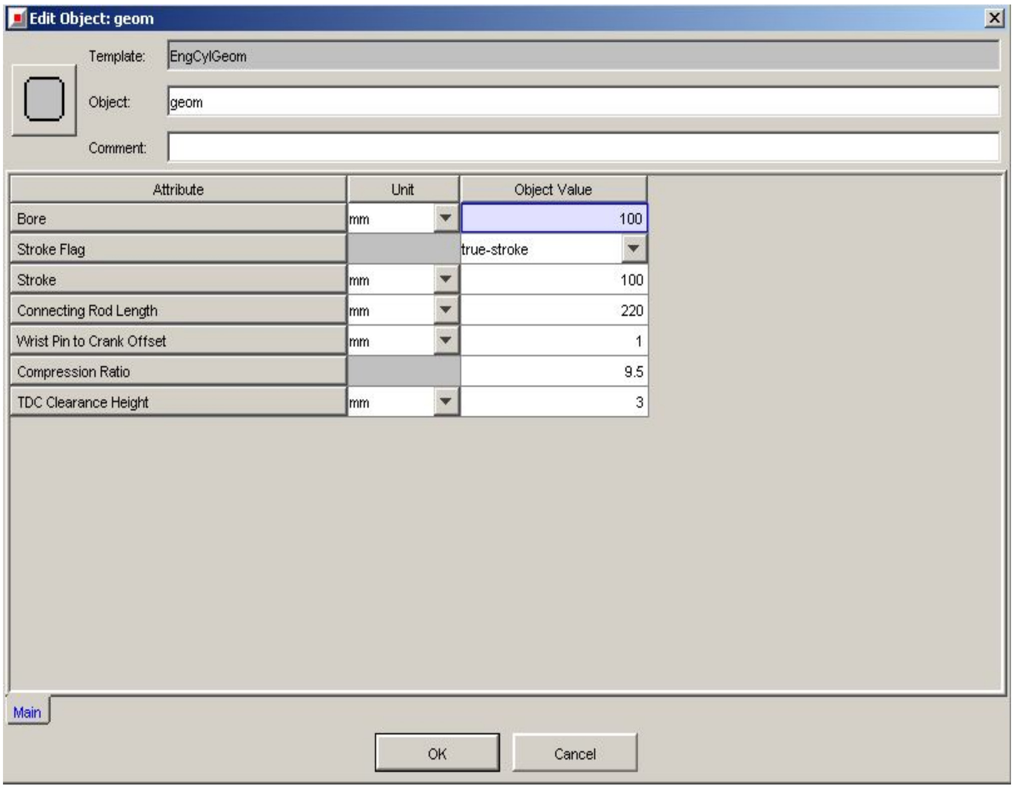
Part: exhvalve-01

Object: exhvalve

Comment:

Attribute	Unit	Object Value	Part Override
Valve Reference Diameter	mm	37.5	
Valve Lash	mm	0.1	
Cam Timing Angle	Cam Angle	126	
Preprocess Plot Request		off	

5)



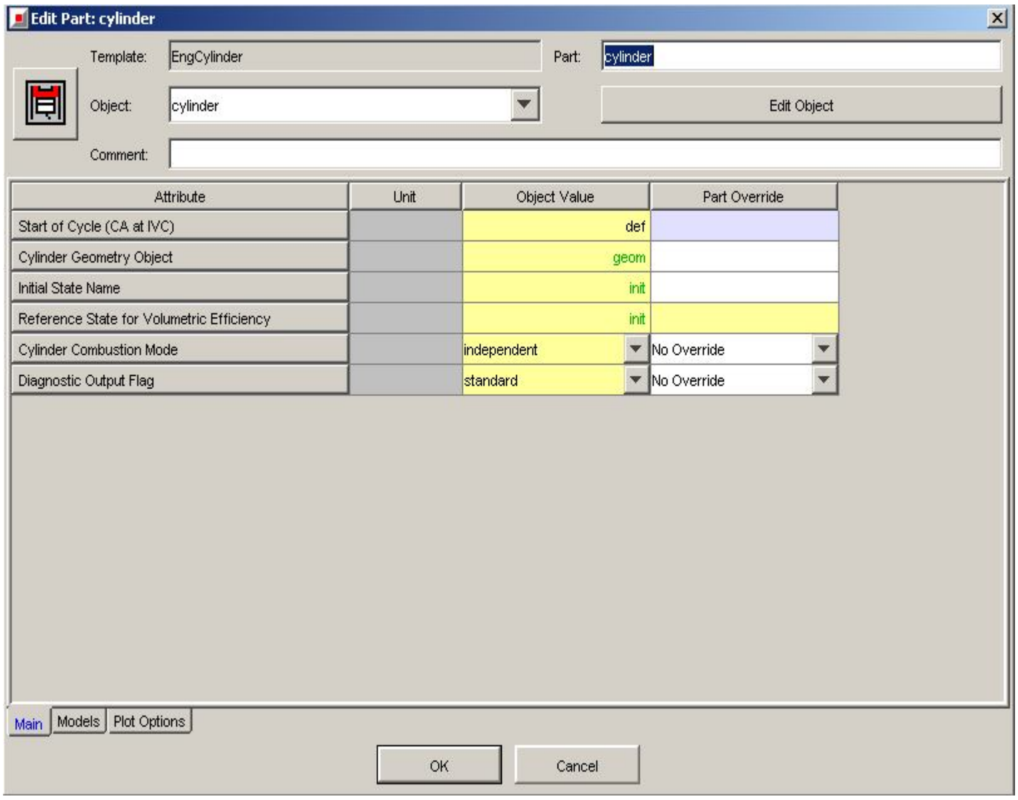
Template: EngCylGeom

Object: geom

Comment:

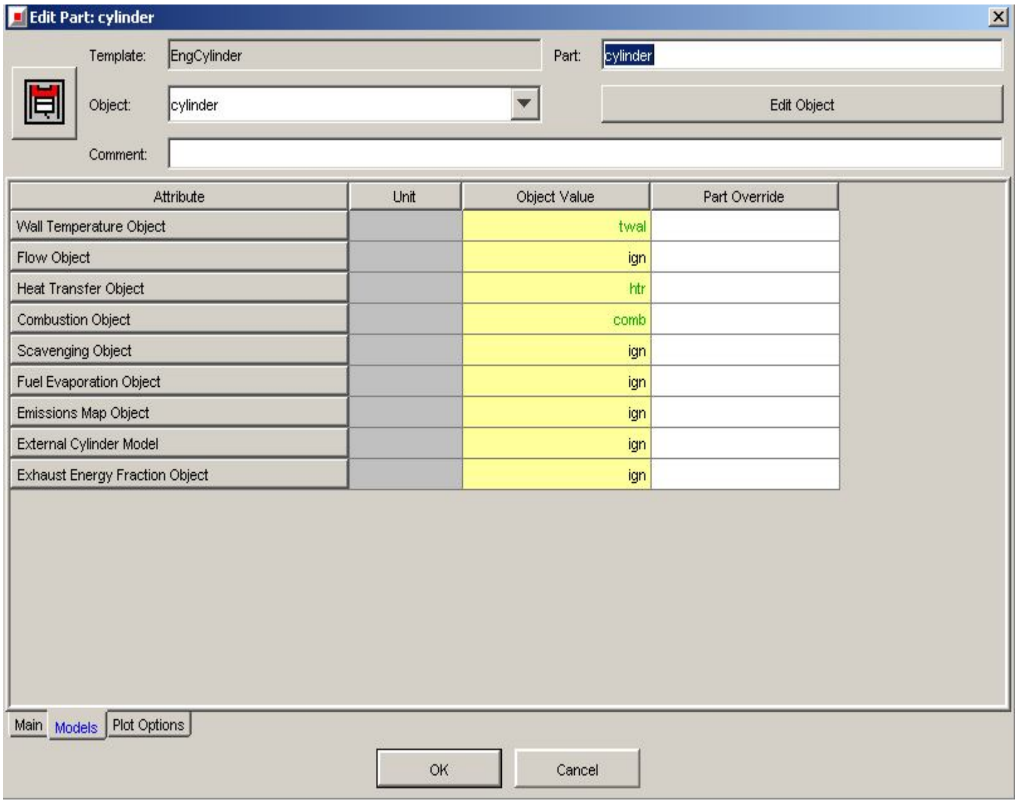
Attribute	Unit	Object Value
Bore	mm	100
Stroke Flag		true-stroke
Stroke	mm	100
Connecting Rod Length	mm	220
Wrist Pin to Crank Offset	mm	1
Compression Ratio		9.5
TDC Clearance Height	mm	3

6)



Template: EngCylinder
Part: cylinder
Object: cylinder
Comment:

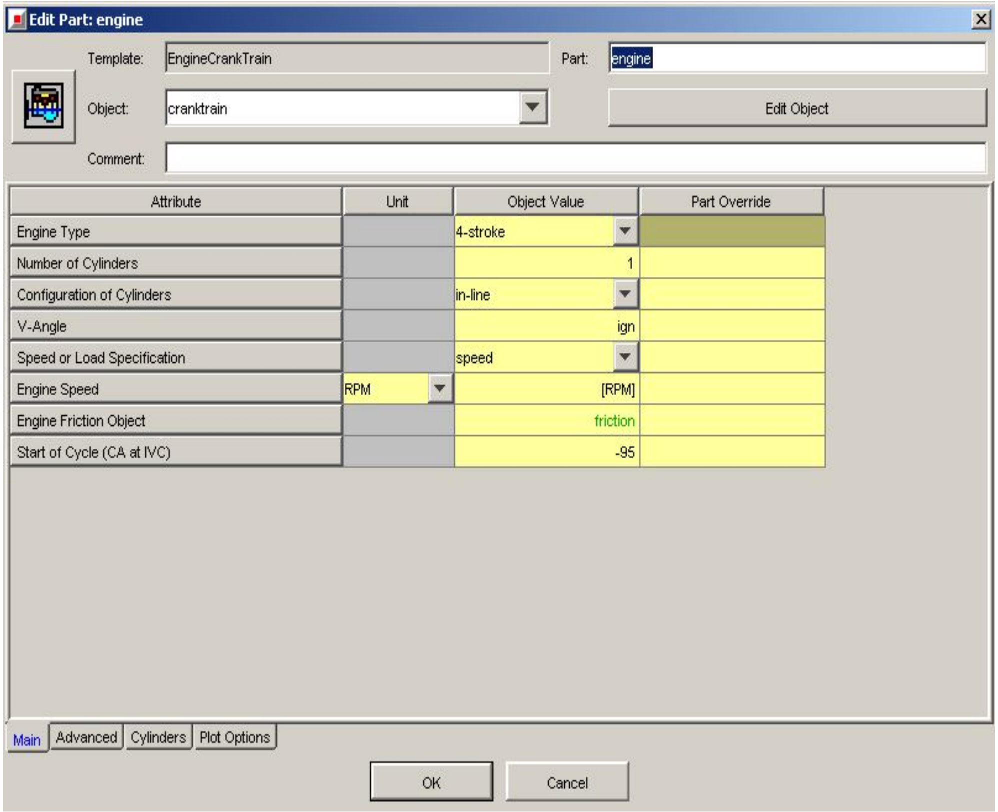
Attribute	Unit	Object Value	Part Override
Start of Cycle (CA at IVC)		def	
Cylinder Geometry Object		geom	
Initial State Name		init	
Reference State for Volumetric Efficiency		init	
Cylinder Combustion Mode		independent	No Override
Diagnostic Output Flag		standard	No Override



Template: EngCylinder
Part: cylinder
Object: cylinder
Comment:

Attribute	Unit	Object Value	Part Override
Wall Temperature Object		twal	
Flow Object		ign	
Heat Transfer Object		htr	
Combustion Object		comb	
Scavenging Object		ign	
Fuel Evaporation Object		ign	
Emissions Map Object		ign	
External Cylinder Model		ign	
Exhaust Energy Fraction Object		ign	

7)



Edit Part: engine

Template: EngineCrankTrain

Part: engine

Object: cranktrain

Comment:

Attribute	Unit	Object Value	Part Override
Engine Type		4-stroke	
Number of Cylinders		1	
Configuration of Cylinders		in-line	
V-Angle		ign	
Speed or Load Specification		speed	
Engine Speed	RPM	[RPM]	
Engine Friction Object		friction	
Start of Cycle (CA at IVC)		-95	

APPENDIX B

1)

#Case 1 **Ratio hydrogen vapor to gasoline vapor**

Attribute Properties	**Hydrogen vapor**		**Gasoline vapor**		**Total 100%**
	0%	**5%**	**100%**	**95%**	
Carbon atom per molecule	0	0	7.93	7.5335	7.5335
Hydrogen atom per molecule	2	0.1	14.8	14.06	14.16
Oxygen atom per molecule	0	0	0	0	0
Nitrogen atom per molecule	0	0	0	0	0
Lower heating value	1.1994e+8 J/Kg	5.997e+6 J/Kg	4.395e+7 J/Kg	4.17525e+7 J/Kg	4.77495e+7 J/Kg
Critical temperature	33.2 K	1.66 K	568.8 K	540.36 K	542.02 K
Critical pressure	13 bar	0.65 bar	24.9 bar	23.655 bar	24.305 bar
Minimum valid temperature	100 K	5 K	100 K	95 K	100 K
Maximum valid temperature	4000 K	200 K	1200 K	1140 K	1340 K
Minimum valid pressure	0.01 bar	0.0005 bar	0.01 bar	0.0095 bar	0.01 bar
Maximum valid pressure	300 bar	15 bar	300 bar	285 bar	300 bar

#Case 2

Attribute Properties	**Hydrogen vapor**		**Gasoline vapor**		**Total 100%**
	0%	**10%**	**100%**	**90%**	

Carbon atom per molecule	0	0	7.93	7.137	7.137
Hydrogen atom per molecule	2	0.2	14.8	13.32	13.52
Oxygen atom per molecule	0	0	0	0	0
Nitrogen atom per molecule	0	0	0	0	0
Lower heating value	1.1994e+8 J/Kg	1.1994e+7 J/Kg	4.395e+7 J/Kg	3.9555e+7 J/Kg	5.1549e+7 J/Kg
Critical temperature	33.2 K	3.32 K	568.8 K	511.92 K	515.24 K
Critical pressure	13 bar	1.3 bar	24.9 bar	22.41 bar	23.71 bar
Minimum valid temperature	100 K	10 K	100 K	90 K	100 K
Maximum valid temperature	4000 K	400 K	1200 K	1080 K	1480 K
Minimum valid pressure	0.01 bar	0.001 bar	0.01 bar	0.009 bar	0.01 bar
Maximum valid pressure	300 bar	30 bar	300 bar	270 bar	300 bar

#Case 3

Attribute Properties	**Hydrogen vapor**		**Gasoline vapor**		**Total 100%**
	0%	**15%**	**100%**	**85%**	
Carbon atom per molecule	0	0	7.93	6.7495	6.7495
Hydrogen atom per molecule	2	0.3	14.8	12.58	12.88
Oxygen atom per molecule	0	0	0	0	0
Nitrogen atom per molecule	0	0	0	0	0
Lower heating value	1.1994e+8 J/Kg	1.7991e+7 J/Kg	4.395e+7 J/Kg	3.73575e+7 J/Kg	5.53485e+7 J/Kg
Critical	33.2 K	4.98 K	568.8 K	483.48 K	488.46 K

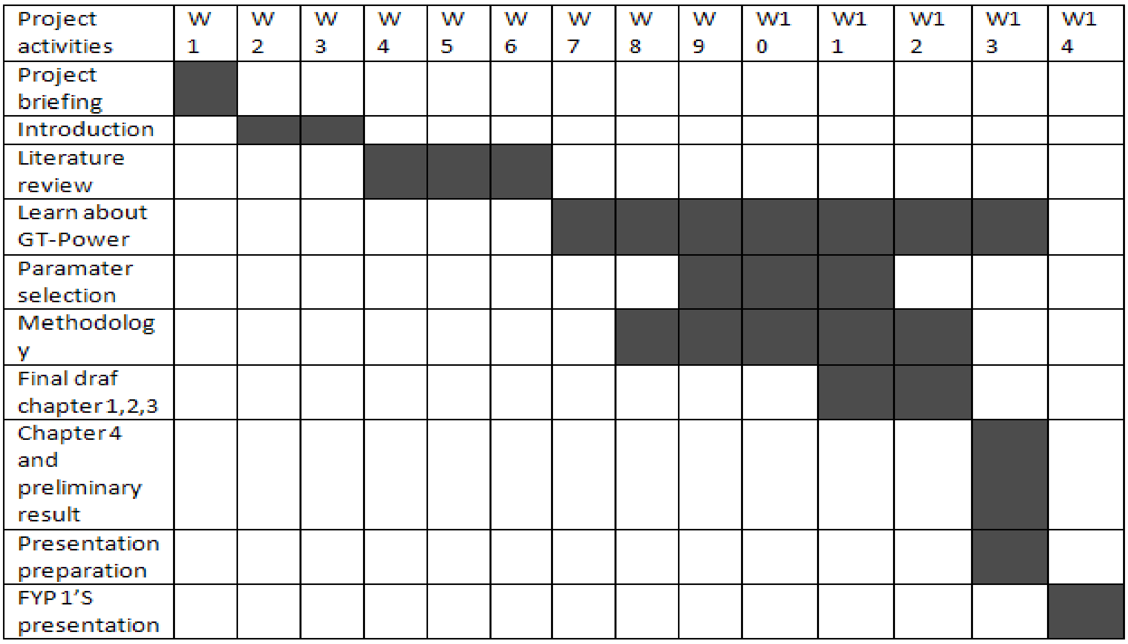
temperature					
Critical pressure	13 bar	1.95 bar	24.9 bar	21.165 bar	23.115 bar
Minimum valid temperature	100 K	15 K	100 K	85 K	100 K
Maximum valid temperature	4000 K	600 K	1200 K	1020 K	1620 K
Minimum valid pressure	0.01 bar	0.00015 bar	0.01 bar	0.0085 bar	0.01 bar
Maximum valid pressure	300 bar	45 bar	300 bar	255 bar	300 bar

#Case 4

Attribute Properties	**Hydrogen vapor**		**Gasoline vapor**		**Total 100%**
	0%	**20%**	**100%**	**80%**	
Carbon atom per molecule	0	0	7.93	6.344	6.344
Hydrogen atom per molecule	2	0.4	14.8	11.84	12.24
Oxygen atom per molecule	0	0	0	0	0
Nitrogen atom per molecule	0	0	0	0	0
Lower heating value	1.1994e+8 J/Kg	2.3988e+7 J/Kg	4.395e+7 J/Kg	3.516e+7 J/Kg	5.9148e+7 J/Kg
Critical temperature	33.2 K	6.64 K	568.8 K	455.04 K	461.68 K
Critical pressure	13 bar	2.6 bar	24.9 bar	19.92 bar	22.52 bar
Minimum valid temperature	100 K	20 K	100 K	80 K	100 K
Maximum valid temperature	4000 K	800 K	1200 K	960 K	1760 K
Minimum valid pressure	0.01 bar	0.002 bar	0.01 bar	0.008 bar	0.01 bar
Maximum valid pressure	300 bar	60 bar	300 bar	240 bar	300 bar

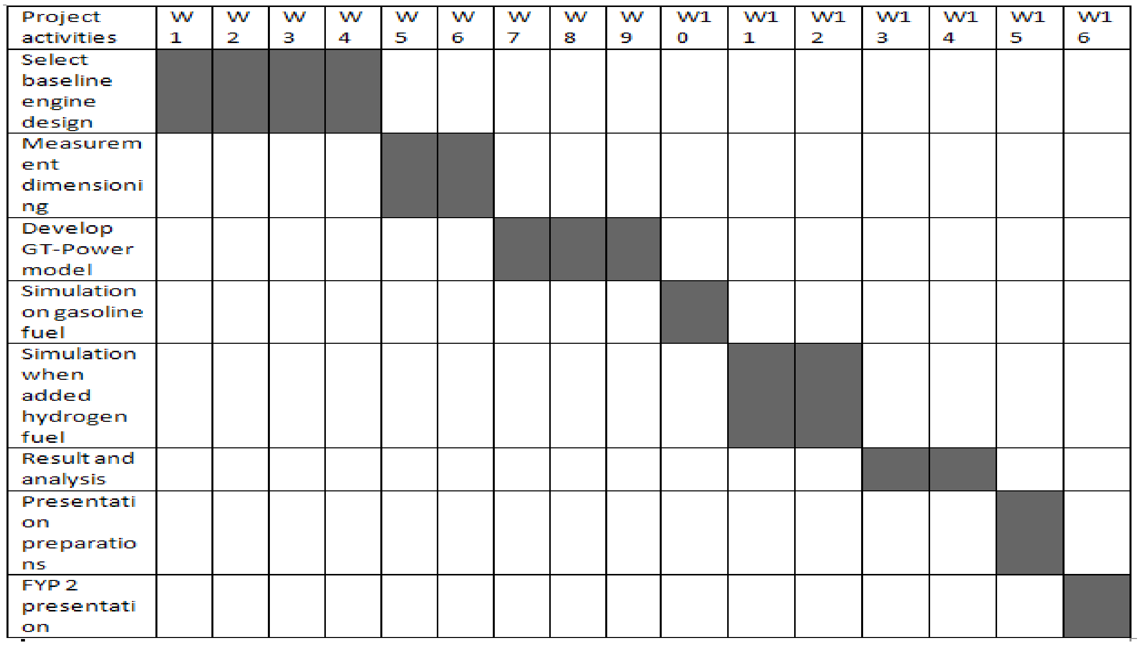
APPENDIX C

1)



Project activities	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
Project briefing	■													
Introduction		■	■											
Literature review				■	■	■								
Learn about GT-Power							■	■	■	■	■	■	■	
Paramater selection									■	■	■			
Methodology								■	■	■	■	■		
Final draf chapter 1,2,3											■	■		
Chapter 4 and preliminary result													■	
Presentation preparation													■	
FYP 1'S presentation														■

2)



Project activities	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15	W16
Select baseline engine design	■	■	■	■												
Measurement dimensioning					■	■										
Develop GT-Power model							■	■	■							
Simulation on gasoline fuel										■						
Simulation when added hydrogen fuel											■	■				
Result and analysis													■	■		
Presentation preparations															■	
FYP 2 presentation																■